

CHAPTER 5
STREAM SIMULATION DESIGN OPTION

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5 STREAM SIMULATION DESIGN OPTION

5.1 Design Method Applicability

5.1.1 Description of Stream Simulation

Stream simulation is a culvert design method intended to create and maintain natural stream processes in a culvert. It is based on the premise that the simulated channel inside a culvert presents no more of a challenge to movement of organisms than the adjacent natural channel. The basic elements of a stream simulation design that will be described in this chapter are:

- Site suitability for stream simulation or any culvert or road crossing;
- Reference reach that is simulated;
- Project profile;
- Culvert bed profile and elevation;
- Culvert length;
- Culvert/stream alignment;
- Effects of large scale floods;
- Effects of floodplain at crossing site;
- Culvert bed material;
- Width of culvert bed;
- Culvert material and shape or other solution; and
- Channel profile control, if necessary.

The “reference reach” is a natural channel in the same stream and in the vicinity of the project, used as a reference for the design. It is typically identified during the pre-design assessment and the selection is verified at several points in the design process. The reference reach serves as a real-world model of a channel configuration that can be self-sustaining inside a culvert and that satisfies the physical conditions (especially slope) of the project site. The term “self-sustaining” refers to the interaction of high flows, the bed, and the culvert to create and dynamically maintain bed material sizes and patterns within the culvert bed that accurately simulates the natural channel. Though a stream simulation project doesn’t necessarily reflect the average conditions of the reference reach, it shouldn’t reflect extreme conditions either. It should be recognized that we are not likely able to duplicate the natural channel precisely.

A key element of stream simulation design is width of the culvert. The width is generally similar to the reference channel bankfull width and will depend greatly on the objectives of the project. If objectives include passage of organisms that require shallow channel margins and/or banklines at high flows, the culvert width will likely include the banklines. Self-sustainability should be an objective. To be self-sustaining, a culvert located in a channel with a wide active floodplain will have to accommodate floodplain flows without disrupting the stream simulation bed.

The stream simulation bed is a sediment mix that emulates the character and dynamics of material in the natural channel; it erodes and deforms similarly to the natural channel. The material is placed inside the culvert in a pattern and shape to mimic the natural channel, and is allowed to adjust in minor ways to changing hydraulic conditions. Since the profile, cross

section, and bed are similar to the natural channel, the hydraulics will also be similar.

A goal of stream simulation is to set the stage so that the channel can adjust to accommodate a range of flood discharges and sediment/debris inputs without compromising aquatic organism passage. Setting the stage means establishing basic channel characteristics of gradient, bed and cross-section shape, bank configuration, and bed material size and structure. Large floods can mobilize and disrupt the armor layer of the bed. Subsequent flows can reestablish the armor layer. Construction of the bed in culvert can be thought of as a disturbance (i.e., the armored layer is destroyed), but it has the necessary bed-material sizes and structure to form an armor layer.

Depending on the type and characteristics of the channel being simulated, the bed might be designed as mobile or key pieces might be designed to not be mobile. Bed material is entrained and becomes mobile at flows of various recurrence intervals based on channel type. Bed material in some streambeds will mobilize at bankfull flow or lower. Coarse material or key pieces in steeper streams with coarser material may not move at flows lower than thirty to eighty year recurrence floods.

In stream simulation design there is no target species of fish or other organism for passage. Timing of migration, swimming ability, and hydrology of migration are therefore not design parameters. As a result, the criteria of the hydraulic design option (velocity, depth, length, passage design flow) are not used to design the culvert. Instead, the physical properties of the natural channel are used as criteria, so that the culvert design produced creates the same passage conditions as the natural channel. By focusing on reproducing the performance characteristics of the natural channel as opposed to maintaining specific hydraulic criteria, passage by species for which criteria have not been developed is more likely to be achieved. Depending on the objectives and scope of the stream simulation project, there are broad categories of species that may or may not achieve passage. A specific design for example may or may not include streambanks and channel margins within a culvert, which might be important for passage of amphibians and small mammals.

It should be noted that the concepts behind stream simulation culvert design can also be applied to the design of short reaches of channel outside of culverts, particularly higher gradient streams where design guidance is not available in the general literature. The width considerations for culverts outlined below need not restrict the size of constructed channels. Guidance on the slope, structure and bed composition of a constructed channel can be found in following sections of this chapter.

The basic premise of stream simulation design is that the simulated channel inside a culvert presents no more of an obstacle to movement of organisms than the adjacent natural channel. Satisfying this premise is a complex relationship of all of the basic elements listed at the beginning of this chapter. Often a specific criterion must be exceeded to make a project practical. In that case the principles behind the criterion and the effect of varying it must be understood by the designer. A safety factor might be applied to other criteria to compensate. Special river engineering, geomorphic, and biological expertise are necessary to design such a project and verify it complies with project objectives.

Because the design of stream simulation culverts requires an understanding of fluvial geomorphology, hydraulics, hydrology, and fish behavior, an interdisciplinary design team is

essential. A typical design team would consist of a civil (hydraulics) engineer, biologist, geologist, and possibly a hydrologist.

5.1.1 Limitations of Stream Simulations

There are limitations of channels in which the stream simulation can be effectively and safely applied, and there are limitations of what natural stream characteristics the method can simulate. Natural stream characteristics that are not duplicated directly in the stream simulation design process include: channel-spanning wood (though experimental interior wood structures have been built), embedded wood, bankline vegetation and root strength, cohesive soils, riparian functions, and some forced configurations of debris and rigid bed forms. Some large geomorphic processes and features such as channel patterns and channel migration cannot normally be simulated in a culvert.

Though they cannot be duplicated, some of these characteristics can be simulated. Large wood that spans the channel provides roughness and complexity and structure. Debris embedded in the natural channel may anchor bed material and in some cases creates all of the elevation change (slope) of the channel. Rigid bed forms such as bedrock exposures stabilize the channel profile and provide roughness. The roughness of these features can be simulated with durable material such as large rock. These options are part of the design process described below.

Slope of the stream simulation cannot vary greatly from the natural reference channel. Stream simulation designs are therefore limited in that they cannot be designed steep to make up elevation lost by an extreme channel incision unless the steeper section is designed with bedforms that resemble a reference reach of that gradient. A stream simulation design can be combined with channel restoration and other profile control techniques to provide passage. However, if the culvert is just backfilled with oversized rock in a random unnatural manner strictly for roughness then it would be a roughened channel and may create a turbulence barrier.

Natural banklines created and supported by vegetation and root structure cannot exist in a culvert and banklines supported by cohesive soil are not possible to create inside of a culvert. These banklines can be simulated by an artificial bankline constructed of rock that is sized to be immobile up to the design flood flow. Other riparian functions are not simulated within the culvert. For example, riparian vegetation is not present for food and energy input.

The hydrology and surface-subsurface water exchange of active floodplains are altered when a culvert is installed with road approach fills that block flow in the floodplain and force the flow to be constricted through a culvert. The alterations might be at least partially mitigated with a larger culvert, additional culverts in the floodplain, and/or overflow dips in the road. These options are explained further in this Chapter.

5.2 Stream Simulation Design Process Overview

The stream simulation design process generally requires that each of the basic elements listed previously be addressed. Figure 5.1 is a graphical representation of the usual order of analysis and design for a stream simulation application.

The site assessment for stream simulation is generally completed during the pre-design phase of culvert design. The assessment focuses primarily on a geomorphic characterization of a defined reference reach and, where applicable, the channel that would be present if an existing culvert or other artificial influences were not present. A detailed description of the site assessment process

is presented in Chapter 3 along with and other pre-design analyses recommended for culvert design.

During the design phase, the basic design process for stream simulation consists of: (1) design of the stream simulation channel, and then (2) design of the culvert to fit around it. The detailed steps necessary to complete these two design elements are presented in sections 5.4 and 5.5, respectively.

Ideally, much of the stream simulation design is empirical, based on the channel configuration of a reference reach from the same stream and near the crossing site that serves as a model to be simulated within the culvert. However, analytical methods may be required where reference reach information falls short. A design is often an iterative process; as design decisions are attempted and completed, previous steps in the design process may have to be repeated to include or compensate for them. A prudent design process would be to do a “rapid design” through the entire design process to verify that a stream simulation design can be accomplished. If it clearly cannot, the designer may wish to consider other options before expending too much effort.

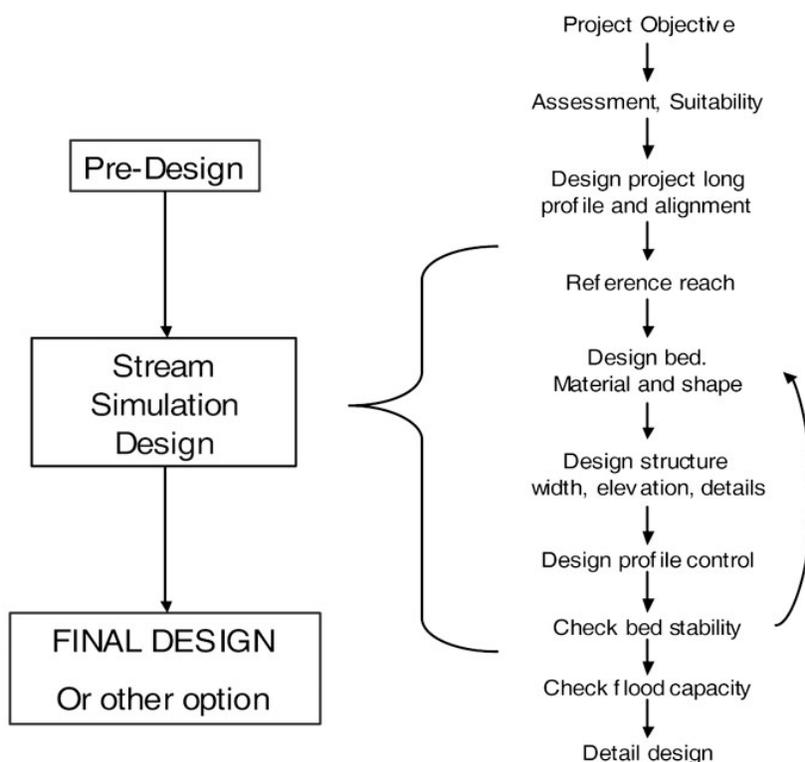


Figure 5.1. Stream Simulation Design Process

5.3 Stream Simulation Channel Design

This section describes the detailed steps necessary to design the bed material, bank material, key features, and channel shape of the stream simulation channel to be constructed inside the culvert.

The intent of stream simulation design is to simulate the natural bed and channel processes of the reference reach or the site. The key to the concept of stream simulation is to create a channel and

bed dimensions, shapes, and patterns that affect the ability of animals to move through the crossing. The reference channel cannot usually be duplicated exactly. Some channel features such as wide floodplains, large channel processes, and debris can't be entirely simulated. The functions of these features are mimicked by other features such as floodplain culverts or extra width of the culvert.

Characteristics of the reference channel are used as the basis for design of the simulated bed. The reference channel cross section, profile, and plan form appropriate for the culvert site are simulated in the culvert. The strategy for the design of the bed material and key features varies depending on the mobility and structure of the bed of the reference channel. These characteristics should be reflected in the constructed channel. Table 5.1 shows channel types, dominant characteristics, and a summary of recommended design strategies. Channel types used here are generally defined by Montgomery and Buffington (1992).

One might design a stream simulation using the reference reach and then find that it doesn't fit the site conditions of the crossing. A common discrepancy that should not be continued in a design is a significant difference in slope between the reference channel and what is needed in the designed channel. In that case an alternative reference reach may have to be located. An analytical design might be required if a valid reference reach is not available.

5.3.1 Reference Reach and Long Profile

As shown in Figure 5.1, once the project objective has been identified and the suitability assessment has been performed, a reference reach is chosen, and ultimately a long profile is surveyed and generated. The long profile includes the reference reach, the road crossing, as well as a reach downstream of the crossing containing channel forming influences.

From the chosen reference reach, a representative cross section is developed including designation of bankfull width, channel features are noted (i.e., bedforms, banklines, etc.), the type of channel is identified (i.e. pool-riffle, step pool, etc.), and gradation curves are developed from bed samples.

Once the longitudinal limits of the long profile are determined and it has been surveyed, a plot of the existing stream profile can be generated that includes channel characteristics and processes that might affect the channel in the future. On this long profile plot, potential profiles of the stream and culvert are drawn considering project objectives and reference reach characteristics. An example long profile is shown in Figure 5.2 and contains a range of future profiles based on field conditions.

