Chapter 9

CULVERTS

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9.1 Introduction

This chapter provides information for the planning and design of highway culverts. The methodology is intended for those with an understanding of basic hydrologic and hydraulic methods and some experience in the design of hydraulic structures.

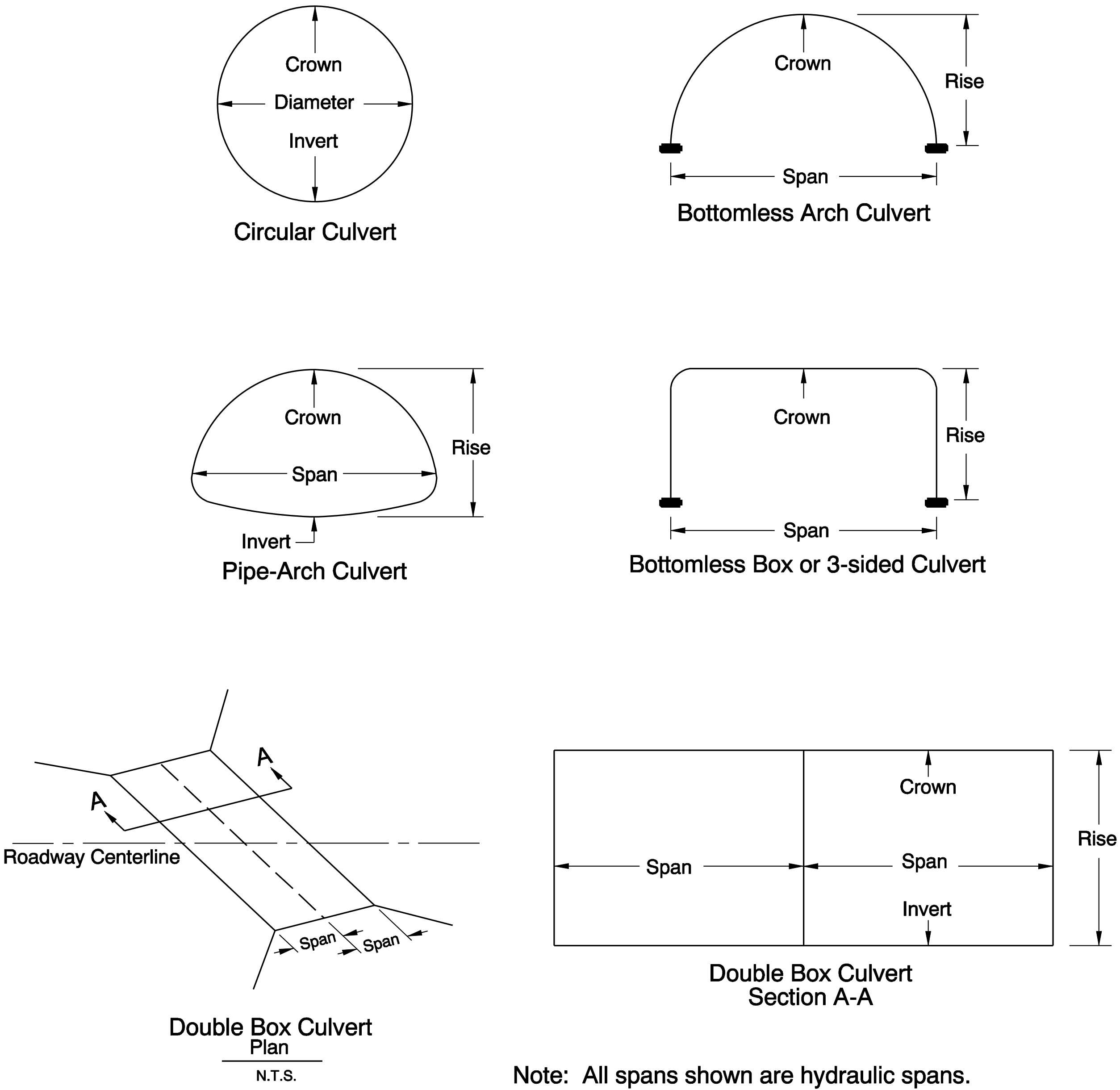
A culvert is a conduit that conveys stream flow or storm runoff through a roadway embankment or past some other flow obstruction. Culverts are constructed from a variety of materials and are available with many different shapes, sizes, and end treatments, as shown in Figures 9-1 and 9-2. Culvert selection factors include roadway profiles, channel characteristics, fish passage requirements, hydraulic performance, resistance to flotation, construction and maintenance costs, and estimated service life.

Culverts may be cost-effective replacements for bridges at some sites. Culverts often do not provide the clearance for navigation, debris, ice, and fish passage as compared to bridges. In addition, scour downstream from a culvert outlet is often deeper and more extensive than scour downstream from a bridge. These factors should be considered before a culvert is recommended at the site of an existing bridge.

9.2 Policy and Practice

General policies of the Federal Highway Administration (FHWA) and ODOT pertaining to hydraulic design are discussed in **Chapter 3**. ODOT practice specific to culvert design are as follows.

- Coordination with other Federal, state, and local agencies concerned with water resources planning will have a high priority in culvert design.
- Safety of the general public is an important consideration in culvert selection.
- Culvert design shall consider the frequency and type of maintenance and make allowance for maintenance equipment and personnel access.
- Sediment deposition and scour shall be considered during culvert design and be minimized when possible.
- Environmental impacts of culverts such as fish passage and disturbance of fish habitat, wetlands, and riparian areas must be considered and minimized as needed.
- Culvert hydraulic performance during the design event shall consider the class of the roadway, the consequences of traffic interruption, the flood hazard risks, economics, and local site conditions.



Circular Culvert

Bottomless Arch Culvert

Pipe-Arch Culvert

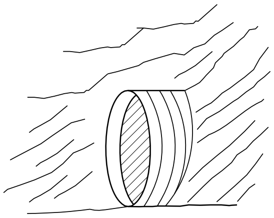
Bottomless Box or 3-sided Culvert

Double Box Culvert
Plan

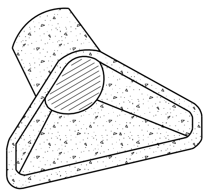
Double Box Culvert
Section A-A

Note: All spans shown are hydraulic spans. For a definition of Bridge span refer to the Bridge Design and Drafting Manual.

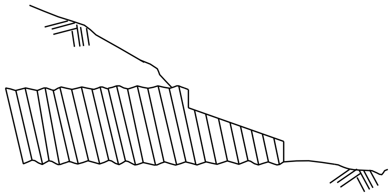
Figure 9-1 Common Culvert Shapes



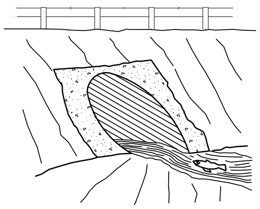
Projecting Barrel



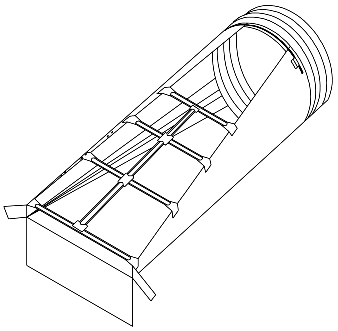
Precast Concrete End Section



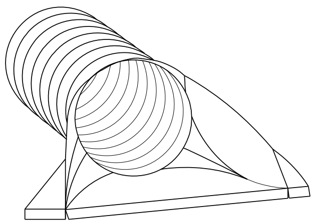
Sloped Mitered End Without Slope Paving



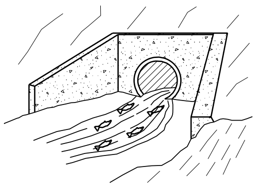
Sloped Mitered End with Slope Paving



Safety End Section
with Safety Bars



Prefabricated Sheet
Metal End Section



Cast-in-Place Concrete
Headwall and Wingwalls

Figure 9-2 Common End Treatments

9.3 Large, Medium, and Small Culverts

Culverts are classified as large, medium, or small. The type and amount of data collected for the design, the complexity of the hydraulic study, and the level of documentation depends on the culvert classification. Regardless of culvert size, they are designed by a professional engineer registered in Oregon or others under the direct supervision of the engineer. Final plans and other documents require an engineer's seal. This is discussed in **Chapter 3**.

Large culverts are:

- circular culverts with diameters more than or equal to 72 inches,
- arch-pipes with equivalent diameters more than or equal to 72 inches,
- box culverts with spans more than or equal to 72 inches,
- multiple barrel culverts with cumulative span widths more than or equal to 72 inches,
- open-bottom culverts of all sizes,
- culverts with complex hydraulic structures such as cast-in-place energy dissipators; drop, side tapered, or slope-tapered inlets, etc. and
- culverts providing fish passage regardless of size.

Medium culverts are:

- circular culverts with diameters more than or equal to 48 inches and less than 72 inches,
- arch-pipes with equivalent diameters more than or equal to 48 inches and less than 72 inches, and
- box culverts with spans more than or equal to 48 inches less than 72 inches.

Small culverts are:

- circular culverts with diameters less than 48 inches,
- arch-pipes with diameters less than 48 inches, and
- box culverts with spans less than 48 inches.

9.4 Sources of Information

The type, source, and complexity of data for a culvert design will vary depending on the location and type of culvert. Large culverts typically require data similar to a bridge location survey, such as a vicinity map, stream or drainage profile and cross-sections, geologic data, etc. Small and medium culverts usually require less data and most of the information can be provided by the roadway location survey. Often information and experience from other agencies can be used to supplement the location survey. This is especially important when fish passage is a concern, as the requirements and guidelines of fish management agencies may dictate the type, size and location of the culvert. Data requirements for typical culvert designs are listed in **Chapter 6**.

9.5 Culvert Design Documentation

The documentation for large culverts is similar to bridges and large channel studies. Smaller and medium culverts require less documentation. Report and documentation guidelines are in **Chapter 4**.

9.6 Definitions

Definitions for many terms used in culvert design are in the glossary at the end of this manual.

9.7 Culvert Vertical Alignment

The vertical alignment of a culvert with respect to the stream is important to culvert hydraulic performance, stream stability, construction and maintenance costs, and the safety and integrity of the highway. Proper alignment is also of particular importance to promote fish passage, and to prevent outlet scour or excessive sediment buildup in the culvert barrels.

A culvert placed too high in relation to the streambed may become a barrier to fish passage if the channel bottom degrades, or lowers, during the life of the facility. Conversely, a culvert placed too low in relation to the channel bottom may lose hydraulic performance if the channel aggrades, or rises. In addition, a culvert placed at a slope different than the natural channel slope may have problems related to both sediment deposition and bed material scour, and this affects both fish passage and hydraulic performance.

9.7.1 Use of Streambed Profiles in Design

Accurate assessment of streambed profiles is essential to determine potential changes in channel bottom elevations. It is important to:

- determine the profile of the existing streambed, called the "existing profile,"
- estimate the profile the streambed will have immediately after the structure is constructed, called the "design profile," and
- estimate the profile of the streambed throughout the life of the structure, called the "long-term profile."

9.7.1.1 Existing Profile

The existing profile is the streambed profile before construction. An example of an existing profile is shown in Figure 9-3a. A small culvert is shown in the figure. This culvert is too small to convey the stream discharges and water pools upstream from the inlet. The pooled water cannot transport bed material conveyed by the stream, and as a result, there is a mound of gravel upstream from the inlet. Excessive flow velocities in the narrow barrel have created a scour hole downstream from the outlet. The existing profile also shows two breaks in the channel grade. The upstream break is due to a rock ledge. The downstream break is caused by a log across the channel bottom.

The existing profile is determined as follows.

Step 1 - Obtain streambed and water surface elevations for some distance upstream and downstream from the culvert. Obtain the elevations and descriptions of control points such as dams, weirs, existing culverts, etc. This information is available from the site survey as discussed in **Chapter 6**.

Step 2 - Plot the profiles of the streambed and the water surface, either electronically or on paper. Note the location and elevations of all control points.

9.7.1.2 Design Profile

The channel profile will almost always be altered to some degree when the new culvert is built. Possible causes of these changes are: removing a culvert and installing another in a different location, eliminating or construction of a control feature such as a weir or tide gate, smoothing out natural irregularities in the channel bottom, roughening the channel with fish rocks, wood, or other structures, or a channel change. This revised profile is the design profile. The design profile is often the basis of the profile shown on project plans. The following steps are used to determine this profile.

Step 1 - Obtain a copy of the existing profile. Locate the proposed structure on the profile. Note the limits of agency right-of-way or easements on the profile.

Step 2 - Estimate and plot the channel profile through the proposed structure. The design profile grade will match the existing stream grade on some installations. Often when a fish-passage structure is built, irregularities in the channel bottom or barriers to fish passage caused by the existing structure are removed during construction, and these changes should be shown. Show control structures such as weirs on this profile if they will be needed. Check to see that all channel re-grading and control structures can be built within agency right-of-way or easements. If not, additional right-of-way or drainage easements may be needed.

An example of construction related changes are shown in Figure 9-3b. In the figure, a longer and larger embedded culvert will replace the smaller existing culvert. It is expected that the sediment mound will be removed and the scour hole will be filled during the construction of the new culvert. As a result, the design profile is expected to have a constant grade upstream and downstream from the culvert. The rock ledge and the log across the channel are shown on the design profile because they will not be affected by construction.

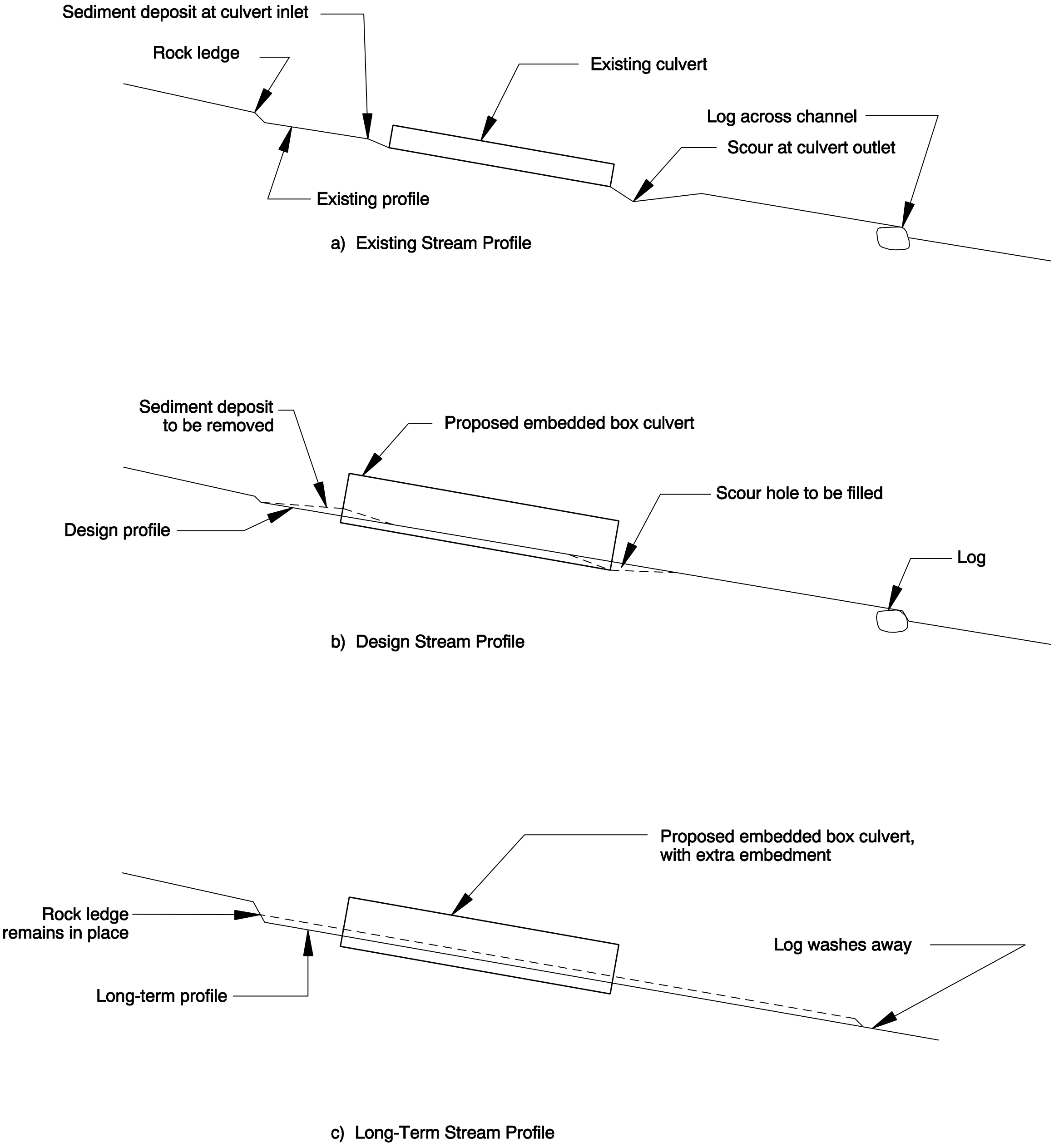


Figure 9-3 Stream Profiles

9.7.1.3 Long-Term Profile

Stream profiles often change with time. Changes in streambed profile are often called aggradation or degradation. Aggradation and degradation are the raising or lowering of the channel bottom elevation, respectively. An alteration to sediment continuity is the primary cause of these changes.

Sediment continuity is a function of sediment supply and channel transport capacity. Sediment supply is provided by the upstream drainage. It is materials carried to the site by the stream, and the greatest amount of transport occurs during floods. Sediment transport capacity is the ability of the stream to move sediment along the streambed. Streams where the sediment supply exceeds the stream transport capacity tend to aggrade. Conversely, streams degrade when the transport capacity exceeds the sediment supply. A detailed discussion of sediment continuity with a list of factors causing changes is in FHWA Hydraulic Engineering Circular No. 20 “Stream Stability at Highway Structures.”

These long-term changes in channel profile can reduce the ability of the culvert to pass fish, provide adequate hydraulic performance, and be structurally sound. Channel degradation can cause embedded, non-embedded, and baffled culverts to become barriers to fish passage. This occurs when the downstream end of the culvert becomes higher than the channel bottom, and fish cannot swim upstream through the barrel. This is often called a “perched” condition. Degradation can undermine open-bottom culvert foundations. Channel aggradation can reduce the flow capacity of all culvert types.

Many factors can cause long-term changes in streambed profile. These causes are most often detected during a site visit. Typical items to investigate are in the following list.

1. Will a dam or other obstruction be built downstream that will decrease the flow velocity through the culvert? If the velocity is decreased, the ability of the stream to carry sediment will also be reduced, and the channel bed could aggrade in or near the culvert. This often occurs at the mouths of streams that discharge into newly constructed reservoirs.

2. Will a dam or other obstruction be removed upstream? The removal could be done by man, such as the demolition of a dam, or by nature, such as the rotting and decomposition of a log across the channel. If the dam or other obstruction has retained bed material, its removal or failure can increase the amount of bed material passing though the site and the channel could aggrade. Conversely, removal of a dam that provides flood control could also increase the discharge and result in degradation.

3. Will changes in land use increase runoff rates? Activities such as converting a forest into a pasture, or converting a forest or pasture to a housing or commercial development almost always increases the discharge. This frequently causes degradation.

4. Will a dam or other obstruction be removed downstream? If the obstruction has retained bed material, the retained material can be carried downstream and the channel may degrade. In addition, if removing the obstruction increases flow velocities through the culvert site, the ability of the stream to carry sediment will also be increased, and the channel can degrade.

5. Will a dam or other obstruction be built upstream from the culvert site? If the obstruction will interrupt the transport of bed material, the channel could degrade.

6. Will changes in land use change their sediment contribution? Improved erosion control in riparian corridors can reduce the amount of sediment washing into the streambed. Converting wildlands to housing or commercial developments can also reduce the sediment availability. This may result in channel degradation.

7. Will the stream be channelized upstream from the culvert? Channelization, especially straightening the channel, can increase flow velocities through the site and cause the streambed to degrade. Conversely, restoring a straightened channel to a meandering waterway can decrease flow velocities and cause aggradation.

8. Is the streambed degrading due to natural erosion? Many streambeds are degrading due to long-term erosion of the stream bottom that is caused by lack of sufficient sediment inflow into the channel (transport capacity > sediment supply). These streams are most often in “V” shaped channels on steep gradients and they probably have headcuts.

9. Are there headcuts downstream that may proceed upstream through the crossing site? A headcut is an abrupt change in channel elevation as shown in Figure 9-4a. Headcuts typically proceed upstream until they are stopped by a ledge of non-erodible rock or a structure such as a dam, a weir, or a culvert if the streambed is erodible. This migration is shown in Figure 9-4b. This type of erosion usually indicates that the streambed profile is readjusting after a change in channel slope, discharge, or sediment load characteristics. In channels with flowing water, headcutting is often shown by the presence of 12 to 18-inch high waterfalls or rapidly moving water in an otherwise placid river or stream. In dry channels, a relatively abrupt drop in the bed of an erodible channel is evidence of a headcut. Headcuts may range in depth from 1 to 9 feet or more. Niagara Falls is an example of a large headcut that is slowly progressing upstream in the Niagara River between Lake Erie and Lake Ontario.

The long-term profile is an estimate of the stream bottom elevations after long-term changes. A long-term profile is shown in Figure 9-3c. This profile shows changes that are expected in the channel profile. It is assumed the rock ledge will last for the design life of the culvert and no changes in profile are expected upstream from the ledge. If the upstream obstruction would be temporary, such as a log, the effects of removing the obstruction should be considered. One effect may be the aggrading of the channel bed when the gravel retained by the obstruction passes through the culvert.

The other long-term change in channel profile is downstream from the culvert. It is assumed the log is a temporary obstruction and it will rot or wash away at some time during the design life of the culvert. If the obstruction was more substantial, such as a rock ledge, it would be considered permanent and the effects of its removal would be ignored. An estimate of the stream profile after the log rots away is shown in Figure 9-3c. It is anticipated that the sediment retained by the log will be carried downstream and the resulting degradation will remove most of the cover over the culvert invert. As a result, a deeper box culvert is chosen and the invert will be buried an extra amount. This way, there will be adequate cover over the invert of the box throughout the design life of the culvert.

The long-term profile is typically determined using the following steps.

Step 1 - Obtain a copy of the design stream profile including the proposed structure. Investigate possible long-term changes to the profile caused by the removal or addition of control structures, such as weirs, dams, logs, etc. The preceding list of factors can be used. Plot estimated profile changes on the design profile.

Step 2 - Estimate the changes to the profile that might occur if known headcuts proceed upstream through the culvert site. Plot these changes on the profile.

Step 3 - Estimate long-term changes, if any, to the entire stream profile. These changes could be caused by aggradation or degradation throughout the reach. These changes are often hard to estimate with any accuracy. Plot these changes on the profile. HEC-20 is recommended as a reference.

> *Note: Long-term channel changes can be difficult to quantify with any certainty. This is especially true of aggradation. Culverts are sometimes designed with extra clearance over the streambed and extra embedment depth so they will function under a variety of sediment continuity conditions.*

Step 4 - Correlate the design data to the existing field conditions if the design is for a replacement culvert. Take into consideration any aggradation, degradation, outlet scour, outlet perching, debris problems, etc. Change as needed the type, size, or location of the proposed structure to assure that it will continue to function after the changes occur in the long-term profile.

9.7.2 Culvert Invert Slope Versus Streambed Slope

The culvert invert slope should match the stream bed slope. Placing the culvert on a flatter or steeper gradient than the natural streambed can cause sediment deposition in the barrel. It can also cause scour that removes sediment from the barrel. This is especially critical for fish passage culverts designed to have a sediment covered invert. Typical areas of deposition and scour are shown in Figure 9-5. Placing a culvert at a slope other than the natural streambed slope should be avoided. The following steps are recommended if it cannot be avoided.

Step 1 - Estimate the streambed profile through the culvert after it attains its expected long-term profile, including any deposition or scour.

Step 2 - Check to assure the culvert will have adequate hydraulic capacity with the profile determined in the previous step. The most common constriction point is the upper end of the barrel when culverts are installed at flatter slopes than the streambeds, as shown in Figure 9-5a. The constriction point can be at the lower end when the barrel is installed at a steeper slope than the streambed, as shown in Figure9-5b. Sometimes a taller or wider barrel will be needed.

