Culvert design and operation guide

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Where we are

Discover how your organisation can benefit from CIRIA's authoritative and practical guidance – contact us by:

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Culvert design and operation guide

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Culvert design and operation guide

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Front cover image **Culvert inspection on the A9 road at Glen Garry in Scotland, shown partially-blocked by sediments washed out from the glacial till (courtesy Transport Scotland)**

Summary

A culvert provides the means of allowing infrastructure (generally a highway, railway or waterway) to cross a watercourse. Culverts are superficially simple structures, but they have the potential to restrict flow (causing flooding), and to adversely affect the aquatic environment. Also, assessment of the hydraulic performance of a culvert can be complex.

In service a well-designed culvert may require little attention from an asset manager other than routine inspection and maintenance. However, there are thousands of existing culverts across the UK, many designed for conditions that have been significantly altered by urban development, climate change and concern about the quality of the aquatic environment. Problems of decaying structural fabric, sedimentation, blockage by debris, and inadequate capacity present an asset manager with a constant demand for assessment, rehabilitation, repair and enhancement. Also, there are increasing environmental pressures, driven by legislation such as the Water Framework Directive, that require asset managers to examine options for improving the environmental performance of culverts, including restoring the watercourse back to a more natural state.

It is in this context that this guide has been drafted to replace the *Culvert design manual* (R168) published by CIRIA (Ramsbottom, Day and Rickard, 1997). This guide adopts a whole-life approach to the design and operation of culverts, with a focus on asset management, reflecting the significant changes that have occurred in the business of asset management over the past 10 to 15 years. The publication also addresses the management of culverts in the context of both the drainage basin in which they sit, and the infrastructure that they form part of.

This is a comprehensive guide covering a wide range of subject matter relevant to the design and operation of culverts, but does not cover the structural design of culverts. Reading the guide from cover to cover is undoubtedly the best way to benefit from the totality of its content, this may not a practicable option for most users. So it is appropriate to attempt to direct users to the parts of the guide that are more relevant to their needs.

The target audience for this guide is intentionally wide, encompassing professionals from a range of backgrounds who are involved in the planning, design, construction and management of drainage works. This includes civil engineers, hydrologists, environmental specialists and other professionals working on highway, waterway and railway infrastructure as well as land drainage and flood alleviation works. The guide provides invaluable guidance for asset managers, consulting engineers, flood risk management practitioners, local authority and drainage board engineers, infrastructure planners and environmental professionals, and is an essential reference for officers tasked with approving culvert works.

This book covers the subject comprehensively in a total of nine chapters. Chapter 1 deals with background issues, including the aims, context and scope of the guide. Chapter 2 introduces the subject of asset management as it relates to culverts. The next two chapters focus on the legal requirements, and environmental considerations. Chapters 5 and 6 cover the complex subjects of hydrology and hydraulics, providing detailed guidance on analytical methods. Chapter 7 discusses the operation, inspection and assessment of culverts, these being important components of good asset management. Chapter 8 then addresses the subject of works to existing culverts including both hydraulic and structural improvements, as well as the removal of culverts (daylighting). Chapter 9 addresses the design of culverts.

The first recourse for the user seeking guidance should be the contents list, which is logically structured and comprehensive. However, all users are advised to read Chapter 1, which sets the context for the guide, and is appropriately brief. For all other sections, the matrix presented in the following table may help the reader find the relevant sections appropriate to their needs.

This is a comprehensive guide covering a wide range of issues pertinent to the management and design of culverts, and there is inevitably some repetition throughout the guide. This is to reduce the risk of users missing vital guidance by selective reading. However, users are urged to read comprehensively, especially if new to the subject.

User guide

For ease of use this table directs the reader to sections of the guide for relevant areas of interest.

User	Area of interest	Relevant parts of guide
Planner in the early stages of project development	Impact on drainage and implications of culverting	Chapters 1, 2, 3, 4
Hydrologist and geomorphologist	Providing appropriate information on low flows, flood flows and sediment dynamics to the designer	Chapter 5
Designer	Concept design	Chapters 1, 2, 3, Chapter 9, Sections 9.1 and 9.2
	Advising on asset management issues	Chapter 2
	Hydraulic assessment to determine the appropriate size of culvert	Chapter 6
	Detailed design	Chapter 9
Regulator, consents officer, or development control officer	Reviewing proposals for culverting with a view to issuing consent	Chapters 1, 3, 4. Refer to Chapters 5, 6 and 9 for guidance on particular aspects of the submitted calculations and designs
Conservation or environmental officer	Understanding the rationale and objectives of effective design and operation of culverts	Chapters 1, 2, 3, 4
	Exploring detailed requirements for the operation of existing culverts	Chapter 7
	Understanding specific issues relating to works to existing culverts	Chapter 8
	Understanding the issues related to the design of a culvert	Chapter 9
Asset manager	Understanding responsibilities	Chapters 2, 3, 4
	Assessment of catchment hydrology, sediment and debris	Chapter 5
	Assessment of culvert hydraulic capacity	Chapter 6
	Inspection and maintenance responsibilities and practices	Chapter 7
	Improvement works to existing culverts, including repairs, extension, increased capacity	Chapter 8 and parts of Chapter 9
	Removal of an existing culvert	Chapter 8
	Design of replacement culvert	Chapters 8 and 9
Maintenance contractor	Inspection and maintenance responsibilities and practices	Chapter 7
	Improvement works to existing culverts, including repairs, extension, increased capacity	Chapter 8 and parts of Chapter 9
Riparian owner and interested members of the public	Understanding basic issues	Chapters 1, 2, 3, 4

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Glossary

Afflux	The maximum increase in water surface elevation in a watercourse due to the presence of a structure such as a bridge or culvert, relative to that which would exist without the structure.
Air entrainment	The development of air-water flow due to interaction between turbulent water and its surroundings, typically in steep conduits or at transitions such as hydraulic jumps. This is a different process to air entrainment in a concrete mix.
Annual exceedance probability (AEP)	Probability of exceeding a specified flow or level in any year (inverse of the return period for an annual maximum series).
Appraisal	The qualitative process of understanding the state of an existing asset or asset system to inform the planning of future interventions.
Assessment	The quantitative process of understanding the performance or structural competence of an existing asset or asset system to inform the planning of future interventions.
Asset management	Systematic and co-ordinated activities that an organisation optimally and sustainably manages its assets and asset system through. This includes their associated performance, risks and expenditures over their life cycles for the purpose of achieving its strategic aims.
Attenuation	Reduction in the peak discharge of a flood as it passes down river due to storage or constrictions.
Backflow	Flow in a culvert or drain in the opposite direction to the normal flow direction as a result of a high downstream water level (most often experienced in tidal waters).
Backwater effect	An increase in water level some distance upstream of a hydraulic structure. The extent of the backwater effect is known as the backwater length.
Bedload	Sediment load in a channel that travels by rolling, sliding or bouncing along the bed.
Boulder trap	A coarse screen with widely-spaced bars designed to trap large sediment rolling along the watercourse as bed load, and to allow the remaining water and floating debris to overtop, usually located upstream of a trash screen.
Catchment	The area of land that drains to a given point on a river, drainage system or other body of water.
Condition appraisal	Includes the range of activities involved with the qualitative evaluation of an asset's condition and performance (ie the gathering of existing data, inspection, investigation and structural assessment).
Condition assessment	A measure or measures of the culvert carried out as a precursor to the performance assessment, for example,

	measurements of degree of sedimentation or in situ tests on the fabric of the culvert.
Condition monitoring	Continuous or periodic inspection, assessment, measurement and interpretation of the resultant data to indicate the condition of the specific component. This will determine the need for some preventive or remedial action.
Control structure	A hydraulic structure with a known relationship between water level (stage) and discharge (or flow rate).
Conveyance	A measure of the carrying capacity of a watercourse or floodplain section.
Critical depth	The water depth at critical flow.
Critical flow	Free surface flow with minimum specific energy for a given discharge and a Froude number of unity. The water depth is known as the critical depth.
Culvert	A closed conduit carrying a watercourse beneath an obstruction such as a road, railway or canal. The term "closed" implies that a culvert has a hard soffit and invert. The term "conduit" implies the conveyance of water some or all of the time, but excluding tunnels and underpasses for vehicles, pedestrians and animals.
Culvert-walkers	People who walk culverts as a sport.
Daylighting	Also known as de-culverting. The removal of a culvert to restore a watercourse to a more natural state.
Debris	Solid materials transported in a watercourse, including natural and man-made, buoyant and non-buoyant materials, but excluding sediment. See also *Trash*.
Designated watercourse	A watercourse in Northern Ireland that the Rivers Agency has powers to undertake, construct and maintain drainage works, to carry out emergency works and to make byelaws. Responsibility for maintenance remains with the occupier. Watercourses that are not designated are known as undesignated watercourses.
Design flood	The discharge or flow adopted for design, usually defined in terms of return period or annual exceedance probability.
Design life	The service life of an asset intended by the designer. This assumes some rate of deterioration up to a point where the asset requires replacement or refurbishment.
Design standard	The design flood for an asset or system chosen to provide an acceptable risk during the design life.
Desilting	Removal of accumulated sediment from the bed of a channel, generally as a maintenance activity. Also referred to as dredging, although this term is more commonly reserved for major works rather than routine maintenance.
Deterministic	Descriptor of method or process that adopts precise, single values for all variables and input values, giving a single value output.

Dewatering	The process of handling and/or reducing significant flows of water (especially groundwater) into an area where construction work is being undertaken.
Discharge	Also known as flow rate or abbreviated to flow. The volume of water passing a given point of an open channel or closed conduit in unit time, normally expressed in cubic metres per second (m^3/s).
Dredging	Underwater excavation, usually including removal of the excavated material.
Drowned weir flow	Flow over crest of weir or other hydraulic structure that does not pass through critical flow, where the upstream water level depends on the water level downstream of the structure.
Easement	A legally enforceable provision allowing access for one party across another party's land.
Energy grade line	An imaginary line showing the total head or the sum of the elevation, pressure and velocity heads, of a flow relative to a datum. The slope of the energy grade line is the energy gradient.
Environmental impact assessment (EIA)	Detailed studies that predict the effects of a development project on the environment and provide plans for mitigation of the adverse affect.
Environmental statement (ES)	A written statement that may be required to detail the effect that a proposed large new development will have on its surrounding area.
Erosion	Removal of particles from the substrate by wind, flowing water or wave action (opposite is accretion).
Failure	Inability to achieve a defined performance threshold. "Catastrophic failure" describes the situation where the consequences are immediate and severe.
Flap gate/valve	A top-hinged gate designed to close when downstream water level exceeds the upstream water level. Frequently used for drainage outfalls into tidal waters and rivers to prevent backflow (see Figure 9.25).
Flashy catchment	A catchment with a watercourse that rises immediately following a period of rain.
Floodplain	Land on either side of a river that is below the highest defined flood level.
Flow duration curve	Graph showing the proportion of time during which discharges are equalled or exceeded.
Flow rate	The volume of water passing a given point in unit time, normally expressed in cubic metres per second (m^3/s). See also *Discharge*.
Fluvial	Relating to a river.
Fluvial geomorphology	The branch of geomorphology that describes the characteristics of river systems and examines the processes sustaining them.

Freeboard	An allowance for uncertainty in design water level and any other physical processes that may affect the ability of an asset to withstand the design water level.
Free surface flow	Flow with a free water surface at atmospheric pressure and exposed to the air.
Froude number	A dimensionless ratio between inertia and gravity forces in a fluid, or between mean velocity and wave celerity. Froude number is unity for critical flow, more for supercritical flow and less for subcritical flow.
Full flow	Flow in a closed conduit in which the water surface just reaches soffit level, but does not flow under pressure.
Gabion	Wire or plastic mesh container filled with stones to protect against scour or form a retaining wall. Available as cuboids, mattresses or tubes.
Geomorphology	The scientific study of the evolution and configuration of landforms.
Geophysics	Quantitative physical methods – especially seismic, electromagnetic and radioactive – for exploring beneath the Earth's surface.
Geophysical survey	Survey methods that produce images of features (such as archaeological and geotechincal) that are hidden below the ground surface. Techniques most commonly applied to archaeological geophysical surveys are magnetometers, electrical resistance meters, ground-penetrating radar and electromagnetic conductivity measurement.
Geotextile	Permeable synthetic or natural fibre fabric used to provide erosion protection, filtration, separation, drainage or soil reinforcement.
Growth curve	A dimensionless curve that expresses the ratio between the median annual flood (QMED) and the flow for another return period or exceedance probability, such as 100-year (one per cent AEP) flow.
Hazard	A situation (physical event, phenomenon or human activity) with the potential to result in harm. A hazard does not necessarily lead to harm and it can be managed.
Head	The total energy per unit weight of fluid expressed in metres of water above a datum.
Head loss	The difference in head between two points due to friction or other features that result in energy loss (eg a transition, step, constriction, expansion, or bend).
Headwall	The retaining wall at a culvert inlet or outlet that provides support to the embankment. The headwall is normally at right angles to the culvert barrel, but may be skewed. The headwall may have wingwalls at an angle to the headwall that provide support to the channel sides and form part of the transition from channel to culvert and vice-versa (see Figures 9.2 and 9.15 and Appendix A5).

Headwater depth	The depth of water above culvert invert at the culvert inlet.
Headwater elevation	The level of water above datum at the culvert inlet.
Hydraulic grade line	An imaginary line showing the sum of the pressure and elevation heads of a flow relative to a datum. For uniform open-channel flow, the hydraulic grade line is the same as the water surface. The slope of the hydraulic grade line is the hydraulic gradient.
Hydraulic jump	Abrupt rise in water level when flow changes from supercritical to subcritical, accompanied by surface disturbance and air entrainment and an associated dissipation of energy.
Hydraulic pressure	The pressure exerted by water (whether at rest or moving) on a surface or structure. Hydraulic pressure has the units of force per unit area and is calculated for water at rest as the product of the depth of water and its density. The pressure can differ for water in motion.
Hydraulic roughness	A measure of resistance to flow due to friction and channel shape.
Hydrograph	Graph showing the variation of discharge or water level over time.
Hydromorphological elements	Terms used in the Water Framework Directive 2000/60/EC to describe the form (morphology) and functioning (flow and sediment regime) of surface waters including rivers. Elements include width, depth, variability and connectivity.
Hydrostatic pressure	The pressure exerted by water at rest (see also *Hydraulic pressure*).
Invert	The lowest internal point of any cross-section in a culvert.
Inverted siphon	A closed conduit with a U-shaped profile, although the term is a misnomer because there is no siphonic action. Also known as sag culvert.
Kinetic energy	Energy possessed by water by virtue of its mass and velocity.
Leptospirosis	A bacterial disease passed from animals (most commonly rats) to humans via infected urine. An acute form of leptospirosis in humans is known as Weil's disease.
Level of service	*"The defined service quality for a particular activity against which service performance may be measured. Service levels usually relate to quality, quantity, reliability, responsiveness, environmental acceptability and cost."* (INGENIUM, 2006). *"The description of the service output for a particular activity or service area against which performance may be measured."* (Roberts and Hollier, 2007).
Main river	A watercourse in England or Wales shown as main river on a map prepared by the Environment Agency under the Water Resources Act 1991. The main river designation includes the watercourse, its banks and any connected drainage works. In England and Wales, the Environment Agency has permissive powers to carry out flood defence works on main rivers but responsibility for maintenance remains with the riparian owner. Watercourses not designated as main river are known as ordinary watercourses.

Manning's equation	An empirical formula for estimating flow in open channels, or free-surface flow driven by gravity.
Median annual flood	Flood with an annual exceedance probability of 50 per cent (return period two years), defined as QMED by the Institute of Hydrology (1999).
Modular weir flow	Flow over crest of weir or other hydraulic control structure that passes through critical flow. The upstream water level is independent of the water level downstream of the structure.
Morphology	The planform and cross-section shape of a watercourse.
Normal flow	Steady, uniform flow in an open channel where the hydraulic and energy grade lines are parallel and Manning's equation applies.
Ordinary watercourse	All watercourses not designated as main river. Permissive powers to carry out flood defence works on an ordinary watercourse lie with the local authority or internal drainage board but responsibility for maintenance remains with the riparian owner.
Outfall	Structure through which water is discharged into a channel or other body of water.
Operating authority	An organisation having permissive powers under Statute to operate, maintain or improve flood defence assets within its operating boundaries (Environment Agency, SEPA, Rivers Agency (NI), local authority or internal drainage board).
Overtopping	The passage of water over a component such as a floodbank or seawall, due to high water levels or wave action. Overtopping does not necessarily represent "failure" of a flood defence to perform its function.
Pathway	Route that enables a hazard to propagate from a "source" to a "receptor", as in the "source-pathway-receptor" concept. A pathway must exist for a hazard to be realised. Pathways can be constrained to mitigate the risks.
Performance assessment	A comparison of present performance against performance requirements. The assessment considers the effect of condition on each performance requirement and the effect of each performance requirement on the performance of the sub-system or system. The key to performance assessment is an understanding of the link between asset (or system) condition and its response under a range of loading conditions. Outputs from this stage are the probability of failure and residual life.
Performance indicator	Also known as performance measure. Specific, measurable and time-related output of a particular asset management policy or project. May be technical such as acceptable wave overtopping rates or conveyance capacity, or more generic such as public satisfaction.
Performance monitoring	Continuous or periodic quantitative and qualitative assessments of the actual performance compared with specific objectives, targets or standards.
Performance requirement	The hydraulic, structural, environmental or other standards that an asset or system is built and maintained to.

Piping	Internal erosion of a water retaining structure, where erosion begins at the downstream face and regresses until a pipe-shaped discharge tunnel is formed in the soil mass or between the soil and a foundation. Failure occurs when the upstream end of the eroded tunnel reaches the upstream face.
Planform	The form of a river or stream when viewed from above, for example, the term "meandering" is a description of a sinuous planform.
Pressure flow	Flow within a closed conduit that is confined by and exerts hydraulic pressure on the conduit walls and soffit. Also known as surcharged flow.
Primary function	For a culvert, the primary function is to convey a drainage channel under an obstruction without excessive restriction.
Probabilistic	Descriptor of method or process in which the variability of input values (eg asset loading and strength) and the sensitivity of the results are taken into account to give results in the form of a range of probabilities for different outcomes (eg failure).
Probability	Measure of the chance that an event will occur. Typically defined as the relative frequency of occurrence of that event out of all possible events and expressed as a percentage with reference to a time period, eg one per cent annual exceedance probability.
Probability density function (PDF)	A mathematical function that describes the relative chance of observing values of a continuous variable. For example, a probability density function could describe the chance that measured river flow could equal a certain value (for example, 100 m^3s^{-1}), or the chance that a single culvert has a certain percentage blockage.
Progressive failure	Failure process where, once a threshold is exceeded, some residual strength enables the asset to maintain restricted performance while further progressive loss of strength takes place. Not as dramatic or quick as catastrophic failure.
Rating curve	A relationship between discharge (or flow) and depth or water elevation at a given point.
Receptor	The entity, such as a person, property or habitat, which may be harmed by an event via a source and pathway. The vulnerability of a receptor can be reduced by increasing its resilience.
Re-grading	Re-profiling the bed of a channel to a lower level or more even gradient (for example, to increase flow capacity or improve land drainage).
Rehabilitation	All aspects of upgrading the performance of a culvert. Structural rehabilitation includes repairs, renovation and refurbishment. Hydraulic rehabilitation covers repairs, renovation and refurbishment.
Residual risk	The risk that remains after risk management and mitigation measures have been carried out. For example, damage predicted to continue to occur during flood events of greater severity than one per cent annual exceedance probability.

Residual service life	Service life remaining at a certain moment of consideration (also known as residual life).
Resilience	In asset management, the ability of an asset or asset system to resist the damaging effect of extreme loading. Resilience measures can, for example, help to achieve design standards beyond the standard of protection.
Return period	The average length of time between flood events of a similar magnitude, a 100-year flood occurring on average once every 100 years. Annual exceedance probability (AEP) is the preferred term for flood risk management, one per cent AEP being equivalent to a 100 year return period.
Revetment	Works to protect the bed or banks of a channel against erosion, typically constructed from stone or concrete blocks.
Riparian	Along the banks of a watercourse. Riparian zones support riparian vegetation and are of environmental importance, providing diverse habitats and supporting a range of ecological communities.
Riparian owner	Owner of land adjoining a watercourse.
Risk	Risk can be considered as having two components: the probability that an event will occur and the consequence associated with that event to receptors. Risk is a function of probability and consequence. Flood risk to a receptor can be indicated graphically by a PDF with probability and consequence as the x and y axes. The area under the curve is the overall risk.
Risk assessment	The process of identifying hazards and potential consequences, estimating the magnitude and probability of consequences, and assessing the significance of the risk(s). A "tiered" approach can be used with the effort in assessing each risk proportionate to its importance in relation to other risks and likely consequences.
Risk management	The systematic process of risk assessment, options appraisal and implementation of any risk management measures to control or mitigate risk.
River continuity	The passage of river flows (of water and sediment) in a longitudinal (downstream) direction. Continuity can be disrupted by natural barriers such as waterfalls, or by hydraulic structures such as dams or weirs.
Roughing screen	A coarse screen designed to collect large debris, usually located upstream of a trash screen, also know also a boulder trap.
Runoff	Overland flow produced by rainfall.
Scour	Erosion of the bed or banks of a watercourse by the action of moving water, typically associated with channel contraction or local feature such as bridge pier.
Secondary function	For a culvert, the secondary functions are all functions other than the primary function. For example, to allow the passage of fish and wildlife.
Security screen	A screen comprising closely-spaced bars, designed to prevent

unauthorised or accidental access to a conduit or other hydraulic structure, which reduce the risk of someone coming to harm.

Sediment Granular or cohesive material such as clay, sand, gravel, cobbles or boulders, which is transported in flowing water and settles or tends to settle in areas where the flow slows down.

Sedimentation The deposition of sediment in the bed of a channel or within a hydraulic structure.

Sensitivity analysis Testing the potential variations in the outcome of an evaluation by altering the values of important factors that have uncertainty.

Service life The period of time after construction or refurbishment when an asset meets or exceeds its functional performance requirements. See also *Residual service life* and *Useful life*.

Site investigation The historic and geologic examination of a potential development site to design the foundations of surface buildings, roads etc. It includes geophysical surveys, trial pits, and boreholes.

Source-pathway-receptor How a hazard propagates from its source, via a pathway to a receptor. For example, in the event of heavy rainfall (the source) floodwater may escape from a river and propagate across the floodplain (both elements of the pathway) to inundate a housing development (the receptor), which may suffer material damage.

Specific energy The energy of a fluid relative to bed level, given by the sum of pressure and velocity heads.

Stakeholder An individual or group with an interest in, or having an influence over, the success of a proposed project or other course of action.

Standard of protection In flood risk management, the annual probability of the design flood level being reached or exceeded. From the receptor's viewpoint, the definition is different, being the annual probability of a flood overtopping or breaching a flood defence asset and causing harm to the receptor.

Standard of service The performance of an asset at a specific point in time.

System Assembly of elements, and the interconnections between them, constituting a whole and generally characterised by its behaviour (eg elements in a structure, or assets in an asset system). Concept also applied to social and human systems.

Stilling basin Structure for dissipating energy of flow, comprising a basin in which a hydraulic jump, flow impact or other form of energy dissipation occurs.

Stone apron Stones, typically placed downstream of a hydraulic structure, designed to dissipate energy and reduce erosion of the bed.

Stoplogs Timber or metal beams spanning horizontally between grooves in piers or abutments of a control structure, used to isolate part of the structure or related reach for maintenance, or to raise the elevation of water retained.

Stop planks	Another term for "stoplogs".
Subcritical flow	Free surface flow with a Froude number less than unity that occurs in channels with mild slopes and is characterised by deep water and low velocity.
Submerged weir flow	Flow over a weir crest where the downstream water depth above crest level exceeds critical flow depth above crest level.
Submergence ratio	The ratio between downstream water depth above weir crest level and the upstream water depth above weir crest level.
Substrate	Material underlying or supporting a structure or another layer of material.
Supercritical flow	Free surface flow with a Froude number greater than unity that occurs in channels with steep slopes, characterised by shallow water and high velocity.
Surcharged flow	Flow within a closed conduit that is confined by and exerts hydraulic pressure on the conduit walls and soffit. Also known as pressure flow.
Suspended load	Sediment that travels at almost the same velocity as the water that transports it and is prevented from settling by the effects of flow turbulence
Sustainability	The concept of development that meets the needs of the present without compromising the ability of future generations to meet their own needs
Tailwater depth	The depth of water above culvert invert at the culvert outlet.
Tailwater elevation	The level of water above datum at the culvert outlet.
Trash	Any buoyant or semi-buoyant material carried by the flow of water in a channel that could accumulate inside a culvert to form a blockage, and will accumulate on a screen. See also *Debris*.
Trash screen	Screen at the inlet of a culvert designed to prevent debris from entering the culvert and causing blockage.
Tree screen	Screen upstream of a culvert designed to prevent tree trunks and branches from blocking a culvert or trash screen.
Uniform flow	Flow with water surface slope parallel to the bed slope and constant depth from section to section.
Uplift	Hydrostatic pressure on the underside of a structure that can act to destabilise the structure.
Useful life	May be expressed as either: a) The period over which a depreciable asset is expected to be used. (b) The number of production or similar units (ie intervals, cycles) that is expected to be obtained from the asset. See also *Residual service life*.
Velocity head	Kinetic energy of flowing water, represented as the vertical height to which water would rise in a pitot tube.

Washland	Low land near to a river or other channel used for the temporary storage of floodwater. Often developed for use of the erection of bunds and control structures.
Watercourse	All rivers, streams, burns, ditches, drains, cuts, culverts, dykes, sluices, sewers and passages carrying or designed to carry water (whether for the time being carrying water or not), excluding pipes or other works for the sole purpose of supplying water to any premises.
Whole-life cost	Total cost of managing an asset over its life, including cost of construction, use, operation, inspection, maintenance and refurbishment, replacement or disposal.
Whole life cycle	The total working life of a culvert including planning, design, construction, maintenance, operation, rehabilitation and removal.
Wingwalls	A pair of retaining walls often provided as an adjunct to a headwall, to support the channel banks at a culvert inlet or outlet and to form part of the transition from channel to culvert and vice versa (see Figures 9.2 and 9.16 and Appendix A5).

Abbreviations

ADA	Association of Drainage Authorities
ADAS	Agricultural and Development Advisory Service
AEP	Annual exceedance probability
AES	Afflux estimation system
AMIN	Annual minimum flow
BAP	Biodiversity action plan
BODC	British Oceanographic Data Centre
BFIHOST	Base flow index estimated from soil type
BW	British Waterways
CAR	Water Environment (Controlled Activities) Regulations
CCTV	Closed circuit television
CDM	Construction (Design and Management) Regulations 2007
CDOG	Culvert design and operation guide
CEH	Centre for Ecology and Hydrology
CES	Conveyance estimation system
CFMP	Catchment flood management plan
CIWEM	Chartered Institution of Water and Environment Management
CSO	Combined sewer overflow
cSAC	Candidate special area of conservation
DfT	Department for Transport
D/S	Downstream
EC	European community
EEC	European economic community
EIA	Environmental impact assessment
EA	Environment Agency
EU	European Union
EGL	Energy grade line
FCA	Flood consequence assessment
FCDPAG	Flood and coastal defence project appraisal guidance
FCERM-AG	Flood and coastal erosion risk management appraisal guidance
FDC	Flow duration curve
FDEU	Field Drainage Experimental Unit
FHWA	Federal Highway Administration
FRA	Flood risk assessment
GEV	Generalized extreme value
GIS	Geographic information systems
GRP	Glass-reinforced plastic
HDPE	High density polyethylene
HDPP	High density polypropylene
HDS	Hydraulic design series

HGL	Hydraulic grade line
HSE	Health and Safety Executive
IDB	Internal drainage board
InSAR	Interferometric synthetic aperture radar
LIDAR	Light detection and ranging
LPA	Local planning authority
LWD	Large woody debris
MAFF	Ministry of Agriculture Fisheries and Food
MDPE	Medium density polyethylene
MEL	Minimum energy loss
pSAC	Possible special area of conservation
pSPA	Potential special protection area
PAS	Publicly available specification
PDF	Probability density function
PPG	Planning policy guidance
PPG	Pollution prevention guidelines
PPS	Planning policy statement
PR	Percentage runoff
PVC	Polyvinyl chloride
QBAR	Mean annual maximum flood
QMED	Median annual flood
RA	Rivers Agency for Northern Ireland
RADAR	Radio detection and ranging
ReFH	Revitalized flood hydrograph
RRC	River restoration centre
SAC	Special area of conservation
SEPA	Scottish Environment Protection Agency
SFCA	Strategic flood consequence assessment
SFRA	Strategic flood risk assessment
SPA	Special protection area
SPP	Scottish Planning Policy
SPRHOST	Standard percentage runoff estimated from soil type
SSSI	Site of special scientific interest
SUDS	Sustainable drainage systems
SWMP	Surface water management plan
TAN	Technical Advice Note
TSO	The Stationery Office
UPVC	Un-plasticised polyvinyl chloride
U/S	Upstream
USACE	United States Army Corps of Engineers
UKCP	United Kingdom climate change projections
UKCIP	United Kingdom climate impacts programme
WaPUG	Wastewater Planning User Group
WIS	Water Industry Specification
WFD	Water Framework Directive

Notation

A	Cross-sectional area of flow
A_b	Cross-sectional area of culvert barrel
A_c	Cross-sectional area of flow at critical depth
A_{dc}	Cross-sectional area of flow in downstream channel
A_{or}	Cross-sectional area of orifice
a_i	Cross-sectional area of screen panel opening
A_s	Cross-sectional area of screen opening/s
A_t	Trial cross-sectional area of culvert
A_{uc}	Cross-sectional area of flow upstream of screen
AEP	Annual exceedance probability
b	Proportion of screen width blocked by bars
b_i	Width of i^{th} screen panel opening
b_i'	Width of i^{th} screen panel opening for partially blocked screen
B	Width of channel, culvert, screen or embankment crest
B'	Effective width of weir crest (width of screen at top of screen blinding)
B_i	Total width of i^{th} screen panel
B_s	Width of screen opening/s
B_s'	Width of screen opening/s for partially blocked screen
c	Constant used in inlet control calculations
C_c	Discharge coefficient for culvert flow
C_d	Discharge coefficient for orifice flow
C_w	Discharge coefficient for weir flow
d	Number of days in year (low flow frequency analysis)
d_i	Height of i^{th} panel opening
d_i'	Height of i^{th} panel opening minus blinding
D	Internal height of culvert
D_e	Effective height of culvert
DL	Design life
D_s	Total height of screen opening
D_s'	Total height of screen opening minus blinding
e	Base of natural logarithm
E_s	Specific energy (pressure head plus velocity head)
E_{sc}	Specific energy at critical depth
E_{sh}	Specific energy of headwater
E_{st}	Specific energy of tailwater
f	Submergence correction factor
f_a	Bulking factor for air entrainment
F	Freeboard allowance for uncertainty
Fr	Froude number
g	Acceleration due to gravity (= $9.81 m/s^2$)
h_{bl}	Head loss due to blinding of screen

h_{bn}	Head loss due to bend in culvert
h_{ex}	Head loss due to expansion and contraction
h_f	Head loss due to friction
h_i	Head loss at inlet
h_o	Head loss at outlet
h_{or}	Afflux for orifice flow through a submerged screen
h_s	Head loss due to screen
h_T	Total head loss
H	Total head (elevation head, pressure head plus velocity head)
H_h	Total head of headwater
H_{hc}	Total head of headwater required to drive flow through culvert
H_{hic}	Total head of headwater under inlet control
H_{hmax}	Maximum permissible total head of headwater
H_{hoc}	Total head of headwater under outlet control
H_{hw}	Total head of headwater required to drive flow over embankment
H_{tw}	Total head of tailwater
i	i^{th} panel in screen
k	Constant used in inlet control calculations
k_{bn}	Coefficient for bend loss
k_i	Coefficient for inlet loss
k_o	Coefficient for outlet loss
k_s	Colebrook White roughness
K	Conveyance
l_{bl}	Length of blinding (for inclined screens)
li	Length of i^{th} panel opening
l_i'	Length of i^{th} panel opening minus blinding
L	Length of culvert barrel
L_{bw}	Length of backwater
v_s	Total length of screen opening
L_s'	Total length of screen opening minus blinding
M	Constant used in inlet control calculations
n	Manning's roughness coefficient for full cross-section
n_i	Manning's roughness coefficient for i^{th} roughness panel
n'	Manning's roughness coefficient for compound channel
N	Number of panels in compound screen
p	Probability of occurrence
p_i	Wetted perimeter for i^{th} roughness panel
P	Wetted perimeter for full cross-section
q	Discharge intensity or discharge per unit width of channel
q_i	Discharge intensity for inlet control
Q	Discharge (or flow rate)
Q_c	Discharge through culvert (for overtopping flow)
Q_w	Discharge over embankment crest (for overtopping flow)
Q_{95}	Discharge exceeded 95 per cent of the time

r	Proportion of screen width blocked by debris
R	Hydraulic radius ($=A/P$)
R_i	Hydraulic radius for i[th] roughness panel
R_{bn}	Radius of bend
s	Ratio of screen gaps to total screen area
S	Weir submergence ratio
S_f	Friction slope
S_{fmean}	Mean friction slope
S_{fprev}	Friction slope calculated for previous location
S_0	Bed slope
T	Return period
V	Velocity
V_b	Velocity in culvert barrel
V_c	Velocity at critical depth
V_{dc}	Velocity in downstream channel
V_s	Velocity between screen bars
V_{uc}	Velocity in upstream channel
W	Width of water surface
WL_h	Water level of headwater
WL_{hic}	Water level of headwater for inlet control
WL_t	Water level of tailwater
y	Depth of water (or hydraulic mean depth)
y_{bl}	Depth of weir flow over screen blinding
y_c	Depth of water for critical flow ($Fr = 1$)
y_{dc}	Depth of water in downstream channel (tailwater depth)
y_f	Depth of flow at face of culvert inlet, immediately upstream of inlet
y_{hgl}	Depth of water approximated from hydraulic grade line
y_i	Depth of water immediately downstream of culvert inlet
y_o	Depth of water in culvert barrel, immediately upstream of outlet
y_n	Depth of water for normal flow conditions
y_s	Depth of water at starting point of backwater calculation
y_{uc}	Depth of water in upstream channel
y_1	Depth of water above crest level upstream of weir
y_2	Depth of water above crest level downstream of weir
Y	Constant used in inlet control calculations
z	Slope of channel sides (1 in z)
z_{bl}	Height of screen blinding above bed
z_{or}	Height of centroid of orifice above bed level
z_s	Depth of sedimentation above culvert invert
z_w	Height of weir crest above bed
Z	Elevation of bed above a datum
Z_{bi}	Elevation of bed at culvert inlet
Z_{bo}	Elevation of bed at culvert outlet
Z_{or}	Elevation of the centroid of an orifice

Z_s	Elevation of bed at starting point of backwater calculation
Z_{si}	Elevation of soffit at culvert inlet
Z_{so}	Elevation of soffit at culvert outlet
Z_w	Elevation of embankment crest
γ	Unit weight
θ	Angle of screen opening to the horizontal
ρ	Density of water
τ_o	Shear stress
φ	Angle of horizontal or vertical bend in culvert barrel
ΔH	Change in total head
Δx	Step length in backwater calculation

1 Introduction

1.1 What is a culvert?

There is no set definition of a culvert but it can be simply described as a closed conduit carrying a watercourse under an obstruction such as a road, railway or canal. In contrast, a bridge can be described as a structure carrying a road or a railway over a watercourse. However, the differences are more than semantic, and the features that distinguish a culvert from a bridge are as follows, although it should be noted that these are not universally applicable:

- length in the direction of flow is significantly greater than the width of the culvert (often more than 10 times)
- a culvert generally has a hard invert (ie the bed of the watercourse through the culvert is part of the structure of the culvert)
- a culvert often has the propensity to flow full in flood conditions (ie the whole of the cross-sectional area is occupied by flowing water)
- a culvert is generally more prone to obstruction by debris or sediment than is a bridge.

Box 1.1 ***Culvert and bridge compared***

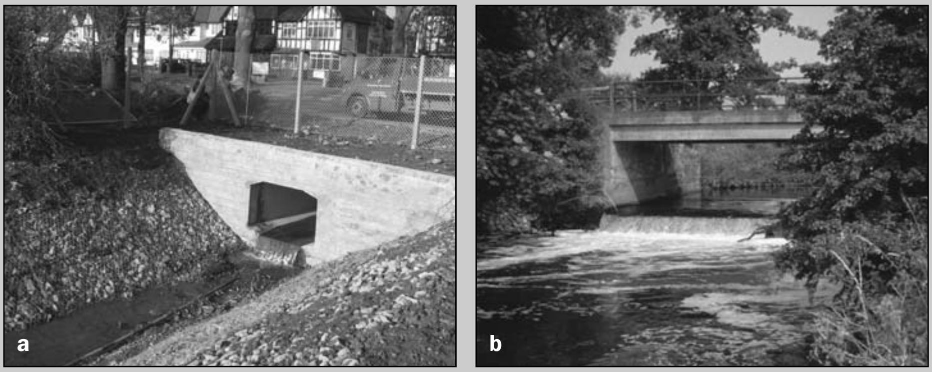


Figure 1.1 *Outfall from a culvert (a) and a structure generally considered a bridge (b)*

Culvert and bridge compared

Figure 1.1a illustrates the outfall from a culvert – the length of the culvert (tens of metres) is many times its width. Figure 1.1b shows a structure that has a span (width) of the same order as the length in the direction of flow, so this structure would generally be thought of as a bridge.

Both structures have a hard invert as is evidenced by the weir effect at the downstream side (note that this is not a desirable feature as it inhibits fish movement). In the case of the culvert on the left, the hard invert is an integral part of the structure. In the photo on the right the hard invert may be part of the structural design, or it may have been added later to arrest bed erosion.

Because of the relative size of the structure in relation to where it sits in the channel, it is possible to conclude that the culvert on the left is much more likely to flow full than the structure on the right. In both cases the invert appears to be sediment-free but the size of the structure makes blockage by debris much more likely in the case of the culvert on the left.

Verdict?

The structure on the left is a culvert by any definition, whereas that on the right would most likely be described as a bridge. This guide relates to the design and management of culverts, but may be applied with caution to structures similar to that illustrated on the right.

Readers of this guide are urged not to focus unduly on the definition of a culvert – the guide will almost certainly be applicable even if the structure concerned does not strictly comply with the definitions described.

One further feature of a culvert that distinguishes it from a bridge is that it is much more easily overlooked than a bridge. This is partly because of relative size, but also because most of a culvert structure is buried and the inlet and outlet can become obscured by vegetation. This feature adds weight to the need for asset managers to keep a comprehensive and up-to-date record of all their structures, which is used to trigger inspections, so that no structure is "lost".

A culvert will almost always be significantly cheaper than a bridge at the same location. However a culvert will generally have the following disadvantages when compared to a bridge:

- more significant adverse effect on the aquatic environment (including watercourse ecology, wildlife migration, sedimentation, debris conveyance, water quality and amenity value)
- increased risk of flooding resulting from the fact that the culvert, by its nature, acts as a constriction on the watercourse
- hazards associated with access into a culvert, both for maintenance operatives and for members of the public (especially children), are more significant.

These disadvantages create focal points for the design of any culvert, and these are discussed in detail later in this guide.

The particular case of a culvert under a waterway should be mentioned here. Such structures are common in the network of canals across the UK and many of them are relatively old. The combination of an ageing structure, and the risk of significant flooding should the culvert collapse, add significantly to the asset management responsibility.

The terminology used throughout this guide is generally self-explanatory. However, a description of the main technical terms used can be found in the glossary, and Box 1.2 includes a schematic drawing with an explanation of the terms used to describe the components of a culvert.

Box 1.2 *The main elements of a culvert*

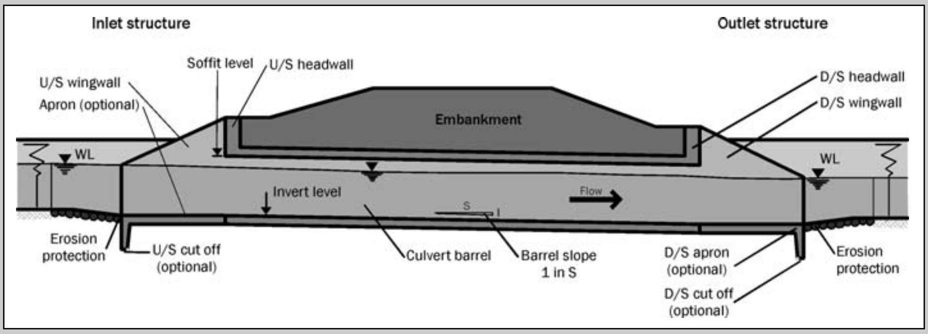


Figure 1.2 *A schematic drawing of a culvert*

Element/feature	Notes
Inlet structure	Forms transition from the channel into the culvert (see Section 9.4). Can be very simple (see Appendix A5.2). May house a screen (see Section 9.4.3).
Barrel	The body of the culvert conveying flow under the road, railway, waterway or other infrastructure. Very wide range of sizes shapes and materials available (see Section 9.3 and Appendix A5.1).
Outlet structure	Forms the transition from the culvert barrel to the channel downstream (see Section 9.5). May house a security screen (see Section 9.5.5). Can be very simple (see Figure 9.28).
Screen Trash screen Security screen	A steel grille designed to prevent debris (trash screen – see Figure 9.14.) or people (security screen – see Figure 9.19) from gaining access to the culvert. The outlet should not have a security screen unless there is one at the inlet. A security screen will always also act as a trash screen and should be designed for this (see Sections 6.9.6 and 9.4.3).
Apron	A solid floor at the inlet or outlet forming part of the transition from the watercourse to the culvert barrel. In many cases no apron is necessary. The most common reasons for an apron are (a) as a stilling basing at the outlet (steep culverts – see Figure 9.24), (b) as part of the support structure for a screen, and (c) as an extension of erosion protection if flow velocities are high (see Section 6.13.3)
Erosion protection Scour protection Revetment	Erosion protection (eg stone pitching) may be provided to the channel bed and banks at the inlet and outlet, depending on the velocity and turbulence of the flow, and the suddenness of change from channel to structure and structure to channel (see Sections 6.13.3 and 9.5.6). May form part of, or replace, the wingwalls (see Figures 9.16 and 9.23).
Headwall	The term most commonly used to describe the retaining wall at right angles to the culvert barrel forming part of the inlet and outlet structures. This wall supports the embankment. Commonly constructed from concrete or box gabions (see Figures 9.5 and 9.16). May be required to have a parapet and/or hand railing for safety reasons (see Figure 9.6). May include an upstand to prevent material slipping into the culvert inlet.
Wingwalls	Extensions to the headwall forming the transition between the culvert and the watercourse. Regularly constructed from concrete, these often have sloping crests and can be parallel to the watercourse or flared out (see Figure 9.16). Often over-elaborate and sometimes unnecessary. Can also form part on the erosion protection measures (eg by using box gabions). May require hand railing (see *Headwall*).
Cutoff	Often not required but may be necessary to add stability to the inlet or outlet structure, to protect against collapse of the apron if there is erosion of the bed, or to reduce seepage (culverts with high head loss).
Head loss	The difference between the water level upstream of the culvert and that downstream. Varies depending on the flow conditions and will increase if flow is restricted (eg by blockage of a screen or obstructions within the culvert) (see Sections 6.2.4, 6.9 and 6.10, and Figure 6.5).

Box 1.2 (contd) *The main elements of a culvert*

Embankment	The earth structure forming the infill between the infrastructure and the culvert structure. Can vary in depth from zero (infrastructure sits directly onto the culvert structure) to many metres (eg culvert through dam embankment).
Invert level	The bed level of the culvert. Normally set below the bed level of the watercourse (see Section 9.3.6). Invert level at outlet is generally lower than at inlet to give the culvert barrel a slope in the direction of flow (see *Barrel slope*).
Barrel slope	It is normal for a culvert to slope in the direction of flow. A slope matching that in the watercourse is commonly adopted. When a culvert flows full (or is surcharged) the barrel slope will have no impact on hydraulic performance. Even when flowing free (as illustrated above) the culvert slope may not be a primary factor in determining the hydraulic performance (see Sections 6.8.2 and 9.3.5).
Soffit level	The level of the "ceiling" of the culvert barrel. When the water level approaches the soffit level at the inlet, the flow conditions will change from free flow to full (surcharged) flow and the upstream water level is likely to change in response to this.
Bedding	Material laid on the foundation to provide support to the culvert. Can be compacted earth, granular material or weak concrete depending on the nature of the ground and the shape and material of the culvert barrel (see Section 9.6.3).
Backfill	The material placed around and on top of the culvert barrel to form the foundation for the infrastructure above the culvert. Backfill should be well compacted to minimise settlement post-construction. The quality of backfill and the degree of compaction are very important for corrugated steel culverts because their structural performance depends on the soil-structure interaction.

1.2 Background

In 1997 CIRIA published R168 *Culvert design guide* (Day *et al*, 1997), which set out to provide a practical guide to the design of culverts. It was aimed primarily at designers in England and Wales, although it was recognised that it would also provide a useful reference for users outside this geographic area. The guide was funded partly under CIRIA's core programme, but with significant support from the Environment Agency, the Department of the Environment, and the Highways Agency. The main objective was to provide guidance for non-specialist engineers on the hydraulic design of culverts, but the guide also provided extensive practical guidance on all aspects of culvert design. It became one of CIRIA's most popular guides.

In 2007 it was recognised that not only did the guide require significant updating, but also that the scope needed extending to cover the whole-life management of culverts. The concept of this guide was developed in recognition of the enormous stock of existing culverts in the UK, many of which have the potential to cause problems for their owners and operators, and it replaces R168.

In this guide a culvert is viewed both as part of a drainage system and as an element of infrastructure. Users of this guide are encouraged to look beyond the immediate environs of the culvert in question, so that its operation and management are based on a sound understanding of the wider environment in which it sits. In effect, this guide promotes a "systems approach", with the culvert forming one element of a wider system. In particular, a thorough understanding of the catchment upstream, and the channel downstream will allow the user to assess the relevance and effects of issues such as fly-tipping, channel sediment dynamics and urban development, and thereby develop appropriate management responses. The guide highlights the environmental implications of culverting, including signposting to relevant legislation such as the Water Framework Directive and the Habitats Directive.

1.3 Aims of the guide

This publication aims to provide guidance on all aspects of the management of culverts throughout their whole life cycle. It contains extensive guidance on the design of new culverts, but also covers the inspection, assessment, maintenance, repair, replacement and removal of existing culverts.

Whereas the primary aim of the guide is to provide information for designers and asset managers, it also addresses the fundamental question: "is a culvert needed?" In this respect the aims are two-fold:

1. To avoid the construction of new culverts in circumstances where an alternative approach would be preferable.
2. To explore the opportunities for the removal of existing culverts ("daylighting") to obtain both hydraulic and environmental benefits.

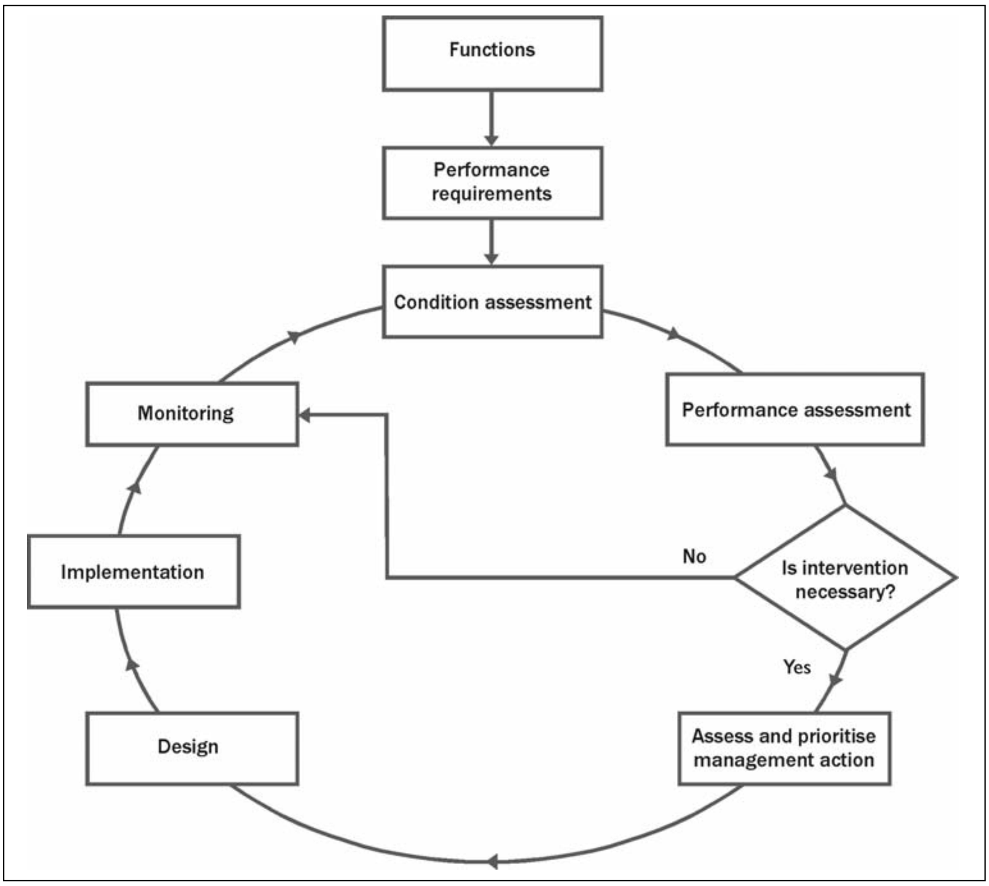
The guide seeks to support asset owners and operators and allow them to manage their culverts effectively and efficiently, with due regard to both hydraulic and environmental performance requirements, and economic, legal and safety constraints. Note that it does not provide detailed guidance on structural design or structural performance.

The detailed requirements of existing environmental legislation (such as the Habitats Directive and the Birds Directive), and relatively new environmental legislation (such as the Water Framework Directive) are excluded from the scope of this guide, although the main requirements are described.

1.4 Context and scope

1.4.1 Whole-life asset management

Effective asset management ensures that an asset continues to perform satisfactorily throughout its design life. In the case of a culvert there is a fundamental requirement that it does not obstruct the conveyance of floods or natural drainage of the land (unless the culvert has been designed specifically to act as a constriction, for example, in the case of a flood storage reservoir outlet structure). Effective asset management also ensures that all other performance requirements, including those relating to watercourse ecosystem, visual amenity and health and safety are achieved, and that the culvert remains structurally sound so that it can continue to provide the infrastructure function it was constructed for. Figure 1.3 summarises the concept of whole-life asset management as it relates to any component of an infrastructure system.



Note that it is possible for performance requirements to change over time and it may be necessary to assess the performance of the culvert against moving goalposts.

Figure 1.3 *The whole-life cycle of asset management*

If the performance of a culvert is judged to be sub-standard, either in terms of its original performance requirements, or when assessed in terms of new or changed standards of performance, then it is necessary to consider, and if justifiable to design and implement, a managed intervention. The asset is then managed as illustrated by the cycle in Figure 1.3. The framework provided in Figure 1.3 is relevant for both new and existing culverts. Further information on its use for both situations is provided in Chapter 2.

Sustainable asset management is fundamentally important to the maintenance of infrastructure in the future. In the past, it has often been the disconnection between the design of an asset and its whole-life operation that has led to the asset being unsustainable. The adoption of the whole-life approach to the management of culverts, as promoted in this guide, will help to ensure the continuous enjoyment of high standards of infrastructure without undue cost to future generations.

With particular reference to existing drainage infrastructure, the recently introduced surface water management plans (SWMPs) will form a vital tool for the management of urban drainage networks, of which culverts are a significant part. Guidance on the preparation of SWMPs is available from Defra (2009).

The effective management of any infrastructure element requires consideration of its design life, ie the number of years that the asset can be expected to perform satisfactorily before it has to be replaced or requires a major refurbishment. The design life of a culvert will depend on its primary function, but is unlikely to be less than 30 years and may be more than 100 years for a culvert under a motorway, mainline railway, or canal. This aspect of design and asset management is addressed in Section 9.1.5.

1.4.2 Scope of this guide

This guide covers the design and operation of culverts from conception to decommissioning, encompassing the whole life cycle of an infrastructure asset. It is intended for use in the UK and reflects the particular requirements of England, Wales, Scotland, and Northern Ireland. Much of the general guidance is applicable to other geographic regions of the world, particularly those in the rest of Europe that share the same environmental legislation. However specific legal and environmental requirements of countries outside the UK are not covered in this guide.

In the context of existing culverts, the guide highlights the four possible options when a culvert reaches the end of its life, or is found to be failing to meet its performance requirements:

1 Refurbishment, returning the culvert to its original as-designed performance.

2 Enhancement, ie adding extra capacity or functionality to the culvert (eg by constructing an extra barrel for flood flows or providing a dry culvert for mammal passage).

3 Replacement (by a different or better structure, meeting increased performance criteria).

4 Disposal (ie demolition, returning the watercourse to a more natural state).

The question of "what is a culvert?" is answered at the beginning of this chapter. This makes it clear that the guide is not limited to a strict definition of a culvert, but covers a wide range of structures that can loosely be described as culverts. There are no specific size or length limitations to culverts for the purposes of this guide. Complex culverts that comprise multiple lengths with different cross-sections, as is often found in ageing urban drainage systems, do not lend themselves to manual hydraulic analysis techniques described in Chapter 6, although the computational methods at the end of the chapter may assist.

Note that most major asset owners (such as the Highways Agency and Network Rail) have dimensional rules that determine whether a particular structure is referred to as a culvert or a bridge. Such rules are generally based on inspection and maintenance regimes and do not invalidate guidance given in this document. British Waterways sets no size limitation but emphasises that the culvert includes all the associated works such as inlet and outlet, inspection accesses, and overflow weir (if integral with the culvert). This is an important point that should apply to all culverts, because poor maintenance or neglect of any component could compromise the performance of the structure.

The guide covers all forms of construction and materials, and all sizes of culvert from 0.45 m diameter to 8.0 m span or larger (see Appendix A5.1).

There is no upper limit to the length of a culvert covered by this guide, although it should be pointed out that the hydraulic analysis of long culverts (in excess of 100m), especially those flowing full, may lend itself more to pipe network analysis. Culverts under motorways extend to 50 m or more, and considerably greater lengths occur where watercourses have been culverted under developed sites.

A tunnel conveying a watercourse is a relatively rare structure, and is not specifically covered by this guide. However, the hydraulic performance of such a structure will be similar to that of a conventional culvert, and the hydraulic guidance presented in this guide may be used with caution. The repair and rehabilitation of tunnels is not covered by this guide but is described by McKibbins *et al* (2010)

Note that this guide does not discuss the structural design of culverts, or address the structural design of repairs or remedial works to culverts.

1.5 The need for a culvert

This guide supports the premise that a culvert is not the only option for a designer faced with having to carry infrastructure across a watercourse. The guide encourages designers to look at options that do not involve enclosing a length of the watercourse, while recognising that in many circumstances there will be no other practical option. This guide also encourages asset owners to look at the possibility of culvert removal and channel restoration ("daylighting") as and when the opportunity for such an option arises.

Culverts are discouraged for several reasons, including:

- a culvert by its nature acts as a constriction on a watercourse and has the propensity for increasing upstream water level (and also flood risk) in conditions of high flow (see Case study A3.2)
- culverting a watercourse has a negative impact on the aquatic environment
- a culvert carries a greater risk of blockage than an open channel, with consequent increased flood risk
- a culvert may have significantly increased health and safety hazards in comparison to an open channel
- culverts are more difficult to maintain and repair than a natural watercourse.

Alternatives to a culvert may include one or more of the following:

- relocating the infrastructure elsewhere to avoid the need to cross the watercourse (perhaps by making use of an existing crossing point)
- using a bridge instead of a culvert (a bridge can be designed to have less impact on the hydraulics and ecology of a watercourse)
- using a ford instead of a culvert for a seasonal watercourse crossing a minor road (not appropriate for flashy streams or high flow rates that could result in people or vehicles being swept downstream)
- diverting the watercourse (and taking the opportunity to improve the ecology and amenity at the same time)
- combining channels so that only one crossing point is needed (for example, replacing two small culverts with one large one).

1.6 Safety first

A well designed and maintained culvert should not present a significantly greater risk to life and limb than the open watercourse it replaces. In situations where entry into the culvert is inherently unsafe (eg the barrel has a steep slope and the invert is slippery), then means of discouraging or preventing entry should be considered, including warning signs, fencing, planting of thorny shrubs, and security screens at the inlet and outlet (see Section 9.4.3). Where it is necessary for operatives to gain entry to a culvert (for example, to remove sediment or debris) then the design should cater for this by incorporating suitable and sufficient safety measures. However the access point should be designed to prevent unauthorised entry.

The features of a culvert that influence the degree of hazard include:

- length: a long culvert with bends and changes of cross-section presents a more significant hazard than a short straight culvert
- slope: a steep culvert in which the flow velocity is high is more hazardous than one with a flat gradient
- full flow: for someone falling into flowing water, a culvert flowing partially full (ie with a free water surface) is unlikely to be significantly more hazardous than an open channel provided that the culvert is short. A culvert with a tendency to flow full in floods is potentially more hazardous because anyone swept into it will not be able to breathe. An inverted siphon, in which the central part is always full of water, is definitely a hazard
- size: it is the smaller end of the culvert size range that probably presents the greatest hazard potential. Such culverts are likely to flow full more often than large culverts, and carry a greater risk of a child becoming trapped or wedged inside
- invert: in low-flow conditions, when a culvert may be accessed by children, the presence of deep sediment, steps or obstructions in the invert that might not be visible, can present extra hazards
- confined space: if there is a risk of an accumulation of noxious or inflammable gas, or such gases could be released by stirring up sediment in the invert, then entry into the culvert for inspection or maintenance should be by an appropriately trained and equipped confined spaces team
- location: a culvert entrance that is near to a residential area but cannot be seen by passers-by is likely to attract children
- rate of rise of flood: a flashy stream, where the water level can rise rapidly, presents a greater hazard than one that takes time to rise
- accessibility: although adventurous children are not put off by difficult access, the probability that a child will be exposed to the hazard is likely to be greater if access to the culvert entrance is easy.

Designers of new culverts and managers of existing culverts should bear these in mind when assessing the hazards associated with any individual structure. The assessment should focus both on accidental entry into the culvert (eg someone falling into the channel upstream), deliberate but unauthorised entry (eg adventurous children or urban explorers caught in a rising flood), and authorised entry (eg someone inspecting the interior). However, it is emphasised that the objective in identifying the hazards is to allow the designer the opportunity to remove or reduce the risk associated with them, and not as an encouragement to provide a security screen at the culvert inlet or at the outlet (see Section 9.4.3).

1.7 Summary

- there should be a presumption against culverting because of the adverse environmental impact and increased risk of flooding. Alternative means of achieving the objective of crossing the watercourse should be sought wherever possible and practicable
- when designing a culvert the designer should maintain a whole-life perspective, taking into account the operation and management needs of the culvert throughout its life as well as the performance requirements
- the design should minimise the risks associated with operation and maintenance of the culvert. In particular the design should minimise the need for entry into the culvert and, where such entry is unavoidable, the design should eliminate or reduce any hazards that would pose a risk to the health and safety of the operatives concerned
- the design of the culvert should minimise its environmental impact and to reduce any risks to members of the public, especially children
- the design of a culvert should not be carried out in isolation but should be undertaken with a full understanding of the drainage system that the culvert will form a part of
- in the case of an existing culvert, which is not meeting its performance requirements, the alternative approaches to remedial works should include considering removal of the culvert and restoration of the natural channel where this is a practicable alternative.

2 Asset management

2.1 Introduction

Asset management is defined in PAS 55 (BSi, 2008a) as follows:

> *"Asset management is the systematic and co-ordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over the life cycle for the purpose of achieving its organisational strategic plan".*

Figure 2.1 shows the overall process of asset programme management from strategic through to operational planning stages.

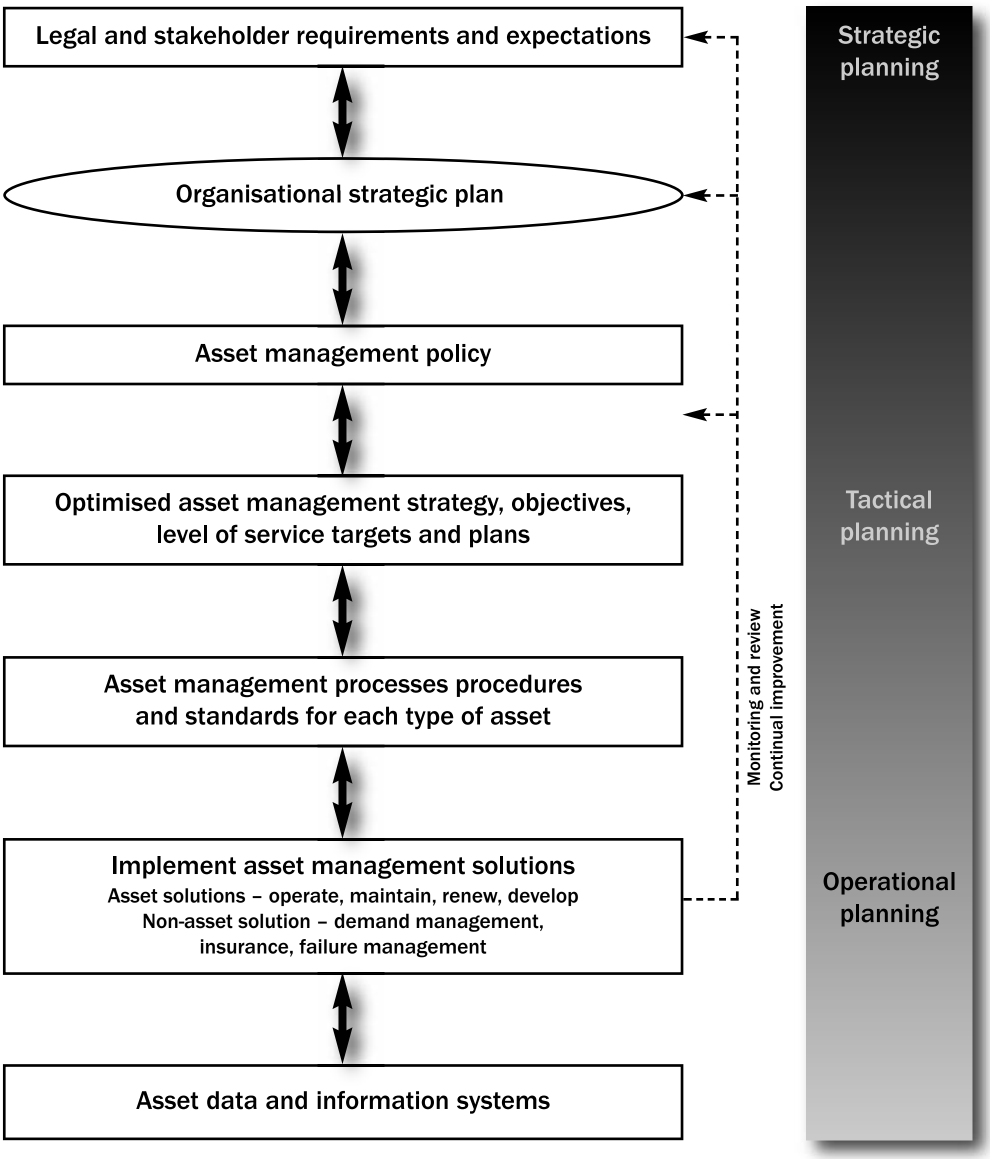


Figure 2.1 ***The total asset management process (reproduced from INGENIUM, 2006)***

Asset management is a major area and the guide does not attempt to describe the process in detail as various organisations who own culverts already have established and varied asset management systems. This section of the guide aims to identify areas of asset management where culverts differ from other infrastructure assets and what should be considered in the development of an asset management strategy. Wider guidance on asset management is provided in Hooper *et al* (2009).

Asset management of a culvert is similar to that of other infrastructure assets. It involves an iterative process of assessment and intervention throughout the life of the culvert to achieve its performance requirements. The stages of asset management for an individual asset such as a culvert within the wider programme management described in Figure 2.1 are illustrated in Figure 2.2. The key stages, together with an indication of where further information about them is provided within this guide, are:

- defining the performance requirements of a culvert (Chapters 1, 3, 4 and 9)
- assessing or designing the culvert against the performance requirements (Chapters 5, 6, 7, 8 and 9)
- monitoring the culvert for deterioration and loss of performance (Chapter 7)
- designing remedial works to achieve performance requirements (Chapters 7, 8 and 9)
- optimising and prioritising solutions (Chapter 2)
- implementing works that could include minor repairs, refurbishment, upgrading, replacement or removal of the culvert (Chapter 8).

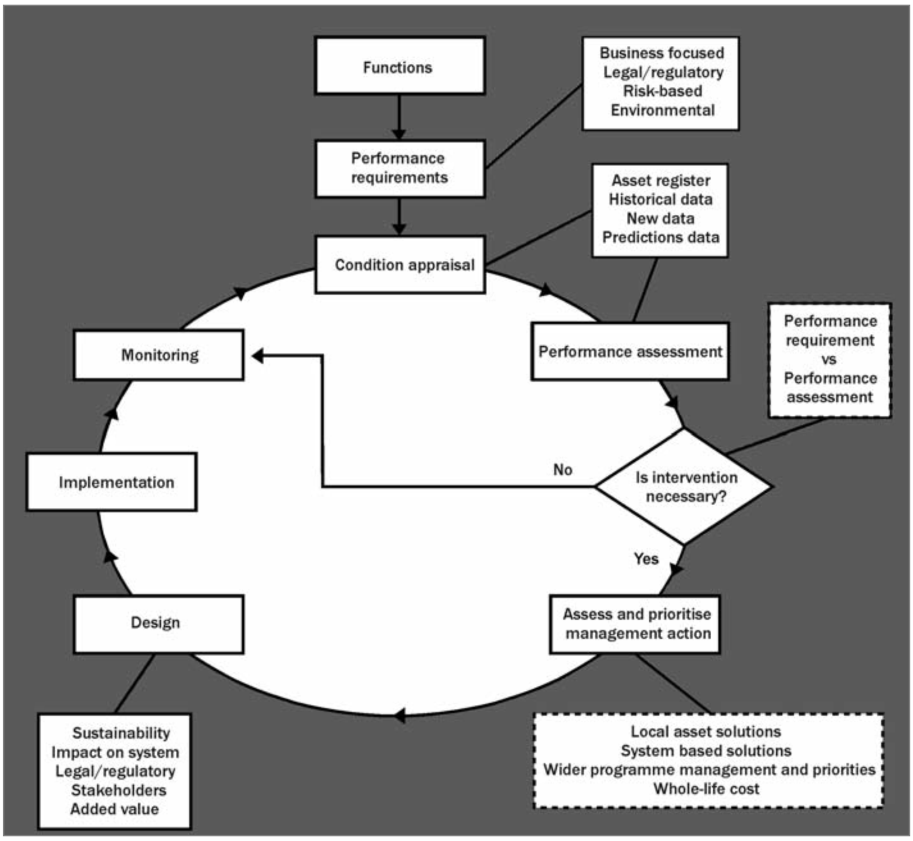


Figure 2.2 *Asset management cycle*

Figure 2.2 requires slightly different interpretations for new culverts as compared with the management of existing culverts.

When the potential for a new culvert arises, the first step is to define clearly what the required function is. Examples of functions for which culverts may be required include:

- to enable trains, pedestrians, or particular types of vehicles or animals gain access from one side of a watercourse to the other
- to allow a new development to occur along the path of an existing watercourse
- to allow continuity or discharge of a new watercourse through an existing development or structure.

The performance requirements to enable achievement of the defined function are then highlighted, incorporating as necessary legislative and policy considerations. The following three stages of Figure 2.2 (condition appraisal, performance assessment and assessing the need for intervention) are not relevant for new culverts. The next step is the appraisal of options for management, noting that culverting is only one of a range of possible options. Other approaches to providing the function for which the culvert is required is assessed at this stage (see Section 1.5 for typical alternative approaches). If this appraisal confirms culverting as the preferred option, then the design is progressed and implemented. On completion of construction the iterative processes of monitoring, condition appraisal, performance assessment and identification of interventions as necessary to maintain the performance requirement, begin.

The asset management process for an existing culvert should start with a good understanding of the performance requirement for the culvert. These could include structural, hydraulic, environmental and health and safety requirements. Where the existing performance requirements are unclear, they should be re-established, ensuring all relevant functional and legislative issues are covered. The iterative processes of monitoring, condition appraisal, performance assessment and identification of interventions as necessary to maintain the performance requirement should then be carried out. Any required intervention will feed into the programme management and prioritisation of the wider asset base, and carried out within this wider context. In the intervening period between identification of intervention and its implementation, ongoing monitoring will continue to identify any changes that may affect the prioritisation.

The frequency of the monitoring depends on the risk of failure that the structure poses (a combination of the probability and consequence of failure). In addition to the monitoring and assessment processes generating the need for interventions, they also provide a useful inventory of the condition and performance of the asset over time. Such information can be useful for re-assessment of the performance requirements over time.

Asset managers can also refer to the checklist located in Table 2.4, which will help to ensure that no issue is overlooked.

2.2 Responsibilities of culvert owners

Culvert ownership can generally be placed into two types, namely:

- the riparian owner (private landowners and infrastructure owners)
- the drainage authority (Environment Agency, local authorities and internal drainage boards).

In either case, ownership of the culvert places a duty of care onto the owner. Failure to maintain the culvert could lead to a loss of structural integrity or hydraulic conveyance capacity. These could in turn result in the loss of function for which the culvert was designed, or cause flooding, environmental damage or unsafe conditions for the operators or public. Case law as identified in Chapter 3 confirms the responsibilities of both culvert owner and drainage authority with respect to culvert maintenance, as both have been found guilty of not fulfilling their obligations with regard to a culvert, which resulted in upstream flooding.

Chapter 3 defines the principal legislation under which riparian owners' responsibilities are defined. A summary of riparian owner's responsibilities is identified in Living on the Edge (Environment Agency, 2007a). A culvert owner's responsibilities with respect to managing flood risk comprise the following:

- to pass on flow without obstruction, pollution or diversion, and without affecting the rights of others
- to maintain the bed and banks of the watercourse (including trees and shrubs growing on the banks), and clear any debris, natural or otherwise, including litter and animal carcasses, even if it did not originate from their land
- not to cause any obstructions to the free passage of fish
- to keep the bed and banks clear of any matter that could cause an obstruction
- to keep structures clear from the build-up of debris.

These are combined with any other duties which the ownership of the structure may have placed on them, for example public safety liability or maintenance of load carrying capacity.

2.3 Asset management processes

2.3.1 Introduction

Figure 2.2 illustrates the asset management cycle for existing culverts. It follows a cyclic process of inspection, assessment and improvement or repair as necessary, leading to a continuous awareness of the state of the assets and ensuring they continue to perform their intended functions. The process of assessment and prioritisation of management actions are the key link into the wider tactical level risk assessment, ensuring that strategic investment decisions can be prioritised. As with any other asset type, the management of data relating to culverts, their impacts on the wider environment and the provision of information links between inspections and planning is an integral part of the overall asset management process. An example of the asset management process is presented in Case study A3.1.

The DfT (2005) provides guidance on the processes used by highways authorities. The code provides information on how asset management can be used in combination with financial planning tools to provide a holistic management system and provides good practice guidance on the management of culverts which are used as highway structures.

Before starting an asset management process it is necessary to identify a series of performance requirements for a structure, this could be defined by a functional and/or a legislative requirement. A culvert can have several performance requirements including structural, hydraulic and environmental requirements, for example this could include the ability of the culvert to pass a defined flow of water, carry a defined load or allow the passage of wildlife.

The performance of the culvert in each of these areas is likely to change over time, so the culvert's performance should be monitored and assessed by regular inspections and performance assessments against its defined performance requirements. Further details and guidance on monitoring and assessing a culvert can be found in Chapter 7.

2.3.2 Performance requirements

The performance requirements of a culvert are based on the following criteria:

- structural capacity
- hydraulic performance
- legislative requirements (eg health and safety, the culvert owner's riparian duties and environmental performance).

The performance requirements of a culvert may change throughout its life, reasons for this could include:

- increase in loading (hydraulic or structural)
- change in legislation (eg new requirements for health and safety or environmental compliance)
- change in the wider environment (eg upstream development, change in the downstream hydraulic conditions).

The critical performance requirements of a culvert are identified in the following sections.

Structural performance

The structural performance requirements for a culvert are dependent on its use and are defined under several standards. The major standards used to define the structural performance of culverts are outlined in Section 7.1.

Hydraulic performance

Several considerations are required to determining an acceptable level of hydraulic performance of a culvert, including the:

- location of the culvert
- history of flooding
- type of watercourse the culvert is located on and its environmental constraints
- risk of blockage of the culvert.

In determining an acceptable level of hydraulic performance of an existing culvert the asset owner should consult with the relevant regulatory or local drainage authority to determine an appropriate level of performance and if a hydraulic performance assessment is required. Information on appropriateness of various forms of hydraulic assessments is included in Chapter 7. Further details on the assessment of hydraulic performance are found in Chapter 5 and 6.

Legislative requirements

The key legislative performance requirements of a culvert are defined by the following:

- environmental legislation (see Section 3.6 for the legislative requirements and Chapter 4 for how they are to be considered)
- health and safety legislation (see Section 3.7)
- duties as riparian owner (see Section 3.2 for the relevant legislation and Section 2.2 for particular responsibilities relating to culverts)
- legislation relating to infrastructure associated with the culvert, eg highway, railway or waterway (see Section 3.3).

2.3.3 Monitoring, condition appraisal and performance assessment

Effective management of an asset system that includes a culvert requires a suitable system of monitoring and assessment of its condition and performance against its performance requirements. This can be used to identify if remedial works are required and to allow these to be programmed. For the monitoring and appraisal to provide effective information to undertake asset management, the way in which inspections are managed and how their results are stored, presented and used are important.

A maintenance inspection and reporting programme should be established for all culverts. The programme should be established and should evolve using a risk-based approach, considering the likelihood and consequence of culvert failure (both hydraulic and structural). As more information becomes available on the asset the programme should be reviewed and adapted as necessary.

Numerous techniques are available for the presentation of data. It is common to use databases, spreadsheets, written reports and figures to record this information. It is becoming more common to record inspection and performance information using geographic information systems (GIS) that offer the extra spatial information. This can also be used to provide links to any as-constructed record that may exist for the culvert. Issues relating to the management of data are included in Chapter 7.

Standard data collection forms and grading approaches are commonly employed by owners of a large number of assets. These data collection techniques can be updated to provide better quality information, thus assisting in the assessment of performance of the culvert.

The methods of performance monitoring and assessment are summarised in the following sections. More details about how they are used in the context of culvert performance management are provided in Chapter 7.

Operational monitoring

During the operation of a culvert, or during regular inspections of a section of infrastructure a monitoring inspection of a culvert is undertaken on a regular basis. This form of inspection should identify if there are any major defects or changes in the performance of the culvert. Examples of current typical inspection frequencies are shown in Table 7.2.

The outputs from the operational monitoring should be fed back into the asset file to provide ongoing performance information on the culvert. They also provide a historical context to assess the rate of change in condition and performance.

Condition appraisal

Condition appraisals use the information from monitoring and inspections to determine the physical condition of a culvert. In conjunction with the historical information on asset condition, it can provide an appraisal of residual life. Where information from visual inspections and monitoring is insufficient to assess the condition of an asset, it may be necessary to support the process with more detailed intrusive or non-intrusive testing, or further monitoring.

Detailed information and guidance relating to condition appraisals of culverts is included in Chapter 7. The output of the condition appraisals can be used as an input to the performance assessment of the culvert. As more organisations move towards a performance-based assessment process, condition appraisals and performance assessments are being carried out as part of an integrated process.

Structural performance assessment

Structural performance assessment should be undertaken regularly to confirm if the culvert has sufficient structural capacity in line with its structural performance requirements and should define if additional remedial works are required. This will usually require inspection of the structural aspects of the culvert and an assessment of the results by competent staff. The particular requirements for different levels of structural inspections are set out by the major asset owning authorities.

The form of structural assessment selected should depend on several criteria including the:

- span of the culvert
- depth of cover over the culvert
- form of construction of the culvert
- degree of live loading on the culvert.

While this document does not focus particularly on the details of structural inspections and assessments, some further guidance on assessment requirements and references is included in Chapter 7.

Hydraulic performance assessment

Hydraulic performance assessment should be undertaken regularly to confirm if the culvert has sufficient hydraulic capacity in line with its hydraulic performance requirements, and should identify if further remedial works are required. This will usually require inspection of the culvert entry, barrel and outlet as well as other aspects of the watercourse that could negatively affect the culvert's hydraulic capacity. The performance assessment should be informed by the inspection and monitoring results and be carried out by competent staff.

The assessment of the hydraulic performance of an existing culvert is usually carried out by combining information about the local culvert capacity (taking into account its dimensions and any blockages or restrictions) with the expected hydraulic loading characteristics, which depend on an assessment of wider catchment physical and environmental information. Several methods can be used for this process, either in isolation or in combination such as:

- full hydrological assessment identifying catchment area and volume/rate of runoff (refer to Chapter 5 and 6)
- hydraulic modelling to include the culvert and a relevant length upstream and downstream of the associated watercourse
- use of existing comparable data/statistics
- pragmatic assessment of existing stream and/or culvert capacities including upstream and downstream of the culvert, taking into account any blockage within the system
- actual performance during an event involving very high flows.

In some cases, these assessments are carried out at the design stage or initial assessment stage for a range of conditions and extents of blockages or restrictions. The performance assessment following each inspection would only involve comparing the current condition (extent of blockage or restriction) with the pre-defined range of performance levels from pre-developed look-up tables or charts.

Table 2.1 indicates the range of hydraulic assessments used by Kent County Council obtained from the Dft (2005) for culverts at various locations.

Table 2.1 *Levels of assessment used by Kent County Council*

	Full hydrological survey and hydraulic model	Comparison of culvert size with that from similar catchments	Assessment of existing watercourse and available information	Comparisons with existing culverts on the watercourse
Urban area – sensitive to flooding	✓			
Urban area – little history of flooding		✓	✓	
Rural area – sensitive to flooding		✓	✓	
Rural area – not sensitive to flooding			✓	✓

The level of appraisal undertaken will be dependent on the level of risk of upstream flooding that a culvert may cause and also any future development plans in the area. It is recommended that the asset owner discusses the level of assessment and the input to the assessment with the relevant drainage authority. Advice on the design standard for culverts is included in Section 5.1.1 of the guide.

Environmental performance assessment

The environmental requirements of the design to meet legislative and policy requirements as well as opportunities for enhancements should be determined through an environmental assessment at the start of the project. The levels of assessment required and information on requirements for environmental receptors such as fauna and flora, visual amenity and water quality are detailed in Chapter 4. Assessment of these receptors post construction can be used to measure environmental performance of the scheme. Monitoring techniques for receptors may be defined by conditions associated to consents and licenses in some cases.

Consideration should be given at the start to opportunities for removing or opening up existing culverts for the benefit of the environment (see Chapter 9).

Health and safety assessment

The size, length, slope, access arrangements, ease of maintainability and flow within culverts can result in them being hazardous to enter. In most cases culverts are defined as confined spaces requiring specialist entry requirements. Issues relating to confined space entry are discussed in Chapter 7.

The risks associated with access into culverts should be considered when making decisions about the provision of access for operation and maintenance staff and security against unauthorised access by the general public. Guidance on identifying the risks associated with culverts is included in Chapter 7 and by the Environment Agency (2009a), the Health and Safety Commission (2009) and Gotch *et al* (2009).

The assessment of the health and safety risks that a culvert presents should be identified at the design stage and recorded in the health and safety file. Where such an assessment has not been completed this should be an initial task that will have an influence in determining the maintenance, inspection and reporting programme.

2.3.4 Deciding whether or not to intervene

It is important that the decision to intervene is based on proper assessment of the current condition and performance of the culvert as compared with its performance requirements. It is also important to determine whether the reason for any performance deficiency is locally due to the condition of the culvert or whether it is as a result of a wider problem within the drainage system. Intervening locally to address a system-wide problem is usually a short-term fix and is unlikely to provide a sustainable solution.

PAS 55-1 (BSI, 2008a) recommends that organisations have processes and defined authority and responsibilities for:

- handling and investigating asset related failures (including failures to meet required functions, performance and condition, incidents, emergencies and non-conformities)
- taking mitigating actions
- initiating corrective or preventative action and confirming the effectiveness of the corrective or preventative actions.

These processes should undergo risk assessments before they are adopted, and the actions to manage the non-conformance should be appropriate to the size of the problem and the asset related risk. All this information should be recorded and documented for future learning.

Identifying who is responsible for taking decisions

Infrastructure assets are generally owned and/or managed by large and complex organisations with very extensive responsibilities. There are likely to be hierarchies within the management, both of the organisation and of the infrastructure assets, with responsibility for decisions delegated to differing levels within the organisation (or within the asset owning organisation and the organisation managing the asset, which may be different). Effective infrastructure management requires a clear understanding of who has the authority to decide how decisions are taken, who will take responsibility for the decisions, and who has the authority to change the decision making process. This is particularly important where ownership and operational responsibilities are complex, as is widely the case for the infrastructure networks that support transport and distribution. There are national and local government responsibilities, a wide range of statutory regulators, complex ownership arrangements, and complicated supply chains for asset management and maintenance work. So, there should be a well defined process of delegation for making decisions at the appropriate level, with a clear understanding of the consequences of the decisions for the operation of the business, the system and the network. In many instances the decision making process will produce the same decisions as the judgements of experienced engineers and technical managers. This is not surprising, because experience allows rapid option evaluation using unwritten rules of thumb. However, it is important that even experienced staff use the decision making process to, for example:

- confirm its validity
- provide an audit trail to demonstrate that the asset management procedures have been successfully implemented
- enable engineers to rationalise and explain decisions clearly to others
- ensure that opportunities for low risk innovation are identified and exploited.

2.3.5 Prioritisation of management actions

To effectively manage an asset and to ensure that funding to maintain and operate an asset can be spent efficiently and works to the structure can be prioritised, a process of risk management is required. A vital element in this process involves the development of a risk assessment that can be used to identify when investment is required. An example risk assessment is shown in Table 2.2.

Table 2.2 ***Example of a risk assessment for asset management intervention***

		Probability of hazard (expressed as condition grade/frequency of flooding)		
		Good condition ***Low flooding frequency***	***Average condition*** ***Regular flooding frequency***	***Poor condition*** ***High flooding frequency***
Consequence of hazard (hydraulic/structural Issues with culvert)	**Low** No consequence to people, property or infrastucture	Negligible risk Routine inspection	Low risk Routine inspection	Medium risk Increased inspection frequency
	Medium Minimal consequence to people, property or infrastructure but high cost of disruption	Medium risk Routine inspection	Medium risk Increased inspection frequency	High risk Assess improvement works
	High High consequence to people property and high costs of disruption	Medium risk Routine inspection	High risk Assess improvement works	Unacceptable risk Undertake improvement works

This form of assessment allows for asset owners to prioritise the need for further inspection or assessment, increased maintenance or remedial works to culverts based on risk.

Business case review

To undertake non routine works such as rehabilitation or improvement of existing culverts, asset managers often have to provide justification to obtain funding for the required intervention to the culvert. It can then be prioritised within the context of other works within their wider programme. For this a business case is often required. These justifications may be based on the expected return on investments or funds, requiring an appraisal of the whole-life costs and comparing to the whole-life benefit or risk reduction. Due to the nature of the benefits and risk reduction, these assessments are often qualitative. The business case highlights particular requirements of the funding authorities or the infrastructure owners or managers.

Whole-life costs

Whole-life costing involves estimating the total cost of a system or structure throughout its entire life taking into account maintenance, repair and rehabilitation as well as initial capital costs. It is an appropriate technique for use in valuing total costs of assets that require regular operation (eg trash screen clearance) and/or recurrent maintenance (eg sediment removal) costs. Whole-life costs can be used to determine if it is more cost effective to invest funding at the start of the project to reduce ongoing maintenance costs. Table 2.3 provides guidance on various elements that are included in the whole-life cost of a culvert.

Table 2.3 *Example of elements of whole-life costs*

Stage	Cost item
Design/inception	Professional fees Consultation Licenses and consents (planning permission, land drainage consent etc)
Construction	Land purchase/compensation Materials Contractor costs Supervision (professional fees)
Operation	Monitoring Inspection Assessment Maintenance Repairs Clearance of trash and debris Disposal of waste
Replacement/removal	Professional fees Licenses and consents Land purchase/compensation Demolition Disposal of waste Construction of replacement

2.4 Implementation of remedial works

When a culvert fails to meet its performance requirements three possible management options can be considered:

1. Rehabilitation or enhancement (returning the culvert to its original as-designed performance or upgrading to provide more capacity or functionality).
2. Replacement (with a different or better structure, meeting increased performance criteria).
3. Removal often referred to as "daylighting" (ie demolition, returning the watercourse to a more natural state). Refer to Case study A3.10 for a specific example.

If no maintenance or other intervention is carried out on an asset, its standard of performance will deteriorate over time. The deterioration of a typical asset can be exemplified by an exponential relationship between performance standard and time as is illustrated in Figure 2.3.

The effect of maintenance of a culvert is to enable it to maintain the standard of performance that it was designed to, or to a desirable standard. The ideal maintenance scenario is for a standard of service to be kept by an optimal maintenance regime. Over time, this may not be practical and the deterioration may continue to a point where major rehabilitation, replacement or upgrade is required. The strategy adopted for various culverts depends on the extent of failure of the supporting infrastructure, and will differ depending on factors such as the infrastructure it carries, its age, access, remoteness and temporary works required to carry out maintenance. The various intervention options are illustrated in Figure 2.3.

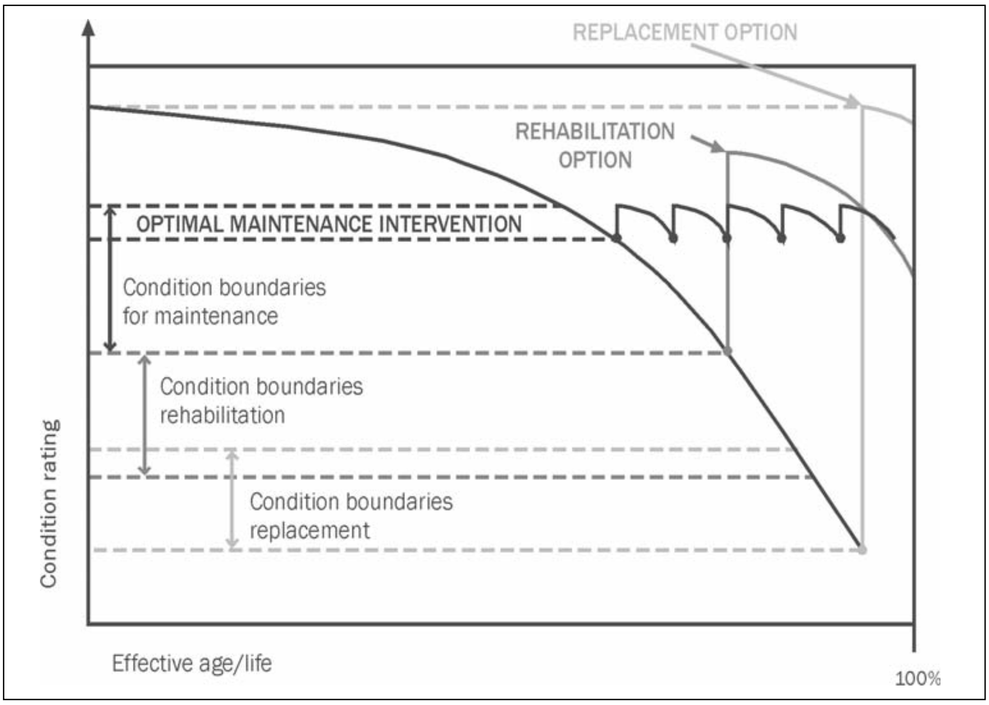


Figure 2.3 *Example of life cycle interventions (derived from INGENIUM, 2006)*

2.4.1 Refurbishment and enhancement options

When a culvert is nearing the end of its useful life and only if the requirement for a culvert of similar performance remains, a major refurbishment is often more cost-effective when compared to complete removal and replacement. This allows the continuing (although sometimes reduced) functioning of the culvert while all or most of the refurbishment continues.

Before developing options to refurbish a culvert, the performance requirements should be reviewed with consideration given to the likely future performance requirements. This may include accounting for future pressures on the system, appropriate environmental enhancements, and improvements on health and safety and access for future operation and maintenance. Various options for the refurbishment of a culvert are identified in Chapter 8.

2.4.2 Replacement options

When it is uneconomic to continue to repair the culvert (eg where repairs are prohibitively expensive or replacement/removal provides a more economic solution), alternative approaches will need to be considered.

At this stage, the performance requirements should be reviewed with consideration given to the likely future performance requirements. Changes in the performance requirements are usually easier (and cheaper) to instigate when replacing or removing the culvert, compared to repairing or refurbishing the culvert.

Alternatively to replacing a culvert, augmentation or duplication could be a more cost effective solution. If sufficient space and access is available an additional culvert could be constructed near to the existing culvert and the existing culvert refurbished to provide increased structural strength. Creation of multiple culverts increases the ability to carry out future maintenance and rehabilitation works without temporarily losing all discharge capacity. Some construction techniques as defined in Chapter 9 allow the construction of culverts without the need to disrupt the infrastructure above the culvert.

2.4.3 Removal options

The Environment Agency and CIWEM currently promote open channel alternatives as a preference to culverts. Section 1.5 provides some of the reasons for this. Avoiding construction of culverts or removing ones that are no longer required will also help further the aim of the Water Framework Directive to achieve good ecological status for all water bodies. As an integral part of removing culverts, opportunities to improve the ecological potential of the watercourse should be taken.

There are situations where the need for connection of both sides of a watercourse still remains, and removing the culvert without providing some alternative means of achieving the objective would not suffice. In such cases, the alternatives that lead to less interference in the natural morphological processes within the watercourse as provided in Section 1.5 should be considered.

As with any watercourse rehabilitation work, careful planning is required to ensure the asset removal achieves its objectives. The main tasks to be considered include:

- defining opportunities, constraints and impacts of removing the culvert
- assessing the impacts of the alternatives on the watercourse, environment and whole-life costs
- ensuring sustainable procurement, construction and waste management techniques
- establishing a monitoring and evaluation programme.

Table 2.4 *Asset management checklist*

Ref	Check item	Notes	Section in the guide
Collect the basic data			
A	***Identify and locate structures***		
A1	Add details to database		2.1
B	***Determine consequence of failure***		
B1	Damage and disruption to infrastructure	Type of infrastructure: railway, highway, waterway, other services located within embankment	2.3.5
B2	Potential flood risk area	Extent of area at risk as a result of culvert blocking or (in the case of a culvert under a canal) flooding from breach in the canal Assess potential damage to property in the flood risk area.	6.13
B3	Environmental consequences	Changes to habitats Impacts on protected species Loss of amenity.	4.2
Define the performance requirements			
C	***Structural***		
C1	Determine required structural performance	Relevant to location and facility carried by culvert	2.3.2
D	***Hydraulic***		
D1	Design flood probability	Determine appropriate annual exceedance probability (AEP) and design life	2.3.2, 5.1.1
E	***Legislative requirements***		
E1	Environmental legislation	Does the culvert form the control to a sensitive environmental site? Would the ecological potential of the watercourse benefit from any specific improvements to the culvert?	3.6
E2	Legislation and performance requirements relating to infrastructure	What performance levels is the culvert expected to act at? What are the performance requirements for the structure?	2.3.2, 3.3
E3	Health and safety	Define the key requirements at the site relating to both public and operational health and safety	2.3.2, 3.7
E4	Riparian owner's duties	Define the riparian owners duties relating to operating the culvert	2.2, 3.1
Condition appraisal and performance assessment			
F	***Inspections***		
F1	Develop inspection programme and frequency Determine condition grading criteria to be used	The development of an inspection programme and frequency ought to be based (in part at least) on historic inspection data (eg screen blockages) and interaction between Sections F, G, U,V and W is required	2.3.3, 7.2

Table 2.4 (contd) *Asset management checklist*

G	Planning of inspections	Determine type of inspection Determine timing constraints associated with access and flow conditions in the watercourse Determine the timing constraints associated with environmental limitations (flora and fauna) Determine data collection requirements and method of recording data Obtain historic information relating to the structure and previous reports Determine if temporary access or site clearance works are required Define if a confined space inspection is required and plan for health and safety	2.3.3, 7.2
H	Condition appraisal	Determine condition of structure based on inspection Determine if immediate remedial works are required	2.3.3
		Performance assessment	
I	Structural performance	Identify if structural assessment is required (based on span and cover to the culvert, age of the structural fabric, time since last assessment, and any material changes to the loading conditions)	2.3.3, 7.1.2
J	Hydraulic performance	Identify level of performance required based on the consequences of failure	5.1, 7.1.3
J1	Hydrology	Catchment descriptors Nature of catchment in terms of hydraulic response and sediment and debris loads Value of the design flood flow	5.1 to 5.6
J2	Hydraulic conditions	Channel form Presence of any control structures upstream or downstream Local hydraulic conditions (eg tidal constraints or flow constriction (outfall from flood storage reservoir) Assess tailwater levels Presence of a screen and assessment of blockage risk Determine capacity of culvert	5.4, 6.3 to 6.14
J3	Consequences of extreme flood and/or blockage of the culvert or screen	Examine blockage scenarios and assess hydraulic performance in extreme flood Determine if any remedial works are required to reduce risk or minimise the consequences	6.12, 9.6.1
K	Legislative requirements	Determine if culvert complies with health and safety legislation (eg risk from falls from height, entry into confined spaces, guarding of control equipment) Determine if culvert meets other performance targets (eg condition grade) Determine if culvert meets other legislative requirements	2.3.2, 3.7, 7.1.4, 7.1.5
		Business planning	
L	Assess if culvert is required	Assess possibility of culvert removal now or in the future	1.5, 9.1
M	Prioritise works	Identify and prioritise remedial works	2.3.5
N	Assess if screen is required	Assess need for a screen if none is present, or possibility of removal if there is a screen	9.4.3, 9.5.5

Table 2.4 (contd) ***Asset management checklist***

Develop remedial works			
O	Identify works required, including works to any screen	To meet the hydraulic, environmental, structural and other performance requirements	8.1, 9.4.3, 9.5.5
P	Construction issues	Access for construction and working space Overhead and underground utilities Assess temporary works requirements and their impacts on development of options Identify restrictions on working methods or timing of the works	9.1.3, 9.6.3
Q	Health and safety	Establish risks and design the works to eliminate or minimise these	9.1.3, 8.2.2
R	Legal issues	Obtain land drainage consent from the appropriate authority, resolve any land ownership issues, obtain planning consent where required	8.2.3
S	Environmental and social setting	Obtain data on wildlife and fish migration, aquatic ecology, landscape and heritage in order to investigate the impact of remedial works	8.2.4
T	Design	Design of remedial works to meet the requirements while satisfying environmental constraints and allowing safe inspection and maintenance in the future	8.3, 8.4, 8.5 and Table 9.4
Monitoring			
U	Inspections	Undertake regular inspections to determine if condition of the culvert changes	7.2
V	Review performance requirements	Review performance requirements for the culvert and reassess if necessary	2.3.2
W	Screen performance	Record all activity related to inspecting and cleaning any screens at the inlet and outlet, including frequency of cleaning, type and quantity of debris removed, evidence of vandalism	2.3.3, 9.4.3, 9.5.5

3 UK legislative requirements

3.1 Legal framework

This chapter provides a summary of the main aspects of the law relating to culverts. It aims to provide pointers to the legal considerations regarding the design, construction, maintenance and removal of culverts. It is not intended to be a comprehensive or definitive text and the user is advised to consult a competent legal authority for definitive advice.

The legal framework regarding culverts varies from country to country within the UK. The law confers rights, powers and duties on the owners of culverts and relevant statutory authorities relating to:

- **rights:** the ability to act or do something, usually conferred as part of land ownership. There is a general right to construct a culvert subject to consent and compliance with other statutory requirements
- **powers:** a legal entitlement to do something, which come from legislation. The powers are usually given to a government or other statutory body. Examples are the powers to carry out flood defence and drainage, and to issue a consent to build a culvert
- **duties:** the requirement to do something, eg apply for a consent, and derived from statute. Duties can also arise from case law.

The onus to maintain a culvert and to ensure it is adequate for its purpose is on the owner of the culvert, the highway authority if it is part of the highway, or on the operating authority if it is a land drainage or flood defence asset.

