Oregon Department of Transportation

Chapter 9
Fish Passage

This page has been intentionally left blank.

Table of Contents

List of Figures

List of Tables

9.1 Introduction

This chapter is a design reference for the classification, assessment, design or retrofit of a roadway-stream crossing to facilitate fish passage. A comprehensive literature review was completed to categorize design procedures and culvert assessment techniques. No new recommendations for a universal design procedure are made; rather, a compilation of design options from various sources that have been modified to meet the climate, species, life stages, and geographic diversity of Oregon.

The purpose of this chapter is to provide fish passage design guidance for road-stream crossings for the waters of the state of Oregon. It provides guidance for new construction, replacement, and retrofitting of existing structures. The methodology is intended for those with a working knowledge of hydrologic and hydraulic methods and experience in the design of hydraulic structures.

Some of the approaches and analyses described in this chapter are more rigorous than is necessary for simple sites; an experienced design team will be able to streamline the process in many cases. Many sites, however, have unique challenges that can only be solved by applying an in-depth understanding of the ecological, biological, hydrologic, geomorphic, and structural components of the design. For complex sites, the use of an interdisciplinary design team, such as environmental, geotechnical, bridge, and roadway is required. To be successful, it is important to recognize where a higher degree of rigor is necessary and to engage specialists in the design when appropriate. This document is not comprehensive for all situations, it refers to other guidance documents that have additional detail.

Hydraulic conditions within road-stream crossings are often more difficult to navigate for fish than those in the natural channel surrounding the structure resulting in barriers to fish passage. Fish must be able to move up and downstream through a structure without undue physical stress brought on by water that is too shallow, excessive vertical drops, high velocity and turbulence, and long runs without relief. These factors can be controlled with the proper design of the new structure or retrofit of existing structures.

Many of the waters throughout the state of Oregon contain one or more native migratory fish species that are currently or were historically present during all or part of the year. The policy of the State of Oregon is to provide upstream and downstream passage of native migratory fish at artificial obstructions. Providing fish passage through bridge and culvert crossings maintains ecological connectivity and, in cases where a barrier exists, increases habitat accessibility for spawning and rearing. For fish passage, the distinction between a bridge and culvert is not as important as the effect the structure has on the form and function of the stream.

Chapter 9

This chapter will provide the following options for providing passage design at crossings:

1. Stream Simulation Design Method
2. Hydraulic Design Method
3. Hydraulic Approval

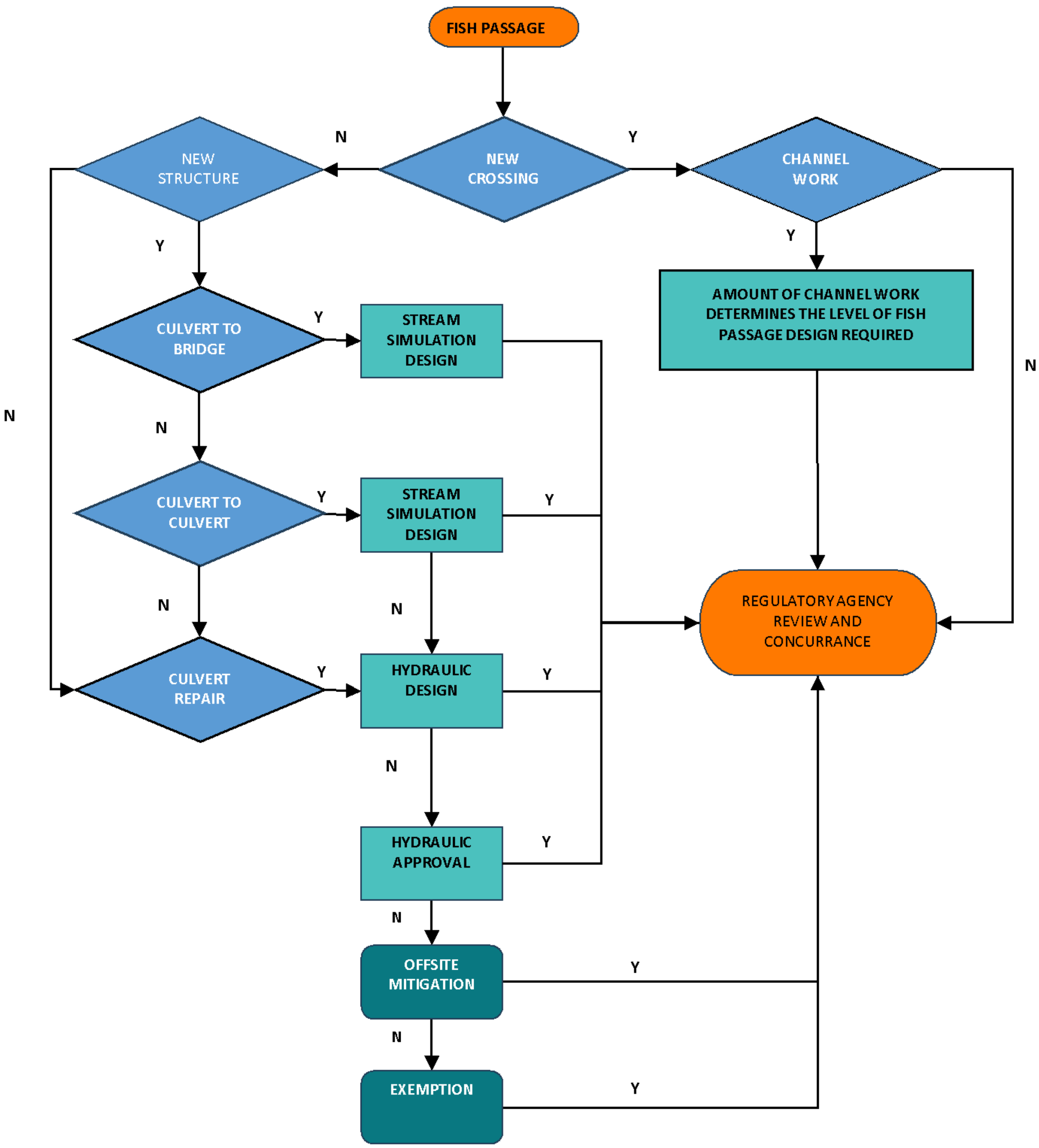


Figure 9.1-1: Fish Passage Project Flow Chart

9.2 Documentation

For Fish Passage Projects, there are several documents that are required throughout the project design life. Refer to the Policy Chapter for a more detailed description of the following required documents:

- Project Scoping Memo
- Hydraulics TS&L Memo
- Draft Hydraulics Report
- Final Hydraulics Report

9.3 Regulatory Compliance

Fish passage structure design is the subject of many environmentally related laws and statutes, including the following:

- Fish and Wildlife Coordination Act, 1934 (Federal)
- Federal Clean Water Act, 1948
- National Environmental Policy Act (NEPA), 1969
- Federal Endangered Species Act, 1973
- Executive Order on Recreational Fisheries, 1995
- Sustainable Fisheries Act, 1996 (Federal)
- Oregon State Statue and Administrative Rules, 2001 (ORS 509, OAR 635-412)

All proposed ODOT facilities and activities must comply with these and other requirements, such as Oregon drainage case law, floodplain development ordinances, permit requirements, and agency design standards.

9.4 Fish Passage Triggers

Oregon Department of Fish and Wildlife (ODFW) and National Marine Fisheries Service (NMFS) use the word "trigger" in reference to an action under fish passage statutes and rules that causes the need for the owner/operator to address fish passage at an artificial obstruction. It is the responsibility of the owner/operator of an artificial obstruction to comply with fish passage rules (OAR 635-412-0060(9). However, if there is a question whether a particular action is a trigger, then ODFW and NMFS liaisons should be contacted for clarification. Fish passage triggers can occur on a variety of road stream crossing types. Bridge work, scour protection, and culvert projects can result in a fish passage trigger. Examples of some actions that trigger fish passage at culverts are provided below.

Conditions that trigger the provision of fish passage at culverts include, but are not limited to:

- All new construction including roads, culverts, overflow pipes, aprons, or wing-walls in a stream channel.
- Widening/extending a road (widening of road fill footprint within a channel), culvert, apron, or wing-walls in a channel, when filling or removing 50 percent of roadbed directly above a culvert unless the 50 percent is only the top one foot of roadbed.
- Cumulatively through time, any repairs, or patches to 50 percent of culvert length.
- Replacing any section of culvert, except misaligned or eroded ends replaced to their original configuration and originally constructed prior to August of 2001.
- Reducing the entire inside perimeter of a culvert (i.e., interior liners) at any point along the linear length of the culvert.
- Any change to culvert from original configuration that reduces current level of fish passage, as determined by ODFW.
- Abandonment of road-stream crossings.

In addition to ODFW, NMFS and US Fish and Wildlife Service (USFWS) may review fish passage design to ensure federal criteria is met for waterbodies containing Endangered Species Act (ESA)-Listed species.

9.5 Hydraulic Approvals

Hydraulic approval is a process that can be utilized in situations where an existing crossing structure meets both the fish passage flow depth and velocity criteria (refer to depth and velocity criteria from Section 9.10.2). This method is most used on existing crossing structures that need rehabilitation. The common flow regimes that would warrant the use of the hydraulic approval process are:

- Tidally influenced.
- Naturally backwatered.
- Low slope systems.

Hydraulic approvals can also be obtained when the hydraulic conditions within the crossing structure are proven to be better than the hydraulic conditions of the natural stream outside the influence of the structure. This can be achieved by a series of flow measurements both upstream and downstream of the structure at known flow rates.

9.6 Fish Passage Hydrology

Crossings should allow fish passage for a range of flows corresponding to the timing and extent of fish movement within the channel reach, as determined by ODFW and NMFS. This section discusses seasonality and design hydrology.

♦ Design Hydrology

The passage design procedure employs four design flows: base flood, design discharge, high fish passage flow, and low fish passage flow.

Base Flood

The base flood (1% annual event (100-year)) is used to check overall channel stability, headwater elevations or overtopping of the crossing structure.

Design Discharge

The design discharge is used to estimate an initial size and type of road stream crossing based on the site-specific flow criteria. Refer to the Policy Chapter of this manual for the appropriate design storm event.

High and Low Fish Passage Design Flows

In a natural stream reach, fish respond to high flow events by seeking out refuge until passable conditions resume (Robinson, 1999). During extreme low flows, shallow depths may cause the channel itself to become impassable ((Clarkin, 2003) (Lang, 2004)). Generally, upper, and lower thresholds bound the flow conditions at which fish passage must be provided and these are defined here as the high and low passage flows.

High passage flow, Q_H, represents the upper bound of discharge at which fish are believed to be moving within the stream, while low passage flow, Q_L, is the lowest discharge for which fish passage is required, generally based on minimum flow depths required for fish passage.

For Oregon, the High passage and Low passage design flows as defined in Table 1:

Table 9.6-1: Fish Passage Design flows

Agency		Hydraulic Design Method
ODFW	High Passage design flow	• 5% exceedance flow for the migration period.
	Low Passage design flow	• 95% exceedance flow for the migration period.
NMFS	High Passage design flow	• 1% exceedance or 50% of the 2-year storm event during the time fish are expected to be present
	Low Passage design flow	Adults • 50% exceedance or 3 ft^3/s, whichever is greater.
		Juveniles • 95% exceedance or 1 ft^3/s, whichever is greater.

For many of Oregon's smaller drainages, the system may not have a Low passage design flow. Be sure to coordinate Low passage modeling flow with the appropriate agency prior to finalizing modeling and design.

9.7 Ecological Approach for Stream Crossings

9.7.1 Ecological Concepts

Rivers and streams throughout Oregon are long, linear ecosystems made up of the physical environment, communities of organisms, and a variety of ecological processes that shape and maintain these ecosystems over time. The long-term conservation of aquatic resources requires the maintenance of healthy and ecologically viable ecosystems. Highway crossings have the potential to negatively affect the ecological integrity of river and stream systems in several ways. To ensure the productivity and viability of river and stream ecosystems, the quality of physical habitat must be protected and restored.

The design guidance within this chapter will help minimize the loss of connectivity for road-stream crossing installations and will aid in the re-connection of aquatic communities where the existing crossings are replaced with structures meeting the design criteria within this chapter.

Access to habitats is a major limiting factor for population recovery and production of many native migratory fish species. By incorporating fish passage design into road stream crossing projects, many other ecosystem functions can benefit.

9.7.2 Importance of Movement

Throughout Oregon, many aquatic species move through rivers and streams for a variety of reasons. The most basic movements are regular daily movements to find food, find adequate habitat and to avoid predators.

Some fish movements are seasonal and linked to the reproductive biology of the species. Different life stages of fish will use different stream habitat types and areas. Access to these various dynamic habitats is crucial for survival. One example of this is during the spawning season, fish move to find spawning areas and smaller individuals may have to move to avoid areas dominated by larger, territorial adults. Adult fish typically migrate and stage in areas of deeper water and more stable hydrology than those in which they spawn. They then migrate to spawning areas that have higher quality habitat conditions for egg and young development such as riffles, flood plains, and headwater streams.

Another example can be movement to more desirable temperature ranges, such as seeking cooler water refugia in tributaries during summer months. This is increasingly more important to many populations in the context of climate change.

In environments like rivers and streams, the location and quality of habitats are always changing. Woody material is an important component of many stream ecosystems. Large logs in the stream can recruit sediments and create plunge pools on the downstream side of the log. Accumulations of woody material can change the local hydraulics of the stream, scouring some areas and depositing the material in other places. Woody material that forms jams across the stream can create large and relatively deep pools. These features are important habitat characteristics. However, they are not permanent features; woody material will eventually break up or move downstream. Flooding, substrate composition, and woody material work together to shape river and stream channels, water depth, temperature, and flow characteristics, creating ever changing habitats within riverine systems. In these dynamic environments, movement is critical for fish to be able to avoid unfavorable habitat conditions and to find areas that are more favorable.

♦ Stream Crossing Effects on Habitats

Streams do most of their habitat construction work (mobilizing and depositing sediments, recruiting, and moving woody material) at a range of higher flows. The highest flows approach or exceed the conveyance capacity of many stream crossings; therefore, the potential for stream crossings to alter the fundamental processes that create and renew physical geometry and habitat properties of the system is highly possible.

♦ Upstream Aggradation

Stream crossings that are narrower than the incoming channel can cause upstream backwatering during high flows. In many cases, debris exacerbates the issue by plugging the structure. This backwatering typically results in sediment deposition, which can extend several channel widths upstream of a crossing structure. These sediment and debris accumulations can create a passage barrier. The accumulation can steepen the local gradient at the structure inlet, sometimes accelerating flow enough to create a passage barrier.

Aggradation also can be induced by a crossing structure that is skewed with respect to the stream alignment. For example, as a cost-efficiency measure to minimize culvert length, culverts are sometimes installed perpendicular to the road and skewed relative to the natural stream channel. Where these pipes force flow to turn abruptly at the inlet, they may induce sediment deposition. Skewed-pipe outlets often direct flow at one bank, causing erosion. A skewed alignment is not always an issue, but the degree of skew should be minimized, or the crossing widened for better potential long-term passage.

♦ Downstream Degradation

Water velocities through a road stream crossing structure can be increased through the narrowing of the stream channel width. As a result, the water flowing out of the downstream end at higher velocities may cause scouring (degrading) of the streambed and banks. Degradation can create good habitat; the deepest pool in the affected reach may be the outlet plunge pool. However, it also creates a vertical discontinuity that often stops or impedes passage. Because the degraded streambed is lower in elevation, the streambanks are incised and may be less stable. Plunge pools caused by local scour at road stream crossings typically do not extend more than 3- to 6-channel widths below the structure.

9.7.3 Stream Crossing Effects on Fish Passage

There are a variety of ways by which crossing structures can impede or prevent the movement of fish and other aquatic species:

♦ Outlet Drop

Elevation drops at the outlet or within a crossing structure can create a physical barrier for many species. Not all aquatic species have strong jumping abilities, and many sub-adult life stages of strong jumpers are not matured enough to navigate vertical drops associated with crossing structures. In addition, outlet pools often have insufficient depth to allow fish to jump into the crossing structures.

Figure 9.7-1: Outlet drop

♦ Physical Barriers

Plugged or collapsed culverts and trash racks can block fish passage. Weirs or baffles; typically designed to facilitate fish passage by increasing depth or decreasing local velocities within a crossing structure, can be barriers for non-target weak-swimming, species which use suction locomotion such as lamprey, suckers, or crawling species.

Figure 9.7-2: Inlet sediment accumulation

♦ High Water Velocities

Water velocities can be too high to pass fish or other aquatic species during some or all times of the year. As stream discharge increases, velocities within culverts increase correspondingly. Average velocities can easily exceed the prolonged swim speed of most fish. In addition, culverts usually contain no resting areas for aquatic species attempting to pass through them. The result is that the fish may have to swim the entire length of the structure at burst speeds causing exhaustion before reaching the end of the culvert.

Figure 9.7-3: High velocities

♦ Insufficient Water Depth

The absence of a low-flow channel can result in water depths too shallow to allow passage for fish or other aquatic species. In streams with highly variable flows, the challenge is constructing a structure capable of passing high flows, while still maintaining a defined low-flow channel like the natural streambed. In these systems the most successful structures are often those that provide bank edges and a low terrace within the structure. When designing these types of crossings, project teams need to pay particular attention to the size, location, and spacing of substrate within the structure to emulate the natural streambed as closely as possible.

Figure 9.7-4: Insufficient water depth

♦ Inlet Transition Velocity

As the last barrier for a fish traversing upstream through a culvert, the culvert inlet requires special consideration. Velocity at the inlet may be higher than in the barrel if bed load deposits upstream from the entrance increase the local slope. Inlet conditions are especially important in long installations, or when successful navigation through a series of other obstacles is required. The addition of tapered wing-walls may significantly reduce the severity of an inlet transition (Behlke, 1991). A skewed entrance will also produce higher entrance velocities than a non-skewed entrance and may create localized sediment deposition areas.

9.7.4 Summary of Ecological Considerations

The impacts of substandard crossing structures on native migratory fish (NMF) affect rivers and streams throughout Oregon. The importance of NMF as fisheries resources and the status of some as federally "threatened" or "endangered" species has focused much attention on fish passage for migratory species. A large amount of time, money, and effort have been expended on the issue of passage barriers for migrating adults. Unfortunately, some efforts to promote upstream passage for adult fish have failed to provide passage for the juvenile stages of the same species. Strategies that focus solely on adult fish but don't address all life stages for a particular species are unlikely to maintain populations over time. In river systems across the state, providing juvenile passage at current barriers is one of the highest priority recovery actions available.

As fish passage strategies are adjusted for adult and juvenile migratory fish, replacing one type of short-term thinking with another must be avoided. Even when a particular species is the primary target for recovery, management strategies that ignore the community and ecosystem context for that species cannot succeed. Strategies that focus only on target species may succeed in the short term, but they can undermine long-term success for other species within the ecosystem.

Given the large number of species that make up most river and stream communities and the lack of information on swimming abilities and passage requirements for most species, using a species-based design to meet the movement needs of an aquatic community is often impractical. An ecosystem approach is the most practical way of maintaining both the species population viability that make up aquatic communities and the fundamental integrity of river and stream ecosystems. Such an approach focuses on maintaining the variety and quality of habitats, the connectivity of river and stream ecosystems, and the essential ecological processes that shape and maintain these ecosystems over time. To minimize negative impacts to an ecosystem, a stream simulation approach to crossing designs is the recommended option.

This document only covers specific areas of the ecological aspects that make up a complete eco-system for aquatic and riparian species. For more detailed information, refer to U.S. Department of Agricultures', Stream Simulation: "An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings" August 2008.