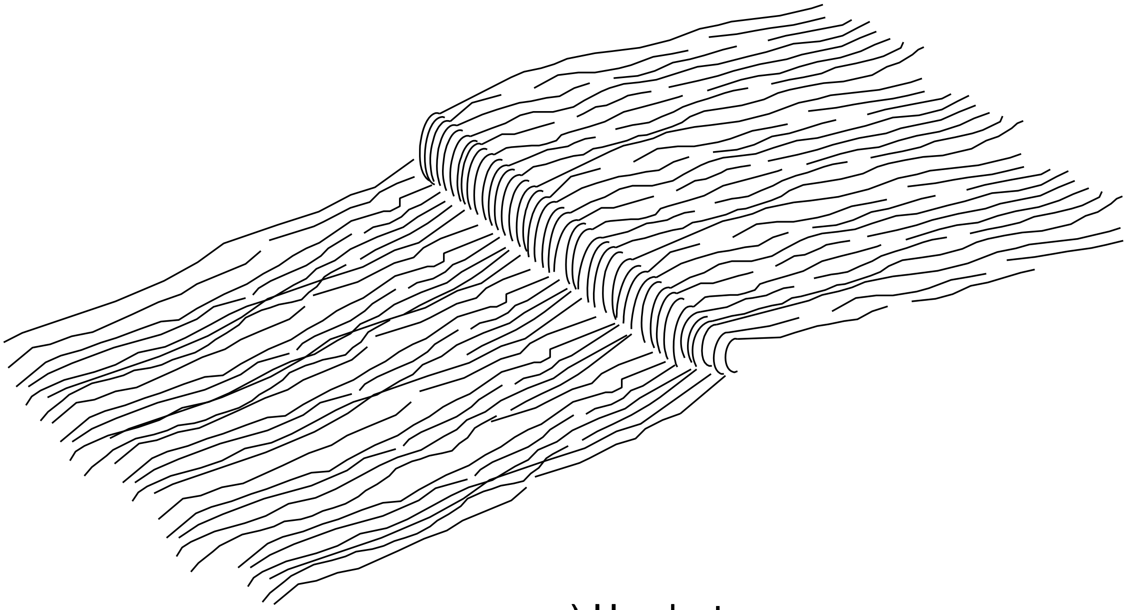
Step 3 - If the culvert is installed on a steeper slope than the stream, check to assure the upstream end of the culvert will retain a cover of bed material. Scour of bed material covering the upstream end is a common problem with culverts at slopes steeper than the natural channel. Scour of bed material throughout the barrel can be a problem with longer culverts, as shown in Figure 9-5c. It may be necessary to provide bed retention weirs within the culvert barrel. Consider the effects of these weirs on fish passage.

Step 4 - Periodic cleaning may be needed at some installations if a large enough barrel cannot be provided. This cleaning should be described in the Hydraulics Report. Approval from ODOT maintenance should be obtained before a culvert is installed that will require periodic cleaning.

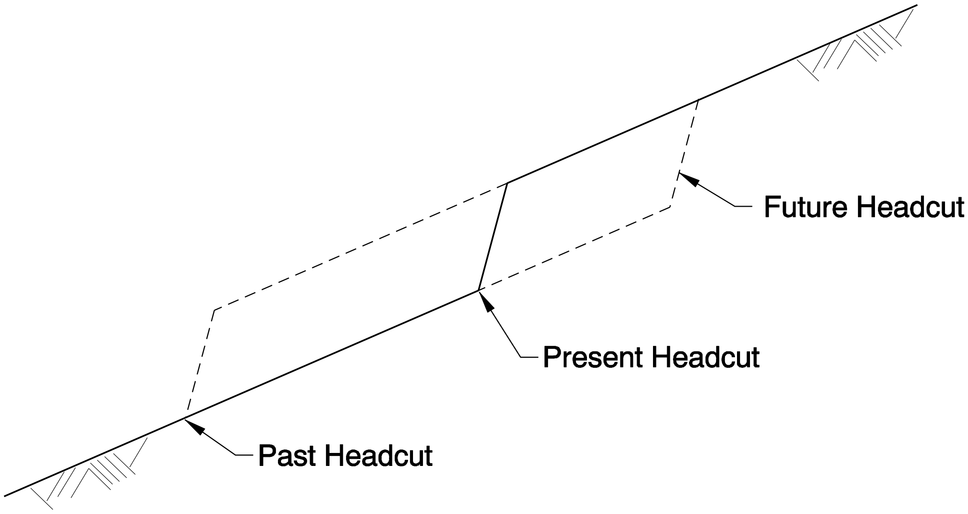
Step 5 - Provide access for maintenance forces if cleaning will be needed. This may include easements, a turnout for vacuum cleaning trucks, access roads, etc.

Step 6 - Verify the environmental documents describing the project impacts mention the need for periodic cleaning. Permits are often needed for cleaning.

Step 7 - Consider an overflow culvert if the subject culvert is susceptible to plugging due to deposition.

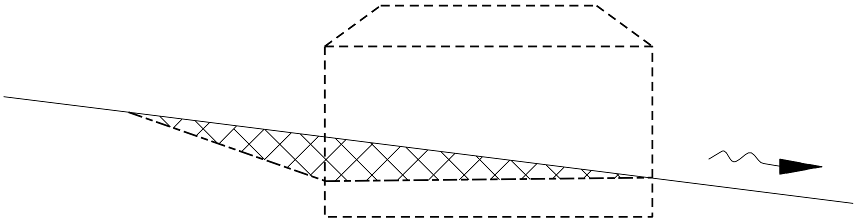


a) Headcut

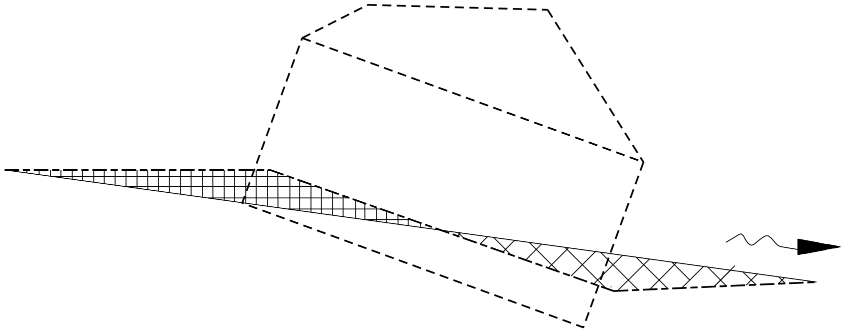


b) Headcut Progressing Upstream

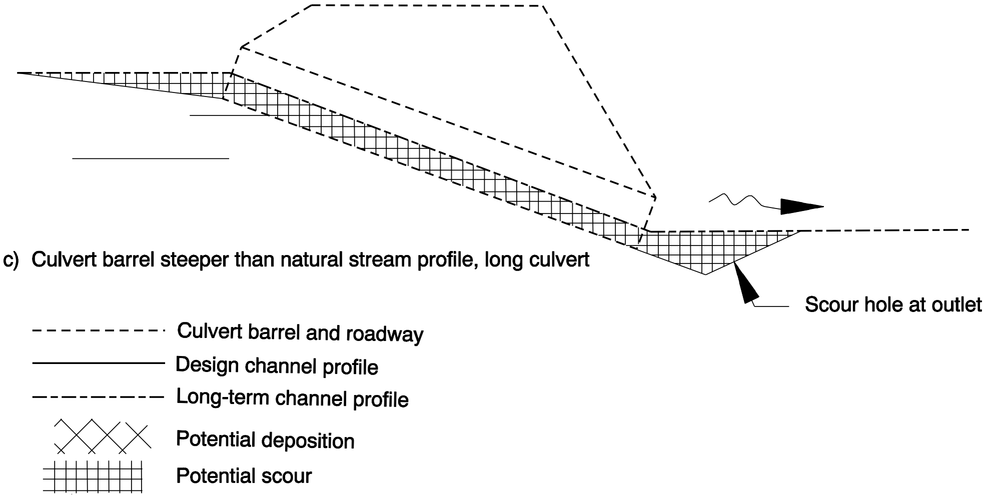
Figure 9-4 Changes in Channel Profile Due to Headcuts



a) Culvert barrel flatter than natural stream profile



b) Culvert barrel steeper than natural stream profile, short culvert



c) Culvert barrel steeper than natural stream profile, long culvert

Figure 9-5 Culvert Vertical Alignment

9.8 Culvert Horizontal Alignment

The culvert horizontal alignment should match the natural stream alignment, as close as practical. This is shown in Figure 9-6a. This is often possible when installing an original culvert at a new crossing or when removing the existing culvert and replacing it with another at exactly the same location.

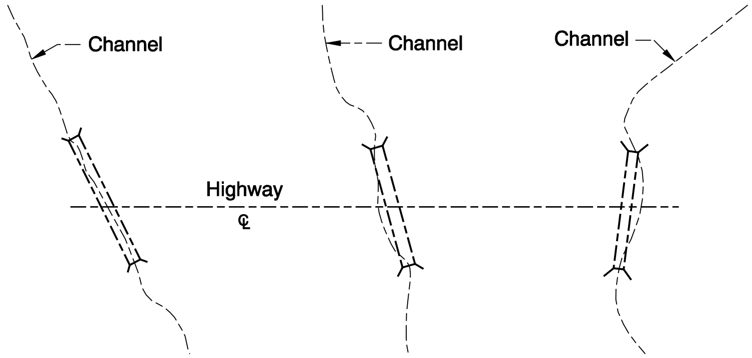
Replacement culverts frequently cannot be installed at exactly the same location as the existing pipes and channel changes are needed. In many cases, the existing barrel must convey flow while the new culvert is being built and it must remain in place during the construction of the new culvert. Short sections of modified channel are needed to route the stream to the new culvert. In other instances, the existing culvert location is not ideal for the relocated or widened road. Stream channel changes are needed to connect the stream to the relocated culvert. These culvert relocations and channel realignments must comply with applicable fish passage and other environmental requirements.

Severe or abrupt changes in channel alignment such as bends should be avoided immediately upstream or downstream of the culvert ends because they create head losses and reduce the culvert hydraulic efficiency, as shown in Figure 9-6. In addition, and of greater concern, a sharp bend in the channel immediately upstream and downstream from the culvert ends promote bank erosion on the outside of the bend and sediment deposition on the inside of the bend. This scour and erosion can adversely affect the culvert structural integrity and hydraulic performance.

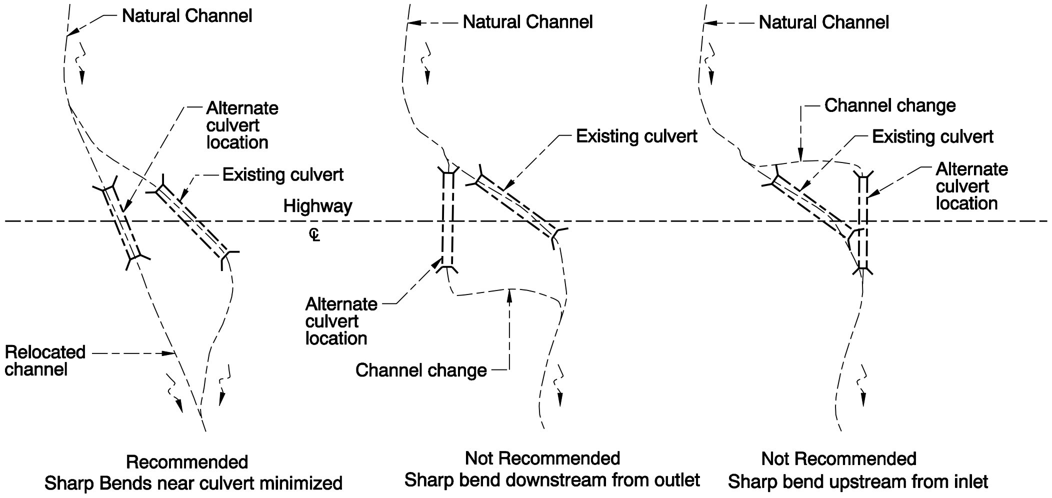
9.8.1 Alignment, Bent Culverts

Straight culverts matching the channel alignment are preferred. Straight culverts cannot be used in all situations, and matching the alignment of a sinuous channel may require a culvert with one or more bends. Design of a culvert with a bend should consider the following.

1. Debris passage. If long debris such as branches or trees are expected to pass through the culvert, these objects must pass through the bent section. Passing long debris may require extra culvert width or long bend radii. Access to the angle points or bends should be provided by a manhole or other means if debris can lodge at these locations. Use of a larger culvert that would not need a bend or a bridge may be the best option at debris prone sites.



a) Culvert located in natural channel



b) Culvert with Channel Change

Figure 9-6 Culvert Location

2. Hydraulic efficiency. A bend may reduce the hydraulic efficiency of a culvert, and the more sudden and sharper the bend, the greater the loss in efficiency. Bend hydraulic losses do not affect culverts under inlet control. They may significantly reduce the hydraulic performance of culverts under outlet control. Smooth large radius bends are preferred if bends are needed. They have a less adverse effect on hydraulic performance.

3. Scour. A bend increases flow velocities inside the barrel at the outside of the bend and downstream from the bend. The increased scour caused by these high velocities should be considered in the scour depth calculations and the footing designs of open-bottom arch culverts and 3-sided boxes. The locations of the higher shear stresses in bends are discussed in **Chapter 8**. The design of open-bottom culverts and 3-sided boxes is discussed within this chapter.

9.8.2 Alignment, Multiple Barrel Culverts and Multiple Culverts

Single barrel culverts are preferred where they can be used. Multiple barrel culverts or multiple culverts may be used where limited vertical clearance between the roadway and the streambed or other reasons preclude use of a single barrel culvert. A double or triple barrel reinforced concrete box (RCBC) is an example of a multiple barrel culvert. Two or more separate corrugated metal pipes at a single site are an example of a multiple culvert. Alignment of either culvert type should consider the following.

1. Barrel spacing. The separate barrels of multiple culverts should be spaced apart in accordance with ODOT Standard Drawing RD300. This will ensure sufficient space is available to compact the backfill. The barrels can be spaced closer if the area around the bottom half of the barrel is backfilled with concrete.

2. Channel characteristics. Installation of multiple barrel culverts or multiple culverts in channel bends or irregular channels may result in sediment deposition in one of the barrels. These problems can be minimized by relocating the culverts so they are in a straight reach of channel with a regular cross-section. Sometimes, with multiple barrel RCBCs, a sill is constructed across the apron to direct low flows into one barrel. A similar method is used with multiple culverts. One barrel is placed lower than the rest to handle the low flows and also to minimize potential sediment problems.

9.9 Alignment, Conflicts with Utilities

Culvert alignment, both vertical and horizontal, is often affected by utilities because many culverts are located in the vicinity of existing or future utilities, such as power transmission towers, sewers, fiber optic cables, etc. ODOT often has given the utility an easement to locate on ODOT right-of-way, and part of the easement stipulates that the utility must be relocated if it conflicts with the ODOT facilities. ODOT can request that the utility be relocated in these cases. In other instances, ODOT may have to locate its facilities to keep them away from the utility or pay for the utility to be moved. This most often occurs where the utility is on private property. ODOT region utilities personnel are responsible for utility location and negotiations with the utility owners.

The utility cannot always be relocated so it is far from the culvert. Instead, it will be near or adjacent to the structure. There are recommended minimum clearances between the utility and the culvert, in some instances. The utility company can often provide information about these clearances. The clearances can be reduced, or sometimes eliminated, if casings or other protection measures are installed around the utility.

Utility corridors should also be considered if they are present. This could be an unoccupied corridor reserved for future utilities or space for additional utilities near existing utilities. An example would be a community that has overhead phone and electrical lines and intends to relocate the lines underground. Corridors may be reserved for the relocation.

Precise utility location can be expensive because it requires detailed surveys. In some instances, excavation is needed to determine the exact utility location. As a result, preliminary culvert design is often done using limited utility data, a comprehensive utility location survey is made, and the detailed utility data is used in the final design. In all cases, the final culvert design should not be made until affected utilities are located. Unanticipated utility conflicts are almost always time consuming and expensive when they are resolved during construction.

9.10 Alignment, Construction Considerations

Often the anticipated construction method affects the culvert alignment. There should be at least one possible method of constructing the culvert, and the construction procedure should be considered when the culvert is designed. The roadway designer is a useful source of information about construction methods and constraints. As an example, the need to maintain the flow of traffic through the project may require special construction considerations such as trenchless excavation or stage construction.

Environmental concerns such as fish passage may also influence construction methods, construction sequence, and as a result, culvert alignment. The ODOT region environmental representative should be contacted about any requirements. Typical methods of constructing culverts are summarized below.

Trenchless Installation – Installing culverts in open trenches across the roadway is often impractical where the excavations are deep and traffic cannot be interrupted or detoured away from the trench location. There are several methods of installing culverts under highways without excavating trenches. These trenchless construction methods include auger boring, slurry boring, pipe jacking, pipe bursting, microtunneling, horizontal drilling, and pipe ramming. These methods are discussed in detail in **Chapter 16**.

The new pipe can be installed in exactly the same location as the existing culvert using pipe bursting and jacking. With the pipe bursting method, the existing pipe is destroyed and the new pipe is pushed or pulled through the old pipe using a pipe bursting head. With pipe jacking, a larger culvert is pushed into the embankment as a sleeve over a smaller culvert and the smaller pipe is removed in sections from the inside of the larger pipe.

The replacement culvert cannot be installed on the same alignment as the new pipe using the other trenchless methods. The existing pipe will interfere with the new pipe installation. An exception is pipe jacking. It can be used on new as well as existing alignments.

Regardless of the chosen method, the new pipe alignment must consider that heavy equipment will be needed at one end of the culvert to install the pipe, and this equipment may require a large flat dewatered pad at an elevation equal to or slightly lower than the streambed. In addition, if the culvert is to be installed on a flowing stream, the water must be kept away from the trenchless excavation operation. Usually the stream continues to flow through the existing culvert during construction and it is diverted to the new culvert after it is built.

Trench Excavation with Detour or Road Closure - Another method of building a culvert is to close the road to traffic and simply dig up the old culvert and install the new culvert. This method provides the most latitude for horizontal and vertical culvert alignment changes.

Two construction methods are commonly used if the culvert is located on a flowing stream. One procedure is to dig a trench alongside the existing culvert, place a bypass pipe in the trench, divert flow to the bypass pipe, remove and replace the existing culvert, divert flow back to the new culvert, remove the bypass pipe, and rebuild the road embankment. With this procedure the old and new culverts can be in the same location. The other procedure is to excavate and build the new culvert, divert streamflow from the old culvert to the new culvert, remove the old culvert (or fill the old barrel with concrete or grout and leave it in place), and rebuild the road. Using this method the old and new culverts have different alignments.

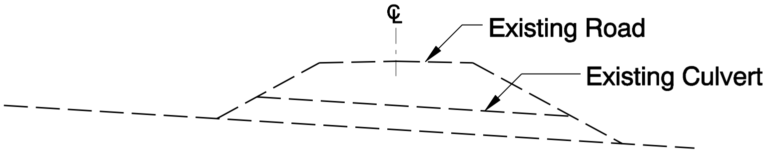
Trench Excavation with Stage Construction – With this method the highway remains open to traffic and the new culvert is built in the same or different location than the old culvert. This procedure is illustrated in Figure 9-7 and it requires careful planning. To summarize the procedure, a long bypass pipe is placed inside the existing culvert and flow is diverted into the bypass pipe. Then a temporary fill and roadway is built alongside the existing road and over one end of the bypass pipe. Traffic is diverted to the temporary road, and a portion or the entire existing culvert is removed and replaced. Last, traffic is rerouted over the new section of culvert, the temporary roadway is removed, the remainder of the old culvert is removed and replaced, and the bypass pipe is removed.

There must be sufficient clearance inside the new culvert for both the bypass pipe and construction activity if the stage-construction method is used. For example, if a structural plate pipe-arch is to be built, there must be enough room in the new culvert for both the bypass pipe and the workers bolting the culvert together.

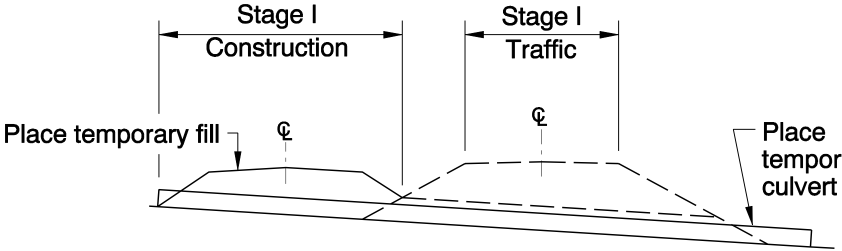
9.11 Fill Heights

An important factor in culvert sizing and vertical alignment is the distance between the surface of the subgrade or the pavement and the culvert crown. This is typically called “cover thickness” or “fill height.” Fill height limitations often influence the choice of the culvert barrel material or the maximum diameter or rise of the culvert.

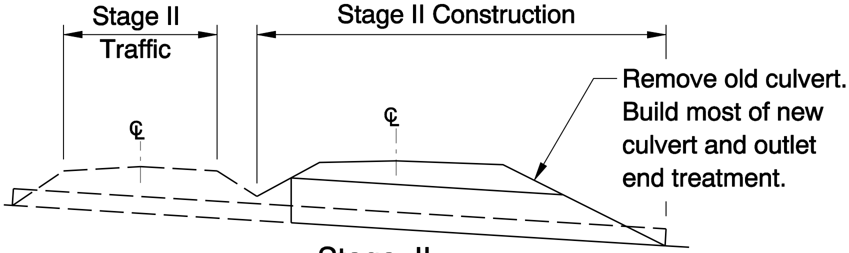
At a minimum, there should be enough fill over the culvert to dissipate the wheel loads from construction activities or traffic. Minimum cover is measured from the subgrade surface to the pipe crown. This distance is usually at its minimum at the roadway shoulder over the upstream end of the pipe but should be checked over the length of the culvert.



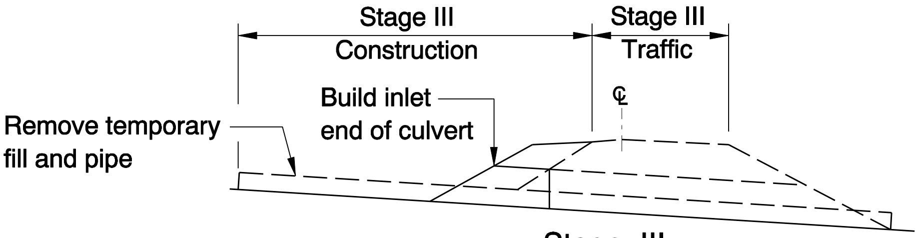
Existing Culvert and Road



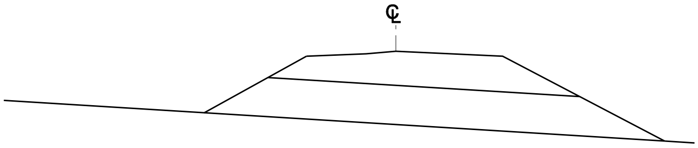
Stage I



Stage II



Stage III



New Culvert and Road

Figure 9-7 Stage Construction

At a maximum, the weight of the fill over the culvert should not be great enough to damage or distort the culvert. Maximum cover is measured from the finished road surface to the pipe crown. It is usually greatest at the roadway shoulder over the downstream end of the pipe but should be checked over the entire length of the culvert.

Fill height tables for metal pipes, concrete pipes, corrugated polyethylene pipes, and cast-in-place concrete box culverts are in the ODOT Standard Drawings. Fill heights for precast box culverts are listed in the American Association of State Highway and Transportation Officials (AASHTO) "Standard Specifications for Transportation Materials." Fill heights for polyvinyl chloride plastic pipes are in **Chapter 5**. Fill heights for the various bottomless arch and 3-sided box culverts are in the trade literature. Methods to protect pipes having minimal cover, and procedures to protect pipes from damage due to high fills, are discussed in **Chapter 5**.

Guardrail support is not a factor in calculating cover heights in most circumstances. There are several rail types that do not have posts projecting into the fill directly over the culvert barrel. Post penetration should be considered in fill height calculations if posts cannot be avoided. Guardrail posts can project 3-1/2 to 4-1/2 feet into the roadway. Exact post and guardrail dimensions are in the ODOT Standard Drawings.

9.12 Minimum Culvert Size

The minimum culvert size is the larger of the following:

- the minimum size allowed by ODOT design criteria, including fish passage and environmental criteria,
- the minimum size that produces an allowable headwater elevation (Section 9.17),
- the minimum size that allows access for maintenance , if needed,
- the minimum size that will allow passage of stream bed material, and
- for bottomless culverts, the minimum size that results in acceptable scour depths.

ODOT Design Criteria - ODOT design criteria specify minimum culvert sizes at many locations, as described in the following list.

- The minimum diameter for median culverts shall be 18 inches unless they are connected to a grated inlet or catch basin, in which case, the minimum diameter shall be 15 inches.
- Culvert pipe under roadway approaches shall have a minimum diameter of 12 inches. These roadway approaches are driveways, minor access roads, etc. Roadway culvert criteria apply to culverts under roadways that intersect the main highway.
- The minimum diameter for roadway cross-culverts shall be 18 inches. The minimum diameter for installations longer than 150 feet or under more than 15 feet of fill shall be 24 inches. Consideration should be given to using a 36-inch minimum diameter on interstate

routes.

Clearance for Maintenance – Culverts with buried inverts on waterways where fish passage is required should provide clearance for channel maintenance such as removing obstructions or replacing lost bed material. Culverts with fish baffles or weirs should provide clearance for inspection, cleaning, and repair. Open-bottom arches or 3-sided boxes should provide clearance for cleaning, footing inspection, footing repair, and renewal of revetment protecting the footings, as discussed in Subsection 9.22.3. ODOT maintenance should be contacted for preferred horizontal and vertical clearances. Maintenance usually requests an 8-foot by 8-foot opening.

Passage of Streambed Material – Almost all ODOT culverts intended to pass fish are designed to retain a layer of bed material over their invert. They are also aligned and sized to minimize scour at the outlet and bed material deposition at the inlet. This is done by providing adequate hydraulic capacity for sediment continuity. Sediment continuity is a balance between the bed load the stream transports into the culvert during floods versus the amount of bed material carried out of the culvert during the same flood. The concept of sediment continuity is discussed in the FHWA publications Hydraulic Design Series No. 6 “River Engineering for Highway Encroachments” (HDS#6) and Hydraulic Engineering Circular No. 20 “Stream Stability at Highway Structures” (HEC#20). Culvert design using the principles in HDS#5 and HEC#20 is beyond the scope of this chapter. At present, these guidelines can also be used to determine the minimum culvert span needed to pass streambed material.