Exercising the right to construct a culvert can lead to potential liability. If it can be shown that the capacity of the culvert was inadequate to replace the carrying capacity of the watercourse and flooding results, then a nuisance or negligence case could arise. This liability is irrespective of whether a statutory consent was given. This is a very complex area of the law and specialist legal advice should be sought. Case study A3.2 provides an example of where a culvert owner was found to fail in its common law obligations, as the culvert reduced the capacity of the channel and caused upstream flooding.

The Bybrook Barn v Kent County Council judgement criticised the highway authority (in this case the county council) for failing to fulfil its common law obligation to ensure that the carrying capacity of the natural stream was not constricted by the highway culvert. The drainage authority (in this case the district council) was also criticised for failure to exercise its power to require that the highway authority improve the culvert known to be causing flooding.

A useful summary of landowner responsibilities (for England and Wales) is provided in the Environment Agency (2007a) and on drainage authority powers in Howarth (2002). The guide from the Institution of Civil Engineers (2010) provides a more recent summary of the legal implications and responsibilities associated with flood risk management, with a whole chapter (Chapter 13) dedicated to culverts. Further information and details of likely constraints in respect of planning requirements should be available from the relevant local authority planning department. This information may well make reference to local drainage assessment guidelines and local plan policies, which may include a policy on culverting.

3.2 Flood defence and land drainage law

3.2.1 England and Wales

Land drainage legislation in these countries differentiates between "main river" and "ordinary" watercourses. Main rivers are designated on maps. The Environment Agency has statutory powers in relation to main rivers. For information on the extent of main rivers contact the nearest Environment Agency office. The term ordinary watercourse describes the remaining watercourses. Local authorities and internal drainage boards (IDBs) have statutory powers in relation to ordinary watercourses. Details of IDB locations are available from the Association of Drainage Authorities website (see *Useful websites*).

The Water Resources Act 1991 covers the powers and duties with respect to main rivers, and the Land Drainage Acts 1991 and 1994 covers those for ordinary watercourses. All give permissive powers allowing the designated drainage authorities to construct, maintain, or remove culverts as required for the purposes of land drainage or flood risk management. They also make provision for the need for consent to construct or modify a culvert. Neither Act imposes a duty on the drainage authorities to repair, remove or construct culverts.

In late 2009 the Government published the Flood and Water Management Bill, which aims to create a more simple and effective regime for flood and coastal erosion risk management. The Bill amends the Water Resource and Land Drainage Acts and aims to provide an integrated approach to flood management between local authorities, water companies and internal drainage boards under the strategic direction of the Environment Agency. In relation to culverts, the Bill will strengthen the consent requirements for culverts as follows:

providing further powers for the Environment Agency, local authorities and IDBs to formally designate culverts as flood management assets and to require the owners to seek consent for their removal or modification

IDB, county and unitary local authorities will take responsibility for consenting and enforcement of culvert work on ordinary watercourses (as opposed to IDBs and district and unitary authorities under the Land Drainage Act).

3.2.2 Scotland

The Flood Risk Management (Scotland) Act 2009 transposes the EU Floods Directive into Scottish law. It also repeals the Flood Prevention (Scotland) Act 1961 and Flood Prevention and Land Drainage (Scotland) Act 1997. The new Act increases the role of the Scottish Environment Protection Agency (SEPA) within flood risk management and places new requirements on Scottish Government, SEPA and responsible authorities (including all local authorities). The focus is on improving understanding and mitigation of flood risk. There are requirements for SEPA to map and assess structures that may cause or reduce flood risk, which is likely to include culverts and culvert screens.

Local authorities are required to assess all local water bodies and determine areas where maintenance may reduce flood risk. They are then required to prepare a schedule of repair and clearance works that they have a duty to carry out. These elements largely replace the Flood Prevention and Land Drainage (Scotland) Act 1997, and there is now a provision for entry to land and for recovery of costs for flood management work under certain circumstances.

Local authorities have a more simplified route to promoting flood management schemes and culvert works, as once they are within the flood management plans they can be confirmed by a local authority rather than needing Scottish Government approval (as was the case under previous legislation). Once a flood management scheme is confirmed, planning permission will be deemed to have been granted, subject to there being no unresolved objections.

There is a presumption against new culverts except for exceptional situations under the new legislation given the emphasis on widespread consultation and sustainability enshrined throughout the Act.

3.2.3 Northern Ireland

The Drainage (Northern Ireland) Order 1973 as amended by the Drainage (Environmental Impact Assessment) Regulations (Northern Ireland) 2001 and Drainage (Amendment) (Northern Ireland) Order 2005 gives the Drainage Council the powers to “designate watercourses”, and the Rivers Agency to undertake, construct and maintain drainage works such as culverts, to carry out emergency works and to make byelaws. The designation of watercourses and sea defences gives extra powers related to the maintenance, repair, replacement, improvement, and construction of culverts and allows public money to be spent on their maintenance.

Schedule 5 of the Order sets out the duties of culvert owners with respect to undesignated watercourses. Occupiers shall “scour out and cleanse and maintain the portion of the watercourse running on or through or bounding the land...that the efficiency of the watercourse is not impaired by reason of any act or omission”. Schedule 6 requires the consent from the Rivers Agency for the construction or alteration of a culvert.

The Rivers Agency may at any time by a notice served in writing on the occupier require the carrying out of maintenance. The Rivers Agency may, if the occupier does not carry out the work, carry out the necessary works and recover the costs, and the occupier shall be guilty of a criminal offence.

3.3 Transport law

Highway, railway and canal legislation has conferred the powers on various undertakings to carry out culverting work to improve drainage.

It should be noted that in addition to the powers provided in the legislation for construction and maintenance, there remains a duty to obtain consent for culverting work as summarised in Section 3.9.

3.3.1 Highways

There are probably more culverts constructed in connection with roads than for any other purpose. In relation to public highways, the main statutes are:

- Section 110 of the Highways Act 1980 gives highway authorities in England and Wales and Northern Ireland the powers to construct culverts for the purpose of road construction and drainage
- The Roads (Scotland) Act 1984 gives highway authorities the powers to construct culverts to provide road drainage or to allow roads to cross watercourses.

3.3.2 Railways

The most important piece of legislation relating to railways and culverts is the Railway Clauses Consolidation Act 1845 and the Schedules attached to various environmental, Scottish and Northern Ireland legislation that amend the Act. The Act gives powers to build culverts as part of railway construction and maintenance and states that culverts are classed as "accommodation works" and that anyone affected by the works has five years from the opening of the railway (Section 73) to object. Once five years have elapsed, the accommodation works are deemed to be acceptable and there is no right to object.

3.3.3 Canals

As with railways, the canal system of the UK was generally developed under private acts of Parliament that provided the powers to construct culverts where required. Following creation of British Waterways (BW), these Acts are overlaid by other legislation. The result is a complex area of law where it is difficult to generalise on the powers and responsibilities relating to canals. The advice of the relevant canal or navigable waterway operator should be sought.

The British Waterways Act 1995 provided BW with powers to enter third party land to carry out maintenance. Section 22 also places duties on BW to take natural beauty and environmental matters into consideration when exercising its powers, as does Section 7 of the Environment Act 1995 on those sections of navigable waterway under the jurisdiction of the Environment Agency.

3.4 Public health law

The Public Health Act 1936 (Sections 259 to 266) gives parish councils and local authorities the powers to undertake culverting if a watercourse is considered to be prejudicial to health, and to require the occupier of any land to clean and repair a culvert.

3.5 Law of nuisance and rights of entry

A nuisance arises where there has been an unreasonable interference with a landholder's interest in the enjoyment of land – in the case of culverts normally arising as a result of flooding. Depending on the ownership and responsibility for a culvert, the nuisance can either be private or statutory. Case law has established that there are obligations on a person who installs a culvert, not only to ensure that it is designed and constructed to accommodate the flows as effectively as the natural channel, but also to ensure that the culvert is continuously maintained to ensure it operates as effectively as the natural channel.

Another consideration that is advisable as part of culvert design is to establish a right of entry or a wayleave or easement to allow maintenance. Failure to do so could lead to trespass on the property of others.

3.6 Environmental law

3.6.1 General legislative issues

All the countries in the UK are subject to European Union environmental directives and regulations that have been incorporated into UK law. Foremost amongst these with respect to culverting work is the Water Framework Directive (2000) (WFD). The WFD places a requirement to maintain or improve the ecological status of a watercourse and in practice places a presumption against culverting for land gain. Culverts for access and beneath roads and railways may be compliant under the Directive provided they do not impact adversely the ecological status of a water body or can demonstrate a series of conditions have been met if adverse impacts occur.

The Habitats Directive is a European Directive aiming to conserve internationally important natural habitats, flora and fauna. It sets requirements for plans and projects likely to affect Natura 2000 sites, as defined by the Directive. These include special protection areas (SPAs), special areas of conservation (SACs), candidate special areas of conservation (cSACs), and possible special areas of conservation (pSACs). Potential special protection areas (pSPAs) and Ramsar sites are also included under UK Government policy. These areas are commonly known as “European sites”. Where a plan or project is deemed likely to have a significant effect upon a European site, an appropriate assessment will be required to determine any adverse effect on site integrity.

An appropriate assessment is distinct and separate from an environmental impact assessment (EIA), which may be required for certain projects, although areas of overlap may exist, and information may be shared. Where practicable, work to satisfy the requirements of the Habitats Directive should be undertaken as part of the EIA process, and documentation should be produced to satisfy both processes.

Under the Conservation (Natural Habitats, &c.) Regulations 1994, permitted development rights are not valid in relation to any project if, in the opinion of the competent authority (typically the local planning authority) the works are considered likely to have significant effects on a Natura 2000 site. In such situations, planning permission will be required, as well as an appropriate assessment.

A brief summary of other environmental legislation follows, in relation to each of the UK countries and more details can be obtained from the relevant environmental authorities (Natural England, Countryside Council for Wales, Scottish Natural Heritage or the Northern Ireland Environment Agency).

There is a general principle that the impact of any culverting work on the environment should be minimised. The requirement for a formal environmental assessment for culverting works that are not executed under permitted development rights lies with the local planning authority, which will consider the application and determination on a case by case basis. If the culvert forms part of a larger scheme, the environmental aspects of the culvert should be addressed as part of the scheme as a whole. However, for standalone culverts, the designer may wish to consult the planning authority for a decision as to whether environmental assessment may be required or voluntarily submit an assessment with the planning application.

If the culvert is within a site of special scientific interest (SSSI) or other statutory environmental designation, the owner or occupier must not carry out any operation that is prohibited in the site notification, unless the consent has been obtained from the relevant environmental authority. Consent is required even if the culvert is outside of the boundary but could have an impact on the designated area.

Disposal of material

The regulations regarding the disposal of material from a culvert or a screen vary from country to country but in most cases a licence is required for the removal and transport of material. It is best that the Environment Agency (England and Wales), SEPA (Scotland) or the Northern Ireland Environment Agency as applicable are consulted before planning to undertake removal of material from culverts and screens.

3.6.2 England and Wales

When consenting culverting works under the Water Resources Act 1991, the Environment Agency must comply with its environmental duties as set out in Sections 7 and 8 of the Environment Act 1995. Similar duties are set out in Sections 61A and 61B of the Land Drainage Act 1991. Such environmental consent is normally dealt with alongside the consent for work in watercourses (see Section 3.9.1).

The construction of a new culvert required in connection with the improvement, maintenance or repair of a watercourse by drainage boards or the Environment Agency may be considered as permitted development under the Town and Country Planning General Permitted Development Order 1995, Schedule 2 Parts 14 and 15. These operations are not considered likely to need planning permission.

Environmental impact assessment is required under a European Directive (EC Directive 85/337/EEC amended by EC Directive 97/11/EC and Article 3 of Directive 2003/35/EC), which has been transposed into English and Welsh Regulations through several regulations. Those most relevant to development in the water environment fall under:

- The Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations SI 1999 No 293, as amended by SI 2000/2867, SI 2006/3295 and 2008/2093. Schedules 1 and 2 of the Act lists the works that are subject to statutory EIA
- Environmental Impact Assessment (Land Drainage Improvement Works) Regulations SI 1999/1783, as amended by SI 2005/1399 and SI 2006/618.

Schedule 2 of the Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations identifies that if the area of works exceeds 1ha or the works are to be carried out by a non-statutory undertaker, the works will be subject to Statutory EIA. This will need to be confirmed by the local authority. It is generally considered good practice to obtain a screening opinion from the local authority regardless of the size of the development. The requirement for a statutory EIA may also negate the permitted development rights, and in this situation planning permission would be required.

Where the area of the works does not exceed 1ha the works will not be subject to statutory environmental impact assessment (EIA). They will be subject to informal environmental assessment under the Environment Act 1995.

3.6.3 Scotland

In Scotland, works in or near watercourses are subject to the Water Environment (Controlled Activities) Regulations 2005 (CAR), (SEPA, 2008a). These were established to satisfy elements of the EU Water Framework Directive. For engineering works the CARs cover inland surface waters and are regulated by SEPA, while coastal and transitional waters are regulated by the Fisheries Research Service under the Food and Environment Protection Act 1985. SEPA has a presumption against culverting and the regulations are structured to prefer crossings that do not interfere with the channel flow or morphology. A culvert carrying a watercourse normally requires a CAR licence depending on the nature of the work:

- culverts that are specified for land gain always require a complex licence
- a temporary crossing over a watercourse less than 5 m in width that is less than 10 m in length and does not result in a narrowing of the channel width may be regulated under the general binding rules
- pipe or box culverts used for footpaths, cycle routes or single track roads in rivers less than 2 m in width would require a registration
- a simple licence is required for all other pipe or box culverts
- maintenance of culverts subject to term contracts may be considered notifiable.

The removal of debris from a culvert or culvert screen falls under the general binding rules of the CARs. Culverts on streams not shown on the 1:50 000 OS map do not require authorisation, but if SEPA is consulted they would seek good practice in terms of the culvert design, including maintenance of habitat, sediment transport, and mammal and fish passage.

The regulatory authority for the CAR regulations is SEPA and more information on the current procedures can be found in SEPA (2008a), with details about CAR provided on the SEPA website (see *Useful websites*). Licenses can take up to four months to be given if no further information is required by SEPA.

3.6.4 Northern Ireland

The Drainage (Environmental Impact Assessment) Regulations (Northern Ireland) 2001 and Drainage (Amendment) (Northern Ireland) Order 2005 amended the Drainage (Northern Ireland) Order 1973 to provide adoption of European Union requirements with regard to the environment. The principal requirement of the Regulations is that the Rivers Agency must determine whether proposed works or schemes are likely to have significant effects on the environment. The regulation sets out the rules on publication of the Agency's decision, the environmental statements and the appeals process, including referral to the Planning and Water Appeals Commission. Further information is available from the Rivers Agency website (see *Useful websites*).

3.7 Health and safety law

The Health and Safety at Work etc Act 1974 (Health and Safety at Work (NI) Order 1978 in Northern Ireland) and its subordinate regulations (such as the Construction Design and Management (CDM) Regulations 2007 and the Confined Spaces Regulations 1997) are highly relevant to culvert projects. The main health and safety issue associated with a culvert is the requirement to maintain, through several provisions, the safety of the public and operatives working on the site – both day and night, in high and low-flow conditions.

Advice on CDM and other health and safety issues can be obtained from the Health and Safety Executives in England, Wales and Scotland and Northern Ireland.

The Construction (Design and Management) Regulations 2007 (for England, Scotland and Wales) and the Construction (Design and Management) Regulations (Northern Ireland) 2007 apply to all new culverts and any maintenance, repair or removal work carried out on a culvert. Section 4 of the 2007 Regulations sets out the duties during construction, but there are obligations throughout the feasibility, design and maintenance phases.

The extent of obligations under the CDM Regulations will depend on whether a scheme is notifiable or not. A culvert scheme is notifiable if it is envisaged that the construction phase will last for more than 30 days/shifts or will involve more than 500 person days or shifts or any new design work. CDM Regulations may not necessarily apply to minor maintenance works so a competent person should be consulted on whether this is the case. Any culvert work undertaken on what is a "permanent" CDM site (such as a railway) is notifiable. If it is determined that the CDM Regulations do not apply to a culvert design or maintenance project, or that a scheme is not notifiable, the reason for this decision must be clearly documented.

The culvert designer should maintain a record of the hazards identified and how these have been cut out through the design process. Any residual hazards should also be identified and recorded so that relevant parties are aware of them.

For culvert design the following issues and questions should be considered as part of a risk assessment (note that this is not an exhaustive list):

- working within excavations
- working within contaminated ground
- working within confined spaces
- working in close proximity to water
- flood risk during construction
- how is blockage to be prevented?
- who is at risk if the culvert is blocked?
- is a safe method of removing a blockage available?
- can the structure be cleaned and maintained safely?
- does the culvert pose a significant risk to the public and, if so, what is the best way to reduce or eliminate this risk?
- access for rescue if required.

The Confined Spaces Regulations (Confined Spaces Regulations (Northern Ireland) 1999 and Confined Spaces Regulations 1997 (for the rest of the UK) require the designer and maintainer of culverts to avoid the need for entry by persons into culverts if at all possible. If entry is essential then a safe method of doing so and also of evacuation is required (see Section 7.2).

Finally, the Occupiers Liability Acts of 1957 and 1984 (in England and Wales) created a duty of care owed by an occupier (person who has control over premises such as a culvert) to its visitors. A duty is owed if the occupier is aware of any danger or has reasonable grounds to believe it exists. The 1984 Act extended this duty to trespassers. To fulfil the duty of care under the Occupiers Liability Acts, a warning or deterrent may be needed at the culvert inlet and outlet and could take the form of warning signs and/or fencing.

3.8 Culverting policies

The UK drainage and flood management agencies have developed policies concerning culverts, and all generally oppose the culverting of watercourses and consider that it is beneficial for watercourses to remain open (Environment Agency, 1999a and SEPA, 2006). This is based on both flood risk and environmental reasons (prevention of an increase in flood risk, loss of habitat and the continuity of the stream corridor). These policies mean that consent to construct a culvert is normally only given where there is no reasonable practical alternative. The general preference is, where practical, to restore existing culverts to open channels – also known as daylighting.

Alongside the Environment Agency in England and Wales there are about 150 statutory internal drainage boards that control culverting in the designated internal drainage districts. The boards are responsible for ordinary watercourses in these districts and set their own individual policies. These broadly follow the Environment Agency's policy on culverting, although there may be local variations. Flood risk management policies and strategies may also contain policies that affect culverting, for example, catchment flood management plans (CFMPs) and surface water management plans (SWMPs).

Although there is a general policy against culverting, sometimes there are situations where culverting is unavoidable, particularly in areas where there is a heavy reliance on man-made drainage systems and there is a high concentration of ditches. Such situations may include short lengths for land access purposes or where roads, railways and other infrastructure cross watercourses. In such cases, open span bridges or the diversion of watercourses can be considered. In cases where a culvert is unavoidable, measures to mitigate the adverse effects of culverting and to improve the environment can be incorporated. All the controlling agencies seek to regulate culvert construction through comments on development applications, the application of legal consenting systems and input into development plans.

3.9 Consenting requirements

Construction, alteration (including removal) or repair of a culvert (and any associated screen) will normally need the consent by bodies other than the landowner. The requirements vary between different parts of the UK. If the culverting works require planning permission, they are likely to be subject to the requirements of a flood risk assessment under planning guidance PPS25 in England (CLG, 2006), TAN 15 in Wales (Welsh Assembly Government, 2004), SPP7 in Scotland, (Scottish Executive, 2004) and PPS15 in Northern Ireland (The Planning Service, 2006).

It should be noted that any approval required and given for the works under other legislation does not negate the need for consents under land drainage or flood defence legislation.

If in doubt, it is best to consult the local development and flood risk management office at the Environment Agency, SEPA, Rivers Agency, IDB or local authority.

3.9.1 England and Wales

Under Section 109 of the Water Resources Act 1991 any person intending to carry out culverting works on or near to a main river watercourse must obtain consent from the Environment Agency, and by-law consent may be required. The Environment Agency can advise on any applicable by-laws in the area.

The Land Drainage Act 1991 (amended by Land Drainage Act 1994) covers consents on non-main rivers or ordinary watercourses. Under Section 23 of the Act proposals to construct or alter a culvert require consent from the Environment Agency or IDB. Consent is also required from the local authority under Section 263 of the Public Health Act 1936.

If substantial temporary works are required to construct or maintain the culvert such as diversion of the watercourse or bunding, separate temporary works consent may be required. Also, the Environment Agency, IDB and local authority by-laws may restrict other works in or near to all watercourses and on the floodplain.

The Flood and Water Management Bill 2009 (to become an Act in 2010) may change some aspects of the consenting process. It is intended that in England, the Environment Agency will be given a new strategic overview role for all forms of flood risk management. The internal drainage board consenting role is under review and the county councils and unitary authorities may take on new consenting roles.

3.9.2 Scotland

The local authority planning departments have controls over culverting under the Town and Country Planning (Scotland) Act 1997 if it is part of a proposed development. SEPA is a statutory consultant for proposals that involve carrying out works or operations in the bed or on the banks of rivers and streams, and the planning departments must consider their views on the merits of any such proposals. The planning authority should be consulted on any proposed culverting works.

Culverts required by new trunk roads or rail links or other major developments are subject to a formal environmental assessment under The Environmental Assessment (Scotland) Act 2005. Other culverting work may also require assessment depending on the results of a screening procedure undertaken by the responsible body under the Act (usually the local authority).

3.9.3 Northern Ireland

Consent for new culverts and the repair or replacement of existing culverts is required under Schedule 6 of the Drainage (Northern Ireland) Order 1973, irrespective of the designation of the watercourse. The consenting authority is the Rivers Agency. More information is available on their website (see *Useful websites*).

Culverting of a watercourse also requires planning permission from the Department of the Environment, Planning Service. PPS15, (The Planning Service, 2006), Clause 8.29 states that culverting and canalisation of watercourses, whether undertaken as an operation in its own right, or as works associated with the development of land, requires planning permission.

Under PPS15 Policy FLD 4, the Department will only permit the culverting of a watercourse in exceptional circumstances. Examples of such circumstances will include:

- where works are necessary as part of a flood relief scheme
- where culverting of a short length of a watercourse is necessary to provide access to, or to part of, a development site
- when it is demonstrated by the applicant that there is no practicable alternative to the culverting of a watercourse.

The Planning Service may also require a flood risk assessment (FRA) if the culvert is considered an exception under Policy FLD 4.

Table 3.1 *Summary of main consenting and statutory requirements regarding culverts*

Country	Legislation giving powers to construct and maintain culverts	Legislation which requires the consenting of culverts (other than planning permission or environmental consent)	Main consenting bodies
UK	***General right to construct a culvert (if the landowner) subject to consent and compliance with statutory requirements***		
England	Land Drainage Act 1991 Water Resources Act 1991 Flood and Water Management Act (forthcoming) Highways Act 1980 Railway Clauses Consolidation Act 1845	Land Drainage Act 1991 Water Resources Act 1991	Environment Agency Internal drainage boards Local authority
Northern Ireland	Drainage (Northern Ireland) Order 1973	Schedule 6 of the Drainage (Northern Ireland) Order 1973	Rivers Agency
Scotland	Roads (Scotland) Act 1984 Flood Risk Management (Scotland) Act 2009 Railway Clauses Consolidation Act 1845	Water Environment (Controlled Activities) Regulations 2005	Local authority (planning department) SEPA
Wales	Land Drainage Act 1991 Water Resources Act 1991 Floods and Water Management Act (forthcoming) Highways Act 1980 Railway Clauses Consolidation Act 1845	Land Drainage Act 1991 Water Resources Act 1991	Environment Agency Wales Internal drainage boards Local authority

4 Environmental considerations

4.1 Introduction

This chapter discusses environmental considerations associated with the design and maintenance of culverts. "Environment" is an all encompassing term and includes a range of receptors that can be impacted such as biodiversity, human health, flora, fauna, soil, water, air, material assets, cultural heritage including architectural and archaeological heritage, landscape. The adverse impacts of building and maintaining culverts have led to the evolution of legislative and policy frameworks for the protection of the water environment, which have to be taken into account in the design and maintenance of culverts.

This chapter sets out the purpose of environmental assessment and the main considerations for the primary environmental receptors that could be affected by works to a culvert.

4.2 Environmental assessment

The construction and maintenance of culverts, whether in a new or existing watercourse, will have an environmental impact on both the watercourse and riparian corridor. The scale and nature (either positive or negative) of the impact is related to the location, the size and the length of the culvert, and the type and quality of the environment where it is located. Each culvert should be assessed in terms of the impacts that it could have on the environment and the main risks posed. Culverts can be placed in watercourses ranging from less than one metre across at the water surface to several metres across. In small watercourses, the effects of a simple culvert on the watercourse can often be as damaging as a culvert in a larger watercourse, which is more technically challenging to the designer. The placing of culverts and the effects on the environment should be considered carefully whatever the size of the watercourse before proceeding.

In many situations, it is unlikely that a culvert is being constructed as a standalone project – it will often be part of an infrastructure project where a watercourse crossing is required. In these cases, the location of the culvert in a watercourse is often necessarily dictated by the overall project requirements. Environmental requirements in relation to the culvert design should still be explored in the early stages of planning so that they can be incorporated within options for the design of the culvert.

4.2.1 The purpose of an environmental assessment

The purpose of an environmental assessment is to understand the current baseline conditions and the impact that constructing or maintaining a culvert will have. Opportunities to improve the environment in addition to mitigating impacts of either design or construction should be identified.

The environmental assessment process should be started early in the project to ensure options for removal or alternatives to culverts can be explored. Throughout the project life cycle, environmental input should be integrated into the design process to ensure environmental performance of the asset within the wider system.

Environmental impact assessment (EIA) is a formal process required under the European Directive (EC, 2003) as transposed through different UK regulations. Environmental assessment needed to support new culverts or maintenance work will not always require an EIA (see Section 3.6, and also Section 4.2.2), but useful guidance can be found on assessment of different environmental receptors in Carroll and Turpin (2002) and IEMA (2004).

4.2.2 Legislative requirements

Early consideration should be given to alternatives to culverts to avoid impact and where possible improve the aquatic environment. As discussed in Chapter 3, the UK drainage and flood risk management agencies have developed policies that generally oppose the culverting of watercourses to avoid loss of habitat and a reduction in watercourse continuity and flow conveyance capacity. These policies encourage where practical, the restoration of existing culverts to open channels – also known as daylighting. Other alternatives to culverting could include clear open span bridges retaining existing bed and banks or diversion of the watercourse.

As described in Section 3.6, new developments are subject to national and international legislation to protect, conserve and improve different aspects of the environment. The legal obligations should be identified at the start of any new development project using specialist environmental advice where necessary and consulting with regulators. Good practice associated with the policies of regulators dictates that environmental assessment should form an important part of the project planning process. The following sections cover some of the specific issues to be aware of in relation to the environment when maintaining and designing culverts.

4.2.3 Consultation

Statutory consultees who can advise on legislative requirements are Natural England, the Countryside Council for Wales, the Environment Agency (England and Wales), SEPA (Scotland), Department of the Environment (Northern Ireland), local authorities and heritage regulators.

Wider consultation can benefit the environmental assessment by establishing the baseline information and recording anecdotal problems. Consultees could include local wildlife and conservation groups, angling clubs, and riparian owners. Further guidance on consultation is included in guides referenced in Section 4.2.1.

4.2.4 Understanding current baseline condition

Establishing the current functioning and quality of the watercourse, the presence of any protected species or habitats or designated sites should be done at the start. Desk based assessment and consultation along with site survey should identify important opportunities and constraints.

4.2.5 Sensitivity of the watercourse and likely response to culvert installation

Physical modification of a watercourse alters the flow and sediment regime in addition to the physical form, for example, the width, depth and bed slope. These changes can then have an effect on a range of environmental receptors that need to be considered as part of the design. The changes resulting from culvert installation on the morphology, flow and sediment regime need to be considered not only in terms of the hydraulic performance but also the environmental acceptability. The type of change will depend on the nature of the watercourse (flow, sediment regime and prevailing ground conditions) as well as the size and length of the culvert. Changes to channel length, planform and size will alter flow regime and as a consequence the sediment regime.

In some cases where modifications are minor this will be limited to hydraulic scour issues. There is the potential for morphological adjustment through erosion and deposition over longer timescales that can affect the physical habitat within the watercourse and other receptors such as landscape or water quality.

It is important to determine the likely response through undertaking a geomorphological assessment to support an impact assessment on main receptors to feedback into the design process. Section 5.5.3 provides more information on assessment of geomorphology for design. Further advice on fluvial geomorphology may be found in Sear *et al* (2003).

4.2.6 Assessing risks, impacts and opportunities

Risks and impacts on the environment associated with main receptors should be determined and fed back into the operational planning or design process where necessary to meet legislative requirements. Opportunities to deliver local, regional or national targets for the environment should be sought where possible. Consultation can help to identify these. The river basin management plan programme of measures identifies actions and measures that can be taken to improve habitat.

4.3 Environmental receptors

4.3.1 Ecology and biodiversity

The current baseline should cover the species abundance and diversity as supported by the current morphology and habitats within the watercourse and surrounding corridor.

Protected species

A large number of species are protected by national and European law under the Wildlife and Countryside Act 1981 (as amended), The Conservation (Natural Habitats, &c.) Regulations 1994, and the Protection of Badgers Act 1992. The list of protected species provided within the Acts is subject to frequent amendments.

Table 4.1 lists some of the species that may be affected by the installation or maintenance of a culvert. This list is not exhaustive and is provided to alert the designer or asset manager to the potential considerations that should be given when planning construction or maintenance work.

Table 4.1 *Protected species most likely to be affected by culvert installation or management*

Animal	What is protected	Where it may be found in watercourses	Other considerations
Water vole	The animal, the burrow and the habitat. On 6 April 2008 water voles received an increased level of protection, becoming fully covered by the provisions of Section 9 of the Wildlife and Countryside Act 1981 (as amended). Before this the water vole was only covered by Section 9(4) and had limited legal protection. Water voles are not listed on the European Habitats Directive 1992 and so are not protected by the Conservation (Natural Habitats, &c.) Regulations 1994 (as amended). Water voles are a priority UK BAP species.	In the banks of rivers, streams and ditches In urban and rural areas	Licence needed to move Can be worked around with special advice
Badger	The animal and the sett (hole). Badgers are protected under the Protection of Badgers Act 1992. This act consolidated previous badger legislation by providing comprehensive protection for badgers and their setts, with a requirement that any authorised sett disturbance or destruction is carried out under licence. Badgers are also listed on Schedule 6 of the Wildlife and Countryside Act 1981 (and amendments)	In copses by watercourses, and in banks of ditches	Licence needed to work near setts and to close setts
Otter	The animal and habitat. Otter are protected under Schedule 5 of the Wildlife and Countryside Act 1981 and Schedule 2 of the Conservation (Natural Habitats &c.) Regulations, 1994 (Regulation 38) Otter are a priority UK BAP species	Streams, rivers and coastal areas In dense vegetation, under tree roots, among rocks	A licence will be required whenever disturbance of otter or damage to their holts is likely to occur
Great crested newt	The animal and the populations of an area, the habitat (ponds and grassland). Great crested newts and their habitats (sites or structures of breeding or shelter) are afforded legal protection by the Wildlife and Countryside Act 1981 (as amended) and the Conservation (Natural Habitats &c.) Regulations 1994 (as amended). Great crested newts are a priority UK BAP species.	In wetland and grassland areas near to the pond, sometimes in very slow flowing ditches	These species are protected under UK and European Law. A licence is needed to survey and manage the species
White-clawed crayfish	The animal and habitat. The white-clawed crayfish is protected under Schedule 5 of the Wildlife and Countryside Act, which makes it illegal to take it from the wild (without a licence) or to sell it. Under Schedule 14 of the Wildlife and Countryside Act it is illegal to release non-native crayfish into the wild without a licence and it is also illegal to allow non-native crayfish to escape from holding facilities. "Reasonable steps" and "due diligence" must be exercised to avoid escapes from holding facilities. Native white-clawed crayfish are a UK BAP priority species.	In the bed of any watercourse	

Table 4.1 (contd) ***Protected species most likely to be affected by culvert installation or management***

Animal	What is protected	Where it may be found in watercourses	Other considerations
Bats (all species)	The animals and habitat. All bats in the UK are included on Schedule 5 of the Wildlife and Countryside Act 1981 (as amended). They are also protected by European legislation, being included on Schedule 2 of the Conservation (Natural Habitats, &c.) Regulations 1994. Taken together, this legislation makes it illegal to: ■ intentionally or recklessly kill, injure or capture a bat ■ deliberately disturb a bat when it is occupying a roost ■ damage, destroy or obstruct access to a bat roost.	In trees and culvert structures	
Breeding birds (all species)	The animals and their habitat. With certain exceptions, all birds, their nests and eggs are protected under Sections 1-8 of the Wildlife and Countryside Act 1981 (as amended). Among other things, this makes it an offence to: ■ intentionally kill, injure or take any wild bird ■ intentionally take, damage or destroy the nest of any wild bird while it is in use or being built ■ intentionally take or destroy an egg of any wild bird ■ sell, offer or expose for sale, have in his possession or transport for the purpose of sale any wild bird (dead or alive) or bird egg or part thereof. Certain species of bird, for example, the barn owl, black redstart, hobby, bittern and kingfisher receive additional special protection under Schedule 1 of the Act and Annex 1 of the European Community Directive on the Conservation of Wild Birds (79/409/EEC). This affords them protection against: ■ intentional or reckless disturbance while it is building a nest or is in, on or near a nest containing eggs or young ■ intentional or reckless disturbance of dependent young of such a bird.	In trees and scrub on the banks of watercourses	It is an offence to disturb any nesting bird during the breeding season (March–August). Any habitat that has the potential to support nesting birds must be removed outside of this period. There is no available licence to disturb breeding birds

Note this table is not a substitute for specialist ecological advice, which should always be obtained when dealing with protected and native species. It does not cover all protected species.

In addition to those species protected under the Wildlife and Countryside Act, consideration should be given to the UK and local BAPs. These documents set out the targets for protecting and improving habitats and species of note within the UK.

Trees that lie within a conservation area as defined by a local planning authority, which measure >0.75 m diameter at 1.5 m above ground level and/or trees that are covered by a Tree Preservation Order are afforded protection under the Town and Country Planning Act.

Fish

Culverts that alter flow conditions, water velocities, or present physical barriers will all affect fish movement. Fish may undergo migrations for many different reasons including:

Spawning: this is the most well known reason for migration. Classic examples are salmon, which migrate many thousands of kilometres including in the sea, and barbel and trout that can migrate many kilometres in freshwater. However many other coarse fish and other species such as chub, roach and dace also make important spawning migrations.

Dispersion: adults of many coarse fish species move upstream to spawn, and juvenile fish (up to one year in age) move downstream to disperse and colonise. Secondary migrations may also take place, eg sub-adults moving upstream.

Feeding: fish may make regular movements to feed. This may follow a diurnal pattern, eg fish holding in one area at night and moving to another by day to feed.

Shelter: fish may move to avoid acute adverse conditions like floods or pollution or other unwelcome physiological challenges. They also may need to be able to move in reaction to seasonal events occurring in summer or winter.

Displacement: fish may get moved passively, being displaced downstream by pollution or being washed downstream by floods. They then need to move upstream to re-colonise once the event has passed.

Armstrong *et al* (2004) provides further information on the affects that culverts may have on the passage of fish.

In the UK, several pieces of legislation specify the need to install fish passes, notably:

- The Salmon and Freshwater Fisheries Act (1975) England and Wales
- The Salmon (Fish Passes and Screens) Regulations (1994) Scotland
- The Fisheries Act (1966) Northern Ireland.

Also, there is a need to improve the natural passage of fish to meet the requirements of the Water Framework Directive, adopt the European Eel Regulations and protect fisheries.

In England and Wales, Defra is currently consulting on updating the salmon and freshwater fisheries legislation and is proposing legal changes to address the passage of fish. Under existing legislation, a fish pass is required when any new structure such as a culvert is built that is likely to prevent the migration of salmon or sea trout. Under the new proposed legislation, this requirement will extend to all migratory fish. The UK environment agencies have the power to make structure owners ensure that new structures are passable to migratory salmonids.

Considerations for design and maintenance

Identification of species requirements

Badger, water voles and otter use bankside areas and the maintenance, installation and operation of culverts can affect their habitat and movement. Design guidance is provided in Chapters 8 and 9 on retrofitting and designing to meet habitat and migration requirements. When undertaking the environmental assessment it is important to consider:

- timing of works
- consents and licenses required for protected species
- design requirements (shelves for mammals, refuge areas, daylighting)
- long-term sustainability of environmental solution.

Vegetation management

Vegetation on the banks and in the channel may need to be cleared during construction or maintenance of a culvert, which can result in tree loss and affect the habitats of protected species.

Plant species should be identified before removal to detect whether any endangered or BAP species will be affected, and to identify the preferred timing of vegetation cutting. River corridor survey is a standard methodology that can be applied for ecological survey.

Late autumn vegetation removal allows a small amount of plant re-growth before winter, protecting river-banks from erosion and maintaining habitats for fish and wildlife. When considering further bank protection for scour control, options to use vegetation should be reviewed in addition to hard engineering.

Invasive species and their management should be assessed. The control and management of these plants requires special consideration, and advice should be taken from the appropriate regulating authority or a specialist.

Maintaining and improving fish passage

The installation or maintenance of culverts has the potential to affect the movement of fish. The treatment of culvert inlet and outlet structures needs consideration to ensure that fish passage is maintained in entering or leaving the culvert. Wherever possible, a culvert should aim to:

- avoid a significant drop in water level either at the inlet or the outlet
- provide flow depths suitable for fish passage on fish migration routes
- provide a natural bed within the culvert, or form a narrower channel within the culvert to maintain a deeper flow
- avoid locally increasing velocities within the watercourse.

Assessment should take account of requirements of migratory species. Habitat needs of coarse fish that may move locally within the system should also be taken into consideration.

National guidance on fish passage provides detailed information on requirements of different species (Armstrong *et al*, 2004). Further information is given in Chapter 9.

Managing invasive species

There may be a need to install or maintain a culvert in an area colonised by invasive species of vegetation. There are established good practice guidelines regarding recommended treatment of invasive species, and fact sheets have been developed by UK authorities:

Environment Agency (2007c) *Guidance for the control of non-native weeds in or near fresh water*

Environment Agency (2007d) *Managing Japanese Knotweed on development sites: the Knotweed code of practice*

NetRegs (2008) *Legal implications of invasive weeds*

SEPA (2008b) *On-site management of Japanese Knotweed and associated contaminated soils*

Wade *et al* (2008) is also a useful reference on surveying and assessing invasive species, management options (suppression, eradication and prevention), and post-management surveillance, monitoring and maintenance to ensure any invasion or reinvasion is dealt with appropriately.

Extensive information on the control of invasive species can also be found on the Great Britain Programme Board Secretariat website (see *Useful websites*). Due to the specialised nature of invasive species control and management, these guidance documents should be consulted before undertaking such work.

4.3.2 Surface water quality

Water quality plays an important role in supporting aquatic ecosystems, recreational amenity and agricultural/industrial use. Water quality can be affected by changes in sediment levels, water temperature, flow, nutrient levels, and dissolved oxygen levels. Good practice culvert design and maintenance can help reduce, mitigate or reverse such water quality impacts.

The Water Framework Directive introduced a new legislative framework for the protection of surface waters. The Directive sets out objectives for the water environment, including several "default" objectives. These include the prevention of deterioration of the status of all surface water and groundwater bodies and the protection, enhancement and restoration of all bodies of surface water and groundwater with the aim of achieving "good status" for surface water and groundwater by 2015.

To ensure compliance with the WFD, there is a need to ensure that new or historic modifications do not result in deterioration in status. The tools and standards for assessing deterioration are currently being developed by UK agencies and will be measured by assessing environmental standards. These cover a range of hydromorphological and physico-chemical elements, which are defined to ensure that the right environmental conditions are created to support the biology.

Baseline assessment of routine monitoring data should be undertaken as part of the environmental assessment process, and consultation with regulatory authorities to identify any historic problems and ways that culvert design and operational management might help. Where the culvert is part of a wider scheme, consideration should be given to whether culvert design may increase pathways from pollutants to the watercourse and potential mitigation for this.

Maintenance and design considerations

Reducing sediment mobilisation

During the construction of a culvert, erosion and sediment mobilisation should be controlled. This can be achieved by installing silt fencing or other in-channel structures (eg hay bales) to trap sediment. The installation of a new culvert off-line should be considered to reduce temporary sediment mobilisation.

Reducing the need for maintenance

Poorly designed culverts can be susceptible to siltation, which can require frequent maintenance and/or dredging. This can result in significant water quality problems (eg through the release of suspended sediments or contaminants). The need for maintenance can be reduced by ensuring sufficient flow through the culvert, including during low-flow conditions.

Preventing ponding

Permitting water to pond upstream of a culvert is sometimes undertaken for health and safety reasons, to discourage unauthorised access. This can sometimes lead to stagnant conditions in the pool making the flow through the culvert odorous and leading to siltation at the culvert mouth. In watercourses with very mobile beds, it may be desirable to install a silt trap or catch pit upstream of the culvert entrance. These can be designed to maintain flow to prevent stagnation and odour problems. Catchment sources of silt/sand may also build up in a waterway, so sedimentation needs to be addressed on a catchment basis and as close as possible to their sources.

Allowing light penetration

Lack of light penetration and poor air circulation can result in water quality impacts. To overcome this issue, open or transparent sections of a culvert can be integrated into the culvert design. Care should be taken to ensure that open sections of a culvert do not result in the transfer of litter or debris into the culvert, which can cause maintenance problems.

Managing sediment

Sediment loads either washed from construction areas or from disturbed sediments in-channel, produce localised, concentrated impacts, as well as cumulative impacts downstream and over longer time periods. Increased runoff flowing through disturbed bare soils will dramatically increase sediment loads entering the watercourse.

Fine sediments blanket stream beds, altering the physical and chemical properties of the watercourse, with the ability to adversely affect aquatic, riparian and floodplain habitats. One major effect of working in-channel along the watercourse is the disturbance of bed armour (comprising of large gravel and cobbles) in gravel bed streams. If the surface material is removed or displaced this gives high flows access to the finer substrate and there may be an elevated sediment load until the armour re-establishes itself.

In addition, the economic impacts would include possible sedimentation of down stream hydraulic structures resulting in the possibility of increased flood risk due to sediments increasing water levels.

The construction or maintenance teams should consult good practice guidance on sediment-related management in and around the watercourse during construction, maintenance or other interventions. Working areas and plant used for construction works should be close to, but not on the watercourse if possible. This will provide space for spill barriers, and for avoiding contact between construction staff and potential hazards within the watercourses. Details on possible mitigation measures can be found in guidance by Murnane *et al* (2006).

During stream bed excavation work, care should be taken to minimise sediment movement downstream. Careful construction is also required to ensure that concrete footings cast in situ do not contaminate the water in the channel.

Guidance on measures to reduce pollution when undertaking works in watercourses are given in PPG5 for England and Wales (Environment Agency, 2007b), SEPA, and the Environment and Heritage Service in Northern Ireland.

Further guidance on construction methods is found in Section 9.6.3.

4.3.3 Land and groundwater quality

Release of potentially contaminated sediment during the construction phase could affect water quality and also ecological receptors such as fish and invertebrates. Appropriate mitigation measures should be adopted during the construction phase to minimise release of potentially contaminated sediment. Good practice guidance should be followed such as Environment Agency (2007b). This states that to avoid silt or sediment pollution, it is appropriate to use methods of work that will not result in the contamination of surface water, and will reduce or eliminate the need to work in the river channel.

There is also the risk that a pollution pathway could be created if a culvert is located close to or surrounding potentially contaminated land. It is likely that this pollution pathway would be associated with movement of contaminated leachate and/or contaminated perched water entering the new culvert and being transported downstream to affect a downstream receptor. An assessment of the land quality surrounding the existing or proposed new culvert should be in accordance with current good practice Defra/Environment Agency (2002a and b) in England Wales. In Scotland reference should be made to appropriate good practice, which includes SEPA (2001) and the Environmental Protection Act 1990. This would be to assess all potential sources, pathways and receptors and where pollution pathways exist, an assessment of the risk level would be undertaken. Guidance by CL:AIRE (2008) should also be followed with regards to contaminated land.

Maintenance and design considerations

An assessment of potential waste material from the site will be required to determine suitability for reuse on site. If not suitable, waste soils will require treatment and further assessment before off-site disposal. This should be done following CL:AIRE guidance (2008).

An assessment is also required for possible disposal of groundwater if it is likely that dewatering would be required as part of the construction phase. In England, Wales and Scotland the requirements of the EU Groundwater Daughter Directive (2006/11/EC) should be followed to ensure that hazardous substances and non-hazardous pollutants do not pollute groundwater.

There is also a need to ensure that correct construction materials are used, especially if soil or groundwater is contaminated with, for example, sulphate, hydrocarbons or chloride. Appropriate guidance should be followed, which includes BRE (2005) and the Environment Agency (2000a).

There should be an assessment of the risk to construction workers from soil and potentially contaminated groundwater. To mitigate the effects associated with excavation of potentially contaminated material, construction workers should follow good site practice and hygiene rules as set out in BS5930:1999 and BS10175:2001. Personal protective equipment (PPE), including nitrile gloves and protective overalls should be worn where appropriate, especially by workers who are likely to come into contact with soil or water.

Where pollution pathways are identified appropriate remedial solutions such as barriers should be integrated into the design. Good practice should be followed to comply with the Environmental Damage (Prevention and Remediation) Regulations, 2009. These regulations apply in England, Wales and Scotland.

Good practice documents include:

Strange and Langdon (1994) *Design and practice guide, contaminated land: investigation, assessment and remediation*

Harris *et al* (1995) *Remedial treatment for contaminated land. Planning and management* (SP111)

4.3.4 Landscape and visual amenity

Care should be taken to minimise any adverse visual impact resulting from the construction of the culvert. Specialist landscape advice may be required to integrate the new structure and associated paths, and planting schemes into the existing environment.

Culverts in both large and small watercourses affect amenity to varying degrees by restricting the view down the watercourse and reducing access to the waterside. Culvert design should aim to avoid detrimental effects on the amenity value of an area. In particular, any visible parts such as screens and headwalls should consider landscape requirements.

4.3.5 Historic environment

Some existing crossings of watercourses or elements of the crossings may have historical value. Many of the culverts within the UK are over 100 years old and several have significant historical features, legal protection or are located within conservation areas. Legislation that protects historic structures in the UK are the Ancient Monuments and Archaeological Areas Act 1979 and the Planning (Listed Buildings and Conservation Areas) Act 1990. If the historic significance or statutory protection status of a culvert is unknown or uncertain, it is important to consult the local conservation officer and/or county archaeologist, preferably at an early stage of any project being considered. Some local authorities also maintain lists of buildings of local architectural or historic interests as part of their development plan. This is often called a local list or supplementary list, and may be available on their websites. Table 4.2 provides summary information on sources of local and national information.

Table 4.2 *Sources of historic information*

Country	National significance	Local significance
England	English Heritage	County archaeologist Sites and monuments record
Wales	Cadw (the official guardian of the built heritage of Wales)	Sites and monuments record Regional archaeological trusts
Scotland	Royal Commission on the Ancient and Historical Monuments of Scotland	Sites and monuments record Regional archaeologist
Northern Ireland	Department of the Environment Monuments and Buildings Record	–

If work is to be undertaken on a protected structure this will have an effect on the specification, supervision and design or any remedial works. Specific permissions are also required for works to historic structures that are obtained either through the local authority, English Heritage, Cadw or Historic Scotland. Work undertaken on a protected structure without consent is a criminal offence, and may result in a fine or even a prison sentence for responsible individuals. It is likely that specialist expertise will be required at all stages of the work from its planning and inception through to its completion.

Further guidance on the conservation of historic structures, including legal and management issues, is given in BS7913:1998.

Wetland areas also contain records of past natural environments including vegetation, climate and human impacts. Culvert works may disturb the cultural information that is contained within soil and peat layers.

4.4 Summary of guiding principles for design and maintenance

The opportunity to remove the culvert and daylight the channel or construct an alternative should be investigated in all projects to ensure this solution is identified and implemented where possible.

If culverts are required, the following principles should guide the design process:

- retain a natural bed
- limit damage to the river-banks
- limit disturbance to natural flow
- ensure alignment works with geomorphological processes.

An environmental assessment with consultation should be undertaken to determine main constraints and opportunities and issues to be considered during the design process. Specialist surveys such as geoenvironmental, ecological or archaeological surveys may need to be undertaken as part of the environmental assessment.

All legal requirements should be taken into account as part of the environmental assessment and mitigation measures designed accordingly. Consents and licenses may be required for protected species or structures.

Site works and plant for the construction period should be close to, but not on the watercourse if possible. This will provide space for spill barriers, and for avoiding contact between construction staff and potential hazards within the watercourses. Installation of most new culverts requires the channel bed to be excavated, unless the new culvert is constructed off-line.

During stream bed excavation work, care should be taken to minimise sediment movement downstream. Careful construction is also required to ensure that concrete footings cast in situ do not contaminate the water in the channel.

Seasonal constraints should be taken into account in construction process and in many cases are statutory requirements.

Further details on specific design issues are contained in Chapters 8 and 9.

5 Hydrology and geomorphology

5.1 Introduction

A hydrological assessment is required to estimate the flow conditions that are to be used in the hydraulic assessment of a culvert's performance and to understand sediment and debris loads and their impact on hydraulic performance. The hydrological processes that convert rainfall into runoff and stream flows are complex, so there are many hydrological assessment techniques suited to different types of catchment or data sources. While the most important requirement is usually to assess culvert performance at high flows, the site should also be analysed within the context of its surrounding catchment. The assessment may also need to consider a range of flow conditions, including low-flows, which are important for understanding any ecological impacts.

This chapter discusses the hydrological factors that are most relevant to a watercourse containing a culvert and identifies recommended analysis techniques. Many culvert sites are on small watercourses, often in urban areas, and so this chapter includes guidance on hydrological methods suitable for these cases.

5.1.1 Main issues

Probability and return period

The performance of a culvert usually has to be assessed for one or more flow conditions expressed in terms of the peak rate of flow (or "discharge") in the watercourse. The hydrological analysis involves estimating the flow rate that has a specified frequency or probability, usually expressed either as a return period (in years) or as an annual exceedance probability (AEP).

The return period T is often interpreted as a long-term average interval between years that contain one or more "events" where the flow rate, Q, equals or exceeds a given value. In this case there is a straightforward relationship between the return period and the AEP, such that AEP = $1/T$. The percentage chance in any one year (100 × AEP) may be preferred when communicating flood risk to a wide audience because it is thought to be easily understood and it emphasises the unpredictability of flooding.

The AEP is difficult to interpret when the return period approaches one year, which is a condition that has sometimes been used in greenfield runoff calculations. However, the return period remains meaningful for events that occur with a frequency of around once per year or more often. In this case the return period is defined in a slightly different way, as the average interval between exceedances of a given flow rate, Q, and it can have a value of less than one year.

Design standard

A suitable design standard should be determined before undertaking any hydrological or hydraulic assessment. This is usually expressed in terms of AEP of the flow rate for which a culvert's performance should be assessed.

The annual probability of flooding (or design standard) should be determined before undertaking any hydrological or hydraulic assessment. A risk-based approach is recommended whereby the annual probability of flooding is chosen based on an appreciation of the consequences of flooding throughout the design life of the structure. This approach is similar to limit state design used by the structural Eurocodes and British Standards.

The acceptable annual probability of flooding appropriate to the design or assessment of a particular culvert is influenced by planning policy, flood and coastal erosion risk management appraisal guidance (FCERM-AG) (Environment Agency, 2010b), or performance requirements such as the maximum number of days lost service or volume of overtopping, which in the case of the larger asset owners may be dictated by corporate standards. Design standards often used by practitioners are one per cent annual probability (100-year return period) in England and Wales, and 0.5 per cent annual probability (200-year return period) in Scotland. Flood insurance may not be available for properties with a likelihood of flooding greater than 1.33 per cent annual probability (75-year return period) in certain circumstances (Environment Agency/Association of British Insurers, 2009).

The probability, *P*, of experiencing a flow of annual exceedance probability AEP over a design life *DL* is given by Equation 5.1 and a range of values are presented in Table 5.1. It can be seen that a one per cent annual exceedance probability condition has a 63 per cent chance of being equalled or exceeded during a 100-year design life.

$$P = 1 - \left(1 - \frac{AEP}{100}\right)^{DL} \qquad (5.1)$$

where

P	=	lifetime probability of exceedance
AEP	=	annual exceedance probability (%)
DL	=	design life (years)

This calculation assumes that the annual probability of exceedance does not change over the design life. Catchment or climate change could call this assumption into question. These issues are discussed further in Section 5.6.

Table 5.1 ***Lifetime probability of exceedance for selected annual probabilities and design lives***

Annual exceedance probability, AEP (return period)	**Design life, *DL* (years)**			
	30	60	100	120
10% (10-year)	0.96	0.99	0.99	0.99
4% (25-year)	0.71	0.91	0.98	0.99
2% (50-year)	0.45	0.70	0.87	0.91
1.3% (75-year)	0.32	0.54	0.73	0.79
1% (100-year)	0.26	0.45	0.63	0.70
0.5% (200-year)	0.14	0.26	0.39	0.45
0.2% (500-year)	0.06	0.11	0.18	0.21
0.1% (1000-year)	0.03	0.06	0.10	0.11

There are many different factors that can influence the hydrological approaches suitable for a particular watercourse and culvert site. The following issues should be considered and included within the hydrological assessment, where relevant:

- scale of the watercourse and catchment area. Many culvert sites will be on small watercourses. This chapter discusses hydrological methods suitable for small and/or highly urbanised catchments. For predominantly rural catchments larger than about 50ha (0.5 km^2) the standard fluvial analysis approaches are likely to be suitable (see Ackers and Rickard, 2009)
- characteristics of the catchment draining to the culvert site, particularly whether the drainage is natural or artificial and whether the catchment is predominantly rural or urban
- availability of existing flow estimates, in particular when the catchment has already been studied as part of a flood risk (or consequence) assessment (FRA or FCS), strategic flood risk (or consequence) assessment (SFRA/SFCA), catchment flood management plan (CFMP) or surface water management plan (SWMP)
- whether there are rainfall or runoff measurements available from gauges nearby. It may be worth commissioning flow surveys to add local flow data for direct analysis, or to assist with calibration and testing of a drainage model in urban areas.
- attenuation due to flood storage. If storage is important within the catchment system containing the culvert site (whether natural storage on a floodplain or artificial impoundment) then a flood flow analysis should consider the flood volume to determine peak flow. In this case, a design hydrograph may be needed, in conjunction with some form of routing model
- performance requirements during low-flow conditions. The performance of the culvert in low or average flow conditions should be checked to assess potential siltation and/or environmental impacts on ecology
- approach to future changes. The analysis may need to include sensitivity tests for climate change or land management change so that a precautionary or managed adaptive approach can be taken.

5.2 High flow estimation methods

5.2.1 Overview

Section 5.2.2 describes methods for high flow analysis, in particular for small catchments, which are typical of the watercourses that culverts are placed within. The recommended approaches are based on best available data and methods, which may involve use of digital databases and software. Alternative hand calculation methods are also given. For sites where flood risk management is a critical issue, where there is upstream storage or where the catchment is particularly complex, then the advice of a specialist hydrologist should be sought at an early stage. The recommended methods are summarised in Table 5.2.

To avoid unnecessary duplication the methods are not described in detail here. There are already detailed descriptions available in the following recent CIRIA guides:

Woods-Ballard *et al* (2007) *The SUDS Manual* (Chapter 4)

Digman *et al* (2006) *Designing for exceedance in urban drainage* (Appendix A7)

5.2.2 Generic approaches

Broadly speaking there are two generic approaches to estimating design flows, as follows:

1 **Rainfall transformation methods based on runoff coefficients**

Uses rainfall data (whether from measurements or from a statistical model) as the primary source of information to determine probabilities. The approach involves modifying the rainfall using a runoff coefficient, multiplied by the catchment area, to derive either a direct estimate of the peak discharge or a flood hydrograph.

Runoff coefficient approaches exploit data from rain gauges, which have generally good geographical coverage and relatively long records. However, runoff coefficients are not physical parameters and have to be modelled or estimated empirically. This transformation from rainfall to runoff is a source of significant uncertainty. This class of methods includes rainfall-runoff models where the "runoff coefficient" may in practice be a relatively complicated function, and might not be obvious to the user.

2 **Statistical methods based on transfer of information from gauged flow data**

Uses measured discharge data from gauging stations as the primary source of information to determine probabilities. The data are analysed to estimate the probability distribution of peak flow rates (the "flood frequency curve"), if necessary transferring information from gauged locations to provide design flow estimates for ungauged watercourses.

Statistical approaches based on analysis of stream flow data avoid the need to estimate a runoff coefficient. They rely on having a good sample of flow data that are representative of the hydrological responses in the watercourse being investigated. Statistical methods are most suitable for rural catchments where estimates are not likely to be influenced because of changes in runoff processes due to urban expansion.

5.2.3 Rural (greenfield) catchments

Definition

A rural or greenfield catchment can be defined as an area where the water draining to the culvert site is predominantly through soils, field drains, natural or maintained surface water channels and overland flow on unpaved land. There is no unique quantitative measure to define what "predominantly" means. Different hydrological methods use different numerical parameters to define "how urban" a catchment is.

Recommended methods for peak flow estimation

The *Flood estimation handbook* (FEH)"statistical method" is the recommended approach for estimating a peak design flow in most rural river catchments (Institute of Hydrology, 1999). It gives a range of options for different situations including simple analysis of gauged flow data and pooled estimation methods for ungauged locations. The FEH methods update the earlier report by the Natural Environment Research Council (1975) and supplementary reports. The FEH is more flexible and makes the best use of current datasets to give the most accurate estimation of flows and associated probabilities. The pooling analysis uses data preferentially from gauged catchments that are similar to the site of interest. The FEH methods are relatively complex and require access to digital datasets and software. Practising hydrologists should have access to, and be familiar with, these tools.

The FEH methods are not recommended in their original form for drained areas smaller than 50ha (0.5 km^2) because the datasets used in calibrating the methods rely on catchments larger than ~1 km^2 and also because the resolution of some of the digital data used in FEH means that spatial catchment parameters (including catchment area) can be prone to error at such small scales. For smaller areas an FEH estimate for the surrounding catchment can be scaled using an accurate estimate of the drained area from maps or survey. This should only be done where the area of interest is representative of the surrounding catchment in terms of soils, geology, topography and drainage. The approach is consistent with the assumption made in most flow estimation methods that the flow rate is strongly related to the drained area. It has the advantage of ensuring that flow estimates for the small area will be consistent with estimates in the surrounding catchment. Where a culvert site is located within a catchment that has been the subject of previous flood estimation studies (for example, for flood mapping study or a flood risk assessment) then it will be worth asking relevant operating authorities such as the Environment Agency, drainage board or local authority drainage department whether there is an FEH flood estimate already available for the surrounding catchment area.

There are alternative methods available that do not require the digital data and software needed for FEH analysis, in particular the Institute of Hydrology Report No 124 (Marshall and Bayliss, 1994) statistical method and the ADAS 345 (Ministry of Agriculture, Fisheries and Food, 1982) runoff coefficient method for open-inlet piped ditches. Both methods are described in detail in Woods-Ballard *et al* (2007).

These methods have been previously recommended because of being specifically developed for small catchments, although it is questionable whether they give a better estimate of design flow for a given return period than the scaling of an FEH estimate from a representative larger catchment. The ADAS 345 method does not include data from many catchments smaller than included in the FEH dataset. The statistical model it provides for flood flows does not show consistent improvement over a statistical model based on a broader sample of catchments, and it lacks the flexibility and recent data that is built into FEH methods. However, the report provides a convenient equation for the mean annual flow rate (QBAR) in terms of map-based FSR catchment characteristics, which can be combined with regional growth curves available in tabulated or chart form to obtain estimates of peak flow for longer return periods (NERC, 1975).

The ADAS 345 method (Ministry of Agriculture, Fisheries and Food, 1982) is a runoff coefficient method for peak flow estimation based on the report by MAFF (1980) and the older Transport and Road Research Laboratory rational method approach (TRRL, 1976). It requires empirical runoff coefficients derived from regression analysis of rainfall and runoff data collected at small drained catchments monitored by the ADAS Field Drainage Experimental Unit (FDEU) and a rainfall intensity model derived in 1962. The ADAS 345 method includes a transfer procedure based on the FSR winter rainfall acceptance potential parameter to allow application to a wider range of soil types. The transfer procedure and rainfall model are sources of uncertainty that have not been evaluated. However the method has the advantage of being suitable for hand calculation.

Recommended methods for design hydrograph estimation

A design hydrograph will usually be required if the culvert site is part of a catchment where flood storage (natural or artificial) is important. If so, the hydrological analysis is likely to be combined with some type of routing model to derive peak flow rates that account for the upstream storage. The recommended method for calculating a design hydrograph is the Revitalised Flood Hydrograph (ReFH) method (Kjeldsen, 2007), which is based on a unit hydrograph rainfall runoff model driven by FEH rainfall statistics. The

ReFH model has been calibrated to provide estimates that are broadly consistent with statistical estimates of peak flow for return periods of around 100 years. The ReFH model is available in a free spreadsheet application from CEH Wallingford but does require the user to obtain FEH digital catchment data.

An alternative approach is the older FSR flood hydrograph model, which was re-stated in volume 4 of the FEH (Institute of Hydrology, 1999) and is available in many river modelling software packages. Where a calibrated model is available this can be used, but for ungauged locations the ReFH model may be considered to have superseded the FSR model.

A quick way to derive an indicative design hydrograph is to use a peak flow estimate to re-scale an existing hydrograph or one obtained from nearby gauged data or a model.

National Sustainable Drainage Systems (SUDS) Working Group recommendations

The National SUDS working group set out guidelines in 2004 for calculating greenfield runoff rates at development sites. Although the guidelines are geared towards design of storage facilities rather than peak flow analysis for culverts, they may be considered relevant to culvert sites. However, *The SUDS Manual* (Woods-Ballard *et al*, 2007) notes that the guidelines have the objective of providing a consistent agreed method for storage design, rather than finding an exact runoff rate. Use of FEH or rainfall runoff modelling methods with catchment-specific local data may help to provide greater confidence. Their guidelines are as follows:

- for sites of 0–50ha, use the ADAS 345 statistical approach to estimate peak flows for the 1, 30 and 100 year return periods for a site of 50ha, then scale the estimate by area
- for sites of 50–200ha, use the ADAS 345 methods
- for sites above 200ha the FEH methods are recommended, although ADAS 345 may still be used.

5.2.4 Urban catchments

Definition

An urban catchment is an area where there is a large proportion of impervious surfaces or where most water is delivered to the culvert via paved surfaces and a piped drainage network. Although quantitative definitions of urban catchments are available, these are specific to each method and cannot be generalised.

Recommended methods

Statistical estimation from flow data is difficult for urban areas because there is a relative lack of good quality, long records for urban catchments, and because urban development can lead to changes in the hydrological response that may cause the long-term flow record to become unrepresentative of current conditions. The FEH contains adjustments for statistical estimation that can be applied to catchments where the FEH parameter URBEXT is greater than 0.025. Note that the FEH statistical adjustment for urbanised catchments implicitly includes the net effect of urban runoff management measures, in so far as these have influenced gauged data in the hydrometric record.

Rainfall-driven methods are generally recommended for hydrological analysis in urban catchments. These are either set up for peak flow estimation (using variants of the "rational method", see Digman *et al*, 2006, Appendix A7), or to derive a hydrograph (using unit hydrograph and time-area methods, see Shaw, 1994). Design rainfall estimates for storm durations of greater than one hour can be derived easily from the FEH statistical rainfall model and digital datasets. The FSR rainfall frequency curves, although not based on such up-to-date measurements, remain useful for shorter durations and are available without needing software or digital data. If a rain gauge exists near the site then it can be useful to apply recorded storm events as inputs to a rainfall-runoff model, especially for storms known to have caused flooding.

The standard approach for urban runoff estimation for drainage design is the Wallingford Procedure (DoE/National Water Council, 1983)), which is available within several commercial software packages. The Wallingford Procedure is a collection of methods, including a modified version of the rational method and a hydrograph method, based on the FSR flood hydrograph model.

The modified rational method is simple and also suitable for hand calculation. It requires two empirical parameters to be estimated, a "time of concentration" (the time taken for all of the catchment to contribute runoff at the outlet) and a runoff coefficient. Both parameters are highly variable when derived from observed data because of differences in rainfall patterns, antecedent moisture and storage conditions between and during storm events. The rational method should be treated as approximate. It is best suited for very small, homogenous, predominantly urban catchments where the response time is fast and the runoff coefficient can be assumed to be consistently high.

The Wallingford Procedure also includes runoff models that are conceptually more sophisticated than the rational method. The hydrograph method incorporates two alternative models for percentage runoff (which is, in effect, a more complex form of runoff coefficient). The new UK runoff model is recommended, because it accounts for antecedent soil moisture and changes in soil moisture during an event (WRc, 2006). It is well suited where there is a mix of pervious and impervious surfaces within the catchment because it accounts for the runoff response from both types. There are guidance notes for the Wallingford Procedure methods available in WaPUG (2002), part of the Chartered Institution of Water and Environmental Management.

There is storage attenuation in many urban systems, resulting from designed features such as balancing ponds or because of overland flow routing and flow through the drainage network. In such cases, the effects of storage can be very important and where the level of risk justifies it, the performance of the culvert should be tested against a range of hydrographs based on differing storm durations. A useful starting point is to test for 1, 4, 12 and 24 hour durations for a range of return periods from two years up to 200 years. Where the sewerage network has an effect on the routing of storm runoff then this analysis may need to be carried out using a full drainage network model. Digman *et al* (2006) provides further guidance.

Table 5.2 *Methods for high flow estimation*

Requirement	Recommendations	Comment
Greenfield (rural) runoff		
Peak flow rate	1 FEH statistical method	For drained areas smaller than 0.5 km² (50 ha) use estimate for surrounding larger catchment and scale by area. Ensures consistency with surrounding catchment estimates. Flexible methods making best use of up-to-date information
	2 IH124 and FSSR14 regional growth curve	Does not require software or new data. Can be calculated using tabulated values, charts and maps. Based on older data
	3 ADAS 345 (rational method)	Based on design charts and map analysis. Uses dated rainfall analysis. Provides estimates for three set values of return period
Hydrograph or volume	1 ReFH rainfall runoff model	Most flexible and up to date approach. Free software for design calculations. For very small catchments use estimate for surrounding area and scale by area as above
	2 FEH Vol. 4 rainfall runoff model	Less consistency with statistical estimates of peak flow than ReFH. Available in older software packages
	3 Scaled hydrograph with peak flow estimate	Use an assumed or gauged hydrograph shape, scaled by a peak flow estimate
Urban runoff		
Hydrograph, peak flow rate or volume	1 Wallingford Procedure hydrograph method (new UK runoff model)	Applied using software. Accounts for pervious and impervious areas, soil moisture changes during the storm and routing
	2 Wallingford Procedure hydrograph method ("original PR" or fixed quick estimate percentage runoff)	Simpler approach. No variation in percentage runoff during event. Both approaches specify a constant % runoff during the event but the original Wallingford Procedure PR is based on an empirical model whereas a fixed PR is an assumed value. WRc (2006) makes conservative assumption that 100% runoff takes place from paved areas and none from pervious areas. Only justifiable for catchments dominated by paved surfaces
Peak flow rate alone	3 Wallingford Procedure modified rational method	Over-simplification of runoff process but provides a method that can be calculated by hand

5.3 Low-flow analysis

Low-flow conditions in rivers and streams are of fundamental importance to the ecological status of the watercourse. Low-flow analysis can be important when designing structures within a whole catchment context. Basic methods of low-flow analysis are discussed in the following subsections.

5.3.1 Flow duration curves

A flow duration curve (FDC) represents the relationship between the magnitude and duration of streamflows (duration in this context referring to the overall percentage of time that a particular flow is exceeded). The shape of the FDC for any river strongly reflects the type of flow regime and is influenced by the character of the upstream catchment, including geology, urbanisation, artificial influences and groundwater.

The FDC is a very useful tool for assessing the overall historical variation in flow, although one drawback is that it offers little information about the timing or persistence of low-flow events. The FDC is often used in defining river flow objectives that may influence the design or operation of a structure like a culvert. For example, a structure may be designed to maintain a minimum depth of flow for some environmental flow objective, often the Q95 flow (the flow exceeded 95 per cent of the time according to the FDC).

The FDC can be derived from gauged data using methods described in standard texts such as Shaw (1994). Methods for ungauged locations, including the LowFlows2000 system, have been produced by CEH Wallingford. For some watercourses, the baseflow may have been estimated by the relevant environmental authority (SEPA, the Environment Agency or the Northern Ireland Environment Agency) and it is worth checking to see if such a value is available.

5.3.2 Low-flow frequency analysis

A low-flow frequency analysis evaluates the probability of flows occurring and remaining below a specified (low) design threshold for a given length of time. Customarily the analysis is carried out with regard to the minimum discharge aggregated over a period of d days in each year (AMIN[d], or the "d-day annual minimum") derived from daily flow series. In the UK case, this is best applied on the basis of calendar years to avoid splitting low-flow periods lasting from late summer through autumn. The Environment Agency has published guidelines that document how to apply the approach in detail, see Zaidman *et al* (2002). Applying a Type 3 generalised extreme value (GEV) or Weibull distribution allows the quantiles of the low-flow distribution to be determined and the return periods of any design events estimated. Regional frequency methods have been developed to use flow data from similar sites to improve estimates for short record sites and to enable low-flow frequency estimation to be undertaken at ungauged sites. See Tallaksen and van Lanen (2004) for an introduction to this subject.

5.4 Tidal boundary conditions

Culverts discharging to tidal rivers, estuaries or open coast locations are often fitted with one-way valves to prevent reverse flow around high water. The tidal culvert becomes tidelocked during the flood tide and water is stored upstream of the valve, then released during the ebb tide when the head difference exceeds that required to open the valve. Since hydraulic performance of the culvert varies during the tidal cycle, hydraulic assessment is required for a range of tide levels. If there is a low risk of flooding upstream of the culvert, a steady-state approach using peak flows and selected tide levels is acceptable, but if people, properties or infrastructure are likely to be at risk from flooding, unsteady modelling using computer software with one or more inflow hydrographs and tidal curves is recommended.

The joint probability of tidal and fluvial events should be taken into account. A simple approach is to analyse two scenarios: design tide level with normal fluvial flow, and design fluvial flow with mean high water spring. More complex scenario testing involves generating a matrix of scenarios or using the Monte Carlo simulation. Further guidance is available in Defra/Environment Agency (2005) and accompanying reports (see *Useful websites*).

The significant tide levels for analysis are the highest and lowest astronomical tide, mean high (and low) water spring, mean high (and low) water neap and meteorological surge.

Astronomical tide predictions are available from the Proudman Oceanographic Laboratory for the 44 Class A tide gauges in the UK (see *Useful websites*) and from the Admiralty Tide Tables for many more ports. Recorded water levels are available from the British Oceanographic Data Centre for the 44 Class A tide gauges (see *Useful websites*). Estuarial water levels may also be available from the Environment Agency, Rivers Agency and SEPA. For intermediate locations, tide levels can be estimated by applying corrections from the Admiralty Tide Tables or interpolation. It should be noted that tide levels are normally given relative to local chart datum and may need to be adjusted to ordnance datum using a correction factor, available from the Admiralty Tide Tables or Proudman Oceanographic Laboratory.

Tidal curves are generally sinusoidal for open coast locations but can be asymmetrical in estuaries and tidal rivers or if a surge is applied. Curves are available from local tide gauges, Admiralty Tide Tables or may be predicted using tidal prediction software. Specialist advice may be needed from a hydrologist. Extreme sea levels for open coasts and estuaries and a tool for designing tidal curves will be provided by Defra/Environment Agency (due 2010).

Tidal outfalls are susceptible to sedimentation due to long-term and cyclical morphological changes and care is required to ensure that any outfall can accommodate likely changes in foreshore level. Tidal rivers and estuaries can exhibit a changing pattern of banks and channels over time: a convex estuary profile is a sign of long-term accretion while a concave profile indicates long-term degradation. Open coast locations are dominated by waves and tend to exhibit annual fluctuations in foreshore level, with lower levels in the winter and after storms and higher levels in the summer. Many coastal locations suffer long-term erosion (although some are stable or accreting).

5.5 Assessment of debris, sediment and geomorphology

5.5.1 Culverts as part of the natural drainage system

A culvert on a watercourse is required to convey not only the flow of water, but also any sediment, trash and debris contained in the flow. The management of debris and sediment are often major factors affecting flood risk in extreme events as well as largely determining routine maintenance requirements. For example, analysis of a flood event in Australia (Rigby *et al*, 2002) showed that in an environment where flash floods occur any culvert or bridge less than six metres wide could be at risk of total blockage from a combination of debris and sediment. In the UK, debris is generally more important than sediment in terms of blockage risk though there have been cases of screen blockage by coarse sediments. Also, sediment build-up tends to occur over a longer timescale, whereas debris blockages can occur in a matter of hours. Culvert inlet screens are particularly vulnerable to blockage by debris (Figure 5.1).

The design of culvert works should consider the passage of both water and sediment for a range of flows, and the potential for partial or complete blockage of the culvert by debris or sediment during high flow events. The impact of works on the morphology, river sediment transfer processes and physical habitats within the watercourse should be assessed to ensure that sound environmental practices are employed from an early stage of the design process. The need to understand and manage sediment movement and geomorphological impact of the culvert on the watercourse is receiving increasing attention as the Water Framework Directive is implemented (and is already required under the Scottish Water Environment (Controlled Activities) (Scotland) Regulations 2005 as outlined in Section 3.6.3).

In urban areas, trapping of sediments within piped systems that then flow into the watercourse can add significantly to total load of fine sediment in the watercourse. Where the area occupied by the low-flow channel within a culvert is oversized then fine sediment may be deposited. Managing fine sediment movement in the urban area may require use of sediment control measures as part of SUDS. Keeping woody material in streams is also increasingly part of restoration and conservation schemes, increasing the risk of blockage of culverts when this material is transported downstream in flood events.

Detailed analysis of sediment movement is a specialist field and the designer should consider appointing a geomorphologist at the start of any investigation into the installation or decommissioning of a culvert. Further advice on fluvial geomorphology may be found in Sear *et al* (2003).

The application of geomorphological investigations and guiding principles has assisted in the design of sustainable culverts in the UK (see Example 5.1 in Section 5.5.3). Measures to reduce sedimentation and allow the passage of sediment to downstream reaches can promote an environmentally-sensitive approach and reduce maintenance costs.

Figure 5.1 ***Sediment and debris deposits at screened entrance to culvert following high flows between fortnightly cleaning (a) (courtesy Leeds City Council) and tree trunk and urban debris including shopping trolleys caught on screen at entrance to long culvert in Sheffield (b) (courtesy JBA Consulting)***

A great deal of debris may be mobilised at higher flows and tends to accumulate at obstructions. Clearing a blocked culvert during a flood event is likely to be impractical and the decision to install a screen to allow removal of debris is a logical response. In practice, even during mundane rainfall events, screens can pose a significant flood risk as they trap an even greater proportion of debris than would be of concern within the culvert and result in a high maintenance burden. The assessment of the risks associated with debris blockage at structures and selection of appropriate mitigation measures is the subject of ongoing research by the Flood Risk Management Research Consortium, and the findings are due in 2011. Four modes of blockage have been identified to date:

1. **Sedimentation:** progressive build-up of sediment within the culvert barrel, from the invert upwards.
2. **Gradual blockage:** debris blockage from the surface downwards by large floating vegetation such as trees or parts of.
3. **Abrupt blockage:** debris blockage by urban materials such as sheet building materials, fences and sheds.
4. **Sudden blockage:** instantaneous and total blockage by large debris such as a table, plank or shopping trolley.

Ideally, any sediment transported by the channel should be carried through the culvert and, to minimise ecological impact, the invert (bed) of the culvert should have a layer(s) of bed material similar to the natural river. This maintains the natural system and sediment continuity and limits the geomorphological change. Sufficient freeboard above flood water level is needed so as to allow not only for floating debris but the impact of sediment on hydraulic gradient. When a blockage or area of deposition is formed, debris and sedimentation impacts often combine and reinforce each other resulting in a much more rapid change and loss of capacity than would otherwise occur.

5.5.2 Debris

Debris may be classed as either woody debris (including vegetation) or urban debris (including fly-tipping). The main consideration for debris and floating materials is whether they are able to pass through the culvert without causing partial or complete blockage, resulting in reduced hydraulic performance or in extreme cases hydraulic, geotechnical or structural failure of the culvert.

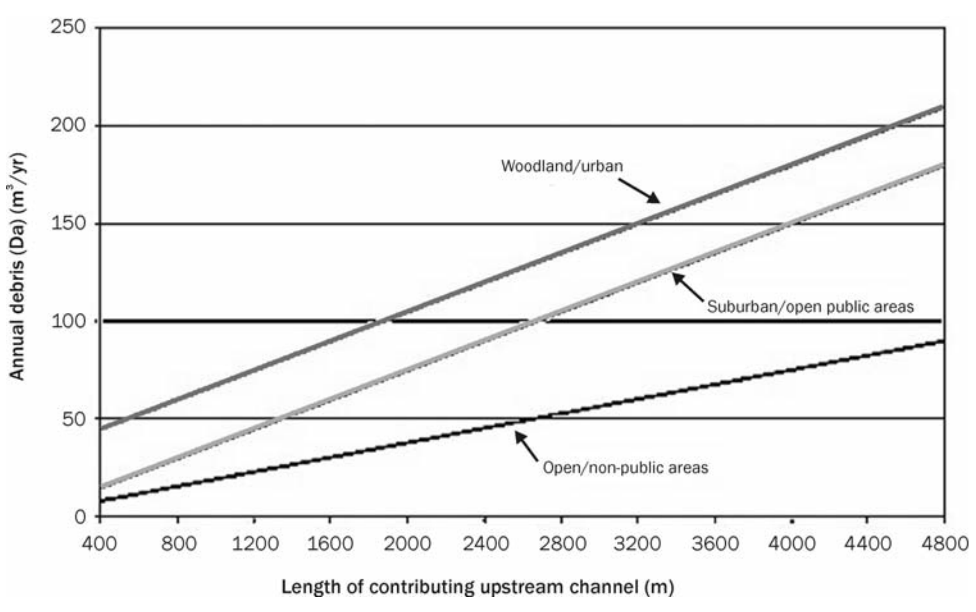
Due to the site specific nature of the problem, there is little useful data on the probability of a particular degree of blockage. The probability is a function of many factors (the amount or type of debris available in the upstream catchment, discharge, culvert dimensions and geometry, and level of maintenance). However, it is highly probable that debris will be transported down the channel during a flood and could block the culvert. So it is important to assess the likely degree of blockage and investigate the consequences in terms of increased water level upstream of the blockage.

Assessing the tendency of a culvert to limit the movement of floating debris is a two-part process involving firstly consideration of the nature of the debris load and its source, and secondly the likelihood of this material accumulating in the culvert. Guidance by the Environment Agency (2009a) gives methodologies for calculating risk of blockage using risk of occurrence and likely consequence. A product of the two factors is calculated and judged against the need to protect the culvert using a screen.

The risk factors influencing accumulation within a culvert are:

- size and number of barrels – as a general rule, the smaller the culvert, the greater the risk of blockage
- number of barrels – multiple barrels can provide greater resilience and flexibility than a single barrel. The risk of blockage is generally higher for multiple barrels, but blockage of one barrel causes only partial loss of capacity, and provides flexibility for maintenance or refurbishment, whereas blockage of a single barrel leads to total loss of discharge capacity
- bends, steps and changes of cross-section – these should be avoided as they can trap larger items of debris and thereby start the process of forming a blockage
- services and other obstructions – services that pass through a culvert form a point for trash to accumulate and should be rerouted
- length – the longer the culvert, the greater the risk, and the more difficult it is to inspect and remove a blockage once formed
- hydraulic design – a culvert that flows with a free water surface, even in large floods, is less likely to trap large debris than one which flows full
- inlet and approach conditions – sharp bends at the entrance to a culvert may induce deposition and debris build-up
- inverted syphons (or sag culverts) have a greater propensity to block. Such culverts should be avoided except in circumstances where there is no other practicable option.

Where possible, debris loads for individual storms should be estimated using data from similar local catchments. Where this is not possible guidance by the Environment Agency (2009a) presents an indicative relationship for giving an estimate of annual debris quantities in a river based on contributing length of river with adjustment for slope and catchment type. This is based on limited data collected in the Thames river basin and is useful for obtaining a broad estimate of the amount of material passing (or prevented from passing) through a culvert. The relationship is reproduced in Figure 5.2.



Note that correction factors should be applied for channel slope

Figure 5.2 *Estimation of the potential quantities of woody debris reaching a culvert (source Environment Agency, 2009a)*

If the flood risk from a likely blockage is unacceptable then in the first instance the culvert should be redesigned to make this risk acceptable (for example, by increasing the culvert size so even with blockage, no properties flood at the design event). It may be possible to identify sources of debris in the catchment and to remove or control these so as to reduce the risk of a blockage, but this is not easily achieved in practice. Woodland management in the catchment can limit quantity and size of woody debris and similar measures may be taken for urban catchments such as limiting the material stored in industrial areas next to the river.

Only as a last resort should a screen be considered for a new culvert as they require significantly more maintenance and can block. The Environment Agency (2009a) gives a risk-based method for assessing the need for a screen for either blockage or safety reasons.

5.5.3 Sediment and geomorphology

Sediment sizes may range from sands, fine silt, clay and organic matter in lowland channels to gravel, cobbles and boulders in steep streams. The mechanisms of sediment movement can be complex and depend on the availability of excess stream power over and above the critical stream power required to mobilise the grains composing the bed material.

The installation, removal or modification of culverts can have significant adverse impacts on the morphology and sediment dynamics of a watercourse for a considerable distance both upstream and downstream of the culvert. Potential impacts include changes to sediment transfer mechanisms, scour and bank erosion near the culvert outlet, sedimentation, impact on the integrity of nearby flood defences and impact on flora and fauna within the watercourse. So it is important that geomorphological assessment, as part of culvert assessment, design or decommissioning, is carried out to identify any impacts locally and further afield. The potential impacts on sedimentation and channel morphology are summarised in Table 5.3 and discussed further in the following section.

Table 5.3 *Potential impacts on sedimentation and channel morphology*

Scale	Impact
Local effects within culvert	Reduced discharge capacity due to increase in effective roughness and reduction in cross-sectional area
↓	Local sediment accumulations, particularly at screens and changes in slope and direction
↓	Abrasion due to bed load
	Reinstatement of the natural watercourse bed
↓	Changes to the natural sediment transfer system
Wider effects on watercourse	Changes to geomorphology due to changes in river path length or constriction of flood flows when installing new culverts or renewing culverts

Transport modes such as bed load movement, suspended bed material or wash load may each need a different approach to analysis and data requirements. Fortunately it is not normally necessary to calculate sediment transport rates as the longer term geomorphological impact is typically independent of the sediment transport rate that primarily affects the rate of change.

Sediments in watercourses are a fundamental element of the physical habitat and have an important role in sustaining and supporting the biological communities that live within them. Sediments support many aquatic plants, provide spawning habitats for fish and provide habitat for many invertebrate populations. To conform to the Water Framework Directive, it is vital that ecological status is maintained, if not improved, by works affecting the watercourse (further details on the Water Framework Directive can be found in Sections 3.6 and 4.3.2).

Reduced discharge capacity

Sediment accumulation in a culvert can reduce its discharge capacity, both by increasing the effective roughness and resistance to flow, and by reducing the available area for flow. The assumption of a clear bed during flood conditions may be unrealistic.

The roughness of a natural river channel bed is much greater than smooth concrete and the composite roughness of a culvert with sediment deposits or a natural bed is closer to that of a river than the commonly quoted values for smooth concrete. River engineers often use Manning's n to represent roughness in a channel, whereas culvert manufacturers commonly quote Colebrook White roughness ks although it is possible to convert between the two. As an illustration, the smooth invert of a new concrete culvert may have a Manning's n of 0.012 (ks of 0.03 to 0.06 mm), whereas the same invert covered in a layer of fine sediment with debris embedded in it might have an n value of 0.03 (ks of 10 to 25 mm). The effect of sediment in pipes was studied in controlled laboratory tests using sand sized materials (Ainger *et al*, 1998). Although the tests focused on the design of sewers for self-cleansing, the information on velocities and hydraulic gradients under different degrees of sedimentation can be applied to the design of culverts for equilibrium with a stable and sustainable sediment bed.

Local sediment accumulations

Local accumulations can occur at transitions such as the culvert inlet, bends and changes in bed slope. An initial blockage or area of deposition can lead to further debris and sedimentation impacts, and a more rapid change and loss of capacity than would otherwise occur. The risk of accumulations should be addressed by design.

Abrasion due to bed load

The conveyance of gravel, cobbles and boulders through a steep culvert without any sediment deposit can cause substantial wear and it may be necessary to provide a high quality concrete invert that can withstand impact and abrasion damage. Large boulders can be excluded from a culvert by the provision of a suitably sized coarse screen at the inlet or in the channel immediately upstream (see Figure 5.3). A primary screen designed to overtop without limiting flow into the culvert requires maintenance to be effective. Sediment traps excavated in the channel bed upstream of a culvert reduce sediment flux but are only effective if sized to contain all the material trapped between maintenance intervals. Further information is given in Section 9.4.4.

Figure 5.3 *An overtoppable boulder trap upstream of a culvert on a steep channel*

Reinstatement of natural watercourse bed

When constructing a new culvert, depression of the invert to allow formation of a natural bed is recommended. To accelerate creation of natural conditions and to avoid erosion of the upstream and downstream bed, the depression may be filled to the design level using selected excavated material from the watercourse (or imported material similar to that in the natural watercourse bed if the excavated material is contaminated or unsuitable). The surface layer of a gravel bed watercourse is normally coarser than the underlying material due to armouring, and placing gravels to mimic the existing size grading for the bed surface would be a further enhancement to minimise the impact of the construction. Good access within the culvert is needed to achieve this.

Following placement, the material should be compacted to reduce mobilisation of loose sediment during the next high-flow event, and should resemble a natural bed, comprising of a range of particle sizes typically found within that watercourse system. In gravel bed watercourses, it is important that a coarse layer is reinstated, acting as a bed armour layer and reducing access of high flows to the finer substrate and reduce the potential for elevated fine sediment loads until the armour layer naturally re-establishes itself. During the reinstatement period, the design team should also consider the migration of fish through the culvert and ensure water depths and velocities are adequate to ensure easy passage.

Impact on sediment transfer system

Maintenance of the natural sediment transfer system is desirable to maintain sediment continuity between upstream and downstream and thereby limit geomorphological change elsewhere. Any sediment transported by the watercourse into the culvert should be carried through the culvert to the downstream channel. This can promote an environmentally-sensitive approach and reduce maintenance costs (see Example 5.1, and is most easily achieved by ensuring that the culvert has a similar cross-section and bed slope to the watercourse.

Example 5.1 ***Designing for sediment transfer***

A study of Hawkcombe stream for Porlock flood defence scheme showed that a change in culvert bed slope and alignment would increase turbulence and deposition of sediment and partial blockage of the culvert during the falling limb of the hydrograph. Hydraulic modelling showed that a v-notch invert rather than a box culvert would concentrate coarse sediment and velocities in the middle of the channel and promote high velocities for a longer duration on the falling limb of the hydrograph, encouraging self-cleansing and reducing the need for maintenance following high flow events. Also, this design promoted the transfer of sediment to downstream reaches, improving sediment continuity.

Impacts on geomorphology

Changes in path length can affect equilibrium, with a significant reduction in stream length leading to erosion upstream, and an increase in stream length potentially causing deposition upstream and erosion downstream. Changes in bed level may also cause channel planform changes as the watercourse adjusts. Erosion of sediment upstream of the culvert can occur following the removal of an undersized culvert, renewal or increasing the capacity of a culvert. Sediments can be released rapidly into the watercourse causing environmental damage. Sedimentation may increase following the installation of a culvert with a flap gate in a tidal zone.

A reduced supply of sediment through a culvert to downstream reaches can induce sediment starvation of the downstream reaches, causing channel instability through bed and bank erosion. In contrast, deposition of sediment immediately downstream of a culvert outlet can result in bed aggradation and impact on subsequent water levels, increasing the flood risk to that area.

The impact of proposed culvert works on the sediment transfer and morphology of the system cannot always be totally avoided but should be assessed and minimised at design stage. A geomorphological assessment may include data collection, field reconnaissance and an historical review. A fluvial audit gives a description of the sources of sediment and areas of deposition along a watercourse reach. The conditions in the watercourse and culvert at bank full flow are frequently examined as this is typically when much of the sediment movement takes place. Post-construction inspections and monitoring are also recommended, and the results can be fed into an adaptive management routine.

Further advice on fluvial geomorphology may be found in Sear *et al* (2003). Detailed analysis of sediment movement is a specialist field and the designer should consider appointing a geomorphologist at the start of any investigation into the installation or decommissioning of a culvert.

5.6 Assessment of future hydrological changes

5.6.1 Guidance on climate change impacts

The potential impacts of climate change on peak rainfall intensity and peak watercourse flow during the design life of a culvert should be examined by sensitivity testing. PPS 25 (CLG, 2006) gives indicative adjustment factors of +10 per cent to +30 per cent for dates up to the year 2115, which are applicable throughout UK. The source and appropriate use of these numbers is discussed in Defra, (2006). PPS25 also gives projected changes in sea level that should be considered for culverts with tidal outfalls.

Defra (2006) provides country-wide adjustment factors for the UK but there is increasing evidence that impacts will vary regionally, or even from catchment to catchment. The latest generation of climate change projections for the UK have greater regional detail and permit more specific impact studies. These climate change projections were published in 2009 and are known as the UKCP09 projections. The UKCP09 data express future climate changes in terms of probability distributions to reflect some of the uncertainties in climate models. A "weather generator" is part of the UKCP09 package, allowing users to create synthetic rainfall records for catchments over the UK for current and projected future climates.

Although UKCP09 does not directly provide change factors for culvert design calculations, it is expected that allied research projects will use the results to publish updated information on changes in watercourse flows and rain storms. The projections are all conditional upon four assumed scenarios of greenhouse gas emissions. The probability of each of the emissions scenarios is not known for sure. So the UKCP09 data, while reflecting some of the technical uncertainties in modelling climate change, does not provide a probabilistic forecast of what will actually happen (UKCIP, 2009).

5.6.2 Impacts of land-use and land management change

Local authority development plans should be consulted to investigate whether the catchment draining to the culvert may be subject to development. If so, it may be appropriate to include this in an urban runoff model used to test the culvert performance, or even to create such a model if the catchment is currently non-urban. Even if SUDS are incorporated into planned developments to mitigate changes in runoff, the debris profile in the watercourse could change, leading to a change in blockage risk. Also, SUDS systems are likely to be overwhelmed in extreme floods that reduce their effectiveness in flow control.

While urban development may be the most significant change in land-use, there has been considerable interest in the effects on watercourse flows of other land management changes such as livestock density, crop type, harvesting practices or deforestation. The science of land management change was reviewed in O'Connell *et al* (2005), which concluded that analyses of historical data have not been able to demonstrate the impact of land-use management on flood runoff due to a variety of other factors, including the variability in the hydrological data, the rarity of flood events relative to the record length, measurement uncertainties and the possible impacts of other changes (such as climatic).

This is an active research area and the user should monitor Defra and Environment Agency research and development outputs for further information.

There is currently no recommended model for predicting land management impacts on runoff. However, there are studies indicating that, at least at small scales, land management and especially practices that degrade soil condition, can increase runoff rates and worsen sediment problems. The impacts may depend on the timing of changes and rain storms, for example, the impact of having heavy machinery on the field followed by intense rain may depend on the initial soil wetness.

Unless specialist expertise is available, it is recommended to adopt a sensitivity analysis approach and test a design with a range of flows, rather than attempt to predict future flow rates. If there are discharge records from a suitable comparison site where other factors are similar (eg climate, slope and geology) then this may be a suitable source of information to provide a test of sensitivity to potential future change in land management. The ADAS345 method (Ministry of Agriculture, Fisheries and Food, 1982) may be adjusted by changing the soil type factor, while the FEH (Institute of Hydrology, 1999) parameters BFIHOST and SPRHOST can be linked to changes in soil condition (Packman *et al,* 2004). Application of these results would require familiarity with the relevant methods and a sound understanding of how the parameters relate to physical properties of a catchment.

6 Hydraulic assessment

6.1 Introduction

The purpose of this chapter is to:

1 Provide a basic understanding of culvert hydraulics to support the concepts used in the design of new culverts and the assessment of existing structures.

2 Introduce quantitative techniques for assessing the hydraulic performance of a culvert over a range of flow conditions.

3 Describe computer software available for hydraulic assessment, along with methods for establishing and improving the quality of, and confidence in, the results.

A culvert and the watercourse it sits in act as a system that operates under a wide range of flow conditions and other environmental loadings such as sedimentation. As a result, the hydraulic performance of culverts should be considered together with the hydraulic performance of the watercourse – a culvert should not be assessed in isolation. The methods in this guide are based on Federal Highway Administration (2005), the conveyance estimation/afflux estimation system (CES/AES) described in guidance by HR Wallingford (2004) and JBA Consulting (2007).

This chapter covers the subject of hydraulic analysis in considerable depth, exploring all the elements that might be relevant in the case of a culvert. This is a deliberate approach aimed at giving users of the guide access to all the common analysis techniques applicable to the full range of hydraulic conditions experienced at culverts. In many situations a simple approach to hydraulic analysis will be relevant, and it will not be necessary or appropriate to undertake, for example, a backwater analysis. For the design of a new culvert, the adoption of free flow performance for the design conditions, and the inclusion of generous allowances for freeboard and sedimentation will simplify the analysis. A more involved analysis is likely to be required in the case of an existing culvert that has been responsible for a flooding problem or, in the case of a new culvert, where factors other than hydraulics dictate the culvert dimensions and configuration.

6.2 Hydraulic theory

6.2.1 Open channel flow and pipe flow

Flow along a watercourse may be described as open channel flow or pipe flow. Open channel flow is characterised by a free surface at atmospheric pressure, while pipe flow is confined within a closed conduit (such as a culvert) and may exert hydraulic pressure on the conduit walls and soffit.

The difference between open channel flow and pipe flow is best illustrated by the longitudinal sections in Figure 6.1. For open channel flow (Figure 6.1a), the hydraulic grade line (HGL) for a given discharge is coincident with the water surface, whereas for pipe flow (Figure 6.1b), the hydraulic grade line indicates the hydraulic pressure head exerted by the water. The stand pipes in Figure 6.1b show that hydraulic pressure is exerted on the culvert soffit, confirming that the flow is confined and flowing under pressure within the culvert. Figure 6.1 also shows the energy grade line (EGL), which indicates the total energy (or head) available to drive the flow along the watercourse. The energy grade line slopes down in the direction of flow due to friction and other losses.

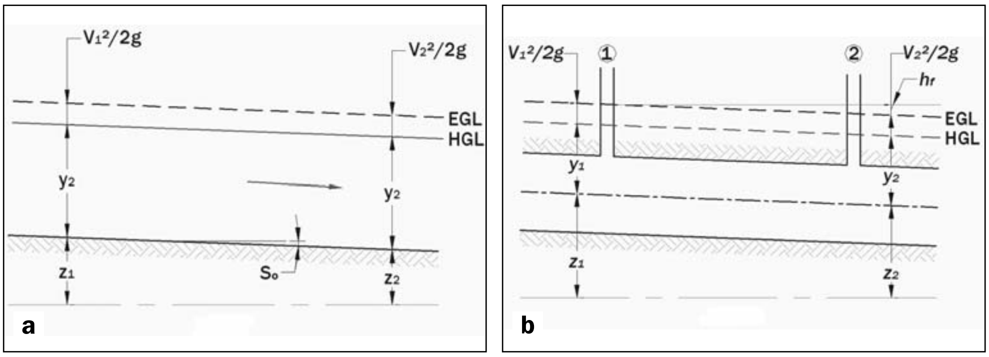


Figure 6.1 *Longitudinal sections for open channel flow (a) and pipe flow (b)*

The total head *H* of the energy grade line (EGL) is the sum of the elevation head, pressure head and velocity head given by the Bernoulli equation (Equation 6.1) while the elevation, *WL*, of the hydraulic grade line (HGL) is the sum of the elevation head and pressure head only (Equation 6.2).

$$H_1 = Z + y + \frac{V^2}{2g} \qquad (6.1)$$

$$WL = Z + y \qquad (6.2)$$

where

Z	=	elevation of bed above datum (m)
y	=	depth of water above bed (m)
V	=	mean velocity of flow (m/s)

6.2.2 Open channel flow regimes

The flow regime of open channel flow may be categorised as subcritical, supercritical or critical (Figure 6.2). It should be noted that these flow regimes do not apply to pipe flow in a closed conduit:

1. Subcritical flow is characterised by deep water and low velocity, and occurs in channels with mild slopes.
2. Supercritical flow has a shallow depth and high velocity. This type of flow occurs in steep channels and is often seen on weirs or spillways. It is seldom sustained over great distances before a transition to subcritical flow occurs.
3. Critical flow is found in the transition from subcritical to supercritical flow, typically where the bed slope changes from mild to steep. An obstruction placed in the steep channel will not affect water levels in the mild channel upstream of the control section.
4. A hydraulic jump may form at the transition from supercritical to subcritical flow, when the supercritical flow reaches deeper water and decelerates, with increasing depth. Energy is dissipated as turbulence and the jump may be unstable.