9.8 Stream Simulation Concepts

9.8.1 Introduction

The purpose of Stream simulation is to provide passage for the variety of aquatic species and life stages present in most streams. To address passage simultaneously for multiple species with different movement capabilities and timing needs, stream simulation takes a very different approach from the hydraulic design method. Stream simulation does not target specific fish or other species for passage, nor does the designer need to match species-specific water velocity, water depth, or crossing length criteria. Instead, through a proposed structure, a continuous streambed that simulates the natural channel’s width, depth, slope, and streambed material is created to connect the reach longitudinally through the crossing. The simulation creates diverse water depths, velocities, hiding, and resting areas through the crossing that allow movement for different species. Given these similar conditions, it is presumed that the simulated channel inside the crossing presents no more of an obstacle to movement than the adjacent natural channel. Stream simulation crossings are larger than traditional crossings, and therefore less prone to debris plugging. This can benefit the highway system by reducing any tendency for debris plugging to cause overtopping or flow diversion.

The goal in stream simulation is to design a stream channel that adjusts to accommodate a range of flood discharges and sediment/debris inputs, without compromising fish passage or having detrimental effects to up or downstream reaches. For the simulated streambed to maintain itself through a broad range of flows, stream processes that control sediment and debris transport and maintain hydraulic diversity must function similarly to the natural channel. In other words, to mimic flows that transport sediment and debris, reworking of the channel bed should **not** be constrained or accelerated inside the crossing structure. Active channel flow is recognized as a good estimator of the channel-forming flow in stable alluvial rivers.

Within ODOT the Active Channel Width (ACW) is used to determine the minimum structure width, however, the bank-full width should also be considered within the stream simulation design. In some situations, the ACW and the bank-full width may be the same.

To create an accurate stream simulation crossing, the simulated channel is initially designed, then the crossing structure (either a bridge or culvert) is fitted over and around the designed channel. The width depends strongly on project objectives and may exceed the reference reach ACW width if necessary for achieving objectives such as bed stability, amphibian, or terrestrial animal passage, or regulatory criteria.

Simulations are not exact replications of real stream channels. Features which cannot be recreated inside a crossing structure include:

- Natural light. (for long closed culverts and arches)
- Cohesive soils. (for all crossing structures)
- Channel-spanning or embedded wood. (for closed culverts and arches)
- Woody material (Debris jams). (for closed culverts and arches)
- Bankline vegetation. (for all crossing structures)
- Channel bends. (for closed culverts and arches)

- Flood-plain functions. (for closed culverts and arches)

Features that provide roughness in a stream channel are essential for stabilizing the bed and creating the depth and velocity variations necessary for aquatic species passage. Though these characteristics cannot be duplicated, some can be simulated with large rock. For example, to simulate natural bank lines, immobile rock can be placed along the channel margin in various arrangements to mimic the natural streambank. Rock can also be used to simulate the grade-stabilizing functions of embedded debris.

For these and other reasons, the design is not a perfect simulation of the natural channel. Where to draw the boundaries of "stream simulation" is not always clear. Although stream simulation is most often described in terms of performance (providing passage for all aquatic species), and free mobility is difficult to verify for all species at a site, success is likely to remain somewhat subjective.

Natural stream channels are diverse and complex, with some degree of unpredictability in their response to runoff events and the effects of land management. Using sophisticated quantitative methods for design, is not a guaranteed that a simulated streambed will sustain itself through the full range of flows it may experience.

9.8.2 Key Elements of Stream Simulation

The reference reach is the key element of any stream-simulation design. When available, a natural and stable reach; preferably upstream and near the project, becomes the design template for the crossing structure. The reference reach must satisfy the physical conditions of the crossing site, especially the slope. It must be self-sustaining inside a confined structure. In other words, flows interacting with the bed and the structure walls will maintain the simulated streambed within the structure. In high flows, although some features of the simulated bed may be immobile, other streambed materials should mobilize and restructure themselves similarly to the natural channel. Sediment transported from upstream should replace eroded material through the structure crossing as it does in the natural channel. Self-sustainability in the simulated channel means establishing basic characteristics of the reference reach, such as gradient, cross-section shape, bank configuration, and bed material size and arrangement. Assume that if a crossing can be modeled to simulate a reach that is representative of the natural channel, passage conditions will be as good as in the natural channel.

The idea of simulating a stable reference reach inside the crossing structure may not be feasible in certain situations. These situations include highly unstable channels that are rapidly changing, such as after a major flood where no stable reference reach exists. Other examples are inherently unstable landforms subject to frequent disturbances, such as alluvial fans and debris prone channels. In these types of systems, hydraulic design methods may be better suited to meet passage conditions.

9.8.3 Stream Reach and Site Assessment

♦ Steps and Considerations for a Site Assessment

1) Topographic survey
    a) Site and road topography
    b) Channel longitudinal profile.
    c) Watershed long profile
    d) Channel and flood-plain cross sections.
    e) Floodplain topography (Lidar data is often used for larger floodplain areas)
2) Measure size and observe arrangement of bed materials.
    a) Pebble count or bulk sample
    b) Bed mobility and armoring.
    c) Bed structure type and stability (steps, bars, key features)
3) Describe bank characteristics and stability.
    a) Active channel width
    b) Bank Full width
4) Assess geotechnical features.
    a) Bedrock location
    b) Soil types
    c) Soil engineering properties
    d) Mass wasting (bank failures)
5) Analyze and interpret site data.
    a) Bed material size and mobility.
    b) Cross section analysis
        i) Floodplain conveyance.
        ii) Bank stability.
        iii) Lateral adjustment potential
    c) Longitudinal profile analysis
        i) Long term degradation potential

    ii) Long term aggradation potential

d) General channel stability

    i) Entrenchment ratio

9.8.4 Data Collection

Data collection for site assessment consists of channel surveys, valley, and road topography, and tying the survey data to observations of geomorphic and other features, including subsurface materials. Much of the assessment is aimed at understanding the site conditions and stream processes that will have to be accounted for in design of the new crossing. As well as the project site, understanding the upstream and downstream reaches is needed to fully understand how a structure will impact the system. These understandings are necessary to predict channel changes and design for those changes over the structure's expected lifetime. Again, the level of effort and detail should correspond to the complexity of the site and the risks associated with placing a structure at the location.

An important goal of site assessment is selecting a model for design of the simulated channel by characterizing the reference reach. However, the reference reach must have a slope very similar to the slope of the simulated channel. The slope may not be known until the project profile design is complete (Section 9.9.2). The reference reach cannot be identified with certainty until after that first design step. There are two ways to handle this logistically:

1. Enough data can be collected during the site assessment to characterize several potential reference reaches at different slopes. This avoids the need to revisit the site and collect additional data once the reference reach is selected during design.
2. After analyzing the project topographical survey and determining one or more potential slopes for the simulated streambed, identify one or more applicable reference reach(es) from the longitudinal profile, and return to the site to characterize their cross-section dimensions, entrenchment, bed material, etc.

Section 9.8.7 goes into detail on selecting the reference reach. Channel morphologic data needed for the reference reach is summarized there.

Good documentation of the field observations is essential for interpreting the survey data, and a complete sketch map is a key complement to the narrative field notes. Refer to the Data Collection chapter for topographic survey requirements.

♦ Channel Types and Bed Mobility

Channel-type classification is a fundamental step toward understanding both current conditions and future channel changes. Classifying the channel using both the Montgomery and Buffington and the Rosgen systems, can provide insights on the dominant geomorphic processes associated with the reach, and on the type and intensity of future channel response to a new or replacement structure, or to structure removal. Refer to (Buffington & Montgomery, 2013) "Geomorphic Classification of Rivers" for more information on channel types and bed mobility.

Design of stream-simulation channel-bed material varies depending on bed mobility in the natural channel. Methods for bed material sampling are also dependent on the channel type and the bed mobility. Refer to the Data Collection Chapter for more information on material sampling.

♦ Site Considerations

Site constraints can affect the design and construction at any site. During the site assessment and preliminary design, identify all the limitations that could constrain the design and construction of the project. A list of common constraints follows:

- Vertical constraints: Road grade and fixed or required elevations influence structure type and clearance and impact the site layout.
- Utilities and property developments: These can affect the ability to reconfigure the site.
- Material constraints: Unavailability of materials may require a compromise on material used or an alternative design solution to stream simulation.
- Site access: Access issues may affect the type of equipment you can use, as well as the feasibility of regrading the channel profile. The availability of space for storing materials can also affect the construction schedule.
- Road closure and detour feasibility: The importance of a road for public travel and access during construction may constrain construction activities.
- Time constraints: Regulatory limitations to protect threatened or endangered species may limit the 'in stream work window' to a few weeks out of the year.
- Backfill material: verify if the existing crossing embankment materials are suitable for backfill
- See what onsite materials (trees, downed logs, riparian vegetation, topsoil, large rocks) are suitable for possible inclusion in the stream- simulation design or stabilization plan
- Temporary Water management: verify diversion potential at the site
- Check site for nearby areas that might be suitable for treating dirty water by filtration through soil and vegetation
- Check site for stockpiling excavations and construction materials if needed?
- See if streambank stabilization measures be necessary upstream or downstream of the crossing

These constraints may limit the extent of regrading or the type of structure, forcing a less-than-ideal solution for the site.

9.8.5 Interpreting Site Data

♦ Sediment Process and Mobility

Site assessment documentation for bed mobility should include:

- Channel types upstream and downstream of the crossing.
- Entrenchment Ratio
- Apparent bed mobility in upstream reach, and mobility indicators: degree of armoring, imbrication, bed structures, dominant particle sizes.
- Evaluation of whether grade controls need to be constructed in the stream simulation design bed.

Information for the reference reach should include:

- For gravel and coarser channels, particle size distribution curve(s) including particle sizes of grade controls if necessary.
- A visual estimate of subsurface fines.
- A qualitative description of the degree of armoring and the apparent stability of the armor layer (determined by packing, particle shape, etc.).
- For highly mobile streambeds, qualitative evaluation of particle sizes: maximum mobile particle size, dominant class, range of sizes present.
- Key feature type, size, function.

In all cases, describe any effects of the existing crossing structure on bed material sizes to help in predicting channel response to removal or replacement.

The composition and characteristics of bed and bank material can provide insight on the frequency of sediment transport, channel stability, and sediment supply. These insights are important during design when decisions must be made about re-grading the project profile, realigning the crossing structure or the adjacent reaches, and designing streambed structures that move at similar flows to the reference reach.

♦ Analyzing the Long Profile

Bed forms, woody material, bedrock, other infrastructure, etc., are not the only possible controls on channel slope. Slope also may vary where the crossing is located at a geomorphic transition, where the downstream channel has incised, or where the crossing itself has modified channel slope by causing sediment deposition upstream.

Many highways are located at geomorphic transitions—natural terrain breaks such as the edge of a valley at the base of the hillslope, or on a natural bench. These terrain breaks can create an abrupt change in stream slope, influencing the shape of the profile and affecting sediment transport along the channel. Designers need to identify these transitions and understand their potential effects on sediment transport and channel stability to accommodate them in the design.

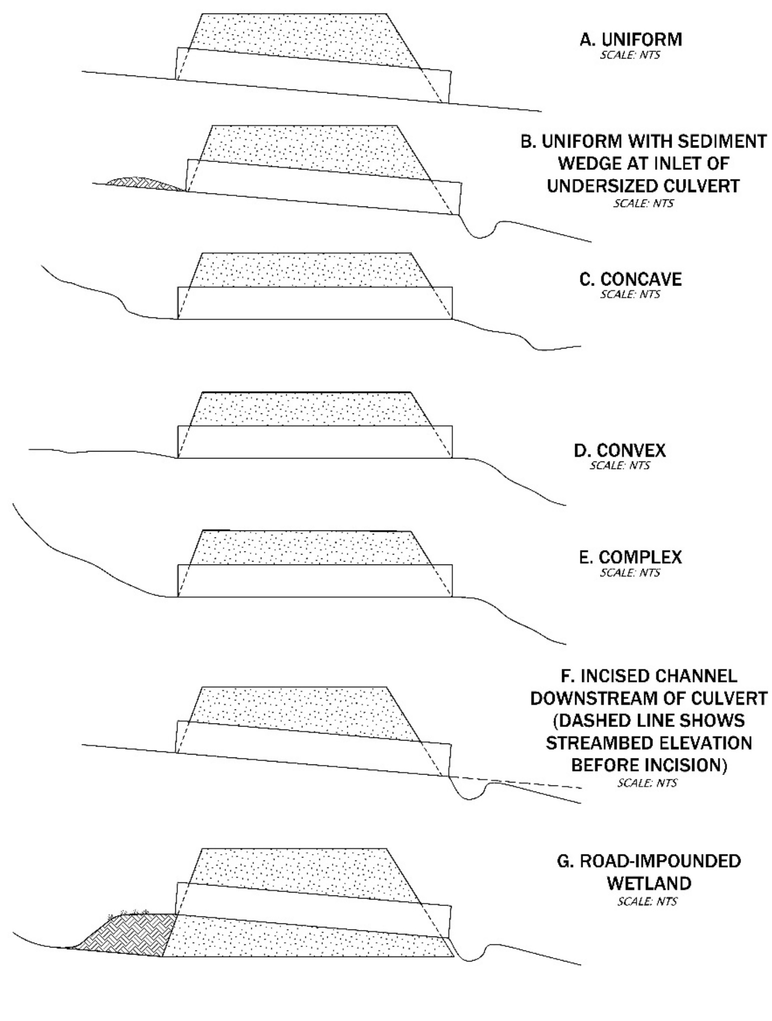


Figure 9.8-1: Road crossing profiles (Forest Service Stream-Simulation Working Group 2008)

Uniform: A uniform profile has no slope transition, making this the ideal crossing situation. Even where the profile is uniform, aggradation upstream of an undersized crossing structure can reduce the local slope. Such a profile can be mistaken for convex if the surveyed longitudinal profile does not extend beyond the aggradation, or if the aggradation is not recognized. Field evidence of aggradation upstream of an undersized culvert can include a relatively high gravel deposit in the center of the channel above the existing structure, a widened and/or divided channel, bank erosion, or a bar deposit just upstream from the culvert with finer sediment than at other locations. An aggraded reach may also appear simpler and more homogenous because structural features such as steps may be buried by sediment. Backwater aggradation is not limited to uniform profiles, of course. It can occur upstream of any undersized culvert. (See Figure 6 (A))

Concave: A concave transition is an abrupt slope transition from steep to flatter, such as on a flat valley bottom near the toe of a hillslope. Such an area is a natural depositional zone, where sediment accumulation through the crossing structure can reduce the structure's hydraulic capacity. Occasionally, sediment deposition can also plug the channel and cause the stream to cut a new channel in a different location. If the excavation for a replacement structure cuts into the bed of the steeper reach and no upstream grade control exists, upstream head cutting, and additional sediment deposition may result. (See Figure 6 (C))

Convex: A convex transition is a slope transition from a mild slope to a steeper one. Depending on how close the crossing is to the grade break, flow acceleration resulting from either the structure or a disturbance during construction can destabilize bed structures that control the downstream grade. Destabilization, in turn, could create a head cut that might migrate upstream through the structure and undermine it. (See Figure 6 (D))

Complex: A complex transition is a profile with both a convex and concave shape. This type of transition has both the upstream problems of the concave type and the downstream problems of the convex type. (See Figure 6 (E))

A road crossing placed at a convex or concave site may exacerbate the natural tendency toward aggradation or degradation if the crossing constricts the stream, or construction disrupts key grade controls. This can lead to a perpetual need for maintenance and the chronic channel disturbance associated with it.

♦ Potential Vertical Adjustment

One of the first steps in stream-simulation design involves selecting the project profile elevation for the streambed that will be constructed. Before selecting the project profile, the team needs to predict the elevations between which the stream bed might vary over the service life of the structure. The upper (aggradation) and lower (long term degradation) lines represent respectively the highest and lowest likely elevations of any point on the streambed surface in the absence of any crossing structure. This section describes the considerations that go into forecasting the aggradation and long-term degradation (total scour) lines for the structure's lifetime.

Depending on channel type and condition, processes that can change the streambed elevation, whether permanently or temporarily, include:

- Channel incision caused by downstream base-level change.

- Increased flows or sediment inputs resulting from land management changes or climatic events in the watershed.
- Aggradation or degradation at a slope transition.
- Erosion and deposition of key features like boulders, steps, and large woody material.
- Channel scour and fill during floods and debris flows.
- Head-cutting upstream of a larger replacement culvert, as aggraded sediment is mobilized.
- Pool formation.

Predict what types of changes might occur and estimate how the channel might respond to those changes. Consider first the potential for large-scale, long-term channel change, such as deposition due to debris flow, or regional channel incision due to base-level changes downstream. Then consider local changes, such as movement of one of more key features or formation of a debris jam. Predicting how such changes may affect bed elevations is necessarily subjective; use every available piece of field and historical evidence available. Be conservative where the probability of vertical adjustment is high, such as where large amounts of wood are in the channel, or where channel incision is expected. If you are uncertain how the channel might change in the future, design conservatively and consider getting additional expertise to help predict future conditions.

In channels where large wood or rock steps control bed elevation, if these key features do not move, they will control the lower limit of vertical adjustment for the lifetime of the replacement structure. On the other hand, loss or outflanking of one or more of these key features could cause a large change in bed elevation over some length of stream as the channel adjusts toward a new equilibrium. The length of stream affected depends on the stability of the adjacent grade controls and on the depth of channel bed lowering. Usually, the material from the failed step moves only a short distance downstream, filling in the downstream pool and reorganizing the bed to form a new grade control.

If the key features are less stable, project how bed elevations are likely to change when they move. In intermediate and low-mobility channels, some amount of channel-bed fluctuation will always occur as wood pieces or rock grade controls enter or move through the channel, or as bedforms and bend locations change. Debris jams or buried small debris can temporarily retain sediment upstream, and they may form a scour pool downstream. If the debris moves, how will the stream adjust? Generally, the height of the grade controls, (log or rock steps, pool-tail crests, debris accumulations) indicates the scale of bed adjustment expected after one or a series of grade controls moves.

In stable channels where the bed surface is not expected to change (e.g., due to base level lowering or changes in flow), the depth of ordinary pools is a reasonable estimate of the lowest likely bed elevation in any slope segment. Unusually deep pools formed by large key features would not be considered in this analysis since they would not form inside a crossing structure.

The depth of surveyed pools, however, represents only a snapshot- in-time of a dynamic channel that undergoes scour and fill during high flows. Although not a limiting factor of local scour or long-term degradation, limited research has shown that, in armored gravel-cobble bed streams, flood scour depths are on the order of twice the thickness of the armor layer, or about twice D90 ((Begelow, 2005); (Haschenburger, 1999)). It makes sense in these cases to expect that, temporarily at least, the bed may be that much lower than the bottoms of pools. If the level of risk warrants, the degradation line can be lowered to account for that.

Channel incision that affects long stream reaches can occur due to a variety of causes. Downstream influences include in-stream gravel mining or channel straightening that cause a head-cut to begin moving upstream; upstream causes might be an upstream dam that reduces sediment loads, or any land management activity that reduces infiltration and increases peak runoff rates. Predicting the degradation line under these conditions requires estimating how much of this large-scale incision may occur at the crossing site and then adding the depth of pool scour to that estimate.

Also think about any features or processes that may cause the channel to aggrade. Some examples are:

- Head-cuts, bank failures, landslides, or debris flows occurring upstream may create a potential for large amounts of sediment deposition in the structure. Debris released by the head-cut can exacerbate the deposition problem. (See Benda and Cundy 1990, for a method of predicting the risk of debris flow deposition).
- Formation of a debris jam and sediment accumulation behind it can easily cause local bed elevations to rise.
- Evidence of recent aggradation or heavy bedload movement may indicate the channel is aggrading, or it may be recovering from aggradation.
- If the channel is unnaturally lacking in debris, consider whether trees falling into the stream in the future might retain sediment and raise the channel-bed elevation.
- Crossings located on tributaries near their junctions with a larger river may experience aggradation if they are backwatered by high flows in the river.