Case 1 – Span the waterway, or channel width, that conveys the Ordinary High Water (OHW). OHW is defined in **Chapter 6**. In almost all instances the majority of sediment is transported within this waterway. This minimum span length is best suited for culverts meeting <u>all</u> of the following:

- culverts on straight stream reaches,
- culverts well aligned to the flow,
- culverts that do not go under pressure flow during the design flood,
- sites where most of the discharge is within the channel during floods,
- sites where the stream is stable in both vertical and horizontal alignment,
- sites where the hydrology can be determined with a fair degree of certainty, and
- sites without a history of problems related to excessive bed load or debris transport.

Case 2 – Span 125 percent of the width of the waterway that conveys the Ordinary High Water plus two feet. This is a minimum waterway width criteria used successfully by other agencies. It is a larger waterway than Case 1, and it is best suited for culverts or sites having <u>any one</u> of the following characteristics:

- culverts on curved stream reaches,
- culverts that cannot be well aligned to the flow,
- sites where there is considerable overbank flow during floods,

- sites where the stream may not be stable in either vertical or horizontal alignment,
- sites where there is greater than normal uncertainty in determining the hydrology, and
- sites with a history of problems related to excessive bed load or debris transport.

These are general guidelines. Regulatory agency guidelines may supercede these criteria in some circumstances.

9.13 Barrel Materials

Culvert barrels are made from a variety of materials. Barrel material selection is based on hydraulic and structural considerations, corrosion and abrasion resistance, the design life of the facility and the service life of the culvert, local government preference, and the need for experimental installations. Guidelines for barrel material selection follow.

1. Materials must comply with requirements in the ODOT "Alternate Materials Policy for Pipe Materials," as discussed in **Chapter 5**.

2. The barrel material must have an adequate design life for the specific site conditions. Special considerations are needed for pipes installed in corrosive conditions or culverts carrying abrasive sediments. Culvert design lives are listed in **Chapter 5**.

3. Culverts designed for fish passage must comply with applicable requirements.

4. Concrete pipe or box sections should not be used without pipe anchors on slopes steeper than 4 Horizontal: 1 Vertical because differential settlement may open the joints. Cast-in-place reinforced concrete structures are acceptable on these steep slopes.

Culvert barrels should be standard sizes whenever possible. Many circular, pipe-arch, and semi-circular arch sizes are listed in Chapter 8 Appendix B and the fill height tables in the ODOT Standard Drawings. Many cast-in-place reinforced concrete box sizes are listed in the ODOT Standard Drawings. Precast concrete box culvert sizes are listed in Chapter 8 Appendix B and the American Association of State Highway and Transportation Officials (AASHTO) "Standard Specifications for Transportation Materials." Sizes of smooth wall polyvinyl chloride pipe are listed in **Chapter 5**. Sizes of the various non-semicircular open-bottom arches and 3-sided boxes are listed in the trade literature.

9.14 End Treatment

The choice of end treatment depends on many interrelated and sometimes conflicting considerations. The designer must evaluate safety, aesthetics, the ability to pass debris, hydraulic efficiency, scouring, and economics. In addition, the end treatment should be consistent with ODOT design criteria unless the exception is approved by the ODOT Geo-Environmental Section's Engineering and Asset Management Unit. This subsection describes many commonly used end treatments, their advantages and disadvantages, and ODOT design practice.

Projecting Ends - A projecting end is a treatment where the culvert protrudes out of the embankment, as shown in Figure 9-2. This end treatment is seldom used on permanent installations, especially with large culverts. Its most common use is on temporary detour pipes and bypass pipes for temporary water management. Projecting ends have these advantages.

- They are the most simple and economical end treatment.
- The inlet edge of a projecting metal culvert has a ring structure with more bending resistance than a non-reinforced sloped end.

Projecting ends have these disadvantages.

- They produce more inlet and outlet head losses than other end treatments because they provide no flow transition into or out of the culvert. An exception is the socket or groove end of a concrete pipe.
- From an aesthetic standpoint, projecting ends may not be desirable in areas exposed to public view.
- They have a poor ability to pass debris. Material carried by the stream, especially woody debris, can snag on the inlet edge.
- Metal pipes with projecting ends are especially vulnerable to uplift from buoyant forces.
- Although the end of a projecting culvert offers some bending resistance, it is vulnerable to damage and collapse if flows carry debris and the culvert is operating under a high headwater. Reinforced sloped ends or headwalls with wingwalls offer greater bending resistance.
- Projecting ends do not have cutoff walls to protect the culvert end or embankment from being undermined by scour. The segments near the ends of concrete pipes with projecting ends are especially vulnerable to separation at the joints if there is embankment scour.

ODOT practice for projecting ends is as follows.

- Projecting ends cannot be used for circular culverts with diameters of 72 inches or greater or the equivalent pipe arch size, or semi-circular bottomless arches with spans of 72 inches or greater.
- Projecting ends are not allowed for culvert ends in unshielded areas within the clear zone,

approach road culverts in cut ditch sections, or on shallow flat sloped embankments five feet or less in height.
- Projecting ends are not allowed on outward helical spiral rib pipe.
- Projecting ends are not suitable for many locations as discussed in this subsection.

Sloped Ends - Sloped ends with the barrel ends cut to match the fill slopes are the standard end treatment for circular, pipe-arch, and bottomless metal arch culverts. These ends are often called mitered ends, as shown in Figure 9-2. Details are shown on Standard Drawings RD318 for concrete pipes, and RD316 for metal and plastic pipes.

Slope paving is a rectangular shaped section of reinforced concrete fabricated around the sloped end. It reinforces the end against bending, provides scour protection, and makes it easier to mow the embankment around the culvert end. ODOT Standard Drawing RD 320 shows slope paving on concrete and metal pipes.

Reinforced concrete collars are a type of slope paving that fits around the upper half of the pipe in a ring shape, rather than the rectangular shape associated with slope paving. The collar around the lower half of the pipe resembles slope paving, and like slope paving, a cutoff wall is included. This end treatment provides most of the benefits of slope paving with a savings in material and fabrication costs. Concrete collars are rarely cost-effective for smaller pipe sizes. When collars are considered during design, it is most often for circular culverts of 66-inch diameter or larger or the equivalent pipe arch size.

Advantages of sloped ends are as follows.

- They are simpler and less expensive than headwalls with wingwalls.
- In the case of metal culverts, they are more hydraulically efficient than projecting ends.
- They are more aesthetically pleasing than projecting ends.
- They are less of a hazard to traffic than projecting ends. For this reason the safety end section version of the sloped end is used in many locations. Safety bars can be fitted to the safety end sections to increase the chances that vehicles will pass over the inlets without damage or injury to the driver. This end treatment is shown in Figure 9-2 and details are shown on Standard Drawings RD324 for concrete pipe and RD322 for metal pipe. Safety end sections with paved end slopes are not shown on the standard drawings. If a paved end slope is needed for an inlet with safety bars it resembles the paved end slope shown on Standard Drawing RD320.

Disadvantages of sloped ends are:

- The inlet edges of sloped ends on metal culverts are especially susceptible to bending and uplift caused by high flows, collisions with debris, or contact with maintenance equipment. This is especially true for ends with flatter slopes and non-reinforced skewed ends on open-bottom arches or 3-sided boxes.

- Sloped ends of both metal and concrete culverts can be undermined by scour. To prevent this damage, sloped ends are often protected by cutoff walls on both ends, as shown on Standard Drawing RD320. In addition, if concrete pipe is used, the sections of pipe near the ends are linked with tie bars as shown on ODOT Standard Drawing RD318.
- Sloped inlets on vegetated slopes are often hard to locate and mow around. To prevent these problems slope paving is required in some applications, as discussed in the remainder of this subsection.

ODOT practice for sloped ends within the clear zone that are not shielded from traffic is as follows.

1. Culverts parallel to the roadway centerline under driveways, road approaches, etc.

    a. Pipe diameters less than or equal to 24 inches and posted speed more than or equal to 45 miles per hour, provide 1V: 6H sloped end or safety end section. No safety bars are required.

    b. Pipe diameters less than or equal to 24 inches and posted speed less than 45 miles per hour, provide 1V: 4H sloped end or safety end section. No safety bars required.

    c. Pipe diameters more than 24 inches and posted speed more than or equal to 45 miles per hour, provide 1V: 6H safety end section with safety bars.

    d. Pipe diameters more than 24 inches and posted speed less than 45 miles per hour, provide 1V: 4H safety end section with safety bars.

    e. Multiple pipes with diameters more than or equal to 15 inches, provide safety end sections with safety bars, using above criteria.

2. Cross-culverts:

    a. Pipe diameters less than or equal to 36 inches, provide either a sloped end to match embankment slope, or a 1V: 6H or 1V: 4H safety end section. No safety bars are required. The embankment slope should be warped and shaped to match the safety end section

    b. Pipe diameters more than 36 inches, provide either a sloped end with safety bars to match the embankment slope, or a 1V: 6H or 1V: 4H safety end section with safety bars.

    c. Multiple pipes with diameters more than or equal to 36 inches, provide either a sloped end, with safety bars to match embankment slope, or a 1V: 6H or 1V: 4H safety end section with safety bars.

Note: Provide safety bars at the inlet if there are safety bars at the outlet, regardless of whether or not the inlet is in the clear zone.

Additional ODOT design practice for sloped ends is as follows.

- Sloped ends are the standard end treatment for circular, pipe-arch, and metal arch culverts with diameters of 72 inches or greater, or the equivalent pipe-arch or arch size. Both ends will be sloped if this treatment is used.
- Reinforced concrete slope paving or collars are required on sloped ends of culverts with diameters equal to or greater than 72 inches. A cutoff wall with a depth of at least 36 inches is required on both ends.
- Slope paving on culverts with diameters less than 72 inches should include a cutoff wall on both ends with a minimum depth of ½ the barrel diameter or 1 foot, whichever is greater.
- Sloped ends with slope paving or safety end sections with slope paving are required on slopes that are 1V: 3H or flatter that will be mowed, or on the main roadways and interchange ramps of interstate highways. Slope paving will be used on both ends of the culvert if it is used. Contact the appropriate District Manager to determine if the slope will be mowed.
- Sloped ends or safety end sections are required on all approach road culverts in cut ditch sections or shallow flat sloped embankments, five feet or less in height.
- Sloped ends on plastic pipes are allowed only in locations where slope paving is required.
- Skew cut sloped ends are not permitted for arch-type pipes. The roadway slopes will be contour-graded to conform with the pipe as shown in detail “Alternate Skew Plan,” Standard Drawing RD320, for arch-type pipes on a skewed alignment with sloped ends.

Headwalls with Wingwalls - Headwalls with wingwalls are the standard end treatment for box culverts and they are occasionally used on circular, pipe-arch, and bottomless culverts. Headwalls and wingwalls for circular pipes and box culverts are shown on Figure 9-2 and ODOT Standard Drawing BR800, respectively. The upstream headwall has a beveled edge to improve hydraulic efficiency. Beveled edges can also be incorporated into the headwall to improve the efficiency of circular pipes, arch-pipes, bottomless arches, and other shapes. This end treatment has these advantages.

- It is one of the most hydraulically efficient end treatments and the cutoff walls protect the culvert ends from undermining due to scour.
- The weight of this end treatment holds the culvert down and it can prevent buoyant failure.
- They are very efficient at passing debris.

A disadvantage of this end treatment is its relatively high complexity and cost as compared to other end treatments.

ODOT design practice for headwalls with wingwalls is as follows.

- Headwalls with wingwalls are an optional end treatment for culverts. Both ends will have headwalls with wingwalls if this option is used. Culverts with diameters equal to or larger than 72 inches should have a cutoff wall with a minimum depth of 36 inches. Culverts with diameters less than 72 inches should have a cutoff wall extending downward the greater distance of ½ the barrel diameter or 1 foot.
- Headwalls with wingwalls are not to be used for culvert ends in unshielded areas within the clear zone, approach road culverts in cut ditch sections, or on shallow flat sloped embankments five feet or less in height.

Concrete Boxes with Grates - Concrete boxes with grates are often used on small culverts draining medians, swales, gutters, depressions in paved surfaces, or roadside ditches. Details of these boxes are shown on Standard Drawings RD364, RD366, RD368, RD370, RD374, and RD378. Applicable safety standards apply to these ends within the clear zone.

Prefabricated End Sections - Prefabricated end sections such as precast end sections for concrete pipes and flared sheet metal ends for metal pipes are shown in Figure 9-2. In many cases, these prefabricated end sections look better and are more hydraulically efficient than projecting or sloped ends. Prefabricated metal end sections have cutoff walls to resist undermining due to scour. Prefabricated concrete end sections, however, do not have cutoff walls and they are vulnerable to scour unless a cutoff wall is constructed under the edges of their aprons. A cutoff wall should extend downward to the greater of ½ the pipe diameter or 1 foot. Although a cutoff wall is the best protection against scour, riprap around the end is also an option.

There are limitations and conditions on prefabricated end section use. These ends, with the exception of the safety end sections, are not approved by ODOT for use within the clear zone in locations unshielded from traffic. They may be used in areas shielded from traffic, only. In addition, ODOT does not have standard plans for the pipe connection details and installation of prefabricated end sections. As a result, plan details are prepared for each installation. Prior approval should be obtained from the Region Technical Center staff before these end sections are included in project plans.

Depressed and Tapered Inlets - A variety of depressed and tapered inlets are used to increase the capacity of a culvert flowing under inlet control. Three types of these inlets, the depressed, the side-tapered, and the slope-tapered inlets are shown in Figure 9-8. Outlet end treatments on culverts with these inlets are usually headwalls with wingwalls. The hydraulic design of these inlets is beyond the scope of this manual and it is covered in the FHWA's HDS #5 "Hydraulic Design of Highway Culverts." These inlets have these advantages.

- The depressed inlet is most often used to reduce the barrel size or lower the headwater elevations to an acceptable level. This can be done because of this inlet has greater hydraulic efficiency. In comparison to a conventional inlet, for a given headwater elevation the depressed inlet provides greater headwater depth above the control section at the upstream end of the barrel (inlet control only). This increased headwater depth produces additional pressure to push the flow through the barrel.

- The depressed inlet provides a drop in elevation between the upstream edge of the inlet apron and the culvert invert. This may be useful if a lower barrel is needed to provide clearance for utilities or pavement. In addition, this inlet can be used to reduce the slope of a culvert and lower outlet velocities.
- The slope-tapered inlet provides the same benefits as the depressed inlet. It provides much greater hydraulic efficiency due to the gradual taper of the inlet throat section.
- The side-tapered inlets do not provide a drop but they have increased hydraulic efficiency when compared to conventional inlets. They may be cost effective in certain situations because they can reduce barrel size. They may also be added to existing barrels to increase their flow capacity.

These inlets have these disadvantages.

- They have a relatively high cost compared to other end treatments. They are specially designed for each application and they require forming reinforced concrete into shapes.
- These inlets are rarely adequate for fish passage.
- These inlets may be more susceptible to clogging than conventional inlets in heavy debris areas.

ODOT practice for depressed or tapered inlets follows.

- Depressed or tapered inlets are an optional end treatment for culverts. A reinforced concrete collar, slope paving, or a headwall with wingwalls should be used at the outlet. Culverts with diameters equal to or larger than 72 inches should have a cutoff wall with a minimum depth of 36 inches. Culverts with barrels less than 72 inches diameter should have a cutoff wall that extends downward the greater distance of ½ the barrel diameter or 1 foot.
- Depressed or tapered inlets are not to be used for culvert ends in unshielded areas within the clear zone, approach road culverts in cut ditch sections, or on shallow flat sloped embankments five feet or less in height.
- Depressed or tapered inlets are not to be used for culverts in debris prone areas or where fish passage is required.

9.15 Culvert Design Flows

An essential step in culvert design is to determine the flood flow versus recurrence interval relationship. Design and check flood recurrence intervals are listed in **Chapter 3**, the contents of the hydrology section of a Hydraulics Report are discussed in **Chapter 4**, and hydrologic methods are presented in **Chapter 7**.

The discharges used in culvert design are different for large, medium, and small culverts. The culvert size classification is defined at the beginning of this chapter. Discharges used in large culvert and some medium culvert designs are:

- the 6-month flow for selection of invert protection (see **Chapter 5**),
- the Design Event (typically the 25 or 50-year storm event, and in some instances, the 100-year flood,
- the 100-year Base Flood, and
- the check flood. The check flood is one of the two flows listed below that results in the highest headwater elevations and outlet flow velocities,
    - the Overtopping Flood, or
    - the 500-year Flood.

Discharges used in small culvert and some medium culvert designs are:

- the 6-month flow for selection of invert protection (see **Chapter 5**), or
- the Design Event (typically the 10-year storm event for road approach culverts, or the 25-year or 50-year storm events for cross-culverts), and
- the Check Flood. The check flood is the more frequent of:
    - the Overtopping Flood, or
    - the 100-year base flood.

Note: The invert protection design is based on sediment and bed material conveyed by the 6-month discharge. This is adequate for most installations. Greater floods may transport larger material at some sites. Designing the invert to resist damage from these greater and less frequent floods is recommended for costly or critical installations.

Culverts are also used for temporary installations such as detours around construction sites, temporary water management, and other applications. Guidance about the discharges to use in their design is provided in **Chapter 3**.

9.16 Peak vs. Attenuated Flows

Discharge increases to a maximum and then recedes when runoff from a storm event passes a point on a stream. The maximum discharge rate is called the peak flow. A culvert is sized to pass this peak flow from one side of the roadway embankment to the other without producing an excessive headwater elevation using the design method presented in this manual.

Often there is considerable volume in the floodplain upstream from the culvert, and a significant amount of water can be stored in this area without producing an excessive headwater elevation. This storage can be considered in the culvert analysis. When upstream storage is considered, it will often reduce the peak flow the culvert must pass. Consequently, a smaller culvert can be used without producing excess headwater. This lower rate of flow is often called the attenuated flow.

Use of peak flows in the culvert design greatly simplifies the hydraulic analysis and it produces conservative results. Most culverts should be designed using this method, including fish passage culverts. In some cases, however, the added complexity of analyzing the attenuated flow may be justified. An example would be an area where there is considerable volume available upstream for storage, fish passage is not an issue, and a reduction in barrel size would significantly reduce the cost of the culvert.

Attenuated flow analyses can be done by hand. Computer programs are available and they greatly reduce the amount of hand calculations. The handiest programs are those which perform all four of the major calculations, such as generating the hydrograph, determining the storage vs. elevation relationship, routing the flows, and performing the culvert hydraulic analysis. The FHWA's HY-8 program in the "HYDRAIN" software package has these capabilities. Guidance on using storage in hydraulic design is presented in **Chapter 12**.

The ODOT culvert design practice is based on experience with culverts sized by the peak flow method, and designing a culvert using attenuated flows should be done with care. The maximum headwater depths upstream from the culvert should not exceed the criteria in the following section. The same method must be used in both analyses in cases when comparing an existing to a proposed condition. An erroneous comparison results if storage is considered in one analysis and not in the other.

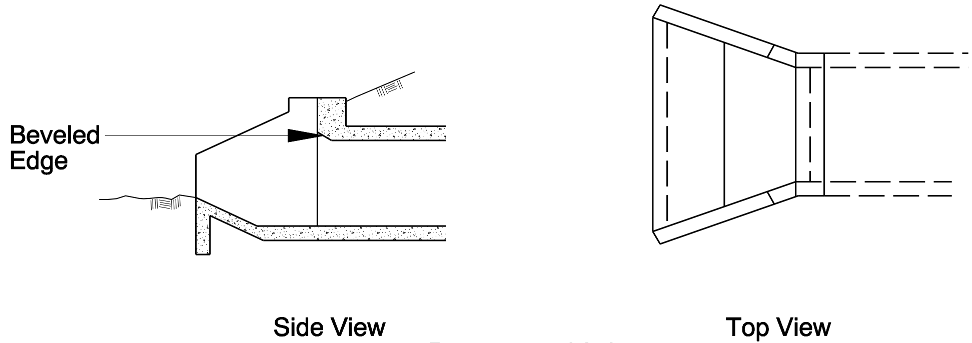
9.17 Maximum Allowable Headwater

ODOT policy is to design the culvert so it does not have a design event headwater elevation (EL_{hd}) that is greater than the maximum headwater elevation the site can tolerate. The headwater elevation EL_{hd} is shown in Figure 9-9. The maximum headwater elevation the site can tolerate is called the maximum allowable headwater elevation. Typical items to consider when determining the maximum allowable headwater elevation are listed below.

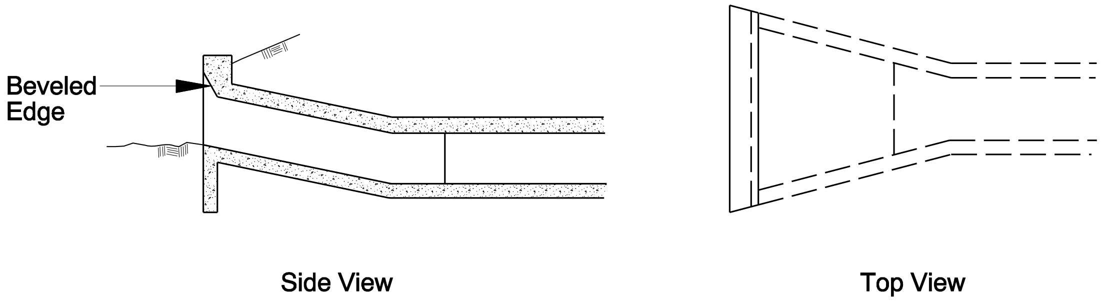
1. Damage to upstream property. In general, unless a flood easement is obtained, flood elevations should not be increased on adjacent property. In most cases, the maximum allowable headwater elevation should not be higher than the floor elevations of upstream buildings or an increase above existing headwater elevations.

2. Requirements of local development ordinances and the National Flood Insurance Program (NFIP). These ordinances often have restrictions on increases in flood elevations. It is recommended that the designer contact the Region Technical Center hydraulics staff for guidance if a culvert is to be placed or replaced in a floodway or floodplain identified in a NFIP Flood Insurance Study.

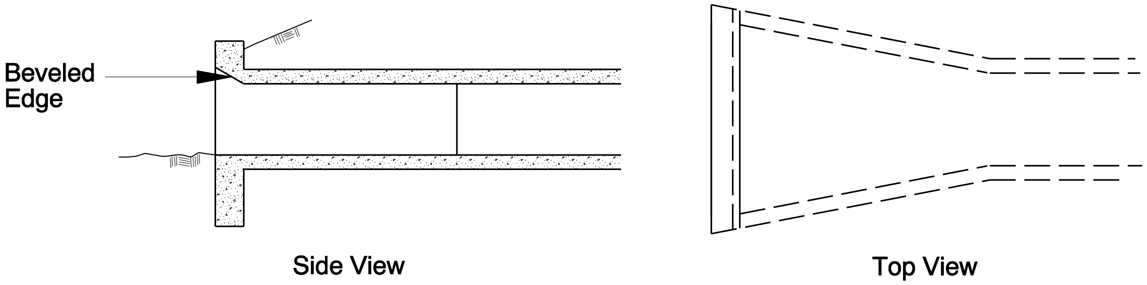
3. Diversion of flow. The maximum allowable headwater elevation should not be higher than the elevation where flow diverts around the culvert. This could be a diversion where the flow rejoins the stream of origin downstream from the culvert. It could also be a diversion where flow is diverted to drainage. An exception can be made if the effects of the bypass flow are considered in the design.



Depressed Inlet



Slope-Tapered Inlet



Side-Tapered Inlet

Figure 9-8 Depressed and Tapered Inlets

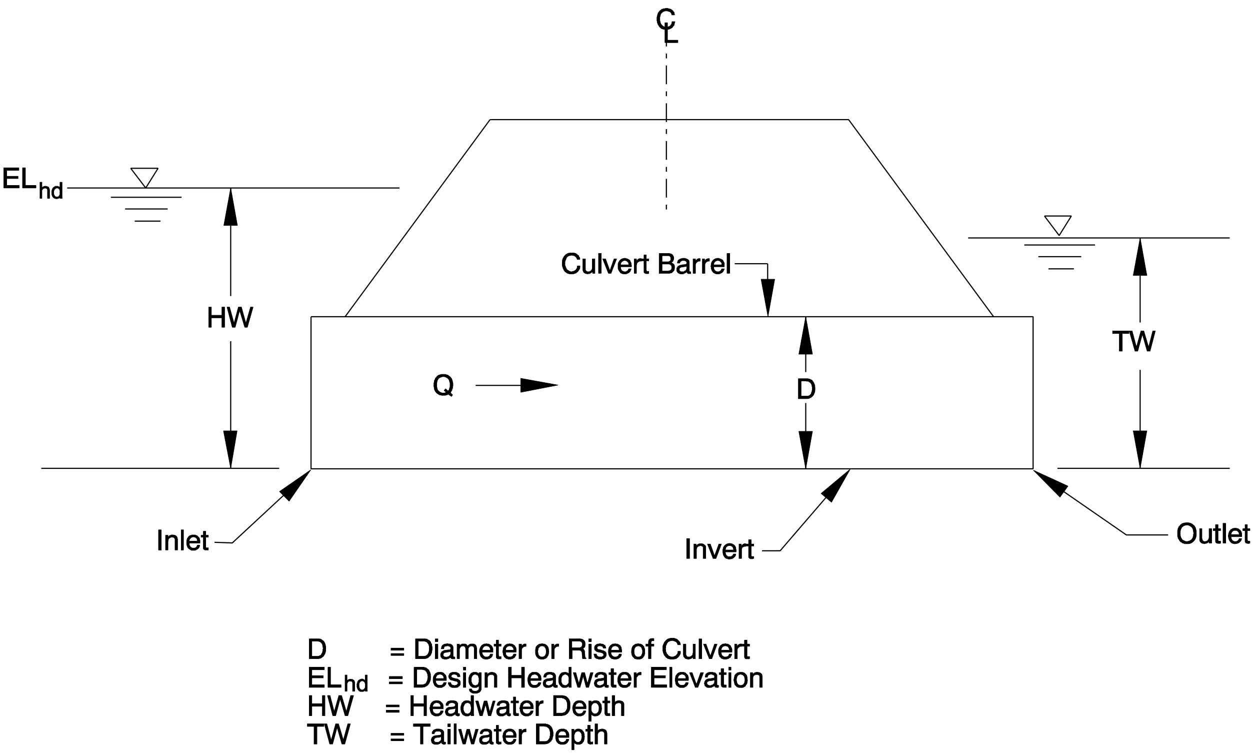


Figure 9-9 Headwater and Tailwater Diagram

4. Traffic interruption. This depends on the importance of the highway and the viability of alternate flood free routes. The maximum allowable headwater elevation should not be high enough to interrupt the flow of traffic, during the design event listed in **Chapter 3**.