Table 5.1. Channel Type

Reference Channel Type	Bed Material	Dominant roughness (structural) elements	Streambed mobility	Recommended Design Strategies
Pool-riffle	Gravel; often armored	Bars, pools, grains, sinuosity banks	Armored beds usually mobilize near bankfull	<ul style="list-style-type: none"> • Simulated bed D_{84} and D_{max} are same as reference reach • Determine rest of bed mix using standard bed material distribution. • Add bands or clusters of material for diversity. • Key features may be important.
Plane bed	Gravel- cobble usually armored	Grains, banks	Near bankfull	<ul style="list-style-type: none"> • Same as pool-riffle.
Step-pool	Cobble-boulder	Steps, pools, grains, banks	Fine material moves over larger grains at frequent flows. Bed-forming rocks move at higher flows depending on size (can be $>Q_{30}$)	<ul style="list-style-type: none"> • Steps are spaced same as reference reach. • Step-forming rocks are sized same as reference reach. • Rest of bed mix is based on sizes of non-step forming materials in reference reach.
Cascade	boulder	Grains, banks		<ul style="list-style-type: none"> • Bed material. • Key features are designed based on reference reach.
Dune-riffle	Sand - medium gravel	Sinuosity, bedforms (dunes, ripples, bars), grains, banks	“live bed”; significant sediment transport at most flows	<ul style="list-style-type: none"> • Simulated bed can be native bed material or standard borrow mix (no smaller than D_{100}).
Bedrock	Rock with sediment of various sizes in transport over the rock surface	Channel boundaries: bed and banks	Sediment moves over bedrock surface at various flows depending on its size. Wood can strongly affect sediment mobility.	<ul style="list-style-type: none"> • Stream simulation bed is bedrock. • Banklines and roughness elements are more important and more difficult to place. • Condition, extent, and shape of bedrock are important. • Bottomless structure
Channels in cohesive materials	Silt-clay	Sinuosity, banks, bed irregularities	Fine sediment moves over immobile channel boundaries at moderate flows depending on its size.	<ul style="list-style-type: none"> • Cohesive bed and banks cannot be constructed. • Clay banks may be similar to culvert walls. • Bottomless structure might leave clay bed undisturbed..

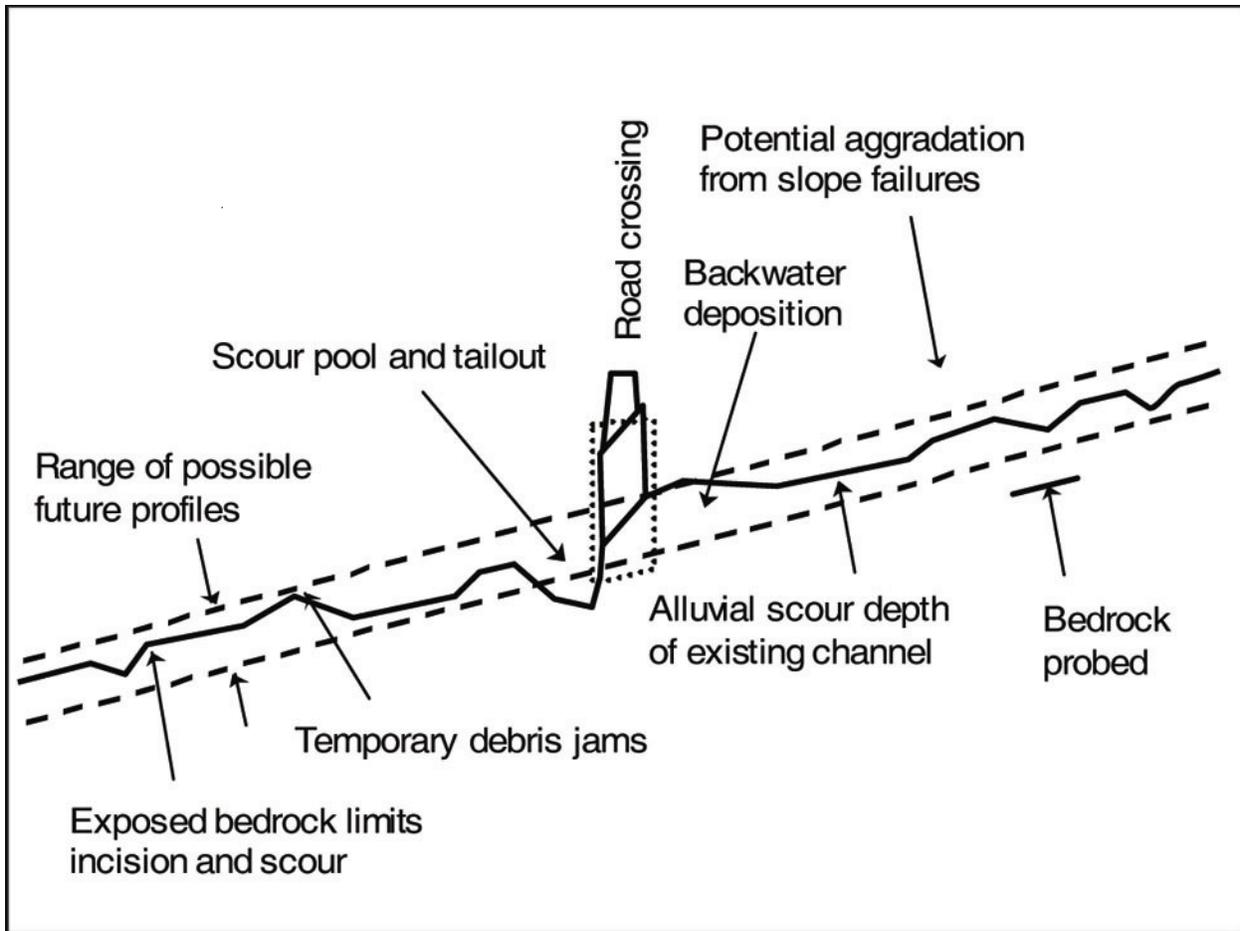


Figure 5.2. Long Profile Example

5.3.2 Bed Material

A key element of the stream simulation design is a well-graded bed material mix, including fines for permeability, which approximates the bed material size of the reference channel. Special cases are bedrock, sand-bedded, and clay channels that cannot be directly simulated as described in following sections. The simplest and most reliable stream simulation design is to incorporate channel bed material and other characteristics of the reference reach into the culvert channel since the reference reach will have the same hydrologic, geologic, and debris inputs as the constructed channel. The culvert bed should also be designed by an analytical process of bed stability.

The design of *pool-riffle and plane bed channels* is described first and most thoroughly. Many of the concepts described for these channels apply to other channel types as well. For example, channel cross-section shape, banklines, large roughness elements, and forcing features likely apply to all designs.

5.3.2.1 Pool-riffle and Plane Bed Channels

This section describes the stream simulation bed design for channels with mobile alluvial bed material; primarily pool-riffle and plane-bed channels. Bed material for channels in this section

can vary from coarse gravel (D84 11.3mm) to small boulders.

The important characteristic of these channels is that the bed material is relatively mobile. It moves during flows that occur annually or every few years. The bed material design described in this section can also be used as the design process for the base material of step-pool channels, which are described later.

An alluvial channel is one that is self-formed and controlled by the sediment it transports. Truly alluvial channels are uncommon in some climates where vegetation, cohesive soils, debris, colluvium, and bedrock influence channels. In those cases, key features may control the channel. The design should be modified to account for those influences as described in a following section on key features.

The channel bed material is designed from field samples of the reference channel, and their gradation curves. The larger sizes of material provide channel stability, bed diversity, and control the most persistent bed forms. Smaller particles are important for controlling bed permeability.

Permeability of the streambed is very important. A bed that is porous can allow substantial flow to move through it, and the entire streamflow may flow in the void spaces below the surface of the streambed. There have been culvert installations where the entire summer streamflow went subsurface every year for at least a decade after construction. The issue is especially critical in spring-fed streams where there may be little bed material transported, and in steep channels where the hydraulic slope can drive the flow subsurface. This applies to designs by reference reach as well as the analytical design approach.

Smaller grain sizes are less important for bed form but are very important for bed permeability and possible bed stability. The stream simulation bed mix should have enough fine materials to fill the voids between the larger particles. There should not be a gap in sizes between any classes of material in the mix; all sizes are needed to create a dense bed. Ideally each class of bed material that makes up the mix will be well-graded so all sizes within the category are represented. This is especially important for the smallest size fractions in a mixture of large material. To reduced permeability of the mix, fill the interstitial spaces with five to ten percent sands and finer. The finer material is also helpful to lock the larger pieces together to help reproduce the stability of the reference channel.

There are commonly concerns about water quality and habitat impacts of including the fine material. Some fine sediment will likely be entrained and transported by low or moderate streamflows that would not normally move the material. Because fines are moved at low flows, they can very likely impact spawning beds and other habitats. These effects might be mitigated by jetting the fine material down into the bed and/or placing a veneer of washed gravel over the surface of the bed. These ideas are described in more detail in the construction chapter of this guide.

Rock can be too large for a culvert. In a culvert with rigid walls, an individual boulder can be too large and create a constriction or bridge with other large particles to form a drop structure across the width of the culvert. These may limit migration path opportunities and be more vulnerable to debris blockages. In a natural situation, a channel usually has the flexibility to scour around a large boulder or debris accumulation. In order to avoid constrictions within the culvert, the width of the bed should be at least four times the intermediate diameter of the largest alluvial particle. Individual permanent (non-alluvial) particles buried in the bed can be larger. Limits are

described in the section on key features.

The bed mixture is placed without separating the armor and sub-armor layers. Most other bed characteristics such as clustering, textural patches, and grain imbrication and embeddedness are not constructed either. For the most part, the mixture is allowed to be distributed by the natural stream flow. An exception to this is for step-pool channels.

5.3.2.2 Step-pool Beds

Step-pools are important for dissipation of energy and the stability of the channel and should be included in the stream simulation design if they are present in the reference channel. Step-pool configurations and characteristics are described in the assessment chapter of this guide. Assessment of the reference channel should include characteristics of the step-pools such as step height and configuration, step spacing, and the size and alignment of key pieces.

Madej (2001) estimated that organization and roughness of the channel bed into regularly spaced steps probably takes several decades after being disrupted by a sediment pulse. Time scale depends on the occurrence of channel organizing flows as well as bed forcing features. Conditions following a sediment pulse are similar to a newly constructed channel bed with no significant sorting or compaction.

Step pools are formed by the largest particles in the bed accumulating and supporting each other to form a weir or step that is more resistant to movement than the individual pieces. Boulders form the framework of steps which supports smaller cobbles and boulders. Steps should be approximated in the initial construction with the expectation that individual rocks will adjust their position and location during high flows to lock together. The length and height of the steps and the step spacing are the important characteristics identified in the reference reach that should be considered in the culvert bed design. Place the step pools at the same spacing as the reference channel. Step pools in natural channels are typically spaced one to four channel widths apart and are closer in steeper channels.

Two classes of material are selected for step-pool channel beds. Additional classes might be needed for banklines and/or key features, which are described in other sections of this chapter. The bulk of the step-pool channel bed is the material between and beneath the step structures. It can be designed from a pebble count of the reference channel similar to what was described for pool-riffle channels. The pebble count in this case should be stratified to cover only areas between steps of the reference channel.

The second class of material is the particles that make up the steps. Key pieces in the reference channel steps should be characterized by size and shape. The steps are sized and designed for long term stability, and a stability analysis should be conducted to verify the material specified is stable during a high design flow. The material between steps will periodically scour and be replenished by the existing bedload moving through the system.

Other features such as channel shape, banklines, and wood and rock forcing features may be important elements to a step-pool channel. If these features are observed in the reference channel, include them in the design of the stream simulation. See the section on key features for more information.

5.3.2.3 Cascade Channel Beds

Bed stability is critical in cascade channels. The bed of natural cascade channels moves infrequently only during events that might recur in the scale of decades. Since cascade channels are steep, if the bed fails it is likely to leave a bare culvert that will not recover by natural replenishment of bed material.

An initial design of the cascade channel can be made by the same process as described for pool-riffle beds. The primary difference between the design of cascade channels and pool-riffle beds is due to the relative mobility of the bed. Cascade channel beds are much less mobile. A stability analysis should be conducted to verify the material specified is stable during a high design flow.

5.3.2.4 Dune Riffle Bed Channels

The key element for stream simulation in these channels is the bed material and its mobility rather than bedforms. The bed material is relatively mobile in these channels so no structure, other than rock bands, is built into the stream simulation bed and the sediment mix for the bed is less critical than for other channel types. It is important to use material that is similar to the natural channel to achieve more or less the same mobility. Bed material should be rounded unless the bed of the reference reach is naturally angular.

Other features such as channel shape, banklines, and wood and rock forcing features such as rock clusters may be important elements to a step-pool channel. See the section on Key Features in the pool-riffle bed design section. Clusters can be made of rock that is one to two times D_{100} but no smaller than coarse gravel. The larger material is used in beds that are more mobile.

5.3.2.5 Bedrock Channels

Bedrock channels often have bedrock exposed in the bed but have banks of other material. They may have other roughness elements such as debris and single or clustered boulders. If channel margins and/or banklines are important to the objective of the project, they should still be designed into the stream simulation. Exposed bedrock is often tilted, so when contained by a culvert, a deep and smooth channel is formed along one wall at low flow. Boulders might be added for roughness in such a case. Special considerations such as embedding, anchoring, or clustering of large boulders may be required to keep them from rolling or sliding out of a bedrock channel.

The condition, extent, and shape of bedrock under a road fill are often not clear even with geotechnical reconnaissance data. Flexibility for design changes based on what is found should be accommodated in the contract.