Using all the information, draw at least two lines on the longitudinal profile to show the range of possible future bed elevations at the site (Figures 7, 8, & 9). Delineate the lines for channel segments outside the influence of the existing structure and then connect them through the project reach as though no structure were there. Draw them approximately parallel to the average grade of each slope segment unless bedrock or other immobile controls dictate a different slope.

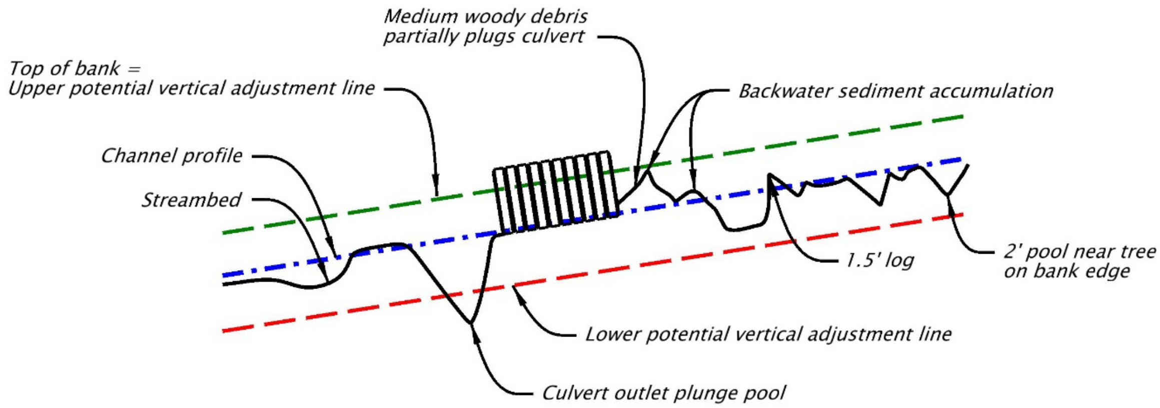


Figure 9.8-2: Uniform Profile

The scenarios represented in the figures illustrate how the aggradation and degradation lines were delineated in three different hypothetical cases.

Figure 7 shows the longitudinal profile of a stream crossing a road in a culvert where:

- The channel profile shape is uniform.
- The stream is in dynamic equilibrium.
- Watershed conditions are stable.
- There is no reason to expect regional channel incision due either to head-cut migration from downstream.
- Or to changes in flow or sediment loads.
- The channel is an armored gravel-cobble pool-riffle channel with some woody material.

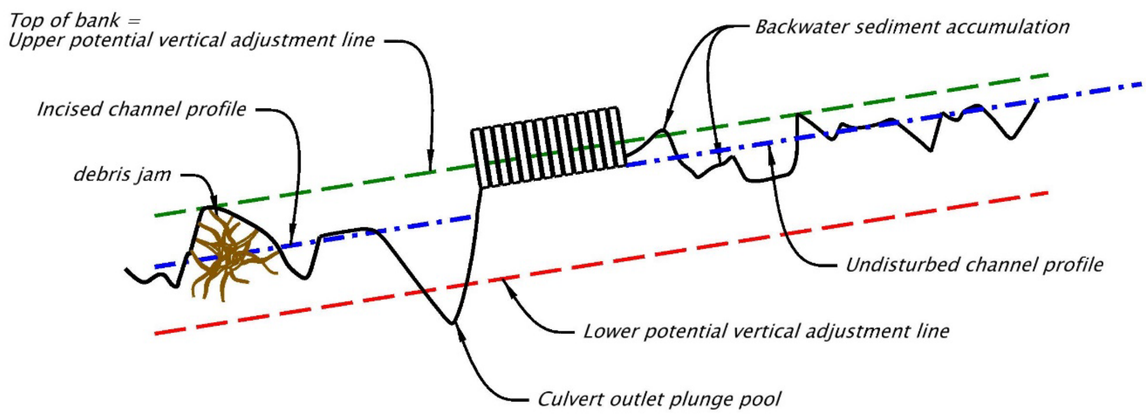


Figure 9.8-3: Incised Channel Profile

Figure 8 shows the same channel after a head-cut moved up from downstream and was stopped by the existing culvert. The incised channel profile is lower than the undisturbed (upstream) channel profile projected downstream. Here, if the culvert were not in place, the head-cut could continue to move upstream causing incision.

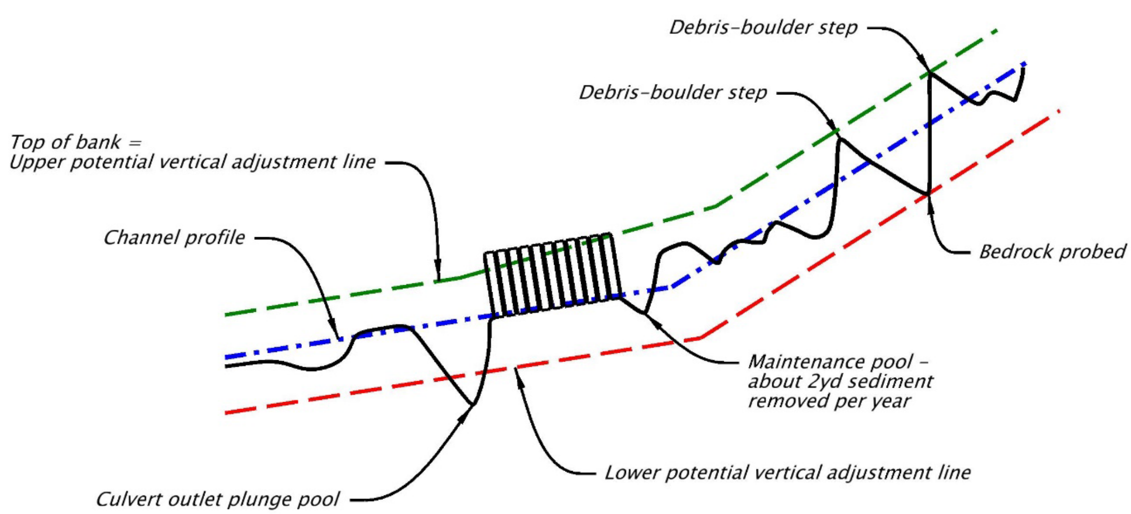


Figure 9.8-4: Concave Slope Transition

Figure 9 represents a concave profile. The road is located where a channel transitions from a steeper grade to a more gradual slope. The steeper channel currently appears stable, but the height and composition of the banks at the valley edge show that the channel has deposited substantial sediment and debris there during past floods.

The aggradation line in this example is drawn at the top of the banks in the valley section, and at the top of the higher banks in the slope transition section. For systems in dynamic equilibrium, the degradation lines in each channel segment are below the bottoms of the pools by a depth of two times D90. For mobile systems, any downstream grade control structure that may not be stable, should be considered and utilized to determine the degradation line for the long profile.

As shown in Figure 9, where a channel has distinct grade breaks, adjustment lines can be drawn in segments. The aggradation and degradation profiles might not be parallel where some feature will limit the possible channel elevation from going higher (e.g., flood-plain elevation) or lower (e.g., bedrock). Drawing several possible profiles to show the range that might be expected at the site, given the existing grade controls and how they might change, is helpful. Where substantial uncertainty in the degree of potential vertical adjustment exists (e.g., in a channel with a highly mobile bed and good potential for debris jam formation), increase the range of potential vertical adjustment to offset the risk of error.

9.8.6 Site Risk Assessment

Continuing to build on the initial assessment and the longitudinal profile analysis, the designer assesses all risks at the site, as well as potential risks for neighboring properties and structures. Use all available data and observations to interpret current project site conditions, predict potential channel changes, and identify significant risks that the design will have to deal with.

♦ Flood Conveyance

When flooding occurs, high floodplain conveyance is an important factor affecting design. When floodplain conveyance is high and overbank flow occurs frequently, it may be necessary to install other floodplain drainage structures under or across the road. The objective is to avoid funneling overbank flows through the main crossing structure, which would destabilize the simulated streambed in the culvert. Alternatively, a bridge or viaduct could be considered as a replacement structure.

To determine whether high floodplain conveyance is an important issue at the site, estimate the depths and velocity of recent overbank flows. Use observations of past flood elevations and floodplain scour and deposition features, together with historical flood data. Floodplain vegetation and erosional and depositional features observed during the cross-section surveys may indicate recent overbank flow depths and should give an indication of the frequency and intensity of overbank flows. The presence of flood swales or side channels, for example, indicates enough overbank flow to cause significant scour. These channels, which can convey large amounts of flow, may also be important refuge or juvenile habitat for aquatic species. Identify them as key locations for flood conveyance and, where appropriate, fish passage. Be sure to evaluate whether evidence of overflow on the flood plain upstream of the road crossing might simply be the result of flow constriction at an existing undersized crossing. If so, a larger structure may be all that is needed to solve the problem. Flood-plain observations will also help in selecting a roughness factor for flood-plain flow estimation if you intend to use a model such as "US Army Corps of Engineers, Hydraulic Engineering Center, River Analysis System (HEC-RAS) or Sedimentation and Rever Hydraulics (SRH-2D).

♦ Potential for Lateral Movement

On streams with a high potential for lateral channel migration, the channel's angle of approach to the crossing structure may become more acute over time. A poor alignment is an especially important risk factor in streams transporting woody material and sediment. Evidence of past channel shifting (e.g., an acute angle of approach to the culvert inlet, bank erosion on one bank) can help in evaluating the risk to the replacement structure. Also consider factors, such as current bank stability, land use, vegetation condition, climate change, and probable future land use changes.

Understanding the natural channel's (pre-disturbance) pattern is essential for proper layout of a stream-simulation installation. Culverts shorten and steepen channels when they are replaced at a channel bend. In the case of a stream simulation culvert, such an increase in channel slope could put the simulated streambed at risk. Using the sketch map and field observations, try to detect the natural channel location and pattern. This would be the starting point for designing the replacement crossing alignment.

It is especially important to consider the natural channel pattern where a crossing is located on a meandering stream. Several options for minimizing risk by keeping the crossing short, aligning it with the stream, and providing efficient transitions. Observations of bed and bank stability are vital in selecting the least damaging option. If a skewed culvert-to-channel alignment is being considered, bank materials and stability will determine whether bank stabilization measures are needed near the inlet or outlet. Where channel straightening cannot be avoided, the channel may respond by eroding either its banks or its bed. Try to predict likely channel responses to such changes by considering the relative resistance of bed and bank materials. Refer to HEC 20 "Stream Stability at Highway Structures" for a more in-depth guidance.

♦ Potential for Head-cutting

Even in a uniform longitudinal profile, simply replacing an undersized culvert with a larger one set lower in elevation can cause the adjacent stream reaches to adjust. Sediment accumulated above the old culvert remobilizes, although usually the adjustment is not large enough to create a problem. Where the downstream reach has incised, however, head-cutting upstream of the replacement structure can be substantial enough to affect buried infrastructure, destabilize streambanks, modify aquatic habitats, etc. Decide whether to control such a head-cut or allow it to progress upstream, considering the trade-offs between the extent and duration of impacts, versus the benefit of allowing the channel to evolve to a natural self-sustaining condition.

Deciding how to handle any expected head-cutting requires answers to questions such as the following:

- How much head-cutting is likely if no controls are implemented?
    - How far upstream might it go?
    - Could it effect upstream structures or properties?
- What effects will the expected head-cut have on streambed and banks?
    - How long will they last?
- Should head-cutting be prevented?
- Should head-cutting be allowed to occur at an uncontrolled rate?
- Should the rate of head-cutting be slowed by temporary grade controls?
- Will the head cut result in unsatisfactory fish passage conditions?

Before making these decisions, be aware of the types of effects head-cuts can have. Bates (2003) identified the following physical, biological, and infrastructure issues for design teams to consider when determining whether to control a head-cut or allow it to occur. Additional coordination with regulatory agencies is needed as part of these considerations.

- **Extent of head-cut:** The upstream distance that a head-cut can travel depends on the stream slope, bed composition, sediment supply to the reach, and the presence of stable debris and/or large rock in the channel. The extent of head-cutting is usually less in coarse-grained or debris-laden channels than in finer-bedded streams because the head-cut is more likely to encounter a stable grade control that prevents it from moving further upstream. A channel with a high supply of mobile bed material will reach equilibrium more rapidly than a channel with a low rate of sediment supply.
- **Condition of upstream channel and banks:** Where a reach has aggraded above an undersized culvert, the channel can stabilize and return to its natural condition after some head-cutting occurs through the aggraded area. If the upstream banks are already marginally stable, however, the degrading channel can undermine and destabilize the banks.
- **Habitat impacts of upstream channel incision:** Allowing a large head-cut to travel freely upstream can damage aquatic habitats. For example, a newly incised channel may be narrow and confined, with habitat diversity and stability reduced because the channel cannot access its flood plain during high flows. Although the channel may evolve back into its initial configuration, substantial bank erosion and habitat instability

may persist for a long time. Where bedrock is shallow, a head-cut may expose it; and, if no debris or sediment structure is left, the stream will have difficulty trapping new sediments to recover habitat diversity and stability. Some bedrock (such as siltstone) is easily erodible once exposed. A head-cut can also cause enough incision to leave side channels perched, inaccessible, or dry. Avoid head-cuts in such areas. Restoring incised stream channels may require substantial channel reconstruction with wood and/or rock structures.

Wetlands can form upstream of many undersized or perched culverts. Although artificial, these wetlands may perform important functions for the riparian ecosystem. Carefully consider their fate when replacing culverts.

- **Habitat impacts to downstream channel from sediment release:** The risk to downstream aquatic habitats depends on the volume and rate of sediment released by a head-cut, as well as the transport capacity in downstream reaches. Downstream of large head-cuts, not only will the total volume of sediment in transport increase, but sediment will move at lower flows until the upstream channel and banks stabilize. Sediment deposition may occur in streambed areas not normally subject to deposition. Small head-cuts may not pose much risk at all to downstream reaches in many steep mountain streams.
- **Decrease in culvert and channel capacity from initial pulse of bed material:** Where bed material is mobile, allowing an uncontrolled head-cut upstream of a culvert may result in mobilizing a pulse of material during a single flow event. As this material moves through the culvert and the downstream channel, it can reduce the system's capacity. A loss of capacity can result in additional deposition and, in extreme cases, can fill the entire channel and plug the culvert.

  Allow less head-cutting where the culvert and/or channel have even a short-term risk of plugging by sediment and debris. Consider similar limitations where structures further downstream are at risk from a loss of channel capacity or where banks are at risk of erosion.

- **Proximity of upstream utilities and structures:** If a head-cut is allowed to continue upstream, it can jeopardize structures in or beneath the channel or on the banks. Asking the utility company to visit the site and locate any lines is common practice. Be aware of the potential effects of increased bank erosion on property and structures near the channel.
- **Potential for new fish passage barriers within the degraded channel:** Consider the potential for channel incision to create barriers to passage of fish or other aquatic species. Buried logs, non-erodible materials, and infrastructure, such as buried pipelines, are commonly exposed by channel head-cuts. As the channel head-cuts to such a feature, the feature itself may become a new fish passage barrier. Adding to the difficulty, these problems may occur where they are not visible from the project site, where access is

more difficult, or across a property boundary. In addition, upstream culverts could become perched, or, if they are embedded, their beds may wash out.

♦ Potential for Wood Debris

To determine if woody material poses a potential hazard to the crossing structure, evaluate the stability, size, and accumulation potential of wood in the project reach. Look for debris accumulations, and dead or undermined trees that could fall into the stream. Ask the following questions:

- Is the crossing in a land type where floods transport large wood and debris?
- Has the existing structure ever had problems with debris plugging?
- Are other nearby structures subject to plugging?
- How large is the wood in transport?
- What is the condition of wood in the reach? Is it durable, or fragile enough to break apart in transport?

To project future debris availability and stability, consider the long-term management plan in the watershed upstream of the crossing. Are debris inputs likely to change?

Where wood is an important structural component of the channel, also consider whether downstream channel conditions and stability depend on upstream woody material inputs. If so, wood transport through the crossing structure may be critical to the long-term stability of the whole reach. In general, stream-simulation culverts with good alignments tend to be large enough to freely pass debris. However, difficulties might occur with large wood and root-wads in low-profile structures or where structures are poorly aligned with the stream.

Table 9.8-1: Risks for Woody debris

Woody material Risk	Description
LOW	• Material dispersed uniformly along the reach (i.e., it has not moved). • Little or no wood available for local recruitment. • Bed material not anchored by debris. • Woody material likely to remain at or near source area.
MODERATE	• Most wood pieces anchored in the channel bed or channel banks. • Potential for local recruitment of wood. • History of occasional maintenance to remove wood at the crossing. • Small translational slides or undercut slopes adjacent to channel.
HIGH	• Most wood pieces not anchored to bed or banks. • Considerable wood available for local recruitment. • History of frequent maintenance to remove wood at the crossing. • Upstream watershed susceptible to debris flows.

♦ Unstable Channels

If the channel is unstable (rapidly incising, aggrading, shifting laterally, etc.), the design will have to address changing conditions as the stream evolves toward a new equilibrium. Any work performed in these situations must factor in both reach-scale and watershed-scale processes:

- Potential cause of the channel instability
  - local land-use activities
  - Higher peak flows, due to watershed development
  - Downstream channel incision
  - Sudden, large lateral movements
  - Extensive bank failures
- Proximity and extent of channel instability in relation to the crossing
- Any restoration activities already planned for improving channel stability
- Anticipated dimensions and configuration of the recovered channel
- Time frame for recovery to a stable channel

It is important to estimate not only the vertical adjustment potential but also future channel dimensions and pattern. The uncertainty about channel change, as well as the unpredictability of future disturbances, can make this kind of prediction very uncertain. Only a qualified and experienced team should perform the site assessment and replacement structure design on an unstable channel. The crossing design should attempt to mitigate the instability at the crossing by increasing the structure size or by bank stabilization measures. In addition, the team should plan for the potential for increased maintenance needs at the crossing.

9.8.7 Selecting the Reference Reach

The reference reach will not be finally selected until the project profile design is complete (see section 9.9.2). However, geomorphic data on one or more potential reference reaches is generally collected during the topographic survey.

The ideal reference reach represents the physical and hydraulic characteristics of the channel that would be expected at the crossing location if the road did not exist. The project profile may have to differ from the natural channel slope for a few reasons. Although the reference reach may not represent historical or average conditions of the project reach, it must be within the range of variation found in the vicinity. Looking at the range of variability in slope, width, etc. in the project area can provide an idea of how far a stream segment can depart from average and still be stable in the system.

Slope is a primary criterion for selecting a reference reach because it drives sediment erosion, transport, and deposition. In stable systems, these processes control sediment characteristics at a given location in the channel. Thus, the design slope through the crossing must be similar to the reference reach slope. Keep in mind that the reference reach is simulated in its entirety; width, slope, length, channel shape, bed characteristics, and roughness are all included in the simulation. This is especially important in unstable systems. The reference reach also should be similar in cross-section dimensions and entrenchment to the reaches upstream and downstream of the crossing. It represents a channel that will reconnect those reaches without creating flow discontinuities.

The reference reach is a stable reach upstream or downstream from the crossing but always outside the influence of the existing crossing structure or other structures with the vicinity. The factors that control channel dimensions in the reference reach must be like those that will control the simulated channel. At most sites, a reference reach can be identified close to the crossing, and the site data collected during the site assessment typically include a reach suitable for use as a reference. Occasionally, the most suitable reference reach may be some distance from the crossing site. This is not a problem if slope, flow, and sediment regimes are similar.