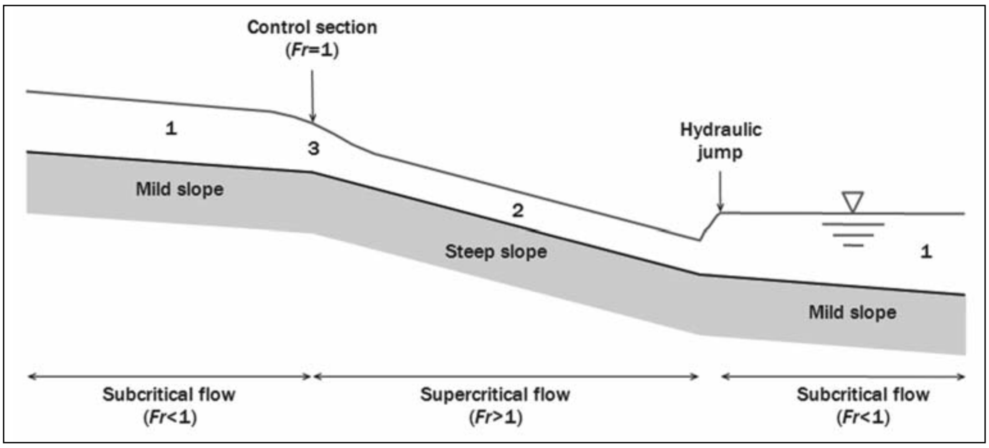


Figure 6.2 *Subcritical and supercritical flow regimes*

Froude number

The Froude number Fr indicates whether open channel flow is subcritical, critical or supercritical and is given by Equation 6.3. When $Fr > 1.0$, the flow is supercritical and is characterised as rapid. Flow with $Fr < 1.0$ is subcritical and characterised as tranquil. If $Fr = 1.0$, the flow is critical.

$$Fr = \frac{V}{\sqrt{gy}} \tag{6.3}$$

where

V	=	mean velocity of flow (m/s)
g	=	acceleration due to gravity (m/s^2)
y	=	hydraulic mean depth (m) = A/W for irregular channels (see Table A1.6 in Appendix A1 for formulae for circular, rectangular or trapezoidal channels)
A	=	cross-sectional area of flow (m^2)
W	=	width of free surface (m)

The divisor $\sqrt{gy}$ is the wave celerity, the speed at which surface waves can travel upstream. In the subcritical flow regime, the water velocity is less than wave celerity and flow characteristics such as depth and velocity can be affected by downstream disturbances or restrictions. For supercritical flow, the water velocity exceeds the wave celerity and disturbances are unable to travel upstream.

Specific energy

The specific energy E_s is the energy relative to the channel bed and is the sum of the pressure and velocity heads (Equation 6.4). The specific energy curve shows specific energy against flow depth for a given discharge (Figure 6.3) and illustrates the variation in specific energy with flow regime. It can be seen that critical depth corresponds with the minimum specific energy E_{sc} and two alternative (or sequent) flow depths, one sub and one supercritical, can exist for any other value of specific energy. These sequent depths are important for predicting the transition from supercritical to subcritical flow. A transition from supercritical flow with a depth y_1 occurs when the downstream depth equals the sequent depth to y_1.

Specific energy E_s is given by

$$E_s = y + \frac{V^2}{2g} \quad (6.4)$$

For critical flow with $Fr = 1.0$, the relationship between specific energy and critical depth is given by Equation 6.5.

$$E_{sc} = \frac{3}{2} y_c \quad (6.5)$$

where

E_{sc} = minimum specific energy for a given discharge (m)

y_c = depth of water for critical flow (m)

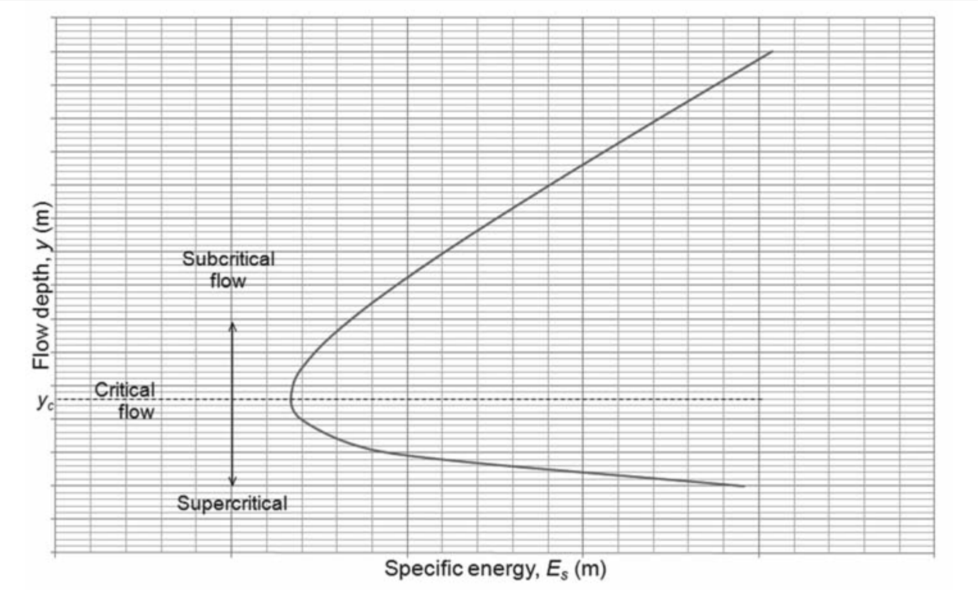


Figure 6.3 *Specific energy curve*

6.2.3 Channel and structure control

Within open channel flow, there are two types of hydraulic control: channel control and structure control.

Channel control

Channel control occurs when the relationship between discharge and water depth is controlled by the open channel.

Normal flow is when a steady discharge (constant over time) passes along a uniform channel (constant geometry and bed slope). Under these conditions, the mobilising action of gravity balances the frictional resistance provided by the channel perimeter and the hydraulic grade line and energy grade line are parallel to the bed slope S_0. When the discharge is unsteady or the channel is non-uniform, and the energy grade line and hydraulic grade line are no longer parallel to the bed slope S_0, but adopt a friction slope S_f, the flow is described as transitional.

The discharge capacity of the watercourse is given by the conveyance K and bed slope S_0 (or the friction slope S_f for transitional flow) (Equation 6.6). Conveyance is a measure of the channel carrying capacity and is related to the geometry and roughness (Equations 6.7 and 6.8). The geometrical parameters affecting conveyance for a one-dimensional (1D) analysis are shown in Figure 6.4.

$$Q = KS^{1/2} \tag{6.6}$$

$$K = \frac{1}{n} AR^{2/3} \tag{6.7}$$

$$R = \frac{A}{P} \tag{6.8}$$

where

K	=	conveyance (m³/s)
S	=	bed slope S_0 or friction slope S_f (m/m)
n	=	Manning's roughness coefficient (from Tables A1.1 and A1.2 in Appendix A1, or calculated using the conveyance estimation system software, as described in Section 6.14)
A	=	cross-sectional area of flow (m²)
R	=	hydraulic radius (m)
P	=	wetted perimeter (m)

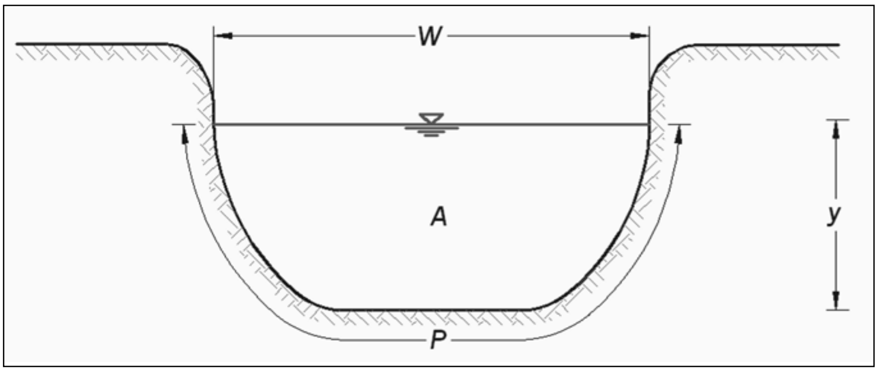


Figure 6.4 *Geometry of open channel cross-section*

Structure control

Structure control by a bridge, culvert, weir, sluice or other hydraulic structure increases (or decreases) the water depth above (or below) and would exist without the structure. A hydraulic structure that controls the water depth is known as a hydraulic control and a relationship between discharge and depth can be defined.

A hydraulic control situated in a mild sloping channel controls the water depth upstream and the difference in water depth from that existing without the structure is known as afflux (this should not be confused with head loss, which is the head difference across the structure). A culvert may raise the headwater elevation upstream to provide the energy to drive the flow through the culvert, with a reduction in water level as the flow accelerates through the culvert (Figure 6.5).

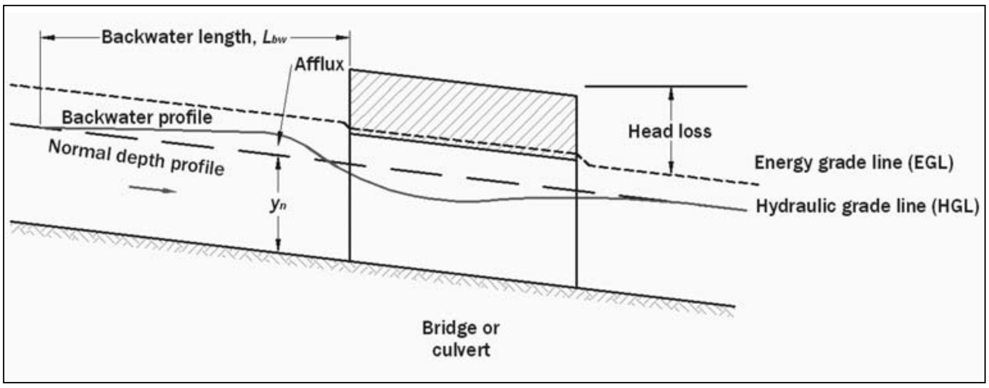


Figure 6.5 *Hydraulic control by a structure*

The water profile affected by the structure is known as the backwater profile and the length of channel affected is the backwater length. The backwater profile can be derived by a backwater calculation and in theory extends upstream indefinitely. In practice, the backwater length L_{bw} may be estimated by Equation 6.9 (Samuels, 1989):

$$L_{bw} = 0.7\frac{y}{S_0} \tag{6.9}$$

where

y = bankfull depth of channel (taken as the upper bound on the magnitude of hydraulic radius) (m)

S_0 = bed slope (m/m)

6.2.4 Culvert geometry

A culvert consists typically of an inlet, an outlet and a culvert barrel of height D, length L and slope S_0. It may include a screen at the inlet or at both the inlet and outlet. The depths of water above the upstream and downstream invert levels are known as the inlet depth y_i and outlet depth y_o respectively (see Figure 6.6). The total head of the headwater and tailwater are H_h and H_t respectively, with the difference between them h_T overcoming friction and other energy losses to drive the flow through the culvert.

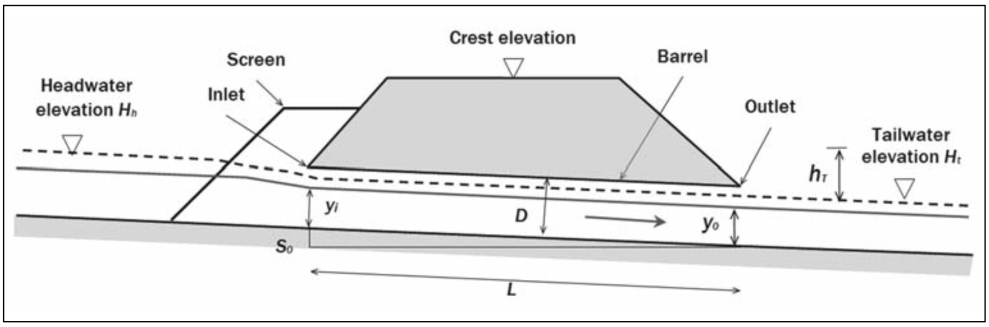


Figure 6.6 *Longitudinal section through a simplified culvert structure*

6.2.5 Culvert flow control

Two types of culvert flow control have been identified: inlet and outlet control, according to the location of the hydraulic control section along the culvert. The hydraulic capacity of the culvert depends upon a different combination of factors for each type of control. The location of the control section and the type of control is dependent on the flow regime: whether subcritical, supercritical or surcharged flow.

Inlet control

Inlet control is characterised by hydraulic control just inside the culvert inlet and supercritical flow through some or all of the barrel. It is a feature of steep culverts and is less common than outlet control. The culvert inlet may be free or submerged, as shown in Figure 6.7. The culvert barrel has greater capacity than the culvert inlet, and the factors affecting culvert performance are the upstream water surface level and inlet geometry, namely the barrel shape, its cross-sectional area, and the nature of the inlet edge (for example, whether it is angular or rounded). Hydraulic characteristics downstream of the control section do not affect the culvert capacity unless they are sufficiently severe to force subcritical flow in the culvert.

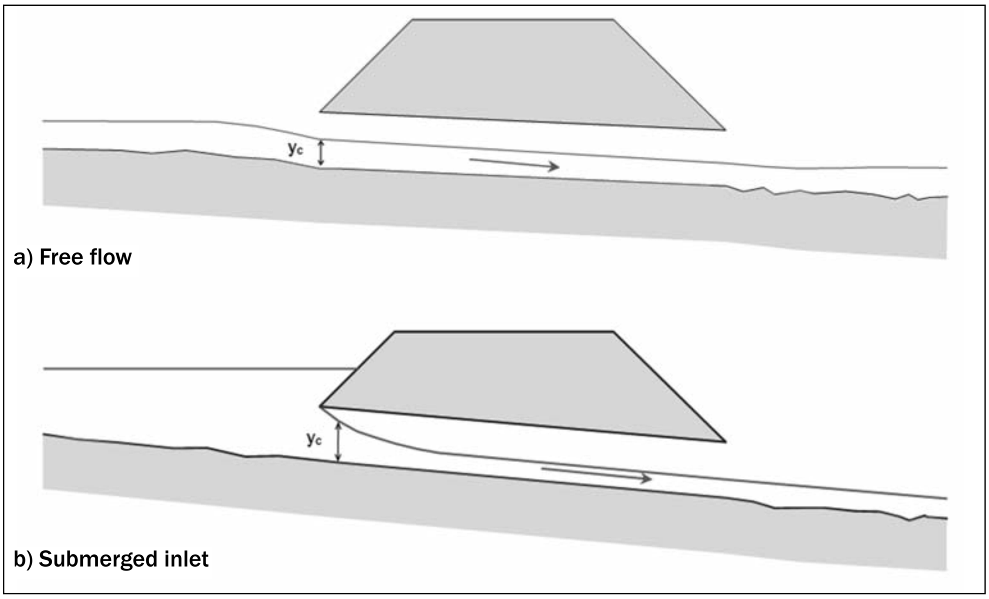


Figure 6.7 *Example inlet control conditions*

Outlet control

Outlet control flow is controlled by the culvert barrel, culvert outlet or the open channel downstream with subcritical free flow or full flow (also known as surcharged or pressure flow) through the culvert barrel (Figure 6.8). Culvert performance under outlet control may be influenced by the geometric and hydraulic characteristics of the culvert and watercourse downstream, including barrel geometry and roughness, tailwater depth at the culvert outlet, as well as hydraulic controls downstream of the culvert.

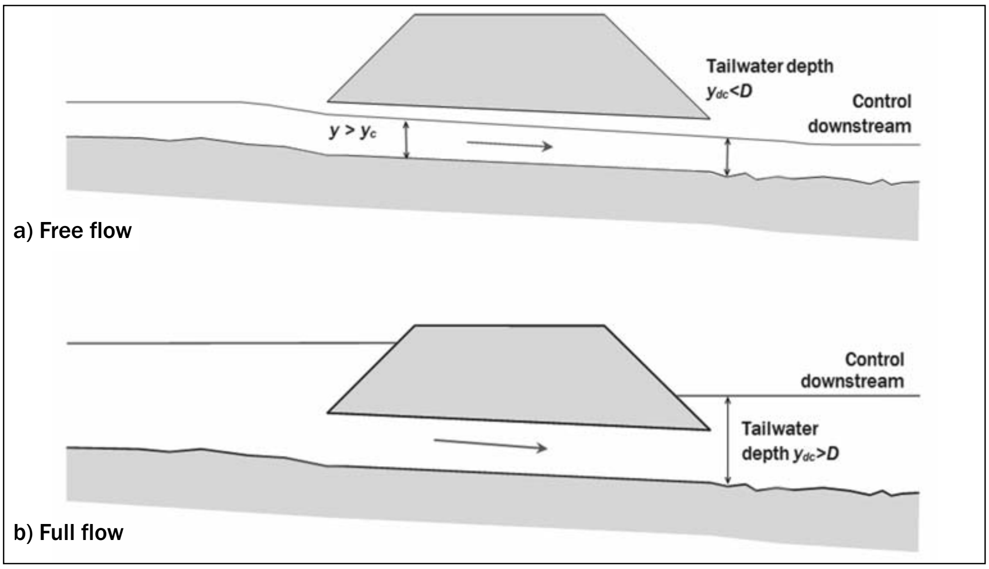


Figure 6.8 *Example outlet control conditions*

6.2.6 Culvert flow conditions

A further sub-division of culvert flow types is possible, with three culvert flow conditions of free flow, full flow and overtopping flow. Flow conditions vary between culverts, and may also vary over time for a given culvert depending on upstream and downstream conditions, barrel characteristics and inlet geometry, as well as the discharge at the time.

Free flow

Free flow is the most common condition because culverts are generally designed to flow freely, even during floods (Figure 6.9). To analyse free surface flow, a control section with a known relationship between depth and discharge should be identified. In the outlet control example of Figure 6.8a, flow is controlled either by the culvert barrel or the open channel downstream of the culvert outlet.

Full flow

Full flow (also known as surcharged or pressure flow) is less desirable than free flow due to the increased risk of blockage. Under this condition, the hydraulic grade line is above the soffit level and hydraulic pressure is exerted on the culvert soffit. A culvert may flow full over all or part of its length – a water surface profile calculation is the only way to accurately determine how much of the barrel flows full (see Sections 6.6 and 6.10). The discharge capacity of a culvert operating under full flow is affected by upstream and downstream conditions and by the hydraulic characteristics of the culvert.

A rare and often transitory flow condition is just-full flow, where the hydraulic grade line touches the culvert soffit but there is no hydraulic pressure on the soffit. This form of flow can lead to cyclical conditions known as gulping.

Overtopping flow

At very high discharges, the headwater level may exceed the headwall or embankment crest level and overtopping flow over the road, railway, canal or other asset occurs, similar to flow over a broad crested weir. This may increase the risk of structural failure if the infrastructure is not designed to withstand overtopping.

Figure 6.9 *Free (a) and submerged (b) flow during flood conditions (courtesy JBA Consulting)*

The free flow culvert on the left (a) has a lower risk of blockage than the submerged culvert beneath the handrailing on the right (b) and poses a lower safety risk because anyone falling into the channel upstream, and being swept though the culvert, is able to breathe.

6.2.7 Culvert flow types

At any given instant, the flow condition is governed either by the inlet geometry (inlet control), or by a combination of the inlet geometry, barrel geometry and tailwater depth (outlet control). As the discharge varies, culvert flow control may also fluctuate from inlet to outlet and many different flow conditions may exist at the same culvert over time. Eight principal types of flow across a culvert structure are discussed and cover the majority of conditions encountered (see Figure 6.10). It should be noted that other flow conditions have been identified but some of these are unusual, unstable or undesirable and are not considered here. The eight flow types are subdivided into three free flow types (headwater level < embankment crest level), two full flow types and three overtopping flow types (headwater level > embankment crest level).

Type 1 Free flow inlet control

Free flow inlet control is controlled by the culvert inlet with supercritical flow through some or all of the culvert barrel. The inlet causes a large energy loss and drop in water level, and the flow accelerates as it contracts into the culvert. If tailwater depth is below the sequent depth for the formation of a hydraulic jump, then supercritical flow extends over the full length of the barrel, but if tailwater depth exceeds sequent depth, a hydraulic jump forms in the culvert barrel and the flow changes from supercritical to subcritical. The latter condition may cause the culvert to prime (to flow full throughout) if the tailwater level rises above the outlet soffit, changing the flow condition to Type 5.

Type 2 Submerged inlet control

A high headwater depth and steep culvert can cause submerged inlet control flow where the culvert inlet behaves as an orifice and the flow separates from the soffit at the culvert inlet. A tailwater depth less than sequent depth at the outlet ensures that the flow remains supercritical for the full length of the barrel, whereas a tailwater greater than sequent depth triggers a hydraulic jump and a transition from supercritical to subcritical in the culvert barrel. A tailwater level above the soffit level causes the culvert to prime, giving Type 5 flow. If the tailwater level is at or close to the outlet soffit, an undesirable situation can arise where the flow conditions fluctuate between Type 1 free flow and Type 5 full flow, leading to sub-atmospheric pressures and structural damage. A further variation of this type is overtopping flow with inlet control.

Type 3 Drawdown outlet control

In this case, the culvert flows with a free surface that is drawn down through critical depth at the outlet. This type of flow occurs most frequently in culverts with a mild slope and free outfall, for example, a protruding pipe or tidal outfall.

Type 4 Backwater outlet control

Backwater outlet control is the type of flow that occurs most frequently in culverts, and for which culverts are generally designed. The culvert flows with a free surface and the water level is controlled by the tailwater level with subcritical flow throughout. The tailwater depth is above critical depth at the outlet but the tailwater elevation is below the soffit of the culvert.

Type 5 Full flow outlet control

Both the inlet and outlet are fully submerged and the culvert barrel flows full or surcharged. The tailwater is controlled by the downstream channel and the headwater level is determined by tailwater level and head losses within the culvert.

Type 6 Modular overtopping flow

Modular overtopping flow ensues once the headwater level exceeds embankment crest level. If the submergence ratio (downstream depth above embankment crest divided by upstream water depth above embankment crest, Figure 6.27) is less than about 75 per cent, then the weir flow is modular, and its discharge coefficient is determinable (Section 6.9.7). Note that surcharged flow occurs within the culvert (provided it is not totally obstructed).

Type 7 Submerged overtopping flow

Submerged overtopping flow occurs when the downstream water depth above embankment crest level exceeds the critical flow depth over the embankment, with a submergence ratio of between 75 and 95 per cent. Surcharged flow occurs within the culvert barrel but the weir flow is no longer modular and the discharge coefficient is reduced accordingly (Section 6.9.7).

Type 8 Drowned overtopping flow

When submergence of about 95 per cent is reached, the weir is drowned and the flow type returns to that of open channel flow. Inevitably, the friction for this condition increases above that for the natural watercourse due to the presence of the drowned structure. As in Types 6 and 7, surcharged flow occurs within the culvert barrel.

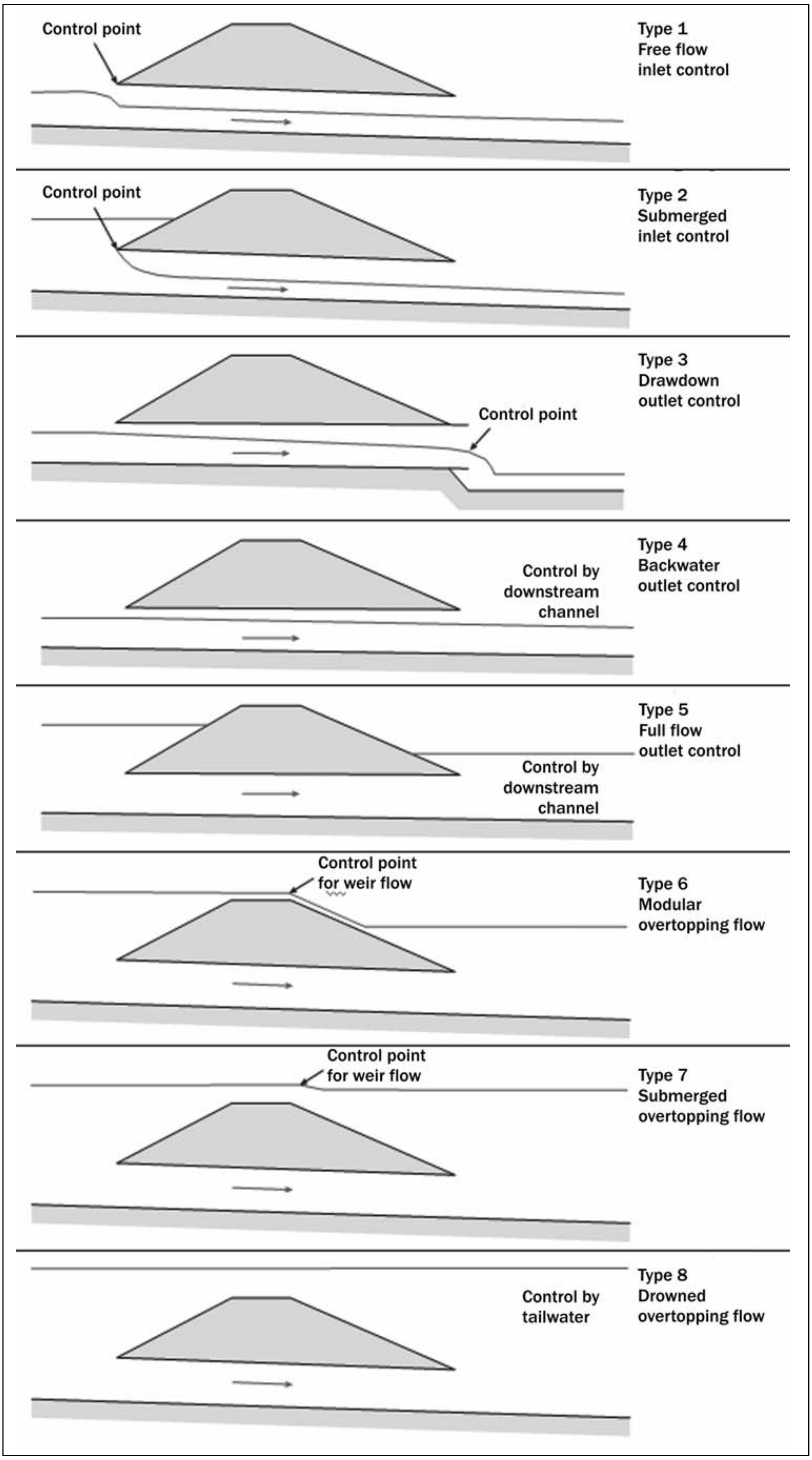


Figure 6.10 ***Flow types for a culvert structure***

6.3 Method of hydraulic assessment

6.3.1 Objective

Hydraulic assessment encompasses both the assessment of existing culverts and the design of new structures, and the objective is to determine whether the existing or proposed culvert meets its hydraulic performance requirements. These may include some (but not all) of the following:

- the ability to convey the design discharge under free flow conditions
- the ability to convey the design discharge without flooding of property or infrastructure, possibly with sedimentation obstructing part of the culvert barrel
- the ability to convey an extreme flood without causing property or infrastructure damage
- the ability to throttle an extreme flood to reduce flood risk downstream
- the avoidance of scour at the culvert outlet
- a stable sediment regime within the culvert barrel
- suitable flow depth and velocity for fish passage
- adequate headroom for mammal passage during the dominant flow conditions.

6.3.2 Hydraulic parameters

The hydraulic parameters of interest are the tailwater and headwater elevation and water level, flow depth through the culvert barrel and velocity of flow in the barrel and downstream (Figure 6.11).

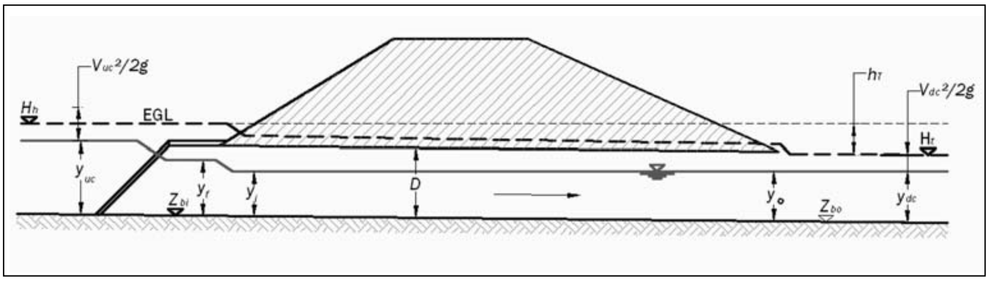


Figure 6.11 *Hydraulic parameters*

Tailwater elevation and water level

The tailwater elevation (and water level) immediately downstream of a culvert outlet are determined by channel or structure control downstream and are important factors in determining culvert capacity under certain flow conditions.

The tailwater elevation H_t is the total energy or head given by the sum of the bed elevation at the culvert outlet Z_{bo}, the depth of water y_{dc} and velocity head in the downstream channel (Figure 6.11 and Equation 6.10). The water level of the tailwater WL_t is the sum of bed elevation and tailwater depth (Equation 6.11). The tailwater head may be taken as an approximation of water level (and vice versa), if the velocity in the downstream channel is low (for example, the velocity head for a flow velocity of 0.7 m/s is only 25 mm).

$$H_t = Z_{bo} + y_{dc} + \frac{V_{dc}^2}{2g} \qquad (6.10)$$

$$WL_t = Z_{bo} + y_{dc} \tag{6.11}$$

where

Z_{bo} = elevation of bed at culvert outlet (m)

y_{dc} = depth of water in downstream channel (m/s)

V_{dc} = velocity in downstream channel (m/s)

Headwater elevation (and water level)

Headwater elevation (and water level) are of importance for the assessment of free flow discharge capacity, maximum discharge capacity and flood risk.

The headwater elevation H_h is the total energy or head immediately upstream of a culvert inlet, given by the sum of the bed elevation at the culvert inlet Z_{bi}, the depth of water at the face of the culvert inlet y_f and velocity head for flow in the upstream channel (Equation 6.12). The water level of headwater WL_h is the sum of the elevation head and headwater depth (Equation 6.13). As for tailwater, the velocity head may be neglected if the approach velocity is low and the headwater elevation may be taken as an approximation of water level.

$$H_h = Z_{bi} + y_f + \frac{V_{uc}^2}{2g} \tag{6.12}$$

$$WL_h = Z_{bi} + y_f \tag{6.13}$$

where

Z_{bi} = elevation of bed at culvert inlet (m)

y_f = depth of water at face of culvert inlet (m/s)

V_{uc} = velocity in upstream channel (m/s)

Flow depth

Flow depth affects the passage of fish and mammals. The flow depth is limited to the height of the culvert barrel in full flow conditions and may vary along the culvert barrel under free flow conditions. The water surface profile and flow depth can be determined by a backwater calculation, either from downstream for subcritical flow or from upstream for supercritical flow. Superelevation due to bends is unlikely to be significant in culvert flow and can usually be ignored.

Velocity

Flow velocity V can be used as an indicator for the assessment of barrel sedimentation and tailwater scour. For short culverts or culverts with uniform flow conditions, the barrel velocity and outlet velocity are similar and either can be used. For long culverts, broken-back culverts or sag culverts with changes in cross-section, bed slope or roughness along the barrel, the flow velocity is likely to change with distance and should be calculated at several points. Flow velocity is given by Equation 6.14 where flow area is the full cross-sectional area of the culvert barrel for full flow A_b or the barrel area minus freeboard for free flow A (Figure 6.12). The cross-sectional area of the culvert barrel should take account of any reductions in area due to fillets, benching or sedimentation. The depth of sedimentation assumed depends on many factors, but as an initial estimate it can be taken to be equal to the depth of depression of the inlet below the channel bed (refer to Figure 9.14).

$$V = \frac{Q}{A} or \frac{Q}{A_b} \tag{6.14}$$

where

Q	=	discharge in the culvert or channel (m^3/s)
A_b	=	cross-sectional area of the culvert for full flow (m^2)
A	=	cross-sectional area of the flow for free flow or open channel flow (m^2)

Shear stress

Shear stress τ_0 is an alternative indicator for the assessment of sedimentation and scour. For a channel this is given by the Chézy formula:

$$\tau_0 = \rho g R S_0 \tag{6.15}$$

where

ρ	=	density of water (kg/m^3) (1000 kg/m^3)
R	=	hydraulic radius of channel (m)
S_0	=	bed slope of channel (m/m)

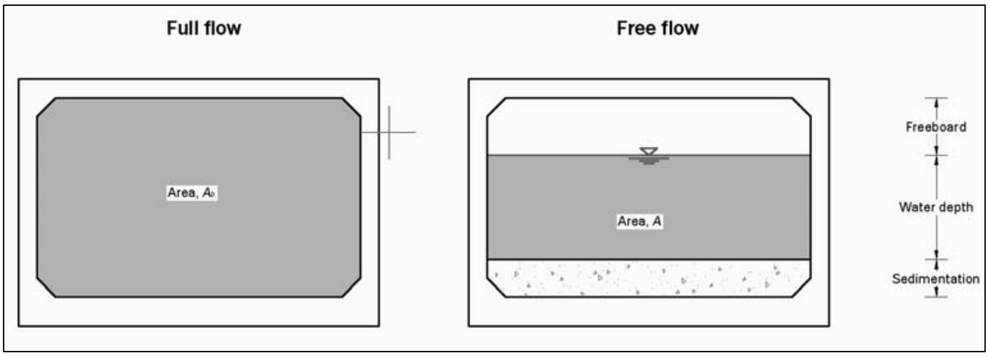


Figure 6.12 *Calculation of barrel velocity*

The cross-sectional area may be reduced by sedimentation in the barrel for either case.

6.3.3 Culvert performance curves

The culvert performance curve for a given culvert shows headwater level against discharge, together with design constraints such as culvert soffit level (minus freeboard), maximum permissible headwater level and structure crest level. From this the free flow discharge capacity, maximum discharge capacity and onset of overtopping can be determined (Figure 6.13). The culvert performance curve is unique to each culvert and will change if, for example, sedimentation occurs. In tidal areas, several combinations of discharge and tailwater level may result in a family of curves. Curves should be generated for both inlet and outlet control and the highest headwater elevation selected for any given discharge (Figure 6.13).

Ideally, a performance curve should be generated for the full range of design discharges from low-flow to the design flood, as well as an extreme flood to assess the consequences of above-design standard events. This is a conservative approach to hydraulic assessment, which ensures adequate performance under all flow conditions, and ignores any transient conditions that might imply higher performance. Sufficient points should be plotted to ensure adequate definition of the curve, although this requires a comprehensive analysis of the culvert hydraulics and is best carried out with the assistance of computer software (see Section 6.14).

A quicker alternative for the user wishing to carry out a rapid assessment or without access to computer software is to calculate just two or three points on the curve such as the free flow capacity and surcharged flow capacity of a given culvert, or the headwater for normal discharge, design flood and extreme flood.

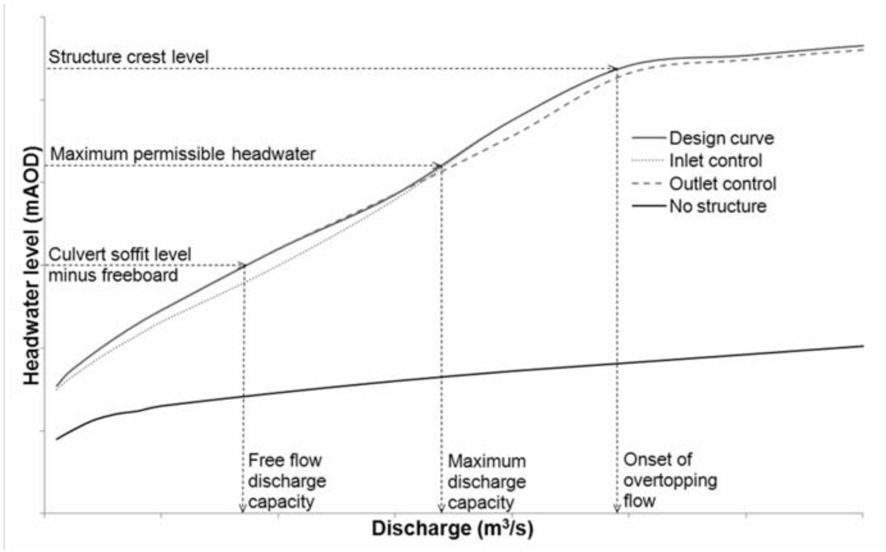


Figure 6.13 *Culvert performance curve for headwater level*

Culvert performance curves may also be plotted for other variables. The performance curve for barrel velocity with minimum permissible velocity for sedimentation and maximum permissible velocity for erosion allows the risk of scour and sedimentation to be assessed (Figure 6.14). However, it should be noted that each threshold relates to a uniform sediment, whereas in practice, most sediments are non-uniform and these thresholds would cover a range of velocities.

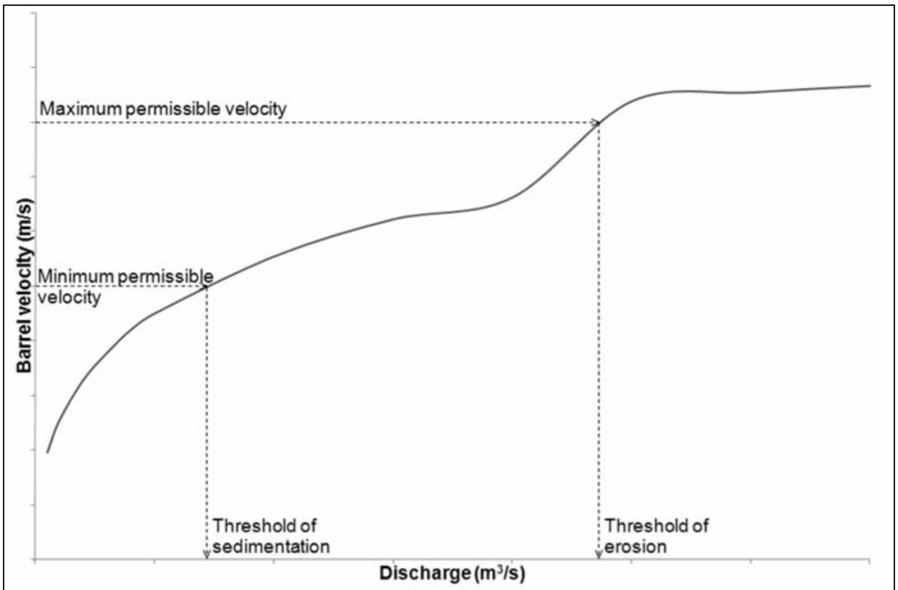


Figure 6.14 *Culvert performance curve for barrel velocity*

6.3.4 Methods of assessing culvert performance

The methods of hydraulic assessment for each flow type are summarised in Table 6.1. A culvert may exhibit several flow types for different discharges and tailwater conditions.

Table 6.1 ***Method of hydraulic assessment for each flow type***

Flow type	Hydraulic control	Flow type	Method of hydraulic assessment
1	Inlet	Free flow	Free flow inlet control equation (Section 6.9)
2	Inlet	Submerged	Submerged inlet control equation (Section 6.9)
3	Outlet	Drawdown	Backwater profile (Section 6.10)
4	Outlet	Backwater	Backwater profile, although an approximate analysis assuming uniform flow in the culvert will often suffice (Section 6.10)
5	Outlet	Full flow	Tailwater level plus total head losses for outlet, friction and inlet (plus bend or screen losses where applicable) (Section 6.10)
6	Embankment	Modular weir	Conduit and weir equation (Section 6.11)
7	Embankment	Submerged weir	Conduit and weir equation with submergence factor (Section 6.11)
8	Channel	Drowned weir	Energy approach (Section 6.11)

The procedure for the hydraulic assessment of existing culverts and the design of new culverts is shown in Figure 6.15 and described in Sections 6.4 to 6.13.

The hydraulic assessment of existing culverts determines the free discharge capacity of a culvert and/or the surcharged discharge capacity that can be carried without the headwater level exceeding a specified maximum permissible level (for example, a road or rail level, or property threshold level less freeboard). The process is iterative, involving an initial estimate of the discharge capacity then calculation of headwater level for inlet and outlet control, until the estimate gives a headwater level similar to the maximum permissible headwater level. The hydraulic design of a new culvert is similar, but involves an extra step (Figure 6.15, Section 6.7). At the start of the assessment, the designer estimates the initial dimensions of the culvert then goes through all the processes involved in hydraulic assessment of an existing culvert. If the chosen dimensions are suitable, the design is complete, but if not, then the process is repeated with different culvert dimensions until the right result is achieved.

Hydraulic assessment may be carried out by hand or using computer software, the latter providing some labour-saving benefits, particularly for the production of performance curves. Methods for hand calculation are described in detail in Sections 6.6 to 6.13 with worked examples in Appendix A2. An overview of computer software is described in Section 6.14.

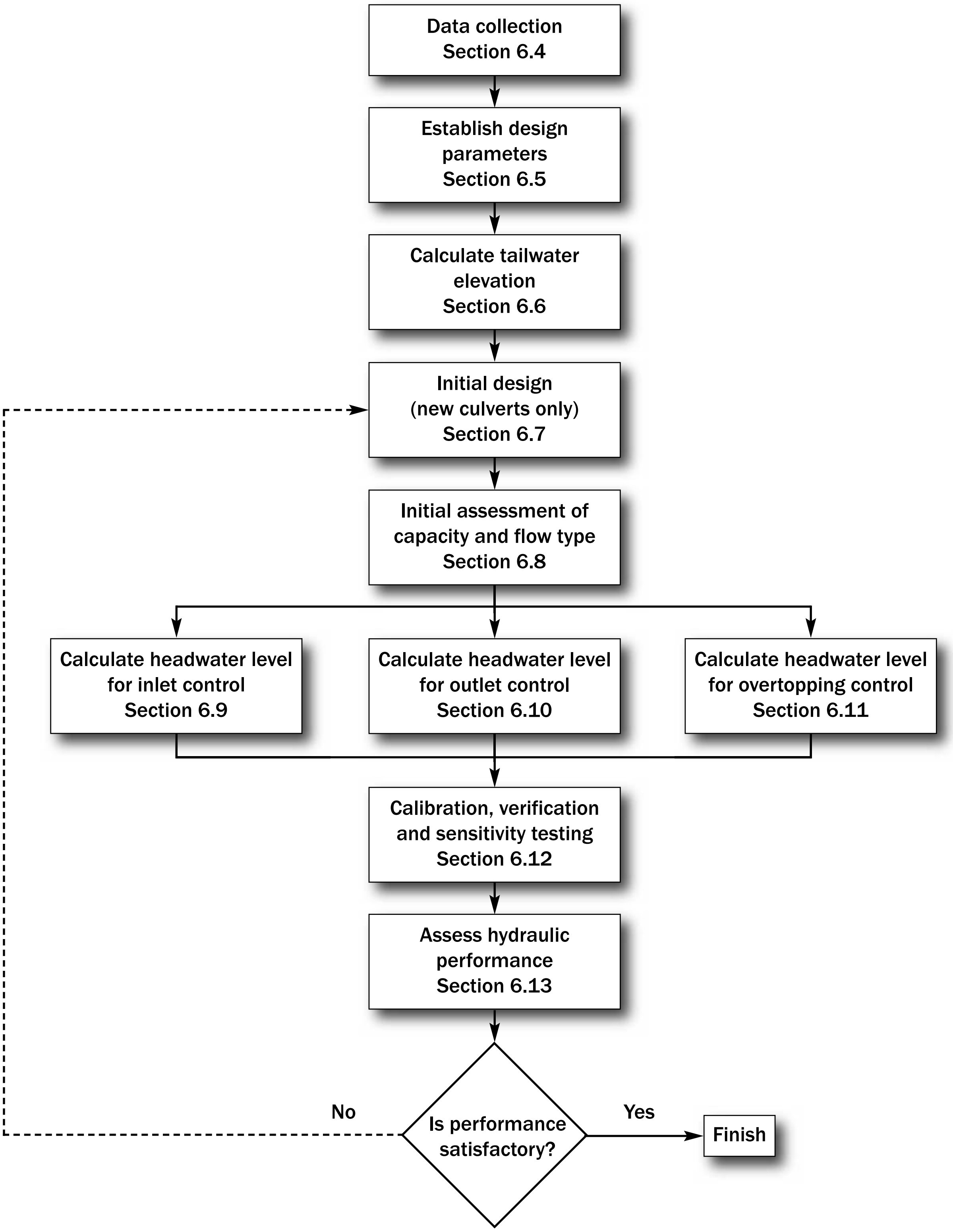


Figure 6.15 *Method for assessing culvert performance*

6.4 Data collection

Data collection is the first step in hydraulic assessment. The data requirements vary according to the type of analysis, but will include hydrological data, boundary conditions, culvert dimensions, watercourse topography, data about the assets at risk from flooding, and the properties of the bed and bank material.

6.4.1 Hydrological data

Hydrological data requirements depend on whether flood storage or attenuation is likely to occur, for example if the culvert throttles the flow or is tide locked, and whether steady or unsteady assessment is required.

For steady-state assessment, the following data are required:

- design flood peak discharge
- design low discharge (typically 95-percentile discharge, ie the discharge that is exceeded 95 per cent of the time, Q_{95})
- boundary conditions at the upstream and downstream limits of the study reach to allow calculation of the starting water surface, typically a known water level, rating curve or normal depth.

For unsteady assessment:

- design flood hydrographs
- design tidal curves (to simulate storage and release of water during the tidal cycle)
- boundary conditions at the upstream and downstream limits of the study reach to allow calculation of the starting water surface. Separate boundary conditions are required for each inflow and tidal condition.

6.4.2 Culvert survey

For the design of new culverts, the culvert geometry is determined by the designer, but for the assessment of existing culverts, a survey is required to obtain:

- barrel shape
- barrel dimensions, including any pinch points (ie steps, changes of cross-section, obstructions)
- barrel length
- barrel slope or invert levels at inlet and outlet (or at all changes of slope, if culvert slope varies along its length)
- number, angles and radii of bends in the barrel alignment
- dimensions of any manholes along the length of the barrel
- barrel material and condition
- depth and composition of any sedimentation
- inlet type or inlet loss coefficient
- outlet type or outlet loss coefficient
- trash or security screens: overall dimensions, length and inclination of screen, bar spacing and opening width
- likely degree of blockage of the culvert or screen if present (based on review of catchment) (see Section 5.5).

6.4.3 Topographic survey

A topographic survey of the watercourse is required, the extent of other surveys depending on the nature of the watercourse and the likely risk of flooding to properties or assets. The following may be needed:

Topographic surveys

- topographic survey showing layout of site, top of banks, top and bottom of slopes, water level
- spot level survey along flood banks
- spot level survey of any upstream flood storage area (to allow generation of water level-volume relationship for unsteady assessment), although this may be unnecessary if remote sensing data is available.

Channel and floodplain surveys

- cross-sections at culvert inlet and outlet (or a single cross-section at the proposed culvert location)
- cross-section upstream of the contraction length (typically half the sum of the floodplain widths) and downstream of the expansion length of the culvert (typically the sum of the floodplain widths), or 30 m in both cases if no other data is available (but note that extra sections may be required if the channel is locally very variable)
- further cross-sections upstream of the culvert (if backwater or flood storage are likely to be important)
- bank levels of upstream and downstream channels
- structure survey of any hydraulic control structures such as weirs, sluices, bridges or other culverts that may affect tailwater level, including sill level and maximum opening height.

Remote sensing

- digital elevation model such as light detection and ranging (LIDAR) or interferometric analysis of RADAR data (InSAR).

Threshold surveys

- threshold levels for properties or infrastructure that may be at risk from flooding.

6.4.4 Ground investigation

Where the risk of scour is a concern, the bed and bank material properties should be obtained to allow the assessment of scour and design of scour protection works. Bed samples for laboratory testing should be taken from the parent material rather than any armour layer at the surface that may give misleading results (say 0.5 m below bed level). For cobbles and boulders, in situ measurement is sufficient. The following properties should be obtained for each layer of sediment:

- for cohesive sediments: bulk density
- for non-cohesive sediments: particle size distribution (and particle density if budget allows, although values can be assumed).

6.5 Establishment of design parameters

6.5.1 Performance requirements

Hydraulic performance requirements are discussed in greater detail in Section 6.3.1 and typically include the passage of a design flood and the avoidance of scour and sedimentation. Some culverts may be required to provide flood storage upstream of an obstruction, in which case the culvert throttles the flow in the watercourse and the design discharge is less than the design flood.

6.5.2 Design constraints

The design constraints affecting the culvert geometry or construction may include:

- geometrical constraints on width, soffit height or invert level, for example, due to rail level or services
- freeboard allowance for uncertainty (see Section 9.3.3)
- invert lowering for sedimentation (see Section 9.3.7)
- site access and construction method, for example, a railway culvert may require pipe jacking to avoid disruption to rail services (see Section 9.6.3)
- access requirements for maintenance.

For the assessment of free flow, the maximum permissible headwater level WL_{hmax} is given by the soffit level at the culvert inlet minus a freeboard allowance for uncertainty. However, it should be noted that it is possible to have a higher headwater level and still have free flow in certain conditions, for example, for inlet control with weir flow at inlet and supercritical flow in the culvert. For the assessment of surcharged flow, for example, to assess flood risk to a road or railway, the maximum permissible headwater level WL_{hmax} may be the level of the asset minus freeboard. In certain circumstances, flow stagnation may lead to the formation of a bow wave with a height equivalent to the velocity head, in which case the total head of the headwater level (including velocity head) should be considered. This is most likely to happen if submerged flow occurs at culverts with vertical headwalls in steep watercourses (high flow velocities).

Freeboard is typically in the range 150 mm to 600 mm depending on the size of the culvert, the type of asset and the acceptable level of risk. Further guidance is available from Environment Agency (2000b), BA59/94 of the DMRB (TSO, 2007) and in Railtrack (2000).

At the start of an assessment, it can be helpful to prepare a sketch of the culvert showing (Figure 6.16):

- plan
- longitudinal section indicating inlet and outlet levels, and maximum permissible headwater level
- cross-sections of the culvert barrel and the channel upstream and downstream.

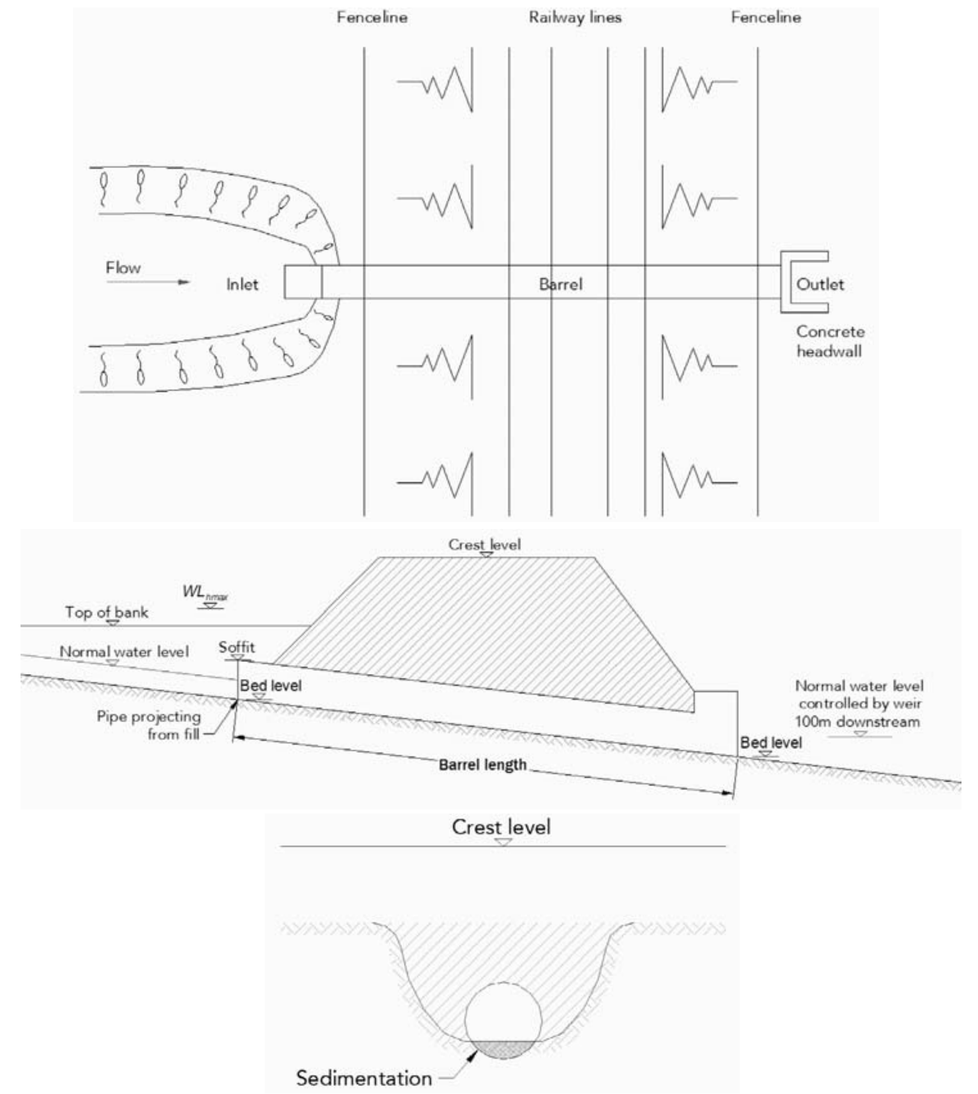


Figure 6.16 *Example of a sketch of a culvert*

6.6 Calculation of tailwater elevation

The tailwater depth y_o and tailwater elevation H_t determine the flow type and culvert performance. Tailwater elevation should be calculated for a range of discharges as the hydraulic assessment process is iterative and more values will be required. The production of a stage-discharge relationship allows the tailwater level for different flows to be read from the graph of the relationship. Tailwater depth y_o may be calculated by two methods:

1 Manning's equation (Section 6.6.1).

2 Backwater method (Section 6.6.2).

6.6.1 Manning's equation

Manning's equation can be a useful starting point and is generally acceptable unless there is a dominant control further downstream (eg a sluice). The normal depth y_n at the culvert outlet is the depth that satisfies Manning's equation for a given discharge Q (Equation 6.16).

$$Q = KS_0^{1/2} = \left(\frac{1}{n} AR^{2/3}\right) S_0^{1/2} \qquad (6.16)$$

$$R = \frac{A}{P} \tag{6.8}$$

where

K	=	conveyance (m^3/s)
S_0	=	representative bed slope of downstream channel (m/m)
n	=	Manning's roughness coefficient of downstream channel (-)
A	=	cross-sectional area of flow in downstream channel (m^2)
P	=	wetted perimeter of downstream channel (m)
R	=	hydraulic radius (m)

6.6.2 Backwater method

The backwater method should be used if tailwater is controlled by a hydraulic structure downstream of the culvert such as a weir or sluice, or where a high degree of accuracy is required. Tailwater depth y is calculated using the backwater method from the control structure working upstream to the culvert outlet. The backwater method is given in Section 6.10.7.

6.6.3 Tailwater elevation

Having obtained the tailwater depth y_{dc}, the tailwater elevation H_t, or total head of the tailwater immediately downstream of the culvert outlet, is then calculated using Equation 6.10.

$$H_t = Z_{bo} + y_{dc} + \frac{V_{dc}^2}{2g} \tag{6.10}$$

where

Z_{bo}	=	elevation of bed at culvert outlet (m)
y_{dc}	=	water depth in downstream channel (m) (from Section 6.6)
V_{dc}	=	velocity in downstream channel (m/s)

6.7 Initial design (new culverts only)

The initial design of a culvert is determined by the performance requirements and design constraints. The culvert cross-sectional area and discharge capacity should be equal to or greater than the next culvert upstream unless the culvert is intended to act as a throttle for flood storage. However, the dimensions of other culverts on the watercourse should not be relied upon to give a definitive size for a new culvert – there should always be a hydrological assessment to base the hydraulic design on. The culvert bed slope and cross-sectional area should normally be similar to the existing watercourse so as to maintain the hydraulic and geomorphological regime and reduce the need for maintenance such as sediment removal. Three methods for initial design are given in the following sub-sections, with further guidance on the selection of culvert size and shape in Sections 9.1.4 and 9.2.

6.7.1 Flow-area method

The initial culvert size and shape may be estimated from the tailwater depth and flow area for the downstream channel. For free flow design, the internal height of the culvert D is at least tailwater depth plus freeboard allowance for uncertainty (y_{dc} $+F$) and the trial area A_t is tailwater area plus freeboard area obtained by extending the free surface vertically above bank level (A_{dc} + FW) (Figure 6.17). For surcharged flow design, freeboard is omitted and the internal height is determined from site constraints while the trial area is simply A_{dc}. An allowance for invert lowering and partial sedimentation should be included in both cases. If it is suspected that sedimentation may be a problem in the culvert, then the barrel velocity method (Section 6.7.3) is suggested.

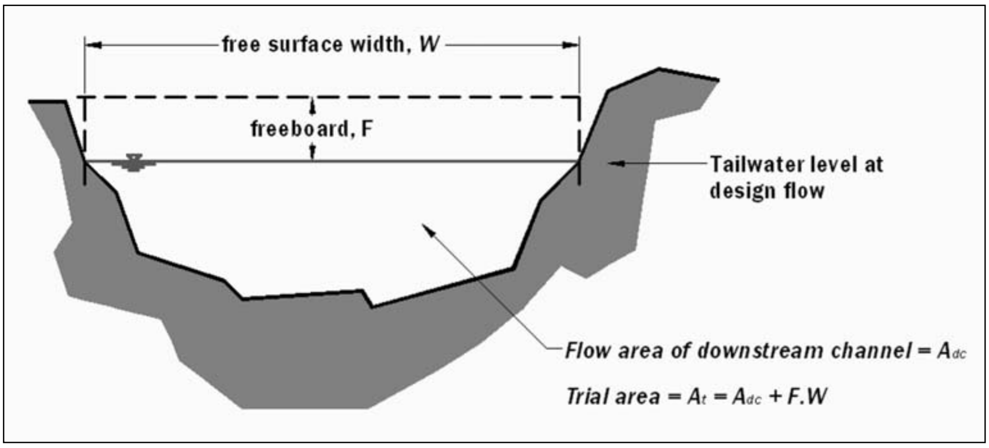


Figure 6.17 *Initial estimate of culvert size using flow area*

6.7.2 Permissible head loss

The initial culvert size may also be estimated from the permissible head loss. The total head loss through a culvert is the difference between maximum permissible headwater level and tailwater level, and is seldom less than 1.5 times the velocity head (Equation 6.17), so the cross-sectional area of the culvert opening A_t is given by the formula for velocity head (Equation 6.18). Note that this shortcut is a guide and is only valid if the culvert is relatively short (eg less than 30 m) because it ignores friction loss in the culvert barrel. In longer culverts the friction head loss becomes more significant.

$$h_T = H_{h\max} - H_t \tag{6.17}$$

$$A = \sqrt{\frac{1.5}{2g}} \cdot \frac{Q}{\sqrt{h_T}} = \frac{1}{3.6} \cdot \frac{Q}{\sqrt{h_T}} \tag{6.18}$$

where

H_{hmax} = maximum permissible headwater elevation (m)

H_t = tailwater elevation for design discharge (m)

h_T = total head loss (m)

Q = design discharge (m^3/s)

6.7.3 Barrel velocity

If sedimentation is likely to be a problem, then selecting a culvert cross-sectional area to give a barrel velocity 10 per cent greater than that in the channel is suggested. This will ensure that the flow velocity is higher in the culvert than in the watercourse, which will help to maintain sediment in suspension through the culvert. However fish passage requirements may preclude higher velocities. Conversely, if a culvert barrel is made significantly larger (especially if wider) than the watercourse, sedimentation can be expected to take place in the barrel. This may be desirable for environmental reasons (fish, wildlife and fauna).

6.8 Initial assessment of discharge capacity and flow type

The initial assessment provides an estimate of discharge capacity and allows the designer to make an informed choice regarding calculation approach for detailed assessment. Two methods are:

- inlet control charts (Section 6.8.1)
- permissible head loss (Section 6.8.2).

6.8.1 Inlet control charts

Inlet control charts show the relationship between headwater ratio (specific energy of headwater/barrel height) and discharge (or discharge per unit width of barrel) for a range of circular and rectangular culverts under inlet control conditions and are suited to steep culverts. Figures A1.3 and A1.4 in Appendix A1 were generated using the free and submerged inlet control equations for concrete culverts with a headwall and a bed slope of 0.01, although the bed slope has only a minor effect on headwater ratio (represented by the term 0.5 S_0 in the inlet control equations).

For more complex culvert shapes, the discharge capacity may be estimated by selecting a circular or rectangular culvert of equivalent cross-sectional area and barrel height, although the area should be calculated more accurately for detailed design. Charts for alternative culvert configurations are available in Federal Highway Administration (2001, revised 2005). Design charts should only be used for initial assessment and should not be used in place of full hydraulic assessment due to the possible influence of site-specific culvert or watercourse characteristics.

6.8.2 Permissible head loss

The permissible head loss method is most suited to outlet control conditions, ie culverts with a mild barrel slope and hydraulic control either within the culvert barrel or downstream. This method is not ideal for inlet control conditions, for example, steep culverts, short culverts or culverts with shallow tailwater.

The headwater level under outlet control H_{hoc} for a given discharge can be estimated using Equation 6.19. The discharge should be revised until the headwater level is the same as the maximum permissible headwater level.

$$H_{hoc} \approx H_t + 1.5\frac{V_b^2}{2g} + L\left(\frac{nQ}{AR^{2/3}}\right)^2 \qquad (6.19)$$

$$R = \frac{A}{P} \qquad (6.8)$$

where

H_t	=	tailwater elevation (m)
V_b	=	velocity in culvert barrel (m/s)
L	=	length of culvert barrel (m)
n	=	Manning's roughness coefficient
Q	=	discharge (m^3/s)
A	=	cross-sectional area of flow, excluding fillets, benching, sedimentation (and freeboard for free flow) (m^2)

R	=	hydraulic radius (m)
P	=	wetted perimeter (m)

It can be seen that discharge capacity increases with bed slope, but this is only true as long as there is sufficient head (ie difference between H_t and H_h) to drive the flow through the culvert. Simply increasing the slope of the barrel will not increase the capacity of the culvert unless the control section is within the barrel and not at the inlet (inlet control) or at the outlet (downstream control). This fundamental fact is often overlooked by inexperienced engineers with the consequence that the capacity of a culvert can be significantly over-estimated.

The Manning's roughness coefficient encompasses energy losses due to both friction and channel shape, and as a result is somewhat crude. The coefficient is commonly treated as dimensionless, although the units are strictly $TL^{-1/3}$. Values are derived empirically and are most easily obtained from lookup tables (see Tables A1.1 and A1.2 in Appendix A1). Note that values are only indicative and where the coefficient is critical, the stage-discharge calculation should be calibrated against observed values (see Section 6.13), or sensitivity tests carried out as a minimum.

A more rigorous approach to conveyance that separates the energy losses due to boundary friction, transverse currents and lateral shear is given in the conveyance estimation system/afflux estimation system (CES/AES) software, which is freely available (see *Useful websites*). This is further discussed in Section 6.14. Further information is also available in Knight *et al* (2009). The CES/AES roughness advisor allows the user to build a unit roughness coefficient from three roughness components representing the surface material, vegetation and irregularity of each roughness zone (channel, floodplain or bank). Roughness values and photographs for a wide range of materials and vegetation types are given in lookup tables (contained within roughness advisor software). The unit roughness is conceptually a different quantity than Manning's n but the CES graphical outputs provide the user with a back-calculated Manning's n value.

If the wetted perimeter of the culvert has different roughness values, for example, due to sedimentation or different materials, as shown in Figure 6.18, then a compound roughness n' should be calculated using either Equation 6.20 or 6.21. Compound channels with multiple roughness panels may require conveyance calculations for each roughness panel and are more easily handled by computer software. Alternative methods are described in more detail in Knight *et al* (2009).

$$n' = \left(\frac{1}{P} \sum_{i=1}^{N} p_i n_i^{1.5} \right)^{0.67} \quad \text{for culverts} \qquad (6.20)$$

$$n' = \frac{PR^{5/3}}{\sum_{1}^{N} \left[\frac{p_i R_i^{5/3}}{n_i} \right]} \quad \text{for river channels} \qquad (6.21)$$

where

N	=	number of roughness panels across-section (-)
n_i	=	Manning roughness coefficient for ith roughness panel (-)
p_i	=	wetted perimeter for i^{th} roughness panel (m)
P	=	wetted perimeter for full cross-section (m)
R_i	=	hydraulic radius for i^{th} roughness panel (m)
R	=	hydraulic radius for full cross-section (m)

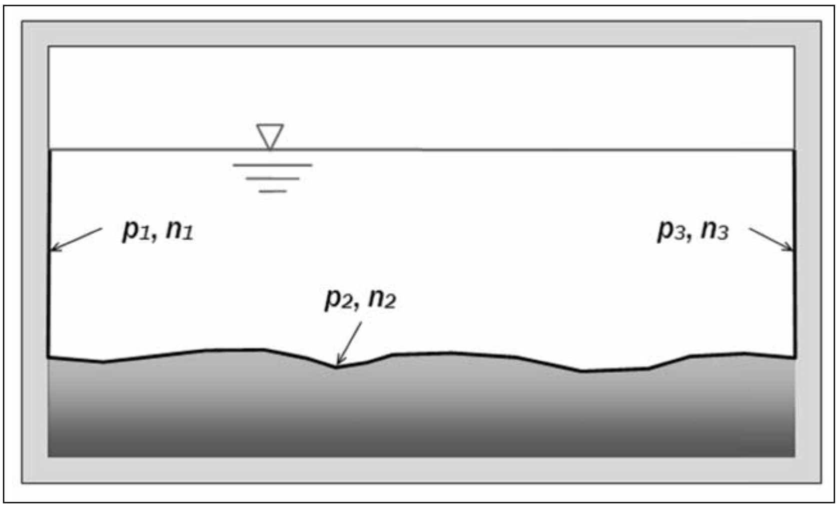


Figure 6.18 *Definitions for compound roughness*

The water depth may be estimated from observed flood levels, if available, or by assuming bankfull flow in the downstream channel. Bankfull flow is sometimes assumed to be estimated by the median annual flood, *QMED* (with a 50 per cent annual probability or two-year return period) for natural channels, although this assumption works less well for urban or heavily modified channels, and may be highly inaccurate for drainage channels in lowland agricultural areas. It can be helpful to produce a discharge-conveyance relationship and the CES/AES conveyance generator can assist with this.

6.8.3 Assessment of probable flow control type

An initial assessment of the culvert flow control type can be helpful before starting detailed calculations to avoid abortive work. There is little benefit in undertaking inlet control calculations for a culvert operating under full flow conditions, or outlet control calculations for a very steep culvert.

Outlet control is more likely for:

- culverts with mild slopes
- culverts with full flow, where tailwater elevation H_t (from Section 6.6) exceeds soffit level at the culvert inlet
- culverts with high tailwater, where tailwater elevation H_t exceeds headwater level for inlet control H_{hic} (from Section 6.8.1).

If outlet control is likely, the designer should start with Section 6.10. If inlet control is viable, for example, for culverts with steep slopes and low tailwater, assessment should start with Section 6.9. If the culvert flow control is unclear, both inlet and outlet control calculations should be undertaken and the highest energy answer selected (ie the answer that gives the highest headwater energy level, as discussed in Section 6.3.3). For culverts with inlet screens, it can be helpful to ignore the screen to start with, then to calculate the screen head loss for the most conservative headwater elevation only (saving some abortive work).

6.9 Calculation of headwater elevation for inlet control

6.9.1 Method

The method for calculating headwater elevation under inlet control conditions (flow types 1 and 2) is summarised in Figure 6.20. The equations and methods are given in Sections 6.9.2 to 6.9.5, with worked examples in Appendix A2.

Figure 6.19 *Culvert flowing under inlet control*

Note the significant drop in water level as the flow contracts into the mouth of the barrel (see also Figure 6.10: type 1 flow).

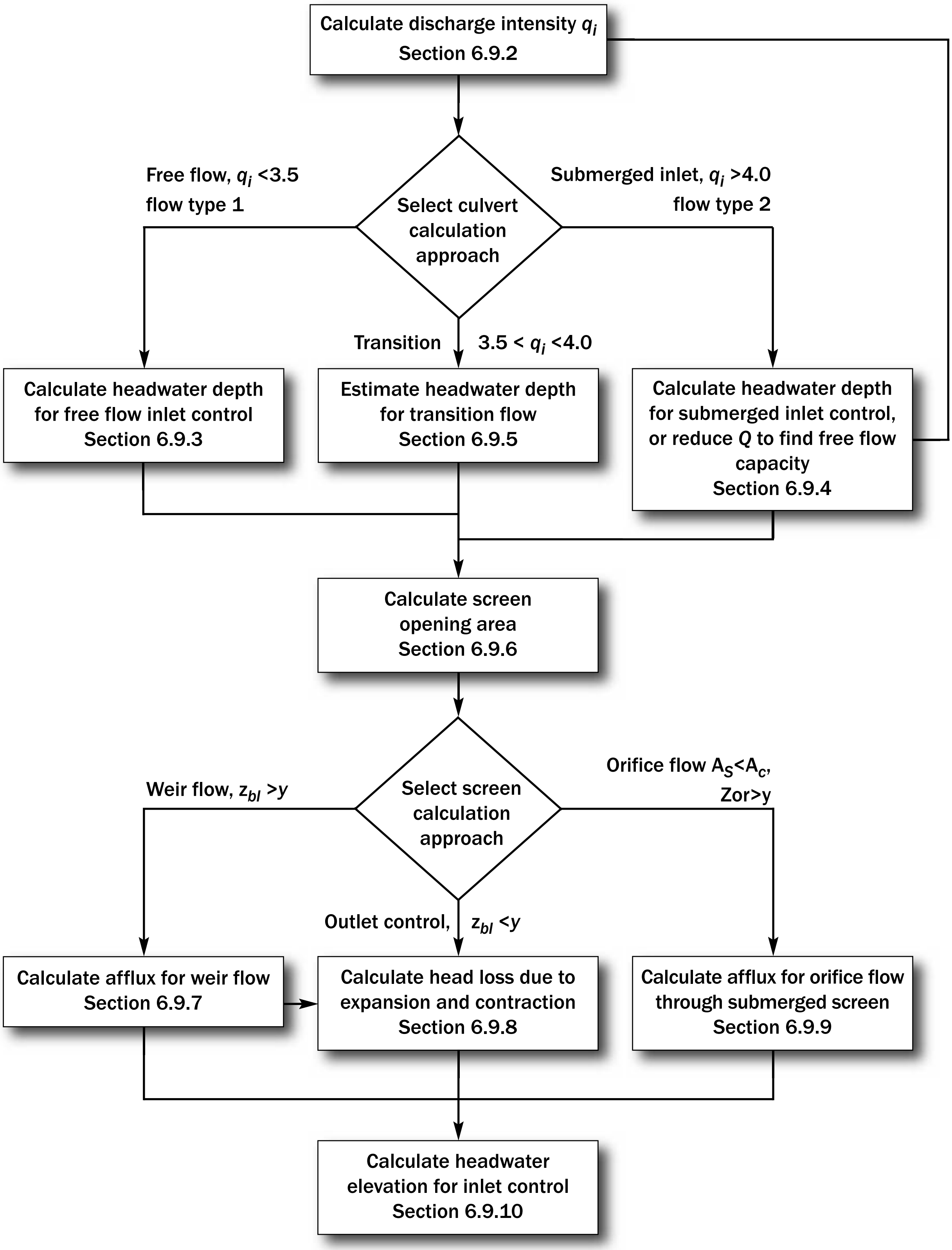


Figure 6.20 *Method for assessing flow under inlet control*

6.9.2 Calculate discharge intensity and select calculation approach

The discharge intensity q_i indicates the type of flow and determines the appropriate calculation approach and is given by

$$q_i = \frac{1.811Q}{A_b D^{0.5}} \tag{6.22}$$

where

Q = discharge (m^3/s)

A_b = cross-sectional area of the culvert barrel (excluding fillets, benching and sedimentation) (m^2)

D = height of culvert barrel (m)

1.811 = dimensionless constant (or 1.0 for imperial units)

If $q_i < 3.5$, proceed to Section 6.9.3 for free flow.

If $q_i > 4.0$, proceed to Section 6.9.4 for submerged flow.

If $3.5 < q_i < 4.0$, proceed to Section 6.9.5 for transition between free and submerged flow.

6.9.3 Calculate headwater depth for free flow inlet control

For free flow inlet control (flow type 1), the FHWA (2001) inlet control equation is used. Two forms of the equation are available: the full equation (Form A, Equation 6.23) and the simplified equation (Form B, Equation 6.25). Tables A1.3 and A1.4 in Appendix A1 show which equation is required and give the constants *k, M, c* and *Y* (although note that Table A1.4 uses a slightly different equation, which is given in the appendix).

If the full equation (Form A) is recommended by Table A1.3 then:

$$\frac{E_{sh}}{D} = \frac{E_{sc}}{D} + k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M - 0.5S_0 \tag{6.23}$$

where

E_{sh} = specific energy of headwater (m)

E_{sc} = specific energy at critical depth (m)

k, M = constants used in unsubmerged inlet control calculations

S_0 = slope of culvert barrel (m/m)

Specific energy at critical depth E_{sc} is given by

$$E_{sc} = \frac{3}{2} y_c \tag{6.5}$$

where

y_c = critical depth (m)

Critical depth, y_c, can be determined from Figures A1.4 to A1.7 in Appendix A1 or alternatively y_c is the depth where

$$\frac{Q^2 W}{g A_c^3} = 1 \tag{6.24}$$

where

W = width of the water surface at culvert inlet (m)

A_c = cross-sectional area of flow at critical depth (m²)

It should be noted that for circular culverts, the width of the water surface, *W*, decreases as critical depth, y_c, approaches height *D* (about $y_c/D > 0.9$), giving substantial increases in discharge, *Q*, greater than the full-bore discharge for a smooth, steep pipe. The designer should take care to ensure that the discharge is realistic for the chosen culvert height, slope and roughness.

If the simplified equation (Form B) is recommended by Table A1.3 or A1.4 then:

$$\frac{E_{sh}}{D} = k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M \tag{6.25}$$

The specific energy E_{sh} is obtained by multiplying the headwater ratio by barrel height. The depth of water upstream of the culvert inlet y_f is given by multiplying by the barrel height and deducting velocity head, although the specific energy may be taken as an approximation if flow velocity is low.

6.9.4 Calculate headwater depth for submerged inlet control

If submerged inlet control (flow type 2) is predicted then the headwater ratio is calculated using the FHWA (2001) submerged inlet control equation (Equation 6.26). If the purpose of the assessment is to determine free flow discharge capacity for an existing culvert then Q_{max} should be reduced, or the culvert should be re-sized if designing a new culvert.

$$\frac{E_{sh}}{D} = c\left[\frac{1.811Q}{A_b D^{0.5}}\right]^2 + Y - 0.5S_0 \tag{6.26}$$

where

c, Y = constants used in submerged inlet control calculations (Tables A1.3 and A1.4 in Appendix A1)

6.9.5 Calculate headwater depth for transition flow

Transition flow between flow types 1 and 2 is best assessed by plotting a dimensionless performance curve using the free flow and submerged inlet control equations above then drawing a transition line between the two arcs, as shown in Figure 6.21. If an overall inlet control equation is required for computational analysis, the simplest approach is to draw the transition line manually, read the co-ordinates of selected points from the line and perform a best fit statistical analysis (this can be carried out using a spreadsheet). The curve takes the form of a fifth order polynomial, and the coefficients are available for some box culvert and inlet types (Federal Highway Administration, 2006b).

$$\frac{E_{sh}}{D} = a + b\left[\frac{Q}{A_b D^{0.5}}\right] + c\left[\frac{Q}{A_b D^{0.5}}\right]^2 + \ldots + f\left[\frac{Q}{A_b D^{0.5}}\right]^5 - 0.5S_0^2 \tag{6.27}$$

where

$a, b, c, \ldots, f$ = polynomial coefficients

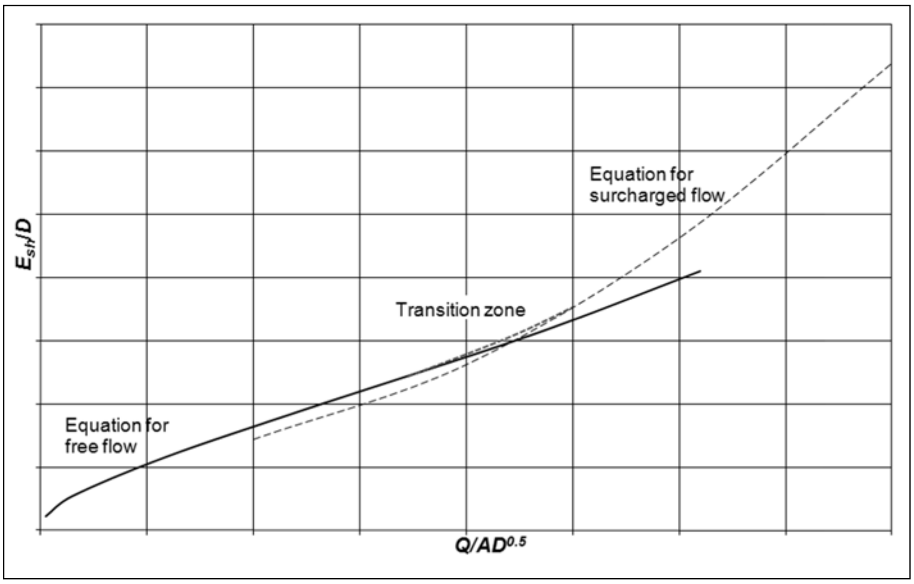


Figure 6.21 *Dimensionless performance curve for culvert under inlet control*

6.9.6 Calculate screen geometrical properties and select calculation approach

The head loss at a clean screen can be attributed to expansion and contraction around the screen bars, as well as friction, although the latter can be neglected for a short structure such as a screen. However, screens are unlikely to remain clean during flood conditions and the extra head loss due to partial blockage or blinding should be considered. Blinding is the accumulation of debris to form an impermeable barrier across the lower part of the screen, similar to a weir (Figure 6.23). This can develop suddenly due to the arrival of large items of urban debris such as mattresses or sheet building materials or build-up gradually due to the accumulation of floating material that extends downwards from the water surface to the bed. Blockage is the accumulation of permeable debris across the screen (Figure 6.22).

Research into the nature and degree of blockage and blinding is ongoing. In the meantime, it is suggested that blinding should be applied to screens in urban catchments, which may attract large objects or screens in rural catchments where natural debris has the opportunity to accumulate over a period of time. Partial blockage should be applied to screens in rural catchments that receive natural debris, screens that are cleaned regularly (including those with automatic cleaning) and screens that receive little debris, perhaps due to another screen further upstream.

The Environment Agency (2009a) recommends adopting a blinding (or blockage) of 30 to 67 per cent of the screen area for design purposes. Sensitivity testing for 100 per cent blinding or blockage should also be undertaken. Working platforms should be treated as impermeable.

Figure 6.22 *Clean screen and screen with partial blockage (courtesy Leeds City Council)*

Figure 6.23 *Screen with debris blinding (courtesy Transport Scotland)*

Calculate geometrical properties of screen

The geometrical properties of screens can be calculated using formulae in Table 6.2. For a clean screen, the opening area is the sum of the areas of the screen panels. For a blinded screen, an in-line weir with a crest level of z_{bl} above bed level is applied immediately upstream of the screen, which reduces the length of the screen opening and raising the upstream water level (Figure 6.24). For a partially blocked screen, a proportion of the screen width r is blocked by debris over the full height of the screen.

It can be helpful to prepare a sketch of the screen showing the screen panels and assumed blinding or blockage. A longitudinal section through a typical compound trash screen with three panels is shown in Figure 6.25. The effective openings are denoted by dashed lines, while blinding covers the full height of the lower screen and is shown by a solid line. The working platforms are deemed impermeable. It can be seen that the total opening area $A_s = a_1 + a_3 + a_3$ for the clean screen, dropping to $A_s = a_2 + a_3$ for the blinded screen, as the lower screen with area a_1 is ineffective due to blinding.

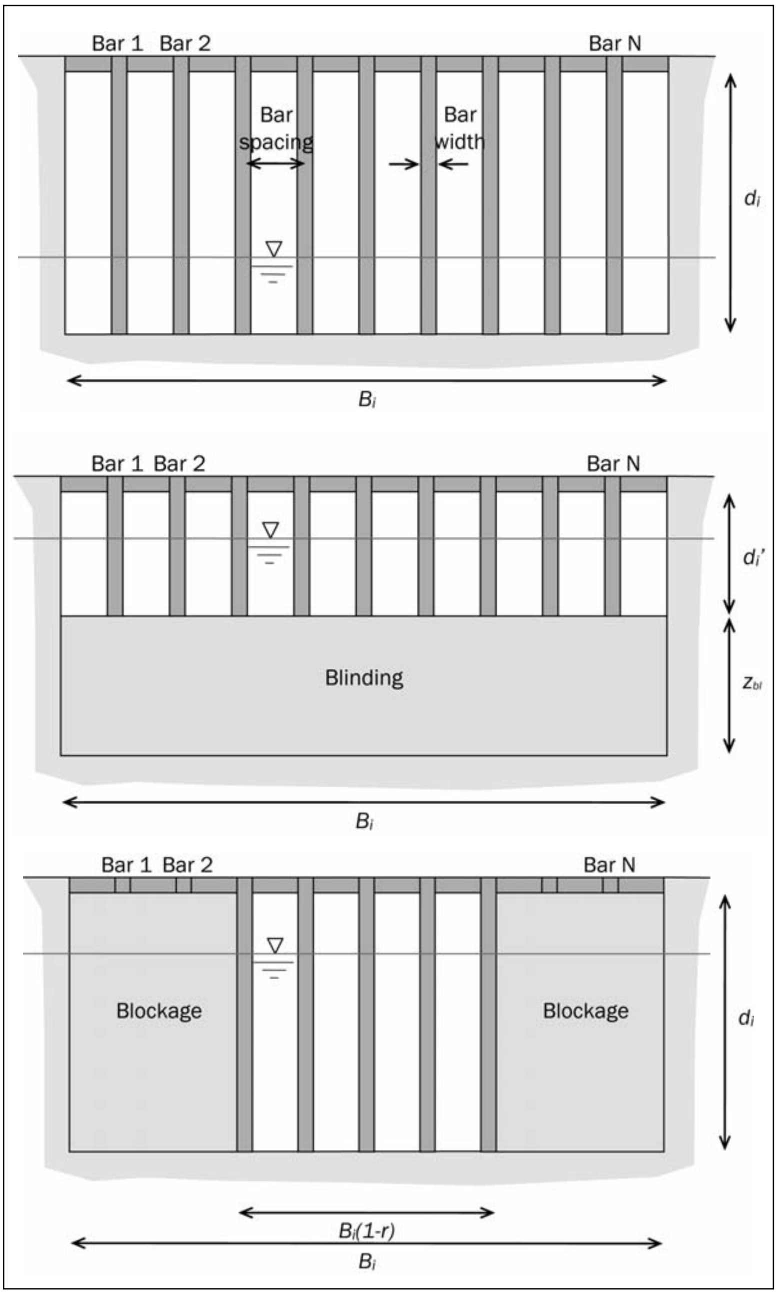


Figure 6.24 *Definitions for opening areas of clean, blinded and partially blocked screens*

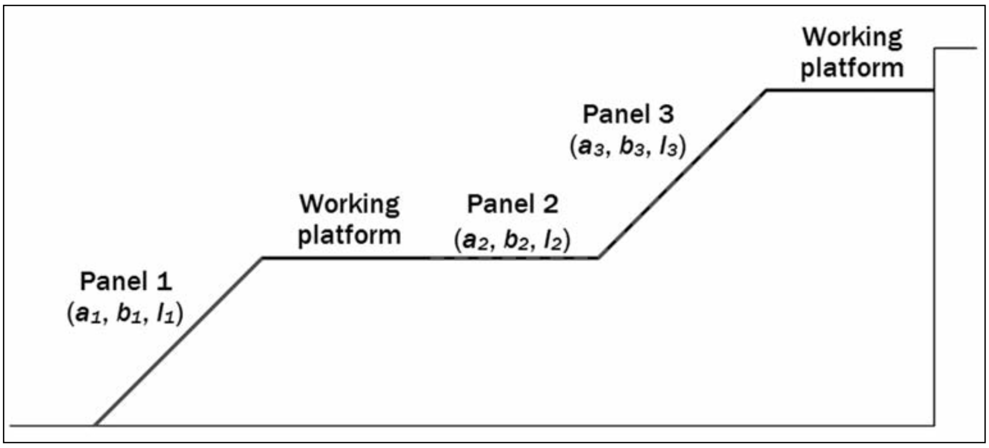


Figure 6.25 *Longitudinal section through compound screen*

Table 6.2 *Geometrical properties of screens*

Variable	Clean screen	Blinded screen	Partially blocked screen
Width of panel opening b_i	$b_i = B_i(1-b)$	$b_i = B_i(1-b)$	$b_i' = B_i(1-r)(1-b)$
Height of panel opening d_i	d_i	$d_i' = d_i - z_{bl}$	d_i
Length of panel opening l_i	$l_i = \frac{d_i}{\sin\theta}$	$l_i' = \frac{d_i'}{\sin\theta}$	$l_i = \frac{d_i}{\sin\theta}$
Area of panel opening a_i	$a_i = b_i l_i$	$a_i = b_i l_i'$	$a_i = b_i' l_i$
Total height of screen opening D_s	$D_s = \sum_{i=1}^{N} d_i$	$D_s' = \sum_{i=1}^{N} d_i - z_{bl}$	$D_s = \sum_{i=1}^{N} d_i$
Total length of screen opening L_s	$L_s = \sum_{i=1}^{N} l_i$	$L_s' = \sum_{i=1}^{N} l_i' - l_{bl}$	$L_s = \sum_{i=1}^{N} l_i$
Total area of screen opening A_s	$A_s = \sum_{i=1}^{N} a_i = \sum_{i=1}^{N} B_s L_s$	$A_s = \sum_{i=1}^{N} a_i = \sum_{i=1}^{N} B_s L_s'$	$A_s = \sum_{i=1}^{N} a_i = \sum_{i=1}^{N} B_s' L_s$

where

i	=	i^{th} panel in screen (-)
N	=	number of panels in compound screen (-)
b_i	=	width of i^{th} panel opening (m)
b_i'	=	width of i^{th} panel opening for partially blocked screen (m)
B_i	=	total width of i^{th} panel (m)
b	=	proportion of screen width blocked by bars (m/m)
r	=	proportion of screen width blocked by debris (m/m)
d_i	=	height of i^{th} panel opening (m)
d_i'	=	height of i^{th} panel opening minus blinding (m)
D_s	=	total height of screen opening (m)
D_s'	=	total height of screen opening minus blinding (m)
z_{bl}	=	vertical height of blinding above bed level (m)
l_i	=	length of i^{th} panel opening (m)
l_i	=	length of i^{th} panel opening minus blinding (m)
l_{bl}	=	length of blinding (for inclined screens) (m)
L_s	=	total length of screen opening (m)
L_s'	=	total length of screen opening minus blinding (m)
θ	=	angle of screen to horizontal (degrees)

Determine calculation approach

The head loss at a screen is determined by the screen design, the nature and degree of blockage or blinding, and the nature of flow in the culvert, all of which influence the type of flow through the screen. Three flow types have been identified:

- subcritical flow
- weir flow
- orifice flow.

Subcritical flow through the screen is controlled by the water level at the culvert inlet, whereas the headwater elevation for weir flow and orifice flow is independent of the water level at the culvert inlet. These flow types may be described as "screen control".

The headwater level may be calculated by one of three methods:

- afflux due to weir flow (Section 6.9.7)
- head loss due to expansion and contraction (Section 6.9.8)
- afflux due to orifice flow (Section 6.9.9).

For clean screens, or screens with a permeable blockage, head loss due to expansion and contraction should be calculated using Section 6.9.8.

For a screen with blinding, the assessment should start with Section 6.9.7 to assess whether weir flow over the blinding is modular, submerged or drowned. If modular or submerged weir flow occurs, the calculation should proceed to Section 6.9.8 to calculate the extra head loss due to expansion and contraction and the total head loss is the sum of the two. If drowned flow occurs, then the upstream depth should be re-calculated using Section 6.9.8 assuming subcritical flow through the screen.

If Section 6.9.7 or Section 6.9.8 show that the screen is submerged with a free flowing orifice, then Section 6.9.9 for orifice flow should be used instead. This is most likely to occur for screens with a high degree of blockage and free flow in the culvert, where the screen opening area exceeds the cross-sectional area of the culvert inlet.

6.9.7 Calculate afflux due to weir flow

The afflux due to weir flow over a blinded screen or a screen with a vertical drop immediately downstream is estimated using the in-line weir method, which assumes that a weir is installed immediately upstream of the screen bars (Figure 6.26).

The afflux for weir flow h_s is:

$$h_s = \left(z_{bl} + y_{bl} + h_{ex}\right) - y_f \qquad (6.28)$$

where

z_{bl} = height of screen blinding above channel bed (m)

y_{bl} = depth of weir flow over blinding (m)

h_{ex} = head loss due to expansion and contraction (m) (see Section 6.9.8)

y_f = depth of water at face of culvert inlet (m)

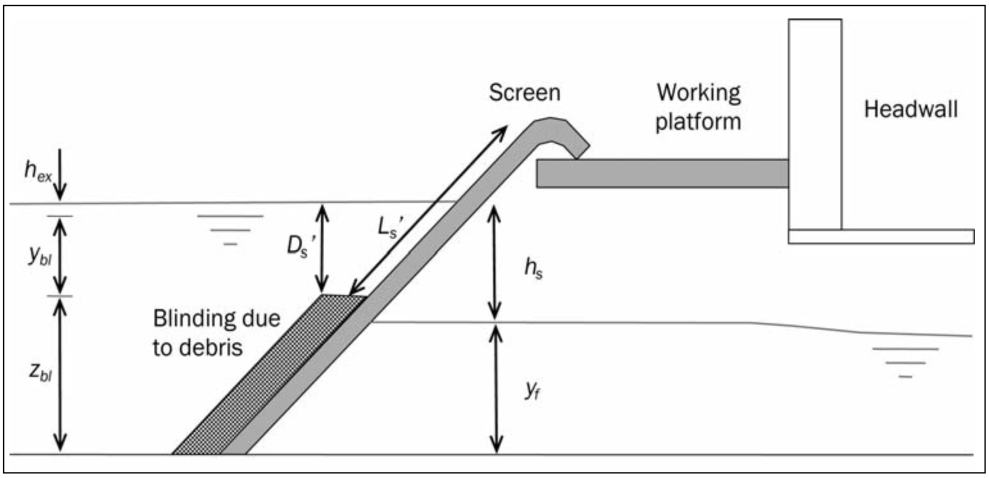


Figure 6.26 ***Definitions for afflux due to blinding***

The depth of weir flow over the blinding y_{bl} is given by the broad-crested weir equation (Equation 6.29).

$$y_{bl} = \left(\frac{Q}{C_w B'} \right)^{2/3} \quad (6.29)$$

where

Q = discharge (m^3/s)

C_w = discharge coefficient for weir flow (typically 1.4 to 1.7) (-)

B' = effective width of weir crest (=width of screen opening/s at top of blinding) (m)

If the depth of flow over the blinding y_{bl} exceeds the total height of screen opening D_s', then orifice flow will occur. The user should go to Section 6.9.9 for orifice flow.

The weir submergence ratio S should be calculated to check the type of weir flow over the blinding (Equation 6.30). If $S < 0.75$, then flow over the blinding is modular (ie passes through critical depth) and Equation 6.29 holds. If $0.75 < S < 0.95$, the weir is submerged, while if $S > 0.95$ the weir is drowned:

$$S = \frac{y_2}{y_1} = \frac{y_i - z_{bl}}{y_{bl}} \quad (6.30)$$

where

y_2 = depth of water above crest level downstream of weir (m) (Figure 6.27)

y_1 = depth of water above crest level upstream of weir (m) (Figure 6.27)

y_i = depth of water immediately upstream of culvert (m)

y_{bl} = depth of water above blinding (m)

z_{bl} = height of blinding above bed (m)

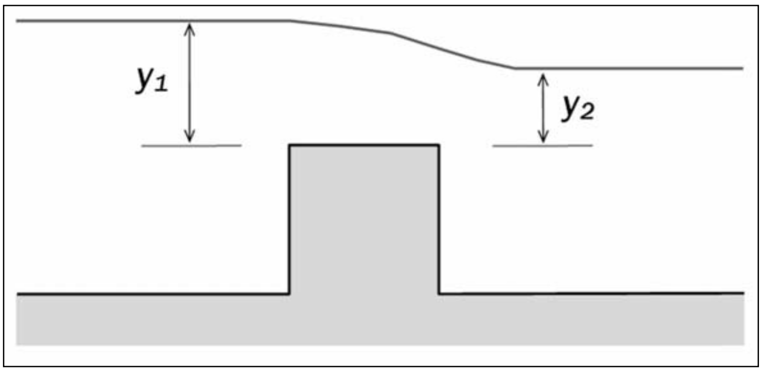


Figure 6.27 *Definitions for weir submergence ratio*

Submerged weir flow

Submerged weir flow (0.75 < S < 0.95) occurs when the downstream water level exceeds the critical depth over the weir. The flow passes through critical and the weir equation still applies, but a submergence correction factor is applied (Equation 6.31).

$$y_{bl} = \left(\frac{Q}{fC_w B'} \right)^{2/3} \tag{6.31}$$

where

f = submergence correction factor (see below) (-)

The submergence correction factor is obtained from Figure A1.8 in Appendix A1, Equations 6.32 and 6.33 (White, 2001) or Equation 6.34 from JBA Consulting (2007).

$$f = 1.045\left(0.76 - S^{4.2}\right)^{0.0645} \quad \text{for } 0.75 \le S < 0.925 \tag{6.32}$$

$$f = 5.7 - 5.245S \quad \text{for } 0.925 < S < 0.985 \tag{6.33}$$

$$f = -25S^2 + 42.9S - 17.422 \quad \text{for } 0.85 < S < 0.985 \tag{6.34}$$

Drowned weir flow

Drowned weir flow (S > 0.95) occurs when the tailwater level exceeds the critical depth and the weir equation ceases to apply. The head loss due to expansion and contraction can be calculated using the method in Section 6.9.8 (friction loss can be ignored for a short structure such as a trash screen).

6.9.8 Calculate head loss due to expansion and contraction

The head loss due to expansion and contraction around screen bars and any permeable debris h_{ex} is given by:

$$h_{ex} = 1.5\left(\frac{V_s^2 - V_{uc}^2}{2g} \right) \tag{6.35}$$

where

V_{uc} = velocity upstream of screen (m/s)

V_s = velocity through screen (m/s)

The velocity in the upstream channel V_{uc}

$$V_{uc} = \frac{Q}{A_{uc}} \tag{6.36}$$

where

A_{uc} = cross-sectional area of upstream channel (m²)

If no better data is available, the cross-sectional area A_{uc} may be estimated by:

$$A_{uc} \approx B y_{uc} \tag{6.37}$$

where

B = total width of screen (m)

y_{uc} = depth of flow in upstream channel (m)

The velocity through the screen V_s is

$$V_s = \frac{Q}{A_s} \tag{6.38}$$

where

A_s = cross-sectional area of flow through screen (m²)

In calculating A_s, the effective area of the screen opening should be selected to suit the direction of flow through the screen.

- the vertical area of the screen opening should be used if flow is parallel to the bed. This is likely to occur for clean screens, vertical screens, inclined screens with partial blockage and inclined screens with drowned flow over the blinding
- the inclined (and horizontal) areas of the screen opening may be used if flow is perpendicular to the bars. This flow condition is most likely to occur for inclined screens with modular or submerged weir flow (over blinding or a sudden drop), or orifice flow.