5. Strength of the highway embankment. Water pooled at the culvert inlet can cause considerable hydrostatic pressure on the upstream side of the highway embankment and the embankment may collapse if the pressure becomes excessive. As a result, an excessively high headwater depth upstream from an embankment may create a hazard to the public, and should be avoided.

6. Hazard to human life. Headwater depths in locations such as urban areas may be a hazard to local residents as well as the traveling public.

7. Damage to the culvert. The hydraulic pressure on the edge of the inlet end of the culvert can be quite large if the culvert is operating under a high headwater. These pressures can collapse the end of the culvert. The thin edges of metal pipes with projecting ends, mitered ends without slope paving or flared sheet metal end sections especially susceptible to this damage.

Note: Circular culverts, box culverts, and pipe-arch culverts should be designed such that the ratio of the headwater (HW) to the diameter or rise (D) during the design flow event is less than or equal to 1.25 (HW/D less than or equal to 1.25). Design discharge HW/D ratios greater than 1.25 are permitted, provided that the impounding embankment is determined to be stable based on the results of an appropriate geotechnical stability analysis and the existing site conditions dictate or warrant a larger ratio. An example of this may be an area with a high roadway fill, minimal debris in the discharge, and no impacted upstream property owners. Generally, the maximum HW/D ratio during the check flood should not exceed 3 to 5.

9.18 Culvert Hydraulic Design

An analysis of culvert hydraulics is an essential tool to design culverts, and it can be done by several methods. One method is to use the procedures presented in this chapter. These methods provide sufficient accuracy for most applications. Much of the information in this chapter was originally presented in the FHWA's "Hydraulic Design Series No. 5 – Hydraulic Design of Highway Culverts" (HDS 5). HDS 5 contains detailed information on culvert hydraulics and culvert design for special applications. It is available from the FHWA website: http://www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=7

Computer programs such as the HY-8 or WSPRO modules in the FHWA's HYDRAIN computer program, or the U.S. Corps of Engineers HEC-RAS program can also be used to analyze culvert flow. Most of these programs can evaluate special situations, such as barrels with irregular shapes or groups of culverts with non-identical barrels. The HEC-RAS and WSPRO programs can also model a culvert and the stream reaches upstream and downstream from the culvert. The HEC-RAS program is particularly useful because, unlike the other programs, it can model a mixed water surface profile when there are both supercritical and subcritical flows in the culvert or the channel.

A fish passage culvert design almost always requires detailed information about the hydraulic characteristics of the channel as well as the culvert. The primary use of this information is to verify the proposed culvert has hydraulic characteristics suitable for passage, and to analyze sediment transport and retention in both the stream and culvert. HEC-RAS or WSPRO modeling has the ability to provide the needed data, and they are strongly recommended for fish passage culvert modeling.

An exact theoretical analysis of culvert flow is extremely complex because the flow is usually nonuniform with regions of both gradually varying and rapidly varying flow. An exact analysis involves backwater and drawdown calculations, energy and momentum balance, and application of the results of hydraulic model studies. In addition, the flow types change in a given culvert as the flow rate and tailwater elevations change. In order to simplify culvert analysis the various flow types are classified and analyzed on the basis of a control section.

A control section is a location where there is a unique relationship between the flow rate and the upstream water surface elevation. Many different flow conditions exist over time, but at a given time the flow is either governed by the inlet geometry (**inlet control**); or by a combination of the culvert inlet configuration, the characteristics of the barrel, and the tailwater (**outlet control**). Control may oscillate from inlet to outlet; however, the concept of “minimum performance” applies. That is, while the culvert may operate more efficiently at times (more flow for a given headwater level), it will never operate at a lower level of performance than calculated. The governing control is determined by calculating the headwater depth for both inlet control and outlet control. The higher headwater elevation indicates the type of control. This method of determining the type of control is accurate except for a few cases where the headwater depth is approximately the same for both types of control.

A general description of the characteristics of inlet and outlet control flow is as follows: A culvert flowing in inlet control has shallow, high velocity flow categorized as “supercritical”. For supercritical flow, the control section is at the upstream end of the barrel (the inlet). Conversely, a culvert flowing in outlet control will have relatively deep, lower velocity flow termed “subcritical” flow. For subcritical flow the control is at the downstream end of the culvert (the outlet). The tailwater depth is either critical depth at the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the factors listed in Table 9-1.

9.18.1 Headwater

Energy is required to force flow through a culvert. This energy takes the form of an increased water surface elevation on the upstream side of the culvert. The depth of the upstream surface measured from the invert at the culvert entrance is generally referred to as **headwater depth**.

TABLE 9-1 FACTORS INFLUENCING CULVERT PERFORMANCE

Factor	Inlet Control	Outlet Control
Headwater Depth	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope		X
Tailwater Depth		X

9.18.2 Tailwater

Tailwater is defined as the depth of water downstream of the culvert measured from the outlet invert. It is an important factor in determining culvert capacity under outlet control conditions. Tailwater may be caused by an obstruction in the downstream channel or by the hydraulic resistance of the channel. In either case, backwater calculations from the downstream control point are required to precisely define tailwater. When appropriate, normal depth approximations may be used instead of backwater calculations. This is shown in the single-section analysis example in **Chapter 8**.

9.18.3 Outlet Velocity

Culvert outlet velocities should be calculated to determine the need for erosion protection at the culvert outlet. Since culverts usually have outlet velocities which are higher than the natural stream velocities, riprap protection or an energy dissipator may be required to prevent downstream erosion. Outlet velocity calculation procedures are discussed and illustrated in **Chapter 11**.

9.18.4 Performance Curves

A performance curve is a plot of headwater depth or headwater elevation versus discharge. The resulting graphical depiction of culvert operation is useful in evaluating the hydraulic capacity of a culvert for various headwaters. Among its uses, the performance curve displays the consequences of higher flow rates at the site and the benefits of inlet improvements. The determination of a performance curve should be routinely done as part of the hydraulic analysis.

In developing a culvert performance curve, both inlet and outlet control curves must be calculated. This is necessary to determine the dominant control for a given discharge as control may shift from the inlet to the outlet, or vice-versa over a range of discharges. The overall performance curve reflects the controlling portions of the individual inlet control and outlet control curves. Figure 9-10 illustrates a typical culvert performance curve. At the design headwater, the culvert operates under inlet control. With inlet improvement the culvert performance can be increased to take better advantage of the culvert barrel capacity.

9.18.5 Culverts Flowing in Inlet Control

Since the control is at the upstream end in inlet control, only the headwater and the inlet configuration affect the culvert performance (Table 9-1). The **headwater depth** is measured from the invert of the inlet control section to the surface of the upstream pool. The **inlet area** is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area, except for some types of improved inlets. The **inlet edge configuration** describes the entrance type. Some typical inlet edge configurations are thin edge projecting, mitered, square edges in a headwall, and beveled edge. The **inlet shape** is usually the same as the shape of the culvert barrel; however, it may be enlarged as in the case of a tapered inlet. Typical shapes are rectangular, circular, and elliptical. Whenever the inlet face is a different size or shape than the culvert barrel, the possibility of an additional control section within the barrel exists.

An additional factor which influences inlet control performance is the barrel slope. The effect is small, however, and it can be ignored or a small slope correction factor can be inserted in the inlet control equations.

The inlet edge configuration is a major factor in inlet control performance, and it can be modified to improve performance. As the inlet edge condition improves, the flow contraction at the inlet decreases. The reduced flow contraction increases inlet performance and allows more flow through the barrel for the same headwater.

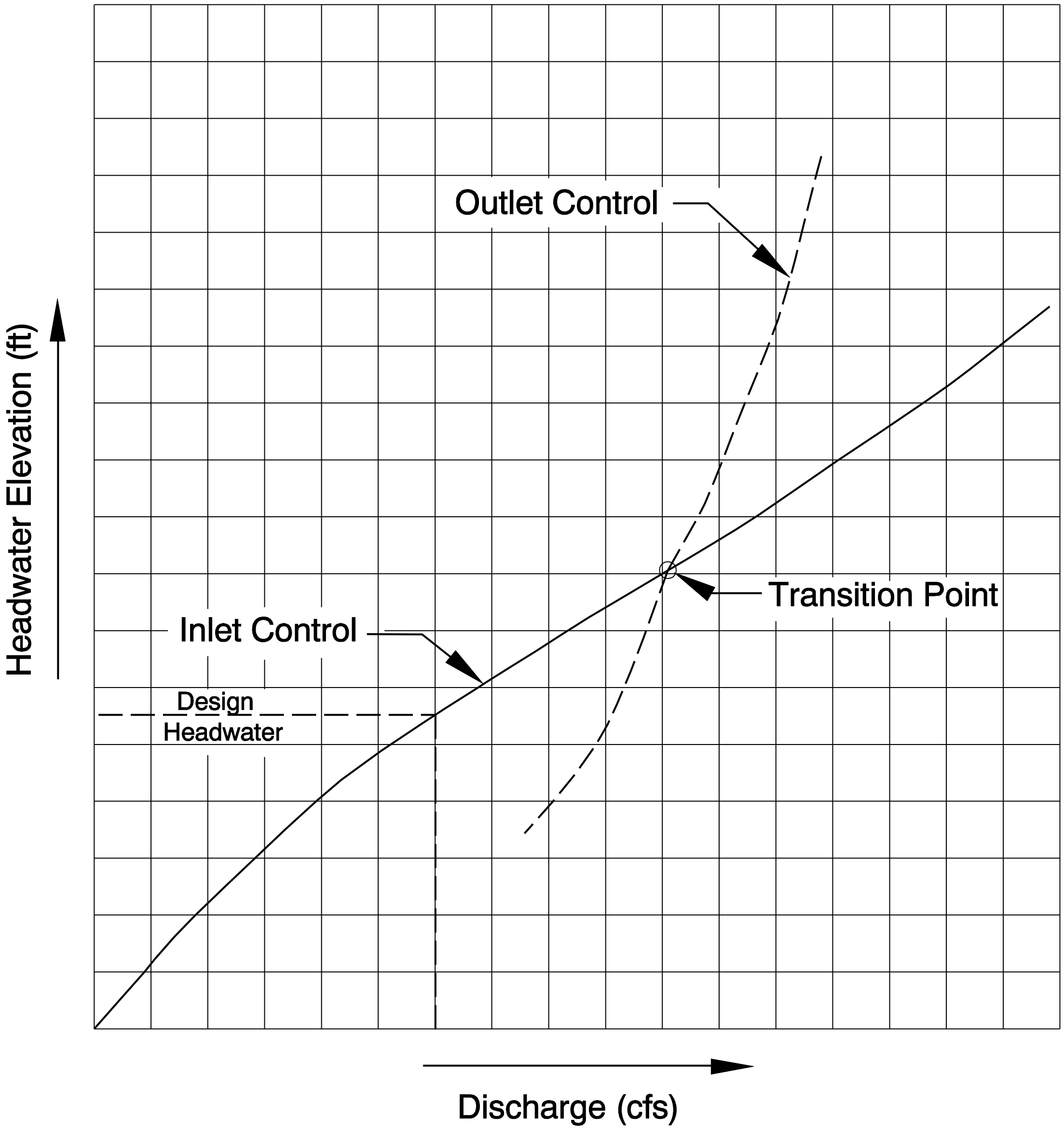
A method of increasing inlet performance is the use of beveled edges at the entrance of the culvert. Beveled edges reduce the contraction of the flow by effectively enlarging the face of the culvert. Although any beveling will improve the hydraulic efficiency, design charts are available for two bevel angles, 45 degrees and 33.7 degrees.

9.18.5.1 Inlet Control Examples

Several different examples of inlet control are shown in Figure 9-11. The flow type depends on the degree of submergence of the inlet and outlet ends of the culvert. In all of these examples, the control section is at the inlet end. Depending on the tailwater, a hydraulic jump may occur downstream from the inlet.

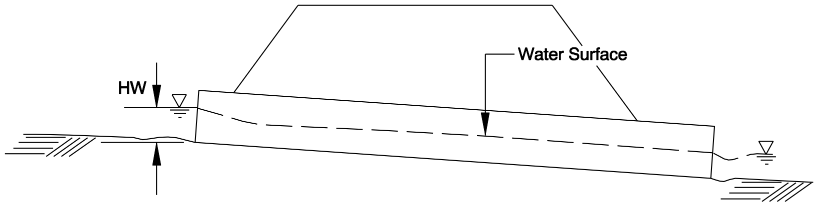
Figure 9-11a depicts a condition where neither the inlet nor the outlet ends are submerged. The flow passes through critical depth just downstream of the culvert entrance and the flow in the barrel is supercritical. The barrel flows partially full over its length and the flow approaches or has reached normal depth at the outlet end.

Figure 9-11b shows that outlet submergence does not assure outlet control. In this case, the flow just downstream of the inlet is supercritical and a hydraulic jump forms in the culvert barrel.

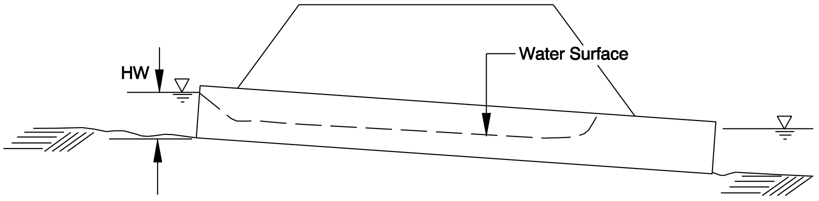


Note: Control shifts from inlet control to outlet control at the transition point.

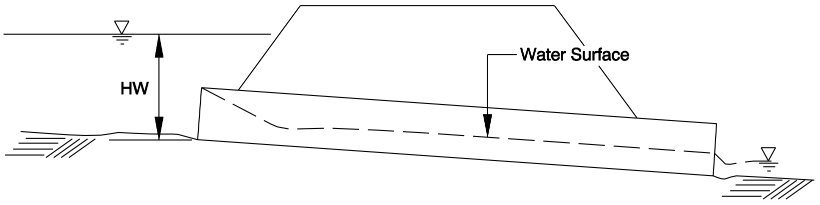
Figure 9-10 Culvert Performance Curve



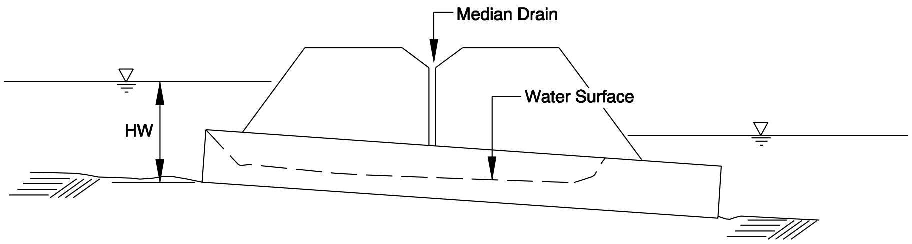
a) Inlet and outlet unsubmerged



b) Outlet submerged and
inlet unsubmerged



c) Inlet submerged and
outlet unsubmerged



d) Inlet and outlet submerged

Figure 9-11 Inlet Control Types

Figure 9-11c is a more typical design situation. The inlet end is submerged and the outlet end flows freely. Again, the flow is supercritical and the barrel flows partially full over its length. Critical depth is located just downstream of the culvert entrance, and the flow is approaching or has reached normal depth at the downstream end of the culvert.

Figure 9-11d is an unusual condition illustrating the fact that even submergence of both the inlet and the outlet ends of the culvert does not assure full flow. In this case, a hydraulic jump will form in the barrel. The median inlet provides ventilation of the culvert barrel. If the barrel were not ventilated, sub-atmospheric pressures could develop which might create an unstable condition during which the barrel would alternate between full flow and partial flow.

9.18.5.2 Inlet Control Design Equations

The equations used to develop the inlet control nomographs are based on two basic inlet headwater conditions. If the inlet is not submerged, it performs as a weir. If the inlet is submerged, it performs as an orifice. Equations for both conditions are in this subsection.

Between the unsubmerged and the submerged conditions a transition zone exists where the equation results do not match. The zone is defined empirically by drawing a curve between and tangent to the curves defined by the unsubmerged and submerged equations. In most cases, the transition zone is short and the curve is easily constructed.

FHWA Inlet Control Equations – The Federal Highway Administration has developed inlet control equations for many culvert shapes and inlet configurations. These equations are discussed in Hydraulic Engineering Series No. 5 “Hydraulic Design of Highway Culverts.”

Equations 9-1a, 9-1b, and 9-1c are unsubmerged and submerged inlet control design equations, respectively. Note that there are two forms of the unsubmerged equation. Form (1) is based on the specific head at critical depth, adjusted with two correction factors. Form (2) is an exponential equation similar to a weir equation. Form (1) is preferable from a theoretical standpoint, but form (2) is easier to apply.

Either form of unsubmerged inlet control equation will produce adequate results. The constants for the equations are given in Table 9-2. Table 9-2 provides the unsubmerged and submerged equation coefficients for each shape, material, and edge configuration. For the unsubmerged equations, the form of the equation is also noted.

Unsubmerged inlet control design equations:

$$\text{Form (1)} \quad \frac{HW_i}{D} = \frac{H_c}{D} + K\left(\frac{Q}{AD^{0.5}}\right)^M - 0.5S \quad \text{(see Notes 1 and 2)} \qquad \text{(Equation 9-1a)}$$

$$\text{Form (2)} \quad \frac{HW_i}{D} = K\left(\frac{Q}{AD^{0.5}}\right)^M \text{(see Note 1)} \qquad \text{(Equation 9-1b)}$$

Submerged inlet control design equation:

$$\frac{HW_i}{D} = c\left(\frac{Q}{AD^{0.5}}\right)^2 + Y - 0.5S \quad \text{(see notes 2 and 3)} \qquad \text{(Equation 9-1c)}$$

Where:

HW_i = headwater depth above inlet control section invert in feet,
D = interior height of culvert barrel in feet,
H_c = specific head at critical depth ($D_c + V_c^2/2g$) in feet,
Q = discharge in cubic feet per second,
A = full cross sectional area of culvert barrel in square feet,
K,M,c,Y = constants from Table 9-2, and
S = culvert barrel slope in feet per foot.

Notes:
(1) Equations, (unsubmerged) apply up to about $Q/AD^{0.5} = 3.5$
(2) For mitered inlets use +0.7S instead of -0.5S as the slope correction factor.
(3) Equation (submerged) applies above about $Q/AD^{0.5} = 4.0$

The equations may be used to develop design curves for any conduit shape or size. Careful examination of the equation constants for a given form of equation reveals that there is very little difference between the constants for a given inlet configuration. Therefore, given the necessary conduit geometry for a new shape from the manufacturer, a similar shape is chosen from Table 9-2, and the constants are used to develop new design curves. Note that coefficients for rectangular shapes should not be used for nonrectangular shapes and vice-versa. A constant slope value of 2 percent is usually selected for the development of design curves. This is because the slope effect is small and the resultant headwater is conservatively high for sites with slopes exceeding 2 percent (except for mitered inlets).

K-TRAN Inlet Control Equations – Inlet control equations for several prefabricated end section types were derived from laboratory model test data by the Kansas Department of Transportation (K-TRAN). Several prefabricated end sections available from proprietary sources were tested. Study results for tapered metal and concrete end sections are published in K-TRAN Report No. KU-94-4 "Development of Hydraulic Design Charts for Type I and Type III Metal and Concrete End Sections for Pipe Culverts." The study results for the non-tapered metal mitered end resembling the ODOT Safety End Section are published in K-TRAN Report 93-5 "Development of Hydraulic

Design Charts for Type IV End Section for Pipe Culverts." The equation variables are the same as those described previously for the FHWA equations, with one addition, as follows:

g = gravitational acceleration, 32.2 feet per second squared

The tapered and mitered prefabricated concrete end section is shown on Figure 9-12 with the dimensions of the largest and smallest end sections tested by K-TRANS. The inlet control equations are as follows:

$$\frac{HW_i}{D} = 1.53\left(\frac{Q}{gD^5}\right)^{0.55} \quad \text{when } 0 \leq \left(\frac{Q}{gD^5}\right) \leq 0.42 \qquad \text{(Equation 9-2a)}$$

$$\frac{HW_i}{D} = 2.13\left(\frac{Q}{gD^5}\right) + 0.055 \quad \text{when } 0.42 < \left(\frac{Q}{gD^5}\right) \leq 0.68 \qquad \text{(Equation 9-2b)}$$

$$\frac{HW_i}{D} = 1.367 - 1.50\left(\frac{Q}{gD^5}\right) + 2.50\left(\frac{Q}{gD^5}\right)^2 \quad \text{when } 0.68 < \left(\frac{Q}{gD^5}\right) \leq 1.30 \qquad \text{(Equation 9-2c)}$$

Note: ≤ *(Less than or equal to)*
≥ *(Greater than or equal to)*

The tapered and mitered prefabricated metal end section is shown on Figure 9-13 with the dimensions of the largest and smallest end sections tested. The inlet control equations follow:

$$\frac{HW_i}{D} = 1.60\left(\frac{Q}{gD^5}\right)^{0.60} \quad \text{when } 0 \leq \left(\frac{Q}{gD^5}\right) \leq 0.41 \qquad \text{(Equation 9-3a)}$$

$$\frac{HW_i}{D} = 2.23\left(\frac{Q}{gD^5}\right) + 0.023 \quad \text{when } 0.41 < \left(\frac{Q}{gD^5}\right) \leq 0.62 \qquad \text{(Equation 9-3b)}$$

$$\frac{HW_i}{D} = 1.289 - 1.61\left(\frac{Q}{gD^5}\right) + 2.90\left(\frac{Q}{gD^5}\right)^2 \quad \text{when } 0.62 < \left(\frac{Q}{gD^5}\right) \leq 1.20 \qquad \text{(Equation 9-3c)}$$

Ten mitered prefabricated metal safety end sections of different sizes, safety bar configurations, and miter slopes were tested. The miter slopes were 1V: 4H and 1V: 6H. The safety end sections shown on ODOT Standard Drawings RD322 and RD324 are typical of the end sections tested. The study developed the following inlet control equations for safety end sections with safety bars.

$$\frac{HW_i}{D} = 1.69\left(\frac{Q}{gD^5}\right)^{0.60} \text{ when} \left(\frac{Q}{gD^5}\right) \leq 0.42 \qquad \text{(Equation 9-4a)}$$

$$\frac{HW_i}{D} = 1.11 - 1.93\left(\frac{Q}{gD^5}\right) + 4\left(\frac{Q}{gD^5}\right)^{2} \text{ when} \left(\frac{Q}{gD^5}\right) > 0.42 \qquad \text{(Equation 9-4b)}$$

The preceding inlet control equations were developed with unobstructed inlet sections. ODOT design practice is to use the hydraulic properties of unobstructed sections in design. The safety end sections were also tested by K-TRANS with varying amounts of debris obstruction. The hydraulic performance equations and conclusions are in K-TRANS Report KU-93-5.