The following considerations go into selecting a reference reach:

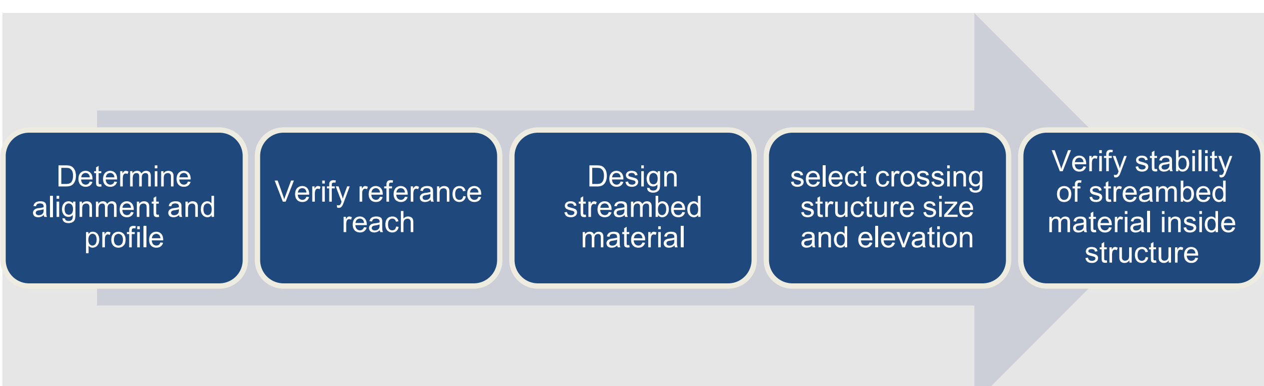
- The reference reach should be out of the area of influence of the existing crossing. Generally, it is upstream of the crossing to avoid any downstream channel changes the crossing may have caused. However, it can also be downstream if crossing effects are localized, and channel dimensions and slope are more appropriate to simulate at the crossing.

- The reference reach channel slope should be like the project profile slope through the road-stream crossing. Before selecting a final reference reach, determine the alignment and profile for the crossing project.
- Cross-section dimensions in the reference reach should be like the reaches near the structure crossing. Entrenchment should also be similar.
- Flow and sediment regimes at the reference reach should be like those at the crossing. No tributary junctions or sediment sources should be between the reference reach and the crossing. The reference-reach bed material must be similar in size and mobility to the reach upstream of the crossing that will supply sediment to the simulated channel.
- The length of the reference reach should be at least as long as the road-stream crossing structure.
- Determine the stability of both the reference reach and project reach. The reference-reach approach for channel design applies only to relatively stable channels.
- Where possible, avoid selecting a highly sinuous reference reach. A good method for testing the feasibility of using a particular reach as a reference reach is to visualize it enclosed in a crossing structure. Consider the characteristics that cannot be simulated, and whether they might compromise the simulation.
- Consider the distribution of channel units upstream and downstream from the stream crossing. For example, pool locations and spacing may dictate that the simulated channel includes a run or pool. The reference reach should include those channel units.

At new crossings, the undisturbed natural channel at the site is the reference reach. Ideally, you would build the crossing over the stream without disturbing it.

9.9 Stream Simulation Design

9.9.1 Steps and Considerations in Design



9.9.2 Crossing Alignment and Profile

The first step in stream-simulation design is to establish the project layout in three dimensions, including:

- The two-dimensional plan view that connects the upstream and downstream channels through the crossing.
- The streambed longitudinal profile that connects stable points upstream and downstream of the crossing.

♦ Alignment

Crossing alignment is the orientation of the structure relative to both the road and the stream channel. If the road crosses a straight uniform channel at right angles, the upstream and downstream channel reaches can be easily connected through a straight crossing. Most alignments, however, are often not this simple.

Poor structure alignment with respect to the stream (skew) is a perennial source of problems. Energy losses due to the channel bend at a skewed inlet means that backwatering and sediment deposition frequently occur upstream, even if the inlet is not plugged. Local bed scour inside the structure inlet is a common problem caused by the inlet contraction, or because flow is focused to one side. A skewed inlet or outlet can also cause severe bank erosion outside the structure by directing the flow at erodible banks. Because all these risks are associated with high flows, visualization of flow patterns at high flows when considering the crossing alignment.

The relationship between the Radius of Curvature (R_c) of the upstream bend and bank-full width is an indicator of the level of risk posed by a skewed alignment. When R_c is greater than 5 times bank-full width, sediment and debris transport is essentially the same as on a straight channel. As R_c decreases, the risk of affecting sediment and debris transport increases and when R_c is less than twice bank-full width, the risk of impeding sediment and debris transport is substantial. More flow is forced to the outside of the bend, and large eddies form on the inside of the bend, impeding flow and reducing the effective width of the channel (Bagnold, 1960); (Leopold, 1964). These transitions at skewed crossings should match the R_c of the natural channels to minimize the sediment and debris issues.

Aligning a properly sized structure parallel to the upstream channel minimizes the risk of backwatering, sediment deposition, debris blockage, and capacity exceedance for that structure. However, aligning the crossing structure with the channel often results in a skewed alignment relative to the road, which can require a longer structure, the installation of headwalls and wing walls, or the need for a bridged crossing.

Another common alignment problem arises where the crossing is located at a bend in the channel. Some options in this situation are:

- matching channel alignment,
- realigning the stream,
- widening and/or shortening the structure,

None of these options necessarily stand alone. The best solution might be optimizing a combination of skew, structure length, and structure width changes.

Consider how far the channel is likely to migrate laterally during the life of the structure. Options for accommodating expected changes include the following:

- Widen the structure and offset it in the direction of meander movement.
- Control meander shift at the inlet with appropriate bank stabilization measures or training structures, such as rock weirs or barbs.

If bank lines are constructed within the structure, the rocks on the outside bank will be exposed to higher shear stresses and might therefore need to be larger than bank rocks in other locations.

♦ Crossing Alignment

One common alignment challenge is shown in Figure 10, where the road is aligned at an acute angle to the stream. Three alignment options for this situation are:

a) Matching culvert alignment to stream alignment.
b) Realigning the stream to minimize culvert length.
c) Widening and/or shortening the culvert.

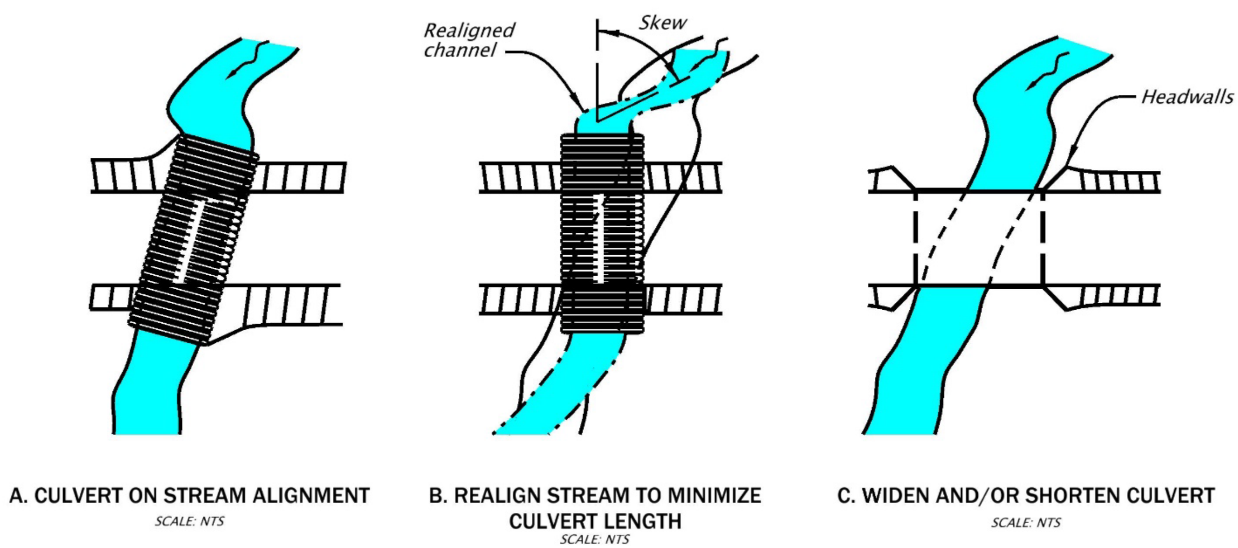


Figure 9.9-1: Crossing alignment options for crossing vs. channel skew.

A project can combine elements of all three options. Other possible approaches include relocating the road to a better stream alignment or building a bridge with a wider span. Of the options above, (B) entails the greatest risk. The risks listed in Table 3 should be evaluated and compared for projects where the road crosses the stream on a strongly skewed alignment. Minor skews are not likely to have important effects on the stream. The effects and impacts listed in Table 3 are general and may not apply to all situations.

Table 9.9-1: Crossing Alignment (Alignment options, attributes, and associated effects)

Alignment Options	Attributes	Associated Effects and Comparison of Options
A) Crossing on stream alignment	Inlet/outlet match channel alignment.	• Risk of debris and/or sediment blockage is low.
	Culvert is long.	• Permanent direct loss of aquatic habitat is highest. • Risk of simulated channel failure and loss of passage is higher vs. shorter culverts
	Culvert is skewed to road.	• Special design and construction methods may be required.
B) Realign channel	Inlet is skewed to channel.	• Probability of blockage by debris and sediment is greatest. • Risk of culvert failure is greatest.
	Channel, riparian area and banks are disturbed.	• Riparian area is removed, and habitat impacted. • Newly constructed and/or over-steepened banks are less stable, risks of bank failure or erosion are higher.
	Channel grade is flattened due to added length.	• Risk of upstream aggradation is increased. • Need for maintenance to remove sediment is increased.
	Outlet may be skewed to channel.	• Risk of bank erosion downstream is greatest.
C) Widen and/or shorten culvert	Inlet/outlet match channel.	• Risk of debris and/or sediment blockage or plugging is low.
	Large open area.	• Culvert capacity is greatest, lowest risk of culvert failure. • Risk of failure due to debris blockage or plugging is lowest. • Opportunities for passage of aquatic and terrestrial organisms are greatest.
	Longer construction duration.	• Risk of construction activity detrimentally affecting wildlife is greatest.
	Area of channel impacts are small.	• Permanent direct habitat loss is least.

♦ Profile

The longitudinal profile and the plan view must be considered together because they are interdependent. When a structure straightens the natural channel, it also shortens and steepens the channel, increasing the velocity and energy of flow through the crossing.

The first step in designing the project layout is to understand the natural channel location and pattern through the crossing area. Understanding the natural channel pattern helps explain how the existing crossing affected both stream length and slope. Try to formulate different layout options that approximate the natural pattern so that the replacement structure conforms better to the natural channel. The project profile represents the surface of the streambed that will be constructed through the project reach to connect the upstream and downstream channel profiles. It corresponds to the slope segments, which connect the grade controls in the natural channel. At new road stream crossing installations where the road alignment is perpendicular to the stream, the existing channel longitudinal profile is the project profile.

The project-profile analysis is one of the most critical elements in a stream simulation design, whether the project is a new crossing, a replacement, or a crossing removal. A good project-profile analysis helps ensure that the new structure will accommodate expected future vertical streambed adjustment.

The scale of any channel adjustment problem caused by the previous structure determines the scale of the solution. The project profile can be short if no large-scale vertical adjustment is anticipated, such as where nearby stable steps or bedrock outcrops anchor the ends of the profile. The project profile will be longer where upstream aggradation and downstream incision at an undersized crossing create a large elevation drop. The profile will be longer still if large-scale downstream channel incision has occurred. In this case, connecting the upstream and downstream channels requires dealing with potential upstream head-cutting and/or downstream channel rehabilitation over a longer stream reach.

Designing the project profile involves the following steps.

1. Identify stable endpoints for the project profile.

   In coordination with geotechnical staff, select stable grade control features upstream and downstream of the crossing that will anchor each end of the project profile. They should be stable enough that they will not be affected by removal of the existing crossing structure. Profile endpoints might be bedrock outcrops or highly stable steps, riffle crests, debris accumulations (e.g., large, well-embedded logs), etc. Several features may be good candidates for stable endpoints, and you might evaluate various project profiles using different combinations of endpoints. In this context, ‘stable’ means the bedform will last as long as the structure lifetime. It does not necessarily have to be permanently immobile. The cobbles on a high-stability riffle crest, for example, may mobilize in the 10% or 4% annual

(10- or 25-year) flood event, but the riffle crest itself will remain at or very near its current location and elevation if the channel is stable.

If the downstream channel is incised, the lower potential vertical adjustment line indicates the length and depth of the potential channel incision upstream. Most alluvial bedforms higher than the lower adjustment potential line would not be expected to constitute stable endpoints in this case. If you decide to allow a head-cut to progress through the crossing, the upstream project profile endpoint would need to be upstream of the projected extent of incision. Alternatively, if you decide to maintain the crossing as a grade control, you may need to construct permanent grade control structures as the project profile endpoints.

2. Delineate possible project profiles.

Draw one or more tentative project profiles between sets of control points to connect the upstream and downstream segments across the crossing. The project profile should extend at least 10x the ACW upstream and downstream as the new crossing structure installation could directly affect the channel. The profile does not show bed topography, only the elevation and slope of the streambed that will be constructed. Calculate slope and length of the profile options.

The best project profile is a uniform one beginning and ending on stable bedforms. However, some project profiles may have two segments with different grades. Sites with convex or concave profiles, for example, might have more than one segment. In these cases, it is recommended the slope break be outside the crossing structure. The same type of segmented project profile, with the steeper section constructed outside the crossing structure, could be used at any site where the elevation change exceeds the slope of available reference reaches and where the adjacent natural channel is stable enough to sustain the transition.

3. Verify the reference reach.

After identifying one or more project-profile options, recheck the reference reach tentatively identified during the site assessment (Section 9.8.7). Determine whether it adequately represents the preferred slope. The reference reach should be straight, and as long as the crossing structure. Ideally the reference reach should also be equal in length to the project profile, but this is not always feasible on meandering streams or where wood is a frequent bed feature. If the tentative reference reach does not match the desired project profile, evaluate other slope segments in the site survey (Section 9.8.4) as a possible reference reach.

If the site assessment survey did not include a reach as long as the project profile, revisit the site to see if the natural channel includes reaches closer to your needs. If not, consider controlling the project profile to fit an available reference reach more closely. This need commonly arises when:

1. there has been a large amount of aggradation upstream and deep local scour downstream of an undersized crossing or,

2. the downstream channel has incised, and the existing crossing structure is acting as a grade control to prevent upstream head-cut migration,
3. the natural channel profile is concave, convex, or complex.

If profile modification will not work, the remaining options for crossing design are to:

- Use a hydraulic or hybrid design method to achieve passage (section 9.10) or,
- Locate a reference reach on a different channel that has similar landscape characteristics: valley type, streambed materials, watershed size, hydrologic regime, etc. This option has strong limitations (see section 9.7.7).

4. Adjust the profile lines if necessary.

Where the project profile will be controlled by permanent grade control structures, the potential vertical adjustment lines may require adjustment to correspond with the project profile and reference reach.

5. Locate key bed features.

Based on the reference reach, determine the spacing, height, and location of any bedforms that need to be constructed. Bedforms are generally spaced based on average spacing in the reference reach. Tying them into the endpoint bedforms, however, sometimes requires varying bedform spacing. Meander bends, which control pool locations, must also be considered when locating the bedforms in the project reach. The average spacing may need to be varied to locate the pool appropriately in relation to the bend. Limit the variability in spacing to the range found in the reference reach.

9.9.3 Crossing Channel

After determining the best horizontal alignment and vertical profile for the site, design the stream simulation channel using the characteristics and dimensions of the reference reach.

This section describes design of the following streambed elements:

- Channel width and cross-section shape.
- Bank lines, margins, and key features.
- Bedforms: pool-riffle, step-pool, or other sequences.
- Particle-size distribution of the bed material.

These elements control channel gradient and provide enough roughness to maintain the diverse range of water depths and velocities needed for fish and other aquatic species passage. The reference reach is the template for all these elements. Flood conveyance considerations and other project objectives, such as terrestrial animal movement, will determine the amount of bank space allowed inside the structure.

A key element to stream simulation design is creating roughness conditions like the reference reach. Total roughness depends on several features, including:

- Channel shape.
- Bedforms (fixed or mobile).
- Key features that constrict the channel and are major roughness elements.
- Vegetation.
- Bank irregularities.
- Channel bends.
- Bed material particle-size distribution.

Not all these features can be replicated inside the crossing structure, but the design still needs to approximate total reference reach roughness. For example, large, oversized boulders (fish rocks) are required to be incorporated throughout the crossing structure by ODFW.

The following sections describe how to simulate those elements that can be simulated. Clearly, since channel bends cannot be simulated, a straight, uniform reference reach is ideal.

Section 9.9.6 describes basic procedures for designing a simulated stream bed using reference reach characteristics and covers special considerations for specific channel types. The key is to mimic those features in the reference reach that influence channel gradient, energy dissipation, bed stability, and physical and hydraulic diversity.

9.9.4 Channel Cross Section

The width of the simulated channel is typically the active channel width of the reference reach or greater. This is not necessarily equal to the crossing structure width. One example of this is the NMFS criteria of 1.5 times ACW for the minimum structure width at or below OHW elevation. Bank features and/or overbank flow surfaces may require additional crossing structure width.

In channels with mobile beds (dune-ripple, fine-grained pool-riffle), complex channel shapes like those that develop over time in a natural channel need not be constructed. However, some bank features should be constructed to set the stage for channel margins to develop.

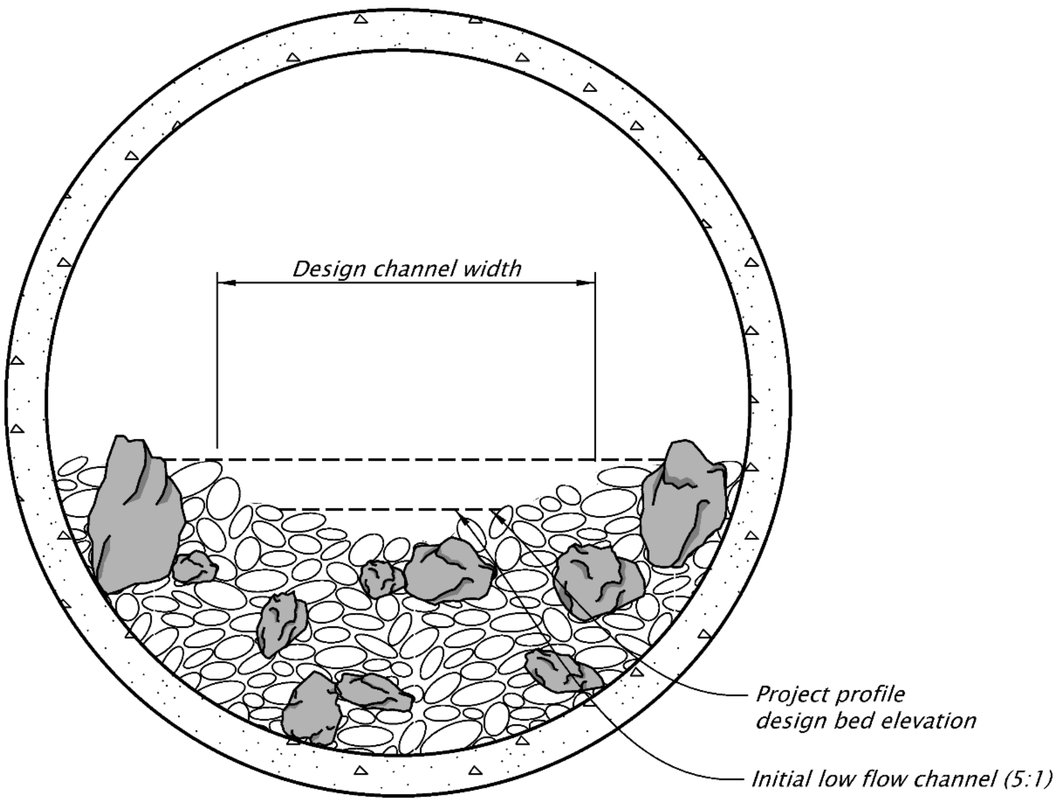


Figure 9.9-2: Channel Section within culvert

Without constructed features, the bed initially tends to flatten into an unnatural flat surface. Then, the main thread of flow often migrates to the culvert wall and progressively erodes a trench along the wall.