6.9.9 Calculate afflux for orifice flow through submerged screen

Orifice flow occurs when a submerged flow at the screen is combined with free flow through the culvert and is most likely to occur if the cross-sectional area of the screen opening is less than that of the culvert inlet (Figure 6.28). In this instance, the headwater level upstream of the screen is independent of the water level downstream of the screen. The afflux due to the screen h_s is

$$h_s = \left[z_{or} + \frac{1}{2g} \left(\frac{Q}{C_d A_{or}} \right)^2 \right] - y_f \tag{6.39}$$

where

z_{or} = height of centroid of orifice above bed (m) (see Figure 6.28)

Q = discharge (m³/s)

C_d = discharge coefficient for orifice flow (typically 0.63 but depends on the orifice geometry) (-)

A_{or} = cross-sectional area of orifice (m²)

y_f = depth of water immediately downstream of the screen (m)

The cross-sectional area of the orifice A_{or} is the minimum of screen opening area A_s and the culvert inlet area A_b (Equation 6.40):

$$A_{or} = \min\left(A_s, A_b\right) \tag{6.40}$$

where

A_s = cross-sectional area of screen opening (minus any blockage or blinding) (m²)

A_b = cross-sectional area of culvert inlet (m²)

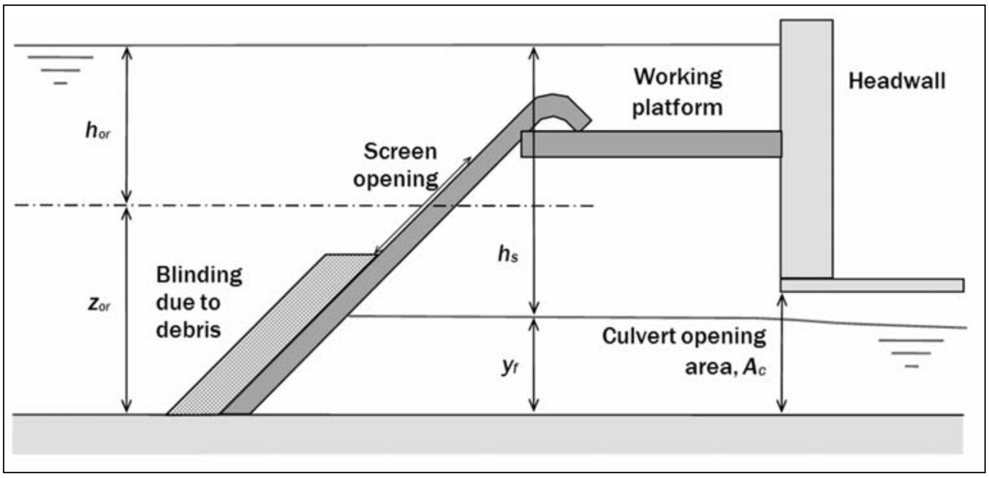


Figure 6.28 *Definitions for orifice flow through submerged screen*

6.9.10 Calculate headwater elevation for inlet control

The headwater elevation for inlet control H_{hic} is

$$H_{hic} = Z_i + E_{sh} + h_s \tag{6.41}$$

where

Z_i = elevation of bed at culvert inlet (m)

E_{sh} = specific energy of headwater (m)

h_s = head loss due to screen (m)

The water level of the headwater for inlet control WL_{hic} is:

$$WL_{hic} = H_{hic} - \frac{V_{uc}^2}{2g} \tag{6.42}$$

where

V_{uc} = velocity in upstream channel (m)

6.10 Calculation of headwater elevation for outlet control

6.10.1 Method

The calculation of headwater elevation for outlet control flow (flow types 3, 4 and 5) is based on energy balance between the headwater and tailwater. The method is summarised in Figure 6.30, with equations and methods in this section and worked examples in Appendix A2.

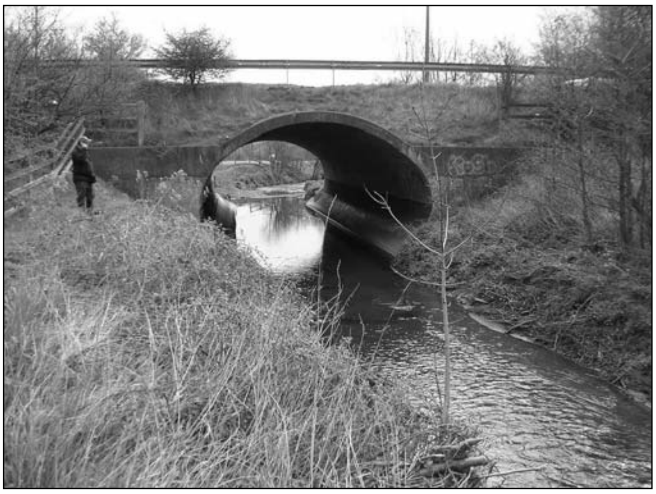


Figure 6.29 *Culvert under outlet control conditions (courtesy JBA Consulting)*

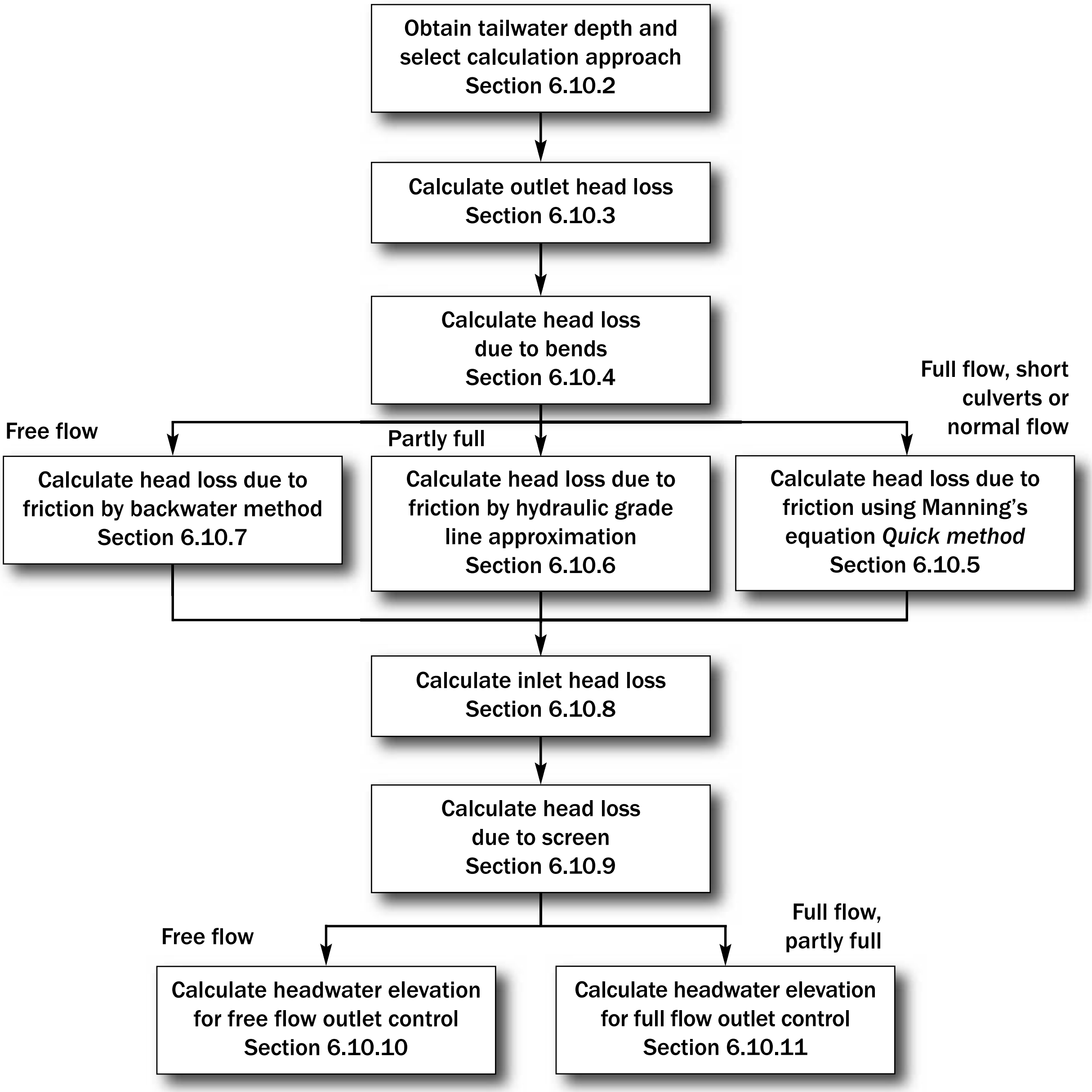


Figure 6.30 *Method for assessing flow under outlet control*

6.10.2 Obtain tailwater elevation and select calculation approach

The headwater elevation for outlet control is dependent on the tailwater elevation and the first step in the assessment of outlet control is to obtain the tailwater elevation H_t and tailwater depth y_o from Section 6.6.

The method for calculating head loss due to friction depends on the length of the culvert, the type of flow and whether free or full flow conditions occur in the culvert barrel. The tailwater depth y_o should be compared with the culvert height D in order to determine whether the outlet is unsubmerged or submerged.

If $y_o > D$, the culvert outlet is submerged (flow type 5) – use Section 6.10.5

If $y_o < D$, the culvert outlet is unsubmerged (flow type 3 or 4) – use Sections 6.10.5, 6.10.6 or 6.10.7

6.10.3 Calculate outlet head loss

Outlet head loss arises from a sudden enlargement in cross-sectional area (Figure 6.31), leading to a reduction in velocity and velocity head, and the dissipation of kinetic energy through turbulence. The outlet head loss is given by Equation 6.43, where outlet loss coefficient k_o is determined by the type of transition and varies from 0.2 for an efficient warped transition to 1.0 for an abrupt transition (see Table A1.5 in Appendix A1). If velocity is low, the value of the coefficient is less important. A useful shortcut is to assume k_o = 1.0 and that water levels upstream and downstream of the culvert outlet are the same (Figure 6.31). Outlet head loss h_o is:

$$h_o = k_o \left[\frac{V_b^2 - V_{dc}^2}{2g} \right] \quad (6.43)$$

where

k_o	=	outlet loss coefficient (typically 0.2 to1.0) (-)
V_b	=	mean velocity in culvert barrel at the outlet (m/s) (Equation 6.44)
V_{dc}	=	mean velocity in downstream channel (m/s) (Equation 6. 45)

Velocity is given by:

$$V_b = \frac{Q}{A_b} \quad (6.44)$$

$$V_{dc} = \frac{Q}{A_{dc}} \quad (6.45)$$

where

Q	=	design discharge (m^3/s)
A_b	=	cross-sectional area of flow in culvert barrel at the outlet (m^2)
A_{dc}	=	cross-sectional area of flow in downstream channel (m^2)

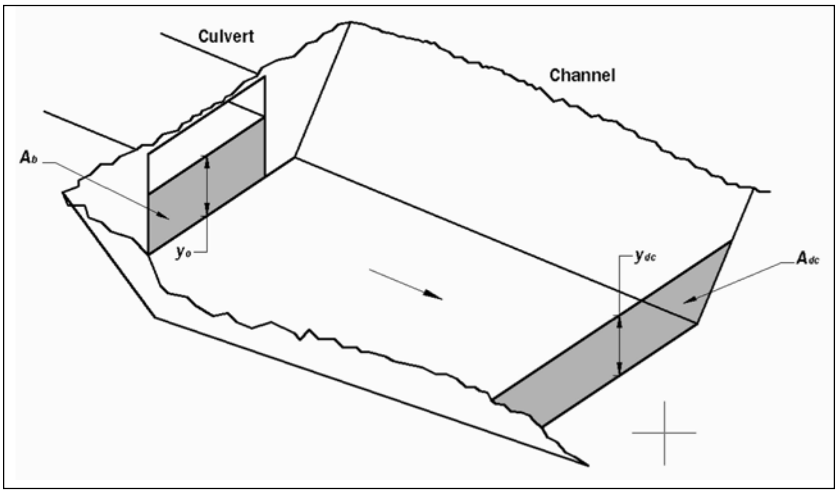


Figure 6.31 *Definitions for outlet head loss calculation*

6.10.4 Calculate head loss due to bends

The head loss due to bends should be calculated for significant bends, ie with an angle exceeding 22.5° or radius to culvert width ratio of less than eight. The head loss due to bends h_{bn} is given by:

$$h_{bn} = k_{bn} \frac{V_b^2}{2g} \tag{6.46}$$

where

k_{bn} = bend loss coefficient (-) (from Figure A1.9 in Appendix A1)

V_b = velocity in culvert barrel (m/s)

For two or more bends in series, the sum of the head losses is the sum of the head loss for each bend.

Vertical bends within inverted siphons or sag culverts may be treated in the same manner. Inverted siphons are designed to carry water beneath obstructions that do not allow the use of a conventional culvert. They are often used beneath canals, although the term "inverted siphon" is a misnomer, because these culverts do not act as true siphons. Inverted siphons operate under full flow outlet control conditions and permit the conveyance of water with minimum headwater and energy loss, but are prone to sedimentation and are not recommended for watercourses with high sediment loads. They also pose safety risks and are susceptible to blockage.

6.10.5 Head loss due to friction by Manning's equation

Manning's equation should be used to calculate the head loss due to friction h_f for culverts with full flow (flow type 5). This method may also be used for short culverts with negligible friction loss, culverts with normal flow conditions (ie where the bed slope and water depth are uniform) and as a quick estimate for culverts with free flow. The method is likely to be most accurate when the culvert invert slope is similar to that in the watercourse. The friction loss h_f is:

$$h_f = L \left(\frac{nQ}{AR^{2/3}} \right)^2 \tag{6.47}$$

where

L = length of culvert barrel (m)

n = Manning's roughness coefficient (-) (see note below)

Q = discharge (m^3/s)

A = cross-sectional area of flow (m^2)

R = hydraulic radius of culvert (m) (= A/P, Equation 6.8)

If the bed, walls and roof of the culvert have similar roughness, then a single Manning roughness coefficient is applied. However if the bed, walls and roof have different roughness values, for example, due to sedimentation, then a compound roughness is applied (see Section 6.8).

6.10.6 Head loss due to friction by hydraulic grade line approximation

If the culvert barrel flows full over part of its length (as shown in Figure 6.32), the head loss due to friction can be obtained by an approximation of the hydraulic grade line y_{hgl}, avoiding a time-consuming backwater calculation. This method is based on research, which has shown that a downstream extension of the full flow hydraulic grade line typically crosses the culvert outlet halfway between the critical depth and the barrel soffit (Federal Highway Administration, 2001 revised 2005).

If the tailwater depth exceeds $(y_c + D)/2$ but is less than the barrel height ($y_o < D$), then the tailwater depth may be taken as y_{hgl} (Equation 6.48) and the headwater elevation calculated by adding the friction loss from Manning's equation (Equation 6.47) (and the inlet losses and velocity head). The method is less accurate for free flow and should not be used for headwater $H_h < 0.75D$.

$$y_{hgl} = \frac{(y_c + D)}{2} \quad (6.48)$$

where

y_c = critical flow depth (m)

D = height of culvert barrel (m)

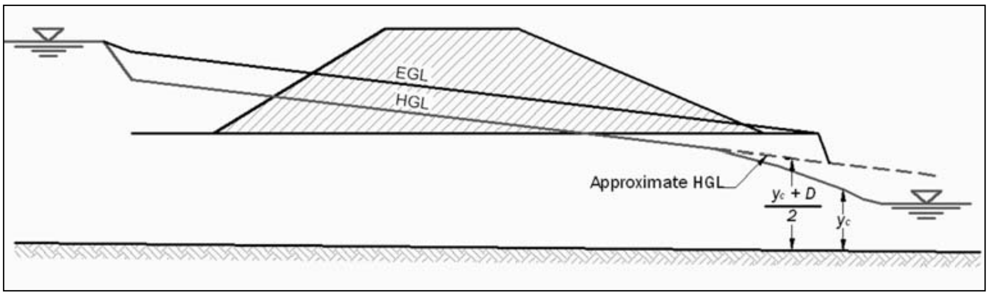


Figure 6.32 *Approximation of hydraulic grade line for partly full flow*

Critical depth y_c is obtained from Figures A1.4 to A1.7 in Appendix A1 or Equation 6.24, y_c being the depth where:

$$\frac{Q^2 W}{g A_c^3} = 1 \quad (6.24)$$

where

Q = discharge (m^3/s)

W = width of the water surface at culvert inlet (m)

A_c = cross-sectional area of flow at critical depth (m^2)

For circular culverts, this equation breaks down as y_c approaches culvert height D and there is little or no error in treating the culvert as full at the outlet for y_c/D greater than 0.9.

6.10.7 Head loss due to friction by backwater method

The backwater method should be used to calculate head loss due to friction for culverts with free flow conditions (flow types 3 and 4), with gradually-varying flow (ie non-uniform flow) and long culverts where friction loss is significant. The backwater calculation derives a water surface profile starting at the culvert outlet and working upstream to the inlet (Figure 6.33), taking into account any change in water depth (and also wetted perimeter) along the length of the culvert.

The standard step method solves the gradually varied flow equation by calculating the change in total head for a given change in distance along the culvert (or channel) (Equation 6.49):

$$S_f = \frac{dH}{dx} = \frac{d}{dx}\left(Z + y + \frac{V^2}{2g}\right) \tag{6.49}$$

This can be re-written as:

$$\Delta H = S_f \Delta x \tag{6.50}$$

where

ΔH	=	change in total head (m)
S_f	=	friction slope (m/m)
Δx	=	distance from previous point (m) (positive if travelling from downstream to upstream, although the standard convention in hydraulics texts is to use negative for travel in the upstream direction and positive for travel in the downstream direction).

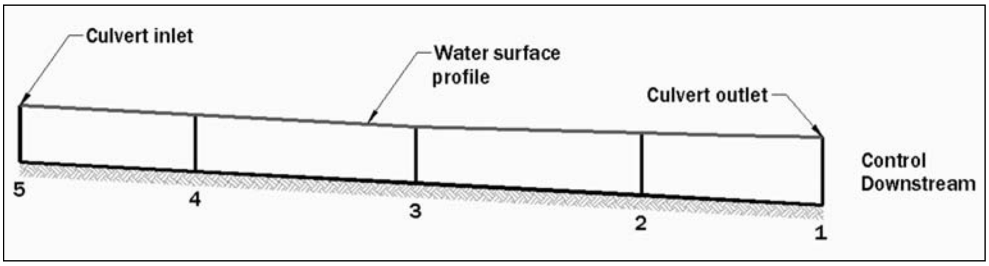


Figure 6.33 *Calculation of head loss due to friction for free flow conditions*

The backwater calculation can be carried out either by hand using Table A1.7 in Appendix A1 or using computational methods described in Section 6.14. The first column corresponds to the start point, where start bed elevation and water depth are Z_s and y_s respectively, and the data for Rows 1 to 15 are known or can be calculated. The standard step method involves four steps (Steps 1 to 4) as follows. A worked example is given in Appendix A2.6:

Step 1 Determine bed elevation

Select a point a known distance from the start point and calculate the bed elevation z for that point. The accuracy of the calculation increases as step length decreases – step length should be determined by engineering judgment:

$$Z = Z_s + S_0.\Delta x \quad (6.51)$$

where

Z	=	elevation of bed (m)
Z_s	=	elevation of bed at start point (m)
S_0	=	bed slope (m/m)
Δx	=	distance from start point to new point (x=0 at start point) (m)

Step 2 Estimate trial water depth and channel properties

Estimate a trial water depth y for the new point and calculate the channel properties that will be needed shortly: area A, wetted perimeter P, hydraulic radius R and conveyance K (Equations 6.8 and 6.6).

$$R = \frac{A}{P} \quad (6.8)$$

$$K = \frac{1}{n} A R^{2/3} \quad (6.7)$$

where

R	=	hydraulic radius (m)
A	=	cross-sectional area of flow (m^2)
P	=	wetted perimeter (m)
K	=	conveyance (m^3/s)
n	=	Manning's roughness coefficient

If the wetted perimeter has different roughness values due to sedimentation or different materials, then a compound roughness coefficient n' should be calculated. Advice on roughness coefficient and compound roughness coefficient is given in Section 6.8.

Step 3 Calculate total head for the new point

Calculate the total head H for the new point using the Bernoulli equation (Equation 6.1):

$$H_1 = Z + y + \frac{V^2}{2g} \quad (6.1)$$

where

Z	=	elevation of bed (m)
y	=	water depth (= pressure head) (m)
V	=	velocity = Q/A (m/s)

Step 4 Estimate head loss due to friction

Calculate the friction slope S_f for the new point (Equation 6.52), the mean friction slope between the new and previous points S_{fmean} (Equation 6.53), and the head loss due to friction between the two points h_f (Equation 6.54):

$$S_f = \left(\frac{Q}{K}\right)^2 \quad (6.52)$$

where

Q	=	design discharge (m^3/s)
K	=	conveyance (m^3/s)

$$S_{fmean} = \frac{\left(S_f + S_{fprev}\right)}{2} \tag{6.53}$$

where

S_{fmean} = mean friction slope (m/m)

S_f = friction slope for current location (m/m)

S_{fprev} = friction slope calculated for previous location (m/m)

$$h_f = \left(S_{fmean}\right)\Delta x \tag{6.54}$$

where

h_f = head loss due to friction (m)

Δx = distance from start point to new point (x=0 at start point) (m)

The total head at the new point is the sum of the total head at the previous point and the head loss due to friction and bends between the two points (from Step 3):

$$H = H_{prev} + h_f + h_{bn} \tag{6.55}$$

where

H_{prev} = previous energy head (m)

h_{bn} = head loss due to bends (m) (if applicable)

If the trial water depth was guessed correctly, the total head at the new point from Equation 6.1 should be the same as the total head required to overcome friction and bend losses from Equation 6.55. If not, the trial water depth should be adjusted and the process repeated until the two are the same. The calculation is then repeated for successive steps to the finish point. At the finish point, the total head loss is the sum of the head losses at each step and the water depth y is that from the successful iteration.

6.10.8 Calculate inlet head loss

The inlet head loss at a sudden contraction in cross-section arises from the convergence of streamlines and is given by Equation 6.56. The inlet loss coefficient k_i is typically 0.5 for a simple flush inlet, although the value depends on the type of inlet and may be obtained from Tables A1.3, A1.4 and A1.5. If flow velocities are low, the inlet loss coefficient becomes less important, for example, the difference in inlet loss for k_i = 0.1 and k_i = 0.5 is only 20 mm for a velocity of 1 m/s.

$$h_i = k_i \frac{V_b^2}{2g} \tag{6.56}$$

where

h_i = head loss at inlet (m)

k_i = inlet loss coefficient (typically 0.5) (-)

V_b = mean velocity in culvert barrel (m/s)

6.10.9 Calculate head loss due to screen

Screen head loss is calculated using the method described in Sections 6.9.6 to 6.9.9.

6.10.10 Calculate headwater elevation for free flow outlet control

If Sections 6.10.2 to 6.10.9 show that water depth remains below soffit level throughout the length of the culvert barrel, then the headwater elevation for free flow outlet control (flow types 3 and 4) H_{hoc} is given by Equation 6.57 and summarised in Figure 6.34. If full flow occurs at any point, then Equations 6.58 and 6.59 should be used. If velocity head is significant, the velocity head should be deducted to give the water level of the headwater.

$$H_{hoc} = Z_i + y_i + h_i + h_s \qquad (6.57)$$

where

Z_i = elevation of bed at culvert inlet (m)

y_i = depth of water immediately downstream of culvert inlet (m)

h_i = inlet head loss (m)

h_s = head loss due to screen (m)

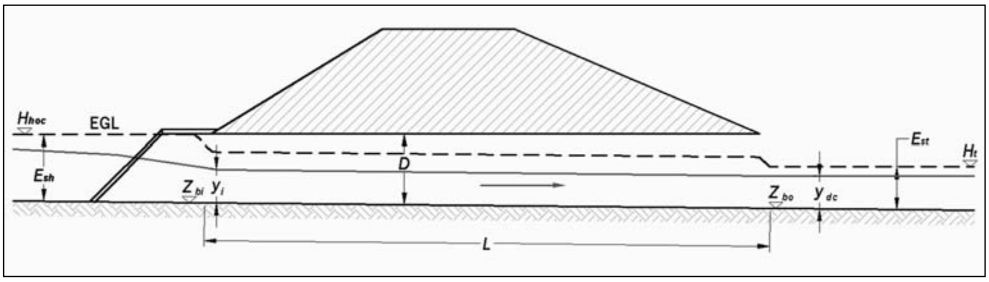


Figure 6.34 *Headwater elevation for free flow outlet control*

6.10.11 Calculate headwater elevation for full flow outlet control

The headwater elevation for full flow outlet control (flow type 5) H_{hoc} is given by Equations 6.58 and 6.59 and is summarised in Figure 6.35. The water level of the headwater is obtained by deducting the velocity head (if this is significant).

$$H_{hoc} = H_t + h_T \qquad (6.58)$$

$$h_T = h_o + h_f + h_{bn} + h_i + h_s \qquad (6.59)$$

where

H_t = total head of tailwater at culvert outlet (m)

h_T = total head loss (m)

h_o = outlet head loss (m)

h_f = friction loss (m)

h_{bn} = head loss due to bends (m)

h_i = inlet head loss (m)

h_s = head loss due to screen (m)

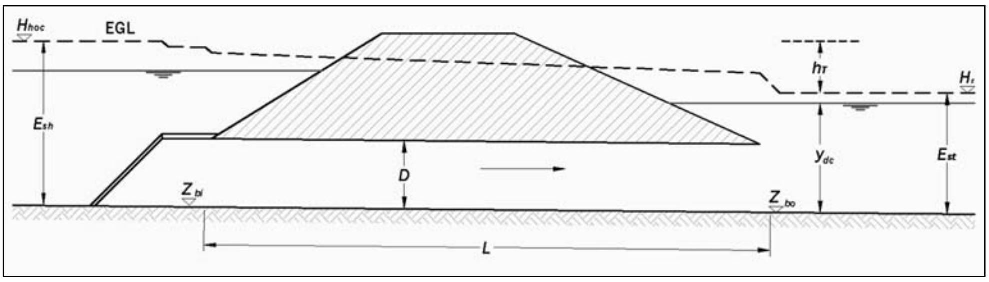


Figure 6.35 *Headwater elevation for full flow outlet control*

6.11 Calculation of headwater level for overtopping flow

The method for calculating headwater level for overtopping flow (flow types 6, 7 and 8) is summarised in Figure 6.37. The equations and methods are given in Sections 6.11.1 to 6.11.8 with worked examples in Appendix A2.

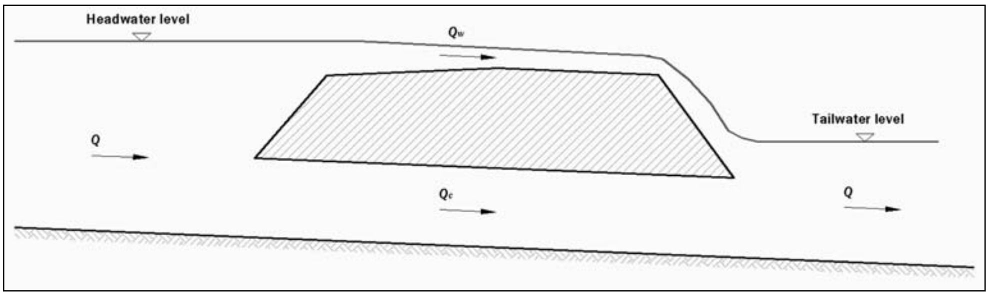


Figure 6.36 *Overtopping flow at a culvert*

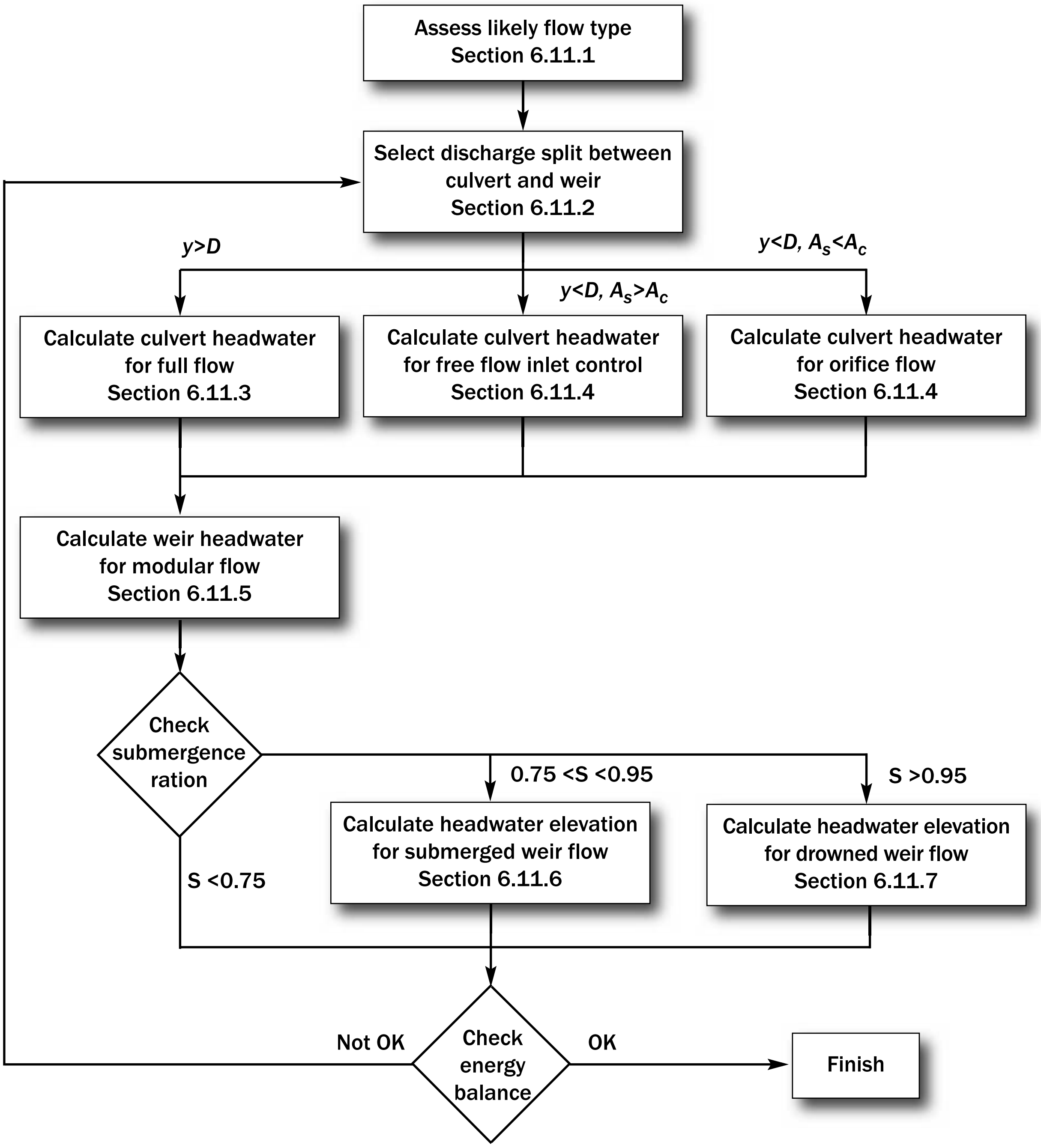


Figure 6.37 *Method for assessing overtopping flow*

6.11.1 Assess likely flow type

Overtopping flow comprises two components: weir flow and culvert flow. The weir flow may be modular, submerged or drowned (Figure 6.10), depending on the submergence ratio, that is the ratio between the downstream depth above the embankment crest level and the upstream depth above the embankment crest level (see Figure 6.27). The culvert flow may be full or free through the barrel. Free flow can only occur with modular weir flow where the tailwater level is below the soffit level of the outlet.

An initial assessment of the likely flow type should be carried out for the design discharge/s. The tailwater level H_t and tailwater depth y_{dc} should be calculated if this has not already been done (after Section 6.6). These will indicate whether the weir flow is likely to be modular and whether culvert flow is likely to be free or full. The headwater elevation required to drive the discharge through the culvert, H_{hc} should be estimated assuming full discharge through the culvert ($Q_c = Q$) and no discharge over the embankment crest ($Q_w = 0$), using either the submerged inlet control equation (Equation 6.62) or orifice equation (Equation 6.63). The following Tests 1 to 4 allow the method for assessing overtopping flow to be determined, although this may change as the calculation proceeds. The methods are summarised in Table 6.3.

Test 1 Assess whether overtopping flow occurs

If $H_{hc} < Z_w$, then no overtopping analysis is required.

If $H_{hc} > Z_w$, then overtopping flow occurs, proceed to Test 2.

Test 2 Assess whether weir flow is modular, submerged or drowned

If $WL_t < Z$, then weir flow is modular, proceed to Test 3.

If $WL_t > Z$, then weir flow may be modular, submerged or drowned. Culvert flow is full.

Test 3 For modular weir flow, assess whether full or free culvert flow occurs

If $y_o > D$, then use Section 6.11.3 for full culvert flow.

If $y_o < D$, then free flow occurs, proceed to Test 4.

Test 4 For free culvert flow, assess whether hydraulic control is provided by the screen or culvert inlet

If $A_s > A_b$, then use Section 6.11.4 for free culvert flow with submerged inlet control.

If $A_s < A_b$, then use Section 6.11.4 for free culvert flow with orifice control by screen.

Table 6.3 *Method for assessing overtopping flow*

	Modular weir flow **$S < 0.75$**	**Submerged weir flow** **$0.75 < S < 0.95$**	**Drowned weir flow** **$S > 0.95$**
Full flow ($y > D$)	Weir equation + outlet control head loss	Submerged weir equation + outlet control head loss	Energy approach
Free flow inlet control ($y_o < D$ and $A_s > A_c$)	Weir equation + inlet control equation		
Free flow screen control ($y_o < D$ and $A_s < A_c$)	Weir equation + orifice equation		

6.11.2 Select initial discharge split

The calculation of headwater level involves splitting the discharge Q between the culvert and embankment such that the headwater level H_{hc} required to drive the culvert discharge Q_c through the culvert is the same as the headwater level H_{hc} required to drive the weir flow Q_w over the embankment. The process is iterative and calculations should be repeated for different discharge splits until the energy balance is satisfied, at which point the discharge split is assumed to be correct. Using computer software is recommended because this may be time consuming.

The total discharge is divided between the culvert and weir:

$$Q = Q_c + Q_w \tag{6.60}$$

where

Q_c	=	discharge through culvert (m^3/s)
Q_w	=	discharge over embankment crest (m^3/s)

6.11.3 Estimate culvert headwater for full culvert flow

Full flow conditions are likely if the tailwater depth exceeds the barrel height (y>D) or the tailwater level exceeds the soffit level at the culvert inlet. This type of flow is outlet controlled and the headwater elevation for culvert flow is the sum of the tailwater elevation and head losses due to outlet, bends, friction, inlet and screen (Equation 6.61).

$$H_{hc} = H_t + \left[k_o \left(\frac{V_b^2 - V_{dc}^2}{2g} \right) + k_{bn} \frac{V_b^2}{2g} + L \left(\frac{nQ_c}{AR^{2/3}} \right)^2 + k_i \frac{V_b^2}{2g} + h_s \right] \quad (6.61)$$

where

H_t	=	total head of tailwater (m)
k_o	=	outlet loss coefficient (-)
V_{dc}	=	velocity of flow in downstream channel (m/s)
V_b	=	velocity of flow in culvert barrel (m/s)
k_{bn}	=	bend coefficient (-)
L	=	length of culvert barrel (m)
n	=	Manning's roughness coefficient (-)
Q_c	=	culvert discharge (m^3/s)
A	=	cross-sectional area of culvert barrel (m^2)
R	=	hydraulic radius of culvert barrel (m) (Equation 6.8)
k_i	=	inlet loss coefficient (-)
h_s	=	head loss due to screen (m)

6.11.4 Estimate culvert headwater for free culvert flow

Free flow through the culvert combined with overtopping of the embankment is less likely than full flow because the conditions that cause overtopping may coincide with high water levels throughout the watercourse, with submergence occurring at both the culvert inlet and outlet. However, free flow through the culvert is possible in the particular case of partial blockage of a screen at the inlet, provided that the culvert outlet is not submerged ($y < D$).

The hydraulic control point should be identified by comparing the cross-sectional area of the screen opening A_s with that of the culvert inlet A_b. The cross-sectional area of the orifice A_{or} is then the minimum (Equation 6.40).

$$A_{or} = \min\left(A_s, A_b\right) \quad (6.40)$$

where

A_s	=	cross-sectional area of screen opening (m^2)
A_b	=	cross-sectional area of culvert inlet (m^2)

If the culvert inlet is smaller ($A_b < A_s$), the headwater elevation is given by the submerged inlet control equation (Equation 6.62)

$$H_{hc} = Z_{bi} + \left(c \left[\frac{1.811 Q_c}{A_b D^{0.5}} \right]^2 + Y - 0.5 S_0 \right) D \quad (6.62)$$

where

Z_{bi}	=	elevation of bed at culvert inlet (m)
c, Y	=	constants used in submerged inlet control equations (Tables A1.3 and A1.4 in Appendix A1)
Q_c	=	culvert discharge (m^3/s)
A_b	=	cross-sectional area of culvert barrel (m^2)
D	=	barrel height (m)
S_0	=	bed slope (m/m)

If the screen opening is smaller ($A_b > A_s$), headwater elevation is given by the orifice equation (Equation 6.63). This equation may also be used for submerged inlet control by the culvert, although the results can be more conservative than the submerged inlet control equation, which is based on empirical data.

$$H_{hc} = Z_{or} + \frac{1}{2g}\left(\frac{Q_c}{C_d A_{or}}\right)^2 \qquad (6.63)$$

where

Z_{or}	=	elevation of centroid of orifice above datum (m)
Q_c	=	culvert discharge (m^3/s)
C_d	=	discharge coefficient for orifice flow (typically 0.63 but depends on the orifice geometry) (-)
A_{or}	=	cross-sectional area of orifice (ie screen opening area or the culvert inlet) (m^2)

6.11.5 Estimate weir headwater for modular flow

For modular weir flow (flow type 6) ($S < 0.75$), the headwater level for weir flow over the embankment crest H_{hw} is:

$$H_{hw} = Z_w + \left(\frac{Q_w}{C_w B}\right)^{2/3} \qquad (6.64)$$

where

Z_w	=	elevation of embankment crest (m)
C_w	=	weir discharge coefficient (-) (typically 1.44 to 1.7, lower values for less efficient weirs)
B	=	width of embankment crest (perpendicular to flow direction) (m)

The weir discharge coefficient C_w varies with weir geometry and upstream head. Further advice is given in BS3680:1990.

6.11.6 Estimate weir headwater for submerged weir flow

For submerged weir flow (flow type 7) ($0.75 < S < 0.95$), the downstream depth exceeds the critical depth over the weir and discharge for a given head is reduced by applying a submergence correction factor (see Section 6.9.7).

$$H_{hw} = Z_w + \left(\frac{Q_w}{f C_w B}\right)^{2/3} \qquad (6.65)$$

where

f	=	submergence correction factor (applied for $0.75 < S < 0.95$, see Section 6.9.7)

6.11.7 Estimate weir headwater for drowned weir flow

For drowned weir flow (flow type 8) ($S > 0.95$), the weir equation ceases to apply and the flow reverts to open channel flow, with full flow throughout the culvert. The energy approach is applied to flow across the culvert embankment with head losses due to friction, expansion and contraction. The wetted perimeter increases to include both the culvert and the embankment, and the flow area includes the culvert and overtopping flow area.

6.11.8 Check energy balance

The headwater elevations for culvert flow H_{hc} and weir flow H_{hw} are then compared to determine whether the culvert:weir flow split is correct.

If $H_{hc} \approx H_{hw}$, then the energy grade line is balanced and the flow split is correct
If $H_{hc} < H_{hw}$, then increase culvert discharge Q_c and decrease weir discharge Q_w
If $H_{hc} > H_{hw}$, then decrease culvert discharge Q_c and increase weir discharge Q_w

If the velocity head of the upstream flow is significant, this should be deducted from the headwater elevation to give the water level of the headwater WL_h.

6.12 Calibration, verification and sensitivity testing

6.12.1 Calibration and verification

Calibration involves adjusting hydraulic parameters such as roughness or weir coefficient to achieve the best fit between calculated and observed water levels for a known discharge, ideally for at least one event with in-channel flow, and at least one event with out-of-bank (or floodplain) flow. Verification is then carried out for further events (if available) to confirm the validity of the results over a wider range of discharge than used for calibration. This process gives the user confidence in the results, although the data required for calibration and verification is often only available for the larger, gauged watercourses. The type of data that is useful includes:

- recorded discharge and levels from gauging stations
- recorded discharge from current meters
- recorded rainfall that may be used to calculate discharge
- observed levels from witnesses, or trash marks or tide marks on buildings.

For smaller watercourses, discharge and level data are unlikely to be available and the results of hydraulic analyses may be verified by carrying out simple reality checks, for example:

- is the flow type consistent with the culvert geometry and tailwater conditions (typically inlet control for steep bed slopes and outlet control for mild bed slopes)?
- is the free flow or submerged capacity consistent with the capacity of the open channel upstream and downstream?
- does the frequency of roadway overtopping agree with historical observations?
- does the head loss agree with that obtained by simple checks?

An estimate of the head loss through a culvert h_T, or the difference between headwater and tailwater elevations, is given by Equation 6.66. This applies to a typical culvert, say 10 m to 30 m long, with typical inlet and outlet configurations and no screen. If the culvert or watercourse model suggests something very different, it is worth carrying out more detailed checks.

$$h_T = 1.5\frac{V_b^2}{2g} \approx 0.08V_b^2 \quad (6.66)$$

where

V_b = velocity of flow in the culvert barrel (m/s)

6.12.2 Sensitivity testing

Sensitivity testing is carried out to examine the effect of variables on calculated water levels, particularly where there is uncertainty in the chosen values. A summary of suggested sensitivity tests is given in Table 6.4 and discussed in greater detail in the following paragraphs:

Sensitivity to hydraulic parameters

As a minimum, sensitivity testing for design discharge, channel roughness and culvert barrel roughness should be undertaken, with extra sensitivity testing to downstream boundary conditions, culvert head loss coefficients and weir discharge coefficient as appropriate. The range of values chosen for each parameter depends on the degree of uncertainty and is a matter of judgement for an experienced engineer or modeller, although suggested values are given in Table 6.4. Roughness should include the viable range of values for Manning's roughness coefficients, taking into account summer and winter vegetation and any other uncertainties. Further guidance on sensitivity testing is given by the Environment Agency (2000b).

Sensitivity to blockage

Blockage of the culvert inlet, culvert barrel or screen due to sedimentation or debris can have a substantial effect on headwater elevation, primarily due to the loss of cross-section, although sedimentation has a dual effect due to increased roughness of the bed. The designer should carry out sensitivity testing to examine the consequences of blockage and make appropriate decisions on the frequency of inspection and maintenance, the need for a trash screen, or the need to assess overland flow routes.

Table 6.4 *Summary of sensitivity tests*

Type of test	Description	Method of testing
Hydraulic parameters	Design discharge	Peak discharge ± 20%
	Channel and barrel roughness	Manning's *n* – viable range taking into account factors such as sedimentation, vegetation and barrel deterioration
	Boundary conditions	Water depth ± 20%
	Inlet and outlet head loss	Head loss coefficient ± 20%
	Weir rating	Discharge coefficient ± 20%
Blockage	Sedimentation of culvert barrel	Proportional sediment depth 5%, 15–25%, 80–100%
	Blinding or blockage of trash screen (if present) or blockage of culvert inlet	30% to 67% depending on catchment, 100%
Bulking	Bulking due to air entrainment	Peak discharge × bulking factor
	Bulking due to debris and sediment load	Peak discharge × bulking factor
Future changes	Land-use change	Forecast urban extent
	Rainfall intensity due to climate change	Peak discharge + 20% (covered by earlier test for design discharge)
	Sea level rise due to climate change	Sea level + sea level rise allowance

Sensitivity tests should be devised to suit the nature of the culvert and catchment and the most probable events. Small culverts and culverts with tidal or flapped outfalls are particularly susceptible to sedimentation. Research in Australia indicates that culverts with an opening (span or diagonal) of 6 m or less are prone to debris blockage, while larger culverts are unlikely to block. Screens are prone to blinding or blockage. Further advice on screens is given in Section 6.9.6.

Sedimentation of the culvert barrel should be tested for proportional sediment depths (ratio of sediment depth to height) of five per cent, 15 to 25 per cent (after Figure 9.14) and 80 to 100 per cent. The five per cent sediment depth assesses the effect of sedimentation on flow capacity due to increased bed roughness and nominal loss of section after Ackers *et al* (1996). The 15 to 25 per cent sediment depth simulates the partly blocked condition that may occur before maintenance if a culvert is not self-cleansing. Sedimentation is simulated by a reduction in cross-sectional area along the culvert length and an increase in bed roughness to allow for the texture of the sediment.

Sensitivity to trash screen blinding should be carried out for blinding of 30 to 67 per cent in accordance with Environment Agency (2009a). Blinding should be applied across the full width of the screen from the invert upwards if possible. In the absence of a trash screen, sensitivity to blockage of the culvert inlet should be carried out if this is considered to be realistic.

The 100 per cent sedimentation (or screen blockage) is rare, but should be tested to assess the consequences of extreme events and assist with the prioritisation of maintenance.

Sensitivity to bulking

Bulking due to air entrainment may occur for supercritical flow in steep culverts or watercourses (Froude number *Fr* greater than 1.6) particularly for barrel-full flows. Current guidance recommends applying a bulking factor, f_a, to the flow depth using the following formulae, which are based on research in the 1940s and 1960s (Haestad Methods *et al*, 2003 and after USACE, 1994):

$$f_a = 0.906e^{0.061Fr} \quad \text{for Fr} \leq 8.2 \tag{6.67}$$

$$f_a = 0.62e^{0.1051Fr} \quad \text{for FR} > 8.2 \tag{6.68}$$

where

f_a	=	bulking factor for air entrainment (-)
e	=	2.718 = base of natural logarithm
Fr	=	Froude number (see Equation 6.3)

Bulking due to debris and sediment is an increase in flow volume due to floating trash and suspended sediment and may affect steep, flashy or heavily-wooded catchments, although this is more of a consideration outside the UK. The bulking factor is the ratio between the peak debris-laden flow and the corresponding peak clear water flow.

Sensitivity to future changes

Future changes during the design life of a culvert may relate to climate change impacts such as sea level rise or rainfall intensity, land-use change and land management change. The effect of these changes on hydrology should be assessed so that asset managers may take a precautionary approach by providing extra design capacity or a managed adaptive approach with designs that can be updated in the future. Further guidance is given in Section 5.6. Current recommended practice is to forecast the urban extent, increase the design discharge by 20 per cent for larger catchments and increase design sea level by a sea level rise allowance (Defra, 2006).

6.13 Assessment of hydraulic performance

A culvert should ideally meet all of its hydraulic performance requirements, although in reality, a compromise may be necessary. The most common performance requirements are discussed in Section 6.13.

6.13.1 Discharge capacity

The first performance requirement of any culvert is that the discharge capacity of a culvert equals or exceeds the design discharge. Two discharge capacities are considered: the free flow discharge capacity is the discharge at which headwater level equals soffit level minus a freeboard allowance for uncertainty, and the maximum discharge capacity is the discharge at which headwater level equals maximum permissible headwater level, typically property threshold minus freeboard. Note that the maximum discharge capacity may be less than the free flow capacity.

The discharge capacity should ideally be assessed by generating a performance curve for headwater elevation (Figure 6.13), including extreme floods and sensitivity testing to ensure that the culvert continues to perform under adverse conditions, for example, sedimentation or blockage. The curve may be plotted as discrete points or as a continuous line depending on whether calculation has been carried out by hand or with the assistance of a computer. An example performance curve for headwater level in Figure 6.13 shows the following:

- headwater level under inlet control H_{hic} for free and submerged flow (from Section 6.9)
- headwater level under outlet control H_{hoc} for free and submerged flow (from Section 6.10)
- headwater level for overtopping flow (from Section 6.11)
- soffit level minus freeboard
- maximum permissible headwater level, H_{hmax}
- structure crest level.

The design headwater elevation should be taken as the larger of H_{hic} and H_{hoc} for any given discharge to ensure that the most conservative control mode is selected. The free flow capacity of the culvert is then the discharge for which the headwater elevation equals culvert soffit level minus freeboard. The maximum discharge capacity is the discharge for which headwater level equals the maximum permissible headwater level H_{hmax}. If the performance curve is poorly defined at the point of interest, calculations should be repeated with smaller or larger discharges until a headwater level H_h similar to the design headwater elevation is obtained.

If improvements in discharge capacity are required, the component/s influencing hydraulic control should be improved, for example, culvert alignment (Section 9.2.3), barrel (Section 9.3), inlet (Section 9.4) or outlet (Section 9.5). For culverts under inlet control, the discharge capacity is determined by the inlet characteristics. Simple improvements available to the designer include the provision of a bevelled edge inlet (or the socket end of concrete pipes), side tapered inlet (flared wing walls) and slope tapered inlet (steep slope down to the barrel) (as illustrated in Tables A1.3 and A1.4 in Appendix A1). These three approaches give potential increases in discharge capacity relative to a square edge inlet of five to 20 per cent, 25 to 40 per cent and over 100 per cent respectively, based on the assumption that the culvert is flowing under inlet control. The benefits may be much lower if the culvert switches to outlet control at high discharges. Further advice is given by Federal Highway Administration (1972).

The lowest head loss is provided by the minimum energy loss (MEL) culvert developed in Australia (see Appendix A6). Streamlined inlet and outlet headwalls provide a smooth hydraulic transition and minimise inlet and outlet losses, and the barrel operates under transcritical free flow conditions (critical or near-critical, with Froude number = 0.6 to 0.8) for the design discharge, ensuring maximum discharge per unit width for a given specific energy. MEL culverts can be practicable on watercourses with mild slopes where minimum or zero afflux is required and long culverts, and are successful at passing sediment and debris. More detailed guidance is available from Chanson (2007).

6.13.2 Flood risk

It is also crucial that a culvert should not increase flood risk upstream or downstream. A culvert may be intentionally undersized as part of a flood risk management scheme, creating flood storage upstream of a risk area and reducing discharge and also flood risk downstream. However, a culvert that is inadvertently undersized acts as a throttle and increases headwater elevation upstream, potentially leading to uncontrolled flooding, embankment overtopping and geotechnical failure. An oversized replacement culvert may create a new problem by passing downstream the peak discharge that was formerly attenuated (see Appendix A6).

Flood risk is assessed by identifying flood risk areas both upstream and downstream of the culvert, and comparing design water levels with property or infrastructure threshold levels, with an appropriate safety margin (freeboard). The culvert hydraulic performance is satisfactory if it can convey the design flood without any flood damage to property and infrastructure. In the case of an extreme flood (probability < 0.05 per cent), the hydraulic performance can be considered satisfactory if any consequent flood damage is within expectations for such an unusual event, and there is no risk to life.

6.13.3 Local scour

Local scour at the culvert outlet risks undermining either the culvert or nearby structures and is undesirable. The risk of local scour is assessed by comparing the maximum predicted velocity (or shear stress) with the maximum permissible value for the erosion of bed material. A culvert performance curve may be plotted for other relevant barrel velocity, outlet velocity or shear stress, similar to that for headwater elevation.

Non-cohesive sediments such as gravel and sand (particle size > 0.06 mm) erode when the mobilising actions of lift and drag exceed the resistance due to weight and friction. Armouring may increase the erosion resistance of well-graded sediments by the preferential erosion of small particles to leave a surface layer of larger particles. This beneficial effect should be ignored in the assessment of scour because erosion of the armour layer during a large flood could expose the parent material, leading to rapid development of scour. The size of the parent bed material should be estimated from a sample below any known armour layer (say 0.5 m below bed level). Cohesive sediments such as clay and silt require relatively large mobilising forces due to the resistance provided by cohesion.

The threshold velocities for erosion and sedimentation for a selection of soil types are available in Table A1.8 in Appendix A1, although for more detailed information, the designer is referred to the Hjulstrom curve, which is widely available on the internet. The critical shear stress for the threshold of motion can be determined using the Shields method or obtained from tables in standard texts on sediment transport (such as May *et al*, 2002, and Hemphill and Bramley, 1989). Relationships between critical shear stress and bulk density for cohesive sediments are also available (United States Bureau of Reclamation, 2006).

If local scour at the culvert outlet is predicted, the designer should estimate the maximum depth and extent of scour, and provide scour protection if the scour is likely to have adverse effects on the performance of the culvert. Basic advice is given in Section 9.5.6, with more detailed advice on the estimation of local scour and design of scour protection in May *et al* (2002).

A culvert that has a drop at the outlet will result in a plunging jet of water. This will form a scour pool unless an adequately sized stilling basin is provided to contain the turbulent water. A drop at the outlet from a culvert is an undesirable feature for fish (see Section 6.13.5) and other aquatic life movement, and should be avoided where possible. It normally occurs where the culvert barrel slope is less steep than the channel slope.

6.13.4 Sedimentation

A bed of natural sediment within the culvert barrel is preferable to self-cleansing from an environmental perspective. The degree of sedimentation and cross-sectional area will vary over time, with long-term equilibrium between the rate of sediment entering the culvert and leaving the culvert. A stable sediment regime is likely if the barrel velocity during the median annual flood *QMED* exceeds the maximum permissible velocity for erosion, ensuring that sediment carried into the culvert from upstream can be carried out again. The threshold velocity for erosion for selected sediments is available in Table A1.8 in Appendix A1. Advice on designing for sedimentation is given in Section 9.3.7.

6.13.5 Fish passage

The final performance requirement, depending on the nature of the watercourse, is the provision of suitable conditions for fish passage. Significant parameters include the water depth, height of drops or weirs, flow velocity, the provision of pools or resting places, physical obstructions and debris accumulation (see Section 9.3.8 and Table 9.3). Detailed advice is beyond the scope of this guide, but further guidance is available in Armstrong *et al* (2004) and the Scottish Executive (2000). The relevant agencies should be consulted to ensure that the design requirements are identified.

6.14 Computational methods for hydraulic assessment

6.14.1 Introduction

Computer software for the hydraulic assessment of culverts has been available since the 1980s. This has allowed fast and accurate analysis of a range of scenarios, for example, analysis of a range of flows or tailwater levels, comparison of an existing and replacement culvert, or different barrel shapes and sizes. The principal disadvantages of software are the learning curve for users, although some packages are more intuitive than others, and the risk of “black box” technology being applied incorrectly by staff without sufficient knowledge of hydraulic theory. The quality of results is directly related to the quality of input data, and the principle of “rubbish in/rubbish out” applies as with all computer models. However developments in graphical user interfaces allow users to check input data and that results are reasonable.

6.14.2 Software requirements

The minimum standard for computer software for culvert hydraulic analysis in the UK is set out in Table 6.5. As a minimum, software should be able to evaluate headwater elevations under inlet and outlet control in metric units using the methods described in the Federal Highway Administration (2005) as described earlier in this chapter. Extra tools to calculate head losses due to trash screens and bends are desirable but not vital because these losses may be manually calculated and incorporated into the final result.

Table 6.5 *Minimum standards for computer software*

Culvert routine	Method
Calculation of inlet control headwater	
Unsubmerged (weir flow)	FHWA (Form A or B) (Section 6.9.3)
Submerged (orifice flow)	FHWA (Section 6.9.4)
Calculation of outlet control headwater	
Tailwater elevation	FHWA (Section 6.6)
Outlet loss	FWHA (Section 6.10.3)
Friction loss for free flow	Standard step method (Section 6.10.6). The direct step method and St Venant equation are also valid but outside the scope of this guide
Inlet loss	FHWA (Section 6.10.8)
Calculation of overtopping headwater	
Modular weir flow	Weir equation (Section 6.11.5)
Submerged weir flow	Weir equation with submergence factor (Section 6.11.6)
Drowned weir flow	Energy approach (Section 6.11.7)

6.14.3 Software choice

Most computer software for the hydraulic analysis of culverts is based on the Federal Highway Administration (FHWA) methodology (Federal Highway Administration, 2005), or on simple head loss calculations applied as a function of velocity head. Different software products vary in terms of the types of culvert structure that can be modelled and how the surrounding watercourse is represented. A selection of software packages currently used by practitioners in the UK is included in the following list, and their functionality summarised in Table 6.6 (see *Useful websites*).

Selected culvert and watercourse models

- **Conveyance estimation system/afflux estimation system (CES/AES) (Knight *et al*, 2009 and McGahey *et al*, 2009)**
- **CulvertMaster (Bentley Systems Inc)**
- **ESTRY (part of TUFLOW) (BMT WBM)**
- **HEC-RAS (US Army Corps of Engineers)**
- **InfoWorks CS (Wallingford Software/MWH Soft)**
- **InfoWorks RS (as above)**
- **ISIS (Halcrow)**
- **MIKE 11 (Danish Hydraulic Institute)**
- **WinDes (Micro Drainage)**

The packages listed are predominantly complex software that can include culvert units within much larger models of a whole watercourse or drainage system. In most cases this can include the analysis of unsteady flows within the watercourse and models that contain multiple culvert structures. Culverts with flapped or tidal outfalls with tidal boundary conditions or flood storage (either in the culvert or in the floodplain upstream) may be modelled using watercourse software capable of modelling unsteady flow.

There are also tools that concentrate on the steady flow analysis of a single culvert. For example, CulvertMaster implements the FHWA methodology including a choice of hydrological flow estimation procedures and user-specified tailwater conditions. The CES/AES stand alone software implements the Conveyance Estimation System (CES) methods for computing the conveyance and backwater profile within a watercourse reach (see Section 6.8.2) and the Afflux Estimation System (AES) for calculation of the hydraulic performance of a culvert located within the reach. Further details about the CES/AES are available in Knight *et al* (2009).

Table 6.6 *Commercially available software currently used in the UK*

Software	Culvert shapes	Inlet losses method	Barrel modelling method	Outlet losses method
CES/AES	Standard shapes only	FHWA	FHWA	Velocity head
CulvertMaster	Standard shapes only	FHWA	FHWA	Velocity head
ESTRY	Standard and irregular shapes	Simple factor of velocity head	Federal Highway Administration (1965), Federal Highway Administration (1972) and Henderson (1966)	Velocity head
HEC-RAS	Standard shapes only	FHWA	FHWA	Velocity head
InfoWorks CS	Standard shapes only	FHWA/CIRIA method or simple factor of velocity head	Closed conduit pressure flow equations	Velocity head
InfoWorks RS	Computational engine is the same as ISIS			
ISIS	Standard and irregular shapes as long as the latter are symmetrical about the vertical axis	FHWA/CIRIA method or simple factor of velocity head	Full open channel flow equations assuming infinitesimally small opening on roof of culvert	Velocity head
MIKE11	Standard and irregular shapes	Simple factor of velocity head	Full open channel flow equations assuming infinitesimally small opening on roof of culvert	Velocity head
WinDes	Standard and irregular shapes	Simple factor of velocity head	Closed conduit pressure flow equations	Velocity head

6.14.4 Modelling complex culverts

Culvert systems are rarely straightforward and advice on the more complex modelling scenarios is provided to assist the less experienced practitioner. However, advice should be sought from an experienced hydraulic engineer or modeller if the practitioner has any doubt about the best modelling approach to a particular problem.

Multiple barrels

Multiple identical barrels in parallel may be modelled using either a culvert or watercourse model. Culverts of different shapes and sizes can be modelled with culvert-only software but this requires the user to simplify (and perhaps combine) them. For more accurate results, watercourse models should be used in these situations. In principle, the watercourse models mentioned in Table 6.6 can accommodate any number of culvert barrels (of different shapes and sizes) by representing them as parallel conduits connected to the bounding river sections by river junctions or their equivalents depending on the software package.

Non-uniform shapes and slopes

Historic culverts and culverts in urban areas frequently exhibit longitudinal changes in cross-section or bed slope. This is characteristic of the UK and reflects the piecemeal development of many culverts over time. Changes in cross-section typically coincide with landowner or land-use boundaries, for example, between housing and a public highway.

One way of modelling a non-uniform culvert with a culvert-only software package is to represent its entire length with the dimensions of the known or perceived controlling section. However, more representative results are likely to be obtained by using watercourse modelling software. In the latter approach, sufficient units should be used to represent all the cross-sections that might act as hydraulic controls such as internal weirs or pinch points, but the level of detail should be appropriate to the length of the culvert. There are various ways that this can be achieved in current commercially available watercourse software packages but simply these boil down to use of either river junctions between the different culvert sections or notional river channels with lids over them so as to ensure pressure flow.

Table 6.6 provides an indication of the in-built capabilities of commercially available software packages in use in the UK to model different shapes of culvert. Whereas culvert-only packages can only model standard shapes, the watercourse equivalent can model irregular shapes (or some slight simplification) as well.

Mammal shelves or benching

Even in a culvert that is fundamentally of standard shape, mammal shelves or benching represent an element of non-uniformity or irregularity. Accurate modelling of these appurtenances requires a software package with in-built capability to capture irregular or semi-irregular (but almost vertically symmetrical) culvert shapes. This should enable specification of the mammal shelf or benching profile within the overall culvert cross-section structure. From Table 6.6 the indication is that of the commercially available software packages in use in the UK, it is only the watercourse (as opposed to the culvert-only) ones that mammal shelves or benching can be modelled with.

Shelf and bracket type mammal ledges are impossible to model accurately. In clean condition their impact is likely to be small provided that the brackets are small relative to the culvert cross-sectional area. However, if the brackets tend to snag debris, causing a build-up, the effect on capacity can be more significant.

Services and other obstructions

The disposition of services in relation to the line and level of the associated culvert can take several forms and the approach to modelling is configuration-dependent. If the service (eg a sewer pipe) runs parallel to the barrel and is mounted on the barrel perimeter, then this can be represented in both culvert-only and watercourse models as a change in culvert cross-section, if the culvert is of standard shape. In those cases where the culvert is non-uniform, irregular or semi-irregular (but almost vertically symmetrical) the profiles of perimeter-mounted services can be represented as part of the culvert cross-section in the manner as described in the previous paragraph.

The modelling approach to adopt is not as clear where the services are suspended within the culvert barrel rather than mounted on the perimeter. One way is to add the circumference of longitudinal crossings to that of the culvert barrel to simulate extra friction. In the case of transverse service crossings (ie those that pass through the culvert barrel from one side to the other), the associated extra head losses can be represented by reducing the cross-section and increasing the inlet and outlet loss coefficients if the crossing is at either end of the culvert, or by modelling an internal head loss. The latter approach is more suited to watercourse-type software.

Trash and security screens

Of the existing commercial software packages in use in the UK, very few incorporate trash and security screen head loss modelling functionality and have either full or partial in-built allowance for representing the vertical alignment and blinding of the screen, the latter sometimes producing unrealistic head loss. The opening area of compound trash screens (comprising both horizontal and sloping screens) can be underestimated as screens are represented by wholly vertical or sloping screens, but providing more width can overcome this.

All the packages incorporate various head loss, blocked obstruction and weir simulation modules. One way of overcoming the limitations in those software packages that have screen modelling capabilities (and the only way of modelling screens in those that do not) is to use their head loss modules as repositories for known or hand-calculated screen losses, and the blocked obstructions and weirs for representing screen blinding.

Flapped or tidal outfalls

Flapped outfalls prevent reverse flow through a culvert due to high downstream water levels and reduce the risk of flooding to low-lying land upstream of the culvert. Flap valves are typically installed on outfalls of culverts through flood defence embankments, for example, in tidal locations or on lowland rivers (Figure 6.38).

Figure 6.38 *Tidal culvert with flapped outfall (courtesy JBA Consulting)*

Unsteady computer modelling is required for the hydraulic assessment of this tidal culvert that carries a watercourse beneath a flood embankment to an estuary. The channel upstream of the embankment provides flood storage when the outfall is tide locked. The rectangular double-door flap valve, one above the other, reduces the head required to open the flap valve and allows the culvert to operate for a greater proportion of the tidal cycle.

Computer modelling of flapped or tidal outfalls may be simple or complex, depending on the objective of the hydraulic assessment and the location of the culvert to flood risk receptors. If the hydraulic assessment of works is required to support a consent application, the modelling approach and required outputs should be agreed with the relevant consenting authority from the start. If the works are likely to affect flood risk, unsteady modelling may be required to allow comparison of water levels and flood extents. Otherwise, steady-state modelling using one or more joint probability events may suffice.

Although steady-state, in principle the existing commercially available culvert-only software packages can model culverted flapped outfalls but if the tailwater conditions consist of a time series of levels (such as a tide curve) then these should be specified as a series of constant steady-state levels. This implies a large number of model runs that may prove infeasible especially if a joint probability analysis is involved. Hydrodynamic (unsteady) modelling with the watercourse software packages is more suitable in these situations. All the commercially available watercourse software packages listed in Table 6.6 have in-built flapped outfall modelling functionality. Opening and closing of the flap is controlled by the water levels upstream and downstream. The head loss due to flow through a flap valve should be allowed for, and can be estimated by applying a coefficient to the velocity head (as for inlet and outlet loss).

7 Operation, inspection and assessment

7.1 Performance monitoring and operation

7.1.1 Introduction

Most well designed culverts require minimal intervention or management to continue to perform their design function. An extra screen, flap gate or flow control (eg penstock) will generally require more frequent intervention to ensure performance is maintained.

During a culvert's working life its performance will deteriorate, and intervention will be required to maintain a minimum performance level, for example, to:

- convey the railway, road or canal safely over the watercourse
- safely convey flow through the culvert without causing increase in flood risk
- maintain good ecological condition in the stream
- continue to meet health and safety requirements.

Continued monitoring will enable the owner to assess whether the performance requirements are being met. Monitoring may take many forms, but can generally be grouped into two types:

- periodic measurements (eg flow gauging, silt depths, structural condition)
- real time monitoring (visual and electronic level, head loss measurement or flow gauging).

Performance monitoring is required to provide information for assessing structural, hydraulic, health and safety, and environmental performance. These are described further in Sections 7.12 to 7.15.

7.1.2 Structural performance

A common form of periodic measurement is the identification of change by visual or dimensional means. This could include, for example, measurement of the level of sediment in the culvert barrel or settlement in the road above a culvert. Measurement of cracks in structural elements over time will indicate whether there is ongoing movement.

Testing typically deals with assessment of structural condition through the use of testing equipment such as a cover meter (for thickness of concrete over reinforcement) or a Schmidt hammer (for concrete strength). Where there is significant doubt about the strength of structural elements, it may be necessary to take core samples for testing in a laboratory.

McDowell *et al* (2002) provides good information on the application of non-destructive testing techniques. The application of non destructive testing for the assessment of structural performance of flood and coastal defences has been developed following a review of practices within similar industries (Ogunyoye *et al*, 2004). These studies concluded that applications such as geophysics can be used to detect voids around or within a culvert or to assess if deformation of the structure has occurred.

For culverts located under highways, where the live loading on the structure forms a low proportion of the overall loading, it is common practice not to undertake an analytical structural assessment. Instead, a visual assessment of performance is undertaken to ascertain its performance. Culverts that fall under this category include:

- culverts and buried structures of 3 m span or less with cover of 1 m or more
- non-masonry culverts and structures that are buried to such an extent that live loading is only of marginal significance when compared with the magnitude of earth pressure acting on the structure
- buried corrugated steel structures.

Advice on the structural performance requirements for highways structures can be obtained from the DMRB (TSO, 2007) or from the relevant highway authority

Following the adoption of Eurocodes in 2010, advice on the performance requirements for highway structures should be obtained from the relevant highway authority (eg Highways Agency or local authority)

Advice on the structural performance requirements of culverts not used as highway structures can be obtained from BS EN1295:1998

Advice on the structural performance requirements for railway structures can be obtained from the Rail Safety and Standards Board (2008)

The structural performance requirements for smaller culverts used under a highway (less than 0.9 m diameter) and for culverts that are not required to cross a highway can be obtained from WRc (2009). The structural performance assessment of a sewer is based on a condition grade appraisal that combines its internal condition, the surrounding soil type and how frequently the sewer surcharges (which could result in loss of the supporting backfill around the pipe). This approach is ideally suited to small culverts with cover greater than 1 m, as it offers a quick and non-intrusive method of determining their structural performance.

7.1.3 Hydraulic performance

The hydraulic performance of culverts can change significantly if a culvert becomes blocked during a period of high flows in the watercourse. At culverts that are known to have high blockage risk, the monitoring of hydraulic performance can help to reduce the risk of upstream flooding by providing a warning of increasing water levels.

Monitoring can provide information on performance directly (for example, water levels upstream of a culvert, head loss through a culvert or associated screen, flow through a culvert, or the level of silt in a culvert) or indirectly (for example, checking for signs of continued blockage upstream of, or within, a culvert). In either case the information obtained requires an assessment to determine the effect on performance. For simple cases, information regarding the impacts of a range of possible scenarios on the culvert performance can be pre-assessed and provided in the form of tables or performance indicators for use in performance assessment. In more complex cases, the analyses and assessment will need to be carried out post inspection or monitoring.

Decisions on the need for intervention should be based on a comparison of the current performance with pre-determined performance requirements (information from the design presented in the health and safety file). Where this does not exist, it may require an evaluation from first principles (for example, hydrological assessment to determine required hydraulic capacity as defined in Chapters 5 and 6).

Recent technological developments have made real time monitoring both more accessible and cost effective. Webcams and remote level gauging can be employed to monitor water levels, head losses or signs of blockage at screens or in culverts. These systems can alert the asset owners to either rising water levels or if an obstruction has occurred at the screen of a culvert, allowing arrangements to be made to clear the screen. Where the potential risk is the blockage of a culvert barrel, the head loss at the inlet and outlet could be measured to provide information on likely blockage. Case study A3.3 provides an example of where webcams have been used to monitor the performance of a trash screen.

The frequency of hydraulic performance monitoring is often risk-based, depending on the risk of blockage of the culvert, or the risk of upstream flooding, leading to more regular monitoring being carried out during times or seasons of high flow. Guidance on performance monitoring of screens is provided by the Environment Agency (2009a). It is suggested that likelihood and consequence of blockage is considered in determining the optimum inspection frequency.

7.1.4 Health and safety performance

Culverts present a health and safety risk to two main groups:

1 Operational and maintenance staff.
2 The public using the area around the culvert (authorised or otherwise).

Culverts, screens and flap valves will require regular inspection, cleaning and maintenance to ensure they remain operable. Maintenance and operational works should be planned to ensure as much as possible the avoidance of, or minimal activity, near culverts during periods of high flow. Where access to a culvert is required during high flow conditions, special consideration should be made to ensure safe access for vehicles and pedestrians. Remote sites may have further risks of poor lighting and poor access conditions. Risks arising from construction, maintenance and repair works are discussed in Chapter 8 and 9.

Common risks to operatives during operational visits (excluding construction and maintenance) include, but are not limited to:

- access and egress
- slips, trips and falls due to uneven and slippery surfaces or limited space working areas
- injury due to manual handling of debris, and the removal of grills and covers
- death by drowning, particularly during high flow conditions
- traffic related accidents at road and railway culverts
- contact with contaminated water, sediment, other biological hazards and other pollutants and debris, for example, hypodermic needles
- entry, asphyxiation and egress in a confined space
- culverts in a poor structural condition because of a lack of maintenance, overloading or vandalism
- changes in the flow of the watercourse, creating problems with egress.

During operational visits suitable avoidance or mitigation measures should be put in place to minimise these risks.

Public safety at culverts should be addressed by a site specific risk assessment. Guidance on this is provided in Chapter 7 of Gotch *et al* (2009). Recommendations are then made for mitigation measures to manage the risk to the public. These measures may include:

- providing safe egress points
- designing out the risks
- security screens
- barriers (such as fencing and planting)
- information (such as signage and publicity).

Health and safety performance monitoring of culverts should be undertaken during any operational activity near to culverts. This should involve a review of site safety by operatives and the results fed into the performance assessment and management of the culvert.

7.1.5 Environmental performance

A culvert, particularly one that acts as or incorporates a flow control structure, will influence the condition of the watercourse. Over time, the geomorphological and ecological condition of the watercourse may deteriorate as the watercourse responds to changes in the flow or sediment regime, or as debris collects at the culvert.

Some historic culverts may not have any provision for fish and mammal passage and could form permanent barriers to movement along the watercourse, which may be detrimental to many species. Information on the extent to which the culvert is restricting the passage of fish and mammals can be identified through an environmental assessment and culvert inspection.

Before inspections, an environmental assessment should be undertaken to identify any risks to the environment and any potential opportunities for enhancement. Chapter 4 provides information and guidance on how to undertake an environmental assessment, but important points to consider include:

- presence of protected species or designated habitats (for example, culverts that are not subject to regular surcharging may be used as bat roost, and assessment of disturbance should be made before inspection)
- presence of invasive species (certain invasive species can cause health and safety hazards and also a risk of further spreading)
- sediment and water quality issues (previous inspections or surveys may have highlighted possible contaminants within the water and sediment that may be released through access works).

Inspection of culverts should include an assessment of environmental impacts on a scale appropriate to the size and location of the culvert. Issues that are worth assessing at culverts include:

1. Is the culvert likely to be a barrier to the movement of fish and other wildlife?
2. Is there evidence of erosion to the watercourse bed and banks resulting in deterioration of habitat or obstruction to fish passage?
3. Is the culvert likely to restrict the movement of sediment and debris along the watercourse?
4. Is there a build-up of debris and trash at the culvert?

5 What is the potential for pollution from the culvert?

6 Is there evidence of exotic and invasive species at the site (eg Japanese Knotweed, Giant Hogweed, Himalayan Balsam)?

7 What are the opportunities to enhance the culvert infrastructure or maintenance?

Where there are no identified risks from the environmental assessment the environmental checklist should be assessed by a competent asset inspector. Where there is any doubt or where environmental risks have been identified through the environmental assessment, the advice of an environmental specialist should be sought. If particular issues have been identified through the environmental assessment or the inspection, further surveys may be required, for example, water quality sampling, geomorphological assessment or ecological surveys such as using tell-tales within culverts to track mammal movement. These surveys will help support decision making about maintenance operations and/or enhancement options.

7.2 Inspections

7.2.1 Introduction

As part of a monitoring programme, inspections can be used to obtain snapshots of condition and performance related information about culverts and their associated systems. The importance and purpose of inspections is explored in Chapters 2 and 3. This section provides guidance on planning for inspections including important considerations such as inspection methods, techniques, timing and health and safety. However, it does not provide detailed guidance on the types and causes of defects found during an inspection as the techniques used vary. It is recommended that an asset owner or operator involves the services of suitably experienced and competent staff or advisers to assist or undertake these processes. Throughout the guide the following terminology for inspections are used:

Table 7.1 *Inspection types*

Inspection type	Details of inspection
Superficial inspection	The purpose of a superficial inspection is to identify and report obvious defects, which if ignored might lead to collapse, blockage, accidents or high maintenance and repair costs. The inspection will normally be carried out without entry
General inspection	This inspection requires the examination of all parts of the structure that can be inspected without the use of access or specialist inspection equipment. Visual aids such as binoculars can be used where necessary. General inspections will normally be carried out without entry
Principal inspection	This inspection comprises a close examination, within touching distance, of all accessible parts of a structure. This should include adjacent earthworks and waterways where relevant to the performance of the structure. A principal inspection should use as necessary suitable inspection techniques, access and/or traffic management works. Suitable inspection techniques for a principal inspection include hammer tapping to detect loose concrete cover and brickwork and paint thickness measurements. Testing is not a requirement for a principal inspection. The inspection should be undertaken with man-entry with the qualified engineer accompanied by a confined spaces team where appropriate In culverts that cannot be safely inspected by man-entry, the inspection could be undertaken remotely by CCTV and the findings recorded by a suitably competent operator
Special inspection	Any other inspection required from those not listed here, usually as a recommendation following one of the above inspections or, for example, after very high flows or loading or an earthquake

7.2.2 Planning

Before undertaking any inspection, a planning stage is required to ensure a safe and efficient inspection process. Of primary importance is access to the culvert where specialist equipment may be required and where confined spaces regulations, diving regulations, or some form of environmental management regulation applies. A risk-based assessment of the frequency of inspections should address the need for the inspections and should look to optimise the frequency.

Inspection planning should consider ownership and site access (Chapter 2), health and safety concerns (Chapter 3) and environmental assessment (Chapter 4). The timing of inspections is important to avoid access during high flows and seasonal environmental constraints for important species using habitats in and around the culvert.

It is recommended that an operational plan is developed, which contains the details of the proposed inspection processes. The plan needs to consider the frequency and nature of the work to ensure continuing performance of the culvert (or drainage system). This document should be updated throughout the life of the asset with feedback from the various operational and maintenance tasks.

Typically the operational plan may provide information regarding the nature and frequency of:

- performance requirements
- design assumptions (including design life, flows and loadings)
- operational tasks and routine maintenance (eg trash screen inspections and clearance)
- inspections, condition appraisals and performance assessments
- health and safety and environmental risks (including arrangements for access, egress, risk avoidance and risk mitigation).

An example checklist and comprehensive planning process for planning the inspection of highway structures is defined by the Highways Agency (2007).

Planning for confined spaces

Many culverts are defined as confined spaces. Confined spaces present high risk environments, accounting for nearly five per cent of construction fatalities in the UK each year (Health and Safety Commission, 2009). Lack of awareness and training during attempted rescues has led to further deaths as the rescuers themselves are overcome.

In the UK, work in confined spaces is covered by The Confined Spaces Regulations 1997, made under the Health and Safety at Work etc Act 1974. In accordance with the Confined Spaces Regulations 1997, a "confined space" has two defining features:

1. A place that is substantially (though not always entirely) enclosed.
2. A reasonably foreseeable risk of serious injury from one of the specified hazards within the space or nearby.

Specified hazards are defined as fire and explosion, loss of consciousness due to heat stress, asphyxiation arising from toxic gas, fumes, vapour or lack of oxygen, drowning in liquid, and engulfment in deep silt or entrapment in accumulations of debris.

Many culverts are classed as confined spaces during construction, inspection, maintenance or repair, or when certain types of work are carried out, although some culverts may be low risk due to ease of access, good ventilation and clean inverts. It should be noted that the risks can change during inspection, for example, due to fumes from the exhaust of vehicles or a change in the access or egress conditions.

No-one should enter a confined space without first having assessed the risks and having put in place an appropriate safe system of working. Methods of planning, management and development of safe systems of works for entry into confined spaces are identified by the Health and Safety Commission (2009).

Figure 7.1 shows a culvert entry following a planned safe system of work.

This was taken during a statutory culvert inspection, which involved a fully equipped team of four including a confined spaces gang accompanying the inspecting engineer and the supervising engineer (the culvert forms part of a reservoir). There was a drawdown valve in a chamber at the far side of the culvert. Access was via a locked gate in the safety railing and a tied ladder behind the camera down to the hard concrete bed.

Figure 7.1 ***Culvert entry following a planned safe system of work (courtesy Andy Pepper)***

The steps involved in planning works to be undertaken in a confined space can be summarised as follows:

- assess the need for manual entry into a confined space for the purpose of carrying out work, and avoiding such entry if it is reasonably practicable to carry out the work by other means
- obtain any relevant available information regarding the site from the asset owner or operator in particular with respect to health and safety hazards
- undertake a risk assessment to determine the level of risk associated with the culvert inspection. In particular, considering difficult access and egress, limited headroom, hidden steps in the invert, deep silt, slippery surfaces underfoot, potential for rapid rise in water depth due to flood flows, speed and depth of flow making it difficult for operatives to keep their balance, sharp objects and potential for bacterial and viral infections (particularly in urban areas)
- develop a safe system of work if confined space entry cannot be avoided. The safe system of work should allow entry under designed operating conditions, safely and with minimal risk to staff. A supervisor should be appointed to ensure that the system is implemented and to note any changes to operating conditions
- ensure that adequate arrangements are made in advance for the potential rescue of any person at work in a confined space in the event of an emergency.

Staff should not enter a culvert if there is any doubt about safety. Lone workers should never enter a culvert. Before staff enter a culvert the water depths upstream and downstream should be checked. Where possible contact should be established with any monitoring centre where forecasts of rainfall or rising water levels may be obtained.

Staff should wear appropriate PPE to avoid contact with water and sediment and should aim to minimise disturbance of silt deposits. In the event that water is accidentally ingested (eg as a result of a fall into the water) or enters an open wound medical advice should be sought.

Planning for diving inspections

When it is not possible to either dewater a culvert to allow access for an inspection and an inspection using remote means is not feasible, a diving inspection may be required.

In the UK all commercial diving work is undertaken under The Diving at Work Regulations 1997 and the associated approved codes of practice. All divers involved in commercial operations are required to hold valid medical certificates, a completed log book and a health and safety approved diving qualification.

Care should be taken to employ divers trained in relevant inspection techniques and to brief them thoroughly.

7.2.3 Frequencies

The types and frequencies of culverts inspection vary from one organisation to another. The decision on appropriate frequency of inspection should consider the following factors:

- the likelihood and consequence of failure
- the access and remoteness of the culvert location
- the programming efficiencies with other assets that require inspection in the area.

Table 7.2 shows typical inspection frequencies from some organisations within the UK with responsibility for a large number of culverts. Timings for general inspections vary widely, but principal inspections tend to be every five to six years.

In addition to periodic superficial inspections it is good practice that the culvert owner or operator undertakes special inspections following high flows in the watercourse, except where there is negligible consequence of blockage or structural damage.

Inspections should be scheduled to suit the environmental constraints in the area of the culvert. During the winter high water levels may prevent inspection or access. Summer inspections may be affected by overgrown vegetation that obscures part of the structure. Spring inspections may be affected by nesting birds and autumn inspections by spawning fish. The inspection planner should consider the scheduling to achieve a successful maintenance inspection programme.

Inspection procedures also vary between organisations and many adopt standard recording systems to record the findings of inspections. Section 7.3.2 identifies the common processes used for the methods of inspecting culverts. Many organisations use scoring systems for condition appraisals to describe the culvert condition. The scoring system may also consider the consequences of failure. This is particularly important when inspecting several culverts to enable prioritisation.

Table 7.2 *Current UK typical inspection frequencies*

Organisation	Inspection policy/frequency
Local highway authorities (England and Wales)	General inspection ~ 2 years Principal inspection ~ 6 years
Environment Agency	Internal culvert inspection ~ 5 years General inspections ~ 0.5-5 years Principal inspections ~ 5 years
British Waterways	Superficial inspection – monthly General inspection – annually Principal inspections – every 10–20 years depending on condition
Highways Agency	Large culverts >900 mm: General inspection ~ 2 years Principal inspection ~ 6 years Small culverts <900 mm: Inspection frequency depends on the last known condition of the culvert
Transport Scotland	Small culverts <900 mm, ~ 6 months urban and 12 months in rural. General inspection ~ 2 years Principal inspection ~ 6 years
Network Rail	General inspection ~ annually Principal Inspections ~ 6 years
Scottish local authorities	Superficial inspection – weekly during periods of heavy rainfall General inspection – annually to 2 yearly
DRD Roads Services	Superficial inspections ~ 1, 2 and 4 monthly General inspections ~ 24 monthly Principal inspections ~ 6 yearly

7.2.4 Data requirements

In the planning of inspections, consideration should be given to the data required and the level of detail. Visual inspections are used to record defects such as visible damage, blockage, sedimentation and cracking. Special inspections are required to obtain more information on condition that cannot be obtained easily from the planned inspections, including the presence of voids around the barrel of the culvert. Further monitoring and inspections may be required to provide information to assess change in performance over a period of time.

Inspections should also consider collecting data from the area surrounding the culvert to provide a context for the observations. This may include catchment characteristics (to assist with hydraulic or blockage assessment) and bypass arrangements to assist hydraulic calculations.

The Highways Agency (2007), provides advice on the data that can be used to inform an inspection. Table 7.3 provides information that can be obtained before and during an inspection.

Table 7.3 *Some useful inspection related information*

Item	When to be collected	Use
Historical information such as record drawings, previous inspection reports	Before the inspection	Allows a trend analysis to be undertaken to determine the rate of deterioration and the effect on performance
Environmental information related to legally protected sites and species, records of invasive species, water and sediment quality	Before the inspection	Allows environmental risks to be identified informing the operational plan, method and, timing of inspection and any required mitigation for disturbance
Antecedent rainfall conditions	Before the inspection	Allows asset to be inspected in the context of preceding conditions
Ambient conditions, weather , water level and flow information	Immediately before and during the inspection	This could affect the condition of the culvert and limit the areas of the inspection
Visual records, photography, video, sketches and dimensional measurements	During the inspection	Effective record of the state and performance of the culvert

7.2.5 Inspection methods and techniques

There are two principal modes of culvert inspections: an inspection that involves man-entry and one that does not. Remote inspections can be used for internal inspections of culverts and are generally used within principal inspections. The method selected is often based on the dimensions of the culvert and health and safety factors, which could include the presence of deep or fast flowing water, suspected contamination or structural instability.

On some culverts, preliminary maintenance work may be required to enable the inspection to be undertaken. These may include opening up access points and screens, de-silting, diversion of flows and temporary structural works. Also, these enabling works may require consents (eg land drainage consent) before being implemented.

Remote inspection of culverts

Remote inspection of culverts should be carried out for those culverts that are too small for man-entry (typically less than 900 mm diameter) or culverts that are affected by permanent high flows or levels, structural instability or hazardous atmosphere. In these circumstances several methods are available to the asset owner including those shown in Table 7.4. The conditions upstream and downstream of the culvert (including, for example, the condition of headwalls, screens, the presence of scour holes or similar and the operation of flow control equipment) will still require an inspection by staff. An example of a culvert inspection using a CCTV system is shown in Figure 7.2.

Table 7.4 *Methods of asset inspection*

Type of inspection	Summary description	Limitations
CCTV inspection	The system comprises: ■ a colour CCTV camera, together with a lighting unit, mounted either on a self propelled tractor, crawler or on skids, which is inserted into the culvert. The tractor may have adjustable speed and be steerable. The camera can incorporate a "pan, tilt and zoom" facility allowing the camera to be directed towards points of interest and to look at features ■ a cable drum, which connects the camera unit to the surface. The cable is usually pulled behind the camera and is fed through a counter so that the location of the camera can be determined ■ a control unit, normally PC-based, which controls the camera, tractor and lighting controls, and a video monitor screen that displays the output of the camera together with a digital display of basic information including the distance from the start point ■ a means of recording the video image and a means of producing still images. Figure 7.3 shows a typical still from a CCTV survey.	In culverts greater than 600 mm diameter the distance of the wall from the camera in a forward facing view becomes further away, requiring greater lighting and higher image resolution. There is a risk of explosive gases in confined spaces and it is recommended that all camera equipment used in culverts should be in an explosion-proof housing. The costs of a CCTV inspection can significantly increase if extensive cleaning is required. The length inspected per day is dependent on conditions within the culvert and the amount of information being collected, but a figure of 400–800 m per day may be taken as reasonable. To undertake the inspection access to the culvert headwalls are required and access for a van is required to power and record the images. A specification for CCTV surveys is contained in WRc (2005a).
Sonar survey	Where the culvert is semi-surcharged, sonar can be used in conjunction with CCTV to generate a 360° view. As the sonar rotates, it is transported through the culvert at a given rate, creating a helical view of the entire culvert. The sonar system allows for detailed measurements to be taken of defects and objects within the inspected space. Defects recognition is based on the ability of sound to pass through the defect. The sonar is able to locate an open break greater than 3 mm in width. The same concept allows measurement of debris and sediment depth. The remainder of equipment is similar to that used for a CCTV survey.	The Sonar system is best used in submerged culverts. It can be used in conjunction with CCTV surveys in partially submerged culverts. The Sonar head is often mounted on the same tractor unit as a CCTV system. A specification for Sonar Surveys is contained in WRc (2005a).
Laser survey	A laser survey can be used to determine the profile of a pipe to a high level of accuracy. The laser equipment can be attached to a CCTV camera inspection unit. The laser survey can be used to: ■ determine the structural shape and cross-sectional area of a culvert ■ identify if erosion, holes, cracks or settlement of the culvert has occurred ■ estimate the amount of siltation within the culvert.	The limitations on the survey are the same as for a CCTV survey.

Figure 7.2 *Culvert inspection using a CCTV system (a) and a typical tractor unit and CCTV camera (b) (courtesy Environment Agency and British Waterways)*

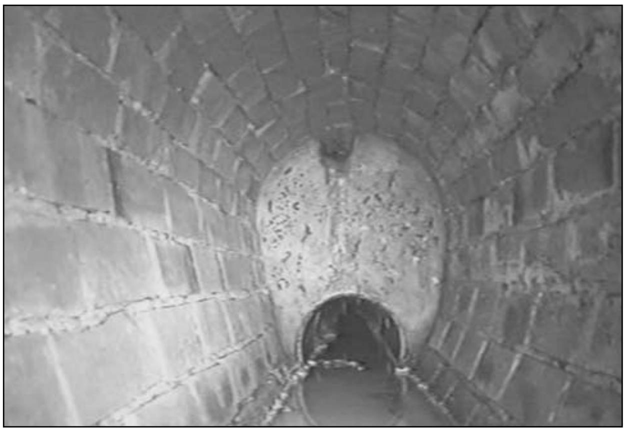


Figure 7.3 *A typical still image from a CCTV survey, showing a change in section of a pipe (courtesy Richard Allitt)*

Physical inspection by staff

Manual inspection of large culverts may be undertaken, provided a safe system of work is established and followed by suitably trained staff. WRc (2005a) states that:

"In the UK, manual inspection costs are significantly more than that of a CCTV inspection survey, this is a result of the number of trained people required to be present for safety purposes. Improved technologies such as the development of pan and tilt cameras, cameras which can work in lower light intensities and lightweight cable systems have also reduced the need for manual inspections. Manual inspections therefore should only be undertaken where a detailed survey is required and where it is known that a CCTV inspection or other non-man-entry options will not produce adequate results."

Where a physical survey is required, it is appropriate to assess the:

- structural condition (eg cracking, missing blocks/bricks and settlement/heave)
- hydraulic condition (eg blockage, sedimentation and scour)
- conditions upstream and downstream of the culvert (eg the condition of headwalls, screens, the presence of scour holes or similar and the operation of flow control equipment)
- environmental condition (including the use of culvert by fauna or contamination sources).

To provide safe access, it may be necessary to make specialist access arrangements (for example, air quality monitoring, boat access, dive survey and erection of scaffold). For access to be feasible, the minimum opening size of any manhole should not be less than those described in BS EN476:1998b, which are:

- an internal diameter of 1000 mm or greater
- a nominal size for rectangular sections of 750 mm x 1200 mm, or greater
- a nominal size for elliptical sections of 900 mm x 1100 mm, or greater.

In some circumstances it may be necessary to undertake advance works to enable physical access to a culvert. Such works would include:

- draining down culvert to allow inspection
- the removal of sediment in the culvert to allow access for inspection
- the removal of access covers, screens and grills
- diversion of flows to permit safe access
- the removal of vegetation.

Figures 7.4 and 7.5 show different environmental conditions and how they affect the safe access for physical inspection by man-entry.

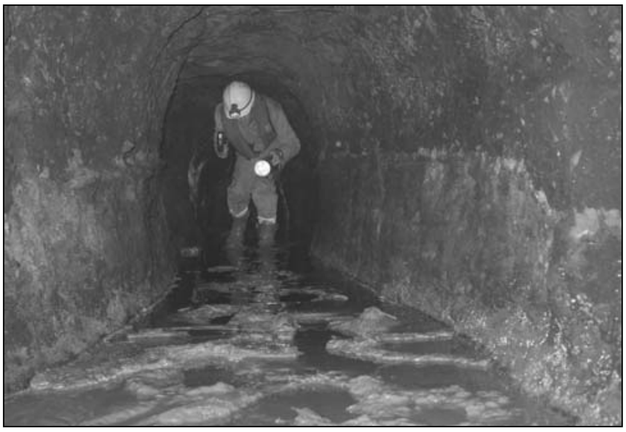


Figure 7.4 ***Physical entry into a culvert (courtesy British Waterways)***

Records from visual inspections may include site notes and measurements, photographs and video to aid further assessment of condition and performance following the survey. Further detailed monitoring and inspection may include structural testing (in situ strength testing), geophysical testing, detailed measurements of settlement/heave and cracking and testing for contamination. Extra monitoring may also provide time series data to allow an assessment of deterioration or performance over time. Case study A3.4 provides an example of methods for undertaking survey work in a culvert comprising different forms of construction.

Figure 7.5 *Culvert where normal levels would prevent access for inspection (courtesy Transport Scotland)*

7.3 Condition appraisal and performance assessment

7.3.1 Introduction

A condition appraisal and performance assessment is required to interpret the results of monitoring and asset inspections, to aid decision making on the need for intervention and the type of intervention required. The appraisal or assessment may also provide comparative performance or condition grades to assist with prioritisation of intervention actions.

A performance assessment should use the condition along with other parameters to assess how the culvert performs against the desired hydraulic, structural, environmental or health and safety performance requirements. A trigger for the assessment might be:

- poor performance (highlighted by flooding, high frequency of blockage or signs of structural distress)
- outcome of routine assessment following inspection
- significant change in the land-use within the catchment (increased hydraulic or structural loading)
- strategic need for replacement (new road/railway etc)
- change of ownership or responsibilities (such as transfer of the management of a watercourse between asset owners, or the de-trunking or adoption of a highway).

7.3.2 Condition appraisal

Condition appraisal considers the observations made at one point in time and compares them with a similar asset in excellent (almost new) condition. The appraisal should acknowledge:

- structural condition (cracking, deformation, settlement, damage etc)
- hydraulic condition (eg sedimentation, blockage, settlement)
- health and safety and environmental condition.

Organisations with significant ownership or management responsibilities for culverts such as highway authorities, British Waterways, Network Rail, Environment Agency and local councils have adopted scoring systems to appraise the condition of culverts. This approach ensures that site observations made by inspectors are recorded consistently to allow the appraisal of multiple assets. A grading system is used and characteristics of each grade are defined along with a photo of a typical example. The guides produced by asset owners do not provide information on how this grade should be interpreted (for example, how performance or residual life can be estimated from condition grade).

Combined with appraisal of condition, British Waterways have made a further refinement to their appraisal process. This involves the application of a performance assessment with a scoring system to identify those assets whose condition may be good, but whose functionality may be inadequate (such as a hydraulically undersized culvert, or a bridge that may be under-strength for modern traffic loadings).

The following documents provide important information on the condition appraisal of culverts:

- **Highways Agency (2007)** ***The inspection manual for highway structures***
  This document provides information on the defect severity rating for highway structures.
- **Environment Agency (2006)** ***National sea and river defence surveys condition appraisal manual***
  Provides advice on condition appraisal process used for river and coastal defence structures, including culverts. This manual was recently updated to incorporate more performance related issues. This enables the outcomes to be more easily related to the associated deterioration and failure processes, linking better to the appraisal.
- **WRc (2004)** ***The manual of sewer condition classification*** **and the** ***sewerage risk management*** **website**
  Gives information on the method of appraising the condition of a sewer.

Condition appraisals using a scoring system are commonly summarised in an overall numerical condition grading. This is a record of the condition at a snapshot in time when the associated inspection was carried out. Condition grades are typically recorded as numbers (for example, 1, 2, 3, 4 and 5) or as percentages (0 to 100 per cent). The grading provides an indication of the appraisal from failed or unserviceable through to pristine or as-new condition. If sufficient records or previous inspection notes exist, it may be possible to use the rate of deterioration from this in conjunction with the latest condition appraisal to assess the residual life. Residual life is not easy to determine and is often a decision based on experience rather than on measurement or calculation. Due to the imprecise nature of the appraisal of residual life it is often described in bands (for example, <1 year, 1–5 years, >5 years). Residual life, however calculated, can then be used to assist in the prioritisation of maintenance works.

Poor condition may be a trigger for intervention, but it is suggested that performance is evaluated before the decision to intervene is made because the condition may not affect the ability of the culvert to perform its function. Feedback from condition appraisals should be considered in the re-appraisal of the asset management strategy, particularly the frequency of inspections and the need for special inspections. In some instances, for example where collapse has occurred (or is imminent), this performance assessment may be no more than a consideration of the consequence of failure (ie any restriction to the flow or disruption to access over culvert is unacceptable).

7.3.3 Performance assessment

Following a condition appraisal of a culvert, an assessment of the performance of a culvert should be undertaken. This will confirm if the culvert has an adequate performance compared to its performance requirements. A guide to the various levels of hydraulic performance assessments for existing structures is shown in Table 2.1.

To undertake a performance assessment further data may be required to adequately assess the performance of the culvert. For example, this may include rainfall and flow records for hydraulic assessment, as-built drawings, geophysical or intrusive testing for structural assessment, and compliance with environmental and health and safety legislation. Results of these assessments can then be compared to the performance requirement, with inadequate performance being a trigger for intervention.

Should both condition and performance be acceptable it is suggested that the operational plan is revisited to ensure that the frequency of inspections remains appropriate. Determination of inspection frequency is discussed in Section 7.2.3.

Guidance on the calculation of hydraulic capacity is given in Chapter 6. It is recommended that a suitably qualified engineer assesses the structural performance of a culvert.

7.4 Prioritisation of works

The process of inspection, condition appraisal and performance assessment will produce information that provides the basis for the decision to intervene. Based on the condition of the culvert, its current performance relative to its performance requirement and the consequence of its failure as described in Section 2.3, the asset owner should be able to prioritise works to their culverts within the context of managing their overall asset base. It is acknowledged that budget constraints may also affect any programme of maintenance or replacement works and a plan of improvement works should be developed to meet the budget based on the prioritisation of the risks and consequences.