Bedrock channels sometimes exist where a bed of alluvial material has been scoured leaving the bedrock exposed. This most often occurs in mountain streams where woody debris has been removed and/or not naturally replenished due to urbanization or forest practices or where a debris flow has scoured the channel to bedrock. The lack of bedrock erosional features such as fluting, longitudinal grooves, and potholes may also indicate that the bedrock is typically covered by a thin veneer of alluvium which may have been recently mobilized during a large flood (the alluvium is typically stable during lesser flows). Restoration of the bed should be considered by placement of debris and/or colluvium to help develop a natural alluvial bed and/or stabilize a constructed bed. Channel restoration is further discussed in the channel profile section in this chapter.

Bedrock channels can also have a thin, continuous or discontinuous veneer of alluvial material that can be mobilized during high flows, only exposing the bedrock during high flows. Hence, flow hydraulics and sediment transport are strongly controlled by the underlying bedrock, not the thin veneer of alluvium.

Other features such as channel shape, banklines, and wood and rock forcing features may be important elements to a bedrock channel. If these features are observed in the reference channel, include them in the design of the stream simulation. See the discussion of key features in the following section.

5.3.3 Channel Shape and Form

This section discusses various elements of channel shape and form including cross-section shape, bed forms, banklines, and key features.

5.3.3.1 Cross-section Shape

The cross-sectional shape (Figure 5.3) of the reference channel is an important part of the stream simulation. If channel margins and banklines are important to satisfy project objectives, they should be included in the channel designs for stream simulation culverts. Channel margins are the shallow corridors commonly formed as gravel deposits near the edges of channels.

The bed of the constructed channel should include a low flow channel. The constructed low flow channel is only intended to provide some shape to the initial bed; it is not expected to persist through flood events. If designed with features as described here, floods will leave the channel with diversity and a thalweg. Construction of an initial low flow channel is especially important if the culvert bed material is larger than the natural bed material.

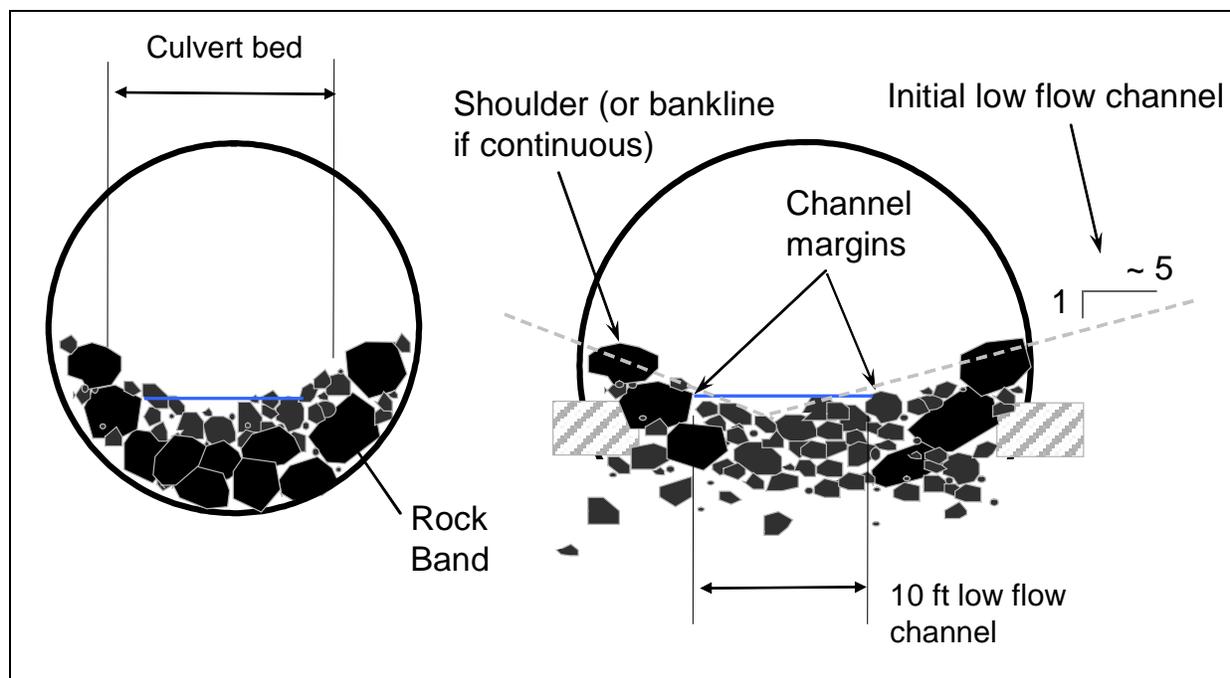


Figure 5.3. Cross-section Shape

The precise shape of the low flow channel is not critical. The lateral slope of the vee shape

should be roughly five horizontal to one vertical. Only a portion of the bed width, perhaps a ten-foot corridor, should have the vee shape. The average bed elevation in the cross section is used as the control elevation for the profile design. The shape and lateral slope should be rough so the bed qualitatively resembles the bed variation in the natural channel.

Some initial sorting of bed material is important. In lower gradient channels, bed forms are fluid and it may take a number of high flows before channel structure is formed. In the meantime, and especially if no bankline is constructed, the bed will tend to be very flat and the flow will be very shallow. The shallowness might be a barrier to migration of fish. There is also a tendency for a trench to develop along one wall of the culvert. The relative smoothness of the culvert wall creates a higher local velocity there that will scour the trench. To prevent either of these situations, rock bands or clusters should be added. Bands and clusters are similar features but of different scales. Bands are diaphragms of rock that occupy the entire cross section of the bed and are spaced periodically through the culvert. Clusters are similar but simply a pile of rocks partially buried at each edge of the channel.

Bands and clusters are not permanent rigid structures; they should be modified by high flows. They are to create diversity in the cross section, which would be created in a natural channel by flow deflections from bankline irregularities, debris, rootwads or other structures. These features should be used in stream simulation culverts with bed gradients less than about four percent and when a continuous rough bankline is not included in the design.

Generally bands or clusters are made of rock that is about one to two times D_{100} but no smaller than coarse gravel. The larger material is used in beds that are more mobile. The features are not structured so a well sorted mix is not necessary. The crests of the bands are lower in the middle, encouraging the channel to move back to the central part of the culvert. The high points of clusters and bands are about two times the diameter of the rock they are made of above the elevation of the bed profile.

Since the rock bands are not persistent, their spacing is not critical. Spacing could vary with slope and channel width and could resemble the spacing of pool riffle sequences in the reference channel. The vertical difference between crests should be less than or equal to 0.5 feet. The vertical distance between crests is suggested only to prevent bands from being hydraulic drop structures.

The bands described here are similar in some ways to steps in step-pool channel configurations. The difference is that the purpose of rock bands in low gradient channels is to create shape and diversity and they are not permanent features. Step pools dissipate energy, create stability, define the longitudinal profile of steep channels, and are more persistent.

The intent is to simulate the roughness and diversity along the bank of a natural channel that provides a shallow migration corridor. In some cases the culvert walls might perform the same function when compared to a smooth vertical bank in the reference channel. Some diversity such as rock bands along the bankline should be provided in any case. Actual pool-riffle features and sorting of bed material are certainly necessary to achieve stream simulation but these are difficult and costly to construct and it is expected that the channel will, for the most part, create these characteristics.

5.3.3.2 Banklines

The diversity, roughness, and shape of banklines may be critical to satisfying objectives of passage of aquatic organisms. Banklines will often not form in constructed channels within culverts, because without root structure, cohesive soils, or the ability to scour into parent bed material, alluvial banklines cannot form. However, bars may form at least through part of the length and on one side of culvert and provide some of the benefits of a bankline.

To simulate a bankline that reflects the range of low flow widths and depths in the reference channel, a line of large rock is placed along each wall of the culvert and the spaces between and behind the rocks is filled with the bed material mix. Fill over the bank rock with bed material so it will wash into place between the rocks. The intent is to create a permanent bankline so material of adequate size to be stable during severe floods is required. An initial estimate of bank material size is based on experience and with consideration of the reference channel. Bank material might be up to twice the size of D_{100} in the channel or six-inch minus quarry spalls, whichever is greater. It might also be based on D_m of the reference channel if that material appears to be non-mobile. Later in the design process the size of the bank rock and other key pieces will be verified with a stability analysis.

Extra culvert width may be necessary to create a stable bankline without constricting the bankfull channel. In lieu of providing the culvert width necessary to place banklines, a bankline could be simulated by roughening the concrete of a footing wall on a bottomless pipe. Ideal roughening would be rocks embedded into the concrete. Embedded rocks could be simulated in the concrete with a special concrete form or commercial precast concrete elements might be built into the bankline. Partially grouted rock might be used to roughen a concrete footing wall. The objective is to increase the stability of the rock without sacrificing all of the flexibility of individual rocks within a limited bank width. Grout might be used to fill about half of the voids behind and between the rocks and it might be tied to the culvert footing wall. Another approach that has been employed is to attach vertical baffles to the walls of metal and concrete pipes. The purpose of the baffles is to create roughness and deposition along the wall rather than to control the overall velocity for fish passage. Baffles would have to be spaced no more than several feet apart so they would act as a continual roughness element.

5.3.3.3 Bed Forms

Bed forms other than rock bands and steps in step-pool channels are not generally constructed within stream simulation culverts. Constructed bedforms will not generally be stable since the materials are not sorted nor the forms built hydraulically by stream forces. The intent is that if the material is provided, bedforms will be created naturally during the first freshets experienced by the project.

Some designers recommend that bedforms be constructed inside the pipe to immediately simulate those bedforms identified in the reference reach. Cobbles and boulders may only be mobilized at flows greater than bankfull. Constructing features with those particles allows the constructed channel bed to respond more naturally during initial high flows. Channel-bed structures such as particle clusters, longitudinal bars, transverse clast dams, etc. can certainly be constructed if observed in the reference reach. Construction of bedforms will add to initial diversity. However, constructed bedforms should not be expected to be permanent features.

Rigidity of the bedforms is generally directly proportional to stream gradient. In reaches where

the entire bed can mobilize, bedforms such as scour pool tailouts are flexible. In steep streams where the bedforms are persistent for long periods, sediment is moved from pool to pool with the key elements remaining stable and intact. In this case artificial steps or cascades should be designed to be stable during flood flows.

5.3.3.4 Key Features

Features that affect the channel form and stability such as colluvium, bedrock, and debris should be characterized in the reference channel and accounted for in the stream simulation design. The reference channel may also have large roughness elements that should be included in the channel design.

Colluvium is generally defined as rocks delivered to the channel by hillslope processes rather than alluvial processes. For the purpose of this guide, we consider colluvium to also include lag deposits from extreme flood events or debris flows, or erratics from glaciers. Forcing features might be partially buried in the bed, buttressing bed material and/or they might block part of the channel cross-section and create roughness. Debris in the reference channel might be in the form of small jams, buried wood that buttresses and/or forms steps, or wood protruding from a bank. The function of either key feature must be included in the simulated channel or the bed material must be modified to compensate for the lack of it. In addition to key features, initial cross section shape and permanent banklines as described previously may be required to achieve project objectives.

The scale and spacing of bed-forcing elements should be set to simulate reference reach conditions. If colluvial material in a reference channel is not recognized as being non-fluvial, a designed channel may end up with much larger bed material than what would truly simulate the reference reach. Colluvium can be recognized by its limited distribution through the length of the channel and by being a unique larger size class in the bed material distribution. There is usually a gap in size classes between the smallest colluvium and the largest alluvial material that can be seen as a bimodal size distribution in a particle size distribution analysis.

Forcing features buried in the bed can be simulated with large rock. Angular rock and clusters of rock have greater stability than round rock and individual rocks. The size and distribution of the rock might be similar to colluvium in the reference channel or as indicated by a stability analysis. The largest alluvial particle should not exceed a quarter of the culvert bed width. Non-mobile key features are not alluvial and may have to be larger. Key features often span the entire channel and should be simulated that way and built with a group of rocks similar to a step pool configuration. A cluster of rocks will provide some diversity of flow and migration paths, will conform better to walls of the culvert and prevent a narrow slot there, and be narrower in the streamwise direction similar to a buried log in a natural stream. The depth of the bed in a culvert should be at least one and a half times the median diameter of rocks used as key features. This will prevent individual rocks from interacting with or bearing directly on the floor of the culvert. Rocks used as key features should be buried by about three quarters of their diameter so they buttress and support the bed. Placement should be similar to step pool controls as described below. Similarly sized rock can be scattered in the surface of the bed to provide a roughness more or less equivalent to that created by forcing features.

There is some risk in depending on non-alluvial material in the culvert for stability. If colluvial material is scoured from the stream simulation culvert, it might not be replenished and therefore

the structure of the project bed may be jeopardized. See the assessment chapter for more background on sources, implications, and identification of colluvium. An analysis should be conducted to verify the stability of colluvial material or individual elements placed to anchor other bed material in the stream simulation (see the section on stability analysis in this chapter). Potential solutions to increase stability include increasing the size of the culvert, increasing size of colluvial material in the culvert, and bed retention sills attached the culvert invert.