TABLE 9-2 CONSTANTS FOR INLET CONTROL DESIGN EQUATIONS

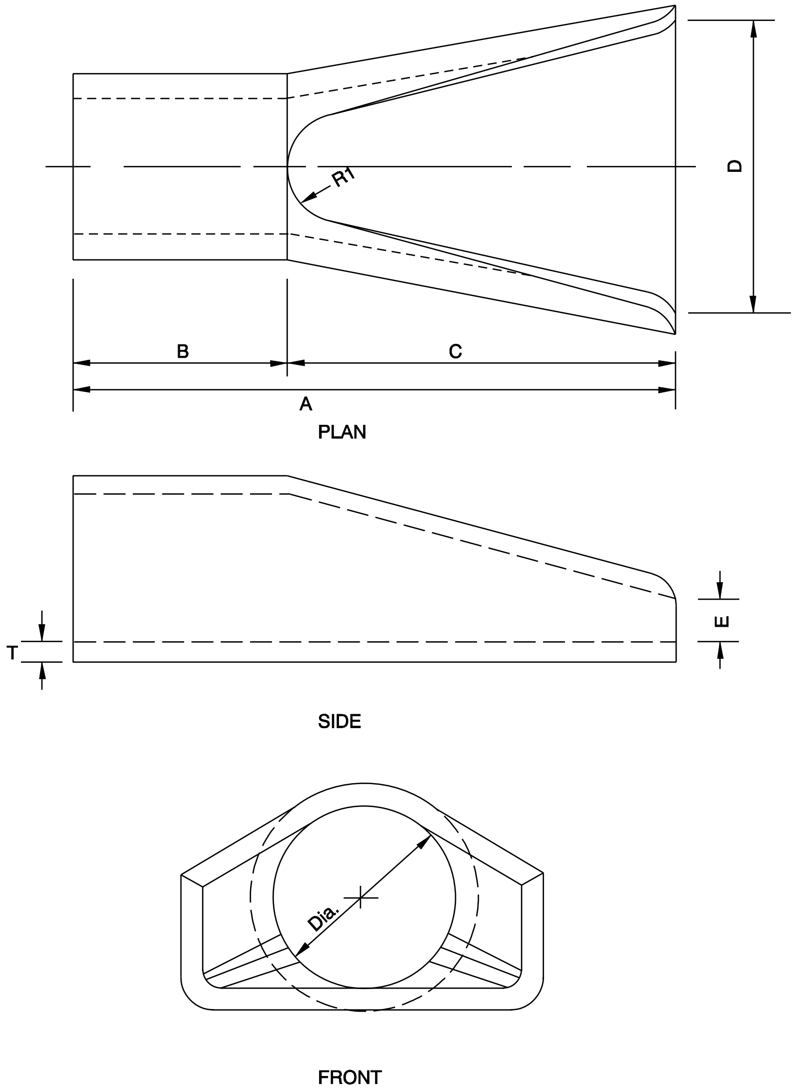
			UNSUBMERGED			SUBMERGED	
SHAPE & MATERIAL	**NOMOGRAPH (Appendix A)**	**INLET EDGE DESCRIPTION**	**EQUATION FORM**	**K**	**M**	**c**	**Y**
Circular Concrete	Chart 1	Square edge w/headwall	1	0.0098	2.0	0.0398	0.67
		Groove end w/ headwall		.0078	2.0	.0292	.74
		Groove end projecting		.0045	2.0	.0317	.69
Circular CMP	Chart 3	Headwall	1	.0078	2.0	.0379	.69
		Mitered to slope		.0210	1.33	.0463	.75
		Projecting		.0340	1.50	.0553	.54
Circular	Chart 6	Beveled ring, 45º bevel	1	.0018	2.50	.0300	.74
		Beveled ring, 33.7º bevel		.0018	2.50	.0243	.83
Rectangular Box	Chart 10	30º to 75º wingwall flare	1	.026	1.0	.0385	.81
		90º and 15º wingwall flare		.061	0.75	.0400	.80
		0º wingwall flare		.061	0.75	.0423	.82
Rectangular Box	Chart 11	45º wingwall flare d=.043D	2	.510	.667	.0309	.80
		18º to 33.7º wingwall flare d=.083D		.486	.667	.0249	.83
Rectangular Box		90º headwall w/3/4” chamfer	2	.515	.667	.0375	.79
		90º headwall w/45º bevel		.495	.667	.0314	.82
		90º headwall w/33.7º bevel		.486	.667	.0252	.865
Rectangular Box		¾” chamfers; 45º skewed headwall	2	.522	.667	.0402	.73
		¾” chamfers; 30º skewed headwall		.533	.667	.0425	.705
		¾” chamfers; 15º skewed headwall		.545	.667	.04505	.68
		45º bevels; 10º – 45º skewed headwall		.498	.667	.0327	.75

TABLE 9-2 CONSTANTS FOR INLET CONTROL DESIGN EQUATIONS (cont)

			UNSUBMERGED			SUBMERGED	
SHAPE & MATERIAL	**NOMOGRAPH (Appendix A)**	**INLET EDGE DESCRIPTION**	**EQUATION FORM**	**K**	**M**	**c**	**Y**
Rectangular Box 3/4" Chamfers		45º non-offset wingwall flare	2	.497	.667	.0339	.803
		18.4º non-offset wingwall flare		.493	.667	.0361	.806
		18.4º non-offset wingwall flare 30º skewed barrel		.495	.667	.0386	.71
Rectangular Box Top bevels		45º wingwall flares – offset	2	.497	.667	.0302	.835
		33.7º wingwall flares – offset		.495	.667	.0252	.881
		18.4º wingwall flares - offset		.493	.667	.0227	.887
C M Boxes		90º headwall	1	.0083	2.0	.0379	.69
		Thick wall projecting		.0145	1.75	.0419	.64
		Thin wall projecting		.0340	1.5	.0496	.57
Horizontal Ellipse Concrete		Square edge with headwall	1	.0100	2.0	.0398	.67
		Groove end with headwall		.0018	2.5	.0292	.74
		Groove end projecting		.0045	2.0	.0317	.69
Vertical Ellipse Concrete		Square edge with headwall	1	.0100	2.0	.0398	.67
		Groove end with headwall		.0018	2.5	.0292	.74
		Groove end projecting		.0095	2.0	.0317	.69
Pipe Arch 18” Corner Radius CM	Chart 13	90º headwall	1	.0083	2.0	.0496	.57
		Mitered to slope		.0300	1.0	.0463	.75
		Projecting		.0340	1.5	.0496	.53

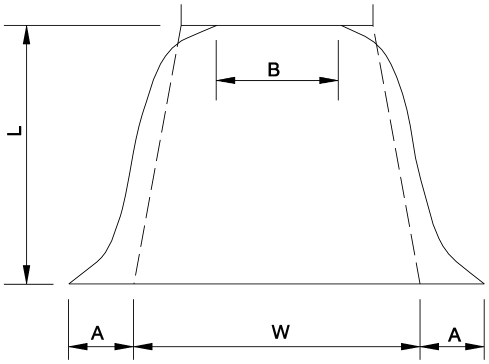
TABLE 9-2 CONSTANTS FOR INLET CONTROL DESIGN EQUATIONS (cont)

			UNSUBMERGED			**SUBMERGED**	
SHAPE & MATERIAL	**NOMOGRAPH (Appendix A)**	**INLET EDGE DESCRIPTION**	**EQUATION FORM**	**K**	**M**	**c**	**Y**
Pipe Arch 18” Corner Radius CM	Chart 14	Projecting	1	.0296	1.5	.0487	.55
		No bevel		.0087	2.0	.0361	.66
		33.7º Bevel		.0030	2.0	.0264	.75
Pipe Arch 31” Corner Radius CM	Chart 15	Projecting	1	.0296	1.5	.0487	.55
		No bevel		.0087	2.0	.0361	.66
		33.7º Bevel		.0030	2.0	.0264	.75
Arch CM	Chart 18 – Chart 20	90º headwall	1	.0083	2.0	.0379	.69
		Mitered to slope		.0300	2.0	.0463	.75
		Thin wall projecting		.0340	1.5	.0496	.57
Circular		Smooth tapered inlet throat	2	.534	.555	.0196	.89
		Rough tapered inlet throat		.519	.64	.0289	.90
Elliptical Inlet Face		Tapered inlet-beveled edge	2	.536	.622	.0368	.83
		Tapered inlet-square edge		.5035	.719	.0478	.80
		Tapered inlet-thin edge projecting		.547	.80	.0598	.75
Rectangular		Tapered inlet throat	2	.475	.667	.0179	.97
Rectangular Concrete		Side tapered-less favorable edge	2	.56	.667	.0466	.85.
		Side tapered-more favorable edge		.56	.667	.0378	.87
Rectangular Concrete		Side tapered-less favorable edge	2	.50	.667	.0466	.65
		Side tapered-more favorable edge		.50	.667	.0378	.71

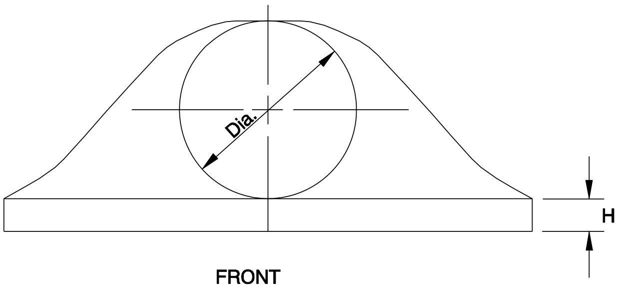


Pipe Dia. (in.)	A (in.)	B (in.)	C (in.)	D (in.)	E (in.)	R1 (in.)	T (in.)
24	73.5	30	43.5	48	9.5	14	3
60	99.0	39	60.0	96	35	24	6

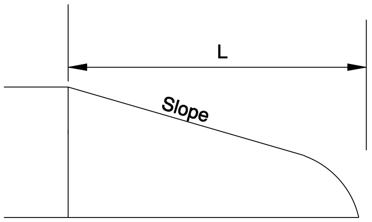
Figure 9-12 Prefabricated Concrete End Section Tested by K-TRANS



PLAN



FRONT



SIDE

Pipe Dia. (in.)	A (in.)	B (in.)	H (in.)	L (in.)	W (in.)	SLOPE
24	10	13	6	41	48	2.5:1
60	18	33	12	87	114	2:1

Figure 9-13 Prefabricated Metal End Section Tested by K-TRANS

9.18.5.3 Inlet Control Nomographs

Inlet control nomographs for many culverts are included in Appendix A. These nomographs are sufficiently accurate for most design purposes. They are not, however, as accurate as the equations. In formulating inlet and outlet control design nomographs in Appendix A, a certain degree of error is introduced into the design process. This error is due to the fact that the nomograph construction involves graphical fitting techniques resulting in scales which do not exactly match the equations.

Most of the nomographs are from FHWA publications. They have precisions of ±10 percent of the equation values in terms of headwater (inlet control) or head loss (outlet control). The inlet control nomographs for the prefabricated concrete and metal end sections, and the safety end section were developed by ODOT based on the K-TRANS equations listed previously in this chapter. Their precision is estimated to be ± 10 percent. The aluminum structural plate conduit nomographs were provided by Kaiser Aluminum, and their precision is estimated to be ±5 percent.

Instructions for Use

1. To determine **headwater (HW)**; given Q, and size and type of culvert.

   a. Connect with a straightedge the given culvert diameter or height, D and the discharge, Q, or Q/B for box culverts; mark intersection of straightedge on HW/D scale marked (1).

   b. If HW/D scale marked (1) represents entrance type used, read HW/D on scale (1). If another of the three entrance types listed on the nomograph is used, extend the point of intersection in (a) horizontally to scale (2) or (3) and read HW/D.

   c. Compute HW by multiplying HW/D by D.

2. To determine **Discharge (Q)** per barrel; given HW, and size and type of culvert.

   a. Compute HW/D for given conditions.

   b. Locate HW/D on scale for appropriate entrance type. If scale (2) and (3) is used, extend HW/D point horizontally to scale (1).

   c. Connect point on HW/D scale (1) as found in (b) above and the size of culvert on the left scale. Read Q or Q/B on the discharge scale.
   d. If Q/B is read in (c) multiply by B (span of box culvert) to find Q.

3. To determine **culvert size**; given Q, allowable HW and type of culvert.

a. Using a trial size, compute HW/D.

b. Locate HW/D on scale for appropriate entrance type. If scale (2) or (3) is used, extend HW/D point horizontally to scale (1).

c. Connect point on HW/D scale (1) as found in (b) above to given discharge and read diameter, height, or size of culvert required for HW/D value.

d. If D is not that originally assumed, repeat procedure with a new D.

9.19 Culverts Flowing in Outlet Control

All factors influencing culvert performance in inlet control also influence culverts in outlet control. In addition, the barrel characteristics (roughness, area, shape, length, and slope) and the tailwater elevation affect culvert performance in outlet control (Table 9-1).

The **barrel roughness** is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient such as the Manning "n" value. Typical Manning "n" values for culverts are presented in **Chapter 8**, Appendix A.

The **barrel area** and **barrel shape** are self-explanatory.

The **barrel length** is the length of the full barrel section from the entrance to the exit of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

The **barrel slope** is the actual slope of the culvert barrel. The barrel slope is often the same as the natural stream slope.

The **tailwater elevation** is based on the downstream water surface elevation. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation.

9.19.1 Outlet Control Examples

Various outlet control flow conditions are illustrated in Figure 9-14. The control section is at the outlet end of the culvert or further downstream in all cases. The flow in the barrel is subcritical for the partial flow situations.

Condition 9-14a represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is often assumed in calculations, but seldom actually exists.

Condition 9-14b depicts the outlet submerged with the inlet unsubmerged. For this case, the headwater depth is shallow so that the inlet crown is exposed as the flow contracts into the culvert.

Condition 9-14c shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsubmerged. This is a rare condition. It requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are usually high under this condition. Critical depth must equal the barrel height for this flow condition to occur.

Condition 9-14d is more typical. The culvert entrance is submerged by the headwater and the outlet end flows freely with a low tailwater. For this condition, the barrel flows partially full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream of the outlet.

Condition 9-14e is also typical, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partially full over its entire length and the flow profile is subcritical.

9.19.2 Outlet Control Hydraulics

This section provides a method to accurately determine headwater depth for culverts flowing full as depicted in Figures 9-14a, 9-14b, and 9-14c. The procedure gives an approximate solution for a free water surface condition throughout the barrel length as shown in Figure 9-14e, or full barrel flow over part of its length as shown in Figure 9-14d. An exact solution to these flow conditions requires calculating the water surface profile through the culvert barrel.

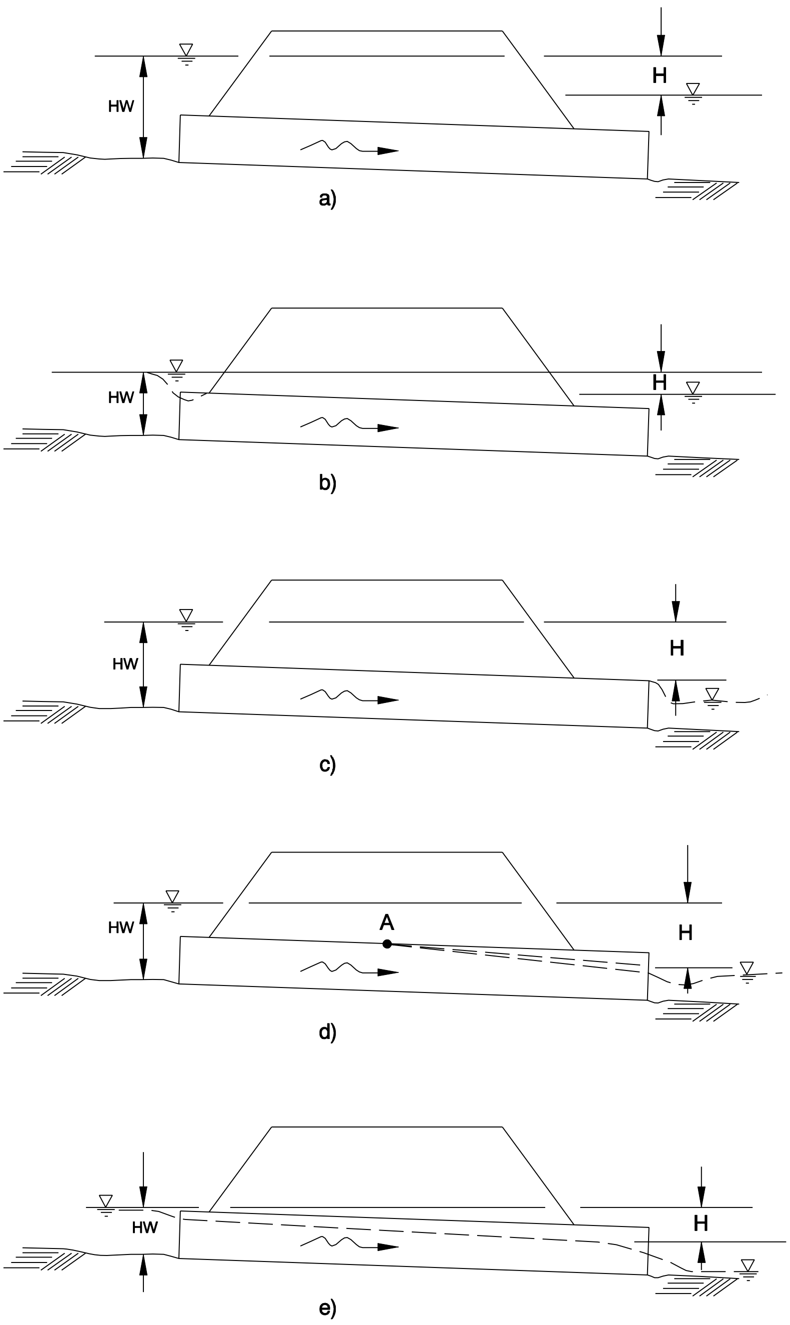


Figure 9-14 Outlet Control Types

Outlet control flow conditions are calculated based on the principle of conservation of energy. The total energy (H_L) required to pass the flow through the culvert barrel is shown in Figure 9-15 and expressed in Equation 9-5. It is made up of three major components. These components are usually expressed in feet of water (head) and include the entrance loss, the friction loss through the barrel, and the exit loss. Other losses, such as bend losses and junction losses, should be included as appropriate.

$$H_L = H_e + H_f + H_o + H_b + H_j \qquad \text{(Equation 9-5)}$$

Where:

H_L = total energy head in feet,
H_e = entrance loss in feet,
H_f = friction loss through the barrel in feet,
H_o = exit loss in feet,
H_b = bend loss in feet, and
H_j = junction loss in feet.

The entrance loss is a function of the velocity head in the barrel ($V^2/2g$) times an entrance loss coefficient K_e. Values of K_e based on various inlet configurations are given in Table 9-3.

$$H_e = K_e \frac{V^2}{2g} \qquad \text{(Equation 9-6)}$$

Where:

K_e = entrance loss coefficient,
V = velocity of full flow in the culvert barrel in feet per second, and
g = gravitational acceleration, 32.2 feet per second squared.

The friction loss in the barrel is also a function of the velocity head. Based on the Manning equation, the friction loss is:

$$H_f = \left(\frac{29n^2L}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right) \qquad \text{(Equation 9-7)}$$

Where:

n = Manning roughness coefficient (Chapter 8 Appendix A),
L = length of the culvert barrel in feet,

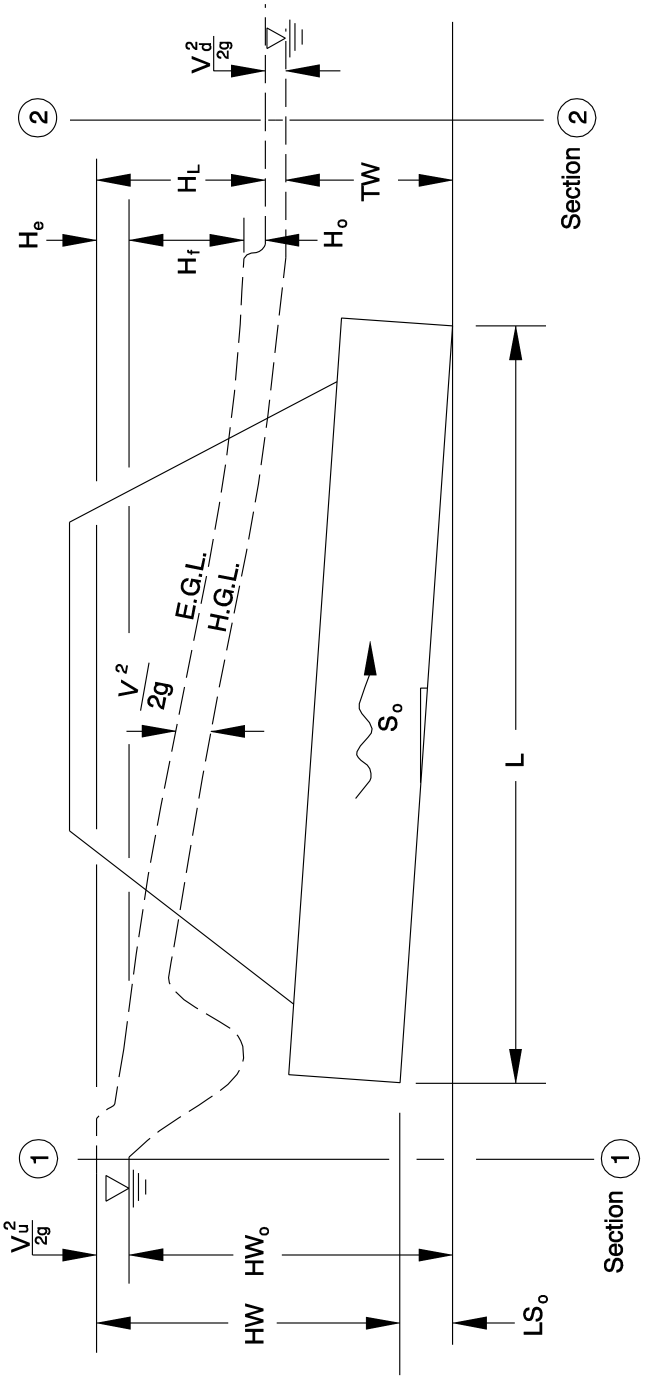


Figure 9-15 Full Flow Energy and Hydraulic Grade Lines

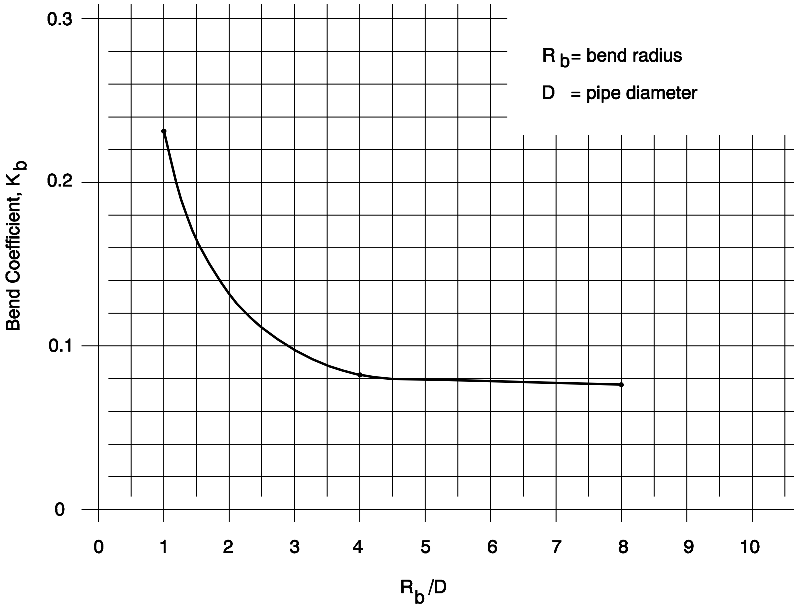
TABLE 9-3 ENTRANCE LOSS COEFFICIENTS

Outlet control, full or partially full entrance head loss

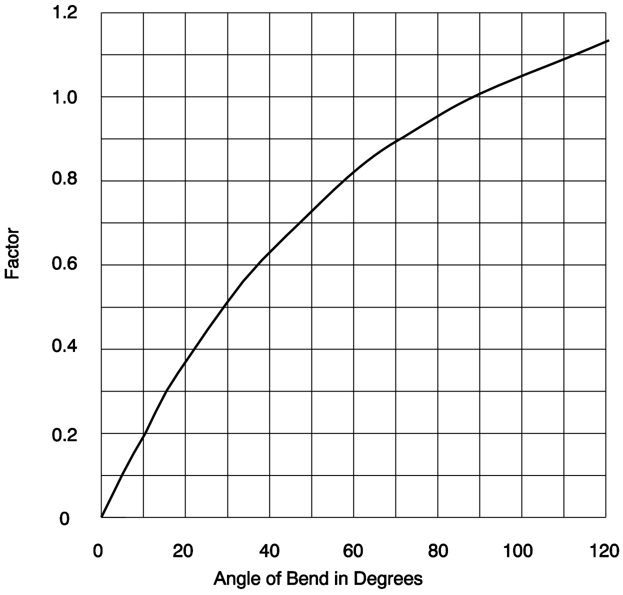
$H_e = K_e (V^2/2g)$

Type of Structure and Design of Entrance	Coefficient K_e
Pipe, Concrete	
Projecting from fill, socket end (groove-end)	0.2
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe (groove end)	0.2
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Mitered to conform to fill slope	0.7
* End section conforming to fill slope	0.5
End section conforming to fill slope (see Figure 9-12), dia ≤ 54 in.	0.35
End section conforming to fill slope (see Figure 9-12), dia > 60 in.	0.30
Beveled edges, 33.7º or 45º bevels	0.2
Side- or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to conform to fill slope, paved or unpaved slope	0.7
* End section conforming to fill slope	0.5
End section conforming to fill slope (see Figure 9-13), dia ≤ 54 in.	0.35
End section conforming to fill slope (see Figure 9-13), dia > 60 in.	0.30
Safety end section with safety bars, dia = 24 in	0.65
Safety end section with safety bars, dia = 60 in	0.85
Beveled edges, 33.7º or 45º bevels	0.2
Side- or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, or beveled edges on 3 sides.	0.2
Wingwalls at 30º to 75º to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of 1/12 barrel dimension, or beveled top edge	0.2
Wingwall at 10º to 25º to barrel	
Square-edged at crown	0.5
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Side- or slope-tapered inlet	0.2

* Note: "End Section conforming to fill slope," made of either metal or concrete, are the sections commonly available from manufacturers. Limited hydraulic tests indicate they are equivalent in operation to a headwall in both inlet and outlet control.



a) Bend Coefficient for 90° bends



b) Factors for Other Than 90° Bends

Figure 9-16 Bend Loss Coefficients

R = hydraulic radius of the full culvert barrel, A/P, in feet (**Chapter 8 Appendix B**),
A = full cross-sectional area of the barrel in square feet (**Chapter 8 Appendix B**), and
P = wetted perimeter of the full barrel in feet (**Chapter 8 Appendix B**).