It is good practice for managers of large asset stocks to develop decision support processes and tools to support prioritisation of works. This tends to be primarily risk-based, taking on board practical issues and constraints. In the case of culverts, important practical issues and constraints include:

- the time of the year, which could affect availability of access, likelihood of safe environmental conditions (for example, water levels, flows and tides) and extent of disturbance to aquatic and marginal habitats
- remoteness of culvert location
- potential for efficiencies or opportunistic timing by taking advantage of other planned works near to the culvert
- timing of operationally convenient or shut-down periods, where works will require disruption to operation over culvert.

The Highways Agency and Transport Scotland use the *Value management of the structural renewal* programme to objectively prioritise work across different categories. The method uses a risk assessment approach where problems with a structure are identified as risk events, their likelihood and consequences evaluated and scores attached to determine the priority of a project.

8 Remedial works

8.1 Introduction

While government policy within the UK is expected to lead to a reduction in the rate of construction of new culverts, the need for management of the existing stock, as they deteriorate over time, to enable continued achievement of their performance requirements remains. This is not helped by the fact that the majority of culverts within the UK are very old, with many over 100 years old. Problems of loss of capacity due to the build-up of sediment and obstruction by debris have been exacerbated by inadequate access provision for maintenance. Also the effects of increased loadings and general age related deterioration has resulted in numerous culverts requiring refurbishment.

The need to carry out works to culverts is normally identified in one of three ways:

- an outcome of a planned process of monitoring, inspection, condition appraisal and performance assessment (see Chapters 2 and 7)
- following an occurrence (such as a major flood event, blockage or collapse) that indicates the performance requirements require updating, or are no longer being met
- following a change of requirement (such as increased loading capacity, increased discharge due to new development or new legal requirements).

The decision on whether or when remedial works should be carried out is strongly influenced by the risks posed by the deterioration and the balance between costs and benefits. Further guidance on the appropriate approaches for deciding on the need for remedial works or its risk-based prioritisation within a wider programme is given in Chapter 2.

Once the decision has been made to carry out works, the types of interventions are:

- works to improve hydraulic performance such as blockage clearance and increasing discharge capacity (see Section 8.4)
- works to improve structural performance such as refurbishing failing parts of the structure or extending the life of the culvert (see Section 8.5)
- works to remove culverts (see Section 8.6).

Several statutory and good practice requirements that are relevant when carrying out works to existing culverts are outlined in Section 8.2. It is important that the planning, decision on type of works and process of execution takes proper consideration of these issues to achieve sustainable outcomes.

8.2 Important considerations

The statutory requirements relating to ownership, operation and refurbishment of culverts are defined in Chapter 3. The whole-life asset management life cycle that works to existing culverts are carried out in is described in Chapter 2.

8.2.1 Decision to carry out works

Any form of intervention to a culvert is likely to have one or more of the following consequences:

- temporary disruption of its function, either access over it, or the discharge of water through it
- disturbance to the environment
- resource implications, manpower, plant, materials and associated costs
- health and safety risk
- creation of waste that may need to be managed or disposed of.

So the reason for carrying out works should be clearly linked to the culvert's inability to achieve its performance requirement. For major refurbishments or when considering options for a culvert at the end of its life, it is important to check that the culvert is still needed, and that there is no alternative method of crossing the watercourse nearby that could serve the same purpose or some other form of crossing or conveyance of water that does not involve culverting. Any opportunity to completely open up the culvert or to reduce the footprint of the culvert should be considered. If achievable, this will lead to a better and safer environment, reduced liability and whole-life resource cost.

If the culvert is still required and there are justifiable reasons to carry out works, then the considerations outlined in Section 8.2.2 are important.

8.2.2 Health and safety

The measures identified within Chapter 7 relating to maintenance inspections are equally valid for maintenance works. Many culverts are classed as confined spaces, because particular care and planning for the associated risks is required before remedial works are carried out on them.

To manage the health and safety risks to the team carrying out the works, and the public the designer should consider the following:

- access for people, plant and materials
- the need for confined space working
- how watercourse flows/water levels are managed during the works
- working space and methods of safely working in the culvert
- measures to keep the public safe during the works.

All of the maintenance works identified in this chapter can be considered "construction works" under the CDM Regulations 2007 with the exception of debris and trash removal, which are considered as routine maintenance. Depending on the length of the project and the number of people on site formal notification of the project may be required by the Health and Safety Executive (HSE). Further guidance on the CDM Regulations can be obtained from the Health and Safety Commission (2007).

8.2.3 Consents and licences

Construction and maintenance works with the potential to affect watercourses require consent in England and Wales under the Water Resources Act 1991 and Land Drainage Act 1991, or in Scotland under the Water Environment (Controlled Activities) (Scotland)

Regulations 2005. Before starting works in the watercourse the drainage authority must be contacted and approval obtained from the relevant authority. Further guidance relating to consents and licence requirements for works near to the watercourse is included in Chapter 3. For England and Wales, PPG5 (Environment Agency, 2007b) provides a general summary of the legal process required for undertaking maintenance works on a structure.

Operational works such as the removal of debris and trash from a channel are not likely to require formal consent. However, major maintenance works are likely to require consent for carrying out the works or for management of the waste arising from them.

Many of the culverts within the UK are very old. A significant number of them have statutory protection as important historic structures. Others are situated in watercourses or sites covered by other forms of environmental protection. Relevant licences and consents are required to carry out remedial works in such designated sites (see Section 4.3.5). Further information regarding the requirements for environmental consents is provided in Chapters 3 and 4.

8.2.4 Environmental assessment

Environmental assessment is needed for minor maintenance as well as major refurbishment works to existing culverts. An environmental assessment should be undertaken during planning of remedial works so environmental risks and impacts can be defined and mitigation identified as part of the planning process. Potential for enhancement of the culvert may also be identified during the environmental assessment prompting further investigation.

The culvert maintenance works that may affect the environment comprise:

- activities in the watercourse bed creating silt disturbance
- temporary watercourse diversions or flow bypass arrangements
- managing the discharge of contaminated water from construction operations
- preventing the discharge of polluting materials into the watercourse
- preventing dust and debris generally, and particularly from entering the watercourse
- waste management on site
- disposal of sediments from any de-silting works.

Chapter 4 provides guidance on environmental assessment and important information associated with culverts that needs consideration.

8.3 Enhancing the environmental value of culverts

Many culverts were designed and built over a century ago. So with the opportunity to improve the hydraulic or structural performance of culverts related to the structural units, current flow and sediment regime comes the opportunity to improve the structure to benefit the environment, particularly aquatic ecology. There are several measures that can be adopted to improve the culvert associated to making the interior of the culvert as similar as possible to the upstream and downstream channel. The following measures may be appropriate, subject to an assessment of the impacts on the hydraulic capacity of the culvert:

Encouraging the development of a natural bed within the channel

Knowledge of the channel bed material upstream and downstream and replicating the size and grade of material is vital for successful substrate placement in new culverts. The culvert should be filled with material to the natural channel bed level, ideally using materials that were excavated from the bed during installation. If this is not possible, or extra material is required, then uncontaminated material should be used that is sufficiently graded.

In gravel bed rivers, it is important that a coarse layer is reinstated, acting as a bed armour layer and reducing access of high flows to the finer substrate and reduce the potential for elevated fine sediment loads until the armour layer naturally re-establishes itself. The design team should consider the depth of water and velocities through the culvert to ensure fish passage remains feasible. Further advice on the design requirements for fish passage is included in Section 9.3.8 and Table 9.3.

Provision of habitat and refuge within the culvert

Culverts reduce the heterogeneity of the channel bed and banks and the potential for migration routes, refuge and habitat for shelter. A range of habitats can be artificially provided to increase the use of the culvert as part of the river network for example:

- provision of a ledge along the length of the culvert (or an extra high flow barrel) for mammals to migrate along the river
- provision of points within the culvert cross-section where velocity changes occur locally to provide shelter and resting areas for fish
- provision of low-flow channels to provide refuge areas and maintain the link to the watercourse
- construction of bat roosts in culverts that are not subject to regular flooding
- construction of alternative habitats such as roosts and wildlife crossing points.

Advice on mitigation measures and the design of features such as mammal shelves and roosts for bats is included in Sections 10.3.4, 10.3.3 and 10.3.6 of the DRMB (TSO, 2007). Case study A3.5 provides an example relating to the construction of mammal ledges within a culvert.

Improving fish passage

In the past, culverts may well have been constructed that cause either delay or total exclusion of migrating fish. The common reasons for these problems include excessive water velocities, inadequate depth or culvert diameter, sudden change of invert level between the culvert and the watercourse, rapid change in stream hydraulics at the upstream inlet, lack of resting places, and debris accumulations causing physical blockage or combination of any of these factors. In such instances there are many structures that can be retro-fitted to improve fish migration, provided the reduction in channel capacity does not pose an unacceptable increase in flood risk.

To remove obstruction to fish migration through culverts at low head, small scale weirs located downstream of the culvert can often provide a low cost but effective solution to maintain passable water depths through the culvert. A series of such weirs can be installed over a length of the downstream channel depending on the overall head difference that is to be overcome.

Problems related to fish passage within the culvert can generally be improved by using the combined effects of increased water depth and reduced water velocity. This is achieved by increasing roughness, in the form of a baffle or other structure, or else by back-watering the culvert using a series of small low head notched weirs. This should not increase the risk of sedimentation in the culvert, health and safety risks at the site, or by a combination of these. Figure 8.1 shows a baffle in the invert of the culvert to improve fish passage.

Note the use of a low-flow channel in the centre of the channel.

Figure 8.1 ***Baffle in the bed of a channel to improve fish passage (courtesy Transport Scotland)***

Because all of these will reduce the capacity of the culvert careful consideration of the risks of doing so is required.

The replacement of flap valves with self regulating tidal gates should also be considered to permit the passage of fish on tidal culvert outfalls. The operation of the gates is discussed in Case study A3.12 and in Section 9.5.4.

Design guidance on easing fish passage related to existing culverts can be found in Armstrong *et al* (2004).

8.4 Improvements to hydraulic performance

8.4.1 Methods

If a culvert is not large enough to discharge the design flow there are many techniques available to improve its hydraulic performance. Table 8.1 indicates the typical measures that can be used to improve the hydraulic performance of culverts. Some of the techniques identified in the table are discussed elsewhere in the guide.

Table 8.1 *Methods for improving hydraulic performance*

Method	Outcome of works and further references	Limitations and restrictions
Reducing the roughness of the culvert by using a lining system	Using a "cured in place" or similar lining system to provide a smoother culvert barrel. Refer to Table 8.4 for guidance.	This will reduce the size of the barrel, however the smoother bore may compensate for the reduced section area. This option will only marginally increase the hydraulic capacity
Streamlining of inlet	Reduces head losses (and increased capacity for the same upstream water level). Stream lining could be achieved by providing bevelled edges or warped training walls (see Section 9.4.2)	Can be an effective solution for under-capacity if the culvert acts under inlet control
Streamlining of outlet	As above	Generally less effective than streamlining the inlet
Removing sediment from the culvert barrel (de-silting)	Increased cross-sectional area available for flow and reduced roughness (see Section 8.4.2).	Likely to be temporary unless there is control over the source of sediment or the wider channel sediment dynamics or cause of local sediment deposition. Methods will be governed by size of culvert, health and safety considerations and environmental impact (see Table 8.2)
Removing sediment from the channel downstream of the culvert	Increased cross-sectional area available for flow, so reduced head loss (see Section 8.4.2).	Likely to be temporary unless there is control over the source of sediment or the wider channel sediment dynamics or cause of local sediment deposition. (see Table 8.2)
Providing an extra barrel near to the existing culvert	Increased hydraulic capacity	May be advantageous for the extra barrel to be set at a higher level than the existing, so that it only carries flow in flood conditions
Pipe-bursting techniques to replace an ageing culvert	Potential for increasing capacity by increasing the size of the culvert (see Table 8.4)	More applicable to stormwater sewers than culverts due to size limitations. Typically limited to pipes no larger than 750 mm diameter
Removal of obstructions such as service crossings and tree roots	Removal of obstructions such as service crossings and tree roots (Figure 8.3 shows an example of blockage caused by pipe crossings)	Will improve the hydraulic capacity by reducing head losses. Also likely to reduce the risk of blockage promoted by debris getting trapped on the obstruction. If obstructions cannot be removed, it may be possible to streamline the flow round them, or to relocate them so that they have less impact
Removal of trash or security screen	Removal of trash or security screen (see Section 8.4.3)	Removes the risk of a large head loss across a blocked screen Should only be carried out if the associated risks (blockage of culvert or loss of life) have been fully evaluated and deemed low enough to be acceptable, or addressed in other ways. Where screen cannot be removed, options to increase the spacing between bars or improve debris removal, eg by installing an automatic screen cleaner, could be investigated

8.4.2 Sediment management

The removal of sediment from culverts can often be a difficult, hazardous and expensive operation that can be reduced by amending the structure or channel or management approaches.

In many cases sediment is removed from in-channel structures, especially culverts, because of many different pressures, which can include:

- public concerns
- flood risk management pressures
- custom and practice, without a clear objective for its removal.

One of the first steps in deciding on appropriate action for solving sediment-related problems is whether the problem is self-limiting (will the sediment-related problem naturally adjust, and the level of sediment reduce over time rather than get worse?), or if the removal of sediment is actually necessary to achieve the required performance requirements. If not, there is a potential to save money and avoid disturbance to the watercourse environment by not removing the sediment.

The basis for assessing whether to undertake sediment management practices should involve an analysis of the consequence of the sediment deposition and appropriate mitigation measures being identified to solve them. If the consequence is high, for example sediment management being required to reduce flood risk to properties and infrastructure, upstream, then management of sediment can be justified.

Operations to remove sediment have the potential to create large volumes of suspended silt within the watercourse. This will require managing to prevent contamination of the watercourse downstream of the culvert. Environmental assessment should determine the sensitivity of the watercourse and feed into the decision making process on the methods to be used to limit environmental damage and the design and implementation of mitigation measures.

Where sediment management is deemed necessary, detailed guidance and advice on the issues and solutions is available through consultation with regulators and documents such as Murane *et al* (2006).

The management of sediment in the culvert can either be active or reactive, depending on the hydraulic capacity of the structure and the risk of upstream flooding. For a structure where access into the culvert is difficult an active management regime may be appropriate, while for a structure with easy access and /or no history of sedimentation problems, a passive regime may be suitable.

An active regime is preventative and could involve management of the reach and/or sediment sources upstream where the problem is more at a strategic scale, or locally undertaking routine works to minimise the deposition of silt within a culvert. A passive maintenance regime is reactive and would involve the removal of silt from a culvert on either a programmed or irregular basis.

When assessing the options associated with the management of silt within a culvert, the following factors associated with the removal of sediment need to be considered:

- access to the culvert for sediment removal operation
- time of the year for sediment removal

- environmental impacts of sediment removal
- frequency of removal of sediment
- type of sediment and contamination issues
- how long deposition has occurred and the extent of compaction.

Reactive sediment management

Reactive sediment management involves the removal of silt once it has reached a threshold level determined by hydraulic analysis and linked to the hydraulic performance requirement of the culvert. This can be an appropriate management technique where sediment build-up is not a wider problem within the watercourse and other local active measures to reduce the chance of future sediment build-up are not appropriate. In some cases, it may be necessary to carry out reactive sediment management to deal with the inadequate hydraulic performance of the culvert in the short-term, but support this with active sediment management to reduce the probability of future sediment build-up.

Table 8.2 indicates the typical approaches to sediment removal used in culverts.

Table 8.2 *Methods for removing siltation*

Method of sediment removal	Brief description of works	Limitations and restrictions
High pressure jetting (not to be confused with very high pressure jetting, which is a demolition technique)	The removal of silt by the use of high pressure jetting. Jetting can be carried out without the need for man-entry into the culvert. Advice on suitable forms of jetting is included WRc (2005b)	The use of high pressure jetting may damage brick built culverts that are in a poor condition. This method will only move silt downstream and may cause a restriction in the channel downstream. It is essential to take steps to stop the sediment laden water from causing a pollution problem downstream. This may add considerably to the cost of this option
High pressure jetting with a vactor unit	Involves the use of a suction tanker to remove silt and water from the culvert. Entry into the culvert by staff is not required	High pressure jetting may damage brick built culverts that are in a poor condition. The method allows the disposal of silt off site. This method of sediment removal uses commonly available items of plant. It is often used in conjunction with CCTV surveys. The environmental impact of such work should be considered. For densely compacted material other forms of break out may also be required
Manual removal	Manual removal of silt from culverts	Should be avoided if possible due to the hazards associated with working within a confined space. Access for spoil removal, suitable ventilation and lighting are required
Mechanical winch system	Silt is dredged using a dragline system without the need for man-entry into the culvert. Once the silt has been winched out of the culvert it can be removed using an excavator and disposed off-site. Entry into the culvert by staff is not required	The system can be effectively used in remote areas where access to the culvert can not readily be reached by road going construction plant. If larger obstructions (eg large branches or rock) are present within the culvert these can be removed easily as part of the de-silting operation
Mechanical removal by machine	In larger culverts where plant access is possible the removal of silt can be undertaken by the use of small excavator or skid steer loader. Excavated material, if contaminated can be disposed of off-site	Limited to large culverts only, entry by staff is required. Access for spoil removal and ventilation is required. Access into watercourse bed for construction plant is required. A good solution for the de-silting of large culverts and removal of large items of debris. Usual confined space considerations apply

Active sediment management

To reduce reactive sediment management the use of an active sediment management regime could be considered. These techniques would require an initial investment, but they will often lead to lower whole life costs because of reduced maintenance requirements. Before changing the geomorphological aspects of the watercourse, a clear understanding of the sources of sediment and their effect on the physical processes within the watercourse is required. The effects of channel geomorphology are discussed in Section 5.5.

The following options could be considered to reduce the build-up of sediments within culverts:

1 **Improvements to the downstream channel or control**

Sediment deposition in a culvert will increase if water levels are backed up by a restricted channel downstream. Improving the downstream channel should reduce the sedimentation problem in the culvert. This could involve vegetation or channel management or removal of obstruction in the watercourse (eg a redundant or unauthorised weir). Section 9.2.3 describes the preferred channel alignment for a culvert.

2 **The construction of a silt trap upstream of the culvert**

A silt trap is an engineered section of the channel in which flow velocities are reduced. This allows sediments to fall out of suspension in the channel at locations where they can easily be removed, reducing sedimentation within the culvert. Sediment traps require regular maintenance to ensure that they remain effective. However, the design team should consider the implications of reducing the transfer of sediment to downstream reaches. The starvation of sediment to downstream reaches could induce channel instability problems such as bed and bank erosion, threatening the design capacity or stability of the watercourse downstream. The trapping of sediment in an existing drainage system may affect the geomorphology and ecology of the downstream channel by removing a sediment source. Before investigating the design of a silt trap, the culvert owner should ascertain the extent of their land ownership and if these works can be undertaken within their legal powers. Notes regarding the design of silt traps are included in Section 9.4.4.

3 **The construction of a primary screen (refer to Section 9.4.3)**

A boulder/roughing screen prevents large debris such as large boulders and large woody debris (LWD) from reaching the entrance to the culvert. This is often installed some distance upstream of the culvert and prevents large boulders and LWD from potential partially or completely blocking the culvert. Also during high flow events, debris can cause severe damage to the culvert increasing costs associated with the operation and maintenance of the structure. A primary screen can be installed within the bed of the channel at a location where there is good access to the channel to allow the safe removal of LWD and boulders, without significant damage to the watercourse environment. This technique has been used successfully on the Mosset Burn Flood Alleviation Scheme in Morayshire, as shown in Figure 8.2 where the risk to blockage from LWD was a main risk to the performance of the scheme. As with any other screen, it will require regular inspection and maintenance to ensure it is performing as it should do and also not causing adverse effects on the channel immediately upstream or downstream. Any such adverse effects can be rectified through adaptive management as part of the post-construction monitoring regime.

Note the timber screen posts are set into a low strength mortared socket, to allow future replacement. Suitable access for the removal of large pieces of debris is provided to the screen.

Figure 8.2 *Primary screen (courtesy Royal Haskoning)*

1 **The installation of low-flow benching in the culvert to increase flow velocities**

As culverts will carry a wide range of flows ranging from flood flows to virtually no flows within their life cycles, the velocities within the culvert can change significantly. In times of low-flow water flows over a large surface area and velocity in the culvert will reduce, resulting in the deposition of sediments into the channel. The use of benching to provide a low-flow channel can reduce the flow area and increase velocities within the culvert (Figure 8.1). The installation of benching can also provide environmental benefits, as it may act as a mammal ledge or improve passage for fish. Further details are given in Section 9.2.4. The installation of benching should be limited to culverts that have an acceptable hydraulic capacity. Before the installation of benching an assessment should be made to check loss of capacity of the culvert during flood flows (refer to Section 6.3).

2 **Wider catchment management**

Given that sediment-related problems in watercourses are often driven by catchment sediment yield and changes within, it follows that controlling sediment input to the watercourse system at source may be a viable solution. Controlling sediment at the source may involve changes to land-use and sediment management, or controls introduced in the headwater streams, reaches and tributaries. This form of wider catchment management should be undertaken in conjunction with the relevant drainage authorities to develop suitable management systems.

The sources of fine grained, catchment derived sediment can take the form of both point sources such as drainage outfalls, tributary confluences and bank instability problems, and also diffuse sources such as bare soils resulting from agricultural work, overgrazing problems or deforestation. Example measures for point source control include installing appropriate erosion control measures or silt traps. In contrast, reduction of high sediment loads derived from multiple sources within the catchment will require a long-term approach and the co-operation of landowners and other relevant parties. Measures can only work effectively if all parties realise the benefits from more environmentally friendly agricultural activities such as change to land management that conserve soil and reduce erosion. This can be achieved through reduced stocking densities, drilling instead of ploughing, and planting of buffer strips to reduce sediment entering the channel. Further information on controlling point and diffuse sources can be found in Sear *et al* (2003) and Wallerstein (2006).

Sediment disposal

It is good practice to incorporate as much of the sediments generated from sediment management within the works or to reuse it locally, subject to compliance with the relevant waste management regulations. Where it is necessary to dispose of sediments, assessment of the condition and volume of sediment to be removed and disposed of will need to be carried out in advance. Transportation of material considered hazardous will need to be carried out by an authorised carrier, the disposal site will need to be identified in advance and confirmation of its suitability to handle the material will be required. To enable this information to be collated the sediment volume should be calculated and the material submitted for chemical analysis.

Good practice guidance on the removal of wet dredging material can be obtained from the Association of Inland Navigation Authorities (2007). If it is intended to reuse excavated dredging on site reference should be made to CL:AIRE (2008). The use of waste exemptions will be subject to the adoption of new regulations likely in 2010 and the users of the guide should seek suitable guidance from the appropriate regulatory authorities (see Chapters 3 and 4).

8.4.3 Removal of debris and trash

Blockages and obstructions within culverts have a significant effect on their performance and have the potential to significantly increase flood risk. A blockage or obstruction to a culvert can occur because of fly-tipped waste in the channel, debris washed downstream or by service ducts installed directly through culverts, or a combination of both.

Figure 8.3 show culverts with significant blockage.

Figure 8.3 *Obstructions within a culvert (a) and debris blocking a culvert entrance (b) (courtesy Richard Allitt and Scott Arthur)*

The risk of blockages occurring within a culvert depends on several factors including the physical characteristics of the catchment, the size of the culvert and its location.

Before selecting which management approach to adopt, it is recommended that a risk assessment is undertaken in accordance with the Environment Agency (2009a). This provides comprehensive and detailed guidance on the assessment of the need for, and the design of, inlet screens to culverts. For a high risk structure an active management regime may be appropriate, while for a low risk structure a reactive regime may be suitable.

An active regime, would involve actively monitoring the watercourse for potential obstructions and arranging for their removal particularly in times of high flow in the watercourse. It could also involve undertaking actions such as the installation or removal of trash screens, improved local stewardship of the area and restricting access to the watercourse. A passive maintenance regime would involve the removal of large objects from the watercourse on either a periodic or irregular basis.

Reactive debris and trash removal techniques

The type of debris and trash accumulating within a watercourse can vary significantly from the build-up of weeds to large items such as mattresses, shopping trolleys and cars. The method of the removal of debris and trash will depend on the access issues.

The safety issues associated with debris and trash will often dictate the method of removal. The typical methods used can vary from the use of mechanical equipment like shovels, weed rakes, mechanical grabs and winches through to automatic weed-screen cleaners. Methods used for the removal of sediment can also be frequently used.

Active debris and trash management

Should a culvert have a known risk of blockages or obstructions there are several active management techniques that can be used to minimise the risks of flooding caused by a blockage or obstruction:

1 **Increasing the size of the culvert**

If blockages are a known problem increasing the size of the culvert can reduce the potential for future occurrence. In the case of larger culverts this is likely to involve the replacement of the culvert, while options such as pipe bursting (for diameters up to 750 mm), may be possible for smaller structures. Increasing the size of a culvert opening may only be economically feasible if the risk of upstream flooding is high with severe consequences. When considering this option the downstream impacts of increased flows should be taken into account.

2 **Installation of trash screens**

The installation of a trash screen could reduce debris and obstructions from blocking a culvert. However the provision of a screen significantly increases the operational costs of the asset and if not maintained may result in upstream flooding. Providing a screen should be considered as a last resort. The design of screens is discussed in more detail in Section 9.4.3 and in guidance by the Environment Agency (2009a). If the design of a new screen is developed as remedial works, further works to the upstream inlet may be required to provide a sufficient area for the screen installation along with accommodation works to provide adequate working and storage areas.

3 **Installation of boundary protection measures**

The installation of physical control measures to prevent access to the watercourse can be used to provide a deterrent for fly-tipping or to limit the migration of straw bales or small debris into watercourses. Examples could include the installation of fencing, and the planting of thorned species of vegetation with adequate secure access points to the channel. To be effective, this approach would need to extend beyond the locality of the culvert to prevent debris from moving downstream. Fencing could be particularly targeted to the boundaries of industries near to watercourses such as supermarkets and farmlands during straw baling season, where there is potential risk of encroachment of debris or carriage by high winds. Before adopting such measures, the culvert owner should ascertain the extent of their land ownership and if these works can be undertaken within their legal powers. This method may make access to the culvert more difficult and could make rescue of trapped people from the watercourse harder.

4 **Wider catchment management**

In areas where fly-tipping is known to be a problem, the asset manager in conjunction with other local partners could consider the introduction of wider catchment based measures such as anti fly-tipping campaigns, educational programmes or the use of high profile prosecutions for fly-tipping. This form of management is likely to be a long-term approach and will need the co-operation of landowners and other relevant parties.

To prevent debris from entering the watercourse in conjunction with local landowners, buffer zones to the watercourse could be established that keep areas above the normal flood line free from debris. For example, in catchments that are densely wooded, a programme to regularly remove fallen trees or woody debris in high risk locations could be used to reduce the chance of a culvert becoming blocked. Advice should be sought from appropriately qualified professionals including an ecologist.

5 **The use of remote monitoring techniques**

For high risk sites where the risk and consequences of an obstruction are high methods such as the remote monitoring of sites have been considered and trialled, these can involve the following:

- the use of remote telemetry upstream and downstream of a screen
- the use of a webcam or a CCTV system to monitor culverts.

Section 7.2.5 provides further information about remote monitoring techniques.

8.5 Structural maintenance and repair techniques

8.5.1 Masonry

The majority of the culverts within the UK are of masonry construction. A large number of masonry culverts have diameters less than 900 mm, resulting in difficulty to access and maintain. The minimum size of culvert suitable for physical entry to undertake remedial works is typically 1.2 m diameter.

Note that the vegetation growth in the barrel may indicate leakage of water through the culvert barrel.

Figure 8.4 *Typical large masonry culvert showing general mortar loss to the culvert barrel (courtesy Ferro Monk)*

Typical defects

Masonry structures typically suffer from the following range of common defects:

1 Loss of mortar: the deterioration of mortar is a pre-cursor to more serious defects that can result in the loss of brickwork to the structure leading to structural failure of the culvert. The loss of mortar can occur from deterioration to the interior of the culvert and also by water seepage from the exterior of the culvert. The loss of mortar can lead to the loss of fines around the exterior of the culvert, and voids in the backfill and subsidence of the ground above. Figure 8.4 shows a culvert with significant loss of mortar, Figure 8.5 shows a culvert that has significantly deformed.

2 Cracking that can be the result of a variety of causes including overloading, vibration, settlement, foundation failure, temperature changes and wetting and drying.

3 The spalling and deterioration of masonry units because of wetting and drying and frost damage.

4 The separation of multiple courses of brickwork within the arch ring resulting in loss of structural capacity of the arch.

5 Deformation because of overloading, water ingress or settlement.

Further information relating to typical defects and repair methods of masonry structures can be found in McKibbins *et al* (2006). Information relating to typical defects and repair methods for smaller masonry culverts less than 900 mm diameter can be found in WRc (2009).

Figure 8.5 *Deformation of a masonry culvert typical large (courtesy British Waterways)*

Table 8.3 indicates a typical range of minor repair and maintenance techniques used for the repair of masonry culverts. Some of the techniques listed require man-entry and are only suitable for culverts with a diameter greater than 1.2 m.

Table 8.3 *Minor repair and maintenance techniques for masonry culverts*

Remedial measures	Brief description of works	Limitations/restrictions /further information
Robotic cutting systems	Robotic cutter systems can be used to clear obstructions in culverts such as tree roots (it may also be worth considering felling any trees that are near to the culvert), fence posts, debris, concrete and bars The system is operated by a specialist team from a specially equipped vehicle carrying all the control systems and CCTV monitoring equipment	Suitable for small culverts only. Manual removal with access scaffolds will be required for larger culverts Further information is available in WRc (2009)
Ensure that any weep holes in the structure or headwalls are working efficiently	Water is an important factor in the gradual deterioration of a culvert's structural fabric. Effective management of water is fundamental to the long-term serviceability of a culvert. The structure should be maintained by ensuring all drainage paths are kept clear and functional, and avoiding the use of impermeable mortars for re-pointing and repair works	Technique is only suitable for man-entry culverts
Removal of vegetation from all parts of the structure	Plants have the potential to disrupt and displace the fabric of a culvert, block drainage and retard the drying out of wet masonry. Ideally they should be completely removed from the structure, and monitored in nearby areas. Vegetation should be cleared away from all parts of the structure and roots removed. Vigorously growing plants and shrubs immediately near to the structure should also be cleared away because their roots may penetrate the masonry and foundation	Technique is only suitable for man-entry culverts
Re-pointing of masonry	Loss of mortar from joints reduces the ability of the masonry to transmit and evenly distribute forces, focusing stresses in localised areas and potentially causing cracking and distortion. The loss of mortar may result in the loss of backfill material to the culvert leading to loss of stability and subsidence Re-pointing should be undertaken on a regular basis to prevent further deterioration of the structure. The mortar used to re-point the culvert should be carefully selected to ensure the masonry can accommodate a small amount of movement and is sufficiently permeable to allow moisture in the masonry to evaporate through the joints For areas of shallow mortar loss manual re-pointing can be undertaken. This involves removing areas of loose mortar and re-pointing using traditional techniques. For areas of deep mortar loss pressure pointing can be used. This involves injecting a suitable mortar under pressure, using spray pointing equipment to fill the void	Technique is only suitable for man-entry culverts Further advice on the selection of mortar is included in McKibbins *et al* (2006)

A typical range of major refurbishment techniques for masonry culverts are shown in Table 8.4. The table includes options for the design of various lining procedures commonly used for sewer rehabilitation works. The design of lining systems are typically based on two main design procedures.

- **Type 1:** Designs assume that the new lining system, its grouted annulus and the existing culvert form a rigid new composite system.
- **Type 2:** Designs assume that lining is designed as a flexible pipe and are used to stabilise the old culvert, which continues to carry the structural loads. Type 2 designs are not normally used on culverts that have severe structural defects.

The UK water industry specifications and guidance notes (see *Useful websites*) provide the most relevant specifications for use in relating to relining works to existing culverts.

Any form of lining works to culverts may affect bat habitat and suitable surveys should be undertaken before the development of any remedial works. Any form of lining and repairs could reduce the cross-sectional area of the culvert and checks should be made of the resulting hydraulic capacities, before completing the design.

Table 8.4 *Refurbishment works to masonry culverts*

Remedial measures	Brief description of works	Limitations/restrictions/ further information
Internal lining systems		
"Cured in place" lining	A flexible liner that follows the shape of the existing culvert is inserted by using water (or air in some cases), which ensures that the liner fits closely against the shape of the existing pipe and maintains its designed thickness The water inside the liner is heated and circulated to cure the resin in the liner. Steam or ultraviolet light is sometimes used to allow the liner to cure. The ends of the liner are then cut neatly at each end of the pipe using specialist cutting equipment	This technique commonly used for culverts with a diameter up to 2.8 m If the existing culvert barrel is in a poor condition, repairs to the culvert will be required before the installation of the lining Further information relating to the design of cured in place linings can be obtained from the sewerage risk management website (WRc, 2009) manufacturers' literature and specialist contractors. Also see Case study A3.6
Pipe bursting	Pipe bursting techniques can be used to replace the barrel of a culvert. Pipe bursting is carried out by driving a mole through the existing culvert, which breaks the existing pipes and pulls through a new structural lining	The maximum size that pipe bursting methods can be used to is 750 mm. This method can cause some localised ground disturbance and maintaining alignment can be difficult
Sprayed lining	Application of structural sprayed concrete, cementitious mortar or polymeric resin to the interior of the culvert to repair and strengthen culverts that are suffering from major defects such as arch barrel distortion, deteriorated masonry and severe cracking. Figure 8.7 shows the installation of a sprayed lining in a culvert	The application of spray linings can be undertaken either remotely or by man-entry into a culvert. The system requires flow diversion during the works to ensure that the lining is bonded to the pipe. See Case study A3.7 for more information
Slip lining	Slip lining involves drawing or jacking a pipe through the existing culvert. The annulus is typically filled with a grout to seal the void. Slip lining an existing culvert will reduce its diameter, however new liners are likely to be smoother than old linings, which minimises the impact on the hydraulic capacity of the culvert. Slip linings are often used when a culvert is showing signs of structural distress and a rigid replacement system can be used. Figure 8.6 shows a culvert following the installation of slip liner	This technique is suitable for both man-entry and non man-entry culverts The lining pipes can be a combination of materials, including MDPE, HDPE, GRP and steel liners. Further advice relating to the design of slip lining systems can be obtained from the WRc (2009), manufacturers' literature and specialist contractors. See Case study A3.8 for more information
Lining with pipe segments	Lining with pipe segments involves the installation of short sections of pipe in an existing culvert. The linings could be used as a permanent formwork system or as structural pipes. Figure 8.8 shows the grouting process used to fill the annulus	These systems require man-entry for installation and grouting works

Table 8.4 (contd) *Refurbishment works to masonry culverts*

Structural repair techniques		
Arch grouting/ ring stitching	Aims to fill voids present within the arch barrel and re-establish the mechanical connection between the arch barrel rings. Overlapping reinforcement dowels can be installed into holes drilled through the internal curve of the arch and grouted into place Grouting can also be used to stabilise voids in the surrounding backfill, which may have developed over time	Works can only be undertaken in large culverts with man access The culvert barrel needs to be structurally sound before the starting of grouting works The limitations of arch grouting is included in McKibbins *et al* (2006)
Backfill replacement or reinforcement	Aims to provide a more competent fill material over the structure. The objective is normally to enable more even distribution of loads, or to reduce the dead loading on the structure by replacing the existing fill with lower density material	Only likely to be economically viable for large spanning culverts with minimal cover
Patch repairs	Patch repairs involve the local replacement of defective stonework or brickwork when it is heavily damaged or deteriorated, aiming to reinstate structural integrity and/or to improve appearance	Works can only be undertaken in large culverts with man access Some patch repairs can be carried out remotely using cured in place patches. Case study A3.9 provides an example on the range of patch repairs that could be undertaken on a masonry culvert
Relieving slabs	Installation of a horizontal reinforced concrete slab over the plan area of the culvert, extending over the abutments. Aims to improve live load carrying capacity of the culvert while eradicating the generation of extra horizontal thrust from the culvert into the abutments at springing level	
Retro-reinforcement	Installation of extra structural reinforcement to the arch barrel. Aims to increase its structural capacity without reducing structure clearances or significantly affecting the culvert's appearance	
Spandrel tie-bars/ patress (spreader) plates	The aim is to prevent the culvert headwalls from experiencing excessive lateral forces or movements due to lateral pressure from the fill, for example, from passing traffic. Reinforcing tie-bars provide structural connection between the spandrels and load is transferred to the new patress plates and tie bars via the headwalls	
Surface thickening	Provision of extra thickness of surfacing to distribute the live loads more evenly through the culvert. It can result in a higher live load capacity for the structure	
Underpinning	Involves the construction of a new foundation for the culvert to allow an improved transfer of loading	Only likely to be economically viable for large spanning culverts where plant access is available into the culvert
Waterproofing and drainage improvements	Provision of an effective drainage system, comprising either a bonded or loose-laid waterproofing membrane above the arch, to prevent water ingress into the structural elements. This prolongs the culvert's serviceable life reducing its maintenance requirements	Only likely to be economically viable for large spanning culverts with minimal cover

Figure 8.6 *Slip lining of a masonry culvert (courtesy British Waterways)*

Note the reduction in the sectional area of the culvert.

Figure 8.7 *Sprayed lining to a masonry culvert (courtesy Ferro Monk)*

Figure 8.8 *Grouting of GRC liner (courtesy Ferro Monk)*

Chapter 8

8.5.2 Corrugated steel structures

A large number of corrugated steel buried culverts have been installed over the past 40 years. The structural performance of these culverts has generally been excellent, where failures have occurred these have typically been related to excessive deformation generated either by poor construction practice or by ground movements.

Figure 8.9 shows a typical corrugated steel culvert with a protective coating.

Note the black paint work is a bituminous protective coating.

Figure 8.9 ***A typical corrugated steel culvert (courtesy Richard Allitt)***

Corrugated steel culverts deteriorate mainly through hydraulic wear in the invert and along the wet/dry line. This effect can be particularly predominant on gravel bedded watercourses. Gravel can abrade and remove protective coatings, exposing the steel substrate to corrosion. Deterioration of culverts is also promoted through exposure to water laden with de-icing salts or sulphur compounds present in the backfill and surrounding soil. Deterioration is often localised and in the extreme results in perforation of the steel shell, which may require strengthening works or, if in an advanced state, replacement of the structure.

Common maintenance and refurbishment techniques for steel culverts are shown in Table 8.5.

Table 8.5 *Repair and refurbishment works to steel culverts*

Remedial measures	Brief description of works	Limitations/restrictions/ further information
Installation of a concrete invert	A concrete invert can be used to line the bottom and the side walls of the steel culvert to prevent corrosion of the steel liner. This could be extended along the sides of the culvert to reduce corrosion	A suitable structural connection between the steel ring and concrete paving is required. Flows should be diverted or controlled during the works
Installation of coated, galvanised steel/GRP sheets along the wet/dry line	Sacrificial coatings can be used to line the bottom and the side walls of the steel culvert to prevent corrosion of the steel liner. This could be extended along the sides of the culvert to reduce corrosion	A suitable structural connection between the steel ring and concrete paving is required. Flows should be diverted or controlled during the works
Grouting the fill to minimise seepage from the exterior of the culvert structure	Grouting may be used to fill voids within the backfill, which stabilise the structure Normally a sand/cement mix is used where structural support is required. Where seepage is occurring into the structure or through the joints into the backfill, an expanding water reactive grout can be used to provide a waterproof barrier	Unless low injection pressures are used, disturbance to nearby structures, services and the overlying infrastructure may occur. Care should be taken to ensure the grout does not pollute existing watercourses or penetrate drains and service ducts
Internal lining systems	See Table 8.4	See Table 8.4
Repairs using "cured in place" patch	See Table 8.4	See Table 8.4
Construction of boulder and trash screens to remove abrasive solids	See Section 9.4.3	
Application of secondary protective coating to maintain and protect the galvanised shell	This involves the refurbishment and replacement of the bituminous coating to a culvert. By the application of new painted surface to the galvanised shell	The success of the application of a coating is dependent on the correct preparation of the steel work. Flows should be diverted or controlled during the works and suitable environmental protection works are required to manage the risk of contamination of the watercourse

The DMRB (TSO, 2007) gives guidance on the inspection, maintenance and repair of corrugated steel culverts.

8.5.3 Concrete box culverts and pipes

Buried concrete box structures and pipes are often used as culverts. They can be of cast in situ or pre-cast concrete construction.

Figure 8.10 shows a typical pre-cast concrete culvert.

Figure 8.10 *A typical pre-cast concrete culvert (courtesy Richard Allitt)*

The Highways Agency have found from their inspection records that most of their buried concrete structures are performing well and have required little in the way of maintenance. However, inspections have identified several common defects relating to the structures that may reduce the service life of the structures without proper maintenance. These commonly include:

- the lack, or failure, of waterproofing systems and poor drainage of the surrounding backfill, leading to the ingress of groundwater. This could result in the loss of backfill to the culvert and accelerate spalling and deterioration of concrete through the ingress of water into cracks
- differential ground movements leading to the cracking of boxes and to the failure of joints between individual units. This can lead to the passage of water through the structure resulting in the deterioration of the concrete
- shrinkage cracks on in situ culverts because of construction. In some cases this can lead to the deterioration of the concrete
- cracking through excessive loading might be seen on structures with particularly low depth of cover
- scour and undercutting of the end elevations may occur because of excessive flow velocities downstream of the structure
- chemical reactions between the cement and aggregate or between constituents in the concrete and surrounding soils such as alkali silica reaction or thaumasite resulting in the degradation of concrete.

The DMRB (TSO, 2007) gives guidance on the inspection, maintenance and repair of buried concrete structures.

The typical range of repair techniques used on these structures is shown in Table 8.6.

Table 8.6 *Repair and refurbishment works to concrete culverts*

Remedial measures	Brief description of works	Limitations/restrictions/ further information
Internal lining systems	See Table 8.4	See Table 8.4 Figure 8.11 shows the installation of corrugated steel lining before backgrouting
Repairs using "cured in place" patch	See Table 8.4	See Table 8.4
Application of waterproofing	The application of a structural waterproofing system to the exterior of a culvert will minimise the ingress of water into the culvert	Will require removal of backfill to culvert and factors such as the depth of cover to the culvert, location of services and the impacts on the highway will define if applying an external system or lining the culvert would be more effective
The installation of replacement joints and seals	Proprietary sealing ring products installed from the inside of the culvert pipe, suitable for concrete and GRP pipe materials. Alternatives include injecting a sealing grout around the outer face of the culvert	Most techniques require man-entry. Localised linings may be used in certain areas
Concrete repairs	As the deterioration of concrete structures occurs through several mechanisms, it is important to understand the failure mechanism. The Concrete Society (2000) gives guidance on the causes of defects, the assessment of these and suitable remedial works. Best practice guidance on the range of concrete repair methods is included in Pearson (2002) with reference to BS EN1504:2004 and The Concrete Society (2009) In some cases electrochemical repair methods can be used to stop the corrosion of the reinforcement. This form of repair is not commonly used in concrete culverts. Further information is available in TSO (2007)	Most techniques require man-entry. A large number of repair techniques are available

Figure 8.11 *Installation of a corrugated steel lining to a pre-cast concrete culvert (courtesy Manuel Lorena)*

8.5.4 Plastic pipes

Glass reinforced plastic (GRP), unplasticised polyvinyl chloride (uPVC), and high and medium density polyethylene (HDPE and MDPE) pipes have been used in culvert construction over the past 30 years. These are usually designed to be flexible and rely on the resistance of the surrounding fill to achieve their structural integrity. Some manufacturers produce heavy-duty polythene pipes that are suitable for carrying high loads at shallow depths. Typical defects related to the GRP, uPVC, MDPE and HDPE pipes comprise the following:

- embrittlement of plastic pipes with age
- failure of joints within pipes
- deformations of the pipes (occurring during the backfilling process)
- thermoplastics such as polyethylene, polypropylene and uPVC tend to creep when subjected to loading.

Repair methods for GRP, uPVC, MDPE and HDPE pipes are defined in WRc (2009).

A typical range of repair techniques for plastic pipes are described in Table 8.7.

Table 8.7 *Repair and refurbishment works to plastic pipe culverts*

Remedial measures	Brief description of works	Limitations/restrictions
Internal lining systems	See Table 8.4	See Table 8.4
Repairs using "cured in place" patch	See Table 8.4	See Table 8.4
Welded patch repairs to the culvert	Fusion welding techniques can be used to undertake repairs to damaged sections of pipes	Man access to the culvert is required

8.5.5 Scour

Structures built in watercourses may be prone to scour around their foundations. In the case of culverts scour tends to occur at the outlet of the culvert, if the depth of scour becomes significant the stability of the foundations may be at risk. Localised scour will tend to occur at the transition between a hardened and natural watercourse bed. The rate of scour depends on the velocities of the discharge flows, artificial restrictions and the resistance of the bed material to this.

May *et al* (2002) provides comprehensive advice on the treatment of scour to existing structures, as well as advice on the design of scour protection measures. The DMRB (TSO, 2007) gives advice on avoiding scour in the design of highway structures in watercourses.

Scour to the downstream of culverts can be managed in several ways. This will depend on the flow velocity, size, depth and location of any scour holes, and access to the watercourse. Typical examples of materials used to limit the effects of scour include:

- rip-rap at the downstream end of the structure, which can either be placed as loose material or be grouted to provide a solid revetment
- gabion revetments or reinforced grass
- grouted bag revetments

- stilling basin to dissipate energy with baffle walls, stilling basin or baffle blocks arrangement, (see Section 9.5.3)
- extending the downstream apron and the provision of cut-off downstream of the apron, for example a sheet-piled cut-off.

8.5.6 Erosion

In channels that are fast flowing and carry a significant amount of coarse sediment, erosion of the structural fabric of the culvert may occur. Typical remedial measures for the fabric of the structure are described in Section 8.4. Measures to prevent coarse sediment from entering the culvert are described in Section 8.4.2.

8.6 Removal of culverts

Since the 1990s the negative impacts of culverting watercourses on flood risk, ecology and amenity have been acknowledged (CIWEM, 2006). In response to this, many culverts in both urban and rural areas have been opened up through the process of watercourse restoration or "daylighting". In the UK the Environment Agency, SEPA and the River Restoration Centre have played a central role in promoting this process. The Environment Agency has developed a specific policy relating to culvert removal. The removal of culverts is also supported by the Water Framework Directive.

Culvert removal provides an opportunity to restore more natural watercourse conditions, reduce flood risk and improve local amenity value. The removal of culverts is only likely to occur following a change in land-use of the surrounding area. Case study A3.10 identifies an example of where culvert removal has been undertaken. Culvert removal has the following potential benefits:

- improvement of the passage of fish, mammals, invertebrates and other aquatic flora/fauna
- recreation of aquatic and riparian habitat
- improvement of water quality by exposing water to sunlight, vegetation, and soil
- relief of choke points and flooding from under-capacity culverts
- improvement of the sediment transfer system by restoring the connection of the watercourse to the floodplain and improving downstream continuity
- reduction of maintenance costs associated with sediment removal and by replacing deteriorating culverts with open drainage that can be more easily monitored and repaired
- increase of hydraulic capacity over that provided by a culvert, by recreating a floodplain
- reduction of runoff velocities and erosion because of natural channel meandering and the roughness of the stream bottom and banks
- creation or linkage of urban greenways and paths for pedestrians and cyclists.

Culvert removal can be an expensive process, particularly for large projects with complex issues. However, there are many opportunities to integrate culvert removal projects into development schemes (eg via Section 106 agreements) or other regeneration initiatives. Many local authorities and nature conservation bodies have policies in place that advocate culvert removal. However, a culvert that is no longer required will continue to incur unnecessary maintenance and repair costs or become a health and safety liability for the owner. Opening it up is likely to be the cheapest option in the long-term.

8.6.1 Environmental considerations

There are several environmental considerations when removing a culvert, and the generic issues are highlighted in the following sub-sections.

Culvert removal provides an opportunity to improve the ecology of a watercourse. Before undertaking capital works, it will be necessary to undertake environmental and geomorphological surveys to identify the existing baseline conditions to determine the impacts of its removal. If the main risks are identified then more detailed investigations, possibly using modelling software, should be carried out to provide a more quantified understanding on sediment dynamics, both locally and at a catchment scale. Example 8.1 indicates an example of a culvert replacement in north London.

It is often feasible to plant vegetation to match native plants and help prevent erosion at the location of culvert removal. The vegetation near to the watercourse is a critical part of fish habitat as it provides nutrients, shade and buffers waterways from sedimentation and pollution during surface runoff.

Example 8.1 ***A culvert replacement in north London***

A 110 m culvert in Harrow, north London was found to be inadequate for flood flows. To reduce the flood risk to the area a new 650 m length of open channel was constructed and this bypassed not only the culvert, but also lengths of lined channel within the area. Combined with reducing the flood risk significant improvements to habitat were made. Further information is provided in Case study A3.10.

Figure 8.12 *The culvert during demolition (courtesy Andy Pepper)*

Figure 8.13 *The work upon completion (courtesy Andy Pepper)*

Flood risk management

Removing a culvert that previously constrained flows could increase downstream flood risk. For areas where this is considered a risk it is important that sufficient modelling is undertaken to assess this and to allow measures to be taken to mitigate any increase in flood risk. Also, the removal of a culvert could induce changes to the longitudinal profile, reducing the integrity of main flood defence structures both upstream and downstream as the watercourse channel reaches a new equilibrium.

Hydromorphology

A geomorphological assessment may be required for in-stream works that affect the geomorphology of a watercourse. Culvert removal may require excavation and grading to correct channel alignments and geometries. If channel incision has occurred and a culvert is providing grade control, removal of the culvert may result in headcut migration upstream and later deepening of the stream channel, locally increased channel slope and loss of pool habitat, or sediment deposition causing localised channel braiding and instability of the streambanks.

In some instances culvert removal, backfilling and reshaping can be considerably more expensive than plugging and digging an alternative, though longer, off course (River Restoration Centre, 2002). Where a new channel is created, consideration should be given to fluvio-geomorphology, flooding and present day use of the riparian area. Removing a culvert and creating a new channel where none exists usually involves a significant amount of earthmoving. It may be necessary to haul away the spoils if reuse on site is not possible.

Water quality and contaminated sediments

In-channel and bankside construction works can release sediments that can smother downstream habitats, affect fish and create blockages to downstream choke points (eg culverts). Construction works can also mobilise sediment-bound contaminants. This is particularly problematic in urban watercourses that are subject to increased levels of runoff, pollution and discharges from sewage treatment works. Slow flowing watercourses with in-channel vegetation also have a high potential to trap and retain sediment-bound contaminants. Once re-suspended, contaminants (eg metals, hydrocarbons etc) can have detrimental impacts to the environment and can also be a risk to human health.

If contamination is suspected, sediment sampling and analysis will be necessary. This information can be used to ascertain the need for mitigation measures (eg on-site treatment, off-site disposal and/or reuse).

When working in watercourses, the Environment Agency's pollution prevention guidance should be adhered to (Environment Agency, 2007b). To reduce the risk of sediment dispersal during construction silt traps should be put in place to ensure that any excessive sediment created by removal is filtered and removed.

Landscape value

Construction plant, earthworks and associated activities are likely to have an impact on landscape value, particularly in rural and urban parkland areas. Efforts should be made to ensure that construction works and materials are screened where possible. The construction duration should also be kept to a minimum.

Cultural resource

There may be rare instances where culverts may be formally listed or scheduled for their historic value. Careful consideration is needed in these cases, and formal consents may need to be secured. Where culvert removal is unavoidable, mitigation measures to decrease the impacts of the project should be proposed.

Community involvement and awareness

Securing local support for projects may be a lengthy process, especially in urban areas where people are unaware of the existence of a watercourse. Urban watercourses may pass through multiple properties, making the process of culvert removal legally complex. Riparian landowners with individual concerns about flood control and development rights may need to be balanced with the community and environmental benefits of culvert removal.

Vandalism and fly-tipping

New watercourses may attract vandalism and/or fly-tipping, with increased deposition of urban waste following floods where re-engineered channels become wide and shallow. Local communities and authorities need to be fully involved in maintenance.

Timing

Culverts should not be removed during fish spawning, incubation, or migration periods (timing windows). Timing windows (periods of least risk) are periods of time when work in and about a watercourse can be conducted with reduced risk to fish and fish habitat. Although the timing window is a time of reduced risk, fish (juvenile or adult) may still be present on site. Care should be taken to avoid harming fish and fish habitat. The timing of any works also needs to ensure that protected species such as bats, reptiles and nesting birds are not affected by the works.

8.6.2 Monitoring and adaptive management

Following removal of large culverts monitoring may be required to assess the effect on parameters including bank and bed erosion, water quality, riparian vegetation, or the passage of fish and macro-invertebrates. Some removals result in very little change, whereas others can mean substantial change. Ideally, locations should be monitored at least once before removal of the culvert to define a baseline condition. When funding and time allow, it may be beneficial to monitor two or more years before culvert removal to better account for environmental variability.

Adaptive management is a structured, iterative process of decision making in the face of uncertainty, with an aim to reducing uncertainty over time via monitoring.

8.6.3 Culvert removal checklist

The following list of issues to be considered has been produced to highlight some of the processes involved with culvert removal. Other factors may also need to be considered.

Issues to consider:

1. Is culvert removal practical?
2. Has an adequate assessment of flood risk been undertaken?
3. Have adequate environmental surveys been undertaken or a review of existing environmental baseline information?
4. Has a risk assessment been undertaken to identify the risk of potential contaminated sediments?
5. Has a geomorphological assessment been undertaken?
6. Have impacts to local cultural resources been considered?
7. Have impacts to riparian owners and stakeholders been considered?

During/post removal

1. Have construction works been scheduled to avoid fish migration/spawning?
2. Have construction works been scheduled to avoid impacts on protected species?
3. Are Environment Agency pollution prevention guidelines (PPG5) being followed?
4. Have silt traps been removed to prevent sediment re-suspension?
5. Has post removal monitoring been considered and planned?

9 Design practice

9.1 The design process

9.1.1 Confirm the need for a culvert

A culvert is an enclosed conduit and can act to constrict flow when compared to an open channel, so the first step in the process of planning a new culvert should be to establish that a culvert is the right answer to the problem. A culvert may seem to be the obvious means to convey a watercourse underneath infrastructure, but it can have significant adverse environmental impacts and may create an onerous maintenance requirement. A culvert can also be the cause of flood damage if it becomes blocked, or if its capacity is exceeded. So when a culvert is being considered in the early stages of infrastructure planning, alternative approaches should also be considered and evaluated (see Section 1.5). However, it is evident that a culvert will nearly always be considerably cheaper than a bridge at the same location, and this will inevitably be a material factor in the decision making process.

In the past, channels have been culverted as a means of exploiting the full development potential of a site. This is now no longer considered to be good practice, and developments should incorporate and improve streams and drainage channels so that they not only convey flows efficiently, but also provide habitats for wildlife and improve the amenity of the area. Culverting should not be a means of overcoming maintenance problems associated with a neglected watercourse, and it will always be preferable to focus on improving the channel both in terms of its hydraulic capacity and its environmental value.

Having decided that a culvert is appropriate, the designer can use the flow diagram in Figure 9.1 as a guide through the design process. The diagram summarises the process and the detail is given in this chapter. Designers can also refer to the design checklist in Table 9.4, which will help to ensure that no issue is overlooked.

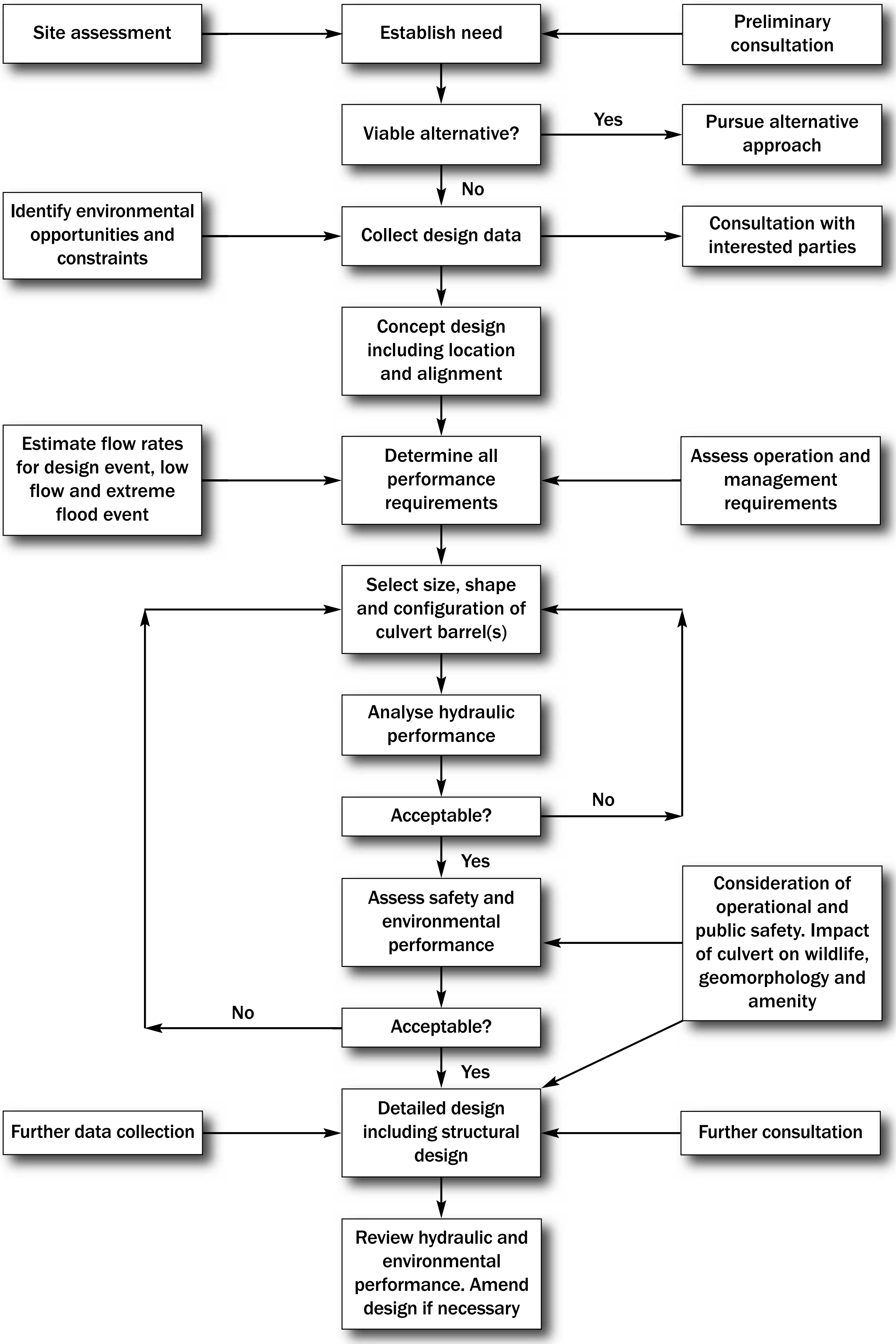


Figure 9.1 *Flow chart for culvert design*

9.1.2 Performance requirements

Once it has been decided that a culvert is the appropriate option, it is important to consider the performance requirements that should be addressed as part of the design process. There are three fundamental performance requirements: structural, hydraulic and environmental, and these should be addressed together with the need to fulfil health and safety requirements. Designing a culvert is not simply a question of choosing a size big enough to carry the design flow – although that may be a good start. There are many factors to consider and conflicting demands often arise. While a compromise is sometimes inevitable, the objective should be to achieve the optimum solution taking into account the following factors:

- hydraulic performance (including any allowance for "future-proofing" so that there is adequate capacity for changes in, for example, climate and land-use)
- conveyance of sediment, trash and debris
- ability to withstand the imposed loads (traffic and hydraulic)
- economy and ease of construction
- safety and security
- environmental acceptability
- asset management requirements (inspection and monitoring, sediment removal, trash and debris removal, maintenance, and eventual decommissioning).

It cannot be over-emphasised that the design is an iterative process and that it is vital in this process to give due consideration to:

- how the culvert performs at both low and high flows
- how the structure will be constructed
- how management of the asset can be helped by good design.

In the early stages of design, it is important to make an assessment of the relative importance of all of the factors that will affect the design. Table 9.1 summarises these and indicates the design parameters that may be influenced by them. This table is intended to act as a summary guide to the designer in the early stages of design, so that no important issue is overlooked. Structural performance has been included in the table but is not addressed in detail in this guide.

Table 9.1 *Culvert design – performance requirements and design parameters*

Performance requirements and other factors		Design parameters
Structural	Ability to carry imposed loads without damage or unacceptable deformation	Culvert materials and structural design. Depth of cover Foundation conditions
Hydraulic	Low-flow performance	Culvert size, slope, length, hydraulic roughness. Single or multiple barrels. Presence of a screen Allowance for growth and urban creep. Availability and suitability of overland flow route for extreme floods
	Flood flow capacity	
	Extreme flood performance	
Hydraulic and geomorphologic	Sedimentation in the culvert	Culvert size, slope, length and shape. Invert level Presence and type of screen Flow velocity in the culvert barrel (high velocities restrict fish migration and may cause scour downstream. Low velocities promote sedimentation) The need for wildlife provision Nature of the invert (eg low-flow channel or gravel bed) Transition from the barrel to the inlet and outlet structures and watercourse
	Trash and debris conveyance	
	Impact on upstream water level	
	Scour in the channel downstream	
Environmental	Fish passage and migration routes for other species	
	Habitat and refuge areas	
	Water quality and landscape	
Management and operational considerations	Access for inspection, maintenance and emergency exit	Culvert size, slope and length Means of access to and into the culvert Flow velocity in the culvert barrel
	Safety and security	Need for screens and warning signs
	Durability	Construction materials
Economic factors	Capital cost	Construction method and materials Presence of a screen Access and egress for maintenance
	Operation and maintenance costs	
	Decommissioning costs	

Designers of new culverts (and indeed the managers of existing culverts) should always look beyond the immediate environs of the culvert site when undertaking design or assessing performance. The nature and extent of the catchment upstream will determine sediment and trash loads as well as hydrology and hydraulic response. The form and condition of the channel downstream will affect hydraulic performance and sedimentation. The longitudinal profile of the watercourse will provide useful information for assessing the hydraulic performance of the system with the culvert in place.

All of these issues are discussed in more detail in the following sections.

9.1.3 Data collection

All engineering design work would be preceded by a data collection phase, which is common or similar regardless of the works being designed. In the case of a culvert, although the structure is frequently simple in engineering terms, the successful design depends upon a full appreciation of the environment (in its broadest sense) that the culvert will operate in. The data that define this environment can be considered in general terms under the headings of hydraulic, engineering, environmental, operational, and legal.

Hydraulic data

The design flood flow is the main factor determining the size of a culvert, although other factors may result in a larger size being selected (for example, the need to gain access for maintenance). For an urban culvert, or indeed any culvert where the consequences of inadequate capacity would be severe, it is common practice to design for the flood with a one per cent chance of being equalled or exceeded in any year (100-year return period). In Scotland the 0.5 per cent (200-year) flood is adopted with an allowance for climate change. In contrast, in agricultural areas a much lower design standard may be acceptable, say the 10 per cent flood (10-year return period). Except where the primary purpose of a culvert is to throttle flows, restricting a culvert size to the bare minimum is likely to be a false economy. Selection of the appropriate design flood should involve consideration of both the likely design life of the culvert (see Section 9.1.5) and the consequences if the design flood is exceeded during its design life. The approaches to flood flow estimation are fully described in Chapter 5.

At the very least the design data should include:

- an assessment of the size and nature of the catchment area upstream of the culvert (this is important both for the hydrological analysis and for the assessment of sediment and debris sources)
- survey of the channel and floodplain at the site and upstream and downstream of it, defining channel alignment, size, slope, bed and bank material, and floodplain extent
- an assessment of maximum allowable flood level upstream of the culvert at the design flood
- investigation of overland flow routes (extreme flood or blocked culvert scenarios)
- any historic records of flood incidents, including flood water levels.

These data will be used not only for the design of the culvert, but also for the assessment of blockage potential. So it is appropriate to consider both the type of data and the level of detail required in this context.

In all cases the designer should take a view as to the likely future development of the catchment, including allowances for urban creep. In the past, rapid urbanisation has led to increased runoff and consequential higher flood peaks in urban watercourses. The design flood should be assessed taking into account any changes to the catchment that are likely to occur during the life of the culvert, including the effects of climate change (see Section 5.6.1).

Although the flood flow estimation is likely to be the driving force in the culvert design, it is also necessary to consider low-flow performance. This is because the low-flow regime is the dominant regime, and will be a significant influence on the culvert's environmental performance. It can also affect the rate of sedimentation or deposition within the culvert, and the maintenance of adequate capacity for flood flows. It is recommended that low-flow data are also collected. These can often be obtained from gauging station records for even small streams that have some water resource or environmental importance. Otherwise, it may be necessary to base estimates on observations and information available from relevant operating and regulatory authorities, local residents and local interest groups. In agricultural land, the low-flow performance of drainage culverts is particularly important to ensure that drainage is not restricted by the culvert (for example, because its invert is too high), so the collection of data on field drain levels is vital.

Culverts can become obstructed by sediment and debris. In extreme cases total blockage can occur with potentially severe consequences. It is vital to make some assessment of the likely sediment and debris loads in the watercourse. Some indication can be gained from knowledge of the nature of the catchment (urban or rural, steep or flat, rock or alluvium, forested or agricultural, arable or pastoral). However, a reconnaissance of the catchment upstream of the site, and the watercourse channel, should reveal the likely type and amount of trash or debris, and the nature of the bed sediment. A methodology for the assessment of debris load from a catchment is presented in guidance by the Environment Agency (2009a). It is possible that reconnaissance will reveal a point source of sediment or debris (eg a vegetable washing facility, or a fly-tipping site) in which case it may be possible for the potential problem to be addressed at source.

Engineering data

The engineering data include a full topographic survey of the site and its environs, and should include some assessment of ground conditions appropriate to the size of the culvert and the design stage under consideration. It is common to encounter weak materials close to alluvial watercourses, and running sand in particular may add considerably to the cost of temporary works required during construction. The presence of a layer of peat below the culvert is likely to result in settlement, which can be significant under a high embankment. Differential settlement can affect the culvert hydraulic performance and may cause structural problems.

The other major element of engineering data is that related to the practicalities of construction, which can be obtained from a reconnaissance of the site and surrounding area. In particular, the designer should consider access for construction plant and materials, and the likely type and extent of temporary works (eg flow diversion and foundation dewatering – see Case study A3.9 for a description of the temporary works employed on a culvert rehabilitation project). Approaches to utility companies should identify whether there are any known services that are likely to be affected by the works. Consultation with the infrastructure owner or manager should identify any requirements for traffic management, road closure, or track possession. In the case of a canal, there may be a requirement for dewatering of the reach affected by the works, which will clearly affect the operation of the waterway.

Full understanding of these and other issues help the designer to decide on the basic construction method, including options such as pipe jacking. It should be noted that works near to highways and railways require particular attention to safety, and working methods should be approved by the appropriate authority. Also, works carried out on or near to a railway line will usually require track possessions (when the railway is closed to rail traffic). Overnight or weekend track possessions are normally arranged several months in advance and the works should be completed in the allocated time slot. It is clear that advance planning, and engagement with the appropriate operating authorities are fundamentally important when contemplating works at active railway lines, and similar constraints may apply in the case of waterways and major highways. Pipe jacking under working railway lines can offer an alternative to track possession, but such works also require liaison with the operating authority, and there may still be speed restrictions and other limitations on use of the track.

Data are also required on the likely imposed loads on the culvert (eg traffic loads) because these have an impact on the structural design of the culvert, and may determine the maximum permissible soffit height (a parameter that may also be important for hydraulic design).

Note the extensive temporary works required on this site and the use of the part completed culvert for access.

Figure 9.2 *A wide rectangular culvert used where headroom was limited (courtesy Andy Pepper)*

Environmental data

Environmental assessment should be undertaken to meet legal requirements outlined in Chapter 3 and to determine a solution that protects the environment and enhances it where practicable. Environmental assessment should determine the baseline environmental condition to allow impact assessment and iterative feedback into the design process. This process will ensure important environmental requirements are captured as part of the design process. In some cases where a culvert forms part of a wider scheme, the assessment may form part of a wider environmental impact assessment of the whole scheme but the same principles will apply. Chapter 4 provides details on data to be captured. Data collation in many cases is likely to be best achieved through consultation with environmental regulators who have knowledge of the wider watercourse network and pressures upon it. Regulators should also be able to advise on the requirements of important legislation (for example, licenses or requirements under the Water Framework Directive and for designated or scheduled sites).

Also, it is important to establish the risks associated with vandalism and safety. Vandalism is not confined to urban areas and can be a serious problem in some remote locations because it can be carried out unobserved. It is necessary to assess the risk and design accordingly. Discussions with local people and owners of local businesses help to identify the degree to which vandalism may be a problem.

With regard to safety, culverts in areas close to schools, recreational grounds, or housing estates tend to present a greater risk than those in remote rural locations or located on private land. Establishing the scale of the risk before starting detailed design helps to avoid problems created by the need to modify the design at a later stage. Contacting the local police force to determine whether there have been any incident reports relating to vandalism or safety may be appropriate if concerns have been raised by local residents.

Asset management

When the culvert has been constructed and commissioned, it should operate satisfactorily for many years. However, it is unlikely to do so unless it is maintained in good order. For a culvert, the importance of regular inspections to ensure that its capacity is not restricted by the accumulation of sediment or debris cannot be over-emphasised. At the design stage it is necessary to consider who will take responsibility for this, and how they will go about it. This is particularly important for any culvert that will have a screen of any kind (trash or security).

Legal issues, consents and approvals

Legal issues include the need for consents and approvals, as well as land ownership rights and maintenance responsibilities. For example, access across land owned by a third party can be particularly important for railway work where land ownership may be limited to a narrow corridor. Use of the rail track for construction access may be possible, but it is likely to require lengthy negotiations with the rail authority and would be subject to stringent constraints. For example, London Underground requires a minimum of nine months advance notice for a weekend track possession, and a longer closure needs at least two years advance warning. Overnight works (during "engineering hours" typically 01:00 until 04:00) normally can be accommodated with 28 days notice.

It is important to explore and resolve these issues at an early stage of the design development so that their influences on the design can be taken into account. Many older culverts come with multiple owners and divided responsibilities, particularly where a culvert has been extended in the past. This situation should not be replicated in the case of a new culvert. Early consultation with all stakeholders will help to resolve these issues and ensure that the final solution is mutually acceptable.

Legal requirements in relation to culverts are fully described in Chapter 3.

Summary of data requirements

Table 9.2 presents indicative data requirements for the design of a new culvert, together with the likely source(s) of the data. The relative importance of the items listed varies depending on the site, but no item listed should be ignored until it has been established that it is not relevant.

Some of the data identified in Table 9.2 will be collected in stages, as the design develops. For example, in the early stages the site investigation may be limited to a reconnaissance survey. Later on in the design, the need for a more detailed assessment of foundation conditions may emerge, involving trial pits and boreholes, as well as searches for the presence of any buried services at the site.

Table 9.2 *Culvert design – summary of data requirements and sources*

Source	Data items
Reconnaissance	Land-use upstream of the proposed culvert site, including the presence of agricultural land drains
	An estimate of trash load and type of trash likely to be generated in the catchment
	Channel description and roughness estimates
	Nature of the bed sediment in the channel and any information on sediment transport
	Channel geomorphology including bed features, bank material, signs of instability
	Construction constraints (especially access)
Topographic survey	Cross-sections of the channel along a representative length of watercourse upstream and downstream of the proposed culvert site, including any floodbanks and nearby floodplain
	Channel bed slope and water surface slope over a representative length
	Highest permissible water level upstream of the culvert for the design flood (for example, in relation to the floor levels of nearby properties)

Table 9.2 (contd) *Culvert design – summary of data requirements and sources*

Environment Agency, SEPA (Scotland), Rivers Agency (NI), and local authorities	Information on measured flows and water levels in the channel (if available)
	Information on any environmental issues that should be considered
	Information on any channel maintenance works
Local nature conservation organisations	Information on locally important habitats and protected species
	Opportunities for enhancing the natural environment
	Information on the ecology and geomorphology of local watercourses
Baseline environmental study (may be obtained through consultation with operational and regulatory authorities)	International, national and local regulatory requirements and constraints, including designated and important sites, habitats and species, biodiversity action plan species and targets, and associated impacts and enhancement opportunities
	Continuing operational and maintenance works
	Water level, flow and quality information (under range of flow conditions)
	Geomorphological surveys (eg river habitat survey, fluvial audit, rapid assessment) Ecological survey data (local and wider catchment)
	Policies and plans relating to landscape
	Records of invasive species
	Detailed information on local habitats and geomorphology
River basin management plan	Listed measures under the programme of measures
Catchment flood management plan	Extensive information on all aspects of the wider catchment with an indication of relevance to flood risk management
Utilities	Information on the presence and location of any buried services
Maps, aerial photos and satellite imagery	Catchment information for the calculation of flow rates and to assist in the estimation of trash and debris load
Available design information	Full dimensions and details of the road or other infrastructure that requires construction of the culvert, as well as imposed loads. Length of culvert needed. Constraints on location of culvert, including inlet and outlet
Site investigation	Foundation conditions (and geotechnical parameters)
Consultation with local residents and any other parties likely to be affected	History of flooding problems
	Land ownership and access constraints
	Use of the watercourse for leisure
	Risk of vandalism

9.1.4 Approach to the design of a new culvert

Once the decision has been made that a culvert is the only practical solution, the design process starts with the data collection phase. This is followed by calculation of the design flood flow, which allows a first estimate of the size of culvert required. Unless there are overriding reasons for not doing so, the culvert design should be based on free flow in the design flood, ie the water level in the culvert should be below the soffit level of the culvert. There are several reasons for this, including:

- less likelihood of blockage by large pieces of floating debris
- the risk of loss of life for anyone falling into the culvert entrance in a flood is lower than if it were flowing full

- the freeboard between the design water level and the culvert soffit allows an element of extra capacity for extreme floods.

When the designer has an estimate of the size of the culvert, then all the other elements of the design can be developed, starting with a sketch design and progressing to the detailed design. All the factors that need to be considered are presented in the following sections of this chapter. Throughout the design process it is vital not to lose sight of the importance of the culvert hydraulic performance, particularly for flood conditions. Compromising on this may result in flooding upstream of the culvert, which can cause a lot of damage to nearby infrastructure and development.

9.1.5 Design life

It is important to consider design life in the early stages of design, as this may influence the types of materials used and the size of the culvert among other things. A permanent structure under a motorway, railway or canal should have a long design life, because of the high cost of replacement or major repair (taking into account the likely disruption that this would involve). Such a culvert is also likely to experience an extreme flood in its lifetime, so compromising on the size of the culvert would not be wise.

For a temporary structure, which may only be needed for a few months, consideration of design life may point the designer in the direction of less durable materials. A temporary culvert is also less likely to be exposed to any given flood event than a permanent structure, simply because it is in place for a much shorter period. A temporary culvert could be of smaller section than a permanent structure at the same site. The important thing is for the designer to understand the expected performance of the culvert over the full range of flow conditions, including overland flow routes associated with flows beyond the capacity of the culvert. The design and the requirements for operational management then need to take proper account of these to ensure effective whole-life management of the performance and risks, taking into account the time period for which the culvert will be in existence (see Chapter 5).

The design life of a culvert is also influenced by its maintenance regime, as with any engineered structure.

It is not appropriate to quote any rigid rules for the design life of a culvert, although it is worth noting that many of our existing culverts are over 100 years old. The designer should consider all the factors mentioned in this section before making a decision. However, it is important to emphasise that enlarging a culvert at some future date is likely to be very expensive and disruptive.

9.2 Design fundamentals

9.2.1 Components of a culvert

Figure 9.3 illustrates the components of a culvert. The three main elements are the barrel (Section 9.3), the inlet (Section 9.4), and the outlet (Section 9.5). A culvert may have a screen at the inlet (see Section 9.4.3), either to trap debris or prevent unauthorised access, or both. The outlet may also have a screen to prevent access (see Section 9.5.5). All of these elements are discussed in detail in the following sections of this guide.

Note that there is a drop in water level across the culvert (the difference between the headwater level and the tailwater level). It is this "head difference" that drives the flow through the culvert. It comprises head losses at the inlet and outlet, as well as friction loss in the barrel. Any bends, steps or changes of cross-section in the barrel will introduce further head losses. There will also be a head loss at any inlet or outlet screen, and this loss will be greater if there is an accumulation of trash or debris on the screen. Failure to appreciate the significance of the concept of head loss can lead to unacceptably high water levels upstream of a culvert, with consequential flood damage to nearby development or infrastructure. The hydraulic analysis of culverts is presented in Chapter 6, whereas this chapter concentrates on the practical design issues.

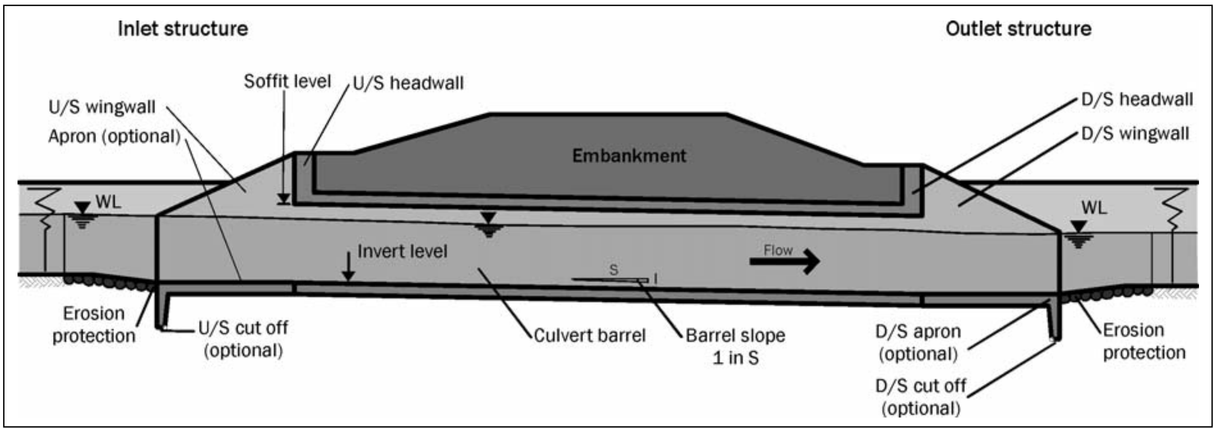


Figure 9.3 *Longitudinal section of a culvert showing components*

9.2.2 The ideal culvert

Features of the ideal culvert include:

- capacity well in excess of the design flow ensuring free flow at all times
- large enough to convey freely all debris carried by the watercourse (no need for a trash screen)
- safe overland flow route available to convey water in the event that the culvert is blocked
- presents no risk to adventurous children (no need for a security screen)
- not prone to the progressive build-up of sediment over time that would lead to a significant reduction in capacity (accepting that seasonal and flood-related depositional trends may be present)
- no steps or changes in slope or cross-section that might reduce capacity, catch debris or cause sediment accumulation
- no bends in the culvert barrel unless they are unavoidable
- readily accessible for inspection and maintenance
- provision for fish passage, migration of other species, and habitat and shelter requirements
- visual appearance in keeping with surroundings
- easy to construct, low cost, long design life and low maintenance.

Of course, it is rarely possible to produce a design that is ideal in all respects. Indeed, some of those features listed may be mutually exclusive. In particular, the quest for a low-cost solution would be likely to lead to a compromise on many of the ideal features. Also, the constraints imposed by the site may make some compromises unavoidable (eg road or rail level dictating culvert soffit level).

A designer of a culvert should seek to provide the most appropriate solution under the circumstances and, in particular, should be fully aware of the consequences of any compromises that are made, and seek to manage such consequences by other means.

9.2.3 Alignment

One of the early decisions to be made is the alignment of a culvert with respect to the watercourse and the infrastructure (or obstruction) under which it passes. A highway or canal engineer generally wants the shortest length of crossing possible (to keep the capital and maintenance costs to a minimum). This may also be preferable for culvert hydraulics and the aquatic environment, but can lead to problems with regard to alignment of the channel, as is illustrated in Figure 9.4.

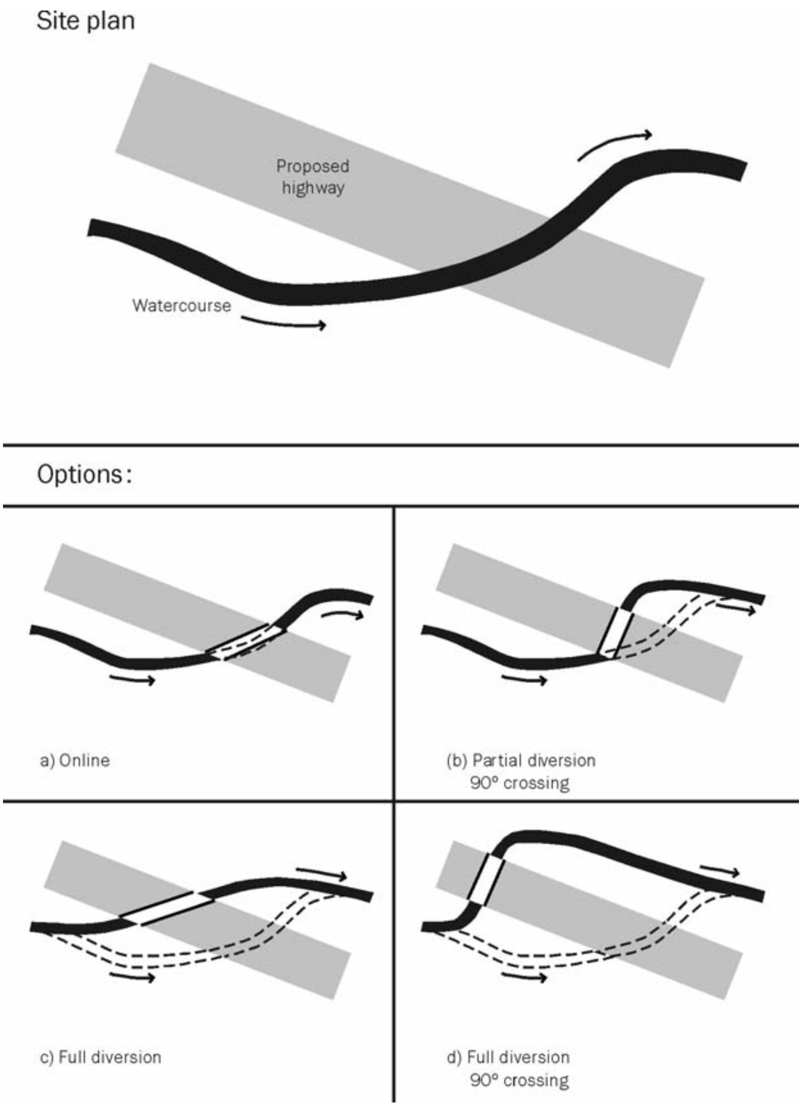
Poor alignment of a culvert with respect to the channel is frequently a cause of problems, and the ideal arrangement of a 90° crossing of the obstruction is often not practicable. Options a and c in Figure 9.4 are both acceptable, having good alignment of the flow at the inlet and outlet, but Option c has the considerable advantage of allowing construction "in the dry". Of course, Option c may be more expensive requiring a longer culvert and watercourse diversion, but this has to be offset against the elimination of a temporary diversion of the watercourse.

In general it is preferable not to alter the river length substantially as this would cause a local change in slope that may affect the channel regime. However, there are situations where a change in slope may be desirable. For example, cutting off a meander in the watercourse would allow the creation of backwater features and enable the culvert to be laid at a slightly steeper slope. A steeper slope in the culvert may be preferable as it will help to reduce sedimentation within the culvert. However, it would be necessary to ensure that the slope was not so steep as to restrict fish movement upstream (see also Section 9.3.5).

Another factor relating to alignment that should be considered at this early stage is the provision of an "overland" flood route so that if the culvert is blocked or if there is an extreme flood, water can safely bypass the culvert without flooding nearby properties or infrastructure.

Initial alignment options can be investigated by superimposing the route of the new highway onto a plan of the channel at the culvert site. This allows the designer to consider a range of options such as those illustrated in Figure 9.4, including realignment of the highway where this is practical. The selected alignment should be studied further on site, to make sure that there are no problems that could be readily avoided by minor changes to the line and location of the culvert.

Where it is impossible to align the culvert to achieve good flow conditions, it is important to design inlet and outlet works to minimise the problem (see Figure 9.6). Bends in the culvert should be avoided if at all possible but if they are unavoidable, long slow bends should be adopted in preference to sharp bends as the latter reduce the hydraulic efficiency of the culvert and tend to trap debris.



Option b is unsatisfactory because of the poor approach alignment that will reduce the hydraulic performance and probably promote sedimentation at the inlet (see Figure 9.5). Option d is an alternative to c, which avoids a skew crossing but has less favourable hydraulic features because of the introduction of two bends into the channel. Final selection of the appropriate alignment depends on a consideration of all the relevant factors. It should be noted that Network Rail standards require a 90° crossing unless there are good reasons for an angled crossing.

Figure 9.4 ***Culvert alignment options***

At this culvert the channel upstream is aligned with the right-hand barrel and sediment has been deposited in the slack water area upstream of the left barrel. The left barrel has significant sediment deposits, reducing its capacity. A small amount of sediment in the left barrel might be acceptable (the determination of what is acceptable would be part of the performance assessment process), and would provide a dry route for wildlife migration in low-flow conditions, but in this case the sedimentation was excessive and had to be removed.

Figure 9.5 *Sedimentation upstream of a double pipe culvert (courtesy Andy Pepper)*

This culvert is not well aligned with the watercourse so the channel has been lined using gabions that both prevent erosion and help to improve the hydraulic conditions. Note the incoming channel on the left. Note also the use of the simple vertical headwall arrangement.

Figure 9.6 *Use of channel lining to improve hydraulic conditions at inlet or outlet (source Day et al, 1997)*

9.2.4 Environmental considerations

A culvert can create an ecologically barren aquatic environment, destroying or degrading habitats as well as restricting or preventing the movement of wildlife up and down the watercourse. Clearly the longer and the smaller (in relation to the watercourse cross-section) the culvert is, the worse this impact will be. The Environment Agency and other regulatory bodies strongly discourage the use of culverts and only allow them to be constructed if there is no other practicable option. This approach is reinforced by the legal requirements imposed by the Water Framework Directive that seeks to preserve, and where possible improve the ecological status of rivers and streams. The days when culverts were constructed to hide a watercourse that had become an open sewer have long gone.

Where a culvert is the only option, there are measures that can be adopted to reduce its environmental impact on watercourse ecology, wildlife and amenity. In general the interior of the culvert should be as similar as possible to the upstream and downstream channel, and provision should be made to allow wildlife to move along the channel corridor. The following measures should be considered:

- depressing the culvert invert to allow a natural bed throughout the culvert (Figure 9.14)
- providing a ledge along the length of the culvert (Figure 9.7), or high level dry barrel (Figure 9.24) for wildlife to travel along
- in long culverts, provision of points along the barrel for mammals to get out of the water onto a continuous ledge that is above normal water level
- ensuring that the velocity of flow in the barrel under normal conditions does not exceed the maximum swimming speed of native fish species, and of other non-native fish species if there is any likelihood of these being introduced during the life of the culvert (see Section 9.3.8)
- choosing a location for the culvert where there will be no need for changes to the gradient of the watercourse and no abrupt changes of flow direction will help to avoid adverse effects on sedimentation and fish passage (see Figure 9.4)
- avoidance of shallow flows (possibly consider a low-flow channel in the invert of the culvert)
- avoidance of a drop in water level at the inlet into the culvert, and at outlet from the culvert
- providing appropriate native bank and marginal vegetation at the inlet and outlet of a culvert to give shelter for fauna entering and leaving (note this should not be allowed to obscure the inlet or outlet, which can restrict flow or make inspection difficult)
- in steep streams, the provision of a resting place for fish at the outlet from the culvert and at its inlet will assist them to move upstream
- the provision of fencing at road crossings to reduce the risk of road kills of fauna.

These factors should be considered in the early stages of design of the culvert as they can be both more difficult and more expensive to incorporate retrospectively, and they may be less effective than measures designed in from the start. The future performance of the culvert should also be considered at the design stage, so as to ensure that changes over the life span of the structure do not incur adverse environmental impacts. For example, if there is a risk of retrogression (erosion) of the channel bed downstream, this should be allowed for by depressing the culvert invert.

Further guidance on fish and wildlife in the context of barrel design is given in Section 9.3.8.

Two approaches to the provision of access through a culvert for mammals. On the left a new concrete culvert has built-in ledges on both sides. On the right a steel ledge has been retrofitted to an old culvert (note also nesting boxes). In both cases it is necessary to consider the level of the ledge with respect to normal and floodwater levels and its effect on debris passage and hydraulic performance. An alternative approach is to provide a dry passage parallel to the culvert (see Figure 9.24). See also Case study A3.5.

Figure 9.7 *Provision for wildlife (courtesy John Ackers and Transport Wales)*

As with all new works, particularly near watercourses, care should be taken to minimise any adverse visual impact resulting from the construction of the culvert. The temptation to pond up water upstream to mimic conditions experienced in high flows should be avoided because it can lead to stagnant conditions in contrast to the desired effect. Ponding also tends to promote siltation in the channel and might create a safety hazard because of the increased water depth.

9.2.5 Consideration of future management

All engineering structures require "management" throughout their working lives, although the degree of intervention required varies widely depending on the nature of the structure. Culverts have often been thought of as "low-maintenance" structures and it is true that a properly designed culvert can require minimal management intervention. However, a poorly designed culvert can create a significant maintenance burden associated with sedimentation in the barrel or blockage of the culvert or upstream screen by debris.

It is vital that the design of a new culvert considers its whole life, from the construction stage through to eventual replacement or demolition. In particular the designer needs to consider:

- durability of the materials used and what maintenance or repair work is likely to be required to keep them in a satisfactory condition throughout the design life (see Section 9.1.5)
- the avoidance of excessive sediment accumulation in the culvert barrel or, if this is unavoidable, design of the culvert to facilitate removal of sediment at intervals
- reducing the risk of blockage of the culvert by debris and, if this involves the use of a screen, a realistic assessment of the requirements for maintaining the screen in a free-flowing state
- the need for safe access into large culverts to allow routine inspection and repair works
- minimising vulnerability to vandalism (particularly applies to trash and security screens, water level monitoring equipment, lighting and telemetry where provided).

In considering these factors, it is important to establish who will be responsible for management of the culvert throughout its life. Those responsible should understand the resource implications associated with their management responsibility, and this should be confirmed as part of the planning and design process.

9.3 The culvert barrel

9.3.1 Barrel options

A culvert should generally have a constant cross-section along its full length (ie not changing in size or shape). The common barrel shape options are:

- circular (commonly concrete pipe, but also corrugated steel, plastic, and glass reinforced plastic (GRP))
- rectangular (pre-cast or cast *in situ* concrete box culverts)
- arch (brick, masonry, pre-cast concrete or corrugated steel)
- small bridge-type culverts comprising abutments and a slab roof (generally confined to older culverts).

Size ranges for commonly used barrel shapes are given in Appendix A5.1. Guidance should be sought from manufacturers for the full range of shapes, sizes and specials for the particular material in question.

For small cross-drainage culverts on minor roads, a pipe culvert is often an appropriate solution. A minimum diameter of 450 mm is recommended as smaller sizes are prone to blockage. For long culverts under motorways, railways or structures under a waterway, pipe diameters of less than 1200 mm should be avoided because of the difficulty of inspection and maintenance. Ovoid (egg-shaped) pipes are common in parts of Europe. They are manufactured in the UK but are mostly used for sewers because the shape maintains flow velocity at low-flows, which helps to keep the culvert clear of sediment.

For small channels, the use of a "bottomless arch culvert" offers the opportunity to minimise the impact on the channel bed. Such culverts can span the width of the channel with no intermediate support. They are available as pre-fabricated units in concrete or steel, and require foundations to be constructed either side of the channel. The stability of such structures depends on the quality of the foundations and the superimposed loading. Guidance should be sought from the manufacturers of the units.

A similar effect can be achieved with any culvert by depressing the invert below the channel bed and by providing a natural bed through the culvert, or allowing one to develop over time.

The three most common materials used for barrel construction are concrete, steel and plastic. These are discussed in Section 9.3.4.

Culvert barrel options are sometimes restricted by the available headroom. In this context, the headroom is the difference in level between the road (or rail or canal bed) level and the design water level through the culvert. The requirement to design for free flow, and the need to maintain a minimum depth of cover over the culvert, together require a road surface level that is considerably higher than the design water level. To some extent it may be possible to address this by elevating the road surface, but this is unlikely to be an option for a railway or a motorway, and is not possible for a canal. A box culvert would provide the best solution in this case because the flat soffit allows maximum use of the cross-sectional area for flow while maintaining minimum cover (see Figure 9.2).

In general, services (sewers, gas mains, water mains, and communications cables) should not be located inside a culvert barrel. This is because they often act to trap debris, and they may be damaged by debris or by maintenance procedures for the culvert. Utility companies should make separate arrangements for the location of buried services alongside a watercourse. If location within the culvert is unavoidable, the culvert size should make allowance for the space required, and the services should be grouped together to present as little obstruction to the flow as possible. Manhole access should be provided to allow regular inspection and clearance of debris.

Two service pipes cross this culvert, significantly reducing its capacity and increasing the risk of blockage. Complete blockage could easily occur in a flood, causing severe flooding to local properties and infrastructure. Such blockages are difficult to remove and can only be cleared after the flood event. In the case of an existing situation such as this, the only solution may be to introduce a trash screen at the inlet, but it should be appreciated that this will impose a requirement for routine and emergency cleaning.

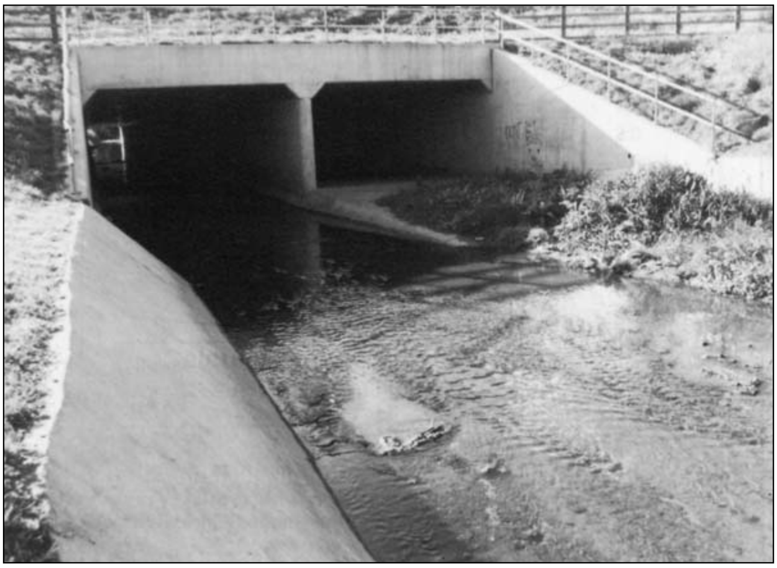
Figure 9.8 *Service crossings within a culvert (courtesy Richard Allitt)*

9.3.2 Single or multiple barrels

The choice between single and multiple barrels is influenced by conflicting requirements, for example:

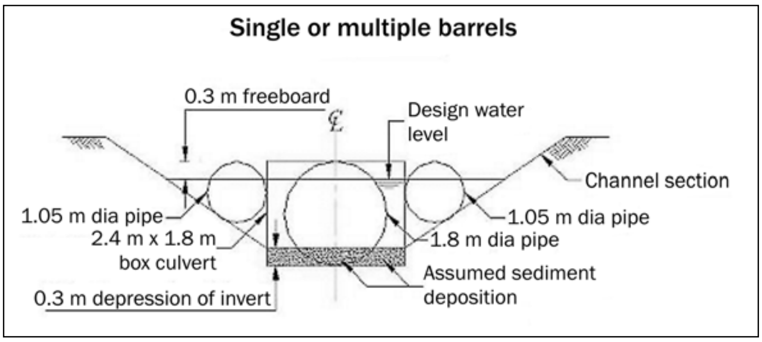
- headroom: may be restricted by road level or presence of services, in which case a multiple barrel structure may be more practicable
- debris conveyance: the bigger the culvert barrel, the lower the risk of blockage
- low-flow performance: multiple barrels offer the facility of low-flow through one barrel only, which reduces sedimentation and maintains water quality by reducing ponding and stagnation (see Figure 9.9)
- inspection and maintenance: made easier by a larger barrel, but with more than one barrel there is the opportunity to dewater one barrel to allow thorough inspection while maintaining the flow through the other barrel(s)
- cost: in general, a single barrelled structure is likely to have a lower capital cost, but this is not necessarily so and the designer should consider the construction process (the need for temporary works, access, lifting requirements), as well as likely maintenance costs, in making a decision. Where several cross-drainage structures are required, for example, along a highway or railway, cost savings may be made by adopting a single standard culvert section, with the number of barrels varied to suit each cross-drainage location. However, this approach is more likely to be applicable overseas where cross-drainage requirements may be seasonal and ill-defined

- hydraulic performance: in two stage or multiple stage channels a complex multiple barrel culvert may match the channel section better than a single barrel, resulting in lower inlet and outlet losses
- wildlife movement: likely to benefit from multiple barrels provided that they have different invert levels (see Figure 9.9)
- practical considerations: for example, the required spacing between pipes making up a multiple barrel. The space should be large enough to assist the construction and compaction of backfill, but not so large as to make the overall culvert width much wider than the watercourse.