Large scale roughness includes bedforms, bank irregularities, large debris, and roughness of channel alignment. The function of large scale roughness is similar to forcing features described above though the features may be of a larger scale. Tight channel bends dissipate energy; if they are replaced by a straight channel, roughness should replace the function of the bends. Buffington and Montgomery (1999) describe the roughness effects of wood, bar formations, and bank irregularities. These characteristics should be described as part of the site assessment and accounted for in the stream simulation design. Unfortunately, there is no established procedure to simulate large scale roughness and simulate it with other materials. The difficulty is in characterizing it as roughness. The general approach of stream simulation is to characterize the roughness of the reference reach bed material and simulate it directly. Large roughness elements such as tight channel bends, channel-spanning debris, and bedrock and tree root outcroppings are not included in that simulation.

The large scale roughness might be simulated with large rocks scattered and embedded into the channel bed. Ferro (1999) describes the roughness created by various arrangements and concentration of boulders placed on a gravel streambed. Another simple method is to quantify the frontal area of all roughness elements in the reference channel and provide the same frontal area in the stream simulation with boulders. A third method is described by Arcemont et al. (1989). The method uses a base roughness value from bed friction, and applies correction factors for the effects of surface irregularities, variation in the shape and size of the channel cross section, channel obstructions, vegetation and flow conditions, and for meandering of the channel. For example, this method can be used to compensate for shape of the channel cross section by adding roughness with boulders or bed material. At this time, none of these methods have been fully developed or applied to stream simulation in practice.

Simulating a channel with large scale roughness elements may be more risky than a purely alluvial channel. These features must be constructed carefully to be successful. This is especially true for steeper channels where dissipation of energy by forcing features is critical to channel pattern, form, and stability. It may be prudent to oversize D_m and colluvium materials, and widen the culvert to reduce risk. See the stability analysis section of this chapter. It is recommended that special geomorphic and engineering expertise should be consulted in these cases.

5.4 Stream Simulation Culvert Design

Now, for the first time in the stream simulation design process, we consider the road crossing structure itself. The design process to this point has defined the probable range of stream profiles at the site, and the shape and material of the stream simulation channel. In this part of the design process, we will determine the culvert elevation, style, shape, and dimensions (diameter or width and height). Culvert shape, dimensions, and elevation are determined iteratively because they affect each other. Design of the culvert itself must be preceded by the alignment, profile, and bed

designs because those elements determine the width of the bed and therefore the size of the culvert. Simply put, the design of the crossing is just fitting a structure around the channel that has been designed. Because there are specific criteria that will influence culvert shape and dimensions, such as depth of cover over the pipe and minimum and maximum embedment depths, it may become apparent to the designer that a culvert is not the optimal solution. Considerations of self-sustainability may also influence the type, shape, and material of culvert structure that is used.

Several conditions might determine the size of the culvert, such as the range of bed profiles, maximum sizes of alluvium and colluvium, bed stability analysis and the width of the channel and banklines to be contained within the culvert. All of these conditions must be satisfied at the same time. The culvert will therefore likely be larger than needed to meet certain conditions that have traditionally been used for sizing culverts strictly for hydraulic capacity.

5.4.1 Culvert Elevation

Once the project bed profile and bed characteristics have been determined, the elevation and slope of the culvert structure itself can be established. The discussion of elevation in this section relates to the invert of a solid structure or to the footings of a bottomless structure. The elevation of the culvert relative to the streambed may be affected by the culvert shape, the expected variance in channel elevation overtime, flood capacity, and the maximum size material in the bed. A preliminary elevation of the culvert might be found but it may be changed later in the design of the culvert width and shape.

Set the culvert elevation and profile to allow the range of channel profiles expected for the life of the project and described in the project profile section. Remember that the stream channel may at some time be at any elevation within that range. One goal of establishing a stream simulation culvert profile is to prevent the invert of the culvert from becoming exposed during its design life. If the invert becomes exposed, the natural stream is certainly not simulated and the bed may not recover and rebuild on its own. A second goal is to maintain flood and debris capacity when the bed is at its highest possible elevation.

Depending on the risk and uncertainty of the range of profiles, provide a safety factor in depth of the culvert invert and height of the culvert. For example, the risk of scouring below the stable footing embedment depth of a bottomless structure may dictate the need for a deeper footing. A larger culvert may be needed where substantial profile change or scour is likely.

An economical design will set the bed near but below the maximum width of the culvert to avoid unnecessary structure width and so the water surface width does not contract with just a small increase in stage. Setting the high bed elevation at the mid-point of the culvert also ensures headroom above it for floodwater and debris. The high profile should be no higher than 50% of the rise of the culvert as measured from either the footings of a bottomless structure or the invert of a pipe.

A minimum bed depth must be provided to accommodate some bed width and depth for minimum bed thickness and to provide a safety factor. A circular culvert embedded into the streambed no less than 30% but no more than 50% of its rise is a good practical guide.

Figure 5.4 shows the relationship between the range of channel profiles and the culvert rise, which is the inside vertical dimension of the culvert. Using the recommended burial range of

30% to 50% given above, the culvert rise must be at least five times the vertical distance between the low and high profiles. For example, if we expect the bed elevation to vary two feet, then the height of the culvert has to be at least ten feet. This size may or may not hold when we size the width of the culvert. Bed stability and debris passage may affect the height of the culvert. Further, both depend on the culvert not becoming submerged during the design flood flow, which is discussed in the stability analysis section of this guide.

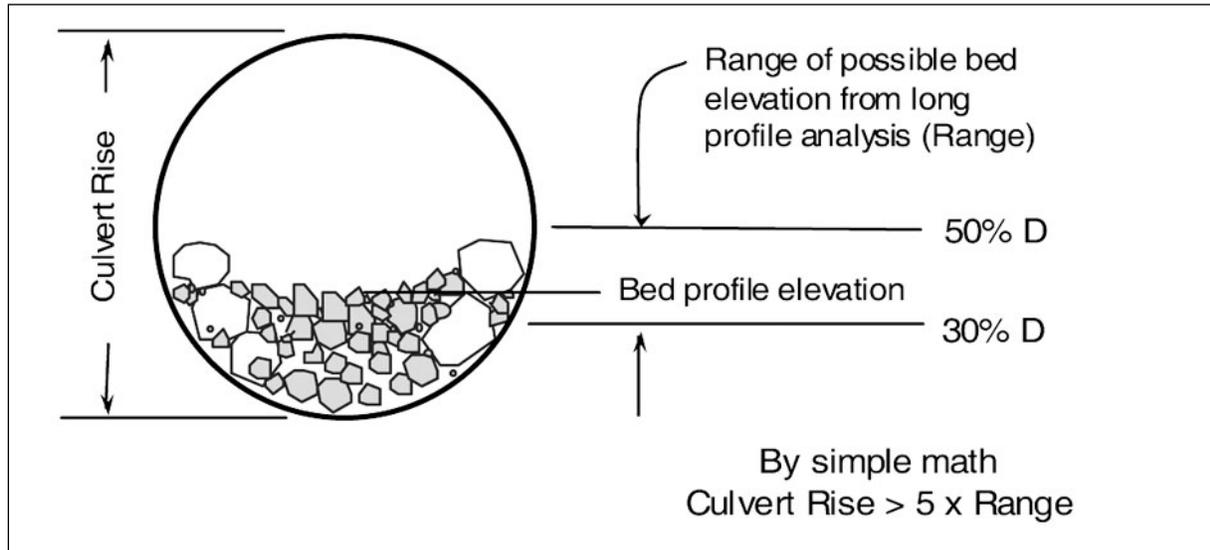


Figure 5.4. Profile Range

There are conditions that may affect these burial and culvert size recommendations. The size of the bed material may affect the depth of the culvert bed and therefore the culvert elevation. For the bed material to be well integrated and able to structure itself the depth of the bed should be at least one and a half times the diameter of the largest colluvial material and four times the largest alluvial material in the bed as described in Section 5.3. The depth of the bed, and therefore the culvert invert elevation, should be checked after the bed material is designed

5.4.2 Culvert Width

The minimum width of a stream simulation culvert shall be equal to, or greater, than the bankfill channel width, but not less than 6 feet. Culvert width addresses self-sustainability, which is the interaction of high flows, the bed, and the culvert to create and maintain bed material sizes and patterns within the culvert bed that accurately simulate the natural channel. Other things that affect culvert width are hydraulic capacity and stability of the culvert bed, as well as construction, repair, and maintenance considerations.

Conditions that might affect width of stream simulation culvert are as follows:

Based on project objectives:

- Width of channel and banks within the culvert
- Self-sustainability of the bed
- Hydraulic capacity of the culvert
- Stability of the bed

- Construction, repair, and maintenance needs
- Passage of mammals
- Reduce risk of blockage by floating debris or beaver activity
- Increased flood capacity and/or bed stability
- Meandering channel pattern part of project objectives

Based on channel characteristics:

- Active floodplain
- Flow concentrations in floodplain
- Channel migrating laterally or meanders translating longitudinally
- Wider channel expected in future
- Channel skewed to road crossing
- Ice plugging in severe cold climate
- Large bed material relative to culvert width
- High water level stage during floods or high tides.

For the stream simulation bed characteristics to be self-sustaining, the culvert must simulate the hydraulics of the natural channel at bed-forming flows. For many low to moderate gradient alluvial channels in humid climates, the bankfull flow is a useful measure for design of the channel. Constricting the channel at that flow will change the character of the bed and deviate from simulating the natural channel. To satisfy this objective, the channel width in the culvert must be at least bankfull width. It may have to be larger than that if water that would normally flow on the floodplain is confined to the culvert.

In cascade and step-pool channels, bankfull width is not directly relevant to the width of the culvert though it is a good initial estimate. It is well documented in semi-arid climates that when the ratio of relatively infrequent flood peaks to the mean annual flood is large, infrequent large floods typically control channel form rather than bankfull flow.

In a confined channel where the stream width does not change substantially with stage, the culvert channel may not need to be wider than the reference channel width as long as the bankline character in the culvert is characteristic of the natural channel and the culvert is sized to safely pass flood flows. Bankline character includes roughness of bank material and bank irregularities. As a word of caution, incised channels may look narrow early in their development but will widen with age (Schumm et al. 1984) or with recovery from disturbance, although widening due to channel evolution is usually gradual and not likely to be significant within the typical design life of a project. Channel widening following recovery from a disturbance should be accounted for. Stream simulation culverts should be sized to anticipate the expected evolution of the natural channel near the crossing as well as the confined channel within the culvert.

If an existing channel is unnaturally wide due to disturbance and you expect it to narrow in the future, the culvert should be sized for the existing channel width with the expectation that recovery will occur inside the culvert as in the adjacent reaches.

If a culvert is located in a channel within a wide active floodplain, flow will be forced from the floodplain into the constriction of the culvert. Three effects of the contraction are of concern.

The additional water forced through the culvert may cause bed scour in the channel at a flow lower than it would occur in the natural channel. The lower critical flow may cause a bed failure. The bed at the culvert inlet is the most vulnerable to failure due to constriction scour. The bed in the vicinity of the inlet is vulnerable to failure even though the hydraulic conditions in the rest of the culvert are similar to the reference channel. It may affect the bed shape or structure so it no longer simulates the natural channel. The third issue is that forcing flow off of a floodplain may affect habitats and movement of aquatic and terrestrial organisms within the floodplain.

Figure 5.5 shows several examples of culverts in channels with and without floodplain contractions. This situation is described thither in the stability analysis section of this chapter.