The exit loss is a function of the change in velocity heads between the outlet of the culvert barrel and the downstream channel. For a sudden expansion such as an endwall, the exit loss is:

$$H_o = 1.0\left(\frac{V^2}{2g} - \frac{V_d^2}{2g}\right) \qquad \text{(Equation 9-8)}$$

Where:
V_d = channel velocity downstream of the culvert in feet per second

The downstream velocity is usually neglected, in which case the exit loss is equal to the full flow velocity head in the barrel. This depicts the case of a culvert discharging into a pool. The outlet loss equation based on this assumption is:

$$H_o = 1.0\frac{V^2}{2g} \qquad \text{(Equation 9-9)}$$

Bend losses are also a function of velocity head in the culvert barrel and a bend loss coefficient K_b. Values of K_b are obtained from Figure 9-16. To determine K_b, first determine the bend coefficient for a 90º bend from Figure 9-16a, and then apply the appropriate adjustment factor from Figure 9-16b. Bend losses can be calculated using the following equation:

$$H_b = K_b\frac{V^2}{2g} \qquad \text{(Equation 9-10)}$$

Where:
K_b = bend loss coefficient

Junction losses are considered where appropriate. Examples of junctions and methods to calculate junction losses are described in **Chapter 13**. Usually it is assumed the pipes entering and leaving the junction are full when calculating junction losses for outlet control.

Inserting the above relationships for entrance loss, friction loss, bend loss and exit loss into Equation 9-5, the following equation for head loss is obtained:

$$H_L = \left(1 + K_e + K + \frac{29n^2L}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right) + H \qquad \text{(Equation 9-11)}$$

Since most culverts have no bend or junction losses, the equation can be reduced to:

$$H_L = \left(1 + K_e + \frac{29n^2L}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right) \qquad \text{(Equation 9-12)}$$

Figure 9-15 shows the energy grade line and the hydraulic grade line for full flow in a culvert barrel. The energy grade line represents the total energy at any point along the culvert barrel. HW is the depth from the inlet invert to the energy grade line. The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel straight lines separated by the velocity head except in the vicinity of the inlet where the flow passes through a contraction.

The headwater and tailwater condition as well as the entrance, friction, and exit losses are also shown in Figure 9-15. Equating the total energy at sections 1 and 2, upstream and downstream of the culvert barrel, the following relationship results:

$$HW_o + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \qquad \text{(Equation 9-13)}$$

Where:

HW_o = headwater depth above the outlet invert in feet,

V_u = approach velocity in feet per second,

TW = tailwater depth above the outlet invert in feet,

V_d = channel velocity downstream of the culvert in feet per second, and

H_L = sum of all losses in feet.

In most cases the approach velocity (V_u) and the downstream velocity (V_d) can be neglected. This depicts the case of a culvert discharging from pool to pool. When the upstream and downstream velocity head are assumed to be zero, the hydraulic gradeline and energy gradeline at Section 1 and Section 2 are coincident. Equation 9-13 then reduces to:

$$HW_o = TW + H_L \qquad \text{(Equation 9-14)}$$

When the approach velocity (V_u) is assumed to be zero

$$HW_o = HW + (L)(S) \qquad \text{(Equation 9-15)}$$

Where:

S = barrel slope in feet per foot

Substituting Equation 9-15 into Equation 9-14, the equation for headwater depth, HW, becomes

$$HW = TW + H_L - (L)(S) \qquad \text{(Equation 9-16)}$$

If it is desired to include the approach and/or downstream velocities, use Equation 9-8 for exit losses and Equation 9-13 instead of Equation 9-16 to calculate the headwater.

To accurately determine the headwater depth for the conditions shown in Figure 9-14d and 9-14e, the water surface profile through the culvert barrel must be calculated. Fortunately an approximate method of computation is available as explained below. The approximate method gives satisfactory results for headwater depths above 0.75D, where D is the height of culvert barrel.

For the condition shown in Figure 9-14d, the culvert must flow full for part of its length. The hydraulic gradeline for the portion of the length in full flow will pass through a point where the water breaks with the top of the culvert as represented by point A in Figure 9-14d. Backwater computations show that the hydraulic gradeline, if extended as a straight line, will cut the plane of the outlet cross section at a point above critical depth (water surface). This point is at a height approximately equal to one half the distance between critical depth and the crown of the culvert $[(d_c+D)/2]$. The elevation of this point can be used as an equivalent hydraulic gradeline; and H_L, as determined by Equation 9-12 or the nomographs, can be added to this elevation to find the water surface elevation of the headwater pool.

The full flow conditions for part of the barrel length, Figure 9-14d, will exist when: the headwater depth HW is equal to or greater than the quantity:

$$HW \geq D + (1 + K_e)\left(\frac{V^2}{2g}\right) \qquad \text{(Equation 9-17)}$$

Where:

HW = headwater depth in feet,

V = velocity of full flow in the culvert barrel in feet per second,

K_e = entrance loss coefficient, and

D = inside height of the culvert in feet.

If the headwater is less than the above value, a free water surface as shown in Figure 9-14e, will extend through the culvert barrel.

Headwater depth HW can be expressed by a common equation for all outlet-control conditions, including all depths of tailwater. This is accomplished by designating the vertical dimension from the culvert invert at the outlet to the elevation from which H is measured as h_o. The headwater depth HW equation is:

$HW = H_L + h_o - (L)(S)$ (Equation 9-18)

Where:

H_L = sum of all losses in feet computed by Equation 9-12 or from the nomographs,
h_o = tailwater depth or $(d_c+D)/2$, in feet, which ever is greater (see Note),
L = length of the culvert barrel in feet, and
S = barrel slope in feet per foot.

Note:

h_o will equal the tailwater depth for conditions shown in Figure 9-14a, 9-14b, and 9-14c.
h_o will either equal the tailwater depth or $(d_c+D)/2$, whichever is greater, for the conditions shown in Figure 9-14d and 9-14e.

9.19.3 Outlet Control Nomographs

Outlet control nomographs solve the equation

$$H = \left(1 + K_e + \frac{29n^2L}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right)$$

for head H when the culvert barrel flows full for its entire length. They are also used to determine head H for some part-full flow conditions with outlet control. These nomographs do not give a complete solution for finding headwater HW, since they only give H_L as calculated in Equation 9-12. Headwater is calculated by incorporating H into Equation 9-18, as follows:

$HW = H_L + h_o - (L)(S)$ (see discussion for "Outlet Control Hydraulics").

Instructions for Use

1.0 To determine **head H** given a culvert size and a discharge Q.

a. Locate the appropriate nomograph in Appendix A for the type of culvert selected. Find K_e for the entrance type in Table 9-3. Determine culvert barrel Manning's "n" value using **Chapter 8** Appendix A or methods in **Chapter 8**.

b. Begin in nomograph solution by locating the starting point on the length scale. To locate the proper starting point on the length scales, follow the instructions below:

(1) If the n value of the nomograph corresponds to that of the culvert being used, select the length curve for the proper K_e and locate the starting point at the given culvert length. If a K_e curve is not shown for the selected K_e, see (2) below. If the n value for the culvert selected differs from that of the nomograph, see (3) below.

(2) For the n of the nomograph and a K_e intermediate between the scales given, connect the given length on adjacent scales by a straight line and select a point on this line spaced between the two chart scales in proportion to the K_e values.

(3) For a different roughness coefficient (n_l) than that of the chart n, use the length scales shown with an adjusted length L_1, calculated by the formula:

$$L_1 = L\left(\frac{n_1}{n}\right)^2$$

c. Using a straightedge, connect the point on the length scale to the size of the culvert barrel and mark the point of crossing on the “turning line”. See Instruction 2.0 for size considerations for a rectangular box culvert.

d. Pivot the straightedge on this point on the turning line and connect with the discharge. Read the head in feet on the head (H) scale. For values beyond the limit of the chart scales, find H by solving Equation 9-12.

2.0 To use the box culvert nomograph for full-flow for other than square boxes.

a. Compute the cross-sectional area of the rectangular box.

b. Connect the proper point (see instruction 1.0) on the length scale to the barrel area and mark the point on the turning line. See Note.

Note: The area scale on the nomograph is calculated for barrel cross-sections with span B twice the height D; its close correspondence with area of square boxes assures it may be used for all sections intermediate between square and B = 2D or B = 1/2D. For other box proportions, use Equation 9-12 for more accurate results.

c. Pivot the straightedge on this point on the turning line and connect with the discharge. Read the head in feet on the head (H) scale.

9.19.4 Critical Depth

Critical Depth (d_c) can be determined by using the mathematical equations in **Chapter 8** or by the critical depth charts in **Chapter 8** Appendix B. **Critical depth should never be greater than the diameter of the pipe or the rise of the box.**

9.20 Procedure for Selection of Culvert Size

Step 1: List the following data on the Culvert Design Sheet (Appendix B).

a. The hydrological data which includes the method used to compute the peak flow, the drainage area, the natural stream slope, the natural channel shape, the design flood and the check flood.

b. The allowable headwater depth, in feet, as discussed in Section 9.17.

c. The inlet and outlet elevations in feet.

d. The barrel slope in feet per foot.

e. The approximate barrel length in feet.

f. The type of culvert for first trial selection, including barrel material, barrel cross-sectional shape and entrance type.

Step 2: Determine the first trial size culvert.

Since the procedure given is one of trial and error, the initial trial size can be determined in several ways:

a. by arbitrary selection,

b. by using an approximating equation such as Q/10 = A (where A = end area) from which the trial culvert dimensions are determined, or

c. by using inlet control nomographs for the culvert type selected. If this method is used, an HW/D must be assumed, say HW/D = 1.5, and using the given Q, a trail size is determined.

If any trial size is too large in dimension because of limited height of embankment or availability of size, multiple culverts may be used by dividing the discharge equally between the number of barrels used. Raising the embankment height or the use of pipe-arch and box culverts with width greater than height should be considered. Final selection should be based on an economic analysis.

Step 3: Find headwater depth for trial size culvert.

a. Assuming INLET CONTROL

i. Using the trial size from Step 2, find the headwater depth (HW) by use of the appropriate inlet control nomograph. Tailwater (TW) conditions are to be neglected in this determination. HW in this case is found by multiplying HW/D obtained from the nomographs by the height of culvert D.

ii. If HW is greater or less than allowable, try another trial size until HW is acceptable for inlet control before computing HW for outlet control.

b. Assuming OUTLET CONTROL

i. Calculate the depth of tailwater TW, in feet, above the invert at the outlet for the design flood condition in the outlet channel. (See general discussion on tailwater)

ii For a tailwater elevation <u>equal to or greater than</u> the top of the culvert set h_o equal to TW and HW by the following equation (Equation 9-18).

$$HW = H + h_o - LS$$

Where:

HW = vertical distance in feet from culvert invert (flow line) at entrance to the pool surface,
H = head loss in feet as determined from the appropriate nomograph or Equation 9-12,
h_o = vertical distance in feet from culvert invert at outlet to the hydraulic grade line (in this case h_o equals TW, measured in feet, above the culvert invert),
S = barrel slope in feet per foot, and
L = culvert barrel length in feet

iii. For tailwater TW elevations <u>less than</u> the top of the culvert, find headwater HW by Equation 14 as in b(ii) above except that

$$h_o = \frac{(d_C + D)}{2} \text{ or TW, whichever is greater.}$$

Where:

d_c = critical depth in feet. Note: **d_c cannot exceed D** and can be determined from the methods in **Chapter 8** or the charts in **Chapter 8** Appendix B.
D = Height of culvert opening in feet.

Note: Headwater depth determined in Step3.b.iii becomes increasingly less accurate as the headwater computed by this method falls below the value D + (1 + K_e) $V^2/2g$. (See discussion under "Culvert Flowing Full with Outlet Control.")

c. Compare the headwaters found in Step 3a and Step 3b (Inlet Control and Outlet Control). The higher headwater governs and indicates the flow control existing under the given conditions for the trial size selected.

d. If outlet control governs and the HW is higher than is acceptable, select a larger trial size and find HW as instructed under Step 3b. (Inlet control need not be checked, since the smaller size was satisfactory for this control as determined under Step 3a).

Step 4: Try a culvert of another type or shape and determine size and HW by the above procedures.

Step 5: Compute outlet velocities for size and types to be considered in selection and determine need for channel protection. Use procedures in **Chapter 11**.

Step 6: Determine invert protection**.**

Use guidelines in **Chapter 5**.

Step 7: Record final selection of culvert with size, type, required headwater, outlet velocity, and economic justification.

9.21 Example

A culvert at a new roadway crossing must be designed to pass the 50-year event with a 100-year check flood. From the hydrologic analysis the peak flow is determined to be 100 cubic feet per second and the check flow is 120 cubic feet per second. From the field location survey, the roadway designer, and the Region Environmental Coordinator, the following information was obtained:

Design a circular pipe culvert. Consider alternate materials. These could be concrete, corrugated metal, or smooth metal pipe with outward helical spiral ribs. Plastic pipe could be used if the barrel diameter is equal to or less than 60 inches. Steel or aluminum metal pipes could be used. Corrugated metal pipe, if used, would have standard 2-2/3 by 1/2-inch corrugations.

Base the design headwater elevation on the subgrade elevation (507.0 feet) with two feet of freeboard (507.0 – 2.0 = 505.0 feet). Set the inlet at the natural streambed elevation. The overtopping elevation is the roadway surface. It should not be overtopped by the 100-year flood. Determine outlet velocities using methods in **Chapter 11** and the need for invert abrasion protection using the guidelines in **Chapter 5**. Fill out culvert Design Sheets for the alternate materials. These sheets are shown on Plates 1, 2, 3.

The size of a corrugated metal pipes is determined first, as shown on Plate 1. The initial selection is a 48-inch diameter pipe. It produces excessive headwater depths during inlet control. This size is too small, and no further calculations are made. A 54-inch diameter pipe is tried next. Inlet and outlet control elevations are calculated and compared for both the design and check floods. The 54-inch diameter pipe size is adequate for both floods and it flows under inlet control.

The need for invert abrasion protection is determined for the corrugated pipe, as shown in Plate 2. Methods in **Chapter 5** are used, and the culvert has a “Low” abrasion level. An additional increment of wall thickness or polymer coating is needed to resist abrasion. Additional protection may be needed to resist corrosion, and it should be considered before the culvert materials are listed on the Pipe Data Sheet. This is discussed in **Chapter 5**.

Inlet Elevation:		500.0 feet
Stream Slope:		0.02 feet per foot
Tailwater computed from Manning's:		50-year = 3.0 feet
		100-year = 3.4 feet
Approximate Culvert Length:		70 feet
Surface of Subgrade Elevation:		507.0 feet
Source of Discharge:		Overland runoff and highway drainage
Waterway bed material:		Silts, sands, and gravels up to ½ inch in diameter
Abrasion history of existing culvert:		Galvanized CMP in-place for 45 years. Some invert perforation due to corrosion and abrasion
Fish passage		Not needed
End treatment		Mitered ends with slope paving, based on roadway design criteria

Outlet velocities are calculated for the design and check floods using methods in **Chapter 11**. These are the "brink velocities" discussed in the chapter. The calculations are shown on Plate 2.

The size of a smooth walled pipe is determined next, as shown in Plate 3. Smooth walled pipes are concrete pipe, smooth walled metal pipe with outward helical spiral ribs, corrugated polyethylene Type D or S pipe, or smooth inner wall polyvinyl chloride pipe (SWPVCP).

Inlet control headwater elevation equations and nomographs are not included in Appendix A for mitered ends on smooth walled pipes. The nomograph scale (2) in Appendix A, Chart 3 for mitered ends on corrugated metal pipes will be used to evaluate the smooth walled pipes under inlet control. The outlet velocities calculations are the same as those for the corrugated metal pipe shown in Plate 2.

9.22 Specialized Culverts

The preceding sections of this chapter discuss the basics of culvert location and design. This section includes additional information about culverts used in special applications.

9.22.1 Culverts with Inlet Boxes and Access Holes

Inlet boxes and access holes can be used to reduce the barrel slope and lower outlet velocity. These features can also be used to provide clearance over the top of the barrel for utilities. This is shown in Figure 9-17.

The hydraulic losses caused by inlets and access holes should be calculated and considered in the design. Grate inlet, box, and access hole losses are discussed in **Chapter 13**. Sediment transport, debris passage, and fish passage should also be considered. These culverts do not provide passage for significant amounts of sediment or debris. They do not provide fish passage.

9.22.2 Fish Passage Culverts

It should be assumed that fish passage will be required at all proposed highway-stream crossing projects regardless of stream size unless told otherwise by the ODOT Region Environmental Coordinator. Fish passage policy is discussed in **Chapter 3**.

9.22.3 Open-Bottom Culverts

Open-bottom culverts are different than typical closed-conduit culverts such as circular pipes, arch-pipes, and boxes because they span the stream channel and they have no bottom. Their most common use is to provide fish passage because, if properly designed, the natural streambed in these culverts does not hinder fish movement. Another less common use, especially in the larger sizes, is to provide cost-effective alternatives to single-span bridges.

Open-bottom culverts are available in many configurations. One type is the bottomless semicircular arch shown in Figure 9-1. These arches are made from corrugated metal structural plates that are bolted together. They are available in span widths from 6 feet to 25 feet in steel, and span widths of 5 feet to 30 feet in aluminum.

Another type of open-bottom culvert is the 3-sided box shown in Figure 9-1. These boxes are made from reinforced concrete or corrugated metal structural plates bolted together. Steel 3-sided boxes are available in span widths from 9 feet 2 inches to 25 feet 5 inches, aluminum boxes are available in spans from 8 feet 9 inches to 25 feet 5 inches, and concrete 3-sided boxes are available in spans from 12 feet to 42 feet.

Open-bottom culverts of all sizes are “large culverts” as defined in Section 9.3. As a result, the hydraulic study and documentation requirements that apply to large culverts throughout this manual also apply to these culverts. Open-bottom culverts require the following additional documentation.

9.22.3.1 Hydraulic Study and Documentation

1. Crown and channel elevations at the culvert ends. These elevations are listed in lieu of the invert elevations in the description of a closed-conduit culvert. The crown is the highest point on the inside of the culvert, as shown in Figure 9-18.

2. Hydraulic data tables for each suitable shape. The hydraulic characteristics of open-bottom culverts of similar rise and span can vary considerably depending on the waterway shape.

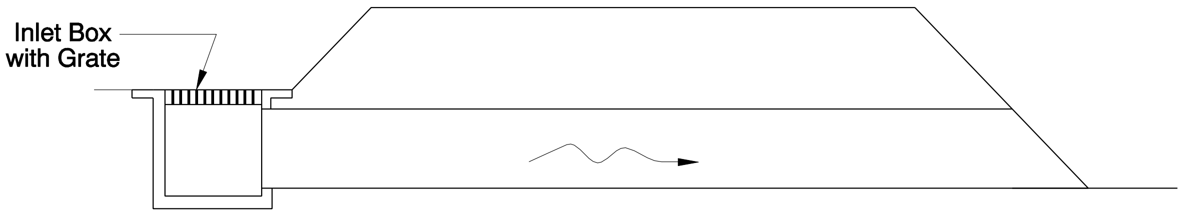
3. A description of predicted scour types including elevations. If the channel is expected to degrade or aggrade during the design life of the structure, this should be noted. The expected change in the channel elevation should be listed.

4. If the channel is expected to degrade, the foundation recommendations should take this into consideration. If the channel is expected to aggrade, the crown elevations or the culvert size should consider this. These aspects of the design should be documented.

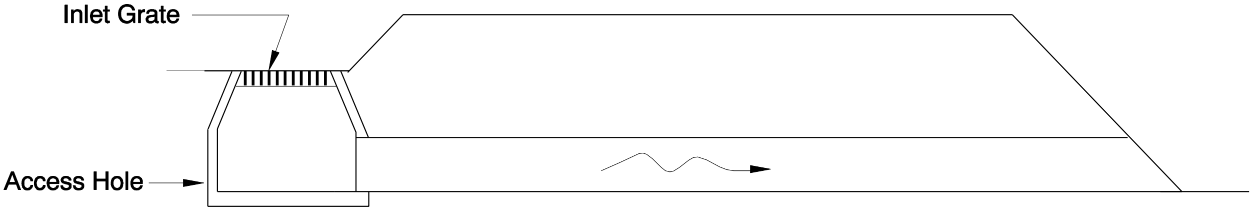
5. A description of the footing protection. If riprap is used, the class of riprap should be noted, whether or not it is to be grouted, and whether or not a filter blanket is needed under the riprap. A detail showing the approximate dimensions of the footing protection should be included. Typically, the footing elevations are not listed or shown. Usually these elevations are determined during the structural and/or foundation design.

9.22.3.2 Minimum Culvert Size

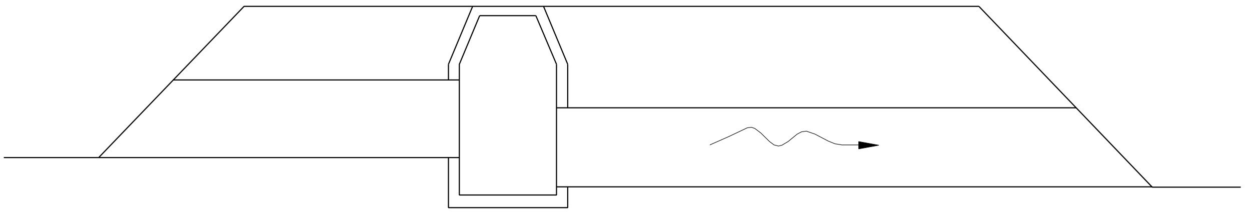
An open-bottomed culvert spans a section of the natural stream channel that is typically composed of loose material such as sands, gravels, etc. Some or all of this material may be scoured away and replaced during large floods. Typically, the loss of bed material occurs during the beginning (rising limb) of the flood and it is replaced as the flood recedes (falling limb).



a) Inlet Box



b) Access Hole with Inlet Grate



c) Access hole

Figure 9-17 Methods to Reduce Barrel Slope

The stream may deposit the bed material upstream from the inlet rather than inside the barrel if the culvert is too small to span the active stream channel. In addition, excessive scour may occur inside the barrel. As a result, care must be taken to assure that the culvert meets or exceeds the minimum culvert size requirements listed in Section 9.12.

It is important that maintenance forces have access to the inside of the culvert for inspection or repair. In addition, revetment may be needed to protect the footings in some instances, and it needs to be inspected and replaced if it is scoured away. Clearance requirements should be requested from maintenance personnel on a project by project basis. Typical clearance requirements are an 8-foot by 8-foot minimum opening width to facilitate small equipment if a scour situation develops.

9.22.3.3 End Treatment

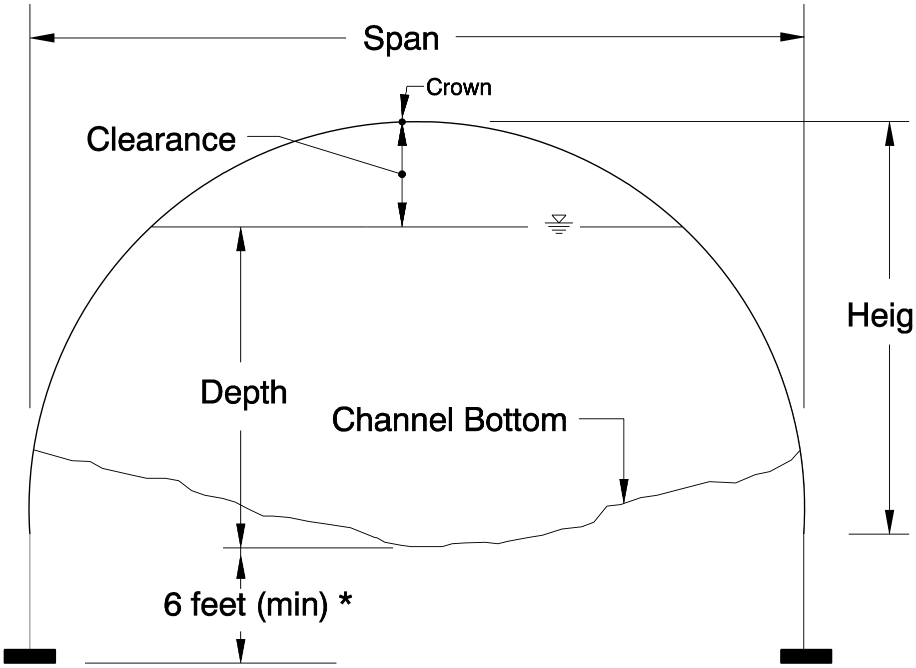
There are many open-bottom culverts on the state highway system. Sloped ends with reinforced concrete collars or slope paving are the most common end treatment for metal open-bottom arches. Headwalls and wingwalls are also used. Headwalls with wingwalls are the most common end treatment for the reinforced concrete arches.