In addition to banks and any other key features, a low-flow channel should be constructed to help keep flow from hugging the culvert wall until a natural bed structure develops. (see Figure 12)

Stream simulations in less mobile channels are often constructed with some initial bed structure such as steps. Specifics for each channel type are described in (Buffington & Montgomery, 2013) "Geomorphic Classification of Rivers".

9.9.5 Channel Bank and Margin Features

In natural channels, the diversity, roughness, and shape of channel margins and bank lines are critical for movement and refuge of some species. For example, terrestrial animals may need dry passage; weak swimmers and crawling species may need margins of slow, shallow water with eddies in which they can rest. At flows between low-flow and bank-full, channel edge diversity is necessary for accommodating the different movement capabilities of all aquatic species. Banks must continue through the inlet and outlet transitions.

Bars may form in a crossing structure, and they may provide some of the benefits of a bank line. However, without root structure, cohesive soils, or the ability to scour into parent bed material, true bank lines will not form naturally inside the structure. Therefore, specific channel-margin features should be designed into the project when they are needed for hydraulic roughness, habitat diversity, or for preventing channel trenching along culvert walls and protecting footings from scour. In designing the bank line/margin, use the reference reach bank height and bank line diversity (including frequency and size of wood or rock protrusions) as a guide. Where wood is an important feature on the channel banks, use permanent rock within the structure to simulate its functions.

Because the intent is to create permanent bank line features, use material large enough to be stable during the high bed design flow. In the absence of vegetation, bank stability inside the structure will depend primarily on rock size, packing, clustering, and embedment. Base an initial estimate of rock size on the reference channel. As a starting point, bank material might be up to twice the size of D95 in the reference reach. If D95 is 3 inches or less, you can use 6-inch-minus quarry or other rock. The size of rocks that appear to be stable in the reference reach may also be a clue to sizing bank line rocks. Later in the design process, a stability analysis will verify that the bank rock and other key pieces are large enough to be stable.

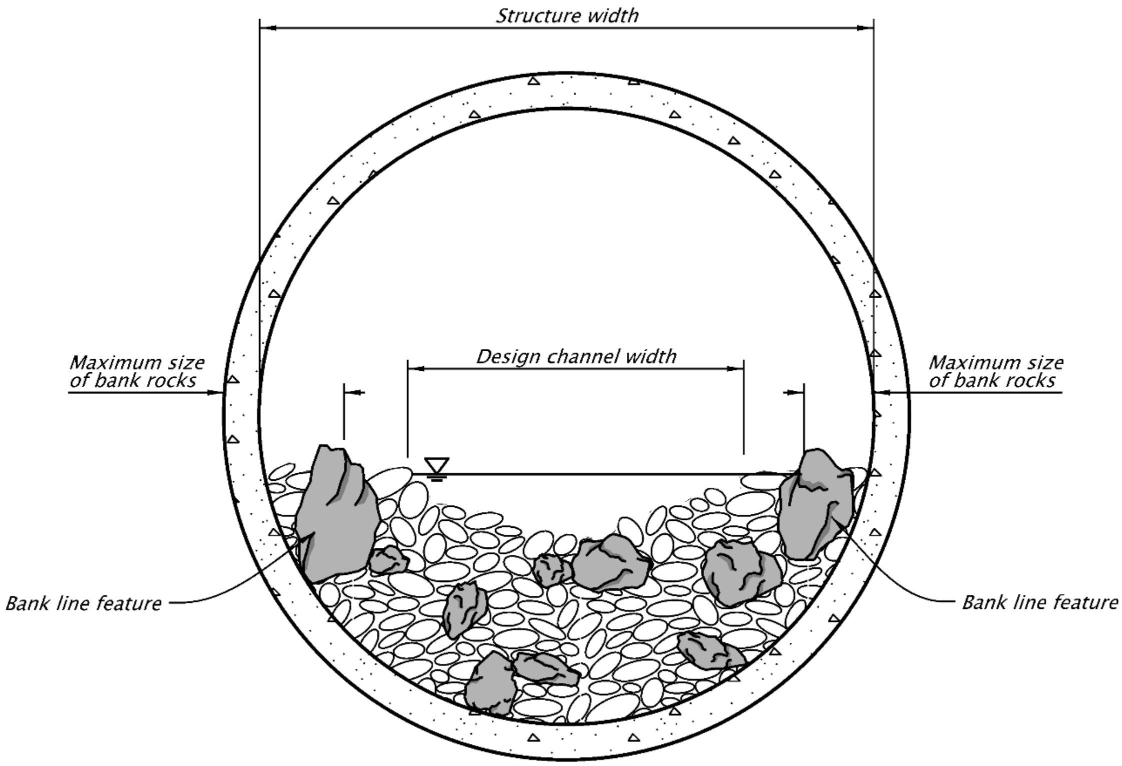


Figure 9.9-3: Bank line features

The simplest bank line is an irregular line of large rock placed along each wall (See Figure 12). Most natural banks are rougher and more diverse than that, and a discontinuous line of rocks or rock clusters may better simulate the reference reach. Clusters of rock obstruct any tendency to scour along the structure wall and help create the bed diversity that exists in natural channels where water deflects off bank line irregularities like woody debris or root-wads. Fill the spaces between individual bank rocks and between the rocks and the structure wall with 'filler' material, so that the finer material helps to stabilize the larger rocks.

Overbank flow surfaces or flood-plain benches are sometimes constructed inside the crossing structure. Construct them the same way as bank clusters or bank lines, with the entire surface being stable rock infilled with filler material. The flood-plain bench should start at bank-full elevation on the margin of the bank-full channel and slope up and out at about 10h:1v (see Figure 10).

9.9.6 Engineered Streambed Material

Stream-simulation bed material, also known as “Engineered Streambed Material”, is designed based on the reference reach particle-size distribution. It should be well graded (consisting of a wide range of particle sizes), and it must include enough sand, silt, and clay (particles less than 2 millimeters in diameter) to fill voids between larger particles and reduce infiltration into the channel bed. The procedure described here produces a particle size distribution curve that approximates the reference reach. Later in the design process, particle sizes may need to be modified to deal with various risk factors; for example, you might increase particle sizes somewhat if the simulation needs to be slightly steeper than the reference reach.

If particle size results from a depth-integrated bulk sample of the reference reach are available, the simulation can have the same grainsize distribution as the bulk sample. However, bulk sampling is difficult in coarse-bedded streams because representative samples must be very large. Typically, stream-simulation bed-material gradation is based on the reference reach pebble count, which represents only the bed surface. In unarmored or weakly armored channels, the surface pebble count characterizes the entire streambed, and the engineered streambed material will have the same gradation as the pebble count. However, in armored channels the surface pebble count underrepresents the smaller sizes in the subsurface and therefore the smaller particle size classes must be either estimated or calculated. The D95, D84, and D50 percentile particle sizes of the reference reach bed become the corresponding grain sizes of the stream-simulation gradation in both armored and unarmored channels. The smaller grain sizes in the streambed are extremely important for bed permeability and stability. A porous bed can allow substantial infiltration and loss of surface flow. The simulation bed mix must have enough fine materials to fill the voids between the larger particles. Do not assume that the stream will transport sufficient fines to seal an open-graded bed surface, because a natural filling-in of the voids can take years. The issue with loss of surface flow is especially critical in steep channels; where bed particles and voids between them are larger, and the steeper hydraulic slope can drive the flow into the subsurface.

Since pebble counts of armored bed surfaces underrepresent the finer material in the subsurface, grain sizes smaller than D50 must be determined another way. One method is the equation developed by (Fuller & Thompson, 1907), which defines dense sediment mixtures commonly used by the aggregate industry. This equation has not yet been widely field-tested for the application of streambed sediments, so apply good professional judgment when using it.

The Fuller-Thompson equation is:

Equation 9.8-1 $P/100 = [\, d/D_{max}]^{n}$

Where: d is any particle size of interest

P is the percentage of the mixture smaller than d,

D_{max} is the largest size material in the mix, and n is a parameter that determines how fine or coarse the resulting mix will be.

An n value of 0.5 produces a maximum density mix when particles are round.

The Fuller-Thompson equation can be rearranged to base the particle size determination on D50 rather than D_{max}. Basing the calculation on D50 avoids a discontinuity in the particle size distribution curve, which otherwise occurs when the actual D50 is different from the value calculated from D_{max}. The equations for D5 through D95 are:

Equation 9.8-2 $D_{95} = 1.9^{1/n}\,D_{50}$

Equation 9.8-3 $D_{84} = 1.68^{1/n}\,D_{50}$

Equation 9.8-4 $D_{30} = 0.6^{1/n}\,D_{50}$

Equation 9.8-5 $D_{10} = 0.2^{1/n}\,D_{50}$

Equation 9.8-6 $D_{5} = 0.1^{1/n}\,D_{50}$

To develop the particle-size distribution curve for the finer portion of the simulation bed mix, use n values between 0.45 and 0.70, a standard range for high-density mixes. The goal is a dense, well-graded bed mix with a percentage and type of fine material (sand, silt, clay) like the percentage and type in the reference reach subsurface. The fines are essential to limit infiltration into the bed and to help lock the larger pieces together. Type and percentage of fines vary with geology and stream slope, but generally the bed mix should contain at least 10-percent fines. If the D5 resulting from the Fuller-Thompson equation is larger than 2 millimeters (0.079 inches) (for n = 0.45, this occurs when D50 is larger than 330 millimeters or 13 inches), adjust the mixture so that fines comprise at least 10 percent. If your field estimates of fines (section 9.8.5) differ substantially from this, adjust the mixture to approximate the field composition.

Using the Fuller-Thompson method does not produce the natural subsurface particle size distribution in the reference reach subsurface; but it does result in a dense, well-graded distribution. Similar results may be obtained by smoothly redrawing the lower half of the particle size distribution curve by hand, such that the tail has an appropriate percentage of fines smaller than 2 millimeters (0.079 inches).

Note that these design procedures result in a bed mix that is coarser overall than the reference reach subsurface gradation. This constitutes a safety factor for the simulated bed. If the bed scours, there will be additional armor material below the surface and the resulting bed surface will become coarser and rougher.

The method of deriving a design gradation from the pebble count is not critical. What is critical is that the design gradation have the following key characteristics:

1. Large particles (D95, D84, and D50) that provide bed structure and buttress finer material should be accurately sized based on the reference reach. In channels where wood controls or influences the channel form, structures composed of angular rock can substitute for wood to simulate channel features in the crossing structure.

2. The entire bed mix should be well graded (poorly sorted). A dense, stable bed requires all particle sizes, so no gap in sizes should exist between any classes of material in the design bed mix. Ideally, each class of bed material that makes up the mix will be well graded before being placed, so that all sizes within the category are represented. This representation is especially important for the smaller-size fractions in a mixture that includes large particle sizes.
3. The percentage of sand, silt, and clay should approximate the reference reach channel bed subsurface and should be adequate to limit bed permeability by filling voids between the larger particles. Including sand, silt, and clay in the simulation bed material commonly arouses concerns about water quality and habitat impacts, because some fine sediment in a freshly constructed bed will move during low flows and could affect downstream fish habitats. Any such effects can be limited during construction by using compaction equipment and water to wash the fine material down into voids between the larger particles in the bed.
4. Bed material rock should be durable, and it should be at least as angular as in the reference channel. If it is less angular, it may be significantly more mobile than intended. It makes sense to try to find local material, as it will more likely resemble the natural bed material. Material salvaged from onsite excavations is usually a very good source of like materials.

9.9.7 Structure Dimensions and Type

Up to this point, geomorphic design methods have been used to define both the probable range of stream profiles at the site and the size, shape, materials, and arrangement of the stream-simulation channel bed.

Now, size the structure by fitting it around the designed channel. This discussion is primarily about culvert design, but similar width and height considerations also apply to bridges and open bottom structures.

Culvert elevation and dimensions are determined at this point because they affect the bed mobility calculations in the next design step. It may take several iterations to select the final dimensions, because the bed mobility calculations may indicate the need to change culvert dimensions. Only the dimensions and elevation of the culvert are determined in this step. Many other considerations enter the final choice of structure type and materials.

One of the goals in stream simulation is that the simulated channel be self-sustaining. That means it must simulate the hydraulics of the natural channel at sediment-transporting flows, especially the flows that create and rearrange major bed structures. To achieve these objectives, the simulated channel must be free to adjust to changes in incoming flow and sediment loads, and the culvert must be large and embedded deeply enough to accommodate both vertical and lateral adjustments.

Several factors go into determining culvert size and elevation. These include:

- The active channel width.
- The bank-full width of the channel.
- The width of any bank lines and overbank surfaces.
- The range of possible bed profiles.
- The maximum sizes of alluvial and immobile rocks.
- The results from the bed stability and flow capacity analyses.

♦ Structure Width

The stream simulation approach avoids flow constriction during normal conditions by using structures at least as wide as the natural channel.

In Oregon, the minimum required agency widths are:

- ODFW
    - 1.2 x ACW +2 ft
- NMFS / USFWS
    - 1.5 x ACW width for single span structures
    - 2.2 x ACW width for multi-span structures