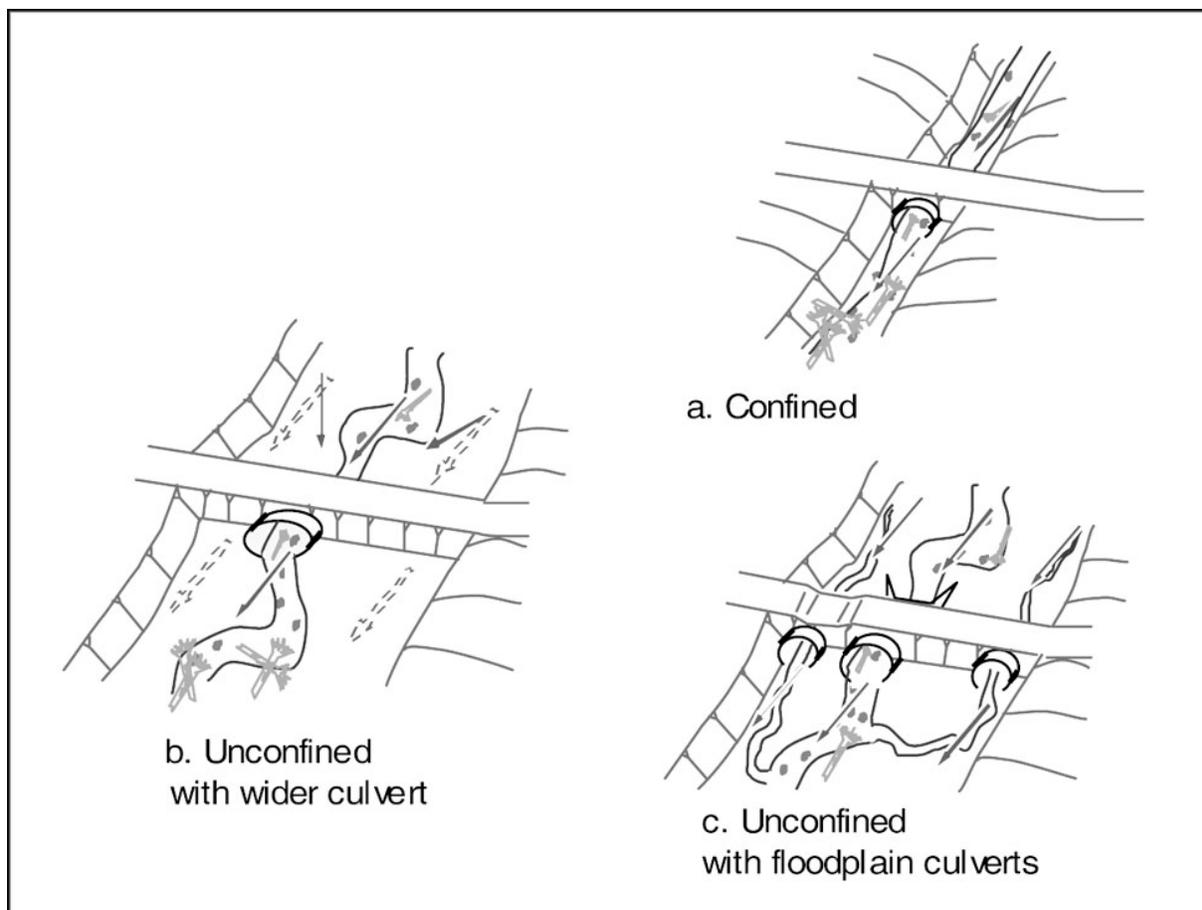


Figure 5.5. Floodplain Contraction

If the channel bends at the crossing site or meanders significantly and the intent is to include this characteristic in the project, the culvert can be enlarged to contain the width of the bend or meander or a portion of it. A special bank design would be required for an outside bend within a culvert. The bank would normally be considered rigid rather than deformable. It should be designed to be permanent and not allow a deep thalweg to be scoured along the bank toe. Some meander migration might also be accommodated by the width of the culvert. Some vertical and plan form variation can take place in a stream simulation culvert if the culvert is wider than the channel width and deeply embedded. Low flow channels will usually meander within the length of the pipe. Additional culvert width might be necessary if the culvert is skewed to the road

alignment as described in the culvert alignment section of this chapter or if natural lateral migration of the channel will likely create a skewed inlet condition.

There is also a lower practical limit to the diameter of culvert that can be constructed as stream simulation. A culvert with a diameter or rise of about five or six feet is a minimum because the bed cannot feasibly be constructed in a smaller pipe except with hand labor. Access may not be an issue if strong hand labor is available and the rock is not too large to manipulate by hand or with hand equipment. This size consideration should also be evaluated relative to future access for maintenance and repair.

5.4.2.1 Floodplain Culverts

Relief pipes can be placed in the floodplain for connectivity through the floodplain. Size of floodplain culverts might be determined by the same parameters and criteria as the primary culvert but using the size of the side channel. Countersink them similar to the criteria for culverts placed in the main channel.

Floodplain culverts should be located at flood swales and side channels so floodplain flow patterns are preserved. If there are no signs of flow concentration, locate culverts at the center of floodplain conveyance. The center of conveyance is determined by calculating the centroid of the flow in the floodplain and if no swales are present it is controlled by the depth of flow and varying roughness across the floodplain. Johnson and Brown (2000) describe a precise calculation technique.

Floodplain culverts might also be necessary to preserve floodplain functions and passage of organisms through the floodplain. They become more useful with increasing width of the floodplain on either bank because that width implies increased separation of channel and floodplain hydraulics that are significant for floodplain form and features. When there are signs of flow concentration in the floodplain, such as swales and side channels, consider adding floodplain culverts. Based on visual assessment of side channels in a humid environment, side channels generally occur when the floodprone width on one bank is more than four times the bankfull channel width. The use of floodprone width for a threshold of floodplain function is an indicator of significant separation of floodplain hydraulics at flows that are effective in creating floodplain form. It might be more or less than that threshold if the floodplain has more or less conveyance.

Floodplain culverts that concentrate flow can create a risk of diverting and capturing the entire channel. If the floodplain is well developed with mature woody vegetation, blockage of the culvert by fallen debris may prevent an entire channel change and still meter flow through. If the floodplain culvert is small enough to create a backwater if the entire flood flow were passing through it, it will push flow and the channel back to the primary culvert. Multiple smaller culverts in the floodplain reduce the risk of channel capture.

5.4.3 Culvert Material and Shape

No single culvert material or shape is best for all stream simulation situations. Figure 5.6 shows shapes and nomenclature of culverts used in this guide. All of these culvert shapes can have natural streambeds within them. If the bankfull channel widths and bed characteristics are the same as the natural channel and there is adequate hydraulic capacity to sustain the stream simulation characteristics though the life of the project, there is little difference among these

designs from the point of view of passage of aquatic organisms.

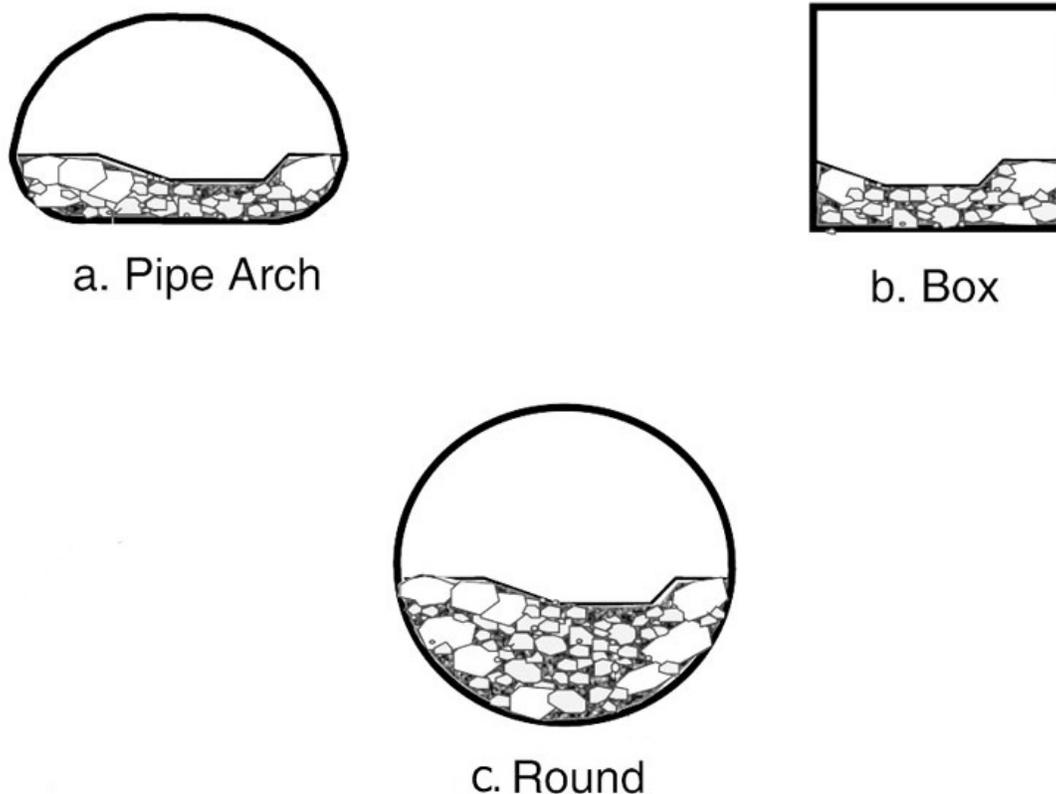


Figure 5.6. Culvert Shape

The shape and material of a culvert can substantially affect the initial and life-cycle costs of a project however. Cost differences may be due to material costs, project sequencing, limitations of project duration, competence of soils for structural loading, location and availability of materials, excavation volume, excavation limitations such as bedrock, and the cost of delivery to remote locations. Other differences include reliability, limitations of hauling over-sized materials, durability and resistance to corrosion and abrasion, risk of vertical instability, debris passage, hydraulic characteristics for stream simulation, and experience of the construction crew.

5.5 Stream Simulation Profile Control

This section contains suggestions on how to design and construct the channel profile.

If a channel steeper than the reference channel is needed in order to make up elevation differential through the project, profile control measures may be necessary. Profile control structures are structures that hold a profile in place. They function similarly to forcing features in a natural channel. They may be artificial or simulate natural conditions, and they may be permanent or temporary and/or deformable. They may or may not comply with the premise of stream simulation depending on whether similar structures are present in the reference channel. Biological monitoring may be necessary to determine the suitability of these constructed features

with respect to passage of specific aquatic organisms.

There are several options for profile control; no single solution satisfies all situations. Depending on the desired project profile and site limitations, control structures may be necessary upstream or downstream of a culvert or a combination of the two. Figure 5.7 shows upstream and downstream options.

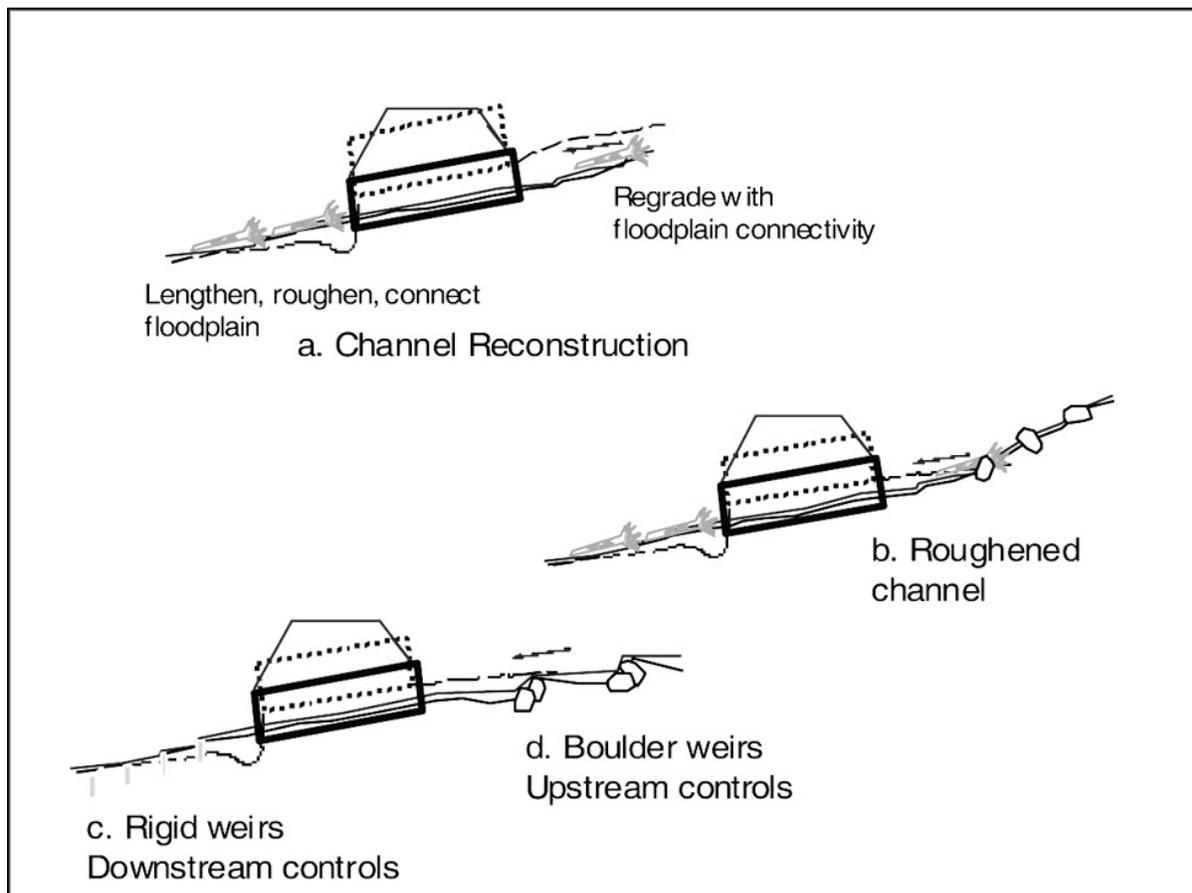


Figure 5.7. Profile Control Options

5.5.1 Headcut

If a decision is considered to allow an upstream headcut to create a new profile, the consideration of this section should be reviewed. The profile control scheme could to allow a headcut, but with structures included to control its extent and/or its rate. Temporary controls such as scattered, buried, or temporary rock structures that are expected to fail over time can mitigate some of the headcut impacts. If debris is to be employed, careful consideration should be given to the potential for its mobility.

5.5.2 Channel Restoration

An elegant and durable correction to achieve passage of aquatic organisms is one that is process-based and that solves the underlying problem rather than forces an artificial profile into a crossing site. Channel restoration as a profile control measure means the downstream (and/or upstream) channel is restored to a natural and self-sustaining condition and in the process the

profile is changed to achieve passage at the crossing. This option can be used in channels that have incised due to unnatural changes in hydrology and/or removal of debris.

Channel restoration is the re-establishment of structure and function of the stream ecosystem with the goal of achieving a condition as close as possible to pre-disturbance conditions and functions. This goal is difficult to achieve in multiple use watersheds where land-use practices have greatly altered the watershed hydrology and sediment regimes.