The end treatment requirements listed in Section 9.14 also apply to open-bottom culverts. In addition, skew cut sloped ends are not permitted on corrugated metal open-bottom arches unless the end is reinforced by a concrete collar, slope paving, or similar treatment. If an arch with unskewed ends is placed on a skew, the roadway embankment should be contour graded to match the ends as shown on Standard Drawing RD320.

9.22.3.4 Hydraulic Modeling

The inlet and outlet control equations and nomographs described in Section 9.18 can be used to analyze open-bottom culverts if a scour analysis is not needed. This would apply to culverts whose footings are solidly keyed into non-erodible material and permanently protected from the scour associated with turbulent flow, high velocity flow, or pressure flow if they occur. Inlet and outlet control nomographs for many arch shapes are included in Appendix A, and hydraulic properties are listed in **Chapter 8** Appendix B. Hydraulic data for open-bottom culverts with other shapes are listed in manufacturer’s trade literature.

A step-backwater analysis is needed if scour elevations must be considered. This applies to culverts whose footings are fully or partially founded on erodible material or soils and rock with an unknown erosion resistance.



* Minimum embedment depth where footings are on erodible material. See 9.22.3.5

Figure 9-18 Clearance for Open-Bottom Culvert

The accuracy required of the hydraulic performance data also influences the study method. Open-bottom arch culverts almost always operate under outlet control, and the outlet control nomographs assume full flow within the barrel when calculating friction losses. This method tends to over estimate friction losses when the culvert barrel is flowing partially full. The step-backwater method can model and accurately calculate friction losses within a partially full barrel.

9.22.3.5 Scour

In general, open-bottom culverts with footings solidly keyed into non-erodible rock can withstand a temporary loss of streambed material due to scour during large floods. Open-bottom culverts with this type of foundation are preferred.

Occasionally open-bottom arch culverts are installed with footings on erodible material. This is done over canals, irrigation ditches, and other sites where all of these conditions can be met:

- the flows are regulated, or if not regulated, they can be predicted with certainty,
- the channel is stable in both vertical and horizontal alignment,
- debris passage is not a concern,
- there will be no hydraulic drops or jumps within the barrel or near the ends,
- clearance can be provided between the culvert crown and the water surface during the maximum predicted discharge, as shown in Figure 9-18,
- flow contraction into the culvert barrel is minimal and contraction scour is not a concern, and
- the footing bottoms are located at least six feet below the channel bottom, as shown in Figure 9-18.

Methods to predict scour in open-bottom culverts are being developed by the FHWA. Research indicates the deepest scour in open-bottom culverts occurs at the corners of the culvert inlet where the flow contracts as it enters the culvert barrel. Reports are available on the FHWA website: http://www.fhwa.dot.gov/engineering/hydraulics/scourtech/index.cfm. The conclusions and recommendations from these studies should be considered when estimating scour.

9.22.3.6 Footing Protection

Typically, the foundation of an open-bottom culvert will be one of these three types.

1. The footings for an existing culvert, the footings for an extension to an existing culvert, or the footings for a culvert proposed at a new location; are, or can be, keyed into solid non-erodible rock. Revetment is not needed to protect the footings in these cases.

2. The footings of an existing culvert are keyed into rock with questionable erosion resistance, or, it is not known with absolute certainty that the footings for a proposed extension or new culvert can be keyed into solid rock for their entire length. Cores, potholes, or other subsurface exploration indicates rock is present at footing depth. Revetment is needed in these cases to assure the footings are protected.

The footings are founded on erodible rock or loose material and the culvert meets the criteria listed in the previous subsection. In this case, the footings are protected by revetment.

A generic footing protection revetment detail is shown in Figure 9-19. The upper surface of the riprap is covered by native streambed material. This provides a natural channel bottom.

Footing protection is designed to resist hydraulic forces from the 25 or 50 year design event, or 100-year flood if the culvert is in a FEMA regulated floodway. The revetment is checked to verify it will remain intact during the more frequent of; the roadway overtopping flood or the 500-year flood.

Note: Footing protection revetment for open-bottom culverts over regulated waterways such as irrigation ditches or canals should be designed using the operating flow. The revetment should be checked to verify it can withstand the greatest flow expected in the waterway. This maximum flow may occur during a flood or storm event if the waterway intercepts and collects runoff.

Two methods of sizing revetment are recommended. They are as follows.

1. Use the tractive force method in **Chapter 15** with the following assumptions.

    a. The rock riprap specific gravity (S_s) is 2.65 unless laboratory tests on the rock indicate otherwise. Use laboratory test results if available.

    b. The angle of repose (ϕ) for riprap produced to ODOT specifications is 41 degrees.

    c. The stability factor (SF) cannot be lower than 1.6

    d. The average flow velocity (V_a) and average flow depth (d_{avg}) are for flow within the culvert.

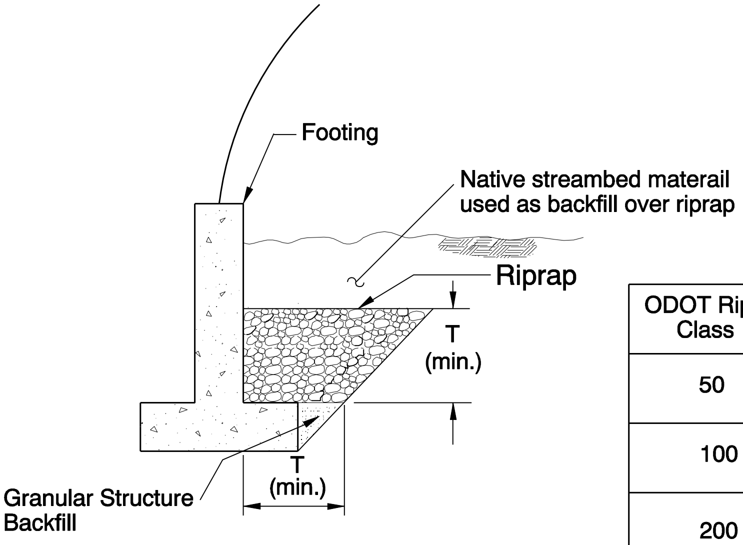
2. Use the ODOT velocity based method in **Chapter 15** with a velocity multiplier of 1.33.

3. Use the modified Isbash relationship in **Chapter 15** with the following assumptions.

    a. The coefficient "K" for vertical wall abutments is appropriate.

    b. The rock riprap specific gravity (S_s) is 2.65 unless laboratory tests on the rock indicate otherwise. Use test results if they are available.

Considerable judgment is needed in the application of these methods. The median diameter (D_{50}) of the riprap should be larger than the greater of the following: the appropriate calculated value, or two to three times bigger than the largest particles transported by the stream. ODOT riprap D_{50} values are listed in **Chapter 15**.



ODOT Riprap Class	T (ft)
50	1.0
100	1.5
200	2.0
700	3.0
2000	4.0

Figure 9-19 Typical Footing Protection Detail

9.22.4 Sag (Inverted Siphon) Culverts

A sag culvert, sometimes called an inverted siphon, is a culvert with multiple sections, as shown in Figure 9-20. The end section inverts are at the elevations of the stream flowlines, and the central section is lower than the end sections. These culverts are used to convey flow under an obstruction such as a highway, railroad, or utility. These culverts are commonly used for conveying irrigation water under highways. In these instances, the elevation changes at each end of the culvert occur in reinforced concrete boxes called "siphon boxes" where the end pipes enter the box at higher elevations than the center pipe. These culverts can provide fish passage.

These culverts can collect sediment because they are the lowest points in the stream channel. A sediment trap may be needed upstream from the culvert if the waterway conveys sediment. There should be provisions for cleaning the culvert such as manholes to allow access to the depressed central section if a sediment trap cannot be provided. The culvert can be cleaned during the non-irrigation season if it is on a canal. Standing water may need to be pumped out to clean the culvert.

Note: Difficulties in the inspection of these types of culverts maybe a concern to regulatory fish agencies. They are unlikely to be approved unless inspection access is provided to the depressed central section when fish passage is required. This could be accomplished by installing manholes to allow access to the depressed central section or providing provisions for underwater inspections. Consult with the Region Environmental Coordinator or project environmental contact.

The design of sag culverts is beyond the scope of this manual. It is discussed in detail in the culverts chapter of the Association of State Highway and Transportation Officials (AASHTO) "Model Drainage Manual."

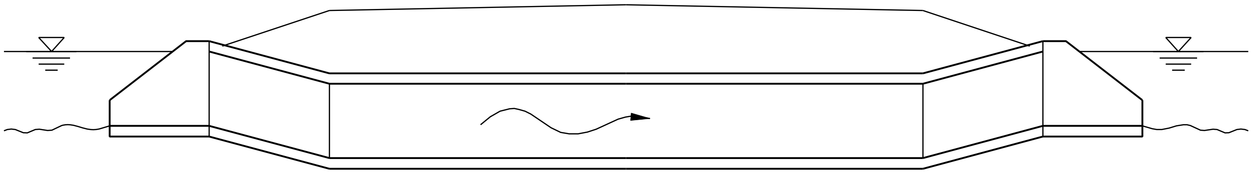


Figure 9-20 Sag (Inverted Siphon) Culvert

9.22.5 Detour Culverts, Construction Access Road Culverts, and Bypass Pipes

Detour culverts are conduits under temporary roads that carry public traffic while the highway construction is in progress. Construction access road culverts are temporary installations under roads used to get equipment to and from the site. Bypass pipes are conduits that carry flow through the construction site so work can be done "in the dry." Detour and access road culverts are usually larger pipes. Bypass pipes are often small diameter flexible pipes that can be moved as needed to keep them away from the construction activities.

Note: Many environmental constraints that apply to permanent culverts also apply to temporary installations. Consult with the Region Environmental Coordinator or project environmental contact.

The minimum end areas of detour and access road culverts are calculated by the agency and included in plans or specifications along with the period of the year when they can be used and any other requirements. Examples of typical recommendations are:

“Detour or access road culverts in place throughout the entire year should have inverts buried in the stream bottom at least one-third the culvert diameter or rise. The minimum net end area, after subtracting the area filled with streambed material, is ____ square feet.”

or

“The minimum end area for a detour or access road culvert in place from the ___ of___ through the ___ of___ is ___ square feet.”

During project development the hydraulics designer has little to no information about the detour or road access pipes. These are placed during construction by the contractor. The hydraulics designer uses “worst case” assumptions to estimate the pipe end area, as follows:

- the maximum headwater depth to diameter ratio (HW/D) is less than or equal to one,
- the tailwater depth is less than critical depth,
- the inlet will be a projecting end,
- the barrel will be corrugated metal, and
- the pipe slope will be nearly flat.

Temporary Water Management bypass pipes sizes are estimated by the hydraulics designer to develop the TWM plan and cost estimates. Guidance for the design of Temporary Water Management facilities are discusses in **Chapter 18**. The preceding worst case assumptions are often used. The pipe end areas are not listed on the contract documents. Instead, a table of estimated daily exceedance discharges is provided. Guidelines for exceedance discharge recurrence intervals are in **Chapter 3** and hydrology methods are discussed in **Chapter 7**.

9.23 Extending Existing Culverts

Often an existing culvert needs to be extended. This occurs most frequently when a roadway is to be widened. It should be verified that the extended culvert will provide adequate hydraulic performance, fish passage, and adequate service life when an extension is considered. Culvert extensions are subject to several requirements based on pipe materials, as described in **Chapter 5**.

The hydraulic performance of both the existing and extended culvert must be analyzed and compared. Often an inlet with increased hydraulic efficiency can be used to compensate for the increased friction losses caused by the longer barrel, and headwater elevations will not be increased by the extension.

An existing culvert meeting fish passage requirements can often be extended if the modified culvert also will meet passage requirements. Extension of a culvert, where the existing culvert must be modified to pass fish, is often considered to be a “retrofit.” These are not always allowed by the regulatory agencies. Any culvert extension involving fish passage where the existing section must be modified to provide fish passage should be carefully reviewed with the project environmental contact in the early stages of the project, and prior to detailed design.

The existing culvert to be extended must have sufficient remaining service life to last for the design life of the proposed project. Often this will require a culvert replacement rather than extension, or the existing pipe will need to be rehabilitated. Trenchless methods are often used for pipe rehabilitation, as discussed in **Chapter 16**.

9.24 Scour at Culvert Outlets

Flow out of culverts is typically fast and shallow in comparison to flow in the downstream channel. In addition, there is often turbulence caused by hydraulic jumps or drops where culvert flow makes a transition to channel flow. These flow transitions can create scour holes in the channel bottom downstream from the outlet. This outlet scour should be considered in culvert design as follows.

1. Place riprap or construct an energy dissipator at the culvert outlet to prevent or minimize scour on ODOT right-of-way or adjacent property. This is the most common solution to outlet scour problems. Outlet scour protection is especially critical for relief culverts and other culverts placed in embankments at elevations higher than the stream flowline.

2. Do not provide scour protection. This can be done if the outlet channel is non-erodible or a scour hole can be tolerated. The scour hole must:

    - not undermine the culvert, embankment, structures, or cause unacceptable damage,
    - be confined to the ODOT right-of-way, or extend off of the right-of-way if suitable easements are obtained from adjacent landowners,
    - not cause intolerable environmental damage, and
    - not obstruct fish passage if fish passage is needed.

The need for energy dissipators should be determined early in the design process. These facilities can significantly increase the cost of the culvert and often require additional right-of-way.

Methods to estimate scour hole size, and procedures to design energy dissipators such as riprap blankets, riprap lined basins, or pipe tee outlet dissipators are presented in **Chapter 11**. Dissipators such as stilling wells, roughness rings inside the culvert barrel, or impact basins are discussed in the FHWA’s Hydraulic Engineering Circular No. 14 (HEC-14), “Hydraulic Design of Energy Dissipators for Culverts and Channels." Scour hole size estimates and the dissipators described in HEC-14.

9.25 Embankment Scour near Culverts

Flow into and out of culverts is often turbulent, especially during large floods. This flow can damage the highway embankments around the culvert ends. The locations where this damage is expected are "scour critical areas" and they are protected by revetment and/or a suitable biotechnical method.

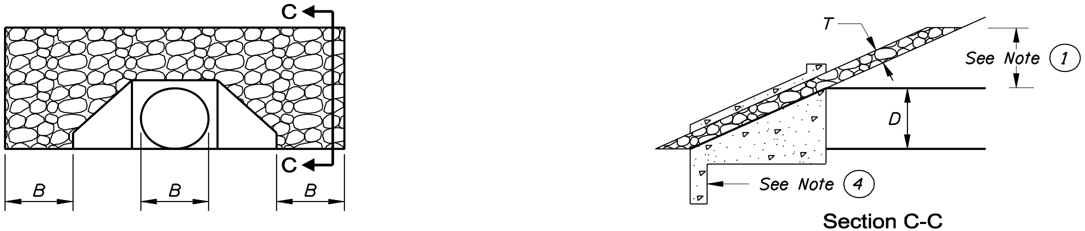
The most common scour protection material is loose riprap, and other types are occasionally used, such as gabions or masonry walls. Vegetal bank protection generally is not adequate unless it is founded on a non-erodible underlayer such as riprap, a cable-reinforced articulating block mat, or an equivalent. Vegetation such as bushes are sometimes planted in riprap. Often the riprap is covered by soil before planting. Typically small willows are used and they are planted as close as 2 feet on centers in areas where their roots will be moist or wet during low flow periods. Large plants are not allowed within specified distances of the highway or near the culvert structure. The hydraulics designer should be contacted for guidance if plantings in riprap are considered.

A description of scour protection for critical areas is included in the Hydraulic Report. Typical embankment protection is shown in Figure 9-21. This protection should extend up the embankment to the lower of:

- the elevation shown in Figure 9-21, or
- the elevation of the bottom of the aggregate base.

A) SLOPED OR PROJECTING END

B) SLOPED END WITH SLOPE PAVING



C) HEADWALL AND WINGWALLS

B = Diameter Of Circular Barrel Or Span Of Pipe-Arch, Box, Or Open-Bottom Arch
D = Diameter Of Circular Barrel Or Rise Of Pipe-Arch, Box, Or Open-Bottom Arch
T = Thickness Of Riprap Blanket. See Table

Riprap Class	*"T" Distance*
50	*12 inches*
100	*18 inches*
200	*24 inches**
700	*36 inches**

** Riprap Backing Required Between Riprap And Embankment*

NOTES:
1. *Minimum Elevation Of Top Of Riprap At Inlet And Outlet Is One Diameter (D) Or 1 Foot Higher Than Design Headwater Or Tailwater Elevation, Respectively, Whichever Is Greater.*
2. *Suitable Vegetation Can Be Planted In Riprap. See Text.*
3. *Additional Protection May Be Needed Downstream From Culvert Outlet. See Chapter 11.*
4. *Riprap Required Around Cutoff Wall At Outlet. Riprap Optional Around Inlet Cutoff Wall Of Single Barrel Culvert. Riprap Required Around Inlet Cutoff Wall On Multiple Barrel Culverts.*

Figure 9-21 Typical Culvert Embankment Protection Details

In general, Class 50 loose riprap is suitable for small and medium culverts, and Class 100 for large culverts. Larger rock is sometimes used when the energy dissipator requires larger riprap, and there may be a cost savings by using larger rock for both the embankment and the dissipator. In other cases, the larger rock may be needed to resist scour. An example is a culvert outlet on a lakeshore. Larger riprap may be needed to resist displacement from the waves on the lake.

Cutoff walls are often used at culvert ends to prevent undermining due to scour. Riprap is placed against the outlet wall. Revetment is also placed against the inlet cutoff wall of multiple barrel or multiple culverts. Riprap is optional around the inlet cutoff wall of single barrel installations. Cutoff wall protection details are provided in **Chapter 11**.

Note: The typical details described in this subsection are applicable for most installations. Some culverts may require additional protection. It is the responsibility of the designer to evaluate the need for additional protection and to include it in the design.

9.26 Debris Control

The potential for debris should be considered in the design. Accumulation of debris at the culvert inlet can result in the culvert not performing as designed and cause damage to the highway, culvert, and upstream property. The presence and extent of an existing debris passage problem can be determined by contacting maintenance personnel and neighboring landowners, examining the site, watershed, and nearby structures, and by reviewing maintenance records. Refer to Appendix C of this chapter for design guidelines when a debris control structure is necessary.

There are several options for coping with debris. Selection of an option should consider:

- the extent of damage that would occur if the culvert plugs in comparison to the cost of a structure which will pass the debris,
- ease of removing debris from the culvert,
- fish passage, if required, and
- preferences of maintenance personnel.

Options for coping with a debris problem are:

1. Retain the debris upstream of the culvert by installing a trash rack. Use of a trash rack is subject to approval by regulatory agencies reviewing the fish passage design if passage is required.

2. Do not put a trash rack on the main culvert and construct an overflow culvert higher on the embankment to handle flow if the main culvert plugs. A trash rack may be needed upstream from the overflow culvert.

3. Select a structure large enough to pass the debris. In some instances this may require a bridge rather than a culvert.

9.27 Piping

Piping is caused by seepage along a culvert barrel which removes fill material, forming a void similar to a pipe, hence the term piping. Fine soil particles are washed out freely along the void and can ultimately cause embankment failure. The water causing seepage typically enters the embankment fill from two locations. One location is an open pipe joint or a hole in the barrel.. The other location is the interface between the barrel and the embankment at the culvert inlet. Precautions against piping include:

- using watertight joints (especially important if culvert operates under pressure flow),
- constructing a headwall or slope paving with a minimum 3-foot deep cutoff wall at the inlet and outlet, or
- placing the culvert in an impermeable bedding.

Note: It is important that cutoff walls are constructed according to plans. Observations of past projects indicate these walls are often not constructed to the specified depths. Cut-off walls are one of the best features to prevent piping.

9.28 Flotation

Flotation is the failure of a culvert that is caused by buoyancy. Buoyancy is an uplifting force that is produced when the pressure outside the culvert is greater than the pressure inside the barrel. The resulting uplift may cause the culvert or the inlet end of the culvert to rise out of the embankment. Typically, when flotation occurs the inlet is submerged and the culvert is flowing partially full under inlet control. The causes of inlet control can be an inefficient inlet, debris blocking the inlet, or damage to the inlet.

Some types of culverts are more susceptible to flotation than others. Vulnerable culverts are usually:

- relatively large pipes with little depth of cover from the roadway embankment,
- thin walled, light, and flexible barrels such as corrugated metal or plastic,
- barrels with projecting ends or mitered ends without collars or slope paving (ends projecting unduly far out of the fill are especially vulnerable), or
- use a mitered end surrounded by large riprap or boulders.

Detour culverts or culverts under construction are typically the most susceptible to flotation because they usually have projecting ends and little cover. Especially vulnerable are culverts operating under inlet control which, due to stage construction or other reasons, project far upstream from the fill. Countermeasures to prevent flotation include:

- use slope paving, concrete collars, or headwalls and wingwalls to weight down and protect the ends of metal pipes,
- consider the possibility that high flows may occur during construction and assure that uncovered pipes do not project far upstream from the fill,
- use multiple culverts rather than a large single barrel to increase fill cover heights, or
- use heavy rigid barrels such as concrete pipe sections linked with tie bars.

9.29 Camber

Culverts installed under moderate to high fills can experience differential settlement. This occurs after the fill settles and compacts and the midsection of the culvert drops to a lower elevation than the outlet. To prevent this from occurring, the culvert is placed with a slightly elevated midsection and the pipe straightens when the fill settles. The increase in midsection elevation is called camber, and it is predicted by the Foundations Engineer. A profile showing the pipe camber needs to be included in the plans.

9.30 Flap Gates

A flap gate, often called tide gate, is sometimes used on the end of a culvert to limit backflow through the conduit. The most common use of a flap gate is to prevent the inundation of upland property on one side of the highway from a high tide or flood on the other side of the highway. Although a flap gate may be useful in certain circumstances, some factors to be considered before it is specified are listed below.

1. Hydraulic efficiency. The effect of a flap gate on the hydraulic efficiency of the culvert

should be considered in the design. Typically the effects are analyzed as “other losses,” as discussed in Subsection 9.19.2.

2. Fish passage. Fish passage requirements can preclude the use of a flap gate or require use of a "fish friendly" gate. The ODOT Region Environmental Coordinator or appropriate regulatory agencies should be contacted before use of a tide gate is considered on a fish bearing stream.

3. Environmental concerns. Installation of a flap gate in a coastal location may alter the circulation patterns of fresh, brackish, and salt water. These changes may affect the plants and wildlife in the vicinity. As a result, a flap gate should not be installed unless potential environmental effects are considered. It may not always prevent flooding upstream of the gate. If the gate stays closed too long and there is considerable runoff upstream, the gate could make the upstream flooding worse or provide no flood protection.

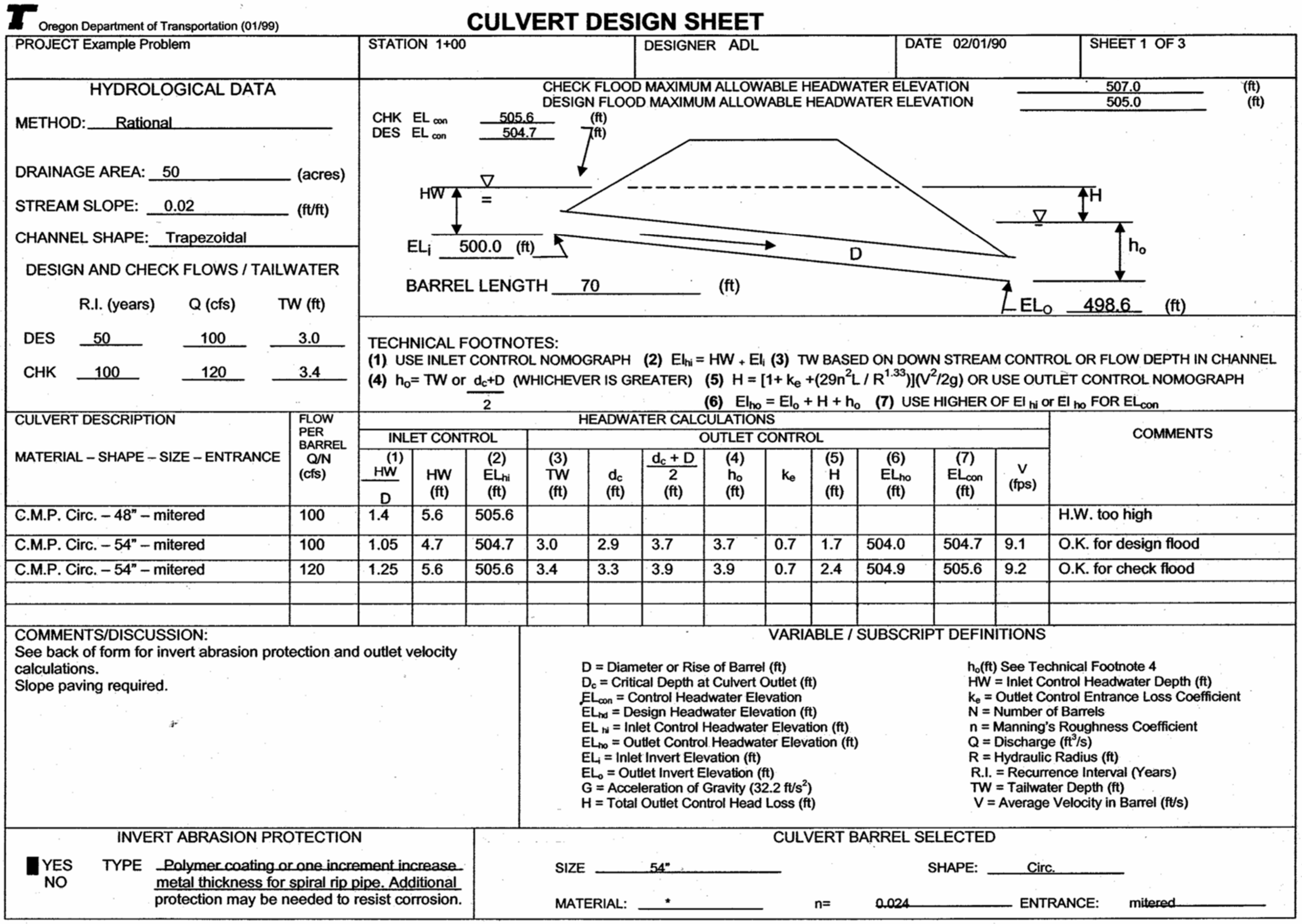
4. Flood control concerns. A flap gate should not be used to control flooding unless the effects on all affected landowners are considered. A gate may relieve flooding at one location and make it worse at another.