The left hand barrel carries dry weather flow helping to keep the invert clean by concentrating the flow in one barrel. The right hand barrel has a higher invert and remains dry in low-flows, allowing the passage of wildlife along the watercourse corridor.

Figure 9.9 ***Twin box culvert – one barrel having a higher invert level***



Parameter	Single box culvert	Triple pipe culvert
	(2400 mm wide × 1800 mm high)	(1 × 1800 mm + 2 × 1050 mm dia)
Gross cross-section area	4.32 m²	4.28 m²
Net section area (excl sediment and freeboard)	2.88 m²	3.30 m²
Wetted perimeter	4.80 m	8.19 m
Head loss through culvert (see notes)	0.28 m	0.28 m
Ease of construction Inspection and maintenance	Heavier lifts Easy access to culvert interior	More complex to build Man-entry not possible in smaller pipes
Hydraulic performance	Less likely to be blocked by debris but does not match channel cross-section well	Risk of blockage is higher but unlikely that all pipes would be blocked. Good match to channel section
Environment	Not ideal because low-flow spread across full width of 2.4 m	Avoids shallow depths at low-flow and provides for wildlife passage

Notes

1 Assumes a design flow of 5 m³/s and overall length of culvert of 50 m (motorway crossing).

2 Inlet and outlet loss coefficients assumed to be $K_i = 0.5$, $K_o = 1.0$ (see Chapter 6).

3 Manning's n in the culvert assumed to be 0.02 allowing for deterioration of the culvert interior over time and sediment in the invert (see Chapter 6).

Figure 9.10 *Single or multiple barrels – a comparison*

This simple example illustrates the choice between a single barrel and multiple barrels. There are of course many other combinations of barrel size, shape and number.

For small and medium sized culverts (cross-sectional area up to five square metres) a single barrel is probably most appropriate. For larger culverts, the most widely held view is that a double barrel is ideal because:

- it allows the depression of the invert of one barrel to carry low-flows
- temporary diversion of flow is easily arranged to allow inspection/maintenance of each barrel in turn
- the flood flow barrel can provide a wildlife route in normal flows.

The multiple barrel option is most commonly used for two stage channels, where the outer barrels are set at a higher invert level and provide extra capacity in flood conditions (see Figure 9.10).

The use of small diameter multiple pipe culverts is discouraged because of their tendency to be blocked by debris and their poor hydraulic performance. For example, take three 600 mm diameter culverts in parallel compared to the alternative of a single 1000 mm diameter barrel. Although the three smaller barrels have a greater total cross-sectional area, their capacity compared to the single barrel is significantly less. This is because in the case of the three barrel option there is a lot more wetted perimeter (water in contact with barrel interior), which creates more resistance to flow (see Chapter 6). However, where a culvert is made up of several large diameter culverts in parallel, this allows flexibility for future maintenance and refurbishment, as work can be carried out on one of the barrels while flow continues through the others.

Another factor in the selection of barrel size is the issue of man-entry (for inspection or maintenance). Pipe culverts with diameters less than 1200 mm are difficult or impossible to access so their use should be avoided if it is likely that man-entry will be required during the life of the culvert.

In the case where headroom is severely restricted it may be better to adopt a wide, shallow box culvert and accept that some freeboard may be lost (see Figure 9.2). The alternative of designing the culvert for full flow by lowering the barrel is not to be recommended except where no realistic alternative exists (for example, under a canal where the soffit level is dictated by the bed level of the canal). This type of structure is often referred to as an "inverted siphon" but the term siphon is misleading as there is no siphonic action involved. A more correct term might be underpass culvert or perhaps a hydraulic underpass. The term sag culvert is also used. However it is described, this arrangement is more prone to sedimentation and blockage by debris, and creates a significantly greater hazard to anyone falling into the culvert. These structures are also much more difficult to clean out if sediment or debris accumulates in them.

Where two or more barrels are used, it may be appropriate to provide a "bull-nose" dividing wall between each pair of barrels. This semi-circular nose helps to ensure that any floating weed or debris passes into one barrel or the other rather than getting snagged on the dividing wall and creating a dam effect. Having the front edge of the dividing wall inclined also reduces the risk of debris accumulation. To achieve this it is necessary to space the barrels sufficiently far apart to allow the construction of the bull-nose. A spacing of perhaps 1.0 m would be of the right order for culvert barrels in the range 1.5 m to 3.0 m width. However, the designer needs to consider construction practicalities and make sure that the spacing of barrels is sufficient to allow efficient compaction of fill between them.

9.3.3 Freeboard

In most cases the design of a culvert is based on free flow, so it is necessary to allow for freeboard between the water level in the barrel and the barrel soffit. For pipe culverts up to 1200 mm diameter, it is suggested that the freeboard allowance is one quarter of the pipe diameter. For larger pipe sizes and box culverts the freeboard should be in the range 200 mm to 500 mm, the choice depending on confidence in the design flow estimate, the depth of the culvert barrel, available headroom, and likely floating debris load.

The Environment Agency gives similar guidance recommending that the barrel size used is larger than that needed based on hydraulic calculations. For example, if the calculations suggest that the required capacity would be given by a 900 mm pipe, the Environment Agency's recommendation is to use a 1200 mm pipe. This would allow for freeboard and sedimentation in the invert (see Section 9.3.6 and Figure 9.14).

9.3.4 Barrel materials

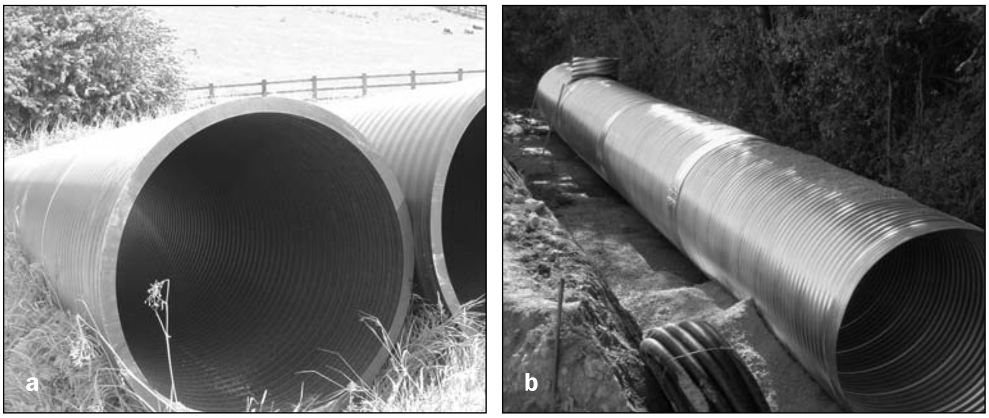
Concrete is now the most commonly used construction material as it is strong, durable, and resistant to erosion, corrosion and fire. Using pre-cast pipes or boxes ensures a high quality dense concrete with a good surface finish, and there is a very wide range of sizes to choose from. In situ concrete may offer more versatility in design, but designers should be aware that pre-cast box suppliers can provide units to suit most practical applications and custom-made units can be provided to meet particular requirements. Custom-made units will be more expensive than standard units, and will require ordering well in advance.

The pre-cast concrete pipe is perhaps the most commonly used option for a culvert and is available in diameters up to 2400 mm. For larger culverts the pre-cast concrete box culvert is often the preferred solution, and it is available in a wide range of sizes from 1000 mm × 500 mm (width × depth) up to 6000 mm × 3600 mm.

Corrugated steel pipes are also available in a wide range of sizes (up to 8000 mm diameter). The larger diameters are not normally used for culverts because they do not match the channel cross-section well, and a box culvert or corrugated steel elliptical or pipe arch structure (see Figure 9.12) is likely to be more appropriate. Corrugated steel culverts require particular attention to the bedding and backfilling during construction, as the surrounding soil provides lateral restraint that is essential for the structural performance of the culvert. Consideration should also be given to durability as problems have been observed with corrosion of steel pipes (owing to aggressive backfill or groundwater) and the erosion of protective coatings (high sediment loads in fast flowing water). The latter can be overcome by lining the invert of a corrugated steel culvert with concrete. Corrugated steel culverts can be assembled on site from small panels bolted together, making them suitable for sites with restricted access.

Plastic pipes offer a viable alternative to concrete in many situations due to recent improvements in strength and durability, and an increased range of sizes. In the context of pipes, the term plastic can be used to mean PVC (polyvinyl chloride), UPVC (un-plasticised polyvinyl chloride), HDPP (high density polypropylene), and HDPE (high density polyethylene). However, HDPE is by far the most commonly used material in plastic culverts. This is because HDPE can be used for pipes up to 3500 mm diameter and the material has high UV light resistance. HDPE pipes are also much lighter than their concrete equivalents and have the extra advantage of low hydraulic roughness (which reduces the friction head loss). However, it should be noted that the smoother inside surface has the disadvantage of making it very slippery, so using HDPE pipes is unwise when man-entry is a known requirement unless the invert is lined with concrete. Also, HDPE does not have the fire resistance of concrete and may be damaged by high-pressure jetting. HDPE pipes can be manufactured in lengths up to 40 m if required, although such lengths clearly present transportation problems. More commonly these pipes are supplied in 6 m lengths. Backfilling for plastic pipe culverts requires more care than for concrete pipes as they do not have the structural strength of their concrete counterparts.

Brick and masonry arch structures are rarely used these days because of their relatively high cost and the time required for construction, but these materials do offer an acceptable and attractive option for finishes to wingwalls and headwalls where appearance is a significant factor (see Figure 9.18).



Note in both cases it is possible to specify specials for junctions and manholes (there is a manhole fitting just visible at the rear of the corrugated steel culvert).

Figure 9.11 *Plastic pipes awaiting installation (a) and corrugated steel pipes being installed (b) (courtesy Tubosider)*

Where the ground has a low bearing capacity the designer should bear in mind that flexible culvert structures distribute loads better to the formation than rigid ones. However, designers should be aware that even if the culvert can survive differential settlement without structural damage the hydraulic performance of the culvert may be adversely affected. This is because the settlement tends to be greatest in the central part of the culvert length (where backfill loads are greatest) and sediment is more likely to be deposited in this lowered section.

Another factor in the selection of material is hydraulic resistance, particularly for long culverts. A culvert with a rough internal finish requires a higher upstream water level than a smooth culvert, other factors remaining equal. Values of Manning's *n* roughness coefficient are given in Appendix A1 but designers are advised not to be too optimistic about hydraulic roughness, as conditions tend to deteriorate with age. To minimise hydraulic resistance the joints between prefabricated units should be correctly aligned taking due account of construction tolerances.

The final choice of barrel material will depend on several factors including the hydraulic and structural requirements, the method of construction, and how easy it is to gain access to the site for plant and materials. Considerations of durability, safety and fire risk may also be appropriate in reaching a decision, as will an assessment of cost. Another factor in the choice of construction material is that of sustainability. All of these mentioned materials have some environmental disadvantages. Trying to identify the solution with the least environmental impact, taking into account use of non-renewable resources and energy consumption in manufacture, transportation and installation, is fraught with uncertainties. It may be worth attempting to assess the environmental impact of the different construction materials in the case of large culverts or multiple culverts, but it cannot be over-emphasised that the final choice should be a balance between all the factors, and not just the environmental impact.

Note how the structure is formed from small panels bolted together on site.

Figure 9.12 *A corrugated steel pipe arch culvert under construction (courtesy Tubosider)*

9.3.5 Barrel slope

Often the slope of the culvert barrel is chosen to match the slope of the natural channel it is replacing. In general, the culvert barrel should slope down in the direction of flow, as this aids the passage of sediment and small debris through the culvert. Designers are sometimes confused by the influence of the culvert barrel slope on its hydraulic performance. This confusion is compounded by manufacturer's design tables that link slope to flow capacity.

However, the slope of the culvert barrel often has little influence on the hydraulic performance. This is particularly true when the culvert is flowing full, but it is also true for part-full flow in short culverts or when the control point is downstream of the culvert. For steep culverts, the control point may be at the inlet, and the slope of the culvert barrel does not determine the flow rate in the culvert in this case. Designers are urged to assess the capacity of a culvert not on its slope, but from an assessment of available hydraulic head loss (see Section 6.2.5).

Although it is recognised that a steeply sloping culvert may be necessary or desirable in some circumstances, the consequences of a steep slope should be appreciated by the designer before this decision is made. Where a culvert alignment follows the channel alignment, making the culvert steeper than the watercourse will result in the outlet being buried in the bed of the channel, with no obvious advantages. If the culvert is steeper because the stream has been shortened (eg a meander loop has been cut-off), then a steeper slope may be acceptable, but it should be appreciated that this may present an obstacle to fish passage. The alternative would be to create a drop at the inlet, or outlet, but again these alternatives also run the risk of presenting a barrier to fish.

If the watercourse that is being culverted is steep, then it would be normal practice to adopt the same or similar slope in the culvert. However, again this may present a barrier to fish. This is because fish can negotiate the steep sections in a natural channel through short bursts of high energy swimming followed by rests in pools and backwaters. Inside a culvert, unless it is very short, the high velocity flow conditions present a challenge and the fish may fail to migrate upstream.

In circumstance where fish migration is not an issue, for example in a stormwater drain discharging to a river, a steep slope in the culvert barrel can have the advantage of allowing use of a smaller pipe size (assuming that the natural topography allows the adoption of a steep slope). High velocity flow in a culvert keeps it clear of sediment and small debris, but may create an erosion problem at the outlet. This can be overcome by using some form of stilling device at the outlet (see Figure 9.25), or by providing suitable erosion protection in the receiving channel. Steep culverts or culverts that retain water upstream should be designed to prevent flow from passing through the backfill surrounding the barrel, as this could erode the fill and cause collapse (see Sections 9.6.2 and 9.6.3).

In the absence of any other overriding factor determining the culvert slope, a slope of 1 in 200 is tentatively suggested as the steepest acceptable for helping to keep the invert clean without making conditions difficult for fish. If there is any doubt about the likely impact on fish migration, advice and guidance should be sought from the local fisheries officer. The issue of culvert slope needs to be considered more carefully if sedimentation is a serious concern because the propensity for self-cleansing depends on the size of the sediment particles. However, it should not be assumed that the culvert slope determines the flow velocity in the culvert, because this will be dictated by the available head to drive the flow through the culvert (ie the difference between headwater level and tailwater level).

It is sometimes necessary to change the slope of a culvert along its length, to suit the topography or avoid excavation in rock. Such culverts are referred to as "broken back". This is not a wholly desirable feature, but may be the pragmatic solution to avoid excessive construction costs. Such construction costs need to be viewed in the context of the whole-life maintenance cost to ensure performance requirements are met. It is suggested that culverts starting with a steep slope that reduce to a flatter gradient should be avoided, because of the risk of sediment or debris deposition on the flatter grade. Where a change of slope is unavoidable, a gradual change from one slope to the other will result in smaller head loss. If a sudden change of slope is unavoidable, it is good practice to provide a manhole at the point where the slope changes.

Steep slopes in large culverts make conditions dangerous for any operatives who have to enter the culvert for inspection or maintenance purposes.

9.3.6 Invert level

The invert level of the culvert should never be higher than the channel bed level, unless this is a deliberate design feature to create ponded conditions (eg for an outlet structure to a flood storage pond). In this case an alternative means of fully emptying the pond may be required. In general it is preferable to depress the culvert invert to some extent for one or more of the following reasons:

- to match better the channel hydraulics (particularly true for pipes because flow area is limited at shallow depths of flow)
- to allow for future re-grading of the channel (common for land drainage culverts)
- to promote nominal siltation in the culvert bed that improves environmental conditions.

Design hint

Wherever a pipe less than 1200 mm diameter is used for a culvert, it is recommended that the hydraulic performance is assessed assuming that the bottom quarter of the diameter is full of sediment and the top quarter is available for freeboard. This still leaves about 60 per cent of the gross cross-section to carry the design flow.

For larger pipes, box culverts and other structures the invert depression should be selected to suit site conditions but should not be less than 0.15 m.

This guidance is illustrated in (Figure 9.14).

For multi-barrelled structures there is much to be said for adopting two invert levels, with one barrel depressed below the other(s) to improve low-flow conditions. In this way the culvert hydraulics can be better matched to the channel hydraulics and conditions for fish and wildlife improved. In larger culverts, such an arrangement can also improve inspection because one or more of the barrels tends to be dry in low-flows, making access easier and safer. However, there is a tendency for siltation and weed growth to occur upstream and downstream of the high flow culvert (see Figures 9.5 and 9.9).

Alternatively, low-flows can be provided for by forming a low-flow channel within the invert of a larger culvert. Pre-cast concrete culverts can be provided with this feature built in, or it can be added later (see Figure 9.13).

9.3.7 Sediment

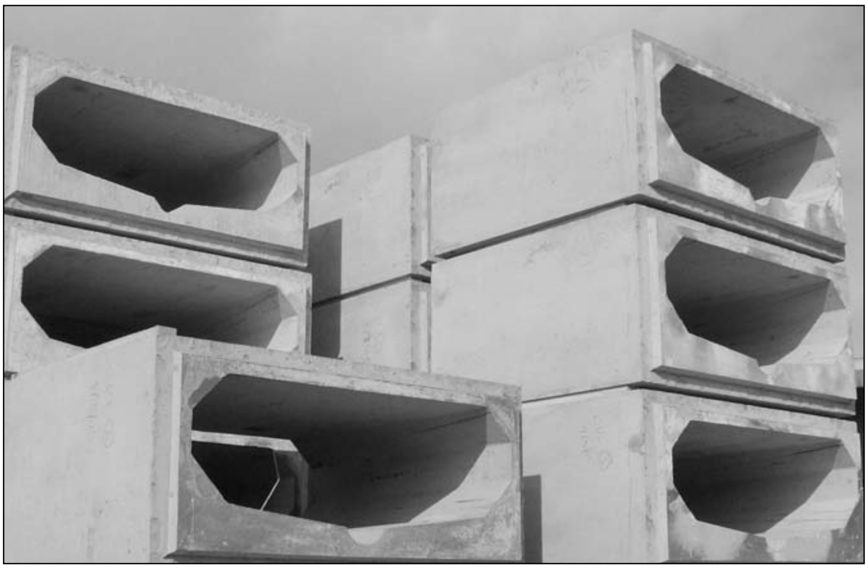
Sedimentation in a culvert is often seen as a potential problem, mainly due to the perception that the ability of the culvert to convey a flood is reduced by the accumulation of sediment in the barrel. However, from an environmental perspective sediment in the culvert barrel may be seen as an advantage, as it helps to maintain the natural regime of the watercourse through the culvert. A clean invert to a culvert will maximise its capacity but present a sterile environment to the aquatic life forms inhabiting the stream. In most cases a thin layer of sediment in the barrel can be positive, provided that it has been allowed for in the hydraulic analysis. Depths of sediment exceeding one third of the height (or diameter) of the culvert are unlikely to be acceptable, unless this is a feature of the design (for example, extra capacity in the culvert that can be mobilised in the future by re-grading the channel and removing some of the sediment from the culvert barrel). In a land drainage context, sedimentation in a culvert can elevate low-flow water levels upstream, restricting field drainage by drowning the outlets from drainage pipes.

Ideally, any sediment transported by the channel should be carried through the culvert. Sediment ranges from fine silt and organic matter in lowland channels, to gravel and boulders in steep streams. The designer should aim to have a velocity of flow through the culvert that is a little higher than in the channel upstream. This helps to reduce any tendency for deposition in the culvert. However, increasing the velocity of flow through the culvert to reduce sedimentation has to be balanced against the increased hydraulic head that is required to drive the flow through the culvert, which results in increased water level upstream.

As recommended in Section 9.3.6, depressing the invert of the culvert below bed level in the channel increases the chances of sedimentation within the barrel – one of the reasons for doing it. So it is common to accept a certain degree of sedimentation in a culvert. Only when the sediment builds up to the point where it is preventing achievement of the culvert's performance requirements should steps be taken to remove the sediment.

The conveyance of gravel and boulders through a culvert can cause substantial wear over the life of the structure and may preclude the use of certain materials. For large culverts, whatever the form of construction, it is always possible to provide a high quality concrete invert that can resist impact and abrasion damage.

Large boulders can be excluded from a culvert by the provision of a robust, suitably sized screen at the inlet or further upstream (see Figure 9.22). As with any screen, regular removal of trapped debris is required to ensure that it continues to perform effectively. Similarly, sediment traps excavated in the channel bed upstream of a culvert can be very effective in collecting sediment of all sizes and preventing damage to the invert, but will only continue to be effective if regularly cleaned out.



These pre-cast units have shaped inverts to improve low-flow performance. It is possible to cast any shape into the invert. The alternative is to depress the invert of a standard box culvert below the watercourse bed and allow a natural low-flow channel to form through the culvert, which may be better for fish and other aquatic wildlife.

Figure 9.13 *Pre-cast concrete box culverts with dry weather channel inverts (courtesy Steve Walker)*

Where there are connections into the barrel of the culvert care should be taken in detailing the junction to avoid build-up of sediment. The aim should be to provide a smooth passage for the flow, avoiding dead areas of water where sediment will accumulate.

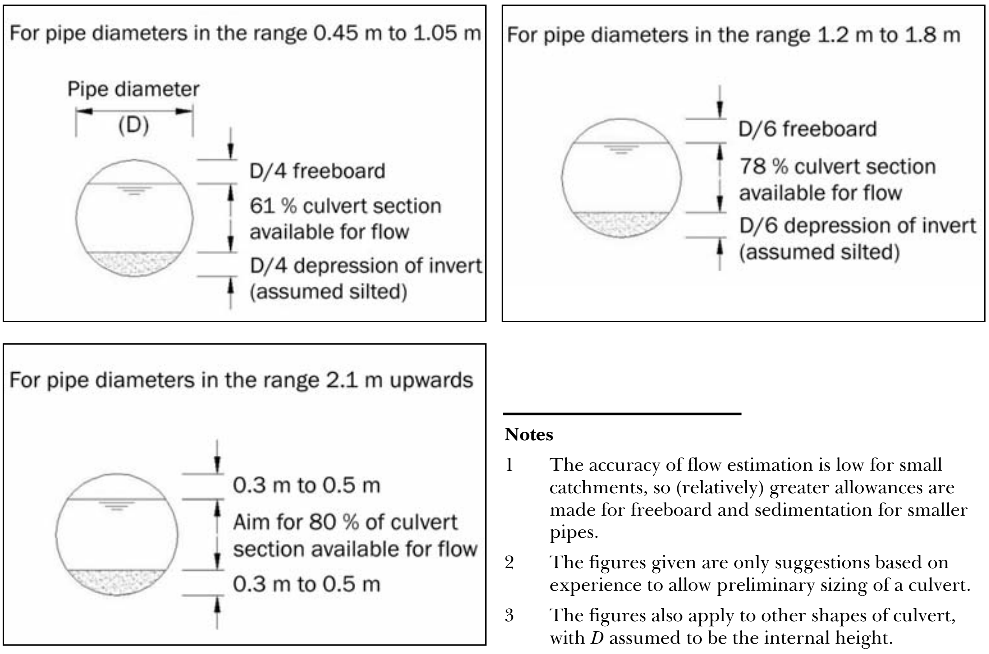
Sediment tends to be deposited in any areas of slow flowing water that may be created by bends, increases of width or depth, or at obstructions. The designer should always try to avoid such features, especially within the culvert, but also in the reaches of the channel upstream and downstream. Where these are unavoidable, provision should be made for regular inspection and sediment removal.

Design hint

As a starting point when sizing a culvert, it is suggested that the designer first estimates the flow velocity in the channel upstream for design flow conditions. The initial sizing of the culvert can then be determined assuming that the flow velocity in the culvert is 10 per cent greater than in the channel upstream. This will help to limit sedimentation risk in the culvert.

The available cross-sectional area of the culvert used in the estimation of flow velocity should exclude the area below channel bed level (assumed to silt up) and the area above design water level (freeboard). See Figure 9.14.

It should be noted that sediment accumulation in a culvert barrel is often the result of a constricted channel downstream. The lack of capacity in the channel downstream causes water levels to back up creating a sediment trap in the culvert and the upstream channel. This problem will persist until the under-capacity in the downstream channel is addressed.



Notes

1 The accuracy of flow estimation is low for small catchments, so (relatively) greater allowances are made for freeboard and sedimentation for smaller pipes.

2 The figures given are only suggestions based on experience to allow preliminary sizing of a culvert.

3 The figures also apply to other shapes of culvert, with *D* assumed to be the internal height.

Figure 9.14 *Suggested allowances for sedimentation and freeboard in a culvert*

9.3.8 Fish passage requirements and habitat provision

Fish

In general, fish can travel upstream through a culvert provided that the conditions in the culvert are not substantially different from those in the channel. Large culverts with a silted bed and a free water surface present few difficulties for migrating fish.

Velocity of flow may be an issue if the culvert is steep. Although certain fish can swim through rapid flow others are not so able and a badly designed structure could close off a migration route. The treatment of the inlet and outlet structures also needs consideration to ensure that fish are not discouraged or prevented from entering or exiting the culvert. Short lengths of channel or culvert with fast flowing water are unlikely to cause problems because most fish have the ability to sustain high speeds for short bursts. Some basic guidance on flow velocities, flow depths and water level drops is given in Table 9.3.

Table 9.3 *Designing for fish (adapted from Scottish Executive, 2000)*

Parameter		Coarse fish roach, dace, chub etc (less than 250 mm)	Brown trout (150 mm) and coarse fish (250 to 500 mm)	Sea trout and brown trout (250 to 500 mm) large coarse fish (more than 500 mm)	Salmon (more than 500 mm)
Maximum flow velocity (m/s)	Culvert length < 20 m	1.25	1.25	1.6	2.5
	Culvert length 20 m to 30 m	1.0	1.0	1.5	2.0
	Culvert length > 30 m	0.8	0.8	1.25	1.75
Minimum depth of water in culvert (mm)		100	100	150	300
Maximum water level drop at outlet (mm)		100	200	300	300
Minimum gap between trash screen bars (mm)		100	100 trout 150 coarse fish	150	200

The permissible flow velocities are based on burst speed for short culverts and cruising speed for long culverts. The maximum length of time that a fish can maintain its burst speed is about 15 seconds. Where screens are fitted to culverts these should be constructed from rectangular or oval cross-sectional shaped bars.

Box culverts with wide flat floors should be avoided on fish migration routes if low-flow depths occur unless a low-flow channel is provided. In some cases the installation of baffles in the invert of a culvert can improve conditions for fish by slowing the flow and locally increasing depth. However, this is not something that is generally recommended because the baffles will have an adverse effect on culvert hydraulics in flood flows and will act to trap debris, increasing the risk of blockage.

Culverts may also form a barrier to non-migratory fish because such species are reluctant to swim through culverts. They may use the culvert for cover where there is no alternative, but predatory fish such as pike can also make use of the shade offered by the culvert, tipping the balance in their favour. It has been suggested that fish find the interior of a culvert less discouraging if natural light is present in the interior, but there is little evidence to support this in the UK. For culverts longer than 50 m it may be worth considering the provision of natural light "chimneys" at intervals along the culvert, but it is recommended that guidance is sought from the local fisheries officer who will be familiar with the species of fish present in the watercourse.

If there is any doubt about the impact of culverting works on fish life in a watercourse, guidance should be sought from the local fisheries officer of the appropriate regulatory authority (for example, the Environment Agency). More guidance is given in Section 4.3.1.

Habitat provision

Watercourses provide havens and movement routes for many forms of wildlife, and culverts can destroy or disrupt habitats or corridors. It is often possible, at minimal cost, to make provision for local wildlife. An example is the provision of a ledge in the culvert (see

Figure 9.7) or high flow barrel, which is dry under normal flow conditions and can be used by wildlife using the river corridor as a pathway (see Figure 9.9). However, before deciding to provide a ledge in a culvert for mammals to use, the availability of other viable routes for the mammals should be investigated. The provision of anything in the culvert that takes up waterway area or might act to trap debris should be avoided if alternatives are available. One option to be considered is the provision of a small diameter pipe parallel to the culvert but above flood level, to be used by small mammals to cross the road or railway (see Figure 9.24). The recommended size for the mammal passage is 600 mm for length of less than 20 m, and 900 mm for greater lengths (TSO, 2007). Case study A3.5 presents examples of mitigation and enhancement works for mammal crossings under highways.

9.3.9 Management issues

Operation and maintenance

Many watercourses carry a heavy load of floating and semi-buoyant debris. This includes the natural products of the environment such as leaves, stems and twigs, branches and even tree trunks, in ascending order of the problems they may create for culvert designers. The debris also includes a wide range of man-made materials including plastic bags, traffic cones, timber pallets, polystyrene, plastic containers (up to oil drum size), and even old beds (see Figure 9.15). It is not unknown for gardeners and allotment holders to use the local stream as a disposal system for debris such as shrub cuttings. All of this debris will be carried downstream in flood flows until an obstruction is reached, where it can rapidly build-up and cause water levels to rise, with the inevitable risk of flooding. Although the provision of a screen at the entrance to a culvert will stop this debris from entering the culvert barrel, it is essential that the screen is cleaned regularly to prevent the build-up of debris from restricting flow into the culvert (see Section 9.4.3). It could be argued that a strategically placed screen could help in the clean-up of a watercourse, by collecting debris in one location where it can be safely removed and disposed of, but this is not a course of action to be recommended. It is far better to discourage use of the watercourse as a rubbish disposal system.

In this case the urban debris has been prevented from entering the culvert by the screen. This type of material could readily block a culvert with severe consequences. Note that there is a bypass facility at this screen to carry flood flows if the main screen is partially blocked by debris.

Figure 9.15 *The results of fly-tipping (courtesy Andy Pepper)*

In the past, little notice has been given to the operation and maintenance of culverts in developing designs. The philosophy, particularly with regard to urban watercourses, was "out of sight, out of mind". Unfortunately, this has led to a proliferation of culverts, often poorly designed and undersized, which have a high risk of blockage and consequential increased flood risk.

Now there is strong pressure to retain open channels wherever possible, and to culvert watercourses only when there is no viable alternative. When culverting cannot be avoided, the following design considerations that have an impact on operation and maintenance should be addressed during the design stage.

Accessibility

All culverts should be designed to allow safe access to the inlet and outlet to help inspection in all flow conditions, including the design flow.

For large culverts, where man-entry is feasible, provision should be made to allow safe access to the culvert interior (when flow conditions allow). Unauthorised access should be discouraged. This can be achieved by the provision of security screens at the inlet and outlet, but this is not a step to be taken lightly, as any screen will act to trap debris, with high maintenance implications. Another option to discourage access – especially to children – is to have a permanently wet channel bed at the inlet and outlet, although it should be appreciated that this may present a safety hazard and may make conditions more difficult for maintenance staff.

It should be noted that entry into a culvert can be a hazardous activity for a number of reasons, including:

- accumulation of gas, fumes or vapour that might be explosive or cause asphyxiation (such gases can be released when sediment in the invert is disturbed by walking through it)
- wet and slippery surfaces
- risk of head injury due to restricted height
- risk of Weils disease (Leptospirosis) from polluted water
- presence of water of unknown or variable depth, with the possibility of concealed steps.

Although it may not be possible to prevent all risks by good design, they can be minimised. Appropriate detailing of the culvert interior and manholes is important. When considering future operation and maintenance works, the designer should be aware of the particular hazards presented by working in confined spaces. In particular, adequate ventilation should be provided inside culverts where man-entry access is required for inspection and maintenance. It is important to ensure that access provisions are also adequate to allow safe egress in normal and emergency conditions. If in doubt guidance should be sought from a health and safety expert.

Obstructions in the barrel

The most common cause of blockage in culverts is obstructions that trap large items of debris, providing the basis for further build-up of trash and debris (see Figure 9.8). Older culverts often have service crossings (often sewers) that obstruct the waterway area by passing through or within the culvert barrel. Such situations should be avoided for new culverts by appropriate relocation of services. It should be noted that relocation to a position immediately upstream of the culvert inlet is not advisable as this can affect the hydraulics of flood flows.

Manholes

Manholes are not normally required on short straight culverts because access can be gained via the inlet or outlet. However, manholes should be provided on long culverts and at bends or changes of cross-section (if these are unavoidable) to help access into the barrel. Manholes should be provided more frequently on slow bends than on straight runs and may be appropriate, in some cases, at changes of ownership. For small diameter culverts (man-entry not possible) it is suggested that manholes should be provided at spacings of about 50 times the culvert diameter (or height for non-circular culverts) to provide access for inspection and jetting. A maximum spacing of 30 m is suggested for culverts that have to be cleaned by rodding or winching. For man-entry culverts it is suggested that manholes should be spaced at intervals of no more than 100 m. If the designer believes that any of these requirements is too onerous, he or she should investigate the risks of blockage (probability and consequence) and make a decision based on a rational assessment of the risks. Manholes should be designed in accordance with the National Annex to BS EN752:2008b.

Where it is feasible that a culvert barrel could be surcharged (ie flow under pressure), manhole covers should be of the lockable watertight variety to prevent escape of floodwaters unless there are reasons why relieving the pressure inside the culvert is desirable. Manholes lifting off in flood conditions present a severe safety hazard because anyone walking through the floodwaters may not be aware of the open manhole. It is important that manholes located in public spaces cannot be lifted and displaced in flood conditions. The use of high security manholes is also recommended for any locations where there is a risk that children may use them to gain access to the interior of culverts. In some urban areas "culvert walking" has become a dangerous adventure for children. Measures to restrict access will reduce the risk of death or injury resulting from this activity.

Particular attention should be paid to the design of the invert of a manhole chamber. Ideally this should follow the profile of the culvert invert, without any steps or obstructions that might encourage siltation or trap debris. This is particularly important if the culvert inlet does not have a trash screen. However, design to optimise hydraulic performance should not compromise the safety of operatives who require access through the manhole. Some local authorities now discourage the use of step-irons in manholes, preferring the safer option of a ladder. Ladders can be made removable (to discourage unauthorised access and reduce hydraulic impact), but it is important to incorporate safe fixings and provide secure storage facilities for the ladder nearby.

Sediment removal

Many culverts require occasional cleaning to remove sediment and debris from the bed. For short man-entry culverts this can be a reasonably simple operation, provided that safe access to the culvert interior is possible.

Sediment traps can be provided upstream (see Section 9.4.4) to prevent damage to the invert of the culvert or to avoid deposition in the barrel, but these should be regularly cleaned out if they are to continue to be effective.

Small culverts may require jetting to remove silt, and this should be considered at the design stage in terms of the number and location of manholes. A sump, perhaps temporary, may be required downstream to collect material flushed out. Cleaning by jetting is most effective in circular pipe culverts. Box culverts can be cleaned using a winch and scraper (or small plant). Corrugated steel structures are more difficult to clean without damaging them.

Very large culverts may require the use of mechanical plant for sediment removal, and the design should make provision for this (eg ramps to the channel bed, adequate ventilation, removable screen, flat invert). The range of mini-plant available for sediment removal means that provisions for plant access can be considered even for culverts of moderate size.

Box 9.1 *Summary of design issues related to the culvert barrel*

To reduce operation and maintenance costs and minimise the risk of blockage, the design of the culvert barrel should be based on the following wherever practicable:

- adequate capacity (generally to carry the one per cent flood plus 20 per cent extra to account for climate change, 0.5 per cent flood plus climate change allowance for Scotland)
- adequate freeboard above design flood level
- no bends in the culvert
- no steps or changes of cross-section within the culvert
- no other obstructions within the barrel
- use of durable materials for the construction of the culvert
- provision of access to inspect the inlet and outlet and, where the culvert is large enough, to gain entry into the barrel.

Finally, it is worth stating that no-one has ever been found guilty of making a culvert too large, whereas there have been many legal cases stemming from undersized culverts.

9.3.10 Extending a culvert

Extending a culvert is often mistakenly seen as a simple process of adding to the length of the barrel and maintaining the same cross-section and slope. Whereas there are occasions when this basic approach is appropriate, for most situations it is important to re-examine the design of the whole culvert, focusing particularly on the hydraulic performance, but also taking into account operation and maintenance impacts, sediment and trash conveyance, and environmental performance (ecology, morphology and wildlife issues). The general guidance given in this chapter should be applied to the extension and any works required to the inlet or outlet. However, there are some specific issues to address when extending a culvert, and these are:

- **hydraulic performance:** extending may increase the overall head loss and result in higher upstream water levels. It is important to check the hydraulic performance of the extended culvert to make sure the capacity is adequate. This is particularly so if the existing culvert is already operating at its limit, or if the extension introduces a bend or a change of cross-section. It is not acceptable to assume that lengthening a culvert using the same cross-section will be hydraulically acceptable
- **safety:** in general, the longer the culvert the greater the risk posed to anyone who enters it (either deliberately or accidentally). It is important to assess the risks before the decision to extend is made, and to incorporate safety improvements into the design (for example, providing security fencing at the inlet)

- **inspection and maintenance:** should be considered as part of the design of the extension. Wherever practicable, the construction of the extension should incorporate improvements that will facilitate inspection and maintenance
- **cross-section:** the culvert cross-section should be maintained through the extension and there should be no steps where the new culvert connects to the old. If it is necessary to have a different cross-section on the new length (for example, because the old culvert is a Victorian brick conduit) then the junction between the two sections should be as smooth as possible so that hydraulic head loss is minimised and to avoid snagging debris. If it is likely that the existing culvert will be upgraded in the future, then a larger section extension is acceptable provided that the transition between new and old is made as smooth as practicable to reduce head loss and avoid creating a trap for debris. Having the larger section on the downstream end of the culvert is better than on the upstream end as there will be less risk of large debris being trapped in the transition
- **slope:** ideally the slope in the existing culvert should be maintained through the extension. If it is necessary to have a different slope in the extension this should preferably be steeper if the extension is on the downstream end of the existing culvert, and less steep if the extension is on the upstream end
- **alignment:** the alignment of the new length should follow the alignment of the existing culvert. If this is not possible, the change in alignment should take place along a smooth curve, or a manhole should be provided at the point of change
- **differential settlement:** between the old and new sections is possible when the new section is constructed on virgin land under an embankment. This could create an undesirable step in the culvert. It is advisable to check and address any foundation conditions that might lead to differential settlement
- **length:** increasing the length of the culvert makes it more of a barrier for fish and wildlife, so it is important to investigate mitigation options.

9.4 The culvert inlet

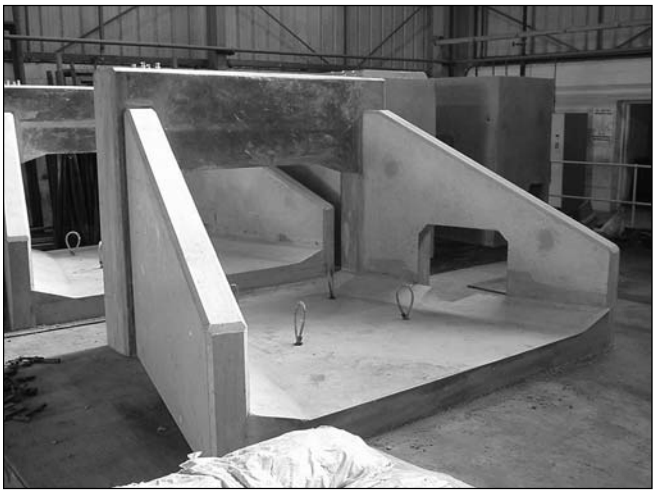
9.4.1 Function of the inlet

The transition from open channel to closed conduit is an important part of the culvert structure, and is frequently a source of problems. In its simplest form, the inlet structure is virtually non-existent – the culvert entrance simply starts where the channel ends. However, in most cases it is necessary to provide some form of inlet structure for one or more of the following reasons:

- to provide a transition from the natural channel to the culvert barrel, so as to avoid excessive head loss or the creation of sediment or debris traps
- to support the earthworks at the entrance to the culvert
- to prevent local scour that might undermine the culvert entrance
- to help the installation of a trash screen or security screen
- to house water level monitoring devices (where required)
- to accommodate a drop in bed level into the culvert
- to assist with future maintenance of the culvert (eg by the provision of stoplogs to allow one barrel to be closed off and dewatered)
- to incorporate an adjustable weir to maintain variable upstream water level (may be an environmental requirement in lowland drainage schemes and is often used on navigable waterways at the inlet to an overflow culvert).

Here the inlet is formed by a box gabion headwall with a slightly inclined front face (for stability). This is easy to construct, is free draining, and in time will become colonised with vegetation. The extra channel lining of mortared stone pitching accommodates an incoming drain on the left. In many cases there would be no need for further erosion protection – the stream channel could be unlined provided that (a) flow velocities are modest and (b) the headwall is long enough to accommodate stable channel side slopes.

Figure 9.16 ***Box gabion headwall at a culvert inlet***



Pre-casting the inlet structure reduces the need for in situ concreting. Note the lifting eyes built in to help handling and the provision for a drainage junction in the right hand wingwall. Units can also be provided in sections to reduce lifting weights.

Figure 9.17 ***Pre-cast inlet structures, complete with headwall and wingwalls (courtesy Tony Elliott)***

9.4.2 Design of the inlet structure

In general, the designer should aim to provide the simplest form of inlet structure compatible with achieving the relevant functions from those listed. In particular, the adoption of structurally complex warped walls to improve the entrance hydraulics should only be considered in circumstances where it is vital to minimise the head loss, or to aid the passage of debris through the culvert. Often a simple headwall is sufficient (Figure 9.18). However, it should be appreciated that the inlet arrangement needs to ensure that the earthworks in the channel and on the road or rail embankment are stable, so that there is no danger of earth material collapsing and obstructing the entrance to the culvert. It is a common error for designers to fail to appreciate the need for the lines and levels of the inlet structure to tie in with the slope of the embankment. This can lead to a structure that is visually unpleasing or, more seriously, unstable earth slopes that are prone to slumping.

The designer should also bear in mind that the inlet and outlet are usually the only visible parts of the structure. As such their visual impact should be taken into account. It may be appropriate to make use of natural stone recovered from excavation works to improve the visual amenity of the inlet and outlet works.

The design of the inlet structure becomes more complicated if it is established that there is a need for a trash screen, or a security screen (see Section 9.4.3).

Hydraulic performance

When the flow of water in a channel is subjected to change (in direction, depth or width) energy is lost in addition to the normal friction losses. This loss of energy is termed head loss, and the more dramatic and abrupt the change is the greater will be the head loss. Hydraulic design of the culvert should account for the head loss at the inlet (entrance loss or inlet loss). In effect, the greater the head loss, the higher the upstream water level for given flow conditions. The estimation of energy losses is described in Chapter 6.

Sometimes, the minimisation of head loss is vital, because it is important to restrict upstream water levels. The simplest way to achieve this is to provide the largest practicable culvert, with minimum change from the channel cross-section to the culvert cross-section. If this is not possible, then the inlet should be designed to provide as smooth a transition from channel to culvert as is practicable. This may include re-profiling of the channel sides at the approach to the culvert. Gradual change is vital for minimum head loss, but this can result in a long and expensive structure that would only be justifiable in certain circumstances (for example, the minimum energy loss culverts developed in Australia) (see Appendix A6). Guidance on the hydraulic efficiency of different inlets is given in Chapter 6.

Basic options

Some of the more common arrangements for inlets (and outlets) are illustrated in Appendix A5.2 In fact, the range of options is wide and it is likely that the solution adopted will be strongly influenced by the site geometry, and the arrangement of the trash or security screen (where required).

Where a streamlined inlet is required, consideration should be given to providing a long transition reach in the channel upstream of the inlet, such that expansions or contractions in plan or elevation are achieved at the modest rate of one-in-ten or thereabouts. In reality, often the biggest change is from a sloping channel bank to a vertical box culvert wall, which cannot readily be smoothed other than by the adoption of warped training walls. These are not recommended unless minimum head loss is essential.

In general the points to remember in inlet design are:

- hydraulic performance: the inlet structure should be aligned with the watercourse so as to minimise head loss and to avoid slack water areas where debris and sediment will accumulate
- ease of construction (avoid complex shapes if at all possible)

- erosion protection: although erosion is more commonly a problem at the outlet (see Section 9.5.6), it can also occur at the inlet, so adequate protection should be provided to avoid problems of undermining or outflanking of wingwalls and headwall
- safety (for the general public and operatives): consider providing handrails on top of high wingwalls and headwalls (the Highways Agency requires the provision of handrails on all headwalls and wingwalls, see Figure 9.6 for an example of this)
- operation: the provision of inexpensive stoplog grooves in the inlet can often simplify maintenance tasks and can allow temporary elevation of the upstream water level (can be useful for agricultural drains that are used for irrigation in the summer). The provision of a concrete apron provides a stable platform for inspecting the culvert
- access: should be a balance between allowing safe access for inspection by operatives and discouraging unauthorised access (by children in particular), but not impeding flow into the culvert.

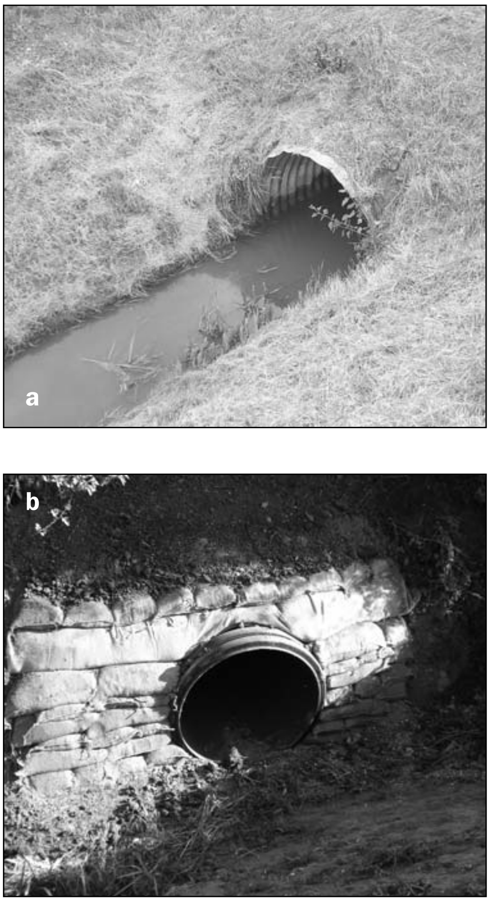


Figure (a) shows the simplest form of inlet with no structure or erosion protection. This is suitable for a culvert on a slow-flowing drain under a farm access road.

Figure (b) shows a similar inlet but with the addition of concrete bagwork to stabilise the steep watercourse bank.

Figure (c) shows the concrete pipe has been effectively disguised as a masonry arch (to match the adjacent masonry bridge, which is not visible in the photograph). The inlet comprises a concrete headwall, faced with masonry. This is a flood relief culvert with an invert level well above normal water level in the channel and so provides a dry wildlife passage that is only inaccessible in times of flood.

Figure 9.18 *Three simple inlet arrangements*

9.4.3 Inlet screen

Function

A screen may be provided at the culvert inlet for one or both of the following reasons:

- to prevent trash or debris from entering the culvert where it could accumulate and restrict the flow
- to prevent unauthorised access into the culvert (particularly by children) so as to avoid a risk of death or injury.

In the case of either a trash or a security screen, the need for the screen should be thoroughly investigated before the decision is taken, because the screen can be a source of problems. In particular, it should be appreciated that both trash and security screens will inevitably trap and accumulate floating debris. Unless such debris is regularly removed the effect could be a dramatic reduction of flow into the culvert with a consequent rise of upstream water level leading to local flooding. There have been many instances where blockage of a screen has caused extensive flood damage, whereas an unprotected culvert might well have been capable of carrying the debris without becoming obstructed.

The need for a trash screen

Screening of flow approaching a hydraulic structure is common practice in the case of land drainage pumping stations and at the inlets to turbines. The reason is simple – the passage of floating material into the pumps or turbines could cause damage or result in serious breakdown of the mechanical plant. In such instances, trash or weed screens are unavoidable and measures have to be taken to ensure that debris is regularly cleaned from the screen.

In the case of a pumping station it is likely that there will be regular attendance by operation or maintenance staff and there is also likely to be power for lighting and telephone or radio to assist telemetry links. The maintenance of the screen is easier to organise.

In the case of a culvert, the need is generally much less obvious and the consequences of screening are more onerous. It is necessary to make specific provision for inspection and maintenance of the screen. As well as routine inspections, a screen often requires emergency response at times of flood when weather conditions may be poor and also it may be the middle of the night.

The message is simple: in the case of a new culvert, wherever possible the design should avoid the need for a screen. This can be achieved by the following design features:

- generously proportioned culvert with free surface flow for the design flood
- no steps, obstructions or changes of cross-section in the culvert (manholes that may be vital in a long culvert, can also be a source of problems by trapping debris, see Section 9.3.9)
- smooth transitions into the culvert
- provision of easy access into the culvert to allow regular inspection.

For existing culverts, where some of these design features are not present, there may be justification for providing an inlet screen, but the decision should be based on a thorough investigation into the real risk of a blockage occurring in the culvert in a location where it would be difficult to clear.

Design of a trash screen

The Environment Agency (2009a) provides comprehensive and detailed guidance on assessing the need for and the design of inlet screens, including some guidance on environmental impacts. The following steps highlight the main points, but designers should refer to the source document for detailed guidance.

Step 1 Confirm need

A trash screen should only be provided where there is a high risk of culvert blockage and when the consequences of such a blockage would be significant. Major indicators are:

- trash/debris load frequently includes large items (eg timber pallets)
- there is a bend or other potential obstruction in the culvert
- the culvert is very long or access to clear a blockage would be difficult.

On a watercourse that has a succession of culverts prone to blockage, and where attempts to control the problem at source have failed, consideration should be given to the provision of a single screen at one particular site upstream of the culverts. This offers the opportunity to reduce maintenance effort by focusing the cleaning operation in one location. This approach could be applied at a catchment scale, having strategically placed screens to address trash collection in selected locations.

Step 2 Estimate debris amounts

Wherever possible, the amount of debris carried by the watercourse should be established by observation over a significant period. This may lead to the discovery of a source of debris that can be eliminated or reduced, but in any case it establishes the nature of the debris and the likely quantities. The results can be used to determine the appropriate area of screen and the bar spacing.

The type of debris is also important. Leaves, twigs and small branches from a wooded valley are readily conveyed by an adequately sized culvert, but will rapidly block a screen. Blockages are usually caused by the accumulation of a wide range of debris supported by one or two large items (planks, timber pallets etc). The worst combinations include plastic fertilizer sacks that, when supported by other debris, can form a dam through which little water can pass. Various forms of aquatic weed that break free from the watercourse bed can also present a blockage hazard on a screen. Such plants often thrive in water with high nutrient levels.

In some locations blanket weed can be very problematic. One such example was a typical concrete lined urban channel where the flow is wide and shallow for most of the time and there were high nutrient levels due to greywater discharges. Such conditions promote the rapid growth of blanket weed that was picked up and conveyed in a flood, and carried to the screen illustrated in Figure 9.15 where it blocked the screen within half an hour.

In the absence of observed data on debris types and amounts, the Environment Agency's guidance on trash and security screens (2009a) provides a method of estimation based on catchment characteristics.

Step 3 Confirm responsibility for maintenance

It is important as part of the design process to confirm who will be responsible for inspecting and cleaning the screen throughout its life. Part of this process includes confirmation that the responsible party is aware of the demands that this will place on it, and has the plant and labour resources appropriate to the task. Depending on the resource capabilities of the responsible party, it may be necessary to design in specific measures to help the maintenance process.

Step 4 Design of a screen

The main features of a well-designed screen are:

- bar spacing – this should not be less than 150 mm, and a wider spacing should be used where appropriate to the dimensions of the culvert and the size of debris to be trapped
- angle of inclination of the screen bars to the horizontal should preferably be 45° and no steeper than 60°
- there should be provision for safe access by operatives to the screen to allow it to be cleared of debris, even in flood conditions
- there should be space for the temporary storage of debris removed from the screen
- lighting should be provided if there is a requirement to clean the screen in the hours of darkness
- the screen and any associated equipment should be resistant to vandalism – if necessary the whole of the inlet structure should be fenced off to exclude vandals
- bypass facility – this should be provided in situations where rapid blockage of the screen could occur, giving insufficient time to mobilise a crew to clear it.

Figure 9.20 illustrates a screen with many of these features.

The installation of water level monitoring equipment should be considered when the consequences of blockage are potentially serious or where the site is remote (see Case study A3.3). This normally involves monitoring the upstream water level and the head loss across the screen, and transmitting the data by telemetry to a location where it can be monitored, or initiating an alarm to warn the owner of the screen that there is a potential problem. It should be appreciated that such a system is only viable if operatives can be alerted and mobilised in time to clear the blocked screen before it causes a problem.

Note this is a relatively short straight culvert so there is no need for either a trash screen or a security screen.

Figure 9.19 *A highway culvert flowing near full (courtesy Jeremy Benn)*

Security screen

Security screens should be provided where there is a significant risk to the general public. Flowing water and confined spaces offer dual attractions to adventurous children and have led to fatalities and serious injuries, but such occurrences are relatively rare and they do not justify the screening of culvert inlets as a general measure. The decision to provide a security screen should be based on a full appreciation of the risks in terms of the hazard presented by the culvert and the likelihood that anyone will be exposed to this hazard. In general a short length of culvert flowing with a free water surface presents no more risk than the open channel upstream and downstream of the culvert (Figure 9.19). Note that a security screen may also be provided at the outlet to a culvert (see Section 9.5.5), but only if there is also a screen at the inlet.

Indicators of high risk in terms of the hazard include:

- long culverts (say more than 50 m)
- culverts that may flow full
- steep culverts with swift flow velocity
- culverts with internal hazards such as steps in the bed or a hydraulic jump.

Indicators of high risk in terms of the likelihood and anyone being exposed to the hazard are:

- a history of previous incidents
- location of the culvert entrance near to areas where children are known to congregate.

In this location the risk to life of the open culvert inlet could not be accepted. Note the good design features – two cleaning platforms (both readily accessible), turned-over bars to help raking debris onto the platforms, space for parking and temporary storage of debris, safety hand railing, whole site fenced for extra safety and security. Note that the horizontal part of the screen behind the lower cleaning platform adds flow capacity but does present a small risk to an operative cleaning the lower screen. The operative may step backwards onto the horizontal screen and lose his footing.

Figure 9.20 ***Security screen upstream of an urban culvert***

Alternative approaches to reducing the risk should be considered before the decision to provide a security screen is made. These include reducing the hazards posed by the culvert, or restricting access in some other way (such as fencing the culvert inlet or planting thorny vegetation to discourage access).

Once the decision to provide a security screen has been made, its design follows that of a trash screen in every respect except that the clear spacing between the bars (and any gap between a bar and the structure) should be 140 mm.

This screen is located in a residential area close to houses. It has clearly been installed to prevent children gaining access to the culvert. However, the design is poor – the bars are too flimsy and there is a gap in the side that would allow access. Also, the design is unnecessarily complicated, there is no need for the platform at the top and the screen could have been less steep to help cleaning. The horizontal bar welded to the screen bars makes raking the lower part of the screen impossible.

Figure 9.21 *Poorly designed security screen (courtesy Richard Allitt)*

Boulder or roughing screens

In situations where large debris is conveyed by a stream in flood, it is often appropriate to provide a coarse screen that can be safely overtopped some distance upstream of the culvert. Such screens are also referred to as roughing screens when they are designed to trap large floating debris such as tree branches. As with any other screen, regular inspection and cleaning is important. Designs vary from simple vertical steel bars embedded in the channel bed, to more conventional screens with bars angled at a suitable rake. All such screens should be designed to overtop safely (ie without causing flooding or erosion) when completely obscured by boulders or debris, and should be robust enough to hold back accumulations of large debris (see Figures 9.22 and 9.23). Case study A3.11 relates to the design of a boulder and debris screen at Boscastle.

These are constructed from old rail track embedded in concrete. They form an effective overtopping enabled trap for any cobbles or boulders rolling along the bed. However they also trap other debris that will build-up if not regularly cleaned out.

Figure 9.22 *Boulder screens upstream of a culvert (courtesy Richard Allitt)*

Figure 9.23 *Roughing screen upstream of a culvert*

A good example of a coarse screen is a wooded area upstream of a culvert. The coarse screen is overtopping enabled and is designed to catch large woody debris that would otherwise tend to block the main screen on the culvert (not seen in Figure 9.23).

Mechanically raked screens

Mechanically raked screens are relatively common at pumping stations where weeds form the major part of the trash load. Such devices are much less common on culvert screens, but have been used in some circumstances. There has been at least one case of a culvert with an automatic screen rake where failure of the rake to operate properly in a minor flood led to complete blockage of the screen and consequent extensive flood damage in an urban area.

Caution is urged in the adoption of automatic mechanically raked screens for culverts. In particular, the designer should establish:

- the type of debris that will be encountered and the ability of the rake to deal with it (wooden pallets and old mattresses can be particularly difficult and may cause failure of an automatic rake)
- whether the operating cycle of the device can cope with the rate of accumulation of trash
- the consequences of failure to operate
- the provision of adequate space for disposal of screen rakings
- the degree to which vandalism could immobilise the system
- the need to provide fail-safe back-up systems
- the need for automatic monitoring of screens using telemetry.

Mechanical raking need not be automatically controlled but could be operated locally by a visiting operative. Such an arrangement may be appropriate for large culverts when manual clearance using rakes is impracticable, but careful thought should be given to the likely frequency of cleaning. A better alternative is to provide access for a lorry-mounted grab that can be brought to the site when necessary. Clearly this option is only open if there is good vehicular access to the screen to allow the safe deployment of the plant.

Owners of culverts have had mixed experience of the use of telemetry to monitor screens for the build-up of trash and to warn of vandalism. There have been problems with vandalism to the telemetry equipment itself (for example, theft of solar panels), but the Environment Agency has had some success in developing vandal-resistant installations. Remote monitoring can greatly reduce wasted effort sending a maintenance gang to a screen that does not need cleaning (see Case study A3.3).

Removal of a screen

Where a screen provides a maintenance headache there are two options: redesign the screen to improve its performance or remove it altogether. The latter option needs careful assessment of the hazards and risks. In the case of a security screen this will involve a thorough investigation of the likelihood of anyone gaining access to the culvert, and the adverse consequences of them doing so. Alternatives such as fencing off the inlet can be considered. For a trash screen, historical records of the nature of debris accumulating on the screen and the frequency of cleaning will be invaluable in assessing whether such material poses a real risk of blockage to the culvert.

9.4.4 Sediment traps

Before considering any measures to address a sediment issue it is important to assess the nature and scale of the problem (see Section 9.1.3). It may be possible to identify a discrete source of sediment and to control it at source (for example, by protecting an eroding bank). Guidance on the assessment of the catchment as a precursor to culvert design is given in Chapter 5. This will include an assessment of the catchment geomorphology, which will identify any significant issues with sediment transport. If sedimentation in the proposed culvert is considered to be a potentially serious problem, the advice of a geomorphologist should be sought, with the aim of designing appropriate mitigation measures.

The creation of a sediment trap is one potential solution. By deepening the channel upstream of a culvert, a sediment trap can be created. This will trap sediment of all sizes, from silt to cobbles, but the percentage of the finer material trapped depends on the size and shape of the trap. Typically the trap occupies the full width of the channel with a total depth (below normal flow level) up to twice the depth in the channel. The length should be at least 10 m.

The longer and deeper the trap is made, the more effective it is in collecting sediment. Indeed, there are likely to be diminishing returns because a more efficient trap removes material that would otherwise readily pass through the culvert. This material has to be regularly excavated from the trap.

Sediment traps should only be considered where:

- for unavoidable reasons the culvert is likely to trap sediment
- the trap can be accessed easily to allow cleaning out
- the responsible authority is committed to cleaning out the trap on a regular basis, and has the means of so doing.

Trapping of sediment may affect the geomorphology of the channel downstream, causing an increase in erosion. There may also be an adverse effect on watercourse ecology that would be contrary to the requirements of the Water Framework Directive. The impact of the sediment trap on the channel downstream should be considered at the time that this option is being considered.

It should be noted that a sediment trap may create a hazardous region of deep water in the channel and the designer should make suitable provision for security fencing or warning signs.

Box 9.2 ***Summary of design issues related to the culvert inlet and outlet***

The photograph illustrates several design points relating to the inlet and outlet of a culvert:

1. In this case the designer has used pre-cast concrete box units for the culvert, with cast *in situ* headwall and wingwalls. Note that there has been erosion of the channel banks near to the ends of the wingwalls, and attempts have been made to stabilise this. A better solution would perhaps have been to provide stone erosion protection in this area.
2. The culvert is short and quite large, so there is no need for a screen of any kind.
3. Timber fencing has been provided around the structure to reduce the risk of vehicles or farm animals getting too close for safety.
4. Steps have been provided along the back of one wingwall, presumably to help access for inspection – but were these really necessary? They may serve to encourage access by inquisitive children.
5. At the time of the photograph, the water level in the channel is very low (the watercourse is tidal). In non-tidal situations, if very shallow depth of flow persists in a culvert it will restrict the movement of aquatic life up and down the watercourse.
6. The culvert invert appears to have been set above the channel bed level. This means that flow depths in the culvert will always be shallow when flow in the watercourse is low. Any dredging in the channel would tend to worsen this effect.

Designers may wish to compare this approach with the different designs featured in Figures 9.5, 9.6, 9.9, 9.16, 9.17, 9.18, 9.19 and 9.29. It will be appreciated that there is no "standard" approach. Designers should assess all the criteria that influence the design of the inlet and outlet to the culvert and then make a decision as to the most appropriate arrangement to suit their circumstances

9.5 The culvert outlet

9.5.1 General

Flow leaving a culvert structure often has a higher velocity than in the channel downstream, and tends to be concentrated in a "jet" rather than spread evenly over the full section of the channel downstream. These factors increase the risk of erosion in the channel immediately downstream of the culvert, on both the bed and the banks. Erosion of the bed has the potential to undermine the culvert, causing it to collapse, and erosion of the banks could outflank the headwall or wingwalls also leading to collapse.

It is appropriate to incorporate measures to prevent or limit scour, or to design the structure to resist it.

Note the simple outlet arrangement, with mortared stone pitching channel lining on the bend in the watercourse. Note also the gravel invert in the culvert (matching that in the watercourse), the use of local stone, and provision of a mammal crossing at higher level.

Figure 9.24 *An outlet from a highway culvert (courtesy Transport Wales)*

9.5.2 Outlet structure

The form of the outlet structure can usually be similar to that of the inlet structure, providing a transition from the culvert barrel to the channel downstream. As for the inlet, the adoption of complex warped wingwalls to maximise head recovery and reduce energy losses, is seldom worthwhile. It requires very long transitions, ideally with changes in cross-section taking place at no greater rate than 1 in 10. However, it is important to design a structure that does not amplify any tendency for erosion, and that eases access to the culvert exit for inspection purposes. In reality, the issue of head loss only becomes significant in situations where the flow velocity through the culvert is significantly greater than in the channel. The same is true of the risk of erosion damage to the bed and banks downstream of the outlet, unless there is a significant drop in water level at the outlet.

Design hint

Although it is important that the need for outlet head loss reduction and erosion protection should always be assessed for each individual culvert, if the velocity of flow through the culvert barrel is less than 1.0 m/s there is unlikely to be a requirement for either.

If the flow velocity through the culvert exceeds 2.0 m/s, then erosion protection at the outlet is almost certainly required and there may be a case for streamlining the outlet to conserve head (see Chapter 6).

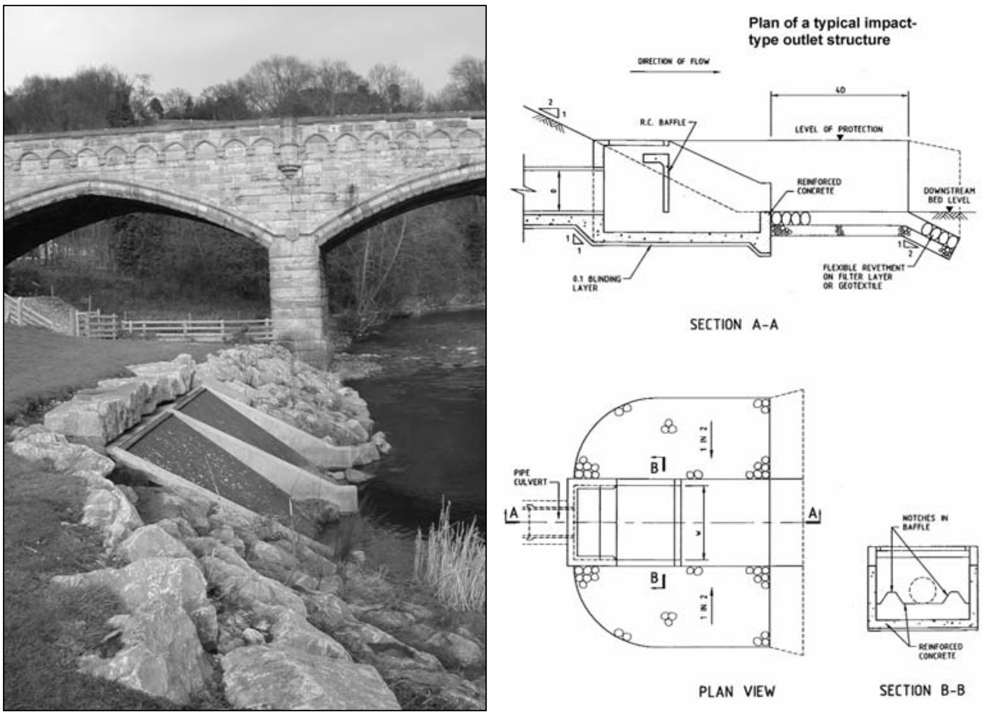
The inlet arrangements shown in Appendix A5.2 are equally applicable to outlet structures, although more extensive or substantial erosion protection may be needed (see Section 9.5.6).

Where the culvert outfalls into a river, erosion of the river-bank may undermine the outfall structure, and bank protection may be required. To reduce turbulence when the outflow from a large culvert joins a river, the outlet pipe should be angled downstream on plan at about 45° where possible.

9.5.3 Energy dissipation

Although the velocity of flow leaving a culvert is generally higher than that in the channel, it is not normally necessary to provide any form of energy dissipation at the outlet because flow velocities are generally moderate (usually less than 1.5 times velocity in the channel). However, where culverts are steep or the head loss is high (for example, outlet from a flood storage reservoir) it may be necessary to provide an energy dissipating device in the outlet structure. This destroys the excess energy and creates relatively tranquil conditions as the flow joins the channel.

Energy dissipation can be achieved by the construction of a stilling basin, but this is only effective if the flow leaving the culvert is supercritical (having a Froude Number greater than unity). Where there is rapid (supercritical) flow leaving a culvert, energy dissipation is more commonly achieved by placing a baffle across the outlet structure, such that the flow leaving the culvert affects the baffle. A typical arrangement is shown in Figure 9.25, together with a photograph of a completed structure. It should be noted that this type of structure can silt up (from sediment carried by the river), because it may only flow intermittently. This can cause the culvert to back-up. The underside of the baffle can be notched (see Figure 9.25) to help deposits of sediment to be flushed away.



Note high velocity flow from a stormwater culvert (twin pipes) is discharged into the river via this impact-type outlet box. The diagram on the right shows the general principle of this type of outlet (single pipe structure). The outlet in the picture has a security screen on it because the location is near a school and in a popular recreation area. The rock revetment is required to protect the river-bank from erosion by fast flowing water in the river, but it also helps the structure to blend in to the local environment.

Figure 9.25 *An impact-type outlet structure*

9.5.4 Flap gates

For culverts that outfall into a river (especially tidal rivers), pass through a flood defence or on to the sea shore, it is often necessary to provide a flap gate on the outfall, to prevent backflow under conditions of high water level. These range in size from off-the-shelf flap valves suitable for pipe outfalls, to custom-made flap gates for large box culverts. In some large land drainage culverts, pointing doors (similar to lock gates) have been used successfully to achieve the same effect.

Flap gates are prone to a range of problems, including:

- theft of metal components for sale as scrap
- vandalism (especially being jammed open by strategically placed planks or other debris)
- sedimentation in the receiving watercourse that restricts the ability of the gate to open (Figure 9.26)
- failure to close because of debris caught in the outfall
- corrosion of hinges resulting in restricted movement and eventual failure
- distortion of the gate (large structures only) resulting in failure to close properly.

These issues can be overcome to some extent by judicious design, but the most important feature is to ensure that the outfall is readily accessible to allow regular inspection and maintenance. The “double-hung” arrangement for flap gate hinges (this is the type used on the gate illustrated in Figure 9.26) is much better at avoiding problems associated with sticking gates than a single hinge. In the double-hung arrangement, each of the two hinges is articulated twice. There are also flexible (rubber or neoprene) alternatives to flap gates that rely on hydrostatic pressure to open and close a simple valve. These have been extensively used in the US but are less common in the UK. They are claimed to be virtually maintenance-free.

Vandalism can be reduced by the provision of a security screen enclosing the outfall. The clear space between bars should be 140 mm, and the screen should be at least 1000 mm from the nearest part of the flap gate and well clear of the gate in its fully open position.

Design hint

Where a flap gate forms a vital component of a flood defence system (for example, on a drainage culvert passing through a tidal flood embankment), the culvert should incorporate a penstock to be operated in the event of flap gate failure. It is normal to locate this in a manhole chamber on the landward side of the flood defence. Some local authorities require two flap gates in series as a failsafe provision in main flood defences. Designers should check local requirements to make sure that these are adhered to.

Note: The effective operation of this outfall has been compromised by the condition of the channel downstream. The flap gate should be free to open under the pressure of the water in the culvert.

Figure 9.26 *Flap-gated outfall (courtesy Andy Pepper)*

The design of the outlet structure should allow plenty of clearance round the bottom and sides of the flap gate, so as to reduce the risk of obstruction by debris and sediment, and ideally the floor of the outlet should fall away from the flap to reduce the risk of sedimentation. Winching points should be provided on headwalls for lifting large flap gates. This helps opening the flap gate for inspection and maintenance.

Flap gates prevent the migration of fish upstream. This is not an issue if the flap is on the end of an urban drain, but for situations where it is necessary to install a flap gate on a fish migration route alternative arrangements need to be considered. The Environment Agency has recently developed a gate that will allow the passage of fish. This was primarily for tidal exchange situations where the gate could remain open for a considerable period, but application in fluvial situations is possible. Details are presented in Case study A3.12.

9.5.5 Outlet screen

Although the risks of death or injury are likely to be lower as a result of entry into a culvert via the outfall as compared to the inlet, it is sometimes advisable to provide a security screen at the outlet. This prevents children from gaining access to the culvert. However, it should be noted that it would be unacceptable to install a screen at the outlet unless there is also a screen at the inlet, because the outlet screen would prevent the evacuation of debris or anyone washed into the culvert through the inlet. The outlet screen bar spacing should be the same as, or greater than, the bar spacing of the inlet screen.

The screen has been designed to be released from a safe position to allow any accumulation of debris to escape. The figure shows the securing mechanism being unlocked. The chain allows the screen to be returned to position for locking after debris has been released. Note the different bar arrangement from that suitable for an inlet screen. Horizontally-aligned bars are better for passing linear debris (such as a plank) and they have been braced to resist vandalism. The whole screen is mounted vertically. None of these features would be acceptable at the inlet because they would make raking difficult.

Note the attractive brick and flint finish to the headwall and wingwalls, the small stilling basin, and the stone erosion protection (the latter is just visible at the bottom of the figure).

Figure 9.27 *Security screen on an outfall from a flood storage reservoir (courtesy Andy Pepper)*

The outlet screen should be removable, or have a lockable access hatch, to allow entry for authorised staff for inspection and maintenance. The option of having a top-hinged screen, not locked or fastened, to allow safe escape of a build-up of debris in a flood may also be considered but the designer needs to be aware that vandals or adventurous children may discover that it does not preclude access.

It should be noted that even with a screen at the inlet an outlet screen will collect trash that has passed through the inlet. This can accumulate over time and the nature of the outlet screen precludes removal of the material by raking. In flood conditions the build-up of trash on the inside of an outlet screen could cause the culvert to surcharge with increased risk of flooding upstream. The arrangement shown in Figure 9.27 is designed to overcome this problem.

This security screen at the outlet from a culvert has become almost completely blocked by small trash that has passed though the inlet screen. The screen is designed to allow the release of the blockage, but this requires an operative to release the locking mechanism. If the blockage is not noticed until it reaches the degree illustrated, the culvert capacity will be severely compromised.

Figure 9.28 *Security screen blocked from the inside (courtesy Andy Pepper)*

9.5.6 Erosion protection

The need for erosion protection

Erosion protection is provided at the outlet to protect against the erosive force of the turbulent flow as water passes from the hydraulic conditions in the culvert barrel to those in the open channel. Erosion of the channel sides can be serious as it leads to land loss and may undermine flood defences. Undercutting of the outlet structure can also occur, causing movement and ultimately failure. Protection is also often needed at the inlet to the culvert for the same reasons, though this is generally not as extensive as outlet protection works.

Where flows are small and of low velocity the protection provided by the natural vegetation cover in the channel may be sufficient. Substantial protection downstream of energy dissipation structures is essential.

Note: In both cases the outfall has been achieved by cutting the pipes at an angle to suit the bank profile. In photograph (a) erosion protection has been achieved by the use of gabion mattress – both this and the bare soil will rapidly become vegetated. In photograph (b) the corrugated steel culvert has been in place for some time and the vegetation is well established. With this example, the invert has perhaps been set a little too high.

Figure 9.29 *Two simple outfall structures: concrete pipe (a) and steel pipe (b) (courtesy Andy Pepper and Amanda Kitchen)*

Types of erosion protection

The type and extent of erosion protection depends on the following factors:

- the flow capacity of the culvert
- velocity and turbulence of flow
- wave action (at outfalls into estuaries, coastal locations and other large water bodies)
- channel bed material
- predicted variation in channel bed levels
- channel-side vegetation
- the consequences of erosion, eg failure of flood defence structures.

Flexible protection is preferred to rigid protection because it can adapt to settlement or local erosion and so maintain protection of the structure against further erosion. Detailed guidance on the design of flexible revetment systems can be found Escarameia (1998). The following types of protection are commonly used:

Grass: this can only be used where flow velocities are low and where the bed and banks are not continually submerged. Soil may either be seeded or turfed. The latter is more expensive but is appropriate if immediate cover is needed. Another alternative is one of the many pre-seeded biodegradable mats that are now commercially available. The mat (generally jute or a similar material) can protect the channel sides until the grass has established a good root network.

Dumped stone (riprap): easy to lay and provides a good transition between the natural channel and culvert outlet. Good quality durable stone should be used. The stone size and layer thickness should be based on flow velocity (or wave action if this is present).

Stone pitching: placed by hand either dry or using cement mortar. Stone sizes and layer thickness can be less than for dumped stone, but labour costs are higher. With mortared (or grouted) stone pitching there is less chance of individual stones being dislodged or removed. However, mortared pitching is not flexible and is not able to adapt to erosion at the edges or settlement.

Gabion mattress: provides good protection as it is flexible and so maintains protection even after movement. Stone sizes and thickness can be considerably less than dumped stone or stone pitching, but the appearance may be less attractive. Main disadvantage is when mesh fails or is vandalised leading to loss of stone. Brushing friable topsoil into the surface of the completed mattress helps to establish vegetation more quickly, and by creating a muddy environment discourages vandalism in the period immediately after construction.

Concrete block systems: available from various manufacturers, either for hand placing as individual blocks or machine placed as linked mattresses. The mattresses can be laid under water but they are less attractive and not as adaptable as the stone-based alternatives.

Where provided erosion protection should extend above the design water level to ensure that any waves or surface turbulence are accommodated.

Most types of protection require an underlayer or filter that provides more protection for the subsoil against erosion, and separates the armour layer from the subsoil.

The underlayer can either be gravel, at least 150 mm thick, or a geotextile. Using gravel has the added advantage of providing improved bedding for the armour layer and giving better in-plane drainage. Where a geotextile is used, the material should be selected after consultation with manufacturers to determine the product appropriate to the situation. For heavy protection, it is common to have an underlayer of a geotextile plus a granular layer.

9.6 Other design considerations

9.6.1 Extreme floods

Intense localised rainfall can result in extremely high flood flows in small catchments. Such storms are not uncommon, tending to occur more frequently in the summer months. An intense storm centred over the catchment upstream of a culvert could easily generate a flood flow well in excess of the culvert capacity. Guidance on this subject in respect of urban drainage systems can be found in Digman *et al* (2006).

Although such storms are not uncommon, the chance of one occurring in a particular location is relatively rare, so it is not normally economically viable to consider it as a design case. However, it is good practice to consider the consequences of extreme floods to assess the need to amend the design. For example, it may be feasible to design the culvert such that excess flood flow can safely bypass the culvert without causing flooding of local properties or infrastructure.

The same considerations apply to a partially blocked culvert. In both cases the provision of an overland flow route that does not cause flood damage to properties or infrastructure will avert serious consequences should the event occur. There have been cases where the only overland flow route available was through houses or, in one case, through the middle of a leisure centre. In one particular instance, the culverting of a brook at the bottom of private gardens led to the householders extending their boundary fences across the top of the culvert. When the capacity of the culvert was exceeded, excess flow along the route of the brook was restricted by the fences and flooding of houses occurred. This could have been easily avoided by providing an overland floodway over the culvert, and protecting this from development. In hindsight the better option might have been to improve the brook as an open channel and discourage residents from using it as a convenient rubbish disposal system (which was the impetus for the culverting in the first place).

In the particular case where the culvert is in an embankment that impounds water if the flow exceeds the culvert capacity, the application of the Reservoirs Act 1975 needs to be considered. A flood storage reservoir (or balancing lake) with a culvert outlet is relevant here. Although the Act was not drafted with flood defence works in mind, if an embankment creates a reservoir that is capable of storing more than 25 000 m^3 above natural ground level, the designer should seek the advice of an engineer appointed to the all reservoirs panel under the Act. Applicability of the Act does not mean that the culvert has to be designed to carry an extreme flood flow, only that the reservoir embankment can be safely overtopped by the flood. Note that the Act applies even if the reservoir only contains water intermittently and for short periods, as is the case with flood storage reservoirs.

Whereas examining the flood risk in the immediate vicinity of a culvert is appropriate to the design of most structures, there are circumstances where it is important to look at the wider hydraulic system. This is likely to involve mathematical modelling and in extreme floods this will involve out-of-channel flow, requiring the use of 2D modelling techniques.

Such modelling techniques combined with good topographic information (for example, from LIDAR surveys) can provide a powerful tool in flood risk management, by identifying the extent of flooding, the routes taken by floodwaters, and the depths of water likely to be experienced. This approach is likely to be of significant value to those responsible for the management of drainage basins in urban areas, where culverts and other drainage structures are common.

9.6.2 Practical considerations

Joints

For culverts constructed from concrete pipes or pre-cast concrete boxes, the individual units are connected by some form of joint. The joint should be flexible, accommodating small movement but not allowing differential settlement at the joint, and most commonly takes the form of a spigot and socket for pipes or a rebated joint for pre-cast boxes. The joint does not generally need to be watertight, but there are instances when this would be desirable, namely:

- where leakage into the culvert from high groundwater or rainwater percolation through an embankment might wash backfill through the joints
- where road salt could be leached into the joints causing corrosion damage (all highway culverts should have a membrane over the top and part way down the sides for this reason)
- where loss of water from the culvert would be undesirable (eg washing out bedding material leading to subsidence).

Joints for flexible pipelines are usually sealed with rubber or neoprene rings. Joints between pre-cast concrete culverts may be sealed where necessary with proprietary sealants such as pre-formed rubber bitumen, or butyl-resin strips. Joints in in situ concrete culverts may take the form of conventional or rearguard waterstops.

Joint sealer can be plucked out by high velocity flow and may be omitted or replaced by an appropriate mortar joint for culverts where high velocities occur. However, mortar in joints tends to fall out over time if there is any movement at the joints. Other proprietary jointing materials such as hydrophilic rubber strips are increasingly used for joints in in situ concrete structures, often extra to a waterstop.

Differential settlement is undesirable because it could lead to steps in the culvert that would reduce its flow capacity and trap debris. If the foundation material is weak or variable, it may be necessary to take extra precautions to cater for settlement. These might include:

- hogging the culvert vertical alignment (ie with the culvert midpoint at a higher level than the inlet and outlet) so that after settlement it adopts an acceptable gradient
- providing reinforced concrete pad footings under each joint so that individual elements of the culvert cannot settle differentially (these are not appropriate for corrugated steel structures)
- for cast in situ work, providing a dowelled joint
- special treatment of the foundation to compact, consolidate or replace weak materials.

Bends

As emphasised in previous sections, bends should generally be avoided if at all possible because of the risks of blockage by debris. Where unavoidable, bend radii should be as large as practicable, giving a long, smooth bend rather than a sharp corner.

For significant bends in box culverts it is preferable to obtain units with angled ends so that a series of these turn the culvert through the required angle. Slow bend units can be readily manufactured to accommodate a reduction of about 200 mm in the length of the inner radius wall, giving about 2° per metre length of culvert for a 6000 mm wide box and 6° per metre for a 1200 mm wide box.

Bends can also be easily designed into corrugated steel culverts, either in the tolerances during erection or by the provision of specials. For in situ concrete work the bend can be constructed to any radius required. HDPE pipes can be supplied in long lengths (up to 40 m) and can accommodate large radius bends (bend radius can be as low as 50 times the pipe radius).

Where a sharp bend is unavoidable, it may be advisable to provide a manhole at the bend, and to bench the culvert invert and sides to stop sharp edges and sudden changes of direction.

Structural and other practical design considerations

The structural design of culverts is not addressed in detail in this guide and readers should consult suitable guidance covering the design of, for example, retaining walls (for the culvert headwall and wingwalls) and embankments. For pre-cast culvert units (pipe or box) and corrugated steel structures the guidance provided by the manufacturer should be followed.

The interaction between a culvert, its foundations and the surrounding backfill can be complex and it is important to seek the advice of an experienced geotechnical engineer. This is particularly important in situations where the culvert passes through a high embankment, or is subject to high live loading, or the foundation material is weak or variable.

The backfill to a culvert should be well compacted to avoid settlement of the road or embankment that it passes under. Compaction of the backfill to a corrugated steel culvert is particularly important, because the strength of the finished structure depends upon the soil-structure interaction. The same is also applicable to large diameter plastic pipes. Normally it is appropriate to use selected excavated material or embankment fill material for backfill, but there may be circumstances where the specification for the backfill has to be upgraded. For steep culverts, the avoidance of free-draining granular backfill or bedding is important so that there is no tendency for flow to travel longitudinally through the backfill (this could erode the fill and destabilise the culvert structure). The same applies to any culvert that is likely to flow surcharged, because escape of water into the granular material could destabilise the embankment causing geotechnical failure. This problem can be overcome by interrupting the granular bedding and backfill by constructing impermeable collars ("puddle flanges") at intervals along the length of the barrel. These can be constructed from concrete or may be formed from clay.

The loading conditions assumed for the design of a culvert should allow for the heaviest likely traffic loads and possibly increased dead loads due to future development above the culvert. Loading conditions during construction may be high (see Figure 9.2).

Hydrostatic forces are not normally significant factors in culvert design but two special cases are worth mentioning. If the culvert is likely to be dewatered in conditions when groundwater level in the backfill is high, the culvert should be checked to ensure that uplift forces are less than the restraining forces (self-weight plus dead load), otherwise there is a danger that the culvert will be lifted by the hydrostatic forces (flotation). For large multiple box culverts, especially underpass structures ("inverted siphons"), the structural design should include the case of one barrel dewatered while other barrels are full.

9.6.3 Construction considerations

Temporary diversion of flows

In most cases it is impossible to plan the construction to avoid periods of high flow in the channel, so it is necessary to cater for normal and flood flows in designing the temporary works. This is not to say that such temporary works should be capable of conveying flood flows, only that the occurrence of such an event should not result in damage during construction. Temporary works in a main river will require approval from the Environment Agency (in England and Wales), and may require approval from other regulatory bodies for non main river. Guidance on the planning and design of river diversions is given in Fisher and Ramsbottom (2001).

Often the normal flow is small enough to allow over-pumping during construction. Alternatively, a small temporary culvert or flume can be constructed to carry the flow alongside the site for the new culvert.

Ideally, the new culvert will be constructed in the dry near to the existing channel, or the channel could be temporarily diverted to allow construction to proceed (see Figure 9.4). Whichever option is selected, it is important to ensure that a flood in the channel does not cause damage to the partly constructed permanent works, to the temporary works or to plant. Floods have a habit of occurring overnight or at weekends and inadequate temporary works can fail with expensive financial and environmental consequences.

Diverting flows within the watercourse around working zones could induce concentrated velocities, possibly promoting erosional forces on nearby walls and embankments during high flow events. Ponding up water levels temporarily to assist diversion by pumping or gravity could promote sediment deposition, increasing water levels and potentially increasing flood risk. Any resulting erosion or deposition has the potential to trigger morphological instability in the form of bank erosion or collapse of a slope or bank.

Specific mitigation measures should be considered and could include minimising construction time within the watercourse, confining working area to small zones, and installing temporary bank protection measures in risk areas. The design team should inspect and monitor regularly throughout the construction phase. This could entail rapid stream reconnaissance assessment using standard geomorphological assessments, identifying areas of active erosion, deposition and instability of existing flood defence structure. Further information on geomorphological assessments can be found in the Sear (2003).

It is important to consider the potential adverse environmental impacts of construction and take steps to minimise or eliminate these. In the case of a watercourse diversion, the design should ensure that the movement of fish is not inhibited.

Sediment management

Sediment loads either washed from construction areas or from disturbed sediments in-channel, produce localised, concentrated impacts, as well as cumulative impacts downstream and over longer time periods. Increased runoff flowing through disturbed bare soils will dramatically increase sediment loads entering the watercourse.

Fine sediments blanket stream beds, altering the physical and chemical properties of the watercourse, with the ability to adversely affect aquatic, riparian and floodplain habitats. One major effect of working in-channel along the watercourse is the disturbance of bed armour (ie the coarser sediments on the surface of the channel bed) in gravel bed streams. If the surface material is removed or displaced this gives high flows access to the finer substrate leading to rapid erosion of the bed, and there may be an elevated sediment load until the armour re-establishes itself.

Details on possible mitigation measures can be found in the guidance by Murnane *et al* (2006).

Possible mitigation measures that could be considered during the construction phase include:

- leave unstable and highly erodible areas as undisturbed open space to minimise erosion
- retain as much existing vegetation as possible to protect against erosion. Common practice is to clear the site and then re-establish new vegetation cover after construction is complete, whereas retention of pre-construction vegetation can be incorporated into the site design to provide several benefits. Retaining existing vegetation in parts of the site that will remain undisturbed provides continuous and more effective protection from erosion than clearing the area and establishing new cover. Root systems help in stabilising the soil, and undisturbed soil retains its structure and moisture holding capacity
- minimise bare soil exposure by managing grading and construction timing. Erosion during construction can be reduced significantly by minimising time between removal of pre-construction cover and establishment of cover. For small construction areas, it is good practice to delay the clearing and grading operations until shortly before construction begins and then apply final or temporary cover to portions of the site that have reached final grade, rather than delaying establishment of cover until all construction activity has been completed.
- timing of works in channel and outside of the channel to take advantage of seasonal patterns of erosion potential within the watercourse. For example, more intrusive construction work could be carried out mostly during the summer months (dry periods) and when high flows in the channel are less likely
- trap sediment on site through measures such as:
- silt fencing to trap sediment in-channel and on steep slopes within the riparian zone
- straw bale dikes could be used in-channel for small areas, allowing water to be impounded and sediment to settle out. Could be used for areas where construction access to the watercourse is critical
- sediment traps, ponds and basins allow water velocities to slow down and encourage sediment deposition in the basin.

Pollution control

Where the risk of spillage into the culvert or watercourse exists, appropriate provision should be made for staff access to isolate any spill. This could include making provisions for booms to control oil slicks, or a penstock on a headwall. Where construction involves the casting of concrete in or near the watercourse it is important to take steps to avoid pollution of the water. If concrete has to be placed under water, additives can be used in the concrete mix to reduce any tendency for washout. For further guidance see PPG18 (Environment Agency, 2007e).

Alternative construction materials and methods

Concrete is now the most commonly used construction material for culverts. It is strong and durable and can be pre-cast in a wide range of shapes and sizes to high tolerances. Plastic (ie HDPE) pipes have become more readily available in recent years and their strength and durability make them viable alternatives to concrete in many instances. They have a considerable advantage because they are light weight, which makes handling easier, and the longer lengths possible also reduce the number of joints required. HDPE and MDPE pipes are approved for use for culverts through railway embankments.

Although most culvert design problems can be solved using conventional concrete box or pipe options, alternatives should be considered if site conditions are unusual. Short corrugated steel structures can, for example, be totally prefabricated and lifted into position where rapid construction is necessary, or partially prefabricated into units that can be man-handled where machine access is not possible.

A large culvert could be formed by two parallel rows of steel sheet piling, propped at invert level and soffit level by concrete slabs that form the floor and roof of the culvert respectively. Such an approach could be applicable in an area where there are weak ground conditions, or where space was limited.

Foundations, bedding and backfill

As with any civil engineering structure, the foundations are important and their ability to support the structure through its design life should not be compromised during construction. Adequate temporary watercourse diversion works (see previous section) are required to keep water out of the foundations, and in conditions of high groundwater it may be necessary to install well-point drainage or similar systems to dewater the excavation.

The foundation should be excavated to the extent required to place the bedding material, and any weak soils should be removed and replaced by compacted backfill. The bedding material would normally be a well compacted granular material for a pre-cast box culvert, blinded with sand to a level surface before laying each unit. To aid installation, to prevent bedding material entering joints, and to obtain good line, level and stability, a weak 75 mm concrete apron can be laid on well-compacted foundation material. Concrete may be required as a bedding material where imposed loads on the culvert are high.

Concrete and plastic pipes and corrugated steel structures are also normally laid on a prepared bed of granular material, shaped to suit the profile of the culvert elements. Guidance should be sought from the suppliers or manufacturers as to the type of bedding required, and how it is to be placed, shaped and compacted. Pipes made from flexible materials such as steel or plastic require more attention to bedding and backfill than concrete culverts, because the structural performance of the culvert depends on its interaction with the surrounding ground.

In the case of multiple barrel culverts with one barrel higher than another, particular care should be taken to compact backfill below the formation of the higher barrel to reduce the risk of differential settlement.

For the structural design of prefabricated culverts (steel, concrete or HDPE), the advice of the manufacturer should be sought.

For steep culverts and any culvert in an embankment capable of retaining water upstream, granular bedding should be provided with impermeable cut-offs at intervals, to avoid problems caused by water flowing through the bedding material.

Pipe jacking

Pipe jacking can be adopted in situations where a culvert has to be provided through an existing embankment and where excavation through the embankment is undesirable (eg under-track crossing through a railway embankment).

Virtually any size of concrete pipe or box can be jacked through the ground, but the process requires a specialist contractor and considerable plant and temporary works, as well as space for thrust and reception pits. Sophisticated lubrication techniques can ensure that the jacking goes ahead smoothly without disrupting the operation of the rail service. Specialist advice should be sought.

Directional auger boring

For smaller culvert sizes, directional auger boring may be appropriate to avoid disruption to an existing highway or rail track. Its suitability will depend on ground conditions and the approval of the highway or rail authority. This type of work should be undertaken by specialist contractors.