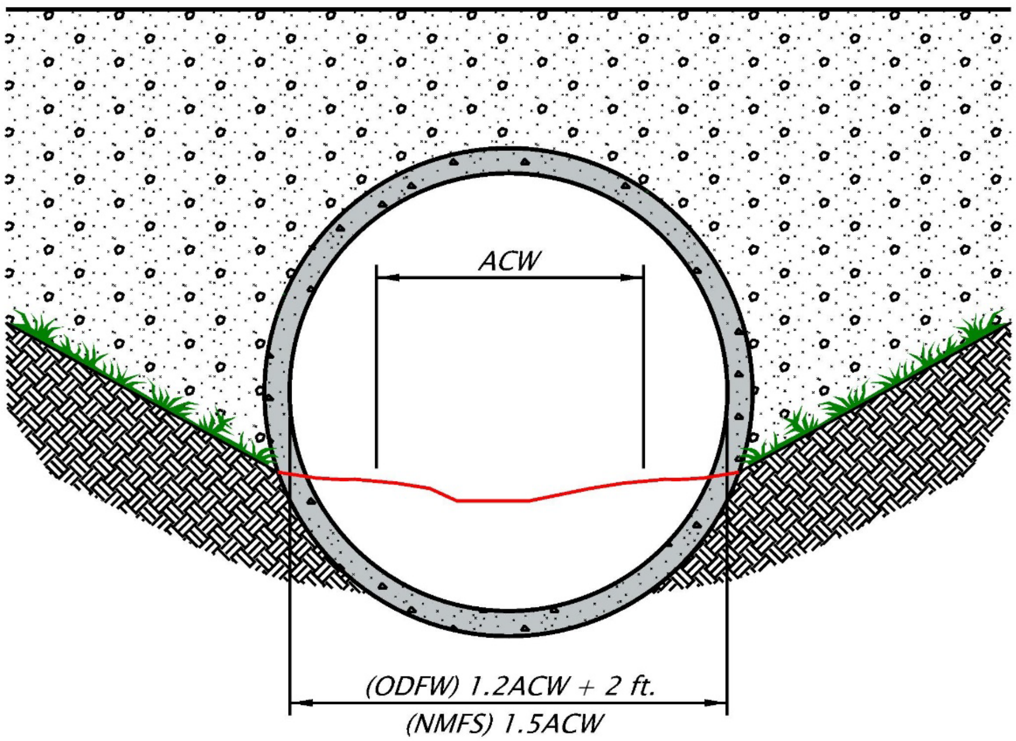


Figure 9.9-4: Circular culvert

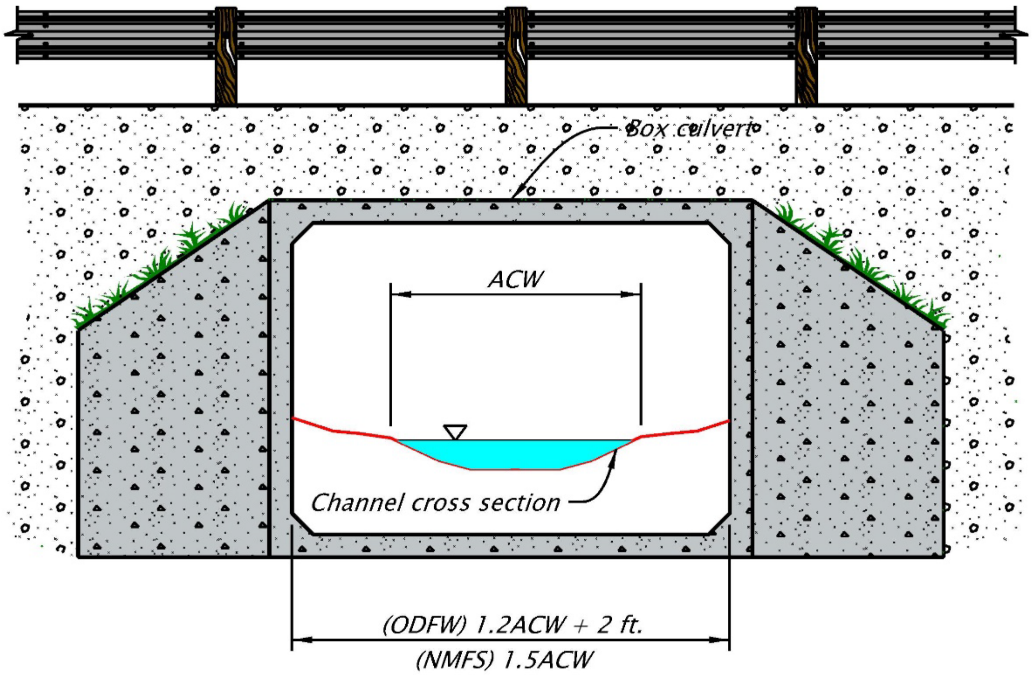


Figure 9.9-5: Box culvert

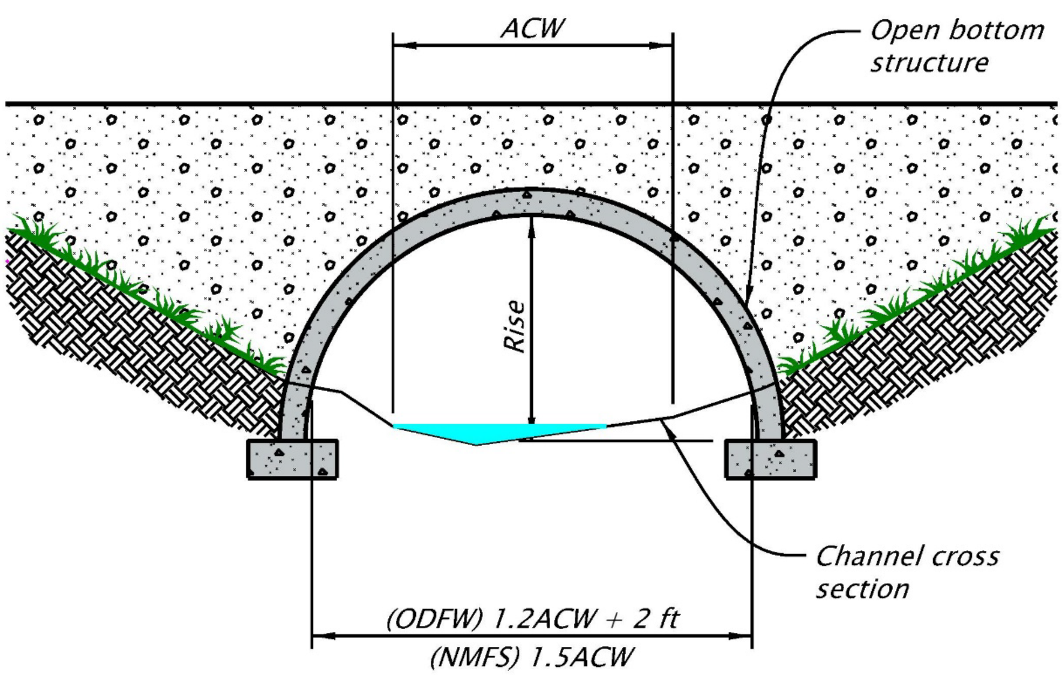


Figure 9.9-6: Open Bottom Structure width

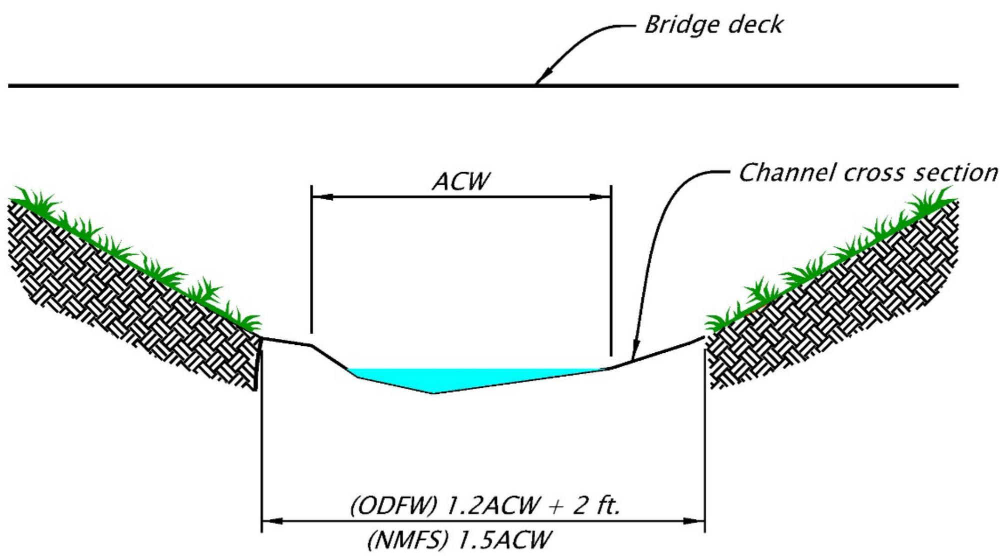


Figure 9.9-7: Bridge Width

The constructed stream channel within a culvert is designed to ensure adequate water depth during low-flow conditions and resist scouring during flood events. Well-designed stream simulation culverts can maintain the continuity of stream bottom and hydraulic conditions, thereby facilitating passage for fish species. Designing culverts to avoid channel constriction and maintain appropriate channel conditions within the structure is a relatively simple and effective approach for accommodating the normal movements of aquatic species and preserving (or restoring) ecosystem processes that maintain habitats and aquatic populations. Where passage for riparian and terrestrial wildlife is desired, stream simulation structures can be adapted for wildlife preferences.

Stream Simulation approaches are based on recreating or maintaining natural stream reach geomorphic elements including slope, channel-bed width, bed materials, and bed form.

The basis of these methods is the presumption that crossings matching natural conditions will readily pass fish that are moving in the natural channel. Design methods are based on a reference reach.

♦ Culvert Width

A variety of factors determine the structure width needed to achieve project objectives and to accommodate site conditions:

The minimum width required is as stated above.

Based on project objectives:

- Stability of the simulated streambed.

- Hydraulic capacity of the culvert
- Risk of blockage by floating debris or beaver activity.
- Construction, repair, and maintenance needs.
- Passage of nonaquatic species.
- Meandering channel pattern.
- Protection of flood-plain habitats.

Based on site characteristics:

- High flood-plain conveyance and potential to concentrate overbank flows within the culvert.
- Lateral channel migration.
- Wider channel expected in the future.
- Channel skewed to road crossing or crossing on channel bend.
- Ice plugging in colder climates.
- Large bed material relative to culvert width.

Extra structure width is necessary for creating a stable bank line without constricting the active channel. In entrenched and moderately entrenched channels, the first estimate of culvert width is simply the minimum agency width required. This initial estimate, of course, is subject to change depending on the results of the stability analysis of the bank line rocks. As noted in Section 9.9.5, where the reference reach has a rough, irregular bank line; the simulated banks may be laterally deeper and may require more structure width.

For a stream-simulation design with banks, minimum culvert width is the agency required minimum width plus twice the maximum diameter of rocks used to construct the banks. [Ex. (1.2ACW+2+(2D100))].

In an un-entrenched channel with an active flood plain, the road fill could block overbank flood flows and force them through the culvert. Section 9.9.8 discusses at some length the risks associated with flow concentration in active flood plains and their possible solutions. Placing additional culverts or dips that permit flood-plain flow through or across the road fill may reduce the risk to acceptable levels. If not, you may also need additional culvert width to allow for an overbank-flow surface within the culvert.

In choosing culvert width, also consider how the largest key-feature rocks (or rock clusters) in the simulated bed will interact with rock and wood pieces moving during high flows. A natural channel can usually scour around a large boulder or debris accumulation. In a culvert, however; a large individual boulder can create a constriction or form a bridge with other large particles, creating a culvert-wide drop structure or debris jam, and possibly limiting passage, culvert capacity, and/or bed stability. A good check is that the active channel width inside the culvert should be at least four times the intermediate diameter of the largest immobile particles in the simulated bed.

Early in their development, incising channels may look narrow, but they will widen with time because the banks become unstable and fail in response to bed lowering (Schumm, Harvey, & Watson, 1984). Size a stream-simulation culvert to anticipate the expected widening of the natural channel near the crossing. On the other hand, if a channel is unnaturally wide from disturbance, and you expect it to narrow in the future; size the culvert for the current channel, with the expectation that recovery will occur inside the culvert as in the adjacent reaches.

As noted in Section 9.9.2, you may need to increase culvert width if the culvert is skewed to the road alignment or if natural lateral migration of the channel will likely create a skewed-inlet condition.

♦ Culvert Height and Elevation

Points on the stream channel bed may at some time be at any elevation within the range of potential vertical adjustment (see Section 9.9.2). The culvert invert elevation and culvert height must allow for these vertical bed elevation adjustments over time. The stream simulation bed should be thick enough (and the invert deep enough) to avoid exposing the bare culvert floor during floods, and to allow large particles to be supported by the finer bed matrix, even at the bottom of a pool at the lowest potential bed elevation. To achieve this, set the elevation of the bottom of the culvert or footing below the lower potential vertical adjustment line, adjusted to include the estimated depth of streambed scour during floods (2 times D90, see Section 9.8.5). For bottomless culverts, structural design of the footing and any engineering scour analysis that may be conducted should be consistent with the Bridge Chapter and may dictate a lower elevation. Placement of bank rocks to protect footings may also affect their depth.

Once the culvert invert elevation is set, determine the culvert height needed to maintain flood and debris capacity when the bed is at its highest possible elevation. Setting the widest point of a round culvert at or above the highest potential bed elevation is an efficient design technique because it uses the full width of the culvert. Generally, it also ensures headroom for floodwater and debris, although very large floating debris may not clear the inlet of the pipe during very high flows.

The project design event is the highest flow that immobile particles are designed to sustain without moving. They are unlikely to remain in place if the culvert inlet becomes submerged and pressurized during a flood. For stability, it is recommended that the inlet not exceed 80-percent submergence during the 1% annual flood and 67 percent where woody material is a significant concern. Ensure that the actual free space is large enough to accommodate the size of debris moving in the channel. Naturally, this does not apply to submergence caused by backwatering when water levels are similar on both sides of the crossing.

Where bed-load transport is high enough, sediment will be replenished, and the bed may reconstruct itself as the flood recedes. Provide a safety factor for invert depth and/or culvert height commensurate with the level of uncertainty and the risk of failure. Where the consequences of failure are large, use a larger culvert or a deeper footing.

Regulatory agencies require stream material embeddedness criteria for stream simulation culverts:

- NMFS requires that culverts include 30% - 50% of backfill, with a 3-foot minimum depth.
- ODFW requires that at least 20% of the culvert depth is embedded.

Regulatory agencies also have minimum freeboard criteria for vertical clearance in culverts:

- NMFS requires 1 foot of freeboard above the 1% annual (100-year) recurrence peak flood elevation.
- ODFW requires at least 3 vertical feet between the ACW elevation and the top of the culvert.

♦ Culvert Shape and Material

Aside from the size, elevation, and alignment issues already discussed, most of the considerations for culvert shape and material involve site conditions, designer preference, and cost. These considerations include:

- Commercial availability.
- Structure longevity. (Refer to Pipe Materials Chapter)
- Road elevation and fill height.
- Streambed and culvert constructability.
- Construction time, sequencing, and allowable ‘in-water’ work period.
- Soil-bearing capacity.
- Site access.
- Flood capacity.
- Geotechnical considerations
- Water chemistry considerations (e.g. tidal or saltwater)
- Bedload and sediment transport considerations

9.9.8 Managing Risk Factors

This section focuses on risks specific to stream-simulation installations as well as the risks that apply to all culverts.

First, reduce the probability of failure by identifying the processes or conditions that could lead to failure, and by mitigating them in design or construction. “Failure” in this context means not only structural failure (culvert washes out, flow diverts down road, etc.), but also failure to achieve stream-simulation objectives. Simply having bed material inside a culvert does not constitute stream simulation. For the project lifetime the simulated streambed should maintain a suite of characteristics like those found in the natural channel near the culvert (bed material type and structure, channel dimensions, flow velocities and depths). Any of the risk factors listed in Table 4 could lead to failure.

Second, recognize that any crossing can fail in an extreme event, and design to reduce the consequences of failure. Methods for reducing failure consequences include preventing diversions down the road or ditch if water overtops the road fill and ensuring that the culvert is accessible and large enough to permit future access for maintenance and repair.

♦ Potential Failure Risks

An installation can have multiple failure risks; evaluate and mitigate each risk in the context of all the others. For example, a straight culvert and road fill placed over a sinuous stream in a wide active flood plain constricts the flood plain and shortens the channel. In addition to adding flood-plain relief dips or pipes and increasing culvert width to mitigate these risks, you could also increase the size of the bed material. However, increasing bed-material size to mitigate for flood-plain constriction, and then again to mitigate for channel straightening, could defeat the purpose of stream simulation. A bed-mobility analysis integrates the risk factors and is frequently the key to determining the magnitude of the risk and finding appropriate ways to mitigate it. In Table 4, asterisks denote design strategies that involve bed-mobility analysis.

If bed-mobility analysis indicates that the simulated streambed materials will move at lower flows than in the reference reach, revisit the site to see if you can find a more appropriate reference reach. For example, if you have selected a project profile that is steeper than the reference reach, see if a natural-channel reach exists at the higher slope—one that may be appropriate as a reference reach. Be sure the new reach meets all the requirements, such as similar length, flow regime, sediment loading, and if possible, entrenchment. Other design solutions may have to be considered also, such as modifying the project profile or enlarging the culvert.

Table 9.9-2: Mitigating Potential Risks

DESIGN CHALLENGE	DESIGN STRATEGY	OUTCOME OF DESIGN STRATEGY
Flood plain constriction	Widen culvert*	• Allows high flows to occupy wider flood plain areas within culvert.
	Increase bed material size*	• Increase bed stability.
	Add flood plain relief culverts*	• Avoid flow concentration.
	Place layer of large rock under streambed material	• Reduces risk of complete loss of stream material. • Reduces risk of upstream head cutting if simulated area fails. • Requires larger culvert to allow for combined depth of rock layer and fully vertically adjustable streambed.

DESIGN CHALLENGE	DESIGN STRATEGY	OUTCOME OF DESIGN STRATEGY
Rapid lateral channel migration	Widen culvert and offset it in the direction of expected channel shift	• Slows development of channel to culvert skew caused by channel shift. • Stream simulation channel may function normally for a longer period before being constrained by culvert
	Provide best possible culvert alignment, stabilize banks, provide flow control structures (rock weirs or J-hooks)	• Prevents channel movement. • May move channel alignment problems to reaches further from the culvert.
Pressurized inlet. (Inlet is submerged; outlet is not submerged)	Increase culvert size to limit headwater depth during high bed design flow to 80% of culvert height above bed.	• Reduces incidence of very high-water velocity in culvert. • Roadway vertical curve can be problem with round culverts.
	Add flood-plain relief culverts. *	• Lower water elevation upstream of crossing.
Downstream channel instability.	Verify vertical adjustment potential, and ensure simulated bed is deep enough, and culvert is large enough to accommodate range of potential profiles.	• Allows for natural variation in streambed elevation as long as actual degradation is within projected limits.
	Provide adequate downstream grade controls.	• Ensures simulated bed is protected from downstream head cut. • Grade controls themselves may become passage barriers.
	Use full-bottom pipe or deepen foundation of open bottom structure; place layer of large rock under simulated bed.	• Deeper foundation reduces probability of structural failure by undermining. • Reduces adjustment potential of simulation. • If simulated bed is eroded, the bed is more likely to reconstruct itself on rough rock surface than on culvert materials.

DESIGN CHALLENGE	DESIGN STRATEGY	OUTCOME OF DESIGN STRATEGY
Steepened channel (culvert steeper than reference reach)	Minimize slope increase; modify downstream and/or upstream channel.	• Simulation is more sustainable over long term.
	Increase bed material size. *	• Increases bed stability.[1]
	Increase width of stream-simulation channel, widen culvert. *	• Reduces shear stress inside culvert.[1]
	If simulation is step-pool type, install bed retention sills.	• Reduces risk of loss of structural rocks.
Submerged inlet.	Optimize inlet alignment and transition; bevel pipe inlet.	• Lowers inlet energy loss and increases culvert capacity.
Long culvert.	Minimize length of culvert using headwalls, lower road profile, etc.	• Allows use of shorter culvert.
	Increase width of stream-simulation channel, widen culvert. *	• Compensates for compounding design flaws
Initial lack of bed consolidation.	Compact bed layers during construction.	• Increases initial bed stability.
	Wash fines in between and around larger material to embed and stabilize it.	• Increases initial bed stability.
	Hand-place key bed features for stability.	• Increases initial bed stability. • Increases construction cost.
	Construct thicker streambed (to elevation higher than design project profile).	• Allows for initial streambed erosion.
Excessive infiltration into streambed.	Design and use well-graded bed material mix (section 8.8.6) with adequate content of sand, silt, and clay.	• Smaller particles fill voids between larger particles.
	Construct densely packed streambed by compacting bed in layers and washing fines into bed layers.	• Minimize large void spaces in new streambed.
Debris blockage, debris flows.	Increase culvert size: Limit headwater depth during 100-year flow to 80% culvert height above bed; ensure open area is	• Provides space for debris to float through culvert.

DESIGN CHALLENGE	DESIGN STRATEGY	OUTCOME OF DESIGN STRATEGY
	large enough for debris being transported.	
Debris blockage, debris flows. (cont.)	Ensure efficient transition from upstream channel (match alignment and width); bevel pipe inlet.	• Facilitates debris and sediment passage.
	Harden fill; design for overtopping and cleanout; plan for possible streambed maintenance after overtopping.	• Structure and road survive overflow and debris blockages.
	Provide inlet riprap or other protection.	• Reduce stream bank erosion caused by backwater eddies during very large flood events.
	Provide access for maintenance.	• Allows removal of debris jam in culvert or at inlet.
Stream diversion.	Increase culvert size.	• Reduces probability of exceeding culvert capacity or blocking with debris
	Provide roadway dip over culvert. Sag vertical curve to avoid diversion during floods and minimize fill height; armor fill.	• Contains overtopping flow at crossing. • Minimizes flood damage to soils and habitats.
	Provide ditch dams; redesign road ditches to direct flood and overtopping water to erosion resistant areas.	• Prevent a stream diversion into a roadside ditch downgrade from the crossing. • Reduce erosion caused by overtopping flows.

♦ Flood-plain Constriction

A wide active flood plain is often considered a highly valuable hydrologic and biological resource. Overbank flows and sediment moving down a flood plain build and maintain many of the unique flood-plain habitats that can be critical for some aquatic and terrestrial species (Naiman, et al., 1992). Project objectives will usually include protecting and/or restoring flood-plain processes and habitats.

The major challenge in constructing a sustainable stream-simulation culvert on a high-conveyance flood plain is the potential for the road fill to block overbank flood flows and force them to concentrate through the culvert. In such installations, bed scour inside the culvert occurs at lower flows than in the natural channel upstream. Material eroded out of the culvert may not be replenished, and the culvert is at risk of bed failure during floods. The inlet area is more susceptible to scour than other areas of the culvert under these conditions because water-surface elevation drops abruptly as the water moves from the backwatered flood plain into the culvert inlet. The inlet may scour even when hydraulic conditions in the rest of the culvert are similar to the reference reach.

Depending on the site, you may want to use a combination of some or all the following design strategies to mitigate the risk.

- Minimize flow concentration.

  In valleys with very high flood-plain resource values, such as important aquatic and riparian habitats, consider building a viaduct or bridge that spans as much of the active flood plain as possible. For stable multichannel systems (anastomosing channels), consider providing for stream simulation on each channel.

  Provide flood-plain culverts at swales, side-channels, and other locations as needed. Add enough drainage structures to avoid unduly concentrating flow in any one area. Providing well distributed flood-plain culverts minimizes the risk that floodplain flows concentrated in a single side channel might divert and capture the main channel. Fish passage conditions should be considered in these applications to reduce stranding potential. Nonetheless, side channels may carry more flow than normal because of the backwater caused by the road fill, and the potential for them to scour should be examined during the design process. In some cases, buried rock may need to be installed just downstream of a flood plain or side-channel culvert to prevent incision. Be aware of the potential for woody material to plug flood-plain culverts and provide enough dips to handle flood-plain flow if needed.

  Side-channels are important fish habitat and require aquatic organism passage. Culverts at these sites should simulate the size and character of the side channel, while providing protection against scour that flow concentration may cause. Side channel and swale road stream crossings may also need to consider egress fish passage to reduce stranding potential.

- Conduct a hydraulic and bed mobility/stability analysis.

These analyses should be done at any site where significant overbank flow is expected on the flood plain. It is particularly recommended where the entrenchment ratio (flood-prone width: bank-full width) is around 6 or higher. This recommendation is based on model results for several forested flood plains in western Washington. This entrenchment ratio threshold will be lower for smoother, un-forested flood plains with high conveyance.

Compare the critical unit discharge or critical shear stress in the stream- simulation channel to the reference reach during a range of flows that will be constricted by the road. The choice of which flows to analyze depends on risks at the site and on flow conveyance. A 10% annual (10-year) recurrence interval flood seems a reasonable minimum flow to use for this analysis in mobile channels with considerable movement of bed material. In intermediate- mobility channels, the flood that moves D84 in the reference reach might be a good choice for a minimum flow for this analysis.

The reference reach critical shear stress or critical unit discharge for this analysis is not the average of the entire floodway. Instead, the analysis considers only the flow within the bank-full or active channel width because that is the flow condition that entrains sediment on the reference reach bed. Use a hydraulic model like HEC-RAS or SRH 2D to predict backwatering behind the road fill, accounting for the effects of multiple flood-plain culverts planned for the site. Compare the reference reach shear stress or unit discharge to the stream-simulation channel, factoring in the additional flood-plain flow that will be forced through the culvert.