Channel restoration can restore in-stream, riparian and floodplain habitats, restore channel processes, reverse bank erosion, and be more self-sustaining than other options of correcting passage barriers. Channel modifications can be used to address a variety of process- and function-related habitat problems that are often symptoms of disequilibrium. The channel restoration option should be considered at both new crossing installations and at culvert replacement projects.

Channel restoration may include reconstruction of the bed up to a natural grade, restoration of floodplains by removal of levees or other constrictions, construction of a floodplain by excavation, and/or building meanders to recreate channel length and diversity. Channels that have been scoured down to bedrock or cohesive channel beds might be converted back to natural alluvial channels. Design elements are channel cross section, profile and bedforms, planform, grade control, bed material, bank reconstruction, riparian revegetation, floodplain, and habitat considerations. A project that includes restoration of an incised channel can be extensive and can extend a considerable distance from the crossing.

Channel restoration can also be applied in aggraded channels upstream of culverts by reconstructing the channel and/or floodplain at a lower and natural grade.

Only some stream ecosystem functions will be recovered by manipulating certain components of the channel. In that case “channel rehabilitation,” as described by the Federal Interagency Stream Restoration Working Group (1998), might be a more appropriate term for culvert removals and replacements. Rehabilitation does not reestablish pre-disturbance conditions, but improves fluvial and ecological processes within the existing conditions of the watershed/channel

Reconstruction of an incised bed to a natural grade might be done with individual structures that are intended to trap bedload and fill over time or by filling the entire channel and building in the structure and diversity of the channel. If individual structures are used, it may be similar to the rigid bed control structures discussed below. The structures should simulate natural channel features and the overall profile should simulate the natural grade.

If an incision is caused by a change in hydrology, restoring to historic conditions will not be self-sustaining, and may ultimately fail. The channel should be designed to fit the current as well as future hydrologic regimes. It is necessary to understand the sensitivity of the channel and how it will be affected by hydrologic changes.

Specific design guidance for channel restoration and habitat components within it are beyond the scope of this document. Additional references and expertise should be applied.

5.5.3 Steepened Channel Options

A channel adjacent to a culvert can be steepened with artificial sills and/or a roughened channel. These designs do not comply with the principles of stream simulation but can complement an

adjacent stream simulation culvert by establishing an appropriate profile without concentrating the most severe hydraulic conditions within the confined culvert. Steepened channel designs might also be used when a culvert is replaced with a bridge. Some aquatic organisms may not be capable of passing through a steepened reach. The project profile may have to be reduced to a range that is acceptable relative to the organisms that will be present.

5.5.3.1 Roughened Channel

A roughened channel is a well-graded mix of rock and sediment with roughness and hydraulic diversity to steepen a channel and provide conditions suitable for passage of some fish and/or other organisms. It provides profile control at a gradient steeper than the natural stream channel.

Although roughened channels can be designed to have banklines, shallow water margins, and other diversity similar to stream simulation designs, the difference between a roughened channel as defined by fish passage experts and stream simulation is that the roughened channel uses channel dimensions, slope, and material to create depths, velocities, low turbulence, and a hydraulic profile suitable for a target species to pass through. This is somewhat equivalent to the hydraulic design option for culverts as described in Chapter 6. The bed material of a roughened channel is not intended to evolve as a natural channel with bed material scouring and replenishing; it is a fixed semi-rigid structure. Individual rocks are expected to adjust position and location but the larger grain sizes are not expected to scour out of the reach. As a result it may be steeper and have more severe hydraulic conditions than other sections of the stream.

Ideally a channel is roughened to the point where the potential energy available at the upstream end of a reach is dissipated in turbulence consistently through the reach and that no excess kinetic energy is present within the reach or at the downstream end. The design for steepened channels downstream of culverts or other fixed structures where any degrading of the channel will result in the culvert countersink or velocity criteria to be exceeded should be conservative. Profile and elevation of the roughened channel are critical to success of the project. The culvert should be countersunk deeper than normally required with the expectation of some degrading of the backwater control.

In order for the roughened channel to be reliable for aquatic passage, it is essential that the bed material remains in the channel more or less as placed. It is expected that the bed material will shift slightly but not move any appreciable distance or leave the reach. Bed stability is essential because these channels are not alluvial. Since they are often steeper and more confined than the natural upstream channel, recruitment of the larger rock in the bed from upstream is not expected. Any large material that is scoured will not be replaced and the entire channel will degrade.

In order to prevent excess infiltration and loss of low surface flows, bed porosity must be controlled. Smaller grains that control the porosity in the roughened channel may gradually be washed out of the bed. This is similar to the bed porosity issue in stream simulation except in that case, material that seals the bed will be continuously replenished. If material transported from the natural channel is too small to be trapped in the voids of the roughened channel bed, the bed will become porous.

5.5.3.2 Artificial Sills

Artificial sills are rigid or gradually deforming structures built in the bed to control the channel profile. If profile control structures are placed downstream of a culvert or other rigid bed feature, and they are the sole means of maintaining the profile, they should be long lasting and stable to maintain the designed elevation. This is necessary because the culvert is a long-term feature at a fixed elevation. Any loss or lowering of the downstream controls could result in another barrier at the culvert or structural risk to the culvert.

Any grade control structures must anticipate future conditions and the probability that continuing channel incision will occur. Scour occurs below grade control structures. When profile control structures are built downstream of a perched culvert, some of the energy that was dissipated at the culvert is moved to the grade control structures. Downstream scour can be exacerbated if there will be substantial bedload infilling between grade control structures upstream. The last grade control structure downstream should always be at or below the existing streambed grade. Additional buried controls are recommended where there is significant variability in bed elevation or possible future incision is expected. Those controls would become exposed and effective only as the downstream channel incises.

When required, control structures upstream may either have rigid elevations or they might be designed with the expectation that they will gradually adjust overtime. The choice depends on project objectives and considerations from the profile design section of this manual. All or part of the upstream headcut may in some cases be allowed to occur uncontrolled. Profile control structures must not be placed near the culvert inlet. If the energy dissipated below the structure scours the culvert bed, the entire culvert bed can be affected and in some cases, entirely washed out of the culvert. The recommended distance to the nearest upstream control is a function of channel width and slope. In channels with slopes up to about four percent and with widths between ten and twenty feet the upstream control should be thirty to forty feet from the culvert inlet. In steeper channels, pools are naturally more closely spaced. Spacing upstream of a culvert might be twice the spacing of step-pools in the natural channel.

These structures are only generally described here, and this level of information is not adequate for design. More specific descriptions, design considerations, applications, and limitations are described by WDFW (2002), U.S. Department of Agriculture, Natural Resource Conservation Service (2001), and Rosgen (1996).

Boulder (Rock) Control Weirs

Low boulder sills have been built for many years to backwater perched culverts and low dams. Though many of those structures have deteriorated and disappeared overtime, they can be durable and effective if well designed and constructed. Their success depends to a very large degree on the size and quality of material used, the care and skill of the hand labor or equipment operator, supervision, and equipment used to place the rocks.

To create a permanent structure, rock should be durable and of a shape that allows individual rocks to be keyed together. Boulders with somewhat of a rectangular form are much more stable than round boulders. See Chapter 8 for sizing of rocks within weirs.

The cross section of the weir crest should slope toward the middle and approximate the cross section of the stream. Structures must be keyed into the banks. Well-graded seal material with

finer material is placed on the upstream side of the structure to control permeability and leakage. Much of the structural integrity and sealing of boulder weirs is provided by bed material that accumulates on the upstream face of the weir. If there is no continued recruitment of sediment to maintain the weirs, they will become more porous, leak, and be vulnerable to failure. Boulder weirs also carry the risk of domino failure. If one weir within a series of weirs fails, the risk of additional weir failures is increased as the added head differential increases plunging flow, scour, and hydrostatic forces on the next weir upstream.

Rigid Weirs

Rigid weirs are fixed, non-deformable structures used to control the channel profile permanently and precisely. They are often built out of logs, sheet piling, or concrete. An advantage of rigid weirs is they can often be built at a steeper grade than other steepened channel options, therefore minimizing the footprint of a project. Rigid weirs are usually considered to have a negative impact to habitat by forming a rigid channel and eliminating complexity and diversity. Full channel spanning structures lack the variety of passageways that stream simulation provides and therefore do not comply with the premise of stream simulation.

5.3 Risk, Problems, and Stability Analysis

There are several potential problems with stream simulation culverts each with varying levels of risk. If the project does not meet the objective of stream simulation because the bed does not adequately simulate the natural bed, it is a *bed form problem*. Passage of aquatic organisms or other project ecological objectives may not be achieved. For example a culvert that causes backwater effects and chronic bedload deposition that threatens the structure and must be maintained could be considered a bed form problem.

A *bed problem* occurs if the bed scours out of the culvert and is not replenished within a reasonable period of time. That problem can extend to the upstream channel in the form of a headcut. These problems can occur if the bed elevation and/or bed material are not appropriately designed, eroded by extreme flood events, or by degrading of the downstream channel. Problems might also occur if the bed structure, packing, and hydraulics of the constructed bed do not simulate the adjacent natural bed.

A *structural problem* may be a problem of a bottomless arch footing bearing capacity resulting in damaging to the structure or road fill. High headwater can cause damage of the road fill or diversion of flow down a road ditch to an area where no stream exists. These problems can occur due to a degrading or aggrading channel downstream, an undersized culvert, debris plugging, poor construction quality or an extreme flood. Considerable stream damage can be caused by fill damage and erosion in both instances.

5.5.4 Analysis for Bed Form and Bed Stability

Stability of bed forms and bed material is evaluated with bed stability models. Start with an understanding of the basis of stability in the natural channel. Does the reference channel depend on key wood features or rock steps? Is the bed fully mobile? Are there elements that are immobile and others that are not? Are key pieces mobile and at what flows?

For elements of the bed that are mobile, do the analysis in comparison to the reference channel. Compare the unit discharge (flow per width of active channel), average shear stress, or critical velocity of incipient motion and higher flows of the constructed channel to that of the reference

channel. If they are the same, then the premise is that the channels behave the same at the flows analyzed. Do the analysis on the portion of the bed material that is characteristic of stability and roughness.

By comparing the hydraulics and sediment entrainment of the reference channel to the designed channel the uncertainties of estimating hydrology and sediment entrainment are reduced. We don't need to know exactly at what flow alluvial material is entrained as long as we know that it will behave the same in both channels. Applying the model this way essentially calibrates some of the model variables.

If key pieces are in the reference channel the designer has to decide whether they are to be considered permanent in the designed channel or not. There is some risk in considering them as not permanent. If colluvial material is scoured from the stream simulation culvert, it might not be replenished and therefore the structure of the project bed could be jeopardized. An analysis should be conducted to verify the stability of colluvial material or individual elements placed to anchor other bed material in the stream simulation.

Stability of colluvium, bank material, and key pieces is treated somewhat differently than alluvial material. Key pieces include colluvium too large to be mobilized, boulders that create banklines, and embedded boulders that are meant to be permanent. In addition to a comparison of hydraulic characteristics in the designed channel and reference channel, the stability of the key pieces should be analyzed at a Q_{25} to Q_{50} design flood.

Step material pieces of step-pool channels might also be analyzed as if they were permanent if they appear to not be very mobile in the reference reach. Key pieces in step-pool features are not likely to move until flood events in the range of thirty to eighty-year recurrence.

Stability of key pieces is analyzed using sediment entrainment models similar to the analysis described above for alluvial material. Two flows should be applied; the flow at which the same pieces in the reference channel are mobilized and a high structural design flow. Both methods are best applied and the results compared as a reality check. It may not be possible to find a flow at which these pieces are mobile in the reference channel. If the model indicates they are not mobile at a flow less than the selected structural design flow, revert to just the structural design flow analysis.

Solutions to increase stability include increasing the size of the culvert, increasing size of colluvial material in the culvert, and bed retention sills. If they are considered permanent, key pieces in the culvert may be designed larger than in the reference reach to compensate for larger shear in the culvert at those high flows and as a safety factor.

While several bed stability models exist for varying bed material distribution and stream slopes, Bathurst Critical Unit Discharge and Modified Shields are the recommended methods by U.S. Forest Service and CA Fish & Wildlife. In theory, the D_{84} particle controls channel roughness, channel form, and bed mobility. This is the target particle size for performing bed stability and mobility analysis. When the driving force in a stream bed is less than the shear stress or critical unit discharge that will entrain the D_{84} particle, this particle is stable. Once the critical shear or unit discharge is less than the driving force, the D_{84} particle will become mobile.