Table 9.4 *Culvert design checklist*

Ref	Check item	Notes	Location in the guide
	Collect the basic data		
A	***Catchment***		
A1	Catchment area	For use in investigating catchment hydrology and establishing flows for design purposes	5.1, 5.2
A2	Nature of catchment in terms of hydraulic response and sediment and debris loads	Rural/urban, wooded/agricultural, steep/flat, sources of sediment and debris	9.1.2, 9.1.3
A3	Is development of the catchment possible during the life of the culvert?	Impact on flood and low-flows as well as sediment and debris loads	5.6
B	***Watercourse***		
B1	Channel form	Representative cross-sections, slope, and geomorphological features to define the channel and allow appropriate design of the culvert	6.4, 9.1.3
B2	Presence of any control structures upstream or downstream	Possible impact on sediment and debris movement, and on water level (downstream of the culvert site)	6.4, 9.1.3
C	Environmental and social setting		
C1	Fauna and flora and the landscape and heritage setting	Data on wildlife and fish migration, aquatic ecology, landscape and heritage to investigate the impact of culverting and possible mitigation measures	9.1.3, 9.2.4, 9.3.8
C2	Local interests and interest groups	Consult widely to discover any local works that might be adversely affected (eg angling, canoeing), also local knowledge about the watercourse (eg flood history)	9.1.3
C3	Vandalism	Establish degree that counteracting vandalism may be an issue for construction and future management	9.1.3
C4	Corrosion and erosion risk	Nature of the water and groundwater, and sediment loads	9.3.4
D	***Construction issues***		
D1	Access for construction	Establish constraints and design accordingly	5.5, 9.6.3
D2	Overhead and underground utilities	Investigate presence of any services that might affect construction methods	9.1.3
D3	Temporary works	Establish need for watercourse diversion, dealing with flood risk, temporary diversion of highway, temporary closure of railway or canal, dealing with utilities	9.6.3
D4	Environmental constraints	Restrictions on working methods or timing of the works	9.6.3
E	***Health and safety***		
E1	Safety risk to the public	Establish real risks and design the works to minimise or stop these	9.1.3, 9.4.3
F	***Management and legal issues***		
F1	Responsibilities	Establish who will be responsible for future inspection and maintenance of the culvert and any associated works	9.2.5, 9.3.9

Table 9.4 (contd) *Culvert design checklist*

F2	Consents	Obtain land drainage consent from the appropriate authority, resolve any land ownership issues, obtain planning consent where required	3.9, 9.1.3
	Define the performance requirements		
G	***General***		
G1	Design life	Relevant to flood risk and choice of construction materials	5.1, 9.1.5
H	***Hydraulic***		
H1	Design flood probability	Annual exceedance probability (AEP) or return period	5.1, 9.1.3
H2	Value of the design flood flow	For sizing the culvert	5.1, 5.2
H3	Typical low-flow	For examining environmental performance	5.3
H4	Extreme flood flow	For investigating consequences of an extreme flood and investigating options to limit damage	5.2, 9.1.2, 9.1.3, 9.1.4, 9.6.1
H5	Local hydraulic conditions	For example, tidal constraints (drainage outfall into tidal waters), or flow constriction (outfall from flood storage reservoir)	5.4, 6.4
H6	Tailwater level	Determine the tailwater level for a range of flow conditions. Establish maximum tailwater level for the design flow.	6.6, 9.2.1
H7	Maximum allowable upstream water level (headwater level)	Establish head losses for the design flow, including inlet and outlet losses, bend losses, screen losses and allowances for sedimentation and screen blockage	6.3 to 6.11, 9.1.3, 9.2.1
H8	Flow velocity for the culvert	Determine allowable flow velocity in the culvert for high and low-flow conditions in respect of sedimentation, fish movement, safety and scour at the outlet	6.3, 9.3.7, 9.3.8
	Develop the design solution		
J	Size	To meet the design flow requirements while satisfying environmental constraints and allowing safe inspection and maintenance, with appropriate allowances for partial sedimentation and freeboard	6.7, 9.3.7 Figure 9.10 Figure 9.14
K	Culvert type and materials	Box, pipe, arch, pre-cast concrete, corrugated steel, plastic, cast *in situ* concrete and masonry: the final choice will be determined by cost, practicality, durability, environmental and hydraulic performance	9.3.1, 9.3.4, Table A1.2
L	***Configuration***		
L1	Alignment	Alignment with respect to the exiting watercourse and the infrastructure	9.2.3
L2	Single or multiple barrels	Taking account of high and low-flows, wildlife and fish movement, inspection and maintenance, and headroom constraints	9.2.4, 9.3.2
L3	Invert level	Generally should be below watercourse bed level to allow for future channel re-grading and/or to allow a natural bed to form in the culvert barrel	9.2.4, 9.3.6
L4	Freeboard	Headroom above design water level in the culvert barrel to ensure that free flow occurs	9.3.3
L5	Slope	Slope of the culvert invert	9.3.5

Table 9.4 (contd) *Culvert design checklist*

L6	Need for low-flow channel in the culvert barrel	Sedimentation and ecological factors	9.2.4, 9.3.7
L7	General arrangement	Headwalls, wingwalls, parapets, safety railings, access provision Depth of cover over the barrel	9.4, 9.5, Box 9.1
M	***Scour and sedimentation***		
M1	Scour	Check the need for scour and erosion protection at the inlet and outlet	6.13, 9.4.2, 9.5.3, 9.5.6
M2	Sedimentation	Investigate the likelihood of sedimentation at or within the culvert and ensure that maintenance needs are passed on to the responsible management body	6.13, 9.3.7, 9.4.4
N	Screening	Establish the need for a trash screen or a security screen after fully investigating the risk factors and establishing the consequences of screening	5.5, 9.4.3, 9.5.5
P	Extreme floods	Investigate performance in extreme floods and make sure that the consequences are appropriate and acceptable	9.6.1
Ensure that inspection and maintenance issues have been investigated and resolved			
Q	Inspection	Define the inspection regime for the culvert and associated works (eg screens) and make sure that the resources are available for these, otherwise revise design to suit available resources	9.3.9
R	Telemetry	Determine need for and effectiveness of any telemetry to warn of, for example, a blocked screen. Determine who will monitor and who will respond	9.2.5, 9.4.2 and Case study A3.3
S	Safe access	Ensure that all maintenance works that require access to the culvert (or into it), or to any screens, can be carried out safely (including, but not limited to, anchor points for safety harnesses, adequate ventilation of man-entry culverts, non-slip platforms for screen cleaning, provision of manholes), or revise design to eliminate or reduce risks	9.2.5, 9.3.9
T	Maintenance	Ensure that there is space for temporary storage of debris removed from the culvert or screen. Explore means of removal and disposal of sediment and ensure that the design includes these	9.3.9, 9.4.3
V	Robustness	Ensure that any screens and associated equipment (such as water level monitors or CCTV) are resistant to vandalism	9.4.3

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Full report <http://publications.environment-agency.gov.uk/pdf/SCHO1109BRHF-e-e.pdf>
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BS EN476:1998b *General requirements for components used in discharge pipes, drains and sewers for gravity systems*
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BS EN752:2008 *Drain and sewer systems outside buildings*

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<http://www.bentley.com>

BRITISH OCEANOGRAPHIC DATA CENTRE
<http://www.bodc.ac.uk>

CONVEYANCE ESTIMATION SYSTEM/AFFLUX ESTIMATION SYSTEM (CES/AES) SOFTWARE
<www.river-conveyance.net>

ENVIRONMENT AGENCY
<http://www.environment-agency.gov.uk/>

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GB PROGRAMME BOARD
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A1 Design data

Table A1.1 ***Roughness coefficients for natural channels***

$$Q = KS_0^{1/2} = \left(\frac{1}{n} AR^{2/3}\right) S_0^{1/2}$$

	Manning's *n*		
Type of channel and desctiption	***Minimum***	***Normal***	***Maximum***
Natural streams (top width at flood stage < 30 m)			
Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
As above but more stones and weeds	0.030	0.035	0.040
Clean, winding, some pools and riffles	0.033	0.040	0.045
As above but some weeds and stones	0.035	0.045	0.050
As above but lower stages, more ineffective slopes and sections	0.040	0.048	0.055
As above but more stones	0.045	0.050	0.060
Sluggish reaches. Weedy deep pools	0.050	0.070	0.080
Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
Mountainous streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high water levels. Bed: gravels, cobbles and few boulders	0.030	0.040	0.050
Mountainous streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high water levels. Bed: cobbles with large boulders	0.040	0.050	0.070
Minor streams (top width at flood stage > 30m)			
Regular section with no boulders or brush	0.025	–	0.060
Irregular and rough section	0.035	–	0.100
Flood plains			
Pasture, no brush			
Short grass	0.025	0.030	0.035
High grass	0.030	0.035	0.050
Cultivated areas			
No crop	0.020	0.030	0.040
Mature row crops	0.025	0.035	0.045
Mature field crops	0.030	0.040	0.050
Brush			
Scattered brush, heavy weeds	0.035	0.050	0.070
Light brush and trees in winter	0.035	0.050	0.060
Light brush and trees in summer	0.040	0.060	0.080
Medium to dense brush in winter	0.045	0.070	0.110

Table A1.1 (contd) ***Roughness coefficients for natural channels***

Trees			
Cleared land with tree stumps, no saplings	0.030	0.040	0.050
As above, with heavy growth of saplings	0.050	0.060	0.080
Heavy stand of timber, some fallen trees, little undergrowth, flood level below branches	0.080	0.100	0.120
As above, but flood level reaching branches	0.100	0.120	0.160
Dense willows, summer, straight	0.110	0.150	0.200

Notes

1 Taken from Chow (1973) – based on rivers in the US.

2 Alternative values are available from Hicks and Mason (1998) for New Zealand rivers or Barnes (1967) for US rivers.

Table A1.2 *Roughness coefficients for culvert barrels*

$$Q = KS_0^{1/2} = \left(\frac{1}{n}AR^{2/3}\right)S_0^{1/2}$$

	Manning's *n*			
Description	***Minimum***	***Normal***	***Maximum***	***Source***
Sedimentation				
Clay (<2µm)	0.018	0.020	0.023	1
Silt (2 mm–60 µm)	0.020	0.022	0.025	1
Sand: fine (0.6 mm–0.2 mm)	0.010	0.012	0.016	1
Sand: medium (0.2 mm–0.6 mm)	0.017	0.020	0.025	1
Sand: coarse (0.6 mm–2 mm)	0.026	0.028	0.035	1
Gravel: fine (2 mm–6 mm)	0.020	0.024	0.028	1
Gravel: medium (6 mm–20 mm)	0.028	0.030	0.035	1
Gravel: coarse (20 mm–60 mm)	0.022	0.035	0.040	1
Cobbles (64 mm–256 mm)	0.040	0.055	0.070	1
Concrete				
Pre-cast concrete pipe	0.010	–	0.011	2
Pre-cast concrete box	0.012	–	0.015	2
In situ concrete	0.015	0.018	0.022	1
Pipework				
Polyvinyl chloride (PVC), smooth inner wall	0.009	–	0.011	2
Polyethylene (PE), smooth inner wall	0.009	–	0.015	2
Polyethylene (PE), corrugated inner wall	0.018	–	0.025	2
Corrugated metal pipe				
Spiral rib	0.012	–	0.013	2
Helical corrugations, 68 × 13 mm[4]	0.011	–	0.023	2
Annular corrugations, 68 × 13 mm[4]	0.022	–	0.027	2
Corrugations, 150 × 25 mm[4]	0.022	–	0.025	2
Corrugations, 125 × 25 mm[4]	0.025	–	0.026	2
Corrugations, 75 × 25 mm[4]	0.027	–	0.028	2
Structural plate, 150 × 50 mm[4]	0.033	–	0.035	2
Structural plate, 230 × 64 mm[4]	0.033	–	0.037	2
Timber				
Stave (long strips joined together)	0.010	0.012	0.014	3
Laminated and treated	0.015	0.017	0.020	3
Timber piling	0.025	0.028	0.030	1
Piles				
Steel sheet piles	0.025	0.028	0.030	1
Brickwork, blockwork and masonry				
Brickwork	0.012	0.015	0.018	1
Ashlar masonry	0.013	0.015	0.017	3

Table A1.2 (contd) ***Roughness coefficients for culvert barrels***

Rubble masonry, pointed	0.017	0.025	0.030	1
Rubble masonry, open joints	0.023	0.032	0.035	3
Blockwork	0.030	0.035	0.040	1
Miscellaneous				
Gabions	0.035	0.038	0.040	1
Riprap	0.037	0.040	0.043	1

Notes

1 For short, straight culverts, Manning's *n* should be similar to the unit roughness values for man-made bank materials (Fisher and Dawson, 2003).

2 Federal Highway Administration (2001, revised 2005).

3 Chow (1973).

4 Manning's *n* varies with barrel size. For diameter less than 1800 mm, helical corrugations may provide lower resistance, but for larger culverts, helix angle approaches 90° and roughness tends to the value for annular corrugations. Values stated are pitch times depth.

Table A1.3 *Coefficients for inlet control equations (simple inlets)*

$\frac{E_{sh}}{D} = \frac{E_{sc}}{D} + k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M - 0.5S_0$ (6.23)	$\frac{E_{sh}}{D} = k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M$ (6.25)	$\frac{E_{sh}}{D} = c\left[\frac{1.811Q}{A_b D^{0.5}}\right]^2 + Y - 0.5S_0$ (6.26)

Nr	Description	Inlet loss	Unsubmerged, Form A		Unsubmerged, Form B		Submerged inlet	
		k_i	k	M	k	M	c	Y
Circular concrete pipe								
1	Headwall, square edge	0.5	0.0098	2.0			0.0398	0.67
2	Headwall, socket end of pipe	0.3	0.0078	2.0			0.0292	0.74
2	Projecting, socket end of pipe	0.3	0.0045	2.0			0.0317	0.69
Circular corrugated metal pipe								
4	Headwall	0.5	0.0078	2.0			0.0379	0.69
5	Mitred to slope	0.7	0.0210	1.33			0.0463	0.75
6	Projecting	0.9	0.0340	1.5			0.0553	0.54
Vertical ellipse, concrete								
7	Headwall, square edge		0.0100	2.0			0.0398	0.67
8	Headwall, socket end of pipe		0.0018	2.5			0.0292	0.74
9	Projecting, socket end of pipe		0.0095	2.0			0.0317	0.69
Pipe arch, 450 mm corner radius, corrugated metal								
10	90° headwall	0.5	0.0083	2.0			0.0379	0.69
11	Mitred to slope	0.7	0.0300	1.0			0.0463	0.75
12	Projecting	0.9	0.0340	1.5			0.0496	0.57
Pipe arch, 750 mm corner radius, corrugated metal								
13	Headwall/square edge	0.5	0.0087	2.0			0.0361	0.66
14	Headwall/33.7° bevels	0.25	0.0030	2.0			0.0264	0.75
15	Projecting	0.9	0.296	1.5			0.0487	0.55
Arch, corrugated metal								
16	90° headwall	0.5	0.0083	2.0			0.0379	0.69
17	Mitred to slope	0.7	0.0300	1.0			0.0463	0.75
18	Thin wall projecting	0.6	0.0340	1.5			0.0496	0.57
Rectangular concrete, 90° headwall								
19	20 mm chamfers	0.5			0.515	0.667	0.0375	0.79
20	45° bevels	0.5			0.495	0.667	0.0314	0.82
21	33.7° bevels				0.486	0.667	0.0252	0.865

Notes

1 Taken from Federal Highways Administration (2001 revised 2005), which contains details of further inlet types and other configurations.

2 Sketches of inlet types and edge types are given in Figure A1.1.

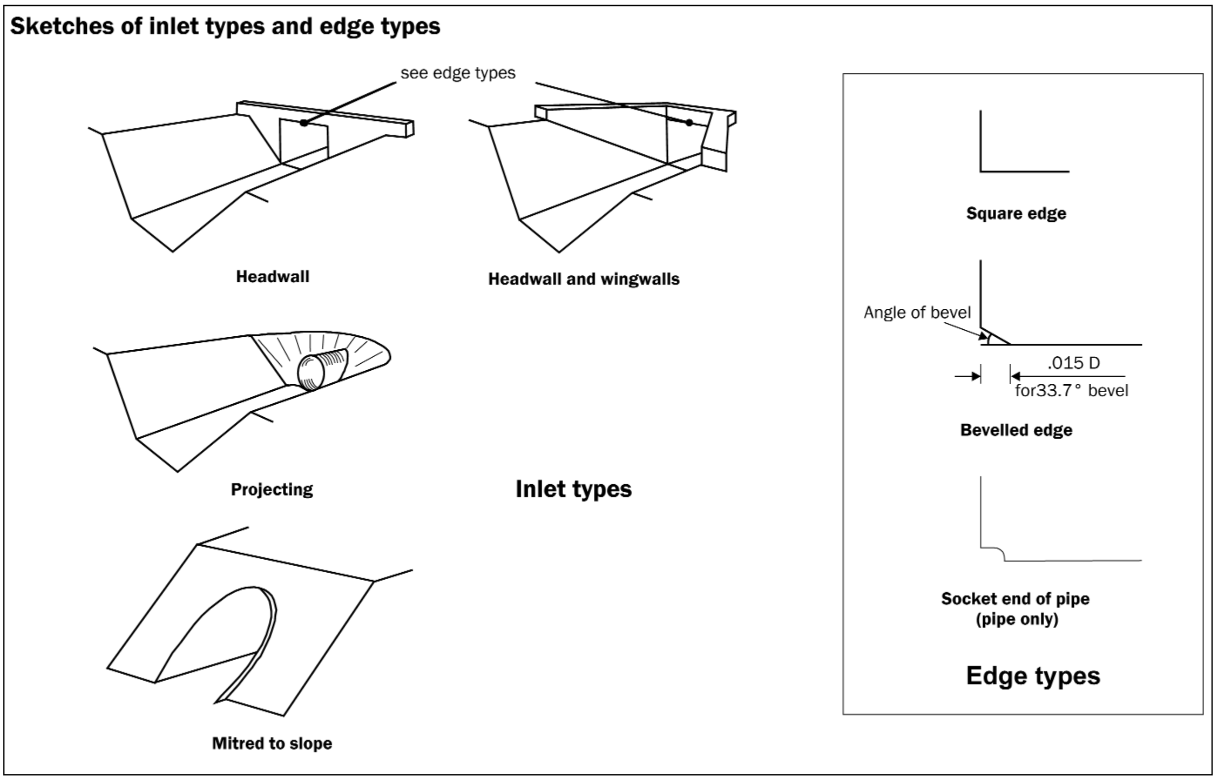


Figure A1.1 *Sketches of inlet types and edge types*

Table A1.4 *Coefficients for inlet control equations (complex box culvert inlets)*

$$\frac{E_{sh}}{D} = \frac{E_{sc}}{D} + k\left[\frac{1.811Q}{A_b D^{0.5}}\right]^M + 0.7S_0$$

Nr	Description	Figure	Inlet loss	Unsubmerged, Form A		Unsubmerged, Form B		Submerged inlet	
			K_i	*k*	*M*	*k*	*M*	*c*	*Y*
Rectangular concrete, 30° to 75° flared wingwalls									
22	Single barrel					0.469	0.696	0.033	0.751
Rectangular concrete, 30° flared wingwalls, top edge bevelled 45°									
23	Single barrel	1	0.26	0.005	1.05	0.44	0.74	0.04	0.48
24	Single barrel, span to rise 2:1 to 4:1	2	0.20			0.48	0.65	0.041	0.57
25	Multiple barrels (2, 3 or 4)	3	0.32			0.47	0.68	0.04	0.62
26	Multiple barrels and 15° skew	4	0.36			0.69	0.49	0.029	0.95
27	Multiple barrels and 30° to 45° skew	5	0.45			0.69	0.49	0.027	1.02
Rectangular concrete, 0° flared wingwalls, top edge square									
28	Single barrel	6	0.79	0.005	0.68	0.55	0.64	0.047	0.55
Rectangular concrete, 0° flared wingwalls, top edge bevelled 45°									
29	150 mm corner fillets	7	0.48			0.56	0.62	0.045	0.55
30	Multiple barrels (2, 3 or 4)	8	0.52			0.55	0.59	0.038	0.69
31	Span to rise 2:1 to 4:1	9	0.37			0.61	0.57	0.041	0.67
Rectangular concrete, 0° flared wingwalls, crown 200 mm radius									
32	150 mm corner fillets	10	0.24			0.56	0.62	0.038	0.67
33	300 mm corner fillets	11	0.30			0.56	0.62	0.038	0.67
34	300 mm corner fillets, multiple barrels (2, 3 or 4)	12	0.54			0.55	0.60	0.023	0.96
35	No corner fillets, span to rise 2:1 to 4:1	13	0.30			0.61	0.57	0.033	0.79

Notes

1 Taken from Federal Highways Administration (2006b). Sketches of inlet and culvert types are given in Figure A1.2. Wingwall and skew angles are measured relative to centreline of culvert barrel(s).

2 Note that complex box culvert inlets use a different form of equation to simple culverts.

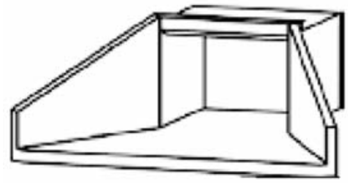
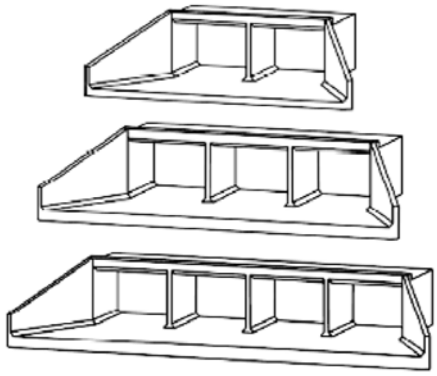
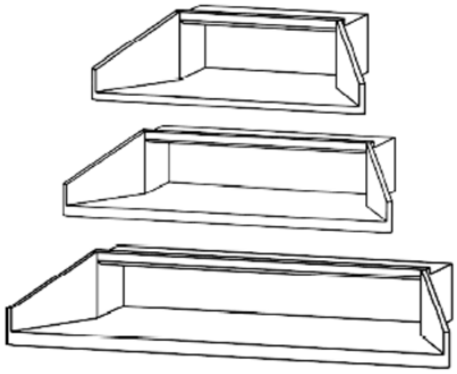
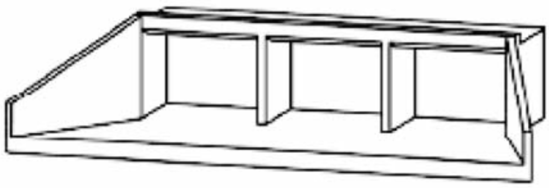
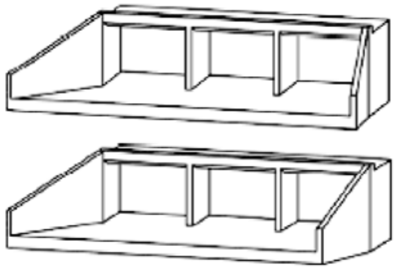
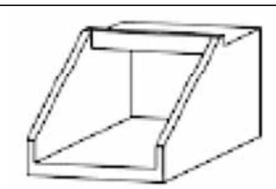
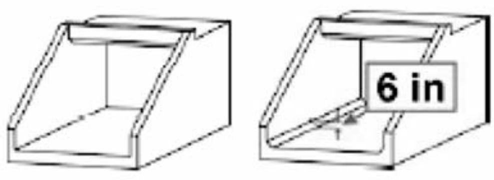
1 30° flared wingwalls, top edge beveled at 45°	
2 30° flared wingwalls, top edge beveled at 45°, 2, 3 and 4 multiple barrels	
3 30° flared wingwalls, top edge beveled at 45°, 2:1 to 4:1 span-to-rise ratio	
4 30° flared wingwalls, top edge beveled at 45°, 15° skewed headwall with multiple barrels	
5 30° flared wingwalls, top edge beveled at 45°, 30° to 45° skewed headwall with multiple barrels	
6 0° flared wingwalls (extended sides), square-edged at crown	
7 0° flared wingwalls (extended sides), top edge beveled at 45°, 0 and 6 inch corner fillets	

Figure A1.2 *Coefficients for inlet control equations (complex box culvert inlets) (courtesy the Department of Transportation, Federal Highway Administration)*

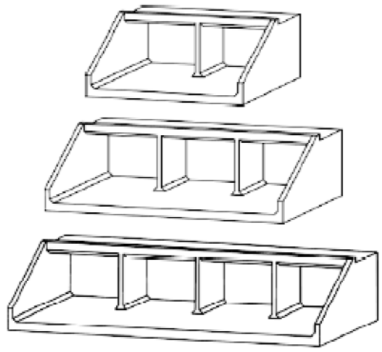
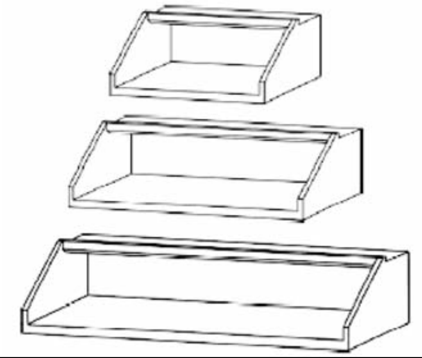
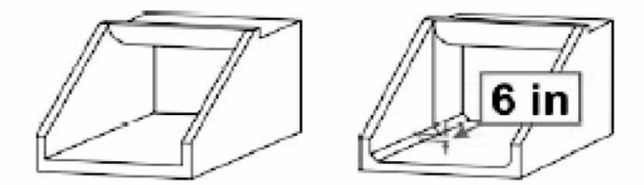
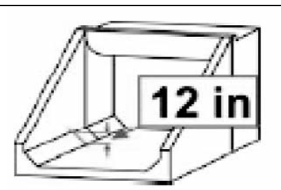
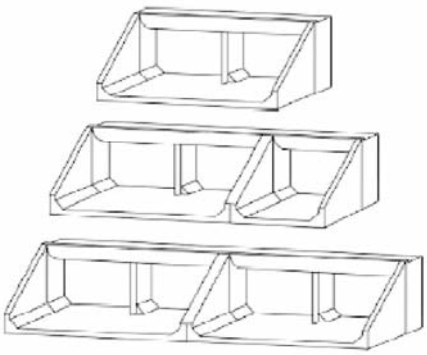
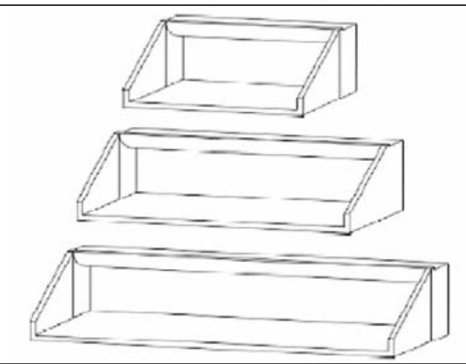
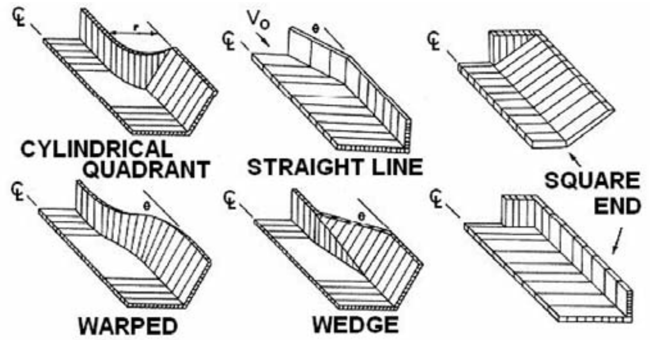
8 0° flared wingwalls (extended sides), top edge beveled at 45°, 2, 3 and 4 multiple barrels	
9 0° flared wingwalls (extended sides), top edge beveled at 45°, 2:1 to 4:1 span-to-rise ratio	
10 0° flared wingwalls (extended sides), crown rounded at 8 inch radius, 0 to 6 inch corner fillets	
11 0° flared wingwalls (extended sides), crown rounded at 8 inch radius, 12 inch corner fillets	
12 0° flared wingwalls (extended sides), crown rounded at 8 inch radius, 12 inch corner fillets, 2, 3 and 4 multiple barrels	
10 0° flared wingwalls (extended sides), crown rounded at 8 inch radius, 12 inch corner fillets, 2:1 to 4:1 span-to-rise ratio	

Figure A1.2 (contd) *Coefficients for inlet control equations (complex box culvert inlets) (courtesy the Department of Transportation, Federal Highway Administration)*

Table A1.5 *Coefficients for inlet and outlet loss*

Type of transition	Inlet loss coefficient k_i	Outlet loss coefficient k_o
Equation	$h_i = k_i \frac{V_b^2}{2g}$ 6.56	$h_o = k_o \left[\frac{\left(V_b^2 - V_{dc}^2\right)}{2g} \right]$ 6.61
Warped	0.10	0.20
Cylindrical quadrant	0.15	0.25
Wedge	0.20	0.30
Straight line (wingwall)	0.30	0.50
Square end	0.30	0.75
Abrupt transition/projecting inlet	0.90	1.0



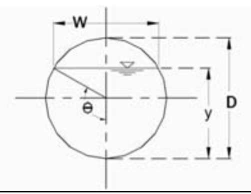
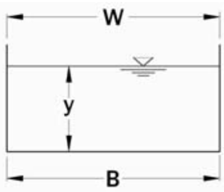
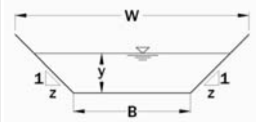
Notes:

1 Data taken from Chow (1973).

2 Figure reprinted with permission from Federal Highways Administration (2006a).

3 If $\tan\theta > \frac{Fr}{3}$, the straight line transition is treated as an abrupt transition (where θ is the angle between the wingwall and the culvert barrel).

Table A1.6 *Design formulae for geometrical properties (from Henderson, 1966)*

Section type	Circular	Rectangular	Trapezoidal
Definitions			
Angle θ radians	$\theta = \pi - \cos^{-1}\left(\frac{2y-D}{D}\right)$		
Flow area A (m²)	$\frac{1}{8}(2\theta - \sin 2\theta)D^2$	By	$(B+zy)y$
Wetted perimeter P (m)	θD	$B + 2y$	$B + 2y\sqrt{1+z^2}$
Hydraulic radius R (m)	$\frac{1}{4}\left(1 - \frac{\sin 2\theta}{2\theta}\right)D$	$\frac{By}{B+2y}$	$\frac{(B+zy)y}{B+2y\sqrt{1+z^2}}$
Top width W (m)	$D \sin\theta$ or $2\sqrt{y(D-y)}$	B	$B + 2zy$
Hydraulic mean depth ỹ (m)	$\frac{1}{8}(2\theta - \sin 2\theta)\frac{D}{\sin\theta}$	y	$\frac{(b+zy)y}{b+2zy}$

Note

1 θ is given in radians, where π radians = 180°.

Table A1.7 ***Backwater calculation by standard step method***

For use with Section 6.10.7, Estimate head loss due to friction.

Design parameters

Row 1	Design discharge, Q =	m^3/s
Row 2	Culvert width, B =	m
Row 3	Manning's roughness coefficient, n =	(-)

Step 1 Calculate bed elevation

		1	2	3	4	5	6	Units
Row 4	Chainage from, start point, x =							m
Row 5	Bed elevation, $z = z_s - S_0.\Delta x$ =							m

Step 2 Estimate trial water depth and channel properties

Row 6	Estimate water depth, y =							m
Row 7	Cross-sectional area of flow, A =							m^2
Row 8	Wetted perimeter, P =							m
Row 9	Hydraulic radius, R = A/P =							m
Row 10	Conveyance, $K = (1/n).AR^{2/3}$ =							m^3/s

Step 3 Calculate total head loss for the new point

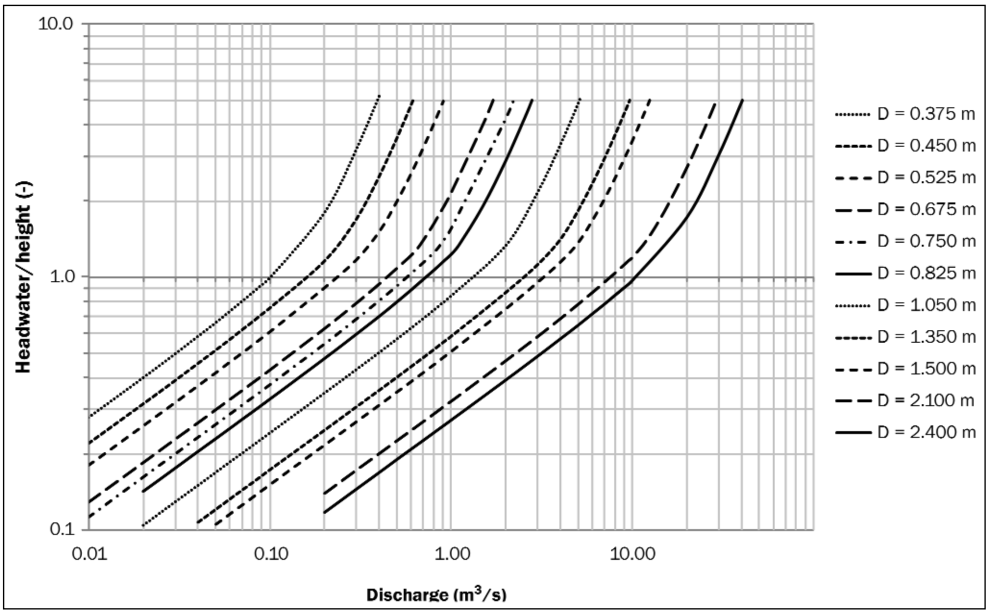
Row 11	Flow velocity, V = Q/A =							m/s
Row 12	Velocity head, $V^2/2g$ =							m
Row 13	Total head, $H_1 = z + y + V^2/2g$ =							m

Step 4 Estimate head loss due to friction

Row 14	Friction slope, $S_f = (Q/K)^2$ =							m/m
Row 15	Mean friction slope, $S_{fmean} = (S_f + S_{fprev})/2$ =							m/m
Row 16	$\Delta x = x_i - x_{i-1}$ =							m
Row 17	Head loss due to friction, $hf = (-S_{fmean})\Delta x$ =							m
Row 18	Head loss due to bends, h_{bn} =							m
Row 19	Total head, $H = H_f + h_{bn}$ =							m
Row 20	Check $H = H_1$?							

Table A1.8 *Maximum permissible velocities for cohesive soils (from Hoffmans and Verheij, 1997)*

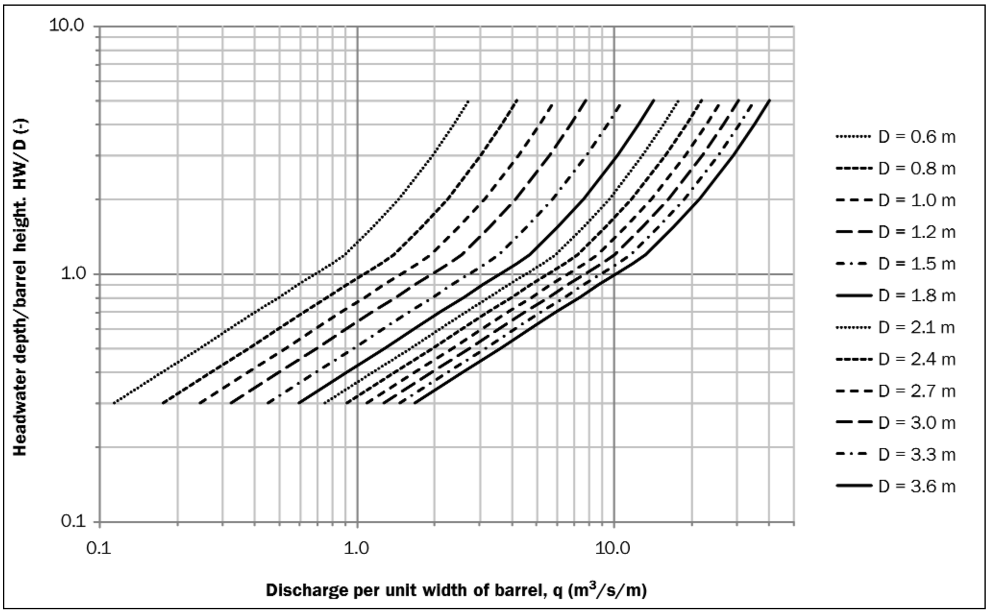
Description	Maximum permissible velocity (m/s)
Clay: low density	0.4–0.6
Clay: medium density	0.8–1.3
Clay: dense	1.2–1.9



Note

Based on inlet control equation for circular concrete culvert with headwall and square edge of pipe, S_0=0.01

Figure A1.3 *Initial assessment of discharge capacity for circular culverts*



Note

Based on inlet control equation for rectangular concrete culvert with headwall and 20 mm chamfers, S_0=0.01

Figure A1.4 *Initial assessment of discharge capacity for rectangular culverts*

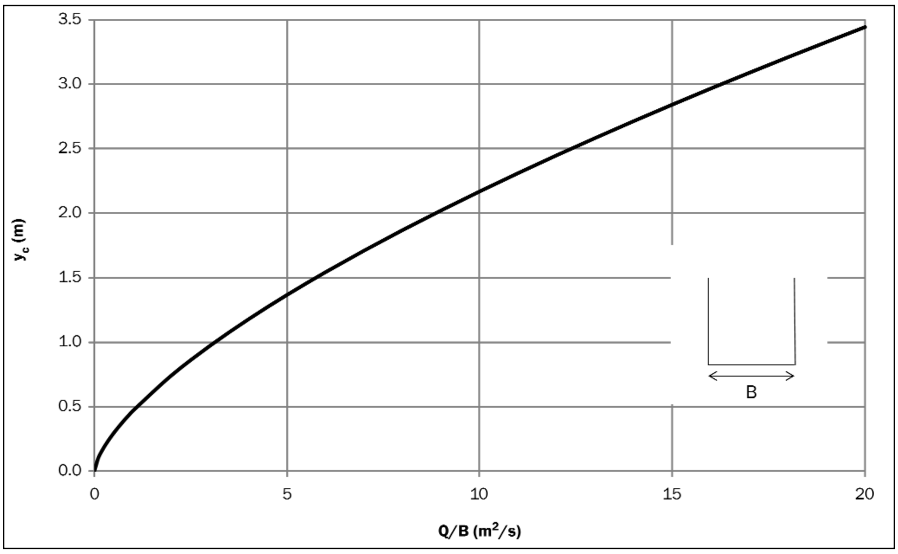


Figure A1.5 *Critical depth for rectangular channels (Q/B = 0 to 20 m²/s)*

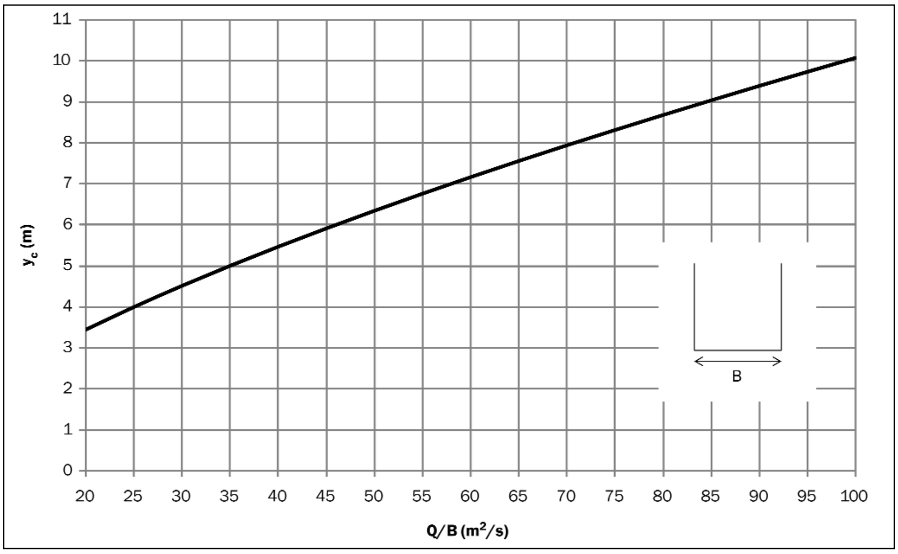


Figure A1.6 *Critical depth for rectangular channels (Q/B = 20 to 100 m²/s)*

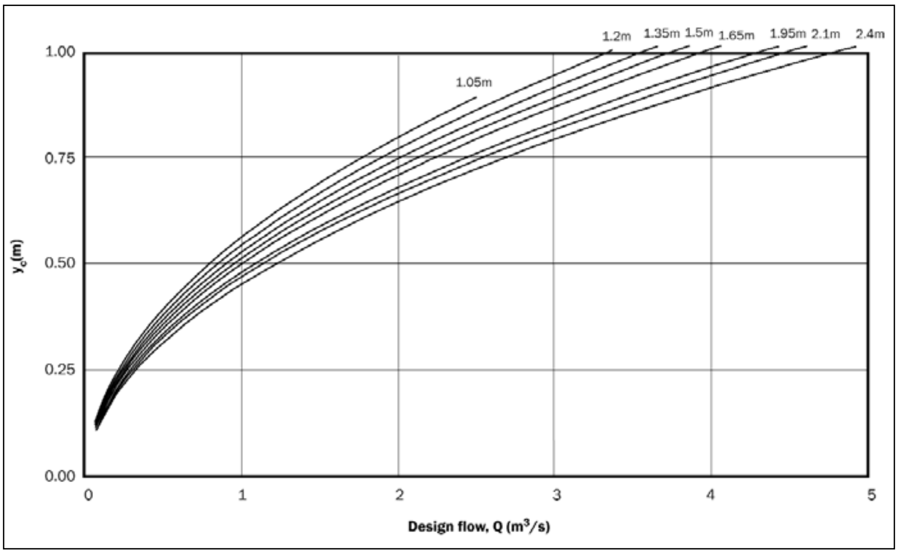


Figure A1.7 *Critical depth for circular culverts (Q = 0 to 5 m³/s) (height D = 1.05 to 2.4 m)*

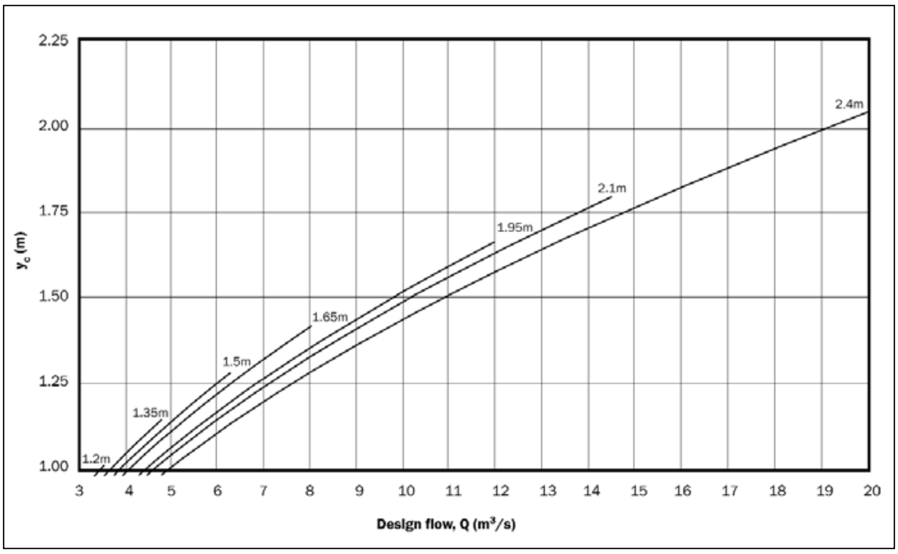


Figure A1.8 *Critical depth for circular culverts (Q = 3 to 20 m³/s) (height D = 1.2 to 2.4 m)*

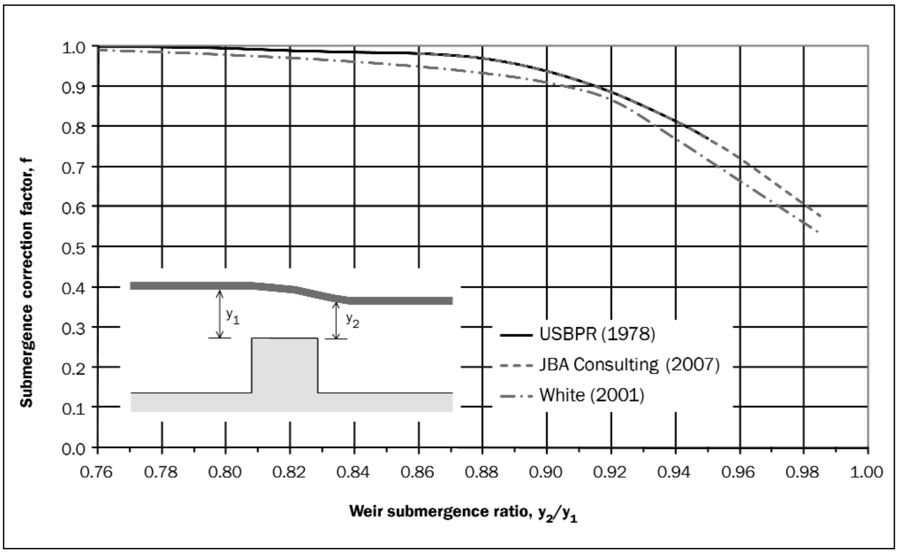


Figure A1.9 *Submergence correction factor for broad-crested weir flow*

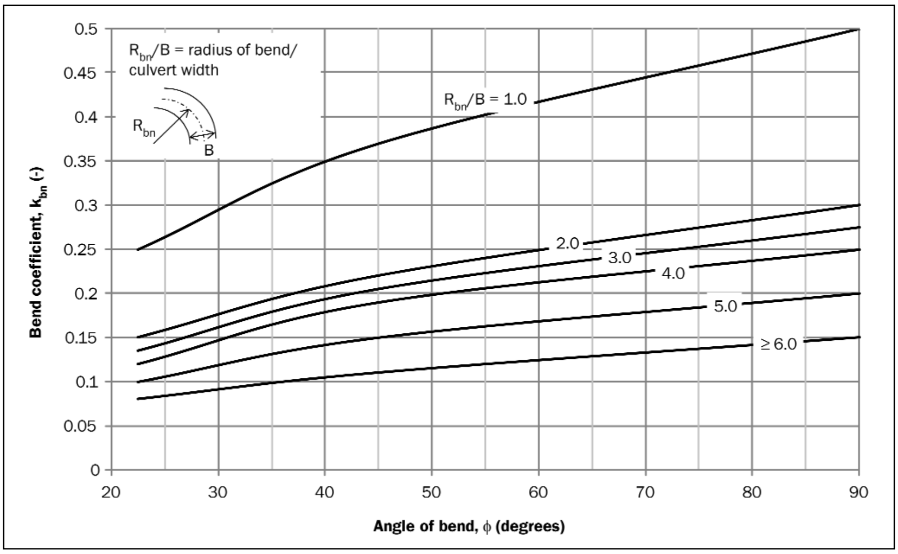


Figure A1.10 *Head loss coefficient for bends*

A2 Worked examples

A2.1 Establish hydraulic performance requirements

Background

A hydraulic assessment is required for the concrete box culvert shown in Figure A2.1. A culvert survey has provided the following data:

Barrel height D = 1.0 m

Effective barrel height D_e = 0.75 m

Depth of sedimentation above culvert invert z_s = 0.25 m

Elevation of bed at inlet Z_{bi} = 100.20 mOD (above sedimentation)

Elevation of bed at outlet Z_{bo} = 100.00 mOD (above sedimentation)

Elevation of soffit at inlet Z_{si} = 100.95 mOD

Elevation of soffit at outlet Z_{so} = 100.75 mOD

Elevation of embankment crest Z_w = 102.00 mOD

There is no vulnerable infrastructure or development upstream, so the maximum allowable water level upstream is determined by the embankment crest level less a safety margin (so that overtopping cannot occur in the design flood).

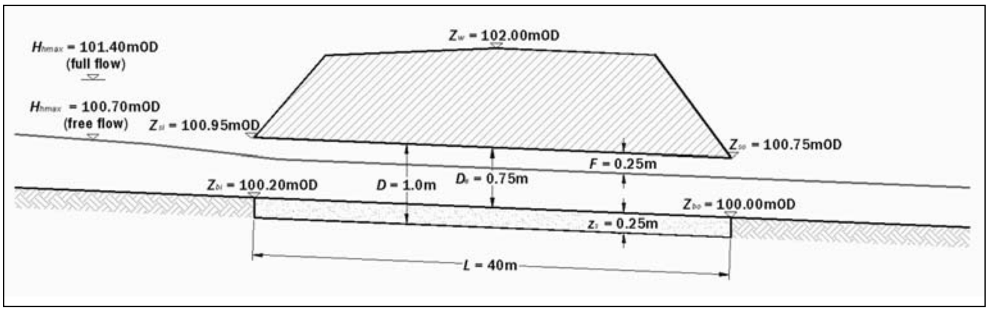


Figure A2.1 *Longitudinal section through culvert*

Calculation

For free flow, maximum permissible headwater level WL_{hmax} is given by soffit level minus freeboard. Freeboard is taken as $F = D/4 = 0.25$ m (after Figure 9.14).

$$H_{h\max} = Z_{si} - F = 100.95 - 0.25 = 100.70 mOD \quad \text{A2.1}$$

For full flow, the embankment crest is taken as the asset level and freeboard is increased to F = 0.6 m to reflect the greater uncertainty associated with soft defences.

$$y = D - z_s - F = 1.0 - 0.25 - 0.25 = 0.5 m \quad \text{A2.2}$$

A2.2 Calculate tailwater level

Background

Tailwater level is required for the concrete box culvert described in Appendix A2.1. The culvert discharges to a trapezoidal channel with no hydraulic structures likely to affect the water level at the culvert outlet (Figure A2.2).

Design discharge, Q = 1.1 m³/s

Width of invert, B = 1.5 m

Side slopes, 1 in z = 1 in 2

Bed slope, S_o = 0.005 (0.5 %)

Roughness coefficient, n = 0.035

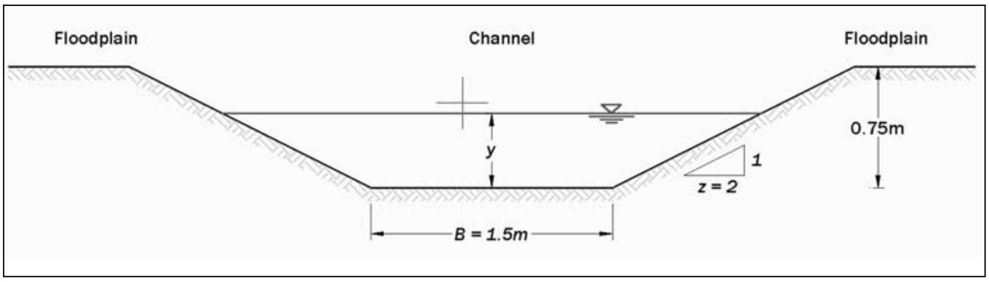


Figure A2.2 *Cross-section through downstream channel*

Calculation

Because there are no hydraulic structures, we can assume channel control (rather than structure control) and use the Manning's equation to estimate water depth for the design discharge.

Calculate normal depth

For an initial guess of water depth y = 0.5 m, geometrical properties are obtained using formulae from Table A1.6 in Appendix A1.

$$A = (B + zy)\,y = (1.5 + 2\times 0.5)0.5 = 1.25m^2$$

$$P = B + 2y\sqrt{1+z^2} = 1.5 + (2\times 0.5)\sqrt{1+2^2} = 3.74m$$

$$R = \frac{A}{P} = \frac{1.25}{3.74} = 0.33m \qquad 6.8$$

$$Q = \left(\frac{1}{n}AR^{2/3}\right)S_o^{1/2} = \left(\frac{1}{0.035}1.25\times 0.33^{2/3}\right)0.005^{1/2} = 1.21m^3/s \qquad 6.16$$

$Q = 1.21m^3/s > 1.1m^3/s$ $\therefore$ water depth too large, try a smaller value

Let us try again with y = 0.48 m

$$A = (B + zy)\,y = (1.5 + 2\times 0.48)0.48 = 1.18m^2$$

$$P = B + 2y\sqrt{1+z^2} = 1.5 + (2\times 0.48)\sqrt{1+2^2} = 3.65m$$

$$R = \frac{A}{P} = \frac{1.18}{3.65} = 0.32m \qquad (6.8)$$

$$Q = \left(\frac{1}{n} AR^{2/3}\right) S_o^{1/2} = \left(\frac{1}{0.035} 1.18 \times 0.32^{2/3}\right) 0.005^{1/2} = 1.12 m^3/s \qquad (6.16)$$

$$Q = 1.12 m^3/s \approx 1.1 m^3/s \qquad \therefore\ S_o\, y_{dc} = 0.48 \text{ m}$$

Calculate tailwater elevation

$$V_{dc} = \frac{Q}{A} = \frac{1.1}{1.18} = 0.93 m/s \qquad (6.14)$$

$$H_t = Z_{bo} + y_{dc} + \frac{V_{dc}^2}{2g} = 100.00 + 0.48 + \left(\frac{0.93^2}{2 \times 9.81}\right) = 100.52 mOD \qquad (6.10)$$

$$WL_t = Z_{bo} + y_{dc} = 100.00 + 0.48 = 100.48 mOD \qquad (6.11)$$

The calculation of tailwater depth should ideally be repeated for a range of design discharges to generate a rating curve.

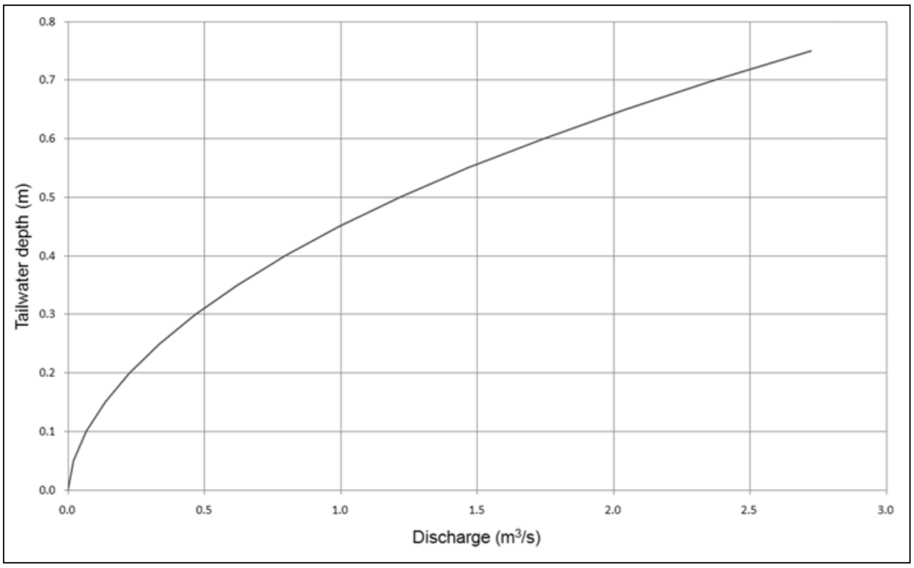


Figure A2.3 *Rating curve for tailwater depth*

Assess likely flow type

The tailwater level (WL_t = 100.48 mOD) is lower than the soffit levels at the culvert outlet (Z_{so} = 100.75 mOD) and inlet (Z_{si} = 100.95 mOD), indicating an unsubmerged outlet and free flow conditions in the culvert barrel. While full flow conditions would indicate outlet control, either inlet or outlet control could occur in this instance. The barrel slope (S_0 = 0.005) is mild, indicating outlet control, so it would be prudent to start with outlet control assessment (see Appendix A2.4).

A2.3 Initial assessment of discharge capacity

Background

An initial estimate of discharge capacity is required for the concrete box culvert described in Appendices A2.1 and A2.2, both with and without sedimentation. We know that:

Barrel dimensions, B = 1.5 m, D = 1.0m, L = 40 m

Depth of sedimentation, z_s = 0.25 m

Freeboard, F = 0.25 m

Allowable water depth, y = 0.5 m (= $D - z_s - F$) (from Appendix A2.1)

Tailwater depth y_{dc} = 0.48 m

Tailwater level WL_t = 100.48 mOD

Tailwater elevation H_t = 100.52 mOD

Roughness coefficient, n = 0.015 for barrel, n = 0.035 for sediment and debris.

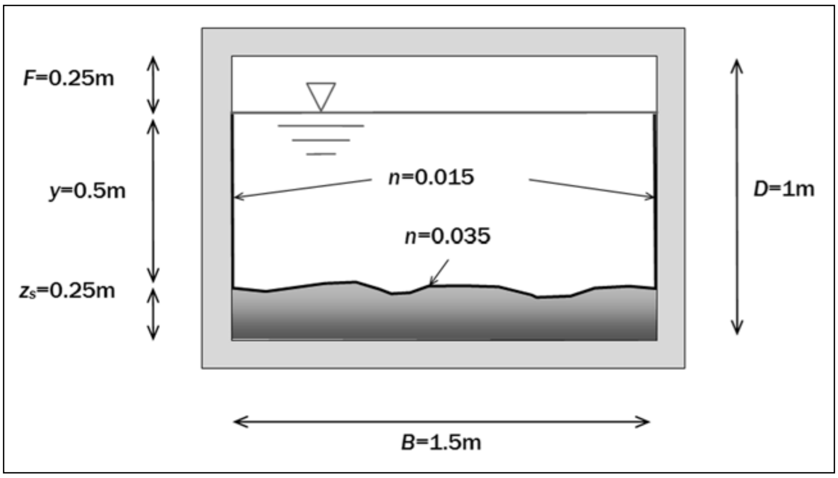


Figure A2.4 *Typical cross-section through culvert*

Calculation

The permissible head loss method is used as the culvert slope is mild, although inlet control charts may be used for steep culverts.

Although the allowable water depth in the culvert barrel y is 0.5 m, we know that the tailwater depth y_{dc} is 0.48 m. Because the depth of flow in the culvert barrel is likely to be governed by the tailwater depth, we shall assume that tailwater depth applies throughout the culvert.

With sedimentation

For water depth y = 0.48 m, the cross-sectional area of the flow A = 0.72 m², wetted perimeter P = 2.46 m and hydraulic radius R = 0.29 m. Compound roughness is

$$n' = \left(\frac{0.48 \times 0.015^{1.5} + 1.5 \times 0.035^{1.5} + 0.48 \times 0.015^{1.5}}{2.46} \right)^{2/3} = 0.028 \qquad (6.20)$$

For an initial estimate of discharge $Q = 1.1$ m³/s

$$V_b = \frac{Q}{A} = \frac{1.1}{0.72} = 1.53 m/s$$

$$H_{hoc} \approx H_t + 1.5\frac{V_b^2}{2g} + L\left(\frac{nQ}{AR^{2/3}}\right)^2 \quad (6.19)$$

$$H_{hoc} \approx 100.52 + 1.5\frac{1.53^2}{2\times 9.81} + 40\left(\frac{0.028\times 1.1}{0.72\times 0.29^{2/3}}\right)^2 = 101.08 mOD$$

$H_{hoc} = 101.08 mOD > 100.70 mOD = H_{h\max}$ $\therefore$ try smaller discharge

For discharge $Q = 0.65$ m³/s

$$V_b = \frac{Q}{A} = \frac{0.65}{0.72} = 0.90 m/s$$

$$H_{hoc} \approx 100.52 + 1.5\frac{0.90^2}{2\times 9.81} + 40\left(\frac{0.028\times 0.65}{0.72\times 0.29^{2/3}}\right)^2 = 100.71 mOD \quad (6.19)$$

$H_{hoc} = 100.71 mOD \approx 100.70 mOD = H_{h\max}$ $\therefore$ discharge capacity $Q \approx 0.65$ m³/s

So for a given tailwater depth, the discharge capacity of the culvert is significantly lower than that of the downstream channel (0.65 m³/s compared with 1.1 m³/s) and the culvert constricts the flow, although this is hardly surprising, as the cross-sectional area of the culvert is nearly 40 per cent less than the channel (0.72 m² compared with 1.18 m² from Appendix A2.2).

This initial assessment of discharge capacity assumes normal flow with water surface slope parallel to bed slope. In reality, the water slope would increase to drive the design discharge of 1.1 m³/s through the culvert, although this would increase water depth above the allowable water depth. Appendix A2.6 shows that a water surface slope of 0.0095 would be adequate to drive the discharge through the culvert.

Without sedimentation

For a water depth $y = 0.73$ m (=0.48 m + 0.25 m), the cross-sectional area of the flow $A =$ 1.10 m², wetted perimeter $P = 2.96$ m² and hydraulic radius $R = 0.37$ m.

For discharge $Q = 1.4$ m³/s

$$V_b = \frac{Q}{A} = \frac{1.4}{1.10} = 1.27 m/s$$

$$H_{hoc} \approx 100.52 + 1.5\frac{1.27^2}{2\times 9.81} + 40\left(\frac{0.015\times 1.4}{1.10\times 0.37^{2/3}}\right)^2 = 100.69 mOD \quad (6.19)$$

$H_{hoc} = 100.69 mOD \approx 100.70 mOD = H_{h\max}$ $\therefore$ discharge capacity $Q \approx 1.4$ m³/s

So the discharge capacity without sedimentation is more than twice that with sedimentation, due to the increased cross-sectional area and the lower value of Manning's *n* for the clean culvert.

A2.4 Calculate head loss at outlet

Background

Outlet head loss is required for the concrete box culvert of Appendices A2.1 to A2.3. We know that for a design discharge Q = 1.1 m³/s, tailwater depth yo = 0.48 m and cross-sectional area of flow downstream of the culvert outlet is A_{dc} = 1.18 m² (Appendix A2.2). The culvert has a square end outlet.

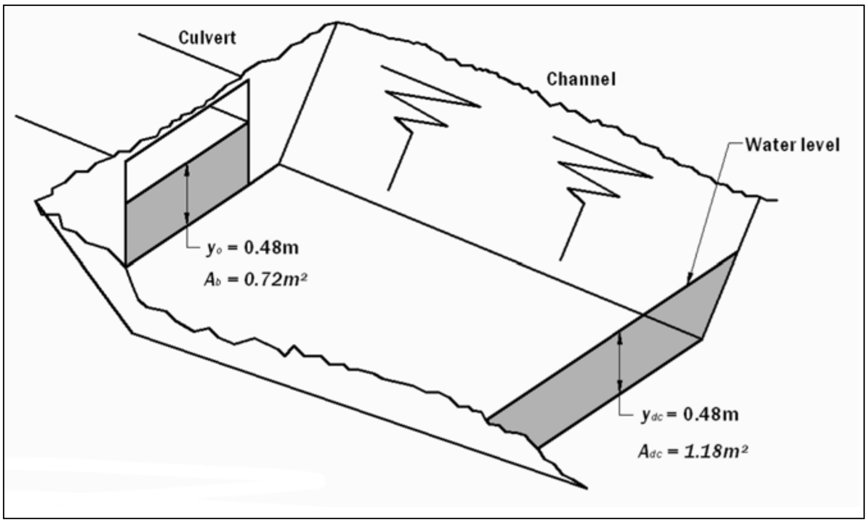


Figure A2.5 *Calculation of outlet head loss*

Calculation

Immediately upstream of the culvert outlet

$$A_b = By = 1.5 \times 0.48 = 0.72 m^2$$

$$V_b = \frac{Q}{A_b} = \frac{1.1}{0.72} = 1.53 m/s \tag{6.44}$$

Downstream of the culvert outlet

$$V_{dc} = \frac{Q}{A_{dc}} = \frac{1.1}{1.18} = 0.93 m/s \tag{6.45}$$

For a square end outlet, k_o = 0.75 from Table A1.5 in Appendix A1

$$h_o = k_o \left(\frac{V_b^2 - V_{dc}^2}{2g} \right) = 0.75 \left(\frac{1.53^2 - 0.93^2}{2 \times 9.81} \right) = 0.06 m \tag{6.43}$$

A2.5 Calculate head loss due to bends

Background

The box culvert of Appendices A2.1 to A2.4 has a bend situated 12 m upstream of the outlet with angle φ = 30° and radius R_{bn} = 10 m. We know that V_b = 1.53 m/s (Appendix A2.4).

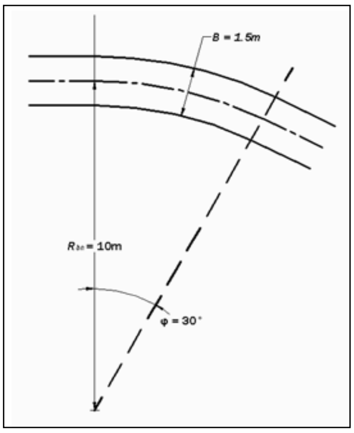


Figure A2.6 *Calculation of head loss due to bends*

Calculation

$$\frac{R_{bn}}{B} = \frac{10}{1.5} = 6.67$$

For φ = 30° and R_{bn}/B > 6.0

$k_{bn} = 0.09$ from Figure A1.8 in Appendix A1

$$h_{bn} = k_{bn}\frac{V_b^2}{2g} = 0.09\frac{1.53^2}{2\times 9.81} = 0.01m \qquad (6.46)$$

A2.6 Estimate head loss due to friction

Background

An estimate of head loss due to friction is required for the box culvert of Appendices A2.1 to A2.5. We know that for a design discharge Q = 1.1 m³/s, outlet (and tailwater) depth y_o = 0.48 m and a bend in the barrel gives a head loss h_{bn} = 0.01 m (at chainage 12.5 m).

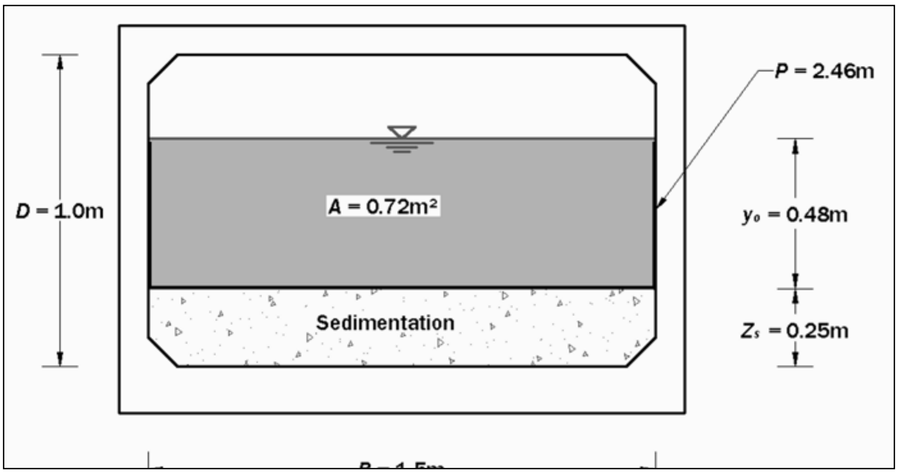


Figure A2.7 *Dimensions for calculation of head loss due to friction*

Manning's equation (quick method)

Manning's equation may be used to estimate head loss due to friction for culverts with full flow, short culverts with a relatively low friction loss or culverts with normal flow conditions (ie where the bed slope and water depth are uniform).

For a tailwater depth of 0.48 m, the cross-sectional area of flow $A = 0.72$ m², wetted perimeter $P = 2.46$ m, hydraulic radius $R = 0.29$ m and compound roughness $n' = 0.028$ (Appendix A2.3). The head loss due to friction h_f and friction (water surface) slope S_f are:

$$h_f = L\left(\frac{nQ}{AR^{2/3}}\right)^2 = 40\left(\frac{0.028\times 1.1}{0.72\times 0.29^{2/3}}\right)^2 = 0.38m \qquad (6.47)$$

$$S_f = \frac{h_f}{L} = \frac{0.38}{40} = 0.0095$$

The friction slope is nearly twice as steep as the bed slope ($S_0 = 0.005$), indicating that the depth of flow in the culvert is not constant, but increases from outlet to inlet. The change in flow depth between outlet and inlet can be estimated from the difference between the bed slope and friction slope.

$$\Delta y = L\left(S_f - S_0\right) = 40\left(0.0095 - 0.005\right) = 0.18m$$

So flow depth varies from to 0.48 m at the outlet to about 0.66 m at the inlet, giving an average depth of 0.57 m. As the calculation of head loss was based on an assumed depth of 0.48 m, it should be repeated with, say, a depth of 0.55 m, and so on until an equilibrium value is reached. Alternatively, the more complicated (but more accurate) backwater calculation can be used (see following section).

Backwater calculation

The backwater calculation should be used for culverts with non-uniform flow or long culverts where friction loss is significant. This method gives head loss due to friction for gradually varying flow, taking into account any change in water depth (and wetted perimeter) along the length of the culvert. The accuracy of the calculation increases as step length decreases – step length should be determined by engineering judgment.

So choose a step length Δx =20 m, giving three steps at x = 0 m, 20 m and 40 m. The backwater calculation is iterative and is given in full in Table A2.1, using the template from Table A1.7 in Appendix A1. Column 1 shows the calculation for x = 0 m, Columns 2 to 4 the iterative calculations for x = 20 m and Columns 5 to 7 the calculations for x = 40 m. The successful iterations are given in Columns 4 and 7. A single iteration for Column 2 is given here in full.

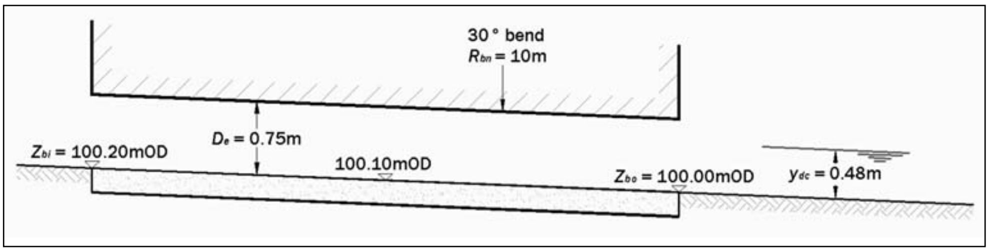


Figure A2.8 *Backwater calculation*

Determine bed elevation

For x = 20 m, the bed elevation is estimated by assuming a uniform bed slope

$$Z = Z_s + S_0.\Delta x = 100.00 + (0.005 \times 20) = 100.10mOD$$

Estimate trial water depth and channel properties

Let us try a water depth y = 0.50 m

$$A = By = 1.5 \times 0.50 = 0.75m^2$$

$$P = B + 2y = 1.5 + 2 \times 0.50 = 2.50m$$

$$R = \frac{A}{P} = \frac{0.75}{2.50} = 0.30m \qquad (6.8)$$

$$K = \frac{1}{n'} AR^{2/3} = \frac{1}{0.028} 0.75 \times 0.30^{2/3} = 12.00m^3/s \qquad (6.7)$$

Calculate total head for the new point

$$V = \frac{Q}{A} = \frac{1.1}{0.75} = 1.47m/s$$

$$H_1 = Z + y + \frac{V^2}{2g} = 100.10 + 0.50 + \frac{1.47^2}{2 \times 9.81} = 100.71m \qquad (6.1)$$

Estimate head loss due to friction

$$S_f = \left(\frac{Q}{K}\right)^2 = \left(\frac{1.1}{12.00}\right)^2 = 0.00840 \qquad (6.52)$$

From Column 1, we have S_{fprev} = 0.00953

$$S_{fmean} = \frac{(S_f + S_{fprev})}{2} = \frac{(0.00840 + 0.00953)}{2} = 0.00897 \qquad (6.53)$$

$$h_f = S_{fmean}\Delta X = 0.00897 \times 20 = 0.18m \tag{6.54}$$

Total head at the new point is

$$H = H_{prev} + h_f + h_{bn} = 100.60 + 0.18 + 0.01 = 100.79m \tag{6.55}$$

$H = 100.79 > 100.71 = H_1$ $\therefore$ try larger water depth until $H = H_1$

Table A2.1 ***Backwater calculation***

Step 1 ***Calculate bed elevation***

		1	2	3	4	5	6	7	Units
Row 5	Chainage from start point, x =	0	20	20	20	40	40	40	m
Row 6	Bed elevation, z =	100	100.10	100.10	100.10	100.20	100.20	100.20	m

Step 2 ***Estimate trial water depth and channel properties***

Row 7	Estimate water depth, y =	0.48	0.50	0.55	0.58	0.58	0.60	0.63	m
Row 8	For rectangular culverts, A = B.y =, A =	0.72	0.75	0.83	0.87	0.87	0.90	0.95	m²
Row 9	For rectangular culverts, P = B + 2y =	2.46	2.50	2.60	2.66	2.66	2.70	2.76	m
Row 10	Hydraulic radius, R = A/P =	0.29	0.30	0.32	0.33	0.33	0.33	0.34	m
Row 11	Compound roughness, n' = $(\Sigma\ pn^{3/2}/P)^{3/2}$ =	0.028	0.028	0.027	0.027	0.027	0.027	0.027	
Row 12	Conveyance, K = $(1/n').AR^{2/3}$ =	11.27	12.00	13.78	14.84	14.84	15.35	16.44	m³/s

Step 3 ***Calculate total head loss for the new point***

Row 13	Flow velocity, V = Q/A =	1.53	1.47	1.33	1.26	1.26	1.22	1.16	m/s
Row 14	Velocity head, $V^2/2g$ =	0.12	0.11	0.09	0.08	0.08	0.08	0.07	m
Row 15	Total head, $H_1 = z + y + V^2/2g$ =	100.60	100.71	100.74	100.76	100.86	100.88	100.90	m

Step 4 ***Estimate head loss due to friction***

Row 16	Friction slope, $S_f = (Q/K)^2$ =	0.00953	0.00840	0.00637	0.00549	0.00549	0.00514	0.00448	m/m
Row 17	Mean friction slope, $S_{fmean} = (S_f + S_{fprev})/2$ =		0.00897	0.00795	0.00751	0.00751	0.00734	0.00701	m/m
Row 18	$\Delta x = x_i - x_{i-1}$ =		20	20	20	20	20	20	m
Row 19	Head loss due to friction, hf = $(-S_{fmean})\Delta x$ =		0.18	0.16	0.15	0.15	0.15	0.14	m
Row 20	Head loss due to bends, h_{bn} =		0.01	0.01	0.01	0.00	0.00	0.00	m
Row 21	Total head, $H = H_f + h_{bn}$ =		100.79	100.77	100.76	100.91	100.91	100.90	m
Row 22	Check $H = H_1$?		Not OK	Not OK	OK	Not OK	Not OK	OK	

In Column 4, $H = H_1$ gives y = 0.58 m and h_{f1} = 0.15 m at chainage 20 m and Column 7 gives y_i = 0.63 m and h_{f2} = 0.14 m at chainage 40 m (the culvert inlet). So the total head loss due to friction h_f is:

$$h_f = h_{f1} + h_{f2} = 0.15 + 0.14 = 0.29m$$

The water depth at the culvert inlet (y_i = 0.63 m) is slightly lower than the initial value obtained using Manning's equation (y_i = 0.66 m), showing that it is worthwhile carrying out the full backwater calculation as described above, even for a relatively short culvert. If the flow in the culvert is uniform, the results from each method will be the same.

A2.7 Calculate head loss at inlet

Background

Inlet head loss is required for the concrete box culvert of Appendices A2.1 to A2.6, together with sensitivity testing for the inlet type. We know that V_b = 1.16 m/s at the culvert inlet (from Table A2.1 in Appendix A2.6). The culvert has a 90° headwall with 20 mm chamfers.

Calculation

For a 90° headwall with 20 mm chamfers, k_i = 0.5 from Table A1.3 in Appendix A1.

$$h_i = k_i \frac{V_b^2}{2g} = 0.5 \frac{1.16^2}{2 \times 9.81} = 0.03m \qquad (6.56)$$

For a warped inlet, k_i = 0.1 from Table A1.5 in Appendix A1.

$$h_i = k_i \frac{V_b^2}{2g} = 0.1 \frac{1.16^2}{2 \times 9.81} = 0.01m \qquad (6.56)$$

Replacing the square headwall with a warped inlet would reduce head loss by 0.02 m. This clearly illustrates the relatively small reductions achieved in head loss if flow velocity in the barrel is relatively low. So the extra expense of creating a warped inlet transition would not be justifiable in this example. If the flow velocity in the culvert was 3.0 m/s, for example, the difference in head loss would increase to 0.18 m, which could be significant in terms of reduced flood risk, and the extra cost of a warped transition might be justifiable.

A2.8 Calculate headwater level for outlet control

Background

The headwater level for outlet control is required for the concrete box culvert of Appendices A2.1 to A2.7. We know that bed level at the inlet Z_i is 100.20 mOD and flow depth y = 0.48 to 0.63 m (Appendix A2.6). Head losses have been calculated as follows: outlet h_o = 0.06 m (Appendix A2.4), bends h_{bn} = 0.01 m (Appendix A2.5), friction h_f = 0.29 m (Appendix A2.6), inlet h_i = 0.03 m (Appendix A2.7). There is no screen.

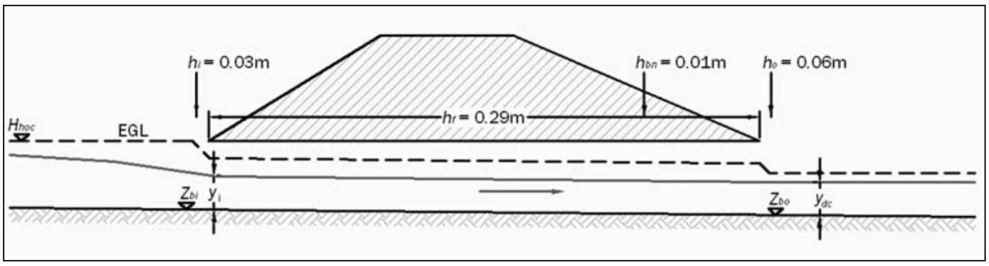


Figure A2.9 *Calculation of headwater for outlet control*

Calculation

Check maximum flow depth against clear barrel height to assess whether free or full flow occurs.

$y = 0.63m < 0.75m$ In Table A2.1, Row 7 $\therefore$ free flow throughout culvert barrel

For free flow, headwater level for outlet control $H_{ho}c$ is given by:

$$H_{hoc} = Z_i + y_i + h_i + h_s = 100.20 + 0.63 + 0.03 + 0.0 = 100.86mOD \quad (6.57)$$

Check against maximum permissible water level for free flow and full flow

$H_{hoc} = 100.86mOD > 100.70mOD = H_{h\max}$ for free flow

$H_{hoc} = 100.86mOD < 101.40mOD = H_{h\max}$ for full flow

The free flow discharge capacity is less than the design discharge, but the headwater elevation during the design flood is less than the maximum permissible headwater elevation.

A2.9 Calculate headwater level for inlet control

Background

The headwater level is required for a steep culvert. The culvert comprises a smooth concrete pipe with a height D = 1.35 m laid on a straight alignment with a uniform slope S_0 = 0.032. The culvert inlet comprises a concrete headwall at right angles to the culvert with the socket end of the pipe cast flush with the face of the headwall. Bed level is 97.63 mOD at the inlet and 96.11 mOD at the outlet. The design discharge is 5 m^3/s and tailwater level is 97.00 mOD.

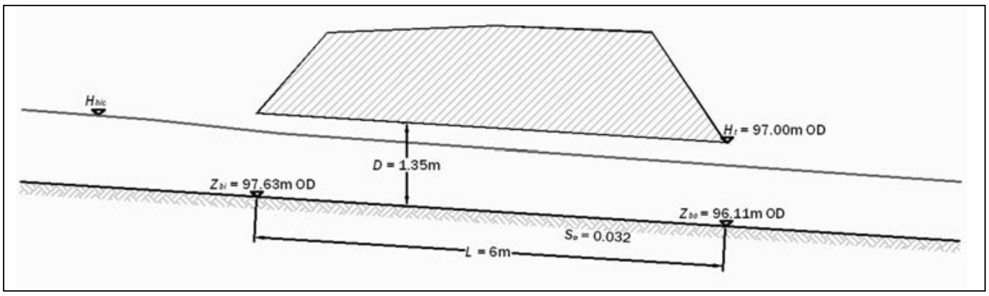


Figure A2.10 *Longitudinal section through culvert*

Calculation

Step 5.1 Calculate discharge intensity

$$A_b = \pi \frac{D^2}{4} = \pi \frac{1.35^2}{4} = 1.43m^2$$

$$q_i = \frac{1.811Q}{A_b D^{0.5}} = \frac{1.811 \times 5.0}{1.43 \times 1.35^{0.5}} = 5.45 > 3.5 \quad \therefore \text{ submerged flow} \qquad (6.22)$$

Step 5.2a Calculate headwater for free flow

From Table A1.3 in Appendix A1, the submerged inlet control equation applies with constants $c = 0.0292$ and $Y = 0.74$.

$$\frac{E_{sh}}{D} = c\left[\frac{1.811Q}{A_b D^{0.5}}\right]^2 + Y - 0.5S_o \qquad (6.26)$$

$$\frac{E_{sh}}{D} = 0.0292\left[\frac{1.811 \times 5.0}{1.43 \times 1.35^{0.5}}\right]^2 + 0.74 - (0.5 \times 0.032) = 1.59$$

The total head of the headwater under inlet control H_{hic} is then

$$H_{hic} = Z_i + E_{sh} + h_s = 97.63 + (1.59 \times 1.35) + 0.00 = 99.78mOD \qquad (6.41)$$

Check headwater level under inlet control H_{hic} with tailwater level H_t to ensure that inlet control is viable.

$$H_{hic} = 99.78mOD > 97.00mOD = H_t \quad \therefore \text{ inlet control viable}$$

A2.10 Calculate head loss due to screen

Background

The head loss due to a screen at a culvert inlet is required. A single screen panel 5 m wide and 1.2 m high is inclined at 45° to horizontal. The screen bars are 10 mm wide at 150 mm centre-to-centre spacing. During flood conditions, the screen is assumed to be 67 per cent blinded and the working platform is impermeable. We know that:

Width of screen panel $B_1 = B' = 5.0$ m

Height of screen panel $z_s = 1.2$ m

Height of blinding z_{bl} = 0.8 m (67 per cent of screen height)

Water depth downstream of screen y_f = 0.70 m

Design discharge, Q = 1.5 m³/s

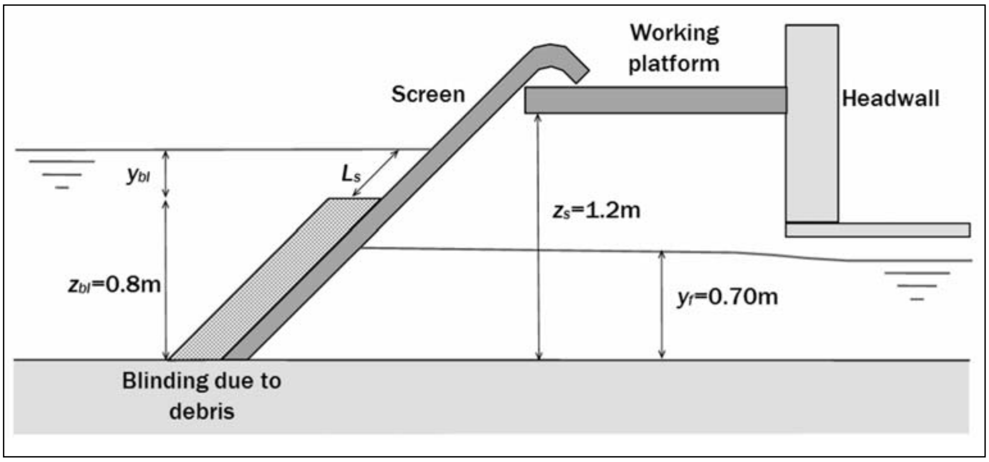


Figure A2.11 *Calculation of head loss due to screen*

Calculation

Calculate opening area of blinded screen

The width of screen opening B_s is given by the overall width (5.0 m) less the space taken up by the 10 mm bars at 150 mm centres (after Table 6.2):

$$b_1 = B_1(1-b) = 5.0\left(1-\frac{10}{150}\right) = 4.67m$$

The height of the screen opening D_s' is

$$D_s' = d_1 - z_{bl} = 1.2 - 0.8 = 0.4m$$

Calculate afflux due to weir flow over blinding

Assuming a weir coefficient of 1.5, the depth of modular weir flow over the blinding y_{bl} is

$$y_{bl} = \left(\frac{Q}{C_w B'}\right)^{2/3} = \left(\frac{1.5}{1.5\times 4.67}\right)^{2/3} = 0.36m \qquad (6.29)$$

$y_{bl} = 0.36m < 0.40m = D_s'$ $\quad\therefore$ not orifice flow

By inspection, the height of the blinding exceeds the water depth downstream of the blinding, so modular weir flow occurs over the blinding and there is no need to apply a submergence correction factor.

Calculate head loss due to expansion and contraction

In the upstream channel

$$A_{uc} \approx By_{uc} \approx B\left(z_{bl} + y_{bl}\right) \approx 5.0(0.8+0.36) \approx 5.8m^2 \qquad (6.37)$$

$$V_{uc} = \frac{Q}{A_{uc}} = \frac{1.5}{5.8} = 0.26 m/s \qquad (6.36)$$

At the screen, we have an inclined screen with modular weir flow over the blinding so the inclined length of the screen opening exposed to flow L_s' is used. After Table 6.2 we have

$$l_1^{'} = \frac{y_{bl}}{\sin\theta} = \frac{0.36}{\sin 45^\circ} = 0.50m$$

$$a_1^{'} = B_1 l_s^{'} = 4.67 \times 0.50 = 2.34m^2$$

$$V_s = \frac{Q}{A_s} = \frac{1.5}{2.34} = 0.64 m/s \qquad (6.38)$$

Head loss due to expansion and contraction h_b is

$$h_{ex} = 1.5\left(\frac{V_s^2 - V_{uc}^2}{2g}\right) = 1.5\left(\frac{0.64^2 - 0.26^2}{2 \times 9.81}\right) = 0.03m \qquad (6.35)$$

The total afflux due to the screen h_s is

$$h_s = \left(z_{bl} + y_{bl} + h_{ex}\right) - y_i = \left(0.8 + 0.36 + 0.03\right) - 0.70 = 0.49m \qquad (6.28)$$

A2.11 Calculate headwater level for overtopping flow (full flow)

Background

A concrete pipe culvert carries a drain beneath an access road which has been lowered locally to allow overtopping. The headwater level for overtopping flow is required. The peak discharge for the extreme flood is Q = 3 m^3/s.

The embankment has a crest level Z_w of 102.00 mOD and crest width perpendicular to the flow direction B of 8 m. Weir coefficient C_w is taken as 1.4.

The culvert has a barrel with height (diameter) D = 1.0 m, giving a cross-sectional area A_b = 0.79 m^2, wetted perimeter P = 3.14 m and hydraulic radius R = 0.25 m. The barrel is straight with length L = 6 m. Roughness coefficient n = 0.011. Bed level at the culvert outlet Z_{bo} = 100.00 mOD and at the culvert inlet Z_{bi} = 100.20 mOD. The culvert has no screen and the invert is clean.

Downstream of the culvert, the tailwater depth y_{dc} = 1.2 m, with a cross-sectional area A_{dc} = 2.3 m^2 and a flow velocity V_{dc} = 1.3 m/s.

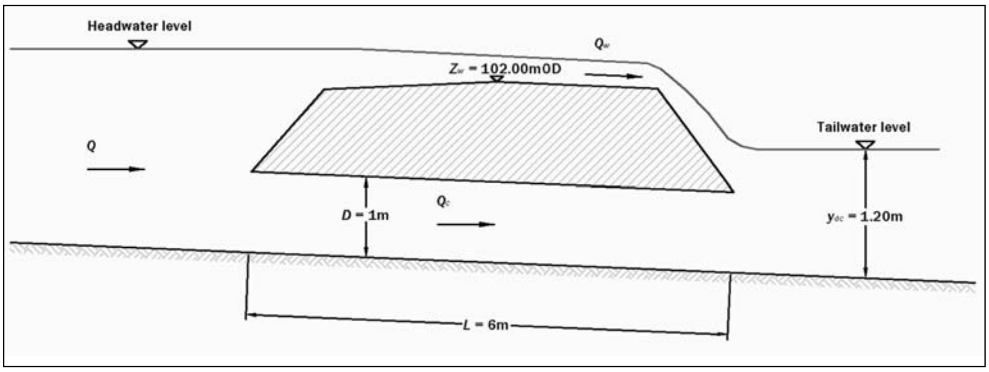


Figure A2.12 *Calculation of headwater for overtopping flow*

Calculation

Step 1 Calculate tailwater level and assess flow type

Tailwater level WL_t is

$$WL_t = Z_{bo} + y_{dc} = 100.00 + 1.2 = 101.20mOD \tag{6.11}$$

Check tailwater level WL_t against embankment crest level Z_w

$WL_t = 101.20mOD < 102.00mOD = Z_w$ $\therefore$ modular weir flow or non-overtopping flow

Check tailwater depth y_{dc} against outlet height D

$y_{dc} = 1.20m > 1.0m = D$ $\therefore$ submerged outlet flow – full flow method required

Step 2 Estimate flow split

Let us take an initial flow split between the culvert and overtopping of Q_c = 2.5 m³/s and Q_w = 0.5 m³/s.

Step 3 Calculate headwater level for culvert flow

Since the culvert outlet is submerged, the method for full flow (outlet control) is used.

Tailwater head H_t is

$$H_t = Z_{bo} + y_{dc} + \frac{V_{dc}^2}{2g} = 100.00 + 1.2 + \frac{1.30^2}{2 \times 9.81} = 101.29mOD \tag{6.10}$$

Barrel velocity V_b is

$$V_b = \frac{Q_c}{A_b} = \frac{2.5}{0.79} = 3.16m/s \tag{6.14}$$

The total head of the headwater for culvert flow H_{hc} is

$$H_{hc} = H_t + k_o\left(\frac{V_b^2 - V_{dc}^2}{2g}\right) + k_{bn}\frac{V_b^2}{2g} + L\left(\frac{nQ_c}{AR^{2/3}}\right)^2 + k_i\frac{V_b^2}{2g} + h_s \tag{6.61}$$

$$H_{hc} = 101.29 + 1.0\left(\frac{3.16^2 - 1.3^2}{2 \times 9.81}\right) + 0.0 + 6\left(\frac{0.011 \times 2.5}{0.79 \times 0.25^{2/3}}\right)^2 + 0.5\frac{3.16^2}{2 \times 9.81} + 0$$

$$H_{hc} = 101.29 + 0.42 + 0.0 + 0.05 + 0.25 = 102.01mOD$$

Step 4 Estimate headwater level for overtopping flow

From Step 7.1, tailwater level is below embankment crest level and we can assume modular weir flow. The total head of the headwater for weir flow is

$$H_{hw} = Z_w + \left(\frac{Q_w}{C_w B}\right)^{2/3} = 102.00 + \left(\frac{0.5}{1.4 \times 8}\right)^{2/3} = 102.13mOD \qquad (6.65)$$

Step 5 Check energy balance

Check headwater for culvert flow against that for weir flow

$H_{hc} = 102.01 < 102.13 = H_{hw}$ $\quad \therefore$ increase discharge through culvert

Iterative calculations reveal that an energy balance is obtained for Q_c = 2.62 m³/s, Q_w = 0.38m³/s and $H_{hc} = H_{hw}$ = 102.10 mOD. Note that the headwater elevation includes the velocity head, although this can often be neglected.

A2.12 Calculate headwater level for overtopping flow (free flow inlet control)

Background

The tailwater level for the culvert in Appendix A2.11 is reduced following the removal of a structure downstream. The new tailwater conditions are a tailwater depth y_{dc} = 0.6m, with a cross-sectional area A_{dc} = 1.6 m² and a flow velocity V_{dc} = 1.9 m/s.

Calculation

Assess flow type

Tailwater level WL_t is

$$WL_t = Z_{bo} + y_{dc} = 100.00 + 0.6 = 100.60mOD \qquad (6.11)$$

Check tailwater level WL_t against embankment crest level Z_w

$WL_t = 100.60mOD < 102.00mOD = Z_w$ $\quad \therefore$ modular weir flow or non-overtopping flow

Check tailwater depth y_{dc} against outlet height D

$y_{dc} = 0.6m < 1.0m = D$ $\quad \therefore$ unsubmerged outlet

Estimate flow split

Let us take an initial flow split between the culvert and overtopping of Q_c = 2.5 m³/s and Q_w = 0.5 m³/s as before.

Calculate headwater level for culvert flow

As the outlet is unsubmerged, flow is likely to be inlet controlled and the submerged inlet control equation applies. For a circular culvert with a square headwall, coefficients are c = 0.0398 and Y = 0.67 from Table A1.3 in Appendix A1.

$$H_{hc} = Z_{bi} + \left[c\left(\frac{1.811 Q_c}{A_b D^{0.5}} \right)^2 + Y - 0.5 S_0 \right] D \qquad (6.62)$$

$$H_{hc} = 100.20 + \left[0.0398\left(\frac{1.811 \times 2.5}{0.79 \times 1.0^{0.5}} \right)^2 + 0.67 - (0.5 \times 0.033) \right] \times 1.0 = 102.16 mOD$$

Estimate headwater level for overtopping flow

From Appendix A2.11, we know that the total head of the headwater H_{hw} = 102.13 mOD for Q_w = 0.5 m³/s.

Check energy balance

Both the culvert and weir headwater elevations are higher than the embankment crest level, confirming that overtopping flow occurs. Check culvert headwater against weir headwater (note that the headwater level includes the velocity head, although this can often be neglected).

$$H_{hc} = 102.16 mOD > 102.13 mOD = H_{hw} \qquad \therefore \text{ reduce discharge through culvert}$$

A2.13 Calculate headwater level for overtopping flow (screen control)

Background

A trash screen is added to the culvert in Appendix A2.12. The screen is poorly designed and susceptible to blinding. The headwater elevation is required for the 67 per cent blinding scenario. We know that the cross-sectional area of culvert barrel A_b = 0.79 m², the cross-sectional area of screen opening (after blinding) A_s = 0.66 m² and the level of the centroid of the screen opening Z_{or} = 101.20 mOD (this is needed for the orifice flow equation).

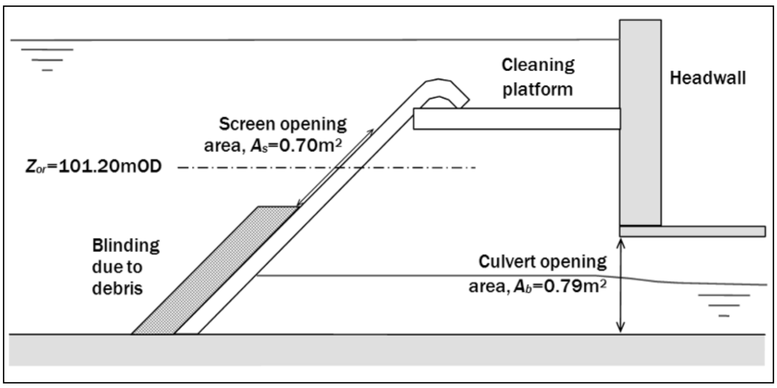


Figure A2.13 ***Calculation of headwater level for overtopping flow with screen control***

Assess flow type

The cross-sectional area of the orifice is the minimum of the screen opening and culvert opening areas

$$A_{or} = \min\left(A_s, A_b\right) = \min\left(0.66, 0.79\right) = 0.66m^2 \qquad (6.40)$$

Since the screen opening is smaller, control is likely to be at the screen.

Estimate flow split

Let us take an initial flow split between the culvert and overtopping of Q_c = 2.5 m³/s and Q_w = 0.5 m³/s as before.

Calculate headwater elevation for culvert flow assuming that control is at the screen

Headwater elevation for culvert flow H_{hc} is given by the orifice equation

$$H_{hc} = Z_{or} + \frac{1}{2g}\left(\frac{Q_c}{C_d A_{or}}\right)^2 \qquad (6.63)$$

$$H_{hc} = 101.20 + \frac{1}{2 \times 9.81}\left(\frac{2.5}{0.63 \times 0.66}\right)^2 = 103.04mOD$$

Estimate headwater level for overtopping flow

From Appendix A2.11, we know that the total head of the headwater H_{hw} = 102.13 mOD for Q_w = 0.5 m³/s.

Check energy balance

Check headwater for culvert flow against headwater for weir flow

$$H_{hc} = 103.04 > 102.13 = H_{hw} \quad \therefore \text{ reduce discharge through culvert}$$

Further iterations show that an energy balance is achieved for discharge through the culvert Q_c = 1.85 m³/s, discharge over the embankment Q_w = 1.15 m³/s and headwater level $H_{hc} = H_{hw} \approx 102.22$ mOD.

Note this is a simple example that illustrates the thinking process and use of the basic equations. Often this type of problem is associated with a flooding incident for which the cause is not obvious, and it is necessary to check a range of scenarios to determine the most likely cause and to develop a solution. In this case the next step would be to check if the culvert is capable of safely conveying 3.0 m³/s (ie without overtopping the embankment) if the screen is completely removed. If this proves to be the case, the next step would be to investigate whether there is a real need for a screen at this location (see Chapter 9 for guidance).

A3 Case studies

Case study A3.1

Asset management within a local authority

By Amanda Kitchen, JBA Consulting and David Oldknow, Leeds City Council

Client: Leeds City Council

Culvert surveys: Mouchel Parkman

Maintenance: Peter Duffy Ltd

Improvements: In-house workforce

Location: Leeds, West Yorkshire

Introduction

An urban area suffered severe flooding twice in quick succession due to intense rainfall and the inability of the drainage infrastructure to cope with the increased volumes of water. The incidents highlighted several areas for improvement in the maintenance of assets and response to flooding. This case study describes the strategy developed by the council.

The problem

The council as land drainage authority has operational powers over culverts totalling 213 km in length in both urban and rural locations. Culverts range from 150 mm square to 2100 × 1500 mm box culverts, with construction including brick and stone masonry, vitrified clay, concrete and corrugated iron. Trash and security screens have been fitted to some culverts, including one and two-stage sloping screens, and vertical screens.

Figure A3.1 *Trash screen showing accumulation of debris between routine maintenance (courtesy Leeds City Council)*

Many culverts had not been inspected internally for decades and blockages and structural problems were undetected until flooding was caused. Watercourse blockages were also caused regularly by debris such as abandoned shopping trolleys.

Asset management action plan

After the first flood, the local authority set up a cross-departmental working group to develop a 33-point action plan. Four months later, the plan was approved and funding was put in place to implement the recommendations. These included maintenance, inspection and assessment, a risk-based programme of improvements, asset management systems, support for others and emergency planning.

Maintenance

The maintenance of watercourses was transferred from the functional departments to the land drainage section, and a specialist contractor was appointed under a term contract. A maintenance plan comprising routine, planned, reactive and heavy maintenance was developed.

The routine maintenance is prioritised according to risk, with fortnightly clearance of over 39 high risk screens and hotspots, monthly clearances of 22 other screens, two monthly clearances of nine screens and three monthly clearances of eight other screens. If a flood watch or flood warning is issued, these high risk locations are also visited immediately, as far as practicable. Photographs of each hot spot are taken before and after clearance, to monitor the rate of debris accumulation and help the council to reassess the frequency of visits in the future. No further flooding has occurred at these locations, indicating that the new regime has reduced flood risk.

Planned maintenance is prioritised according to perceived risk. An ecological appraisal is carried out before clearance of any section to avoid disturbance of wildlife habitats, and natural woody debris is left in place or secured to the banks to provide habitat, where this does not pose a flood risk.

Reactive maintenance is carried out when the local authority is notified of blockages by inspectors, members of the public or others, with work prioritised according to flood risk. Abandoned shopping trolleys are removed by a private company at no cost to the council, under local authority powers to recover trolleys and charge costs to the owner. Trolleys are removed daily and around 7300 trolleys were removed in nine months.

Asset management system

A dedicated asset engineer was appointed to set up and manage improved asset management systems for all water assets, including culverts. The systems are based on geographical information systems (GIS) and will allow greater flexibility and sharing of information. The systems are now being populated.

Inspection and assessment

A substantial programme of internal inspections was implemented using closed-circuit television (CCTV). Sometimes access was only possible after manhole replacement or construction. Pan-and-rotate camera heads with zoom facility, in combination with a steerable crawler unit were found to be more effective than the rigid CCTV cameras designed for sewer surveys. The surveys and inspections will be stored on the improved asset management system.

The inspections showed that the fabric of older culverts is often in surprisingly good condition, although several internal culvert blockages were found. The blockages have been removed and cleaning to remove silt has started, although some repairs will require capital works.

Hydraulic assessment

The hydraulic assessment of 350 existing major highway culverts (diameter >900 mm) is carried out collaboratively. Surveys are managed by the bridges section and carried out by a contractor. Data collected includes photographs, dimensions, access, distance from the nearest property and ease of inspection from the highway. The data are passed to the land drainage section for hydraulic assessment, with physical modelling if necessary. Any under-capacity culverts are then considered for possible inclusion in the capital programme for improvements by the bridges section.

Improvements

Heavy maintenance and minor improvements are carried out by the land drainage section, prioritised according to the probability and consequences of failure. Works to date have included culvert lining and repair, new inlet structures and new trash and security screens. The installation of a primary trash screen to trap large debris such as supermarket trolleys, and preventing blockages, has already proved its worth during a flood event.

Figure A3.2 *Trash screen following cleaning (courtesy Leeds City Council)*

Emergency planning

Emergency planning was improved in partnership with other agencies. A county-wide flood response protocol with clear roles and responsibilities was developed by the council, ratified by all partner agencies and incorporated into their flood plans. The protocol was tested in a multi-agency exercise and worked well.

The response to calls from members of the public was streamlined. A multi-agency checklist of questions for use in call centres was developed to help staff establish the type of flooding and direct callers to the most appropriate organisation. The council is also working with other agencies to develop the Environment Agency Floodline service into a one-stop number, so that the public can call one number to report any type of flooding.

The flood mitigation and recovery response was improved, with an emergency co-ordination vehicle and trailer containing flood recovery resources providing new capability for rapid deployment. Round-the-clock standby support for major flooding emergencies is provided by the maintenance contractor.

Stakeholder engagement

Liaison between agencies is ongoing and regular meetings take place between the local authority, the Environment Agency and the water company to discuss specific flooding problems. A permanent multi-agency technical forum to address development control issues as well as flooding is proposed.