If you have already added flood-plain relief culverts to the design, and shear stresses are still higher in the main channel culvert than in the reference channel, the following two strategies provide options for offsetting the difference. These two strategies should normally be combined.

- Increase crossing structure width.

Widen the structure and construct a flood-plain surface inside. The width of the simulated bank-full channel should remain the same to avoid aggradation during moderate flows, and possible loss of low-flow passage.

The constructed flood plain will relieve some of the excess shear stress by accommodating some of the overbank flow. All surfaces above the bank-full channel should slope toward the bank-full channel at a slope of about 10h:1v.

Widening the culvert is not a panacea. Channel adjustments inside the structure are likely to change the installation over time. For example, unless the structure flood-plain surface is wide enough that water depth and velocity in the simulated active channel are like the reference reach, the simulated channel may incise. After that, flood flows will not access the overbank surface as easily, water depth and velocity at flows above bank-full will increase, and the original problem will not have been solved. For this reason, widening the structure is generally combined with increasing bed material particle sizes.

- Increase bed material particle size.

As mentioned previously, particle size can be changed only to a moderate degree if the simulated bed is expected to be self-sustainable. It is recommended to not increase D84 more than 25-percent over the reference reach.

If you increase bed-material sizes, increase each size class D50 and higher by the same percentage, and recalculate the finer particle sizes to maintain the dense-bed mixture (review Section 9.9.6). Consider how the new particle-size distribution will fit into the channel context and whether that distribution is likely to achieve stream-simulation objectives.

If an unacceptable risk of bed failure still exists after all the mitigation measures above have been applied, place individual large rocks in the bed to buttress the bed and provide additional roughness. Another option is to bury a layer of riprap deeply below the simulated streambed. The riprap should be deep enough that under normal conditions the simulated bed can scour and fill on top of it without being affected by it. Thus, the depth of the stream-simulation bed on top of the rock layer should be the same as if it were on top of the culvert floor (Section 9.9.7). The riprap layer thickness should be no less than the D_{max} stone, or 1.5 times D50, whichever is larger.

♦ Rapid lateral channel migration

Where a channel is experiencing rapid lateral shift, structure-to-channel skew will intensify over time. Section 9.9.2 describes the problems associated with skew, and ways to mitigate them. If a channel is shifting very rapidly, the most effective solutions might be relocating the road to a more stable site or placing a temporary structure that can be moved.

Possible solutions for channels where lateral shift is less extreme include widening the structure and offsetting it in the direction of expected shift. Adjust the size of bank line rocks if needed to accommodate a deeper pool that can form as the bend becomes more acute. Bank-stabilization and flow-training structures such as rock weirs, can be built above the crossing to slow down or minimize channel shift.

♦ Steepened channel

Steepening the simulated channel relative to the reference reach increases bed slope and shear stress (compared to the reference reach) and creates a higher potential for bed failure. Increases of up to 25 percent in particle size and/or channel width are likely to be within the range of variance of most natural channels and constitute a reasonable design limit. Nevertheless, conduct a bed mobility analysis whenever the stream- simulation channel is steeper than the reference reach. Additional coordination with regulatory agencies is needed in these situations.

The analysis may suggest that an increase in bed-material size or channel width is necessary to offset the increase in slope. An increase in channel width reduces the calculated average shear stress to resemble a flatter reference reach. Do not accept such a solution without thinking through how it will work in the real simulation. For example, in a natural channel, short, steep reaches are normally narrower than average rather than wider, with larger bed material and/or key pieces. If the thalweg in the steeper simulation incises so that flow width narrows, the calculated increase in stability due to increased channel width may not persist. In such a situation, burying a layer of large size rock below the simulated streambed to prevent excess scour might be a useful added safety factor. An added benefit of the extra channel width is that it provides capacity for large floods, making failure less likely.

Where the reference reach is steeper than the channel immediately upstream, analyze the mobility of the larger particle sizes in the simulated channel compared to the same sizes in the upstream reach that will be supplying sediment. Those sizes should be mobile at similar flows in both reaches for the simulated channel to be self-sustaining.

Avoid steepening a channel past a geomorphic threshold that would, in nature, make the channel a different type. Staying within the 25-percent guideline will usually prevent the design from exceeding a channel-type threshold; however, if a threshold would be exceeded, first verify that a more appropriate reference reach does not exist. For example, if the reference reach is a 4-percent plane-bed channel but the required crossing slope is 5 percent, investigate whether step-pool reaches exist nearby. If no more appropriate reference reaches exist, consider building the appropriate channel type as a hybrid design. In this example, the hybrid installation would be a step-pool channel. Steps would be designed for immobility during the high bed- design flow, because if the step-forming rocks wash away, they may not be replenished from upstream. If either a step-pool channel or one with other key features (such as wood) is steepened, consider decreasing the spacing of steps or key features to increase roughness.

♦ Downstream channel instability

If the elevation of the channel bed downstream of the crossing degrades beyond the range to which the project can adjust, the simulated streambed could fail to function. If a risk of continued channel degradation downstream could jeopardize the structure, reevaluate your plans to control vertical adjustment potential. Consider restoring the downstream channel and/or adding grade control structures to support the project profile.

Design conservatively. Take extra care in projecting vertical adjustment and, if possible, ensure that the structure can accommodate it. One safety measure is to use a full-bottom culvert with a layer of large rock placed below the simulated bed. Even if the simulated bed partially or entirely washes away, the opportunity to reconstruct it will still exist. The layer of large rock will protect the upstream reach from channel incision. In a bottomless structure, increase the depth of footings. Consider placing a layer of immobile rock below the streambed elevation and constructing the simulated bed on top of it, giving the bed enough depth to make normal vertical adjustments (such as scour pools).

♦ Inlet control

A stream-simulation bed will likely fail if the culvert is in inlet control, especially if the inlet is submerged and a high head differential exists between inlet and outlet. These conditions produce a strong flow contraction in the culvert near the inlet. In culverts flowing in inlet control, supercritical flow—a very high velocity flow extremely rare in alluvial channels—occurs in at least part of the culvert.

Conduct a culvert analysis and verify that supercritical flow does not occur at the high bed-design flow. HY-8 and HEC-RAS with the lid function are good tools to use for this because they analyze flow inside the barrel of an embedded or open-bottom culvert. Be conservative, because high-flow hydrology, effects of debris, and culvert inlet losses are all uncertain.

If supercritical flow is likely to occur, or if the inlet may be submerged, one obvious solution is to increase the culvert size. It is recommended that headwater depth at the high bed-design flow not exceed 80 percent of the culvert opening above the bed (67 percent where debris is a significant hazard). Improving the culvert alignment with the upstream channel and/ or designing an efficient culvert inlet configuration, such as a wingwall, may lower the headwater and reduce the flow contraction near the inlet.

Again, if the site has an active floodplain, adding flood-plain culverts will reduce flow concentration through the culvert.

♦ Initial lack of streambed consolidation

In natural channels, hydraulic forces sort and structure bed materials so that they are in relatively stable positions and orientations. In newly constructed streambeds, the risk of bed failure during a flood is somewhat higher until moderate flows sort, structure, and consolidate the new bed. Characteristics like armoring and imbrication cannot be constructed and must be allowed to develop naturally.

Although low initial stability cannot be quantified, there are several ways of managing the risk:

- Add extra material initially to allow for some bed erosion and consolidation.

  In post construction monitoring of steep stream- simulation channels, it has been found that the constructed beds had lowered by about 20 percent of their depth in the first few years after construction, likely from a combination of consolidation and erosion of fine material. These were steep channels, and the material had not been consolidated or compacted during construction.

- For beds composed of grain sizes up to cobbles, compact the bed during installation.

Compaction can be done mechanically, by washing fines into the bed, or both. As bed material size increases, mechanical compaction becomes more difficult and more likely to damage the culvert. Bed structures such as steps and key features therefore become more important.

These bed structures will support the alluvial part of the bed until it is consolidated. Ensure step and key-feature stability by specifying that individual rocks be placed so that they are in direct contact and support one another.

- Increase the size of the bed material slightly.
- Monitor the effects of high flows until bed structure develops and be prepared to repair any bed failures.

♦ Excessive infiltration into streambed

The lack of natural sorting and bed consolidation also results in a potential for excessive streambed permeability and the risk of losing surface flow during low flows. A well-graded bed mix with at least 10-percent sand, silt, and clay content is designed to avoid large empty spaces in the new, loose bed. Construction practices, such as ensuring the bed material is not segregated during handling, compacting the channel bed in layers, and washing the fines into each layer help to reduce initial infiltration rates.

9.10 Hydraulic Design Method

9.10.1 Description and Application

Unlike stream simulation, the hydraulic design approach involves designing a structure for passage of targeted fish species and life stages by creating a hydraulic environment that is compatible with the fish's swimming and leaping abilities over a specified range of flows. The hydraulic conditions generally evaluated are jump height, water velocity, depth, and turbulence. The design objective is to achieve the desired hydraulic conditions at flows that the target fish are expected to move through the road stream crossing. General considerations include the effects of crossing

slope, size, material, and length. Flow control structures such as baffles, weirs, formal fish ways or oversized substrate, are commonly utilized to create adequate hydraulic conditions.

Hydraulic Design is most applicable to culvert crossings but can be used for new and replacement structures in situations when the system is unstable, and a reference reach cannot be established. This technique can generate a smaller crossing structure, while still meeting fish passage criteria including jump height, average cross-sectional velocity, and flow depth. Hydraulic Design is specifically tailored to meet target fish species requirements but produces a less connected design than Stream Simulation. These designs are applicable for slopes up to 5% (Robinson, 1999) (Bates, 2003) (Katopodis, 1992).

9.10.2 Criteria and Guidelines

♦ Width

Refer to Section 9.9.7 Structure Width.

The minimum culvert width shall be 6 feet on channels with ESA listed species. (National Marine Fisheries Service, 2022)

♦ Fish Passage Design Flows

Refer to Section 9.6, Table 1 for High and Low Fish Passage design flows.

♦ Vertical Clearance

The minimum culvert vertical clearance between the culvert bed and ceiling should be more than 6 feet, to allow access for debris removal. Smaller vertical clearances may be used if a sufficient inspection and maintenance plan is provided with the design that ensures that the culvert will be free of debris during the passage season.

♦ Slope

The slope of the reconstructed streambed within the crossing should not exceed 125% of the approximate average slope of the adjacent stream from approximately 10 channel widths upstream and downstream of the site in which it is being placed, or in a stream reach that represents natural conditions outside the zone of the road crossing influence. If embedment of a culvert is not possible, the maximum slope should not exceed 0.5%.

♦ Culvert Embedment

The bottom of the culvert should be buried into the streambed a minimum of 20% of the height of the culvert below the elevation of the tailwater control point downstream of the culvert, or 1 foot, whichever is greater.

♦ Water Velocity

The average water velocity in the crossing refers to the calculated average of velocity within the flow area at the fish passage design flows. In most instances, upstream juvenile fish passage requirements should also be considered in design.

In Oregon, the maximum average water velocities are:

- ODFW
    - 2 fps (feet per second)
- NMFS
    - 1 fps at the High passage design flow

♦ Hydraulic Drop Height

Hydraulic drops between the water surface in the culvert and the water surface in the adjacent channel should be:

ODFW:

- 6 inches if juvenile fish are present and require upstream passage.
- 1 foot if juvenile fish are not present or do not require upstream passage.

NMFS:

- Hydraulic drops at, or adjacent to, the inlet, inside the culvert, or at the outlet do not provide good fish passage and should not be included in design.

♦ Minimum Flow Depth

Minimum water depth at the low fish passage design flow should be:

ODFW:

- 1.0 foot for all salmonids
- 0.5 feet for all species of juvenile salmon, and native migratory fish species, as measured in the centerline of the culvert.

NMFS:

- 1.0 foot for all adult steelhead, chinook, coho, and sockeye salmon
- 0.75 feet for pink and chum salmon
- 0.50 feet for all species of juvenile salmon, and native species, as measured in the centerline of the culvert.

9.11 Backwater Control Structures

9.11.1 Rock Sizing

In designing a Backwater Control Structure, the material used within the structure must resist active forces of drag, lift, and buoyancy while subjected to flowing water in a river or stream. The cap layer rocks, as well as the rocks beneath in a weir, will resist the collective active forces, and must be sized accordingly. The methods for sizing rocks comprising backwater control structures within ODOT are:

- Boulder Cluster Design
- Hydrostatic (Overturning Moment)
- Boulder Weirs

After calculating rock size using the three methods mentioned above, engineering judgment shall be incorporated in deciding which result should be used for design and construction. The most conservative or largest rock size is not necessarily the best choice, especially if a great disparity exists between the sizes calculated using these methods.

Table 9.11-1: ODOT Riprap Classes (from Bank Protection chapter, Table 15-3)

Standard Riprap Class	D50 (ft)	W50 (lbs.)	D100 (ft)	W100 (lbs.)
Class 50	0.56	15	0.83	50
Class 100	0.66	25	1.05	100
Class 200	0.93	70	1.32	200
Class 700	1.32	200	2.01	700
Class 2000	2.01	700	2.85	2000

9.11.2 Boulder Cluster Design Method

This simplistic approach uses a table containing minimum boulder diameters and their associated critical shear stress (Tc) and critical velocity (vc) assuming a rock/boulder angle of repose equal to 42 degrees (approximately 1.8:1) and rock specific gravity equal to 2.65. The Tc and vc values were determined considering drag, lift, and buoyancy forces acting on the rocks/boulders. For the minimum diameter given in the following table, the rock/boulder will be stable during turbulent flow with it fully immersed. In other words, incipient motion will occur for a given rock/boulder diameter when stream velocities are higher than the critical velocity shown in Table 6.

Table 9.11-2: Minimum rock diameter, Boulder Cluster Method

Generic Rock Class	Min. Dia. (in)	Tc (lb./sf)	vc (ft/s)
Very Large Boulder	>80	37.4	25
Large Boulder	>40	18.7	19
Medium Boulder	>20	9.3	14
Small Boulder	>10	4.7	10
Large Cobble	>5	2.3	7
Small Cobble	>2.5	1.1	5

If an average stream velocity equals 12 ft/s, a minimum rock diameter of 15 inches can be interpolated from Table 6. From Table 5, a 15-inch or 1.25-foot rough diameter boulder would be classified as a (round up to next Class) D50, Class 700 rock, having weight equal to 200 pounds.

9.11.3 Hydrostatic (Overturning Moment) Method

For this method, resultant pressure and buoyancy forces are considered acting on a single rock within a weir, and this rock will resist these forces through its mass. Frictional resistance between the rock being analyzed and the stream bed would also resist these active forces but is being ignored because this force is small. Conservatism is further applied by also ignoring the mass resistance of backfill on the downstream side of a rock. Essentially, a top layer rock is analyzed on a level, frictionless plane where only its mass will prevent movement. A free-body diagram of the hydrostatic forces is shown in Figure 17.

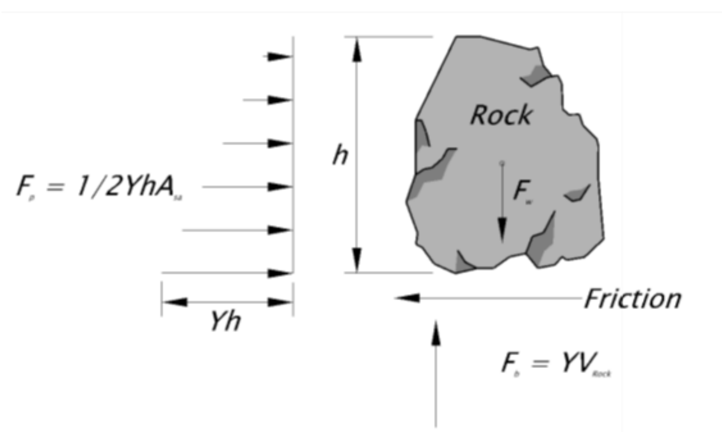


Figure 9.11-1: Rock free body diagram

Equation 9.10-1 $F_P = \frac{1}{2} \Upsilon h A_{sa}$

Equation 9.10-2 $Fw = \Upsilon V_{rock}$

Where:

F_P= Pressure Force (lb.) Fb= Buoyancy Force (lb.)

F_W= Mass of Boulder (Rock) (lb.)

h= Height of Water Column Associated with Design Storm Flow (ft.)

Υ= 70 lb./ft^3 (Water & Suspended Sediment)

Asa= Surface Area of Boulder (Rock) (ft^2)

V_{rock}= Volume of Boulder (Rock) Based on Radius= $4/3\pi r^3$ (ft^3)

The first step is to determine the height of the water column or flow depth associated with the design flow from the HEC-RAS model of the stream channel. Next, an initial estimate of rough rock diameter is performed so that mass, rock volume, and surface area can be calculated.

Once the active and resistive forces are determined for a chosen rock diameter, overturning moments can be calculated, and stability analyzed based on the ratio of the sum of active and resisting overturning moments. Moment-ratios (∑MResist/∑MActive) below 1 signify instability, equal to 1 indicate neutral stability, and ratios above 1 show stability. Rock diameter can be varied until proper stability results are achieved. See Table 7 for an example of overturning moment and stability analysis.

Table 9.11-3: Example of Hydrostatic forces (F) and Overturning Moments (M)

fP (LBS)	FB (LBS)	FW (LBS)	MP (FT-LBS)	MB (FT-LBS)	MW (FT-LBS)	∑ACTIVE: MP+MB (FT-LBS)	∑RESIST: MW (FT-LBS)
6,752	13,504	24,000	22,147	45,795	120,000	67,942	120,000

Factor of Safety= $\sum M_{Resist} / \sum M_{Active}$= 120,000/67,942= 1.8

9.11.4 Boulder Weir Design

♦ Weir Embedment

The depth or embedment of the boulder weir is dependent upon the estimated scour potential for the site. An exact method for determining scour depth at a boulder weir does not exist, but it can be estimated by one of two methods: Field Inspection/Topographic Survey and Toe-Scour Estimate Equations.

♦ Toe Scour Estimation Method

For this method, scour depth will be calculated considering the boulder weir as a stabilized bend-way. Like a bend-way section of channel, the vortex-shaped boulder weir will be subjected to secondary currents, which cause higher velocities and shear stresses. These conditions will trigger greater scour around a boulder weir, as well as changes in sediment transport and supply.

The toe-scour equation is empirical and was developed by synthesizing laboratory and field data. The scour depth calculation is dependent upon mean channel depth and water surface width upstream of a bend or weir, in addition to centerline bend radius and maximum water depth in bend.

Within the scour depth calculation, two ratios are incorporated. The first ratio is the centerline bend radius divided by the water surface width upstream of a bend or weir (Rc/W), while the second ration is this same water surface width divided by the mean channel depth upstream of a bend or weir. (W/D_{mnc}). Since the equation is empirical, limits apply to its use, more specifically to the R_c/W and W/D_{mnc} ratios. Based on the range of field and laboratory data sets, R_c/W is limited from 1.5 to 10 and W/D_{mnc} limited from 20 to 125. In other words, when W/D_{mnc} is calculated to be less than 20, a value of 20 must be used. Conversely, a value of 125 must be used when W/D_{mnc} is calculated to be above 125.

As for the R_c/W ratio, it is of course dependent upon the centerline bend radius. Because the toe-scour equation is being adapted to apply to boulder weir design in straight and bending channel sections, 1.5 will be used as the default value. By using 1.5 for all cases, calculated potential scour depths will be conservative.