5. Maintenance. A flap gate may be held open by debris, it can be damaged, and is subject to wear. Periodic inspection and/or maintenance may be needed.

6. Embankment stability. The flow restriction caused by a flap gate may result in a difference in water surface elevations on either side of the highway. The ability of the roadway embankment to withstand the resulting hydrostatic pressure should be considered before a gate is specified.

ODOT policy addressing tidegates is posted on the ODOT Business Services website. The designer should review this policy and assure the proposed design is in conformance.

PLATE 1



Oregon Department of Transportation (01/99)

CULVERT DESIGN SHEET

PROJECT Example Problem	STATION 1+00	DESIGNER ADL	DATE 02/01/90	SHEET 1 OF 3

HYDROLOGICAL DATA

METHOD: Rational

DRAINAGE AREA: 50 (acres)

STREAM SLOPE: 0.02 (ft/ft)

CHANNEL SHAPE: Trapezoidal

DESIGN AND CHECK FLOWS / TAILWATER

	R.I. (years)	Q (cfs)	TW (ft)
DES	50	100	3.0
CHK	100	120	3.4

CHECK FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION 507.0 (ft)
DESIGN FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION 505.0 (ft)

CHK EL_{con} 505.6 (ft)
DES EL_{con} 504.7 (ft)

EL_i 500.0 (ft)

BARREL LENGTH 70 (ft)

EL_O 498.6 (ft)

TECHNICAL FOOTNOTES:
(1) USE INLET CONTROL NOMOGRAPH **(2)** $El_{hi} = HW + El_i$ **(3)** TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL
(4) h_o= TW or $\frac{d_c+D}{2}$ (WHICHEVER IS GREATER) **(5)** $H = [1+ k_e +(29n^2L / R^{1.33})](V^2/2g)$ OR USE OUTLET CONTROL NOMOGRAPH
(6) $El_{ho} = El_o + H + h_o$ **(7)** USE HIGHER OF El_{hi} or El_{ho} FOR EL_{con}

CULVERT DESCRIPTION MATERIAL – SHAPE – SIZE – ENTRANCE	FLOW PER BARREL Q/N (cfs)	HEADWATER CALCULATIONS												COMMENTS
		INLET CONTROL			OUTLET CONTROL									
		(1) $\frac{HW}{D}$	HW (ft)	(2) EL_{hi} (ft)	(3) TW (ft)	d_c (ft)	$\frac{d_c + D}{2}$ (ft)	(4) h_o (ft)	k_e	(5) H (ft)	(6) EL_{ho} (ft)	(7) EL_{con} (ft)	V (fps)	
C.M.P. Circ. – 48" – mitered	100	1.4	5.6	505.6										H.W. too high
C.M.P. Circ. – 54" – mitered	100	1.05	4.7	504.7	3.0	2.9	3.7	3.7	0.7	1.7	504.0	504.7	9.1	O.K. for design flood
C.M.P. Circ. – 54" – mitered	120	1.25	5.6	505.6	3.4	3.3	3.9	3.9	0.7	2.4	504.9	505.6	9.2	O.K. for check flood

COMMENTS/DISCUSSION:
See back of form for invert abrasion protection and outlet velocity calculations.
Slope paving required.

VARIABLE / SUBSCRIPT DEFINITIONS

D = Diameter or Rise of Barrel (ft)
D_c = Critical Depth at Culvert Outlet (ft)
EL_{con} = Control Headwater Elevation
EL_{hd} = Design Headwater Elevation (ft)
EL_{hi} = Inlet Control Headwater Elevation (ft)
EL_{ho} = Outlet Control Headwater Elevation (ft)
EL_i = Inlet Invert Elevation (ft)
EL_o = Outlet Invert Elevation (ft)
G = Acceleration of Gravity (32.2 ft/s^2)
H = Total Outlet Control Head Loss (ft)

h_o(ft) See Technical Footnote 4
HW = Inlet Control Headwater Depth (ft)
k_e = Outlet Control Entrance Loss Coefficient
N = Number of Barrels
n = Manning's Roughness Coefficient
Q = Discharge (ft^3/s)
R = Hydraulic Radius (ft)
R.I. = Recurrence Interval (Years)
TW = Tailwater Depth (ft)
V = Average Velocity in Barrel (ft/s)

INVERT ABRASION PROTECTION

■ YES
NO

TYPE Polymer coating or one increment increase metal thickness for spiral rip pipe. Additional protection may be needed to resist corrosion.

CULVERT BARREL SELECTED

SIZE 54"
SHAPE: Circ.
MATERIAL: *
n= 0.024
ENTRANCE: mitered

PLATE 2

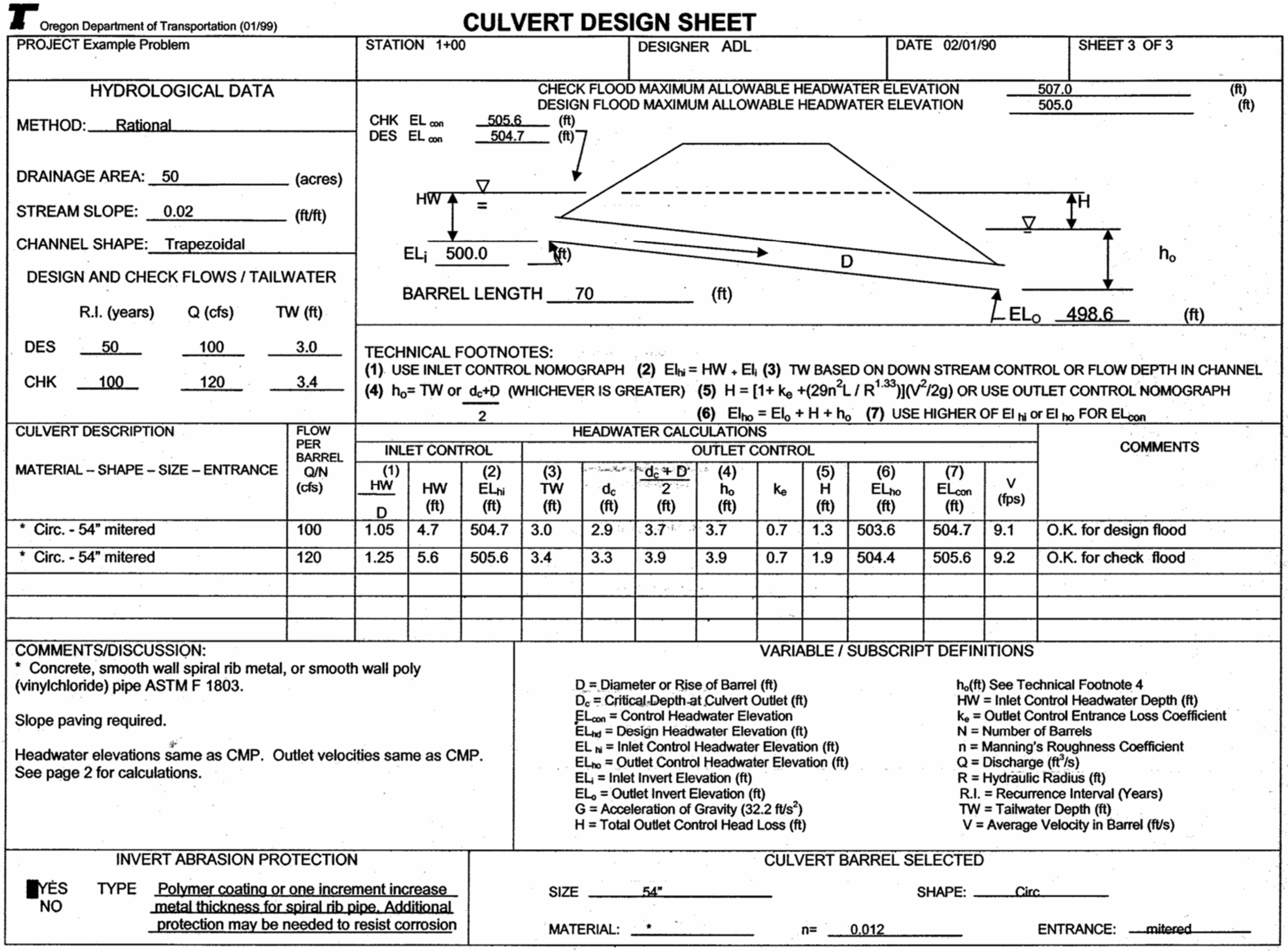
Sheet 2 of 3

Invert abrasion protection calculations (See Chapter 5)

Q_2 = 2.6 cfs Q_{6mo} = (0.66) (Q_2) = 1.7 cfs = invert abrasion protection design flow
Culvert will flow at normal depth for most of its length during the 1.7 cfs discharge.
Normal depth = 0.49 ft, normal velocity = 4.2 ft/s (see Chapter 8).
Bed materials as large as coarse gravels are present. The 1.7 cfs discharge can carry this material through pipe. Use polymer coating or 1 increment increase in barrel material thickness, as per Chapter 5 for "Low Abrasion" conditions.

Outlet velocity calculations (see Chapter 11) :
Normal flow depth in culvert during 100 cfs design flood = 2.7 ft TW depth = 3.0
Normal flow depth is less than TW depth. Case 2 flow occurs. Flow depth at outlet is TW depth.
d/D = 3.0/4.5 = 0.67 $A_{full} = \pi(4.5/2)^2 = 16\ ft^2$ From hydraulics element chart in Chapter 8 Appendix B, a/A_{full} = 0.70
a = 0.70 x 16 = 11 ft^2 V @ Q_{100} = 100 cfs/11 ft^2 = 9.1 ft/s <=
During 120 cfs check flood, normal depth = 3.0 ft, TW depth = 3.4, Case 2 flow occurs
d/D = 3.4/4.5 = 0.75 From elements chart: a/A_{full} = 0.81
a = 0.81 x 16 = 13 ft^2 V @ Q_{120} = 120 cfs/13 ft^2 = 9.2 ft/s <=

PLATE 3



Oregon Department of Transportation (01/99)

CULVERT DESIGN SHEET

PROJECT Example Problem

STATION 1+00

DESIGNER ADL

DATE 02/01/90

SHEET 3 OF 3

HYDROLOGICAL DATA

METHOD: Rational

DRAINAGE AREA: 50 (acres)

STREAM SLOPE: 0.02 (ft/ft)

CHANNEL SHAPE: Trapezoidal

DESIGN AND CHECK FLOWS / TAILWATER

	R.I. (years)	Q (cfs)	TW (ft)
DES	50	100	3.0
CHK	100	120	3.4

CHECK FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION 507.0 (ft)

DESIGN FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION 505.0 (ft)

CHK EL_{con} 505.6 (ft)

DES EL_{con} 504.7 (ft)

HW

H

D

h_o

EL_i 500.0 (ft)

BARREL LENGTH 70 (ft)

EL_O 498.6 (ft)

TECHNICAL FOOTNOTES:

(1) USE INLET CONTROL NOMOGRAPH (2) $El_{hi} = HW + El_i$ (3) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL (4) h_o= TW or $\frac{d_c+D}{2}$ (WHICHEVER IS GREATER) (5) $H = [1+ k_e +(29n^2L / R^{1.33})](V^2/2g)$ OR USE OUTLET CONTROL NOMOGRAPH (6) $El_{ho} = El_o + H + h_o$ (7) USE HIGHER OF El_{hi} or El_{ho} FOR EL_{con}

CULVERT DESCRIPTION	FLOW PER BARREL	HEADWATER CALCULATIONS												COMMENTS
		INLET CONTROL			OUTLET CONTROL									
MATERIAL – SHAPE – SIZE – ENTRANCE	Q/N (cfs)	(1) $\frac{HW}{D}$	HW (ft)	(2) EL_{hi} (ft)	(3) TW (ft)	d_c (ft)	$\frac{d_c + D}{2}$ (ft)	(4) h_o (ft)	k_e	(5) H (ft)	(6) EL_{ho} (ft)	(7) EL_{con} (ft)	V (fps)	
* Circ. - 54" mitered	100	1.05	4.7	504.7	3.0	2.9	3.7	3.7	0.7	1.3	503.6	504.7	9.1	O.K. for design flood
* Circ. - 54" mitered	120	1.25	5.6	505.6	3.4	3.3	3.9	3.9	0.7	1.9	504.4	505.6	9.2	O.K. for check flood

COMMENTS/DISCUSSION:

* Concrete, smooth wall spiral rib metal, or smooth wall poly (vinylchloride) pipe ASTM F 1803.

Slope paving required.

Headwater elevations same as CMP. Outlet velocities same as CMP. See page 2 for calculations.

VARIABLE / SUBSCRIPT DEFINITIONS

D = Diameter or Rise of Barrel (ft)
D_c = Critical Depth at Culvert Outlet (ft)
EL_{con} = Control Headwater Elevation
EL_{hd} = Design Headwater Elevation (ft)
EL_{hi} = Inlet Control Headwater Elevation (ft)
EL_{ho} = Outlet Control Headwater Elevation (ft)
EL_i = Inlet Invert Elevation (ft)
EL_o = Outlet Invert Elevation (ft)
G = Acceleration of Gravity (32.2 ft/s^2)
H = Total Outlet Control Head Loss (ft)

h_o(ft) See Technical Footnote 4
HW = Inlet Control Headwater Depth (ft)
k_e = Outlet Control Entrance Loss Coefficient
N = Number of Barrels
n = Manning's Roughness Coefficient
Q = Discharge (ft^3/s)
R = Hydraulic Radius (ft)
R.I. = Recurrence Interval (Years)
TW = Tailwater Depth (ft)
V = Average Velocity in Barrel (ft/s)

INVERT ABRASION PROTECTION

☒ YES
NO

TYPE Polymer coating or one increment increase metal thickness for spiral rib pipe. Additional protection may be needed to resist corrosion

CULVERT BARREL SELECTED

SIZE 54"

SHAPE: Circ.

MATERIAL: *

n= 0.012

ENTRANCE: mitered

APPENDIX A - CULVERT PERFORMANCE CHARTS

These charts provide nomographs to determine inlet and outlet control headwater depths for common culvert shapes. Nomographs for additional culvert shapes are in FHWA Hydraulic Design Series No. 5 "Hydraulic Design of Highway Culverts."

Note: *The outlet control nomographs provide accurate estimates of headwater depths if there is full flow in the culvert barrel and a submerged outlet. The nomographs may slightly overestimate headwater depths if the barrel flows partially full.*

INDEX TO CULVERT PERFORMANCE CHARTS

Chart	Shape	Material	Control	Comments
1	Circular	Concrete	Inlet	Inlet projecting or in headwall
2	Circular	Concrete	Inlet	Prefabricated concrete end section
3	Circular	Metal	Inlet	Corrugated or structural plate pipe with inlet projecting, mitered, or in headwall. **(Use Scale 2 for ODOT sloped end with or without slope paving.)**
4	Circular	Metal	Inlet	Safety end section with bars **(Use for concrete or metal barrel.)**
5	Circular	Metal	Inlet	Prefabricated metal end section
6	Circular	Metal	Inlet	Reinforced concrete beveled ring around inlet
7	Circular	Concrete	Outlet	
8	Circular	Metal	Outlet	Corrugated metal pipe

INDEX TO CULVERT PERFORMANCE CHARTS, CONTD.

Chart	Shape	Material	Control	Comments
9	Circular	Metal	Outlet	Structural plate pipe
10	Box	Concrete	Inlet	Top edge square with wingwalls
11	Box	Concrete	Inlet	Top edge beveled with wingwalls **(Use Scale 2 for box culvert shown on ODOT Standard Drawing BR 800.)**
12	Box	Concrete	Outlet	
13	Pipe-Arch	Metal	Inlet	Corrugated pipe-arch with inlet projecting, mitered, or in headwall **(Use Scale 2 for ODOT sloped end with or without slope paving.)**
14	Pipe-Arch	Metal	Inlet	Structural plate pipe-arch with inlet projecting, or in headwall with or without beveled edge and 18-inch corner radius
15	Pipe-Arch	Metal	Inlet	Structural plate pipe-arch with inlet projecting, or in headwall with or without beveled edge and 31-inch corner radius
16	Pipe-Arch	Metal	Outlet	Corrugated metal
17	Pipe-Arch	Metal	Outlet	Structural plate with 18-inch corner radius
18	Arch	Metal	Inlet	Structural plate arch with inlet projecting, mitered, or in headwall with $0.3 \leq \text{Rise/Span} < 0.4$

INDEX TO CULVERT PERFORMANCE CHARTS, CONTD.

Chart	Shape	Material	Control	Comments
19	Arch	Metal	Inlet	Structural plate arch with inlet projecting, mitered, or in headwall with $0.4 \le$ Rise/Span < 0.5
20	Arch	Metal	Inlet	Structural plate arch with inlet projecting, mitered, or in headwall with $0.5 \le$ Rise/Span
21	Arch	Metal	Outlet	Structural plate arch with earth bottom and $0.3 \le$ Rise/Span < 0.4
22	Arch	Metal	Outlet	Structural plate arch with earth bottom and $0.4 \le$ Rise/Span < 0.5
23	Arch	Metal	Outlet	Structural plate arch with earth bottom and $0.5 <$ Rise/Span

CHART 1

HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

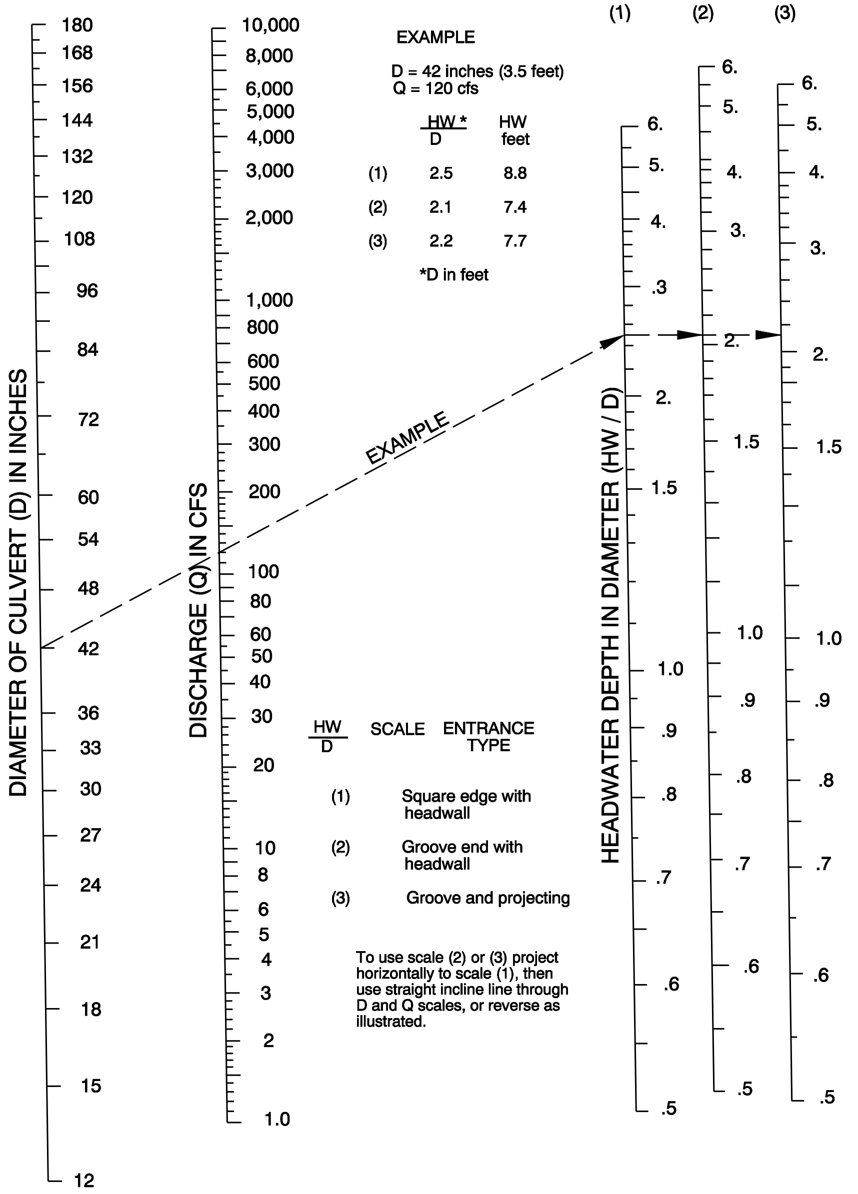
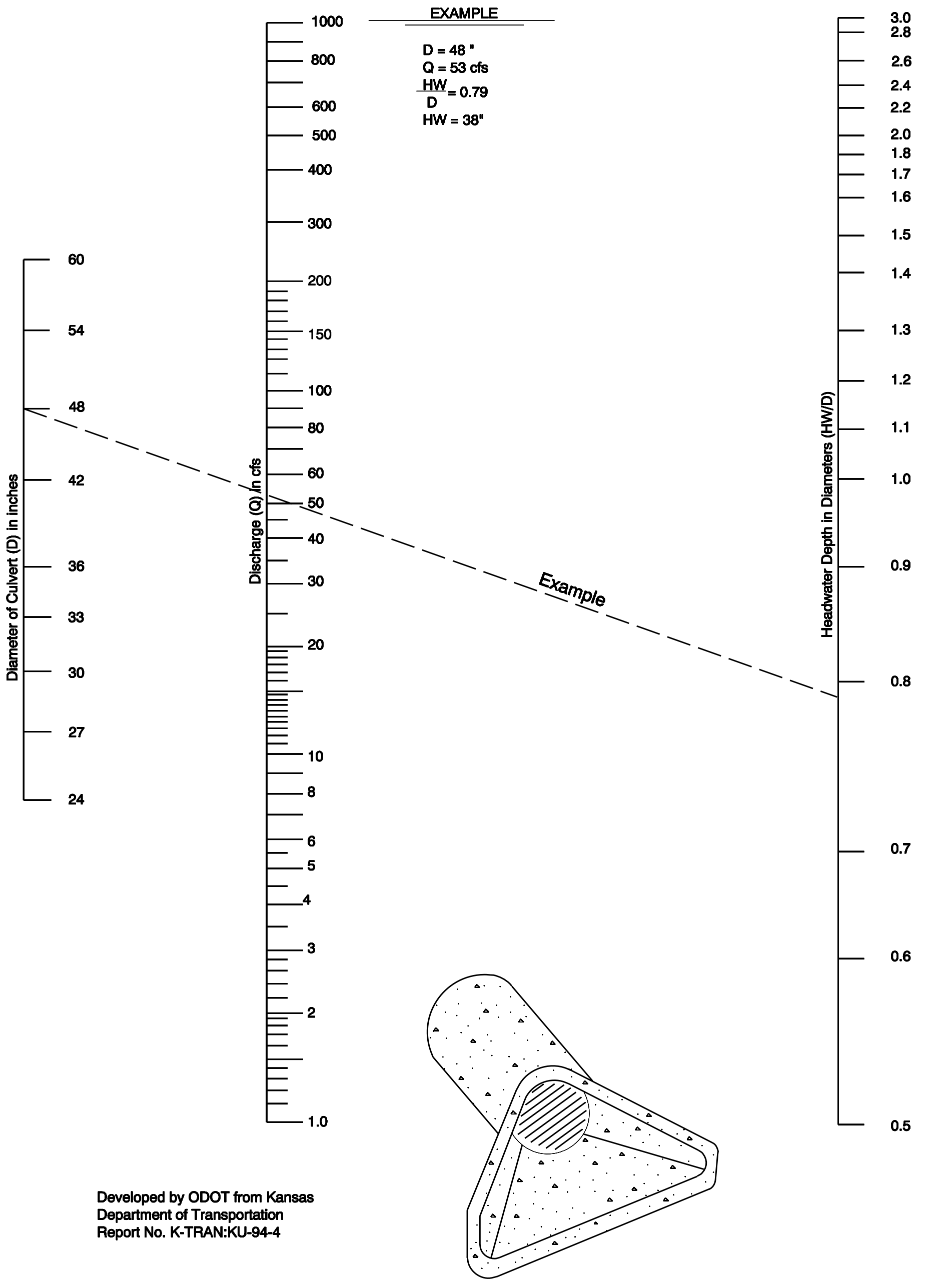


CHART 2

HEADWATER DEPTH FOR PREFABRICATED CONCRETE END SECTION IN INLET CONTROL



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