The council developed a package of measures to help private owners and communities to fulfil their responsibilities, including attendance at flood fairs and public information campaigns.

Conclusions

The severe flooding experienced in the area triggered the development of new asset management techniques and resources to reduce the risk of flooding. The benefits have seen increased internal and external collaboration and better value for money.

Case study A3.2

Responsibilities of culvert owners

By Richard Allitt, director, Richard Allitt Associates Ltd

Location: Ashford, Kent

Introduction

Bybrook Barn garden centre near Ashford in Kent, suffered flooding from Bockhanger Dyke on three occasions in seven years due to a highway culvert that had been adequately sized at the time of construction, but had become undersized due to development within the catchment. A legal case against Kent County Council led to an important decision on the law of nuisance that is now widely referred to in technical and legal circles (Bybrook Barn Garden Centre v Kent County Council, 2001, BLR 55). This case study summarises the background, legal findings and the implications for culvert owners, highway authorities and insurers.

Background

Bockhanger Dyke is a tributary of the river Great Stour, which flows around the perimeter of the Bybrook Barn Garden Centre in open channel. Downstream of the garden centre, the watercourse flows through Cemetery Lane culvert, originally a 900 mm diameter pipe set slightly below bed level of the watercourse with partial sedimentation (Figure A3.3). Another section of open channel follows before Canterbury Road culvert, a 3000 mm × 1100 mm box culvert. The watercourse then flows in open channel for about 200 m before discharging to the Great Stour.

Figure A3.3 *Cemetery Lane culvert before replacement (1996) (courtesy Richard Allitt)*

Cemetery Lane culvert was thought to be constructed by the highway authority, Ashford District Council, in the 1930s. By the 1990s, the responsibility had transferred to Kent County Council as the highway authority.

At the time of construction, the catchment was predominantly rural with extensive woodland and some ribbon development. Over the following 60 years, the catchment changed, with housing, hotel and retail development, extensive car parking and the M20 motorway. Runoff from these developments was discharged to Bockhanger Dyke without attenuation. In the early 1990s, construction of a science and business park started, with runoff attenuation provided by online and offline balancing ponds and lakes.

From the 1990s, flooding from Bockhanger Dyke affected Bybrook Barn Garden Centre on three occasions in seven years. The first flood in 1993 affected the garden centre only, as the doctors' surgery had not yet been built. After this incident, the owners of the garden centre wrote to Kent County Council expressing concern about the inadequate hydraulic capacity of Cemetery Lane culvert, but no action was taken. In 1996, a second flood caused £100 000 of damages to the garden centre, doctors' surgery and M20 motorway. The flooding mechanism, captured on a video later used in court, was identified as overtopping at Cemetery Lane and overland flow across the road. A third flood in 2000 caused flooding of the car park, external areas and a corner of the main building at the garden centre.

Legal case for nuisance

After the 1996 flood, inspection of Cemetery Lane culvert showed that the cause of flooding was inadequate hydraulic capacity rather than blockage. At this point, Bybrook Barn Garden Centre (the Claimant) commissioned a hydrological and hydraulic modelling study and brought a case for nuisance against Kent County Council (the Defendant). The case was dismissed in the High Court in 1999 but upheld in the Court of Appeal in 2000. A petition for leave to appeal was dismissed in the House of Lords in 2001. The main points are discussed here.

Expert witness findings

Before the court hearing, expert witnesses acting for the claimant and defendant agreed on the following technical points:

1. Flooding at the garden centre with the original 900 mm diameter Cemetery Lane culvert had an annual probability of between three and 10 per cent in summer with a dry catchment, increasing to as much as 20 per cent with winter rainfall and average catchment wetness. These values were later updated to 10 to 25 per cent in summer and as high as 50 per cent in winter using data from the 2000 flood. This extra information and the analysis of the August 2000 storm was compiled into a supplementary report that was used when the case was heard at the Court of Appeal
2. Flooding would not have occurred if Cemetery Lane culvert had not been built and the watercourse had remained as an open channel.
3. Flooding would not have occurred during the 1996 flood if the culvert had been large enough to convey a 1 in 30 year flow.
4. Backwater from the Great Stour was not a significant factor.

Nuisance

The garden centre argued that the council had long known of the flood risk and that it was reasonable for the council to enlarge the culvert before the 1996 flood. However, the hydraulic capacity of the culvert was adequate at the time of construction and only became inadequate because of later development upstream, a fact that presented a difficulty for the garden centre. The council argued that it had not increased flows in the watercourse, and a culvert that was not a nuisance when first constructed could not become a nuisance at a later date. This argument was rejected in an important decision, which found that a watercourse structure may become a nuisance even if it is not a nuisance when first constructed.

Responsibility for the nuisance

In the High Court, the council was found to be aware of the risk of flooding but considered that its responsibilities for the culvert were limited to structural performance. The council argued that it had no liability to take action to improve hydraulic performance, and rebuilding the culvert would imply responsibility for thousands of bridges and culverts that might require similar work. This argument was rejected.

Reasonableness

The council also argued that the cost of culvert replacement was unreasonable given their limited resources and a backlog of essential maintenance. The test in Leakey v National Trust was applied and it was found the council had not taken reasonable steps in the circumstances. The Court of Appeal emphasised that the question of liability in this sort of case is determined by an application of the test of reasonableness as between neighbours. It was made clear that a poor landowner would not be expected to do as much as a prosperous landowner. The Court of Appeal held:

> *"The factors which in my view point in favour of liability are the following. The Defendants' predecessors must have chosen to construct a culvert to put the natural stream under the highway…[This] places on them a high obligation to see that the natural stream can continue to flow under the highway…The highway authority has the means of preventing the flooding by enlarging the culvert at some cost but basically without great difficulty…."*

Remedies

It was held that it was reasonable for the council to rebuild the culvert so as to afford the garden centre reasonable flood protection. The council was ordered to replace and enlarge the culvert (Figure A3.4) and the garden centre was awarded damages reflecting the losses sustained in the flood.

It is worth noting that the Land Drainage Act 1991 (Clause 24) allows local authorities or internal drainage boards to serve notice requiring the abatement of nuisance caused by obstructions in watercourses. The notice may be served on the person who erected or altered the structure, or any person who has the power to remove the obstruction, and allows the recovery of costs from the parties benefiting from the works.

It is also important to note that an Act of God such as exceptional rainfall it is not necessarily an adequate defence in the case of nuisance. If an owner is aware of the flood risk caused by his culvert and fails to take reasonable steps to abate the risk, then the fact that a flood occurred in circumstances where the rainfall was exceptionally heavy is not a defence if reasonable steps would have prevented the flood.

Figure A3.4 *Cemetery Lane culvert after replacement (2003) (courtesy Richard Allitt)*

Nuisance

Nuisance is a condition or activity that unduly interferes with the use or enjoyment of land. It is a nuisance to allow your trees to overhang your neighbour's land, to undermine your neighbour's foundations by digging a hole on your land, or interfere with your neighbour's enjoyment of his land by causing noxious smells or excessive noise to emanate from your land. It is also a nuisance to allow your culvert to become blocked causing land upstream to be flooded, or to interfere with a natural watercourse with the consequence that you neighbour's land is flooded.

Nuisance from natural forces Leakey v National Trust

In Leakey v National Trust [1980] 1 QB 485 it was held that an occupier of land owed a general duty of care to a neighbouring occupier in relation to a hazard on his land whether that hazard was natural or man-made. It was held that the occupier had to take reasonable steps to remove or reduce the hazard. As to what constituted reasonable steps, this depended on the circumstances of the case. So the following example was given:

> *"Take by way of example...the landowner through whose land a stream flows. In rainy weather it is known the stream may flood and the flood may spread to the land of the neighbours. If the risk is one which can readily be overcome or lessened, for example, by reasonable steps on the part of the landowner to keep the stream free from blockage...he will be in breach of duty if he does nothing or does too little. But if the only remedy is substantial and expensive work, then it might well be that the landowner would have discharged his duty by saying to his neighbours who also know of the risk and who have asked him to do something about it 'you have my permission to come on to my land and to do agreed works at your expense'...the question of reasonableness of what had been done or offered would be decided on a broad basis in which, on some occasions, there might be included an element of obvious discrepancy of financial resources."*

Conclusions

The Bybrook Barn case extended the law of nuisance such that a watercourse structure, which becomes an obstruction over time may be deemed a nuisance, even if it was not a nuisance when first constructed.

The decision affects all owners of watercourse structures (public or private) who have a duty to take reasonable steps to abate flood risk to neighbouring land if they become (or ought to be) aware of any risk. Owners are advised to design proposed culverts not just for current flows but flows that are reasonably foreseeable because of increased development.

The decision also affects highway authorities that may have to replace or enlarge culverts or bridges that restrict the flow in a watercourse. Principal inspections should include an assessment of hydraulic as well as structural performance, and where new developments are likely to increase the runoff into a watercourse, highway authorities are advised to seek the reconstruction of bridges and culverts using the planning system.

Case study A3.3
Screen design and operation

By Stephen Chapman, flood incident management, Environment Agency, and Steve Barge

Client: Environment Agency

Design: Atkins

Principal engineer: Atkins Ltd

Principal contractor: Van Oord ACZ (TJ Brent Ltd)

Subcontractor: Sewer Services

Location: Ottery St Mary, East Devon

Introduction

The town of Ottery St Mary, in Devon, lies at the bottom of the Furze Brook catchment and the centre of the town has been built on the floodplain of the Furze Brook that now runs in a culverted channel through the town. The Furze Brook is a tributary of the River Otter and has a catchment of about 135 ha. Land-use is predominantly agricultural. Field slopes are steep and the soils are mostly clay. Parts of Ottery have suffered repeated flooding from the Furze Brook since the mid 1980s, the primary cause being inadequate hydraulic capacity of the 545 m long culvert carrying Furze Brook beneath the town.

In 2003–2004 flood alleviation works costing £4.2m were constructed. The works included replacement culverts, channel improvements and a diversion channel. Although the scheme was based on a design flood of one per cent annual probability (100-year return period), a precautionary approach was adopted for the replacement culvert, which was designed to accommodate the 0.66 per cent annual probability (150-year return period) flood. This approach reflects the difficulty of carrying out maintenance and future improvement works to a long culvert under a town centre.

The works

The works involved two replacement culverts and one new culvert, along with channel improvements and a new 200 m long diversion channel carrying Furze Brook directly to the River Otter.

The 545 m long brick arch culvert (Chapel Lane) beneath the town centre was replaced by a 1350 mm diameter circular culvert. Physical constraints demanded a portfolio of construction techniques, and pre-cast concrete pipes were laid in open cut trenches beneath wider streets, while a segmental glass-reinforced plastic (GRP) liner was installed by hand-dug tunnelling techniques where the culvert passed under buildings and narrow streets. The avoidance of road closures reduced public disruption.

The length and relatively small diameter of the culverts required that screens were provided at the inlets to reduce the risk of culvert blockage and to ensure that unauthorised or accidental access to the culverts was prevented.

The historic character of the town meant that aesthetic and environmental considerations were of prime importance during the design process. All concrete channels and inlet and outlet structures were random rubble stone clad, and extensive landscaping works were carried out where the scheme crossed a public amenity area. Also, open channel works through public amenity and agricultural areas were designed with an open stone asphalt layer (to provide scour resistance and hard inverts for maintenance), overlaid with topsoil and pre-seeded coir matting to provide a natural channel appearance.

Note the benched channel invert designed to reduce head loss at the inlet.

Figure A3.5 *The inlet to the Chapel Lane culvert before the installation of the screen*

Post scheme works

Since the completion of the scheme, three flood events from the Furze Brook have affected properties in Ottery. On each occasion, significant amounts of trash (tree branches, twigs, crop debris, domestic garden rubbish, pallets etc) accumulated on the culvert inlet screens and obstructed the water flow. The Chapel Lane screen was sufficiently blocked within an hour to cause escape of flood water from the channel. This, combined with the effects of surface water flooding, caused more than a dozen commercial properties to be flooded.

The design of the screen has been changed as a result of these events, and the loss of confidence in the performance of the trash screen has led to a rigorous screen monitoring protocol:

- screens are checked before rainfall (based on Met Office forecasts)
- two men monitor the performance of the screen on–site, on the receipt of a heavy rainfall warning for East Devon or a rainfall intensity alarm (20 mm/hr) at the Ottery St Mary rain gauge.

At the Chapel Lane culvert telemetry has been installed to monitor water levels. Sensors are located on both sides of the screen to indicate if the screen is blocked. The telemetry will issue an alarm should a significant difference between the upstream and downstream water levels be recorded.

A remote webcam has been installed to view the lower section of the trash screen. The cameras have an in-built infra red sensor so that images can be taken in the dark. Access to the images recorded from the webcam is through the Environment Agency's telemetry system.

The cameras are based on mobile phone technology. The cameras are small and mobile and are powered by batteries. They do not need mains power or fixed telephone lines. The cameras can be deployed in any location that has acceptable mobile phone reception.

They are set up to take timed images each day and send to an email account. The cameras can also be polled by text messaging. The image can be sent back to the mobile phone or to an email account. This will allow the duty officer to monitor conditions at the screens before an event and the performance of the screens during an event.

Although the equipment is located within a narrow, deep (2.5 × 4 m) brick lined channel, a satisfactory signal is available. The screen is well protected from intruders. The battery pack is located at the entrance to the site so that access down to the screen is not required except to maintain the camera unit.

Trash screen at Chapel Lane – looking upstream

Site of camera on left bank

Camera

Site of battery. Top of screen behind road parapet. Battery case padlocked to wall

View from camera showing lower screen and first platform (flow from right to left)

Night view from camera

Figure A3.6 *Screen at Chapel Lane as seen from the webcam*

Kennaway Road screen

This site is upstream of the Chapel Lane screen and has not been as critical in terms of blockages to date. Nevertheless, level sensors have been installed at this site, together with a camera. The camera views the lower part of the screen and has no views of private property. The battery pack is sited at the top of the screen for easy access. The camera is attached to railings around the screen.

Figure A3.7 *Kennaway screen looking upstream*

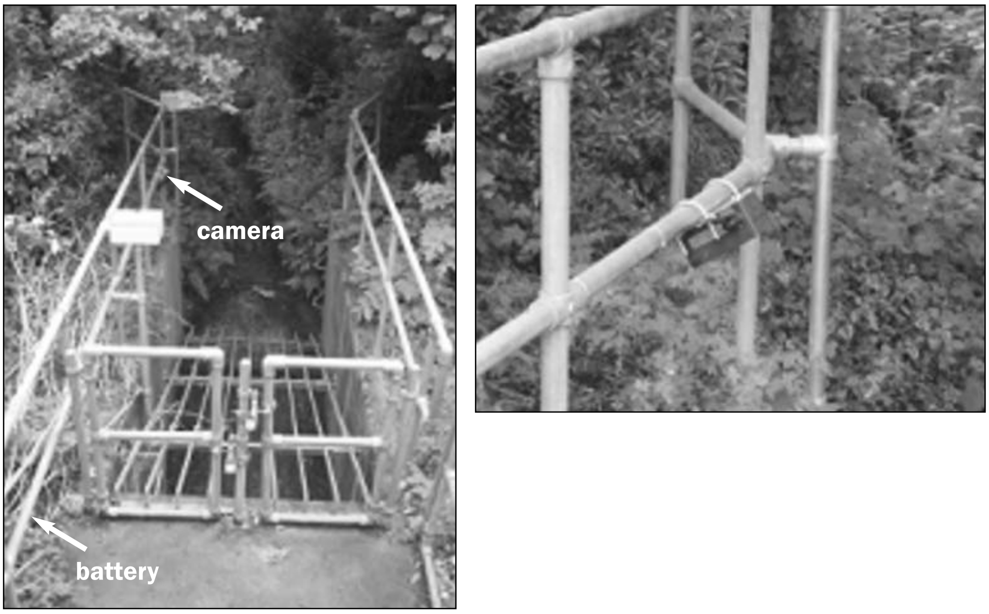


Figure A3.8 *Camera sited on railing*

The site is less secure as it is directly off a quiet suburban road. The battery pack is chained and padlocked to the railings and hidden in undergrowth. The camera is locked to the railing by a padlock and wire.

Operation of the system

Operational duty staff use the remote monitoring equipment for assessing conditions at the screens before potential high flow events. Due to the low lead times between the onset of debris collection and overtopping of the culvert, even with remote monitoring, staff are still deployed in response to heavy rainfall warnings.

The type of telemetry installation selected has the following advantages:

- does not require fixed utilities (electricity supply or telephone line)
- short installation time
- low cost
- the deployment of the units does not require high technical skills
- there are fewer issues regarding privacy than with other cameras systems such as CCTV
- independent of other telemetry systems and the associated costs
- images can be accessed by mobile phone – the system does not require a laptop and connection from home.

Lesson learned

The original design of the Chapel Lane screen had closely spaced bars (less than the 140 mm now recommended) for safety reasons. This approach resulted in the screen becoming obscured quickly, leading to local flooding. Even with improvements to the design, it has proved necessary to implement a monitoring programme using telemetry to make sure that the screen can be cleaned before it blocks sufficiently to cause flooding. The following lessons have been learned:

- unconventional screens require careful design to ensure that they perform as intended and that they can be cleared of debris in a timely manner in a flood event
- for screens with a history of blockage, and especially those with short lead times, the installation of remote monitoring equipment (cameras and level sensors) can provide operational staff with an early warning, allowing them to mobilise and address the problem before it results in flood damage
- telemetry systems do not have to be expensive
- the use of battery powered systems and mobile phone telephony allows systems to be located at remote sites where mains power and telephone lines are not available.

Case study A3.4

Terrestrial laser scanning of culverts

By Doug Barker, George Baker and Suzanne Callaway, Capita Symonds Ltd

Client: Environment Agency, Cornwall area

Principal contractor: Total Surveys Ltd

Location: Plympton, Cornwall

Background

Terrestrial laser scanning or ground based LIDAR provides a new means of capturing the geometry of complex culverts.

Survey data was required to inform the representation of a culvert in a hydraulic model of Long Brook in Plympton. The culvert is about 40 m in length, with the width and height varying non-systematically along its length. The opening width of the culvert is about 1.5 m, and the opening height is 1.05 m (Figure A3.10). In addition to the complexity of the variable geometry, there are a series of pipe crossings across the culvert, and metal and timber beams that constrict the channel at intervals through the culvert.

Figure A3.9 *Culvert entrance*

Traditional surveying techniques would be difficult to employ at this location. The opening of the culvert is small, making access and working conditions difficult. Also, due to the highly irregular variations in culvert width and height, identifying where best to take a survey cross-section is not a simple decision. For the purpose of the hydraulic model it was important that the maximum constriction and any other complex features within the culvert were identified and recorded.

The survey process

Terrestrial laser scanning was selected as an appropriate survey technique due to the irregular nature of the culvert. Also, health and safety concerns about accessing such a confined space meant that there was good reason to limit the time spent in the culvert and the possible need for further survey in the future. Terrestrial laser scanning allows large quantities of data to be collected in a relatively short time-frame. The laser scanner used was a Leica HDS 6100, accurate to ±1 mm from a range of 25 m and capable of scanning half a million points per second.

To undertake the terrestrial laser scanning, a series of reflective targets were set up along the culvert to form control points that remain *in situ* for the entire duration of the survey. For the first of a sequence of scans the laser scanner is located at the entrance to the culvert and this location is surveyed with a total station to determine its precise position. By using the starting position and targets all scan data is accurately geo-referenced.

The laser scanner is moved along the culvert and 360° scans undertaken at regular intervals. The frequency and spacing of the scans are determined by the exact nature of the culvert. Scans need to be undertaken either side of obstructions crossing a culvert to enable all sides to be accurately scanned. For a more constricted culvert, more scans are required due to the restricted view of the scanner from one point to the next. The detailed survey of the culvert took about two to three hours to complete.

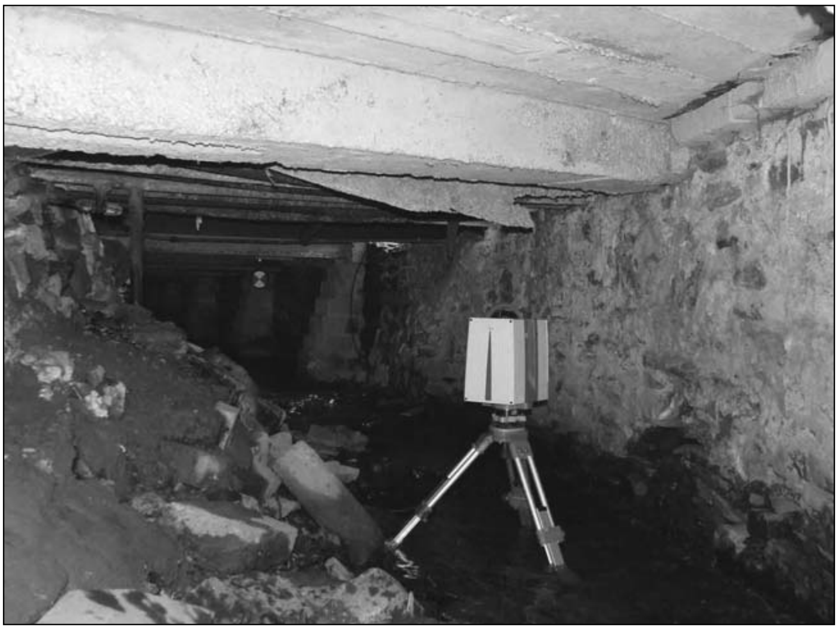


Figure A3.10 *Laser scanner setup within culvert*

Once complete, the data was processed and the data from all scans combined. Combining the data is based on identifying the location of the fixed targets through the culvert. An example of the resulting point cloud data (the points measured from the survey in a 3D format) is shown in Figure A3.11, also showing two fixed targets used in geo-referencing the data.

Figure A3.11 *Output from point cloud of laser scanning survey*

Once the data has been processed, software can be used to extract cross-sections from the point cloud at any specified location, and through any plane or orientation. The resulting cross-sections can then be brought into a CAD package for final processing and presentation.

In addition to the standard CAD drawings, the surveyors were also able to provide more deliverables derived from the scan data. Firstly the point cloud was used to generate animated "fly-throughs" of the culvert, providing a dramatic visualisation of the culvert. Secondly, the scan data was provided in TruView format, supported by Leica free TruView panoramic point cloud viewer. This allows software users to view, zoom in, or pan over point clouds naturally and intuitively. Also, users can extract real 3D co-ordinates and accurately measure distances.

On completion of the survey the hydraulic modeller had not only the cross-sections that they would normally have, but also an ability to undertake a virtual tour inside the culvert, gaining a detailed appreciation of its complex geometry, materials and roughness characteristics without the need to enter the culvert.

The client is now investigating plans to open up the culvert into open channel. Further culvert design details can be extracted from the existing point cloud without the need to re-survey.

Advantages in using terrestrial laser scanning have been:

- speed of survey leading to reduced time in the culvert
- highly detailed and accurate survey data
- greatly improved presentational options
- point cloud data can be revisited and reused for other applications.

Case study A3.5

Mammal crossing mitigation and enhancement: application of mammal ledges to culverts and Installation of "dry culverts"

By Dorian Latham and Mark Knowles, Environment Team, A-one Integrated Highway Services (A-one Integrated Highway Services is a 50/50 joint venture partnership formed by Halcrow and Colas appointed by the Highways Agency as managing agent contractor (MAC) for the Area 14 network)

Client: Highways Agency

Principal contractor: Colas as part of A-one Integrated Highway Services

Location: Area 14 Network (the Area 14 network is located in the north-east of England and comprises 300 km of motorways and trunk roads in North Yorkshire, Durham and Northumberland)

Introduction

The population of otters in Northumberland has only recently recovered (O'Hara, 2005) after suffering a significant decline that was reflected throughout England (Strachan and Jefferies, 1996). The Highways Agency has a target to provide 250 otter protection measures nationally (road underpasses, tunnels or ledges) to reduce deaths of mammals via "road kill". Otter and other mammal deaths have been attributed to surcharging of culverts during peak rainfall events, resulting in them being forced to navigate the crossing of busy carriageways. This case study describes the works carried out in Area 14 as part of the Highways Agency biodiversity action plan (HABAP) and describes the aims to reduce road kills by providing a safe crossing point for otters and other mammals.

The problem

The HABAP states that at least 100 otters (Lutra lutra) are killed on roads in England and Wales each year. Within Area 14, which covers parts of North Yorkshire, County Durham and Northumberland, the Highways Agency data shows 36 otter road kills were recorded on the A1 (a major truck road) between 2002 and 2006.

The majority of otter road deaths occur between November to December and March to April. These correspond with periods of high rainfall when river water levels are high. It is believed that the increase in road deaths is as a consequence of animals being required to cross the carriageway when the culverts are impassable.

Proposed solution

One solution to the problem is the installation of a "dry" culvert, constructed to compliment the culverted watercourse and provide safe passage at periods of high flow. An alternative is to provide an otter ledge through a larger box culvert or bridge structure that will maintain dry passage above the flood water. Both provide safe passage without forcing the otter or other medium-sized mammal onto the road.

Data collection

As managing agent contractor in Area 14, A-one has a requirement to record and monitor road kills on the network. This road kill information was used to identify "hot-spots" on the network. Also, A-one has surveyed over 250 water crossing points (ie where the road crosses over a watercourse, or underpass) to determine if they act as a wildlife crossing, particularly for species including otter, badger and other mammals. This information has been supplemented by field based species surveys on the various watercourses crossed by the road network for otter and water vole and desk studies.

Studies have shown that badgers (Meles meles) are fairly adaptable and will use man-made structures including culverts, to pass under roads. If correctly sited on or near to an existing badger path, such underpasses will maintain connectivity of home ranges (TSO, 2007). If otters cannot pass through culverts due to high water levels and rapid flow, they may be forced onto roads and so risk being killed by traffic.

Analysis and design considerations

TSO (2007) states that a 600 mm diameter culvert is satisfactory to provide an underpass for mammals for lengths of up to about 20 m. In this case study the length of the culverts range from 22 m to 40 m, depending on the road type. The A1 is a dual carriageway over Back Burn at Felton, single carriageway over Belford Burn and single carriageway (with an overtaking lane) over Common Burn at Berwick. Back Burn and Belford Burn culverts are 600 mm in diameter (about 30 m and 40 m long), while that at Common Burn is 900 mm (about 30 m).

The need for the dry culverts was identified in part due to the capacity of the culvert on the watercourse during higher flow events. Cylindrical culverts on small watercourses can fill rapidly, reducing the air space available and making swimming more difficult. Channelling of water through the pipe during high flows increases the risk that otters could be drowned. The dry culverts are positioned so that they will not flood, providing safe access up and downstream even during high water levels. Otters can be guided to the passage by means of a channel or fence running from the river-bank to the dry culvert entrance.

Having concluded that the existing crossings were not performing as wildlife crossing points, the next decision was to determine if the structure would be suitable to receive a retro-fit mammal ledge. For a ledge to be considered the culvert should ideally be of sound construction and square walled. It was decided that there should be a minimum of 600 mm headroom and a minimum of 150 mm clearance from the maximum observable water level. Ledges were designed to carry 200 kg static loading. The loading is high, because the construction design manager highlighted that the ledges could attract youths so a loading sufficient to support an adult male was recommended.

Consideration was also given to the likelihood of vandalism attack. To date ledges have only been installed in remote rural areas away from major conurbations. If these considerations had not favoured a ledge option, the design process would have led to consideration of the installation of a dry culvert.

Implementation

Five dry culverts and two mammal ledges were constructed over five years by the Highways Agency through the MAC Area 14 contractor A-one.

Otter ledges

The otter ledges are between 20 and 30m in length and 350 to 450 mm wide. The desired headroom is 600 mm and the ledges are positioned at least 150 mm above the maximum recorded flood water level. Hydraulic capacity for all but an extreme event (ie 1 in 1000 year event) was not considered to be a constraint.

The ledges are attached to the culvert side walls by positioning brackets, fixed with epoxy resin anchor bolts and then fixing tactile "Durbar" galvanised steel plates to these brackets to form the walkways. The ledges connect to dry banks outside the culvert to allow easy mammal access onto the ledge and encourage use.

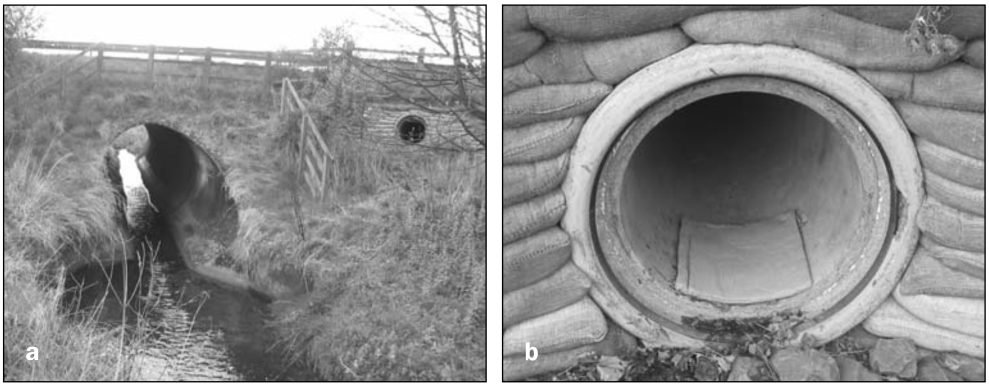
Figure A3.12 *Otter Ledge on Hartley Burn with fencing at Big Water (a) and Little Waters, Gateshead-Newcastle Western Bypass, A1 (b) (courtesy Dorian Latham)*

Dry culverts

Three dry culvert sites have been selected for this case study on the A1 in Northumberland. The three selected sites are located on Back Burn, Belford Burn and Common Burn, all of which are crossed by the A1 north of Newcastle. The dry culvert at Belford (Belford Burn) was installed in 2003, but not fenced until 2005. The underpasses at Felton on Back Burn and at Berwick on Common Burn were constructed in 2006, and these culverts were fenced at the time of installation. The distance between the three sites (Felton in the south and Berwick-on-Tweed to the north) is about 46 km. Otters have been recorded at all seven locations.

The dry culverts are extra structures that are installed outside the height of the highest recorded flow on the watercourse and with reference to the Environment Agency's flood zone maps. As the culverts are separate structures they should have no effect on the hydrology of the existing culverts on the watercourses for this scale of event.

The culverts were constructed from standard concrete pipes, where possible 900 mm diameter sections were used. It should be noted that if the crossing length had been less than 20 m a 600 mm pipe could be used. The pipes were positioned within 30 m of existing watercourse crossings, and at an elevation that allows them to provide a dry crossing point in flood conditions.



Note the clay pad at the entrance for monitoring mammal movement.

Figure A3.13 *Dry mammal culvert with fencing on Belford Burn, Northumberland A1 (courtesy Dorian Latham)*

Culverts were installed above maximum observable water level, with the pipes laid at a slight fall to allow for drainage. The culverts were installed as close to the existing watercourse as possible to encourage otters to locate it. The culverts were constructed using a trench cut system, where possible using traffic management that was already in place for road reconstruction.

Badger specification plastic coated galvanised mesh fences were used as part of the mitigation measures, with careful attention to ensuring that weak points such as access gates were made "badger-proof" using hardened surfacing at these points to prevent digging.

Monitoring

The use of the installed dry culvert structures has been monitored through the application of the novel methodology of a clay drain seal placed at the entrance to record the paw prints of mammals (Baker, Knowles and Latham, 2007). This method provides a simple and cost effective means of monitoring. Drain seals are commonly used in pollution control to close drains in the event of a pollution incident. The seals are available from several suppliers.

The clay pads provide a means of recording the paw prints of mammals entering or exiting the culvert. Pads have been placed at culverts selected for this case study and have been checked on a regular basis since September 2007. At each visit any evidence of animal tracks was recorded, the pad was photographed, and then thoroughly wetted and smoothed to remove any tracks and leave a clean surface to record any tracks made later. This trial has shown the "clay pads" as an effective method of recording mammal tracks, valuable information has been obtained that can help to inform future culvert design and mitigation schemes.

Figure A3.14 ***Detail of clay pad at culvert entrance (courtesy Dorian Latham)***

The pads have recorded evidence of badger, water vole, brown rat, hedgehog and mink using the culverts. Spraints (otter dropping) have also been recorded on the ledge. Badger prints were recorded frequently on the pads showing "upstream" and "downstream" movements, this concurring with the general conclusion of previous studies that badgers are reasonably accepting of many underpass types. The dry culverts were also used by other mammals demonstrating that these structures provide an opportunity for passage by mammals that could otherwise be restricted by even low river flows.

Figure A3.15 *Badger prints on clay pad (courtesy Dorian Latham)*

Figure A3.16 *Badger caught on camera (courtesy Dorian Latham)*

Conclusions and learning outcomes

No otters were recorded as road kill during the study period at Back Burn, Belford Burn or Common Burn. Otters have been recorded using the ledge at Big Waters on the Gateshead – Newcastle Western Bypass.

It is important that the ledges and dry culverts are installed with otter/badger fencing to the appropriate specification as described in TSO (2007). Also, when installing these structures they should be located on the banks that the mammals already favour. This can be identified through fieldwork and recorded field markings (footprints, feeding signs, location of entry/exit points from the river etc). It could be beneficial to discourage use of the opposite banks by suitable planting (observing Environment Agency planting offset guidelines).

Case study A3.6

Investigation and refurbishment of canal culvert

By Chris Reynard, British Waterways

Client: British Waterways, Wales and Border Counties

Contractor: On-Site Ltd

Manufacturer: Brandenburger GmBH

Location: Monmouthshire & Brecon Canal, South Wales

Introduction

The Monmouthshire & Brecon Canal suffered a major breach due to embankment failure on 16 October 2007. A risk assessment identified a 16 mile length with a high residual risk of breach. This length was de-watered to allow a safety review of all 31 culverts with the objective of reducing the risk of future breaches. This case study describes the cleaning, inspection and refurbishment of a 23 m long twin-barrelled random rubble masonry culvert with nominal diameters of 890 mm.

The problem

The Monmouthshire & Brecon Canal is a contour canal built on steep hillsides above the valley floor, with many culverts beneath the canal carrying watercourses or outflow from bed valves and penstocks, some of which are disused or lost. Flow through the culvert can increase rapidly and the culverts are susceptible to sedimentation and debris accumulation. Water issuing from the embankment or hillside below the canal can be caused by seasonal springs, canal leakage, or disused culverts or canal de-watering sluices, the cause often being difficult to identify.

Most of the culverts are circular, constructed from random rubble or radial thin slab (a single compressive ring of coursed rubble masonry, as shown in Figure A3.18) with open unmortared joints, and have the potential to deteriorate rapidly, causing breaches. Principal causes of breach are:

- blockages causing internal flow constriction and masonry erosion, leading to collapse or blow through the canal bed
- shallow cover beneath the canal bed and on the offside (opposite the towpath side), leading to leakage and eventual collapse or blow through the canal bed
- collapse of the culvert barrel leading to loss of extrados material and eventual blow through the canal bed
- surcharge pressures in the culvert due to downstream alterations by others such as culverting with undersized pipes leading to blow through the bed or embankment.

Although culvert inspections are carried out on a 10 to 20 year cycle under the British Waterways asset management procedure, inspections on the Monmouthshire & Brecon Canal have only been partially completed in the past due to consolidated sediment and the risk of breach during high pressure jetting. To overcome this, a 16 mile length of canal was de-watered to allow a safety review of all culverts without the risk of breach. Several culverts were scheduled for refurbishment, with works varying from local repairs, re-lining, headwall reconstruction and approach channel repairs, to decommissioning of redundant culverts. Culvert 36 was identified for refurbishment.

Cleaning and inspection

Preliminary works included a bat survey, vegetation clearance and the removal of debris from the culvert approaches. Rubber-tracked excavators and tracked dumpers were used to minimise land disturbance. Each culvert barrel was de-watered in turn with watercourse diversions through the other barrel. Biodegradable sediment control matting was placed in the downstream watercourse to trap disturbed sediment and prevent pollution. On completion, these mats can be fixed to the bank to provide instant bank stabilisation and a rich seedbed for vegetation.

Figure A3.17 *Outlet end before initial clearance showing largely collapsed headwall and large tree and debris blockage (courtesy British Waterways)*

Figure A3.18 *Outlet headwall after initial clearance (courtesy British Waterways)*

High pressure water jetting was used to clean the culvert following an initial closed-circuit television (CCTV) survey to assess the work required and identify any potential defective areas. As the canal channel was de-watered, there was no risk of breach during cleaning operations. A tractor was used with an off-road trailer and vactor unit, with a maximum flow rate of six litres per second and a maximum working pressure of 204 bar. Gravels, sand and silt were removed from site by the tractor vactor or decanted into other equipment. The clean culvert was then surveyed using a remote-controlled pan, tilt and zoom CCTV camera with lighting mounted on a small traction unit.

Figure A3.19 *Unit used for cleaning and removal of waste (courtesy British Waterways)*

Condition assessment

The culvert was in poor condition. The culvert barrels were reasonably intact but had suffered some distortion, with areas of open joints, and displaced and missing masonry blocks that exposed the ground beyond the extrados. There was significant inflow of water from the canal channel above and the culvert was partially blocked with deposited sand, gravels and cobbles. The headwalls were partially collapsed with a mature tree growing immediately above the outlet. The approach channels exhibited both scour and partial blockage.

Option identification and appraisal

Design constraints included access, barrel size and hydraulic performance requirements. The site was remote and access was limited to light plant and all-terrain vehicles, without incurring the cost of a temporary access road. Access to the inlet headwall on the canal offside was also difficult, whereas the outlet on the towpath side was easier. Man-entry work was precluded by the 890 mm barrel diameters.

Two options were identified: replacement and re-lining. Replacement was rejected due to access constraints, temporary works requirements and extensive excavation required to cut through the puddle clay canal lining, install new pipes and restore the lining with imported puddle clay.

Re-lining was preferred, being more cost-effective and less disruptive, but it was important to match the lining system to the condition of the culvert and site constraints. A semi-structural lining was required due to the distortion in the culvert profile and missing masonry units, with fill to the annulus between the lining and culvert intrados to ensure structural effectiveness and prevent seepage. Maintenance of hydraulic capacity dictated minimal loss of diameter and a low-friction lining. Finally, the lining needed to be installed from the outlet.

Preferred option

A cured-in-place lining was selected to provide a thin-walled (10 mm) structural lining with minimal loss of section. The glass-reinforced plastic lining was formed by winding resin and glass fibre around a mandrel slightly smaller than the existing barrel then delivered to site uncured in a light-proof bag. The soft lining was pulled through the culvert, inflated with compressed air and then cured by a small ultraviolet light train. The inflation and curing process was monitored by a CCTV camera on the light train and took 20 to 30 minutes. Grout pipes attached to the liner during installation allowed injection of a non-shrink cementitious grout into the annulus. The headwalls were also rebuilt in the vernacular style.

Figure A3.20 *Outlet headwall following refurbishment (courtesy British Waterways)*

Conclusions

A canal breach highlighted the need for a safety review of culverts on a contour canal that had been inspected infrequently due to sedimentation and the risk of breach while the canal was in water. A comprehensive safety review of all culverts and refurbishment of several culverts was carried out while a length of canal was de-watered. A cast-in-place lining suitable for non-man-entry culverts with poor access was selected. The smooth semi-structural lining should reduce the tendency for debris to accumulate and allow the repaired culvert to be cleaned using high pressure jetting equipment without risk to the canal.

Case study A3.7

Culvert rehabilitation – *in situ* Ferrocement structural lining

By Rob Whale, Ferro Monk Systems Ltd

Client: Swansea Housing Association

Consultant engineers: Clarke Bond

Principal contractor: Hale Construction Ltd

Subcontractor: Ferro Monk Systems Ltd

Location: Burlais Brook, Cwmfelin, Swansea

Introduction

Ferro Monk's patented Ferrocement structural lining solution was used to carry out rehabilitation work to strengthen a culvert running beneath a new housing development, in Cwmfelin, Swansea in south Wales. This was the second time the company had been asked to do work on rehabilitating a section of the Burlais Brook culvert. The company was originally contracted by consultant engineers, Clarke Bond, during Phase One of the same development. The initial works, undertaken by Ferro Monk during Phase One of the development, involved rehabilitation using *in situ* Ferrocement structural lining. This technique was again used for Phase Two of the development when further strengthening was required to allow for increased loading.

Background

The culvert runs under land reclaimed from the site of an old tin plate works.

Burlais Brook culvert is a brick arch, masonry wall and cobbled invert construction, ranging in section from 1450 mm high × 1800 mm wide to 2200 mm high × 1800 mm wide. The culvert runs directly beneath a brownfield site, with Phase Two being 261 m in length and ranges in depth from 6.0 m to 11.0 m.

Figure A3.21 ***Man-entry inspection, showing initial condition of the culvert and person bent forward walking away from the camera (courtesy Ferro Monk)***

Design considerations

The culvert was required to be strengthened to allow for an increased depth of infill material over most of its length and also to safely carry full highway loading for the new main access road serving the 100+ housing development.

Before the proposed infrastructure and building works, the culvert needed to be strengthened, to withstand the increased loading. Clarke Bond contacted Ferro Monk again to discuss possible solutions to cope with the proposed increased loading on the culvert for Phase Two.

In addition to increased loading, further design considerations were also required due to the depth and condition of the culvert. However, with the flexibility of the Ferrocement system, all this was easily accommodated.

As in Phase One, it was decided to manufacture and install a twin pre-cast invert system, due to the width of the culvert, heavy flows, and restricted access. This made manual handling in the confines of the culvert much easier, and fluming the existing flows from one side to the other during construction also possible.

Monitoring the sheer volume of designs involved on a project like this was a big challenge and meant it was important to ensure everyone involved on the project knew exactly what reinforcement went in any given location. Taking into consideration all the existing physical conditions and incorporating them into the design, the Ferrocement solution had to take into account five different cross-sections and six different depths and ground loadings, resulting in a complex array of reinforcement installation configurations. The final design involved the installation of five different reinforcement build-ups over five sections, each with a different finished lining thickness, within the 261 m length of culvert.

Rehabilitation works

Two new large diameter side entry manholes were built alongside the existing culvert to ensure safe and convenient access for Ferro Monk. Lining work then progressed using *in situ* Ferrocement structural lining. *In situ* sprayed Ferrocement incorporating pre-cast inverts is a Water Research Centre (WRc) approved Type 1 lining system, fully compliant with water industry specifications.

Figure A3.22 ***Installation of reinforcement ready for spraying of structural lining (courtesy Ferro Monk)***

Ferrocement linings are ideal for the repair and rehabilitation of sewers, tunnels and culverts suitable for man-entry. They consist of a thin shell of reinforced concrete that provides a high cement content, low water/cement ratio – a high density product with superior mechanical properties particularly suitable for meandering structures.

Figure A3.23 ***Completed structural lining of culvert (courtesy Ferro Monk)***

Case study A3.8

Repair/remediation – timber heading and GRP re-lining of culvert

By Gwynne Rees, Insituform Technologies Ltd

Client: Network Rail

Principal contractor: Edmund Nuttall

Subcontractor: Insituform Technologies Ltd

Location: Grayswood, Surrey

Introduction

The project undertaken was the refurbishment of a partially collapsed brick culvert beneath a large railway embankment using specialist trenchless technology techniques.

Background

The culvert carries a substantial watercourse through a heavily wooded area and under a large railway embankment.

The structure is a 1200 × 750 mm horseshoe shaped brick culvert, 167 m long.

From the entrance, the culvert dives down at a steep gradient before levelling out and continuing on towards its outfall.

Figure A3.24
Entrance to the culvert, showing large angled brick wingwalls and brick headwall. A pump was used to enable works to be carried out

Figure A3.25
Inside the culvert, showing a peculiar drainage inflow

Desk study and investigations

Over many years, the natural action of water at the base of the slope caused considerable erosion to the brick invert of the culvert. This caused the sides and crown of the structure to fail, causing a partial collapse. It is at this point that structural failure occurred.

Figure A3.26
Inside the barrel of the culvert showing erosion to brick work and lateral movement of the RHS wall

Figure A3.27
View showing lateral movement of sidewalls and partial collapse of roof element

Investigation results and conclusions

It was identified that a substantial amount of work would be required to refurbish and maintain the structural integrity of the culvert. Due to the location of the affected section of culvert and the depth from ground level being some 11 m at that point, any refurbishment works would be difficult to undertake.

The solution decided upon was to remove the damaged section of culvert and replace it with a GRP lining with structural grouting. The GRP pipe in comparison to the existing brick culvert would give excellent flow characteristics, dramatically reduced friction at the levelling out point and a substantial increase in structural strength (due to the introduction of a combination of GRP and grout)

Design development and enabling works

It was decided that the technique to be used for this project would be a traditional timber heading. The heading would be excavated and constructed from within the existing culvert. This would eliminate the need for extensive excavations from ground level.

The heading would start and finish at a point where the culvert is at its original shape.

Work would progress by removing the damaged section of culvert and replacing it with structurally designed timber frames, suitable for withstanding the surrounding ground pressure.

Figure A3.28
Installation of new timber framed heading

Figure A3.29
Installation of new timber-framed heading

Figure A3.30 *View showing completed timber-framed heading*

Re-lining of the culvert

Once the timber heading was complete, GRP pipes were then inserted. These form a continuous pipeline through the timber heading.

Once in position and sealed the annulus around the GRP pipeline and the space behind the timber heading were grouted, forming a complete structural pipeline joining the two existing sections of brick culvert.

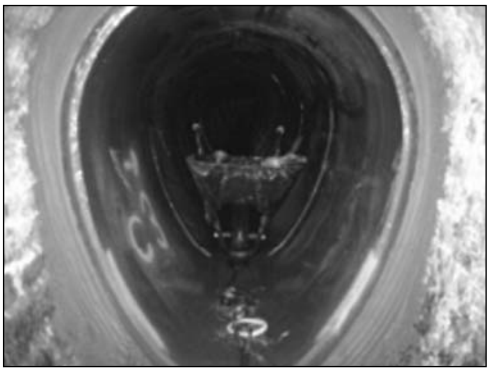


Figure A3.31
Installation of GRP pipe and grouting between annulus around GRP pipeline and behind timber heading

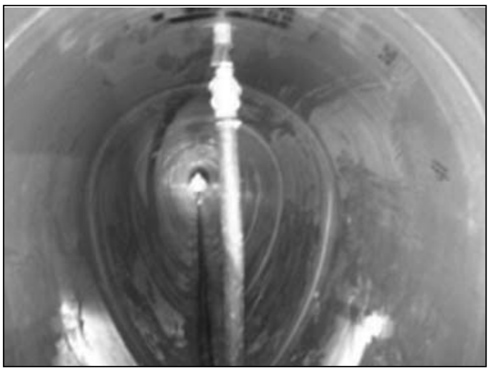


Figure A3.32
View showing completed re-lined culvert

Case study A3.9

Denham culvert, Grand Union Canal

By Chris Reynard and Antonia Zotali, British Waterways

Owner: British Waterways

Location: Grand Union Canal, Denham Country Park, Buckinghamshire

Background

Denham Culvert is a 200 year old five barrel, brick constructed structure located to the east of the village of Denham and is situated immediately upstream of Denham Deep Lock on the Grand Union Canal. The culvert structure allows the River Frays to pass beneath the canal.

The headwalls are concave in shape resulting in the length of the barrels varying between 16.3 m to 18.3 m in length. The barrels are typically 1.8 m wide × 1.4 m high at the outlet end with arch shaped crown on vertical side walls and originally a flat timber invert consisting of longitudinal boards on transverse beams. The culverts are located within Denham Country Park with site of special scientific interest (SSSI) designation.

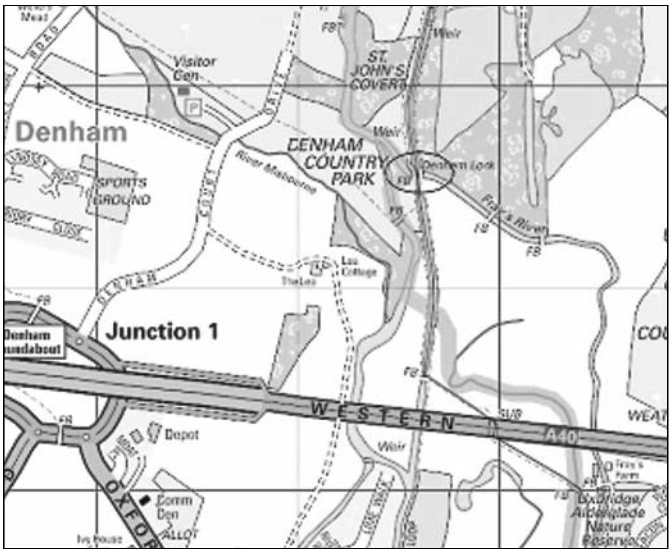


Figure A3.33 *Location of the Denham culvert*

The problem

Denham culvert was identified as being in poor condition from a principal inspection (PI). The main problems identified were thought to have been caused by scour at the inlet and included:

- settlement and bulging of the headwalls
- open radial cracks throughout the culverts, combined with water ingress and root penetration into the culvert
- one of the barrels was missing an 8 m long section of its timber invert from the upstream headwall combined with significant settlement

- siltation of the culverts, which had resulted in increased water depth and occasional flooding of a nearby British Waterways (BW) waterside property during rainy seasons.

Further deterioration of the Denham Culvert could have led to the collapse of the culvert resulting in a breach of the Grand Union Canal. This would have caused flooding of near properties and part of the site of specific scientific interest (SSSI) causing adverse environmental impact.

Without regular cleaning and de-silting, the culvert could become blocked resulting in flooding of the River Frays with similar consequences as above.

As a result remedial works were deemed necessary to prevent a possible breach, loss of the canal pound, and flooding.

Scope of works

The initial scope of works consisted of:

1. Establishment of temporary access.
2. Installation of fabric dam and dewatering of the canal above the culvert to reduce the loading on the culverts and risk of failure.
3. Temporarily raising an existing weir north of the culverts to lower water levels.
4. Dewatering each culvert and managing water levels around the work site.
5. Removal of a large willow tree near to the culvert that had caused cracking with root penetration in one of the barrels.
6. Removal of the deposited material from the culvert barrels.
7. BW to undertake full man-entry PI inspection in a confined space.

The following extra works were scoped following the principal inspection:

1. Underpinning with *in situ* concrete to all sidewalls.
2. Re-pointing to radial cracks and grouting to voids where required.
3. Removal of the existing timber invert and replacement with new *in situ* concrete slab.
4. Installation of upstream cut-off pile wall and *in situ* concrete apron slab.
5. Re-pointing to the headwall structures.
6. Localised improvements to the towpath and ancillary waterway furniture.
7. Soft bank protection installation to the downstream north-west bank.

Approvals

The site is located within a conservation area and is a site of both environmental and historic importance. The local authority had been kept informed with the proposed repair details to ensure they would be sympathetic to the local environment. Consent was also required for any tree works.

Before the works were carried out, land drainage consent (LDC) both for the temporary and permanent works had to be obtained from the Environment Agency (EA) and assent from Natural England (NE) as the site was near to the SSSI and in a protected area.

Access to the culvert was achieved by a temporary access road (bog mats and geotextile) from the neighbouring Buckinghamshire golf course. The route of the temporary road was through an existing wooded area, over an existing timber bridge and out onto the flood plain near to the culverts. Access across the footbridge was limited to five tonnes. Larger plant was able to cross the river with permission from the Environment Agency.

There were several shade and lime dependent ferns growing on the brick faces of the culvert, namely wall rue and harts tongue fern and these were preserved. Woody vegetation and grasses were removed.

Site restrictions

As part of the Environment Agency LDC conditions it was only permissible to reduce the River Frays normal flow by a maximum of 40 per cent. This volume of water would be diverted to a nearby river. In the event of an emergency or instruction from the Environment Agency, the sandbag dam would be removed.

Dredging the river bed had to be restricted within the culverts and up to five metres either side of the culvert. The dredging could only go as deep as the original bed of the river which is made up of gravel. No gravels could be removed. This process could not involve any machinery, all of the material had to be dug out by hand to minimise the risk of compressing the river gravels.

Only two culverts could be dewatered at one time, which dictated shifting the cofferdam three times during the works.

The design

Design principle

The purpose of the project was to repair the culvert to a condition grade C (fair) or better and for the structure to be removed from BW arrears list. The condition prior to the works was D (poor).

The agreed approach taken was for the site works to primarily facilitate a full and complete Principal Inspection (PI) of the structure. As defects were identified BW prioritised the permanent repair works based on the inspection results. The primary design principles were to:

1. Underpin the diaphragm walls where the footing had been scoured or undermined.
2. Install an apron slab and cut-off structure to the upstream of the culvert to prevent further scour/deterioration of foundation.
3. Replace the existing timber invert in the barrels where it was found to be absent or severely degraded with a new concrete slab.
4. Re-point, grout and strap radial cracks to prevent further movement and potential water ingress from the canal.
5. Re-point existing headwall structure to prevent further deterioration.
6. Remove all silt from culvert invert to assist the PI but also to substantially improve the flow characteristics and minimise the flooding events to local buildings.
7. Provide future means of dewatering each culvert to reduce the cost of mobilising to site, stop log structure to be used as necessary for general maintenance and future PI inspections.

Construction

Site establishment and temporary access to culvert

Access to the culvert was established via Buckinghamshire golf course. Access was achieved from an existing surface access path and temporary timber bog mats that were selected due to easy installation and removal. Separate pedestrian access routes were established primarily using the canal towpath.

Diversion of flows from culverts (River Frays)

To reduce flows along the River Frays temporary one tonne sand bags were placed on the upstream horseshoe weir. In the event of storm or flood conditions the temporary weir structure would be breached to ensure all flood water could pass through the works.

Dewatering of culverts

Steel sheet piles were installed at the upstream end of the culverts and the downstream end of the culverts were isolated from the river with a temporary sand bag structure. The culverts were then dewatered using pumps during working hours only.

The initial dewatering of the culverts was considered to be a high risk activity due to the unknown condition of the culvert barrels. A risk assessment was carried out before entry was made into any of the dewatered culverts and this dictated the necessity to dewater the canal above the culverts. Temporary dams were installed in the canal and the canal was dewatered locally to minimise the risk of collapse and inundation.

Construction of underpinning/apron/invert repairs

The existing silt/bed gravels overlying the culvert inverts were removed by hand. The material was transferred to the upstream end of the culvert where an excavator transferred the material by skip to the river-bank.

On removal of the material an inspection was undertaken by BW, to confirm the extent of underpinning works to the diaphragm walls and invert replacement. Underpinning to the diaphragm walls was undertaken first so that the rest of the structure could be safely worked on. The existing timber invert and formation material was also removed by hand. A rail and bogey system was established to enable the excavated material to be moved to the upstream end of the culvert. This material was again removed to the nearby bank as a backfill for the protection works.

On completion of the concrete works to the invert and walls the sheet piles cut-off and apron structure was constructed.

To help with future dewatering, a set of 12 steel pockets constructed of SHS 200 × 200 mm (external), 5 mm thick and 350 mm long have been installed within the concrete apron slab. The intention is that these steel box sockets can be used to house I beams to act as king posts in a temporary works arrangement.

Conclusion

The condition of the culvert is now assessed as reasonable (condition grade C). The underpinning repairs to the inlet headwall should prevent further movement although monitoring using the established levelling base along the top of the inlet headwall will continue to check this assumption.

The concrete repair to the invert within the barrels will prevent further scour.

The pointing repairs to the circumferential cracks are largely cosmetic and some dripping water infiltration was noted following the water being put back into the canal. However as the cause of the movement has been addressed (ie scour prevention) and the structure underpinned at the inlet end, the cracks should not deteriorate further.

Case study A3.10

River Pinn diversion to remove river from culvert (daylighting)

By A T Pepper, director, ATPEC Ltd

Client: London Borough of Harrow

Principal contractor: AccordMP

Subcontractor: Pumpwise Dredging

Location: Harrow Arts Centre, Harrow

Summary

A culvert was found to be inadequate for flood flows, and the chosen solution was to divert the river in open channel on a new route. This provided a reduction in flood risk as well as significant improvements to habitat.

Background

The culvert was a circular brick culvert, about 1 m in diameter and 170 m long, with several bends. Downstream of this culvert were many culverted crossings and sections of concrete lined channel.

Although the culvert was in an urban area most of the upstream catchment is rural land use on London Clay. The culvert and the downstream channel were on land owned by the London Borough of Harrow, as was a nearby playing field.

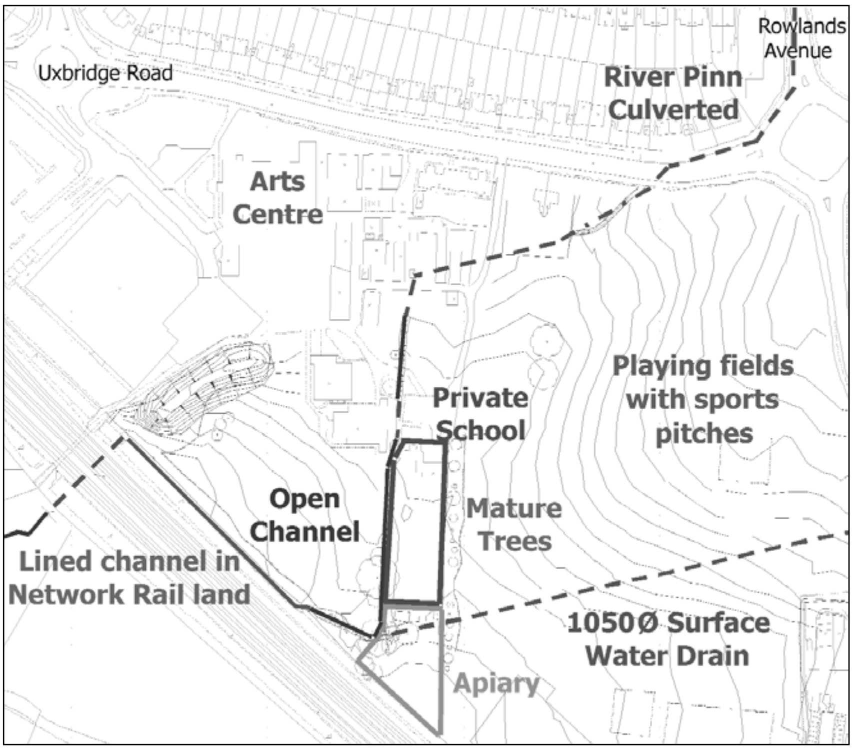


Figure A3.34 *Site location and features (courtesy Andy Pepper)*

Design

A scheme was drawn up to divert the River Pinn in open channel along the edge of the playing fields. This would necessitate rearranging some of the pitches on the playing field, and taking them out of use for at least one season. The length of open channel was about 650 m, and this bypassed not only the culvert, but also the lengths of lined channel.

Site investigation showed that the soils were largely clay, with bands of gravel, but no contamination. The surplus spoil from the excavation of the new channel was to be used to level sloping and uneven areas of the playing field.

A fluvial geomorphologist was employed to advise the designers so that a natural river channel could be replicated from the outset, as it was recognised that the clay banks and bed would not readily be eroded.

No aquatic or marginal planting was proposed, as it was felt that the upstream catchment would naturally provide native plant stock.

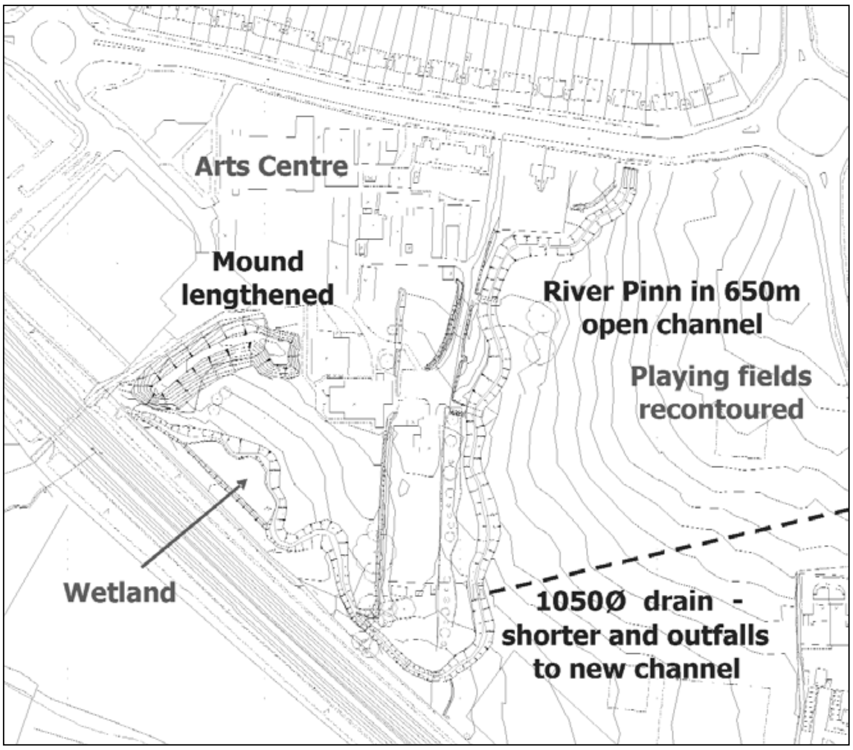


Figure A3.35 *Overall scheme as-constructed (courtesy Andy Pepper)*

Implementation and learning outcomes

Construction was carried out in August to October 2006, and has required no further maintenance. In places the gravels present have been moved by high flows to create riffles, but no major changes in planform have taken place and none are anticipated.

The playing field was stripped of topsoil, the spoil excavated from the channel was spread to form a level surface and the topsoil replaced. A specialist sports field contractor then prepared the surface and reinstated the grass.

Figure A3.36
Demolition of brick-lined culvert (courtesy Andy Pepper)

Figure A3.37
Final removal of existing culvert and preparation of new channel bed (courtesy Andy Pepper)

Figure A3.38
As-constructed re-alignment of watercourse post-daylighting (courtesy Andy Pepper)

Figure A3.39
Final scheme with vegetation growth (courtesy Andy Pepper)

Case study A3.11

Boscastle (River Jordan) flood defence scheme

By Russell Corney, principal civil engineer, Halcrow Group Ltd

Client: Environment Agency

Designers: Halcrow

Location: Boscastle, Cornwall

Background

The primary purpose of the Boscastle (River Jordan) flood defence scheme is to defend 10 residential properties, eight commercial properties including the Wellington Hotel and the only road link between the residential and commercial parts of Boscastle from fluvial flooding to a standard in excess of 1 in 100 years. A secondary objective was to provide environmental enhancements. These were to be achieved by working within the historic context and with natural processes to develop an economically viable and environmentally sustainable solution.

Factors contributing to flooding on the River Jordan

Contributing factors were gently sloping areas high in the Jordan catchment funnel, and rainfall into the steep and narrow lower valley. This results in a high energy river that has a mobile bed of coarse sediment, which it conveys through the catchment.

The catchment is relatively small and its characteristics result in the river responding very quickly to storm events. This results in "peaky" behaviour where large sediment is mobilised and then dropped again once the peak in river energy passes. Historically this has created large slates and spar stones being dropped inside the culvert and blocking it, leading to flooding and, on occasion, damage to the culvert.

The old culvert changes shape as it passes beneath the Wellington Hotel, changing from tall and thin to wide and flat. This change also encourages the deposition of sediment beneath the hotel as the river's power reduces as it enters the wider section.

Design approach

The geomorphological characteristics of the Jordan catchment contributed significantly to the evolution of the scheme design. An extended geomorphological assessment undertaken in 2003 found that the potential for bed load movement within the River Jordan catchment is high overall and is unlikely to be supply-limited. The potential for deposition of sediment in the culvert was found to be high due to fluctuations in stream power and the existing culvert's general lack of hydraulic uniformity. An accumulation of sediment within the culvert presented a potential flood risk, maintenance issue affecting culvert longevity.

The proposed scheme has been developed to maintain the natural movement of sediment through the catchment while reducing the potential for it to block the culvert. This is achieved in several ways:

- screening: a screen has been constructed 80 m upstream of the culvert inlet. A wide bar spacing of 300 mm was used so as to exclude only the largest debris that could block the culvert, allowing less coarse sediment to progress downstream. The screen does not have a gap at its base because this would allow large slate debris to pass underneath with the potential to block the culvert. The location of the screen was chosen to reduce the risk of flood damage in the event that the screen blocks in a flood.
- uniform and larger culvert cross-sectional area: this results in an increased capacity but also reduces the potential for the culvert to be blocked by sediment
- gradient increase: increasing the gradient progressively along the length of the culvert will keep sediment moving through the culvert
- tree clearance: the sycamore trees between the screen and the culvert entrance have been replaced by smaller leaved, indigenous species to reduce the risk of woody debris blocking the culvert

Figure A3.40
River Jordan debris screen as-built (courtesy Environment Agency)

Figure A3.41
River Jordan debris screen following high-flow event in June 2007. Note that debris has accumulated upstream of the screen up to the level of the cleaning platform (courtesy Environment Agency)

Figure A3.42
River Jordan debris screen following high-flow event in June 2007 (courtesy Environment Agency)

Case study A3.12
Self regulating tide gate (SRT)

By Mike Williams, technical specialist (habitat creation), flood risk mapping and data management, Environment Agency (Devon)

Client: Environment Agency

Project partners: East Devon District Council

Contractor: Stoneman Engineering

Location: Axe Estuary, Seaton, East Devon

Introduction

Previous land drainage and flood defence developments along the East Devon coast have resulted in massive loss of inter-tidal habitat. Conventional drainage outfalls are an integral part of these defences, but are a significant obstruction to fish. They prevent access to spawning and feeding areas, especially by migratory species.

Climate change and sea level rise has increased the problem. EU and UK legislation requires action to redress habitat losses. Managed realignment is one solution, but regulated tidal exchange (RTE) can create or restore habitats without increasing flood risk. This allows controlled tidal inundation of land behind defences.

Background

Self regulating tide gates (SRT) have been extensively used for RTE projects for at least 20 years and have been widely adopted overseas, particularly in the eastern US. Such gates are available in the UK but they are expensive. They have to be imported, with cost, technical support and sustainability implications, so there has been poor uptake in the UK.

The Environment Agency felt it was possible to improve on the American design and have it produced locally, with better technical support. Funding was provided through the Agency's flood risk science research programme and two years later a prototype has been installed on the Axe Estuary at Seaton in East Devon.

Design stage

The criteria for the generic design were that it:

- is fail-safe and can be applied to existing outfalls
- can operate automatically without the need for any power source
- requires a minimum of attendance and maintenance
- is applicable to a range of tidal and fluvial locations
- will help fish passage.

The new design is based around a rotary gate that is typically open at low tide and then closes at high tide to prevent water levels behind defences from rising too high. The design is a simple concept, in which rotation is caused by a float, but it is highly adjustable and adaptable to a wide range of situations.

Prototype construction, installation and monitoring

A prototype valve was installed in January 2009 at Black Hole Marsh near Seaton by the Environment Agency and East Devon District Council as part of the Axe Estuary Wetland Project. There is now a one year period of operation and testing.

The gate is fabricated from 8 mm 316 stainless steel, with the parts laser cut. At Seaton the culvert through the embankment is 900 mm diameter but the Environment Agency believe that it should be possible to use the design for sizes between 300 mm and 1200 mm diameter. The tidal range at Seaton is about 3 m and the SRT has simply replaced the original rubber flap, bolting on to existing fittings with the use of an adaptor plate.

Figure A3.43 *Installation at Seaton nearing completion, January 2009 (courtesy Environment Agency)*

The whole assembly weighs around 550 kg and includes its own gantry to help installation of the various parts. Opening rotation operates due to three floats, each providing 40 kg of buoyancy. Closing takes place with the help of two 60 kg counterweights plus an adjustable amount of water in a float.

At Seaton, the new SRT is being used to create a saline lagoon as part of East Devon District Council's Axe Estuary Wetlands Project. Here the gate uses a variant that is closed at low tide to prevent ingress of freshwater, opening at mid-tide when the salt wedge underlying the fresh has reached the gate, and then closing again to prevent high tides from causing flooding.

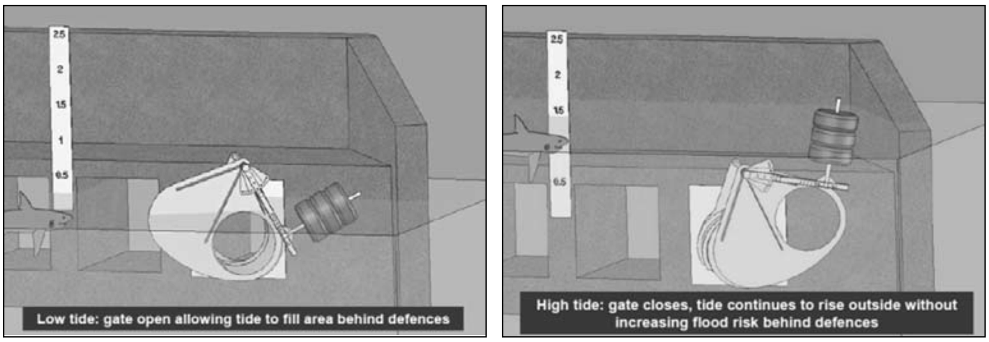


Figure A3.44 *Normal operation of the self regulating tide gate (SRT)*

Conclusions and learning outcomes

The rotary SRT was designed, fabricated and installed by Stoneman Engineering from Willand in Devon, but the Environment Agency has patented the design to keep some control over its manufacture. However, it was always planned to make it available, especially in the UK, and was designed to be produced locally by any suitably experienced engineering company. A "how to do it" guide is being produced as part of an Environment Agency R&D project.

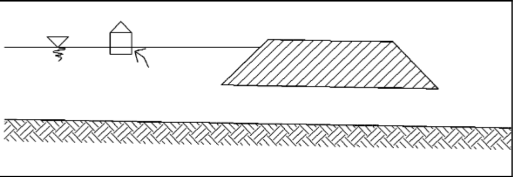
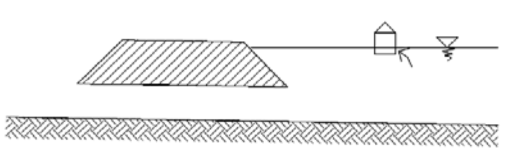
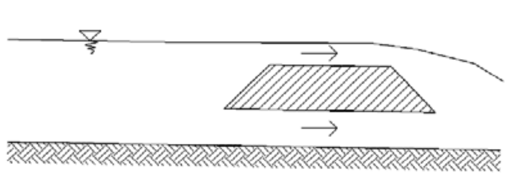
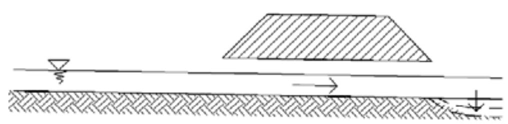
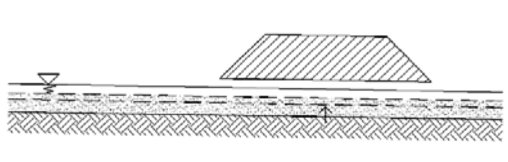
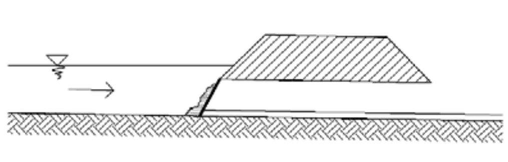
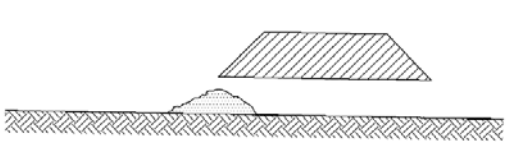
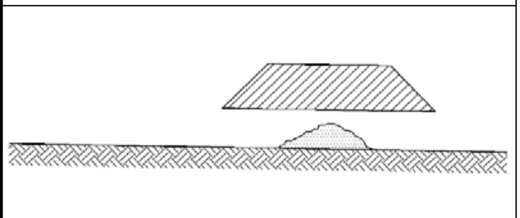
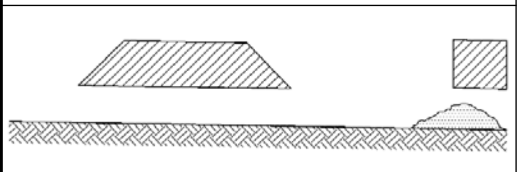
One of the advantages of the new design is that it can be incorporated into existing flood defence structures and is easily adapted to different locations. Another important advantage is that it is much easier for fish to move freely in and out through the valve. This is a major improvement on conventional valves that can injure fish or stop them gaining access to wetlands or parts of river systems.

There has been much interest in the new design, both within the Environment Agency and elsewhere. Already plans are underway to install another SRT on the Hampshire coast, where it will be used to create saltmarsh. The gate is also being considered for replacement of traditional flapped outfalls to open up parts of catchments that are currently inaccessible to fish, without increasing flood risk.

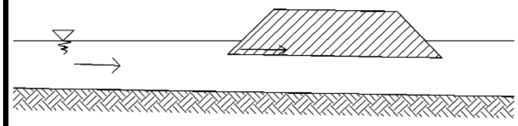
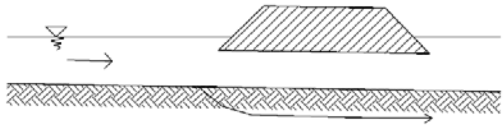
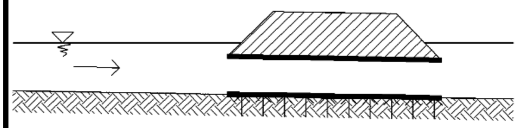
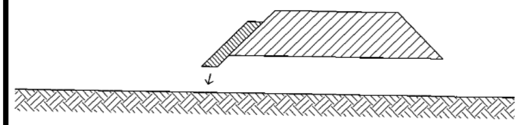
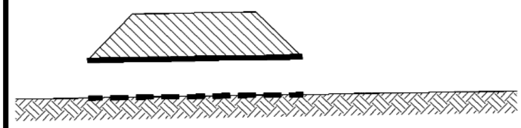
As well as estuaries and coastal sites the new device can also be adapted for use on rivers and freshwater wetlands. The Environment Agency team managing this project believe that it could soon be used in habitat creation projects across the country.

A4 Failure modes

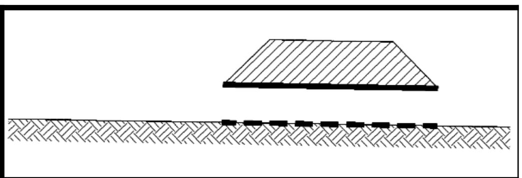
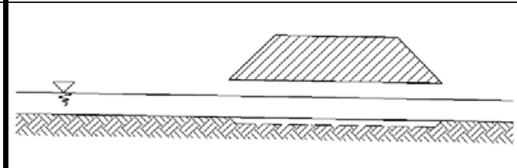
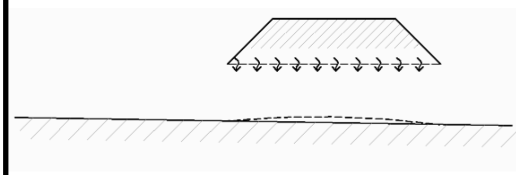
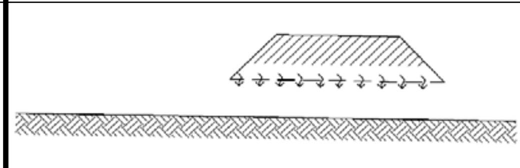
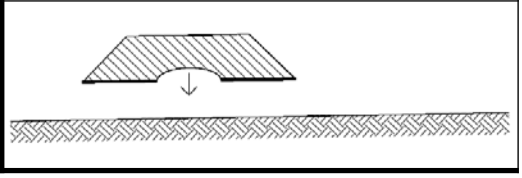
Hydraulic failure modes

1 Flooding upstream Culvert throttles the flow causing an increase in headwater level and flood storage upstream of the embankment. The peak discharge downstream of the embankment is reduced.	
2 Flooding downstream Culvert has capacity in excess of the channel, which passes the peak discharge causing an increase in downstream water level and flooding of properties downstream of the embankment.	
3 Overtopping Overtopping of embankment due to above-design standard flood, culvert blockage or tailwater conditions. There is a risk of geotechnical failure due to scour or piping if the embankment has not been designed for overtopping	
4 Local scour at culvert outlet Local scour due to culvert outlet velocity exceeding that which the bed material downstream can resist.	
5 Sedimentation of culvert barrel Sediment accumulation within the culvert barrel due to slower flow velocities. This leads to reduced cross-section, increased bed roughness and reduced discharge capacity.	
6 Blinding of screen Blinding due to the accumulation of floating debris or sediment, often during periods of high flow, leading to reduced opening area increased head loss and increased headwater level.	
7 Blockage of culvert inlet Blockage of the culvert inlet by floating debris or sediment, often during periods of high flow leading to reduced opening area, increased head loss and increased headwater level.	
8 Blockage of culvert barrel Blockage due to accumulation of floating debris or sediment in the barrel, leading to reduced opening area increased head loss and increased headwater level. The risk is increased by bends, changes in cross-section, or service crossings within the culvert.	
9 Blockage downstream of culvert Blockage downstream of the culvert, leading to increased tailwater level. The flow regime in the culvert may switch from inlet control to outlet control or overtopping.	

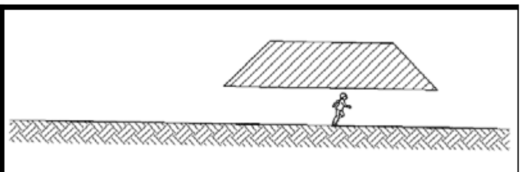
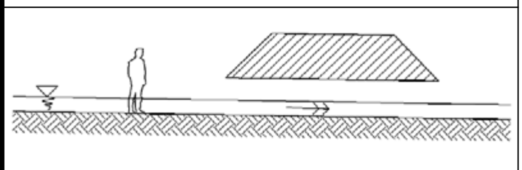
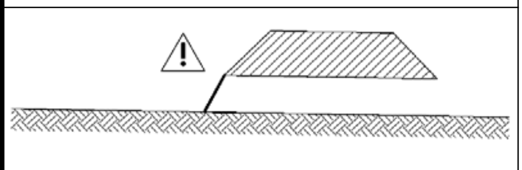
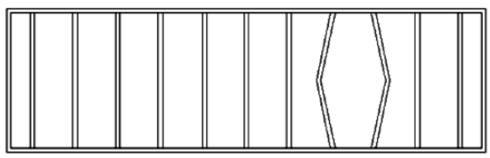
Geotechnical failure modes

10 Piping (short-term) Piping failure of embankment due to short-term seepage during submerged flow conditions. The risk of piping failure is high for permeable embankments that have not been designed as water-retaining structures. Failure can be sudden.	
11 Piping (long-term) Piping failure of embankment due to long-term seepage during normal flow conditions. Piping may occur if the culvert becomes blocked and water is forced to find an alternative route through the embankment foundation.	
12 Flotation Uplift of structure due to mobilising action of hydrostatic pressure exceeding the resisting actions of weight (and friction if applicable).	
13 Subsidence Bearing failure or differential settlement due to poor ground conditions, poor load distribution, excessive load or high groundwater.	
14 Slip failure Can often be caused by rapid drawdown of water level following an extended flood event. Embankment material slides down to block the culvert inlet or outlet. Culvert inlets and outlets below steep slopes or rock armour revetments are particularly vulnerable. The problem can be mitigated by adding an upstand to the headwall or extending the culvert.	

Structural failure modes

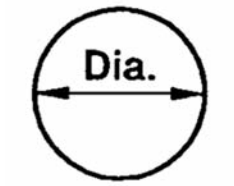
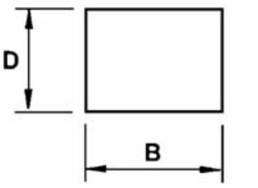
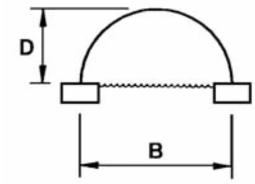
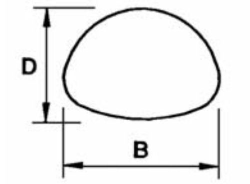
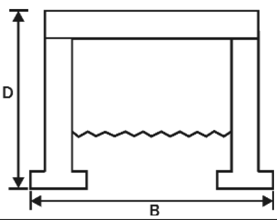
15 Corrosion of barrel Long-term corrosion of barrel due to aggressive ground or water conditions such as saltwater, sulphates, acid, chemical attack. Particularly affects steel structures.	
16 Erosion of barrel Long-term erosion of barrel due to passage of coarse sediment along the culvert invert. Affects less durable materials such as plastic, corrugated steel.	
17 Loss of mortar Loss of mortar from masonry joints due to weathering or aggressive ground conditions. Consequences can include the long-term ingress of fines, sedimentation of the culvert, subsidence of the overlying ground and structural instability.	
18 Loss of masonry units Loss of masonry units due to loss of mortar or long-term water damage or other cause, leading to incomplete arch. Consequences include structural instability.	
19 Collapse of culvert barrel Collapse of barrel due to excessive action (or load) or inadequate structural resistance, leading to culvert blockage and loss of infrastructure.	

Health and safety failure modes

20 Deep or fast water Deep or fast water leading to risk of loss of footing during inspection or maintenance.	
21 Unauthorised entry Unauthorised entry by children or culvert-walkers with risk of hazard due to confined space conditions, slips, trips and falls.	
22 Poorly designed screen Poorly designed screen creating hazards for screen operatives, for example, due to manual handling of debris, slips, trips and falls	
23 Vandalism of screen Vandalism of trash or security screen leading to impaired performance.	

A5 Culvert barrel options and typical inlet arrangements

A5.1 Culvert barrel options

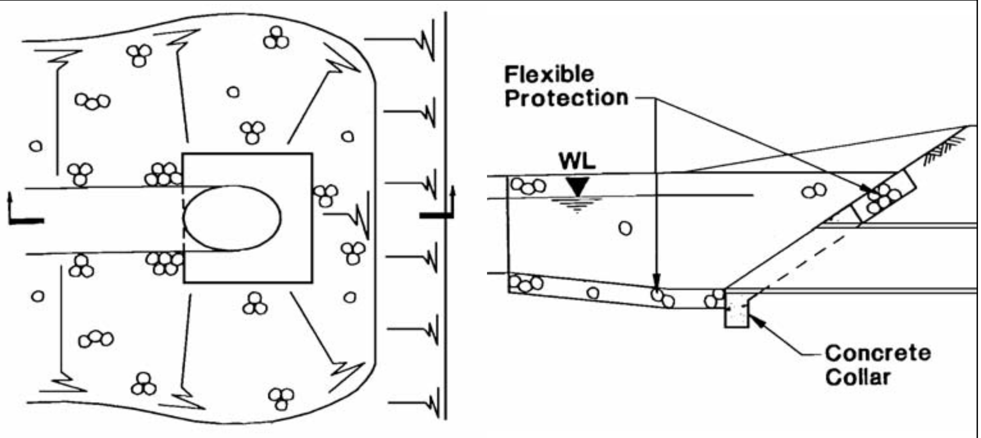
Type	Shape	Materials	Size range (dia or B × D)	
			Minimum	*Maximum*
Pipe		Concrete Other Corrugated steel Plastic	0.45[1]	2.4 8.0 0.6 n/a
Box		Pre-cast concrete *In situ* concrete	1.0 × 0.6 See notes[2]	6.0 × 3.6 B<12.0
Arch		Corrugated steel Brick/masonry/concrete	1.8 × 0.9 B>1.5	12.0 × 8.5 B<12.0
Pipe arch		Corrugated steel[3]	0.8 × 0.6	12.0 × 8.5
Complex		*In situ* concrete Pre-cast with *in situ* addition[4]	See note[2]	B<12.0 B<6.0
Bridge[7] (abutment flat deck)		Pre-cast/stone abutment with stone/metallic slab	0.3 × 0.3	1.8 × 1.0

Notes

1 0.45 m diameter (450 mm) is the minimum recommended size for any culvert.
2 *In situ* concrete minimum sizes are limited by construction practicalities.
3 Corrugated steel culverts are available in a wide range of shapes and sizes.
4 Pre-cast concrete boxes can also be provided in a wide range of standard sizes as well as specials, and can have features such as a low flow channel cast in.
5 Different barrel shapes and sizes can be used in combination to form a multi-barrelled structure.
6 All dimensions are shown in metres.
7 Common with Network Rail.

A5.2 Typical inlet arrangements (also applicable to outlet structures, but outlets generally require more erosion protection in the channel)

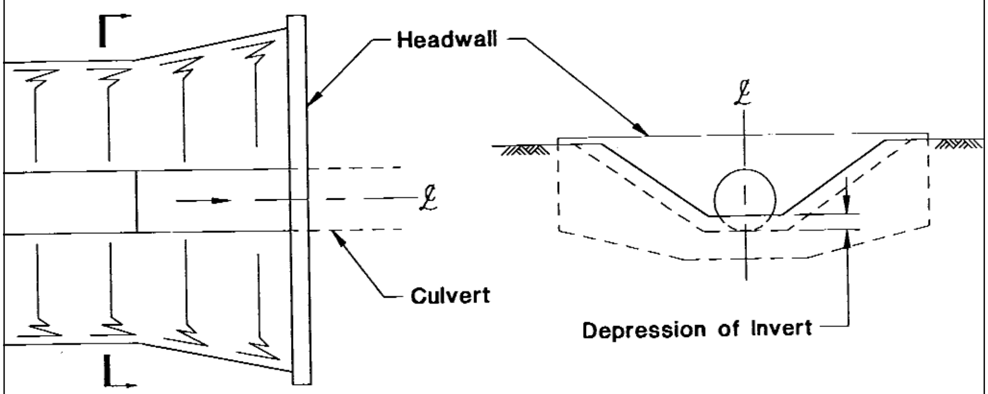
a) Simple



Plan

Section

b) Straight headwall

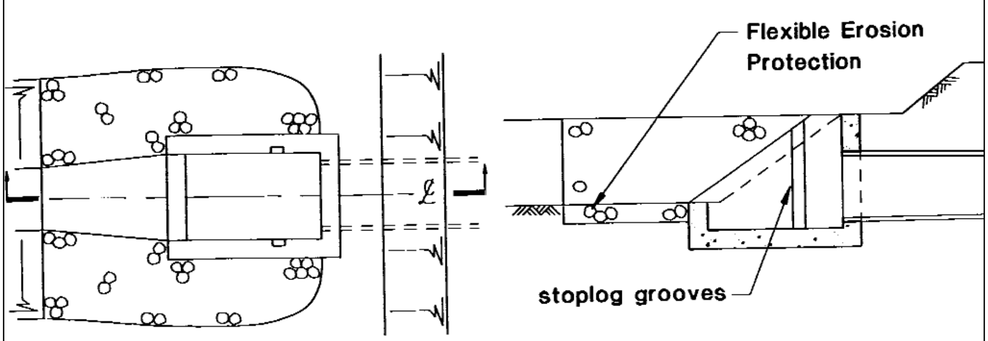


Plan

Section

(details of erosion protection omitted for clarity)

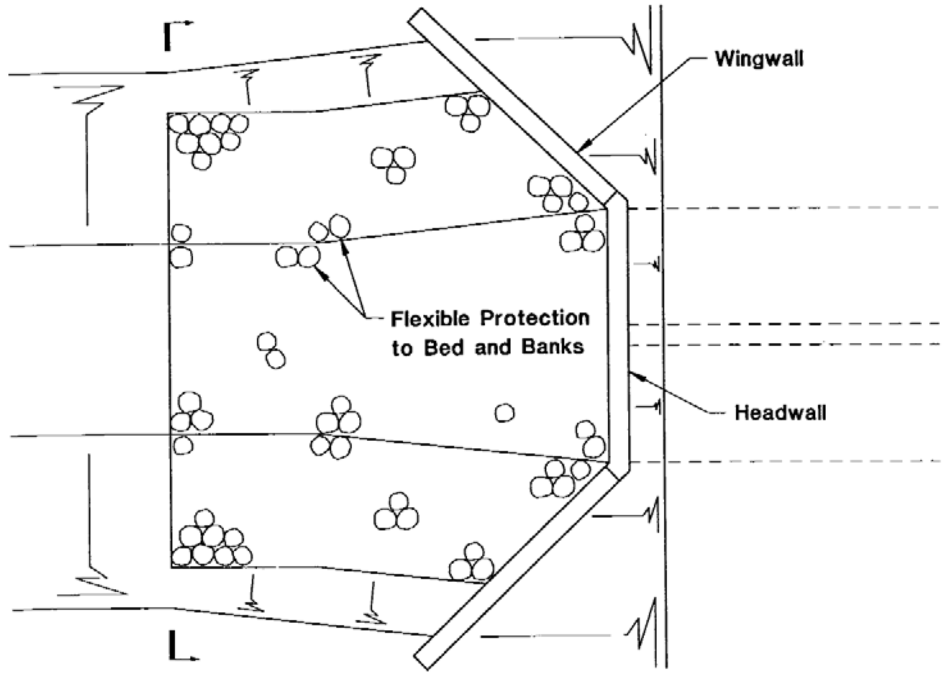
c) Box structure (small culverts)



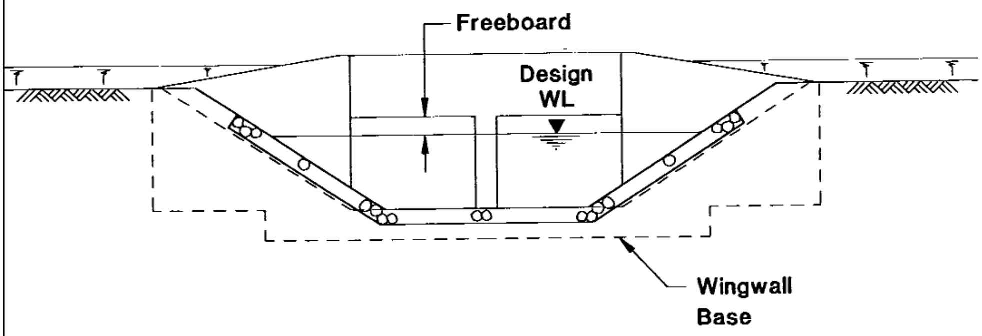
Plan

Section

d) Box culvert (double barrel)



Plan



Section

A6 Design of minimum energy loss culverts

A6.1 Introduction

A minimum energy loss (MEL) culvert minimises afflux for a given discharge by providing streamlined inlet and outlet conditions and near-critical flow through a deep, narrow barrel. The span is smaller than for equivalent conventional structures, thereby reducing costs in some circumstances, and the design encourages the passage of ice and sediment load without clogging or silting.

The design concept was developed in Australia in the late 1950s as a means of reducing the size and cost of culverts and bridges. The first MEL culvert was completed in 1961 and over 150 structures operate successfully in Australia (Chanson, 2007), although there are no known MEL culverts in the United Kingdom. This appendix provides preliminary design guidance and advice on limitations and suitable and unsuitable applications.

A6.2 Design principles

The hydraulic design of MEL culverts involves two basic principles: streamlining of the flow and critical flow conditions throughout the structure. Streamlining of the flow is achieved by designing the inlet and outlet to avoid significant form losses, and the flow should be hydraulically smooth without flow separation and recirculation. A typical culvert with warped wing walls is shown in Figure A6.1. Critical flow conditions give maximum discharge capacity per unit width for the design discharge and may be achieved by lowering the bed. The result is minimum head loss and near-constant total head along the culvert, although the culvert may also be designed for non-zero afflux. Supercritical flow should be avoided.

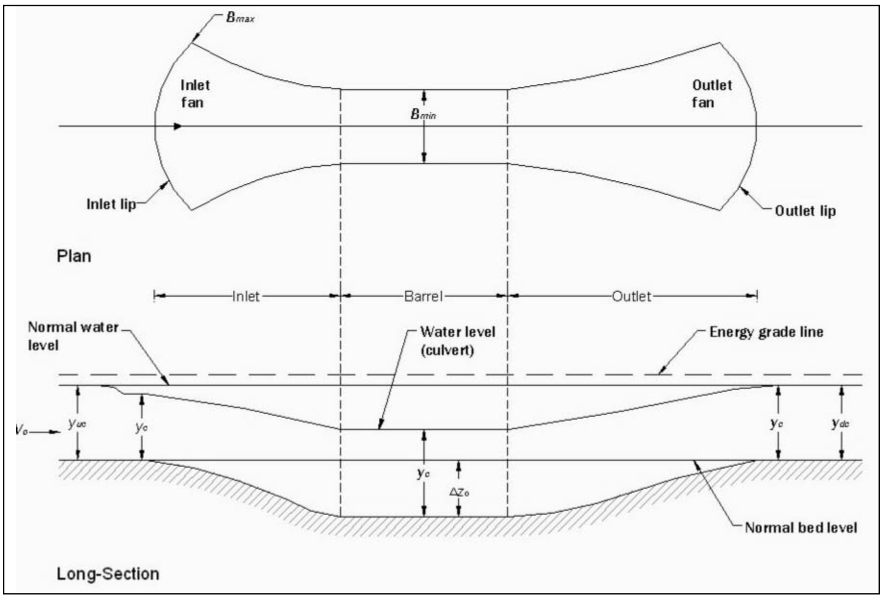


Figure A6.1 *Plan and longitudinal section through minimum energy loss culvert*

A6.3 Method of preliminary design

The method of preliminary design is summarised here, based on Chanson (2004). The designer is referred to Cottman and McKay (1990) or Chanson (2001) for comprehensive guidance.

Step 1 Determine design constraints

The design discharge Q, tailwater level H_t and maximum permissible headwater level H_{hmax} are determined. The required energy grade line can then be drawn on a long section, as in Figure A6.1.

Step 2 Determine initial dimensions

The initial dimensions of the barrel and transitions are determined assuming critical flow (Froude number $Fr = 1.0$) and ignoring energy losses. The barrel width B_{min} for a given invert drop Δz_o (or invert drop Δz_o for a given barrel width B_{min}) is given by Equation A6.1, while the width of the inlet lip B_{max} is given by Equation A6.2.

$$B_{\min} = \frac{Q}{\sqrt{g\left(\frac{2}{3}(E_{sc} + \Delta z_o)\right)^3}} \qquad \text{(A6.1)}$$

$$B_{\max} = \frac{Q}{\sqrt{g\left(\frac{2}{3}E_{sc}\right)^3}} \qquad \text{(A6.2)}$$

where

Q	=	design discharge (m^3/s)
E_{sc}	=	specific energy in the floodplain upstream in the absence of a culvert (m)
z_o	=	maximum depth of barrel below normal bed level (m)

Step 3 Determine initial geometry

The geometry of the transitions (inlet and outlet) are then designed by drawing a flow net, such that the equipotential lines (lines of constant invert elevation) are perpendicular to the streamlines (parallel to the flow direction) at all locations. The culvert can be curved in plan and need not be symmetrical. Having determined the geometry, the bed level is then lowered and raised at the same rate as the specific energy of the flow increases or decreases. The transition length is typically one to three times the difference between the inlet and barrel widths and a transition bed slope of 1:4 to 1:15 is likely to be suitable.

Step 4 Adjustment for energy losses

The bed level through the culvert is then adjusted to take account of energy losses (due to friction, inlet and outlet) by carrying out a full backwater analysis (Section 6.10.7).

Step 5 Check hydraulic performance for other discharges

Finally, the hydraulic performance is checked for smaller and larger design discharges.

Limitations and applications

The design is recommended for use on watercourses with a rectangular cross-section only, since design is complex and may become unreliable on non-rectangular watercourses.

Several designs are likely to be viable for any given site due to the variety of inlet and outlet shapes, such as parabolic, elliptic or hyperbolic curves. Flow velocities tend to be higher than for a conventional culvert and the transition area requires a concrete apron to prevent scour. The culvert may also require a low-flow channel.

Suitable and unsuitable applications are summarised in Table A6.1 below (based on Cottman and McKay, 1990). The choice between the MEL culvert and conventional designs is influenced by economics. In Australia, the MEL culvert is found to be cost-effective for flat floodplains with limited available afflux and for long culvert barrels (Chanson, 2007).

Table A6.1 ***Suitable and unsuitable applications for minimum energy loss culverts***

Suitable applications	Unsuitable applications
Mild watercourses with subcritical flow that is relatively wide and shallow Floodplains or ephemeral watercourses with intermittent flow Watercourses where excavation of the bed is viable Watercourses passing between obstructions or along narrow easements	Steep watercourses with supercritical flow over bedrock or boulders, or with well-defined, deep and fast flow Watercourses with continuous flow (due to cost of construction) Watercourses where excavation of the bed is unviable (eg due to underground services) Areas where ponded water in depressed inverts is unacceptable (eg urban areas) Short culverts (barrel length less than 6 m) High abutments (height greater than 6 m)

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A culvert provides the means of allowing infrastructure to cross a watercourse. Culverts are superficially simple structures, but they have the potential to restrict flow (causing flooding), and to adversely affect the aquatic environment.

This guide replaces the *Culvert design manual* (R168) published by CIRIA in 1997. It adopts a whole-life approach to the design and operation of culverts, with a focus on asset management, reflecting the significant changes that have occurred in the business of asset management over the past 10 to 15 years. The publication also addresses the management of culverts in the context of both the drainage basin in which they sit, and the infrastructure that they form part of.

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