Finally, the equations used in estimating scour depth in this method are:

Equation 9.10-3

$$\text{Scour Depth} = D_{mxb} - D_{mnc}$$

Where:

D_{mxb} = maximum water depth at weir (feet)

D_{mnc} = mean channel depth upstream of weir (feet)

Equation 9.10-4

$$D_{mxb} = 1.14D_{mnc}(1.72 + 0.0084W/D_{mnc})$$

Once the scour depth is calculated, this depth will be used to specify the embedment depth of the boulder weir with reference to the channel bed finished grade surface. The height of boulder weir above the channel bed will be determined during the hydraulics analysis.

The total height of the boulder weir, equal to the height above channel bed plus the embedment depth, must be equal to or greater than the recommended ODOT riprap class thickness recommended in Table 15-5, of the Bank Protection Chapter of the ODOT Hydraulics Manual.

After the height of the weir is determined through hydraulics analysis, which is measured above the channel bed, the total boulder weir thickness must be equal to or greater than the required minimum found in Table 15-5. If the embedment depth plus the boulder weir height is less, the minimum riprap Class layer thickness would control.

Below the boulder weir, a filter blanket layer is needed to provide filtration beneath all boulder weirs. This filter layer will prevent soil movement and loss of fines from piping and ultimately improve boulder weir stability. This filter blanket shall be as recommended in Table 15-6, located in the Bank Protection Chapter of the ODOT Hydraulics Manual.

The components of boulder weir geometry include crest width, side slope ratio, and plan-view radius. As mentioned previously, the side slope ratio will be 1:1.5 for all boulder weirs, but the crest width and plan-view radius must be calculated. The crest width is simply expressed below, where D50 is associated with the boulder weir riprap class.

Crest Width = 2 x (Boulder Weir D50)

The other boulder weir geometry element to consider is the arc, plan-view shape. See Figure 18. The mid-chord offset of the arc is equal to 3 times D50 of the boulder weir riprap class. The chord length will equal the active channel width (ACW). After determining the mid-chord offset and chord length, the radius of the arc can be determined with the equation below:

Equation 9.10-5

$$R = \frac{L^2}{8m} + \frac{m}{2}$$

Where:

R = boulder weir radius (ft.)

L = chord length (ft.)

m = mid-chord offset= 3 D50 (ft.)

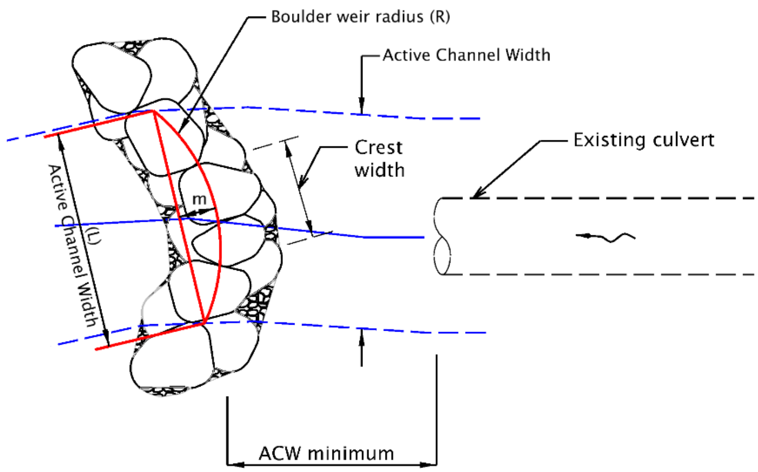


Figure 9.11-2: Boulder Weir Plan section

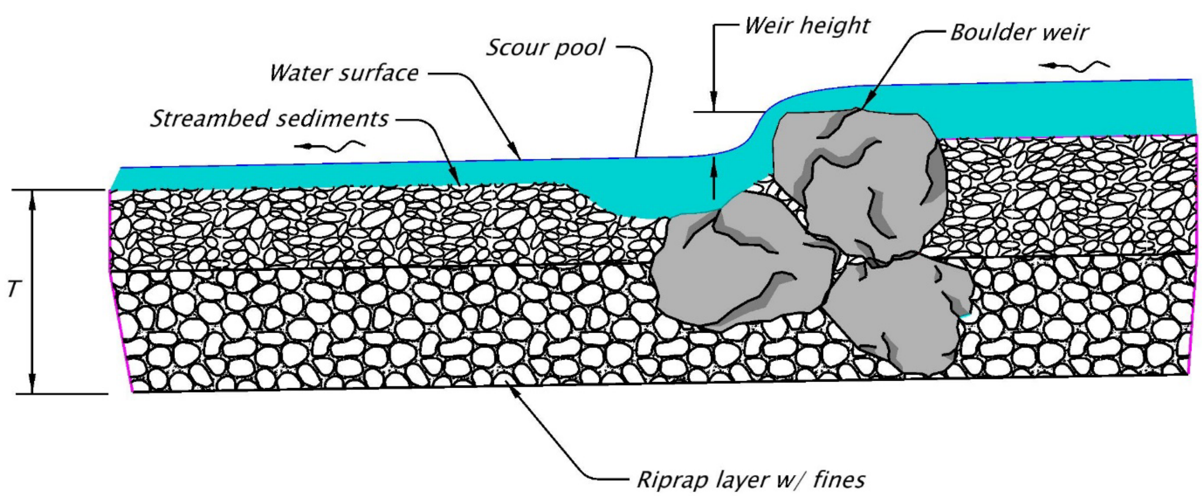


Figure 9.11-3: Boulder weir profile section

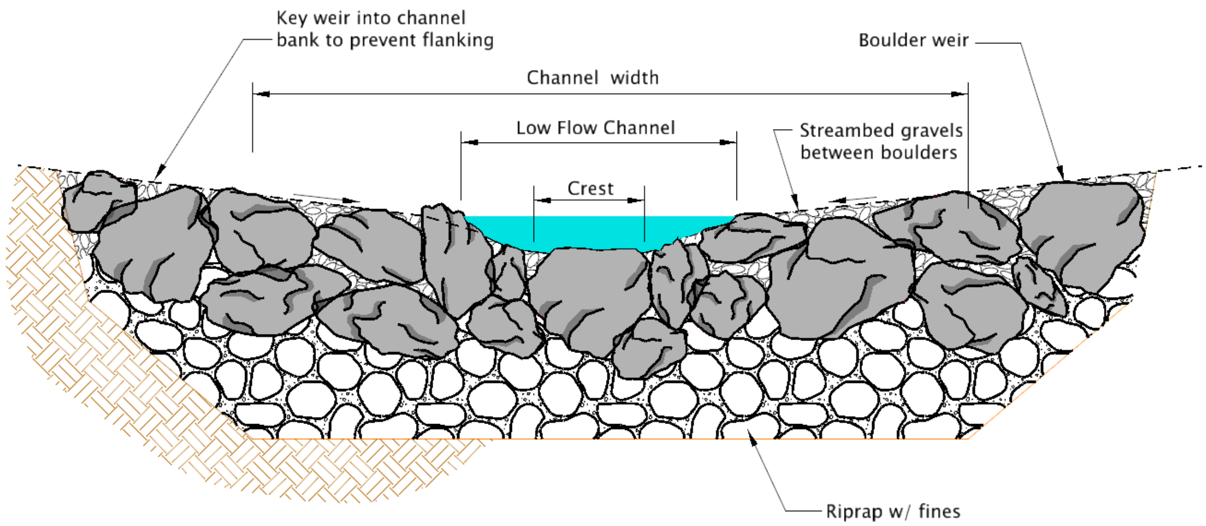


Figure 9.11-4: Boulder weir section

9.11.5 Step Pool Composition

The portion of the stream between boulder weirs is the pool or step-pool, which has a total thickness defined in Figure 19 as T. The total thickness is measured from the creek bed finished grade to the top of the backing layer. T dimensions will vary for each project depending on boulder weir embedment depth and vertical step height within the pools.

As also seen in Figure 19, the step-pool is composed of two layers of equal thickness. The top layer is either native bed material or engineered streambed material, and these materials should be well compacted to 90% relative compaction during placement. The function of the top layer is to support habitat and to allow the development of various micro-pools that will promote resting areas for fish as they move through the boulder weir/step-pool system.

During construction, the top 1-foot to 3-feet of the excavated creek bed can be stockpiled on site and later placed or returned to the creek as the step-pool top layer according to specified dimensions. If the excavated material is deemed unsuitable, streambed sediments can be imported and placed.

For a boulder weir backfill, use a layer of riprap which has a filler material “washed” into the voids to provide a sealed layer to provide stability for the weir as well as keeping the stream flow from going subsurface. This method shall be designed to withstand the stream velocities at the design event based on the Open Channels Chapter of the Hydraulics Manual.

At the downstream end of a boulder weir within the step-pool, a scour pool should be constructed. This scour pool will encourage fish to rest before jumping over the boulder weir. A 2-foot pool depth is desired at the downstream end of a boulder weir but should be dependent upon the site conditions. Even though a scour pool will form naturally over time as flow plunges over a weir, the constructed scour pool will provide immediate benefit after construction.

9.11.6 Boulder Weir and Step Pool Layout

Through an iterative hydraulics analysis, the spacing and height of the boulder weirs, as well as the low-flow notch/channel dimensions are verified. These components are varied during the hydraulics modeling process until the velocity and depth requirements are satisfied. For the ODOT/ODFW Culvert Repair Agreement, there are no specified requirements to meet although the designer should try to maximize the fish passage improvements while minimizing the hydraulic impacts from the loss of flow capacity.

For a series of boulder weirs, the spacing should be close to 1.5 x the ACW. This is mainly governed by the construction process, where individual boulder weirs could intersect, and their physical definition could be lost if they are placed too close together. Instead of having a series of individual boulder weirs, a larger pile or mass will develop without clear definition of each boulder weir and the pools between them. If this occurs, the boulder weirs and pools will not function properly for fish passage.

At each boulder weir, a maximum 6-inch vertical step in the new stream profile is typically placed to minimize the longitudinal pool slope between weirs and eliminate a vertical and/or velocity barrier to fish. The boulder weir will dissipate the increase of energy at a step. With a flatter pool slope, the velocity and depth criteria are more easily achieved. The use of vertical steps is especially beneficial when dealing with significant elevation changes within the project limits, which would create steep pool slopes. The overall stream gradient can be softened by having a 6-inch grade changes at each weir location yet provide relatively flat pool slopes or smaller grade changes between weirs. For boulder weir design, the pool slope can vary between 0% and 4% but is ultimately controlled by the velocity and depth criteria.

To determine the number of boulder weirs, the preliminary boulder weir spacing, the preliminary project length, the number of step-pools, the step-pool slope (gradient), and the number of vertical steps, the procedure below should be followed. Figure 21 shows a vertical barrier (excessive scour pool) just below a perched culvert, which is a very common application for boulder weir/step-pool system in mitigating this type of impediment or barrier.

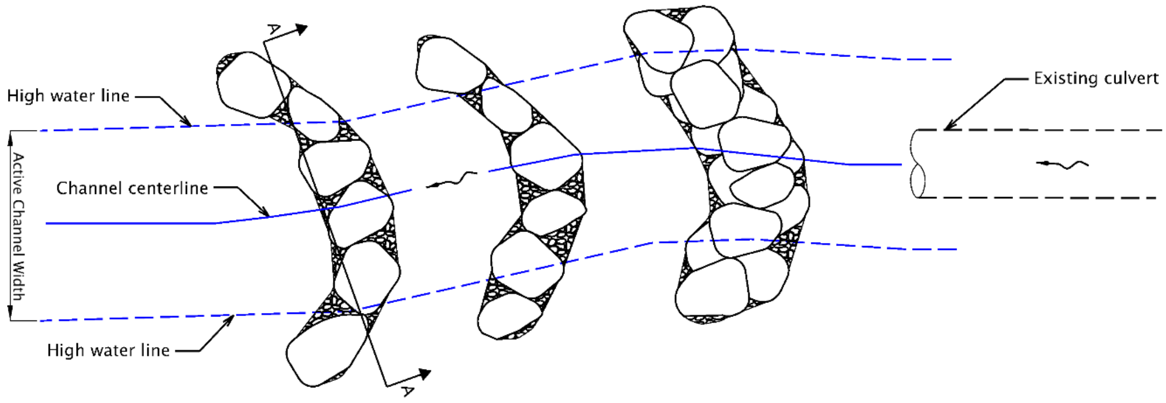


Figure 9.11-5: Step Pool Layout

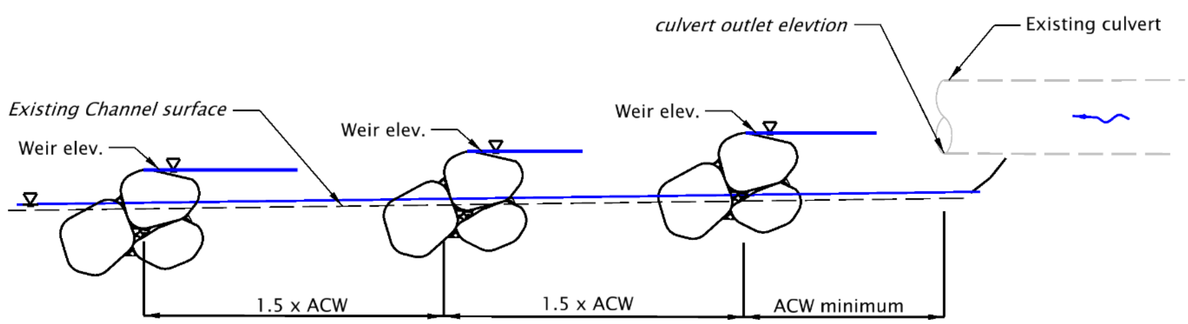


Figure 9.11-6: Step Pool Profile

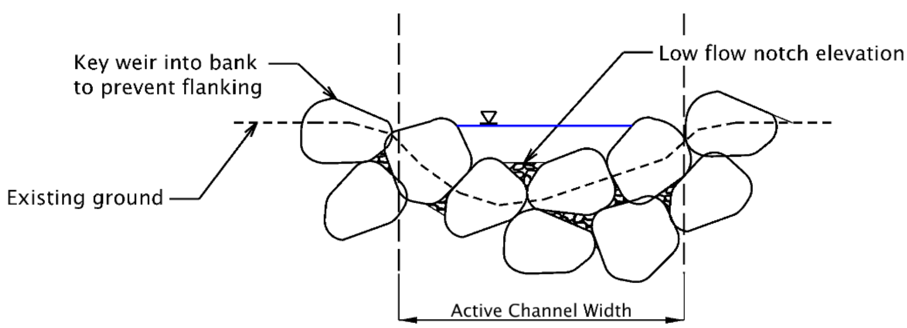


Figure 9.11-7: Weir Section

9.12 Additional Fish Passage Considerations

9.12.1 Tide Gates

Fish passage criteria and design considerations at structures with tide gates usually requires extensive early and often coordination with not only regulatory partners (ODFW, NOAA) but also with right of way and permitting staff. Common metrics associated with passage criteria include modeled velocity and depth of fish passage conditions through the structure during various tidal and river stages, and considerations for duration of gate opening, area and depth of inundation on land around the tide gate, and other factors. Fish passage criteria specific to tide gates can result in water inundation changes in extent and frequency for adjacent property owners and often requires extensive modeling and survey for anticipated property impacts. In addition, any work on structures with tide gates should follow the ODOT policy on tide gate ownership and maintenance, as described in Memo MAI 06-04. In some circumstances, repairs can be completed on culverts with tide gates under the ODOT/ODFW Culvert Repair Programmatic Agreement (CRPA), provided the tide gate is removed as the fish passage improvement. This can result in drastic changes to tidal impacts up and downstream, so this option should be used only when these impacts are acceptable to property owners. It is recommended to engage the project Region Environmental Coordinator (REC) and Biologist early in project development to better understand site specific conditions associated with tide gate projects.

9.12.2 Beaver Dam Analog and beaver associated projects

Fish passage criteria and design is prescriptive and evolving for projects promoting or mimicking beaver dams or beaver dam analogues. Restoration practitioners across the west are using natural materials in various ways to mimic or promote beaver activity on the landscape for restoration of ecological processes. These approaches include construction of beaver dams, installation of vertical post structures to promote dam development, and other similar project types. Dependent upon project objectives, these treatment types can be a very low cost and low maintenance approach to resorting areas for enhanced fish habitat conditions. Similarly, projects seeking to reduce or limit beaver activities and impacts to road stream crossing structures, such as through pond levelers or beaver deceivers, must consider fish passage criteria, best management practices, and water inundation extents to be successful. It is recommended to engage the project REC and Biologist early in project development to better understand site specific conditions associated with beaver type projects. ODFW has several design criteria resources available, including the “Beaver Restoration Guidebook” available on the instream habitat structure home page; [ODFW Fish Passage Requirements (state.or.us).]

9.12.3 Fish Passage during construction

State and Federal regulations require that in stream projects provide volitional fish passage through or around a project area during construction. For projects located on smaller stream systems, this usually only applies to downstream passage, where out-migrating juveniles can be carried downstream through a gravity bypass system or similar. For larger river systems, both upstream and downstream passage is required, and usually results in a staged construction sequence where only part of the stream channel is isolated at any one time. The Temporary Water Management Chapter contains some considerations on how to design a facility for safe and efficient fish passage during construction. The site-specific requirements and fish passage considerations should be coordinated with the project REC or Biologist early in design to ensure the plan will meet state and federal requirements.

9.12.4 Fish Ladders (Fishways)

Fish ladders or fishways are not a common project type for road stream crossings, however; some scenarios may dictate this approach for providing fish passage. Physical constraints, such as a very steepened channel, vertical profile differences at confluence areas, or constrained right of way may limit design options to using constructed ladders or fish ways. Both state and federal regulatory agencies have specific criteria for these project types, and it is usually based on the fish species and life stages present at the crossing. Early and often coordination with the project REC and Biologist, in addition to ODFW and NOAA engineering staff, is strongly advised for projects considering the use of a fish ladder or fishway to ensure success.

9.13 Works Cited

Bagnold, R. A. (1960). *Some aspects of the shape of river meanders.* U.S. Geological Survey Professional Paper 282E. 135-144.

Bates, K. K. (2003). *Design of road culverts for fish passage.* Washington Department of Fish and Wildlife.

Begelow, P. E. (2005). *Testing and improving predictions of scour and fill depth in a northern California.* River Research and Applications. 21: 909-923.

Behlke, D. E. (1991). Fundamentals of culvert design for.

Buffington, J., & Montgomery, D. (2013). *Geomorphic Classification of Rivers.* Elsevier Inc.

Clarkin, K. (2003). National inventory and assessment procedure for identifying barrriers to aquatic organism passage at road-stream crossings.

Fuller, W. B., & Thompson, S. E. (1907). The laws of proportioning concrete. *Journal of the Transportation Division*.

Haschenburger, J. K. (1999). *probability model of scour and fill depths in gravel-bed channels.* Water Resources Research. 35, 2,857-2,869.

Katopodis, C. (1992). *Introduction to Fishway Design.*

Lang, M. (2004). *Improving stream crossings for fish passage.* Humboldt State University Foundation.

Leopold, L. B. (1964). *Fluvial processes in geomorphology.* New York: Dover Publications, Inc.

Naiman, R. J., Beechie, T. J., Benda, L. E., Berg, D. T., Bisson, P. A., & MacDonald, L. H. (1992). Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. *Watershed Management: Balancing Sustainability and Environmental Change*.

National Marine Fisheries Service, W. C. (2022). *Guidlines for Salmonid Passsage at Stream Crossings in Oregon, Washington, and Idaho.*

Robinson, E. e. (1999). Oregon Road/Stream Crossing Restoration Guide.

Schumm, S. A., Harvey, M. D., & Watson, C. C. (1984). Incised channels. *Water Resources Publications*.

Figure 9.13-1: Who needs a crossing structure.