The equations for the two bed stability/mobility methods and their associated parameters are as follows:

Modified Shields Method

$$\tau_c = \gamma R_c S_e$$

$$\tau_{c-D_{84}} = 102.6 \tau_{D_{50}} D_{84}^{0.3} D_{50}^{0.7}$$

Parameters: Bed slope < 5%

$R_c/D_{84} > 5$ [Note: D_{84} in (ft)]

$D_{84}/D_{50} < 25$

Bed particle range between 0.39” – 9.75”

D_{84} = 84th percentile particle size (ft or int; see above equation notes)

D_{50} = 50th percentile particle size (ft)

τ_c = Driving Force: Boundary Shear Stress (psf)

γ = Unit Weight of Water (lb/ft³)

R_c = Hydraulic Radius (ft)

S_e = Energy Slope or Bed Slope (ft/ft)

$\tau_{c-D_{84}}$ = Critical Shear to Entrain D_{84} Particle (psf)

$\tau_{D_{50}}$ = Shields Parameter to Entrain D_{50} Particle (dimensionless)

Critical Unit Discharge Method

$$q = \frac{Q}{W}$$

$$q_{c-D_{84}} = q_{c-D_{50}} \left(\frac{D_{84}}{D_{50}} \right)^b \quad [\text{Note: } D_{50} \text{ in (in)}]$$

$$q_{c-D_{50}} = 0.15 g^{0.5} D_{50}^{1.5} S_c^{-1.12} \quad [\text{Note: } D_{50} \text{ in (ft)}]$$

$$b = 1.5 \left(\frac{D_{84}}{D_{16}} \right)^{-1}$$

Parameters: Bed slope between 2% - 5%

2.75” < D_{50} < 5.5”

6” < D_{84} < 9.75”

$R_c/D_{84} < 5$ [Note: D_{84} in (ft)]

q = Driving Force: Critical Unit Discharge (ft²/s)

Q = Flow (cfs)

W = Active Channel Width (ft)

D_{84} = 84th percentile particle size (ft or in; see above equation notes)

D_{50} = 50th percentile particle size (ft or in; see above equation notes)

D_{16} = 16th percentile particle size (in)

$q_{c-D_{84}}$ = Critical Unit Discharge to Entrain D_{84} Particle (ft²/s)

q_{c-D50} = Critical Unit Discharge to Entrain D_{50} Particle (ft^2/s)

S_c = Channel Bed Slope (ft/ft)

b = Particle Size Range Measure (dimensionless)

g = gravity (32.2 ft/s^2)

See Section 5.6.2 for the application of these two bed stability/mobility methods.

A thorough analysis should be completed if specific thresholds of slope, entrenchment ratios, or culvert length are exceeded as described previously. The models don't create solutions that are reliable by themselves. Consider them as tools to be applied with geomorphic and engineering expertise. Consider how a channel might be affected structurally and geomorphically, and use the analysis models to help quantify changes.

The models can be used to modify the channel bed width or the bed material size to compensate for a flow constriction or an increased slope in the simulation channel. For example, a natural reach with a slope steeper than the upstream channel will generally have larger bed material but may be narrower at flows when bed material is entrained. The channel may naturally narrow due to deposition at moderate flows but the increased width will help ensure that the stream simulation bed material will be stable at those flows even if deposited material over it comes and goes.

If size of the bed material is increased, each size class should be increased at the same ratio. The bed material can only be increased in size a limited amount (25%) and still be able to consider the design as simulating the reference channel.

5.5.5 Bed Material Sizing

Prior to analysis associated with bed mobility and material sizing, the stream simulation culvert diameter, slope, shape, and entrenchment depths should be determined and considered to be nearly final. If a bridge is chosen, instead of a culvert, bridge variables such as length height, and foundation type should also be nearly final. Depending on analysis results, these culvert or bridge design parameters (variables) may have to be modified to balance the hydraulic differences between the stream simulation culvert or bridge and the reference reach. This topic will be discussed in more detail in the process below.

The following is a process for bed stability/mobility analysis and bed material sizing:

In this guidance document, the process for analyzing stability/mobility and sizing the design bed material is based on the U.S. Forest Service method. This method of analysis and design is recognized by CA Fish & Wildlife.

Grain Size Distribution Curve

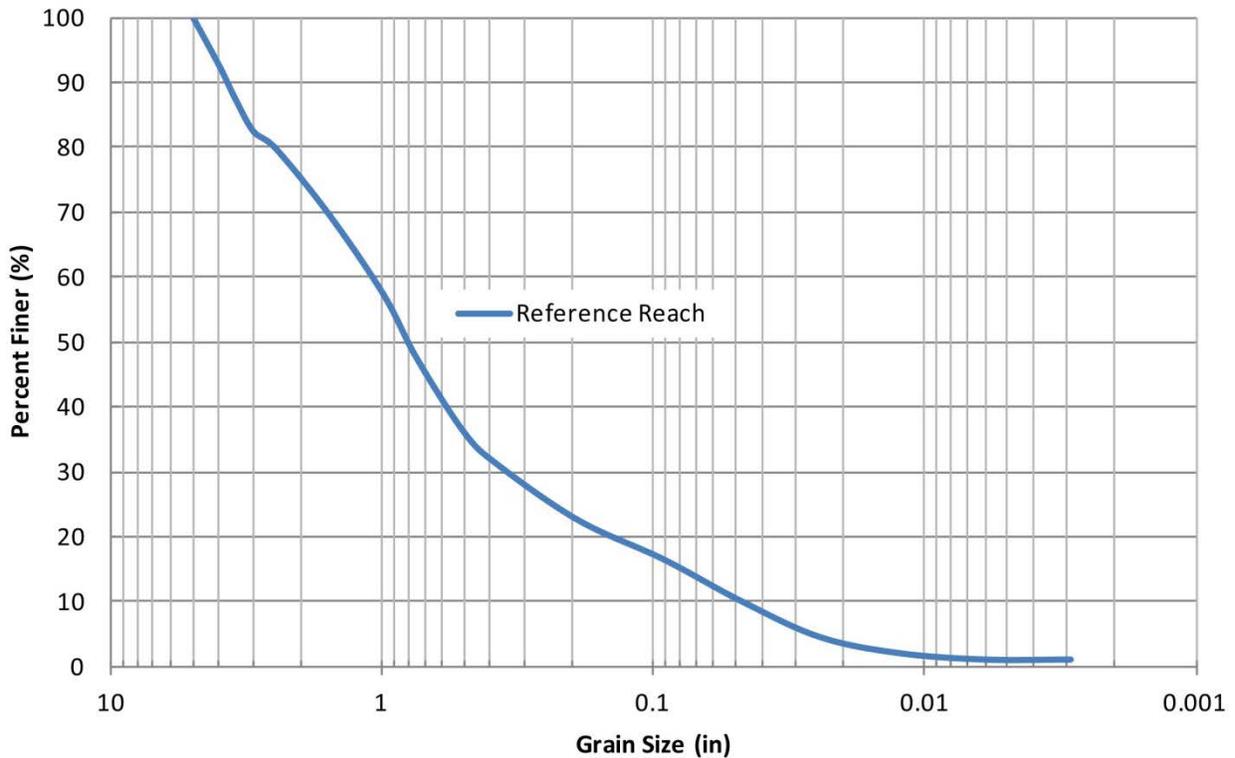


Figure 5.8. Grain Size Distribution Curve

- Step 1. For the reference reach stream bed, request soil sampling (6-inch depth), sieve analysis, and gradation curve generation from District Materials Lab.
- Step 2. From the gradation curve, determine D_{16} , D_{50} , D_{84} particle sizes of the reference reach streambed.
- Step 3. Using reference reach cross-sectional and long- profile data, find the active channel width and stream gradient (slope).
- Step 4. Create a HEC-RAS model that includes the reference reach, and iterate flow values until active channel flow width from Step 3 has been achieved. From results, find flow area and wetted perimeter for active channel discharge. Calculate hydraulic radius (R).
- Step 5. Determine whether to use the Modified Shields or Critical Unit Discharge Method for stability/mobility analysis by calculating parameters unique to each method:

Modified Shields Method

Bed slope < 5%

$R_c/D_{84} > 5$

$D_{84}/D_{50} < 25$

Bed particle range between 0.39" – 9.75"

Critical Unit Discharge Method

Bed slope between 2% - 5%

$$2.75'' < D_{50} < 5.5''$$

$$6'' < D_{84} < 9.75''$$

$$R_c/D_{84} < 5$$

Note: Choose the stability/mobility method where the most parameters are met.

**** For use of Modified Shields Method, follow Steps 6a through 18. For use of Critical Unit Discharge Method, follow Steps 19a through 25.**

Modified Shields Method

Step 6.

- a. Choose a minimum of 5 flows between the zero and bankfull discharge values to be used in the mobility/stability discharge analysis.

Step 7.

- a. Using HEC-RAS model that includes the reference reach, perform analysis for each of the flows chosen in Step 6a.

Step 8.

- a. From HEC-RAS model results for each of the trial flows, find flow area, wetted perimeter, energy slope. Calculate hydraulic radius for each flow.

Step 9.

- a. In table below, determine Shields parameter based on median bed material (D_{50}). This will be the value τ_{D50} to use in Step 10.

Table 5.2. Shields Parameter

Particle Classification Name	Range of Particle Diameters	Shields Parameter
	(in)	(dimensionless)
Coarse Cobble	5 – 10	0.054 – 0.054
Fine Cobble	2.5 – 5	0.052 – 0.054
Very Coarse Gravel	1.25 – 2.5	0.05 – 0.052
Coarse Gravel	0.63 – 1.25	0.047 – 0.05
Medium Gravel	0.31 – 0.63	0.044 – 0.047
Fine Gravel	0.16 – 0.31	0.042 – 0.044
Very Fine Gravel	0.079 – 0.16	0.039 – 0.042
Very Coarse Sand	0.039 – 0.079	0.029 – 0.039
Coarse Sand	0.019 – 0.039	0.033 – 0.029
Medium Sand	0.0098 – 0.019	0.048 – 0.033
Fine Sand	0.0049 – 0.0098	0.072 – 0.048
Very Fine Sand	0.0025 – 0.0049	0.109 – 0.072
Coarse Silt	0.0012 – 0.0025	0.165 – 0.109
Medium Silt	0.000614 – 0.0012	0.25 – 0.165
Fine Silt	0.000307 – 0.000614	0.3 – 0.25

Step 10.

- a. Find driving force: boundary shear stress and calculate entrainment threshold for D_{84} particle for each flow from Step 6a.

Table 5.3. Modified Shields Method

Modified Shields Method								
Hydraulics				Particle Mobility/Stability				
Discharge	Energy Slope	Hydraulic Radius	Driving Force: Boundary Shear Stress	D_{50}	D_{84}	Shield's Entrainment for D_{50}	Critical Shear Stress to Entrain D_{84} Particle Size	D_{84} Particle Mobile
Q (cfs)	S_e (ft/ft)	R_c (ft)	τ_c (psf)	(ft)	(ft)	τ_{D50}	τ_{c-D84} (psf)	(yes/no)
REFERENCE REACH CROSS SECTION								
6	0.0138	0.43	0.370	0.071	0.271	0.049	0.53	No
8	0.0135	0.50	0.423	0.071	0.271	0.049	0.53	No
10	0.0132	0.56	0.464	0.071	0.271	0.049	0.53	No
12	0.0131	0.62	0.504	0.071	0.271	0.049	0.53	No
14	0.0131	0.67	0.545	0.071	0.271	0.049	0.53	Yes
$\tau_c = \gamma R_c S_e$								
$\tau_{c-D84} = 102.6 \tau_{D50} D_{84}^{0.3} D_{50}^{0.7}$								

Step 11.

- a. Compare driving force and threshold movement values to determine D_{84} particle mobility at each flow. If D_{84} does not become mobile for any of the trial flows, select flows greater than bankfull discharge and repeat Steps 6a – 10a until a flow is found that moves the D_{84} particle. If all flows cause movement of D_{84} particle, choose lower flows until a flow is found where D_{84} particle is stable

Step 12.

- a. Plot τ_c vs Q . Find the corresponding flow with τ_{c-D84} threshold shear. This will be the critical flow that causes incipient motion of the D_{84} particle within the reference reach.

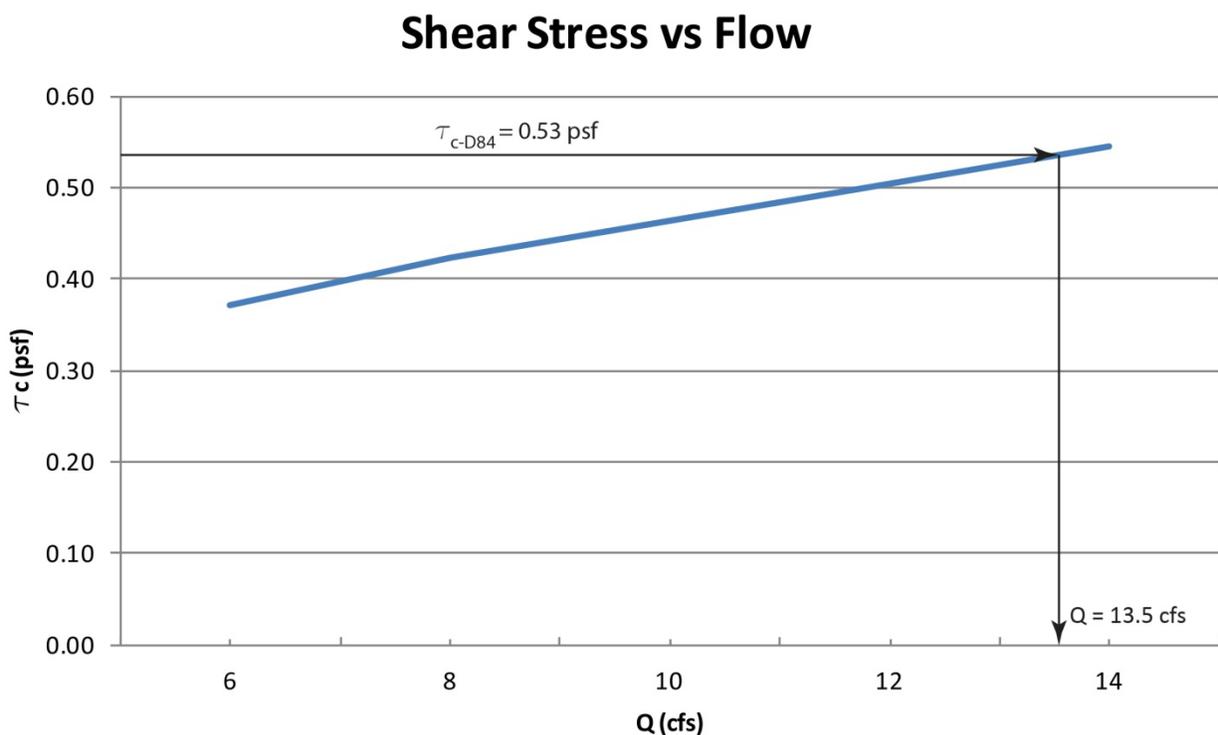


Figure 5.9. Shear Stress vs Flow

Step 13. Select an initial D_{84} particle size for the design bed material to be placed inside the stream simulation culvert or bridge. The goal is to select a size that will mobilize inside the culvert with a similar discharge as the reference reach. Based on the D_{84} estimate, shift the reference reach curve to match the D_{84} estimate and read D_{50} from trial curve. This trial parallel curve is temporary until all analysis is complete.

****Repeat Steps 6a – 12a for the design reach inside the stream simulation culvert or bridge.**

Note: The HEC-RAS model for Step 7a must include the stream simulation culvert or bridge. Also, the method for finding wetted perimeter and flow area (Step 8a) will be different for the

culvert than the reference reach. In HEC-RAS, the culvert/bridge tabular results do not present wetted perimeter and flow area values. For the culvert or bridge, the flow area and wetted perimeter will need to be measured and calculated manually from the wetted cross section graphical results in HEC-RAS. Once these values are measured and calculated, hydraulic radius can be obtained.

Step 14. Compare critical flow of the reference reach and design reach that causes respective D_{84} particle to move. Also, compare D_{84} particle sizes between reference reach and design reach. Are the sizes within 25% of each other, and do they mobilize at similar flows?

Step 15. Once the final D_{84} particle diameter has been determined, shift the gradation curve from the reference reach to match the D_{84} design particle diameter. This will create parallel gradation between the reference reach and the design reach. This is the final gradation curve for the design reach.

Grain Size Distribution Curve

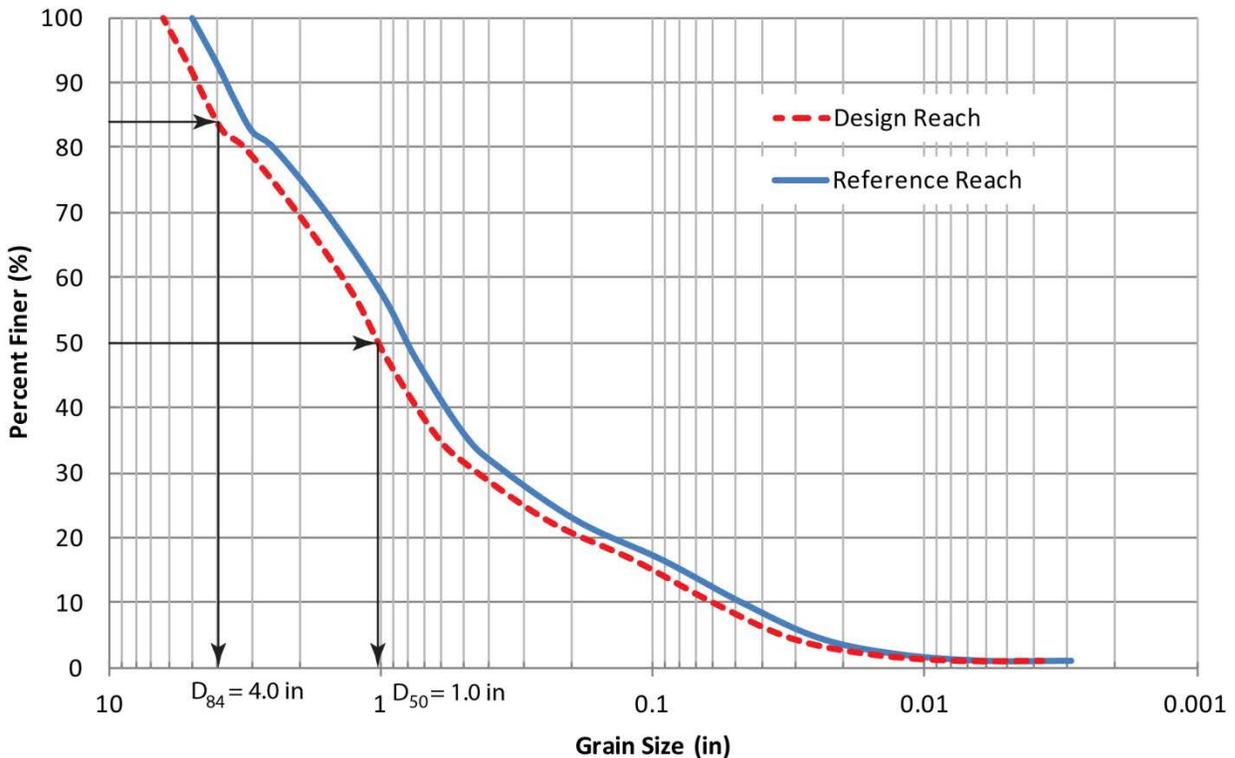


Figure 5.10. Grain Size Distribution Curve (Design)

Step 16. From the new design reach gradation curve, determine D_8 and D_{16} particle size.

Step 17. Using Fuller-Thompson method, calculate D_8 and D_{16} particle size to achieve a high density mixture to seal simulated bed and control permeability. In the equations below, use D_{50} from the design gradation curve. The values of “n” will typically range between 0.45 – 1.1 to meet the high density mixture desire. The goal in this

analysis is to have D_8 particle diameter be approximately 0.08 in and the value of “n” should be chosen accordingly. If the reference reach D_8 and D_{16} particle sizes are below the calculated particle sizes, the gradation curve for the simulated culvert bed will not need to be adjusted.

$$D_{16} = 0.32^{1/n} D_{50}$$

$$D_8 = 0.16^{1/n} D_{50}$$

Step 18. Calculate stream simulation bed minimum thickness.

Min. Thickness = $4 \times D_{84}$ design reach

Critical Unit Discharge Method

Step 19.

- a. Choose a minimum of 5 flows between the zero and bankfull discharge (or greater) values to be used in the mobility/stability discharge analysis.

Step 20.

- a. From stream topography, find stream bed (channel) slope for each flow. Also, determine active channel width for cross section of interest.

Step 21.

- a. Find driving force: critical unit discharge and calculate entrainment threshold for D_{84} particle for each flow from Step 19a.

Table 5.4. Critical Unit Discharge Method

Critical Unit Discharge Method										
Hydraulics				Particle Mobility/Stability						
Discharge	Active Channel Width	Driving Force: Unit Discharge	Channel Slope	D_{16}	D_{50}	D_{84}	Particle Size Range Measure	Critical Unit Discharge for D_{50}	Critical Unit Discharge to Entrain D_{84} Particle	D_{84} Particle Mobile
Q (cfs)	W (ft)	q (ft ² /s)	S_c (ft/ft)	(in)	(in)	(in)	b	q_{c-D50} (ft ² /s)	q_{c-D84} (ft ² /s)	(yes/no)
REFERENCE REACH CROSS SECTION										
15.00	12.00	1.250	0.01	0.07	0.82	3.25	0.03	2.64	2.76	No
20.00	12.00	1.667	0.01	0.07	0.82	3.25	0.03	2.64	2.76	No
25.00	12.00	2.083	0.01	0.07	0.82	3.25	0.03	2.64	2.76	No
30.00	12.00	2.500	0.01	0.07	0.82	3.25	0.03	2.64	2.76	No
35.00	12.00	2.917	0.01	0.07	0.82	3.25	0.03	2.64	2.76	Yes
q = Q / W										
b = 1.5 (D ₈₄ /D ₁₆) ⁻¹										
$q_{c-D50} = 0.15 g^{0.5} D_{50}^{1.5} S^{-1.12}$										
$q_{c-D84} = q_{c-D50} (D_{84}/D_{50})^b$										

Step 22.

- a. Compare driving force and threshold movement values to determine D_{84} particle mobility at each flow. If D_{84} does not become mobile for any of the trial flows,

select flows greater than bankfull discharge and repeat Steps 6a – 10a until a flow is found that moves the D_{84} particle. If all flows cause movement of D_{84} particle, choose lower flows until a flow is found where D_{84} particle is stable

Step 23.

- a. Plot q vs Q . Find the corresponding flow with q_{c-D84} threshold shear. This will be the critical flow that causes incipient motion of the D_{84} particle within the reference reach.

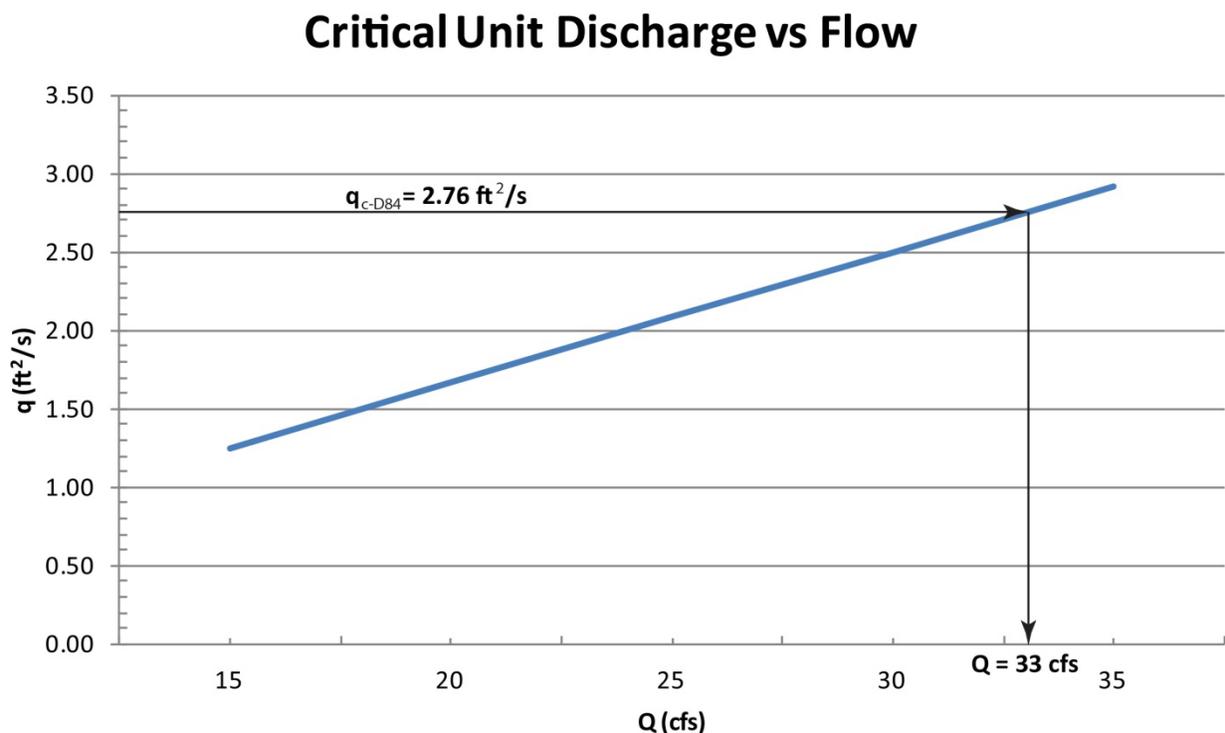


Figure 5.11. Critical Unit Discharge vs Flow

- Step 24. Select an initial D_{84} particle size for the design bed material to be placed inside the stream simulation culvert or bridge. The goal is to select a size that will mobilize inside the culvert with a similar discharge as the reference reach. Based on the D_{84} estimate, shift the reference reach curve to match the D_{84} estimate and read D_{50} and D_{16} from trial curve. This trial curve is temporary until all analysis is complete.

****Repeat Steps 19a – 24a for the design reach inside the stream simulation culvert or bridge.**

Step 25. Follow Steps 14-18.

As described previously in this chapter, banklines, bed forms, and key features of the reference reach can be incorporated into the specified interior culvert bed material. The larger rocks forming such creek formations and features will most likely be too large for normal sampling and sieve analysis. Therefore, the designer must gather these rock sizes and their forms by

method of field conditions as a guide. Any material used to mimic banklines , bed forms, and key features of the reference reach must resist movement for a Q_{25} to Q_{50} storm.

See CA Fish & Wildlife's *Part XII: Fish Passage Design and Implementation* document for recommendations on placing this simulated bed material in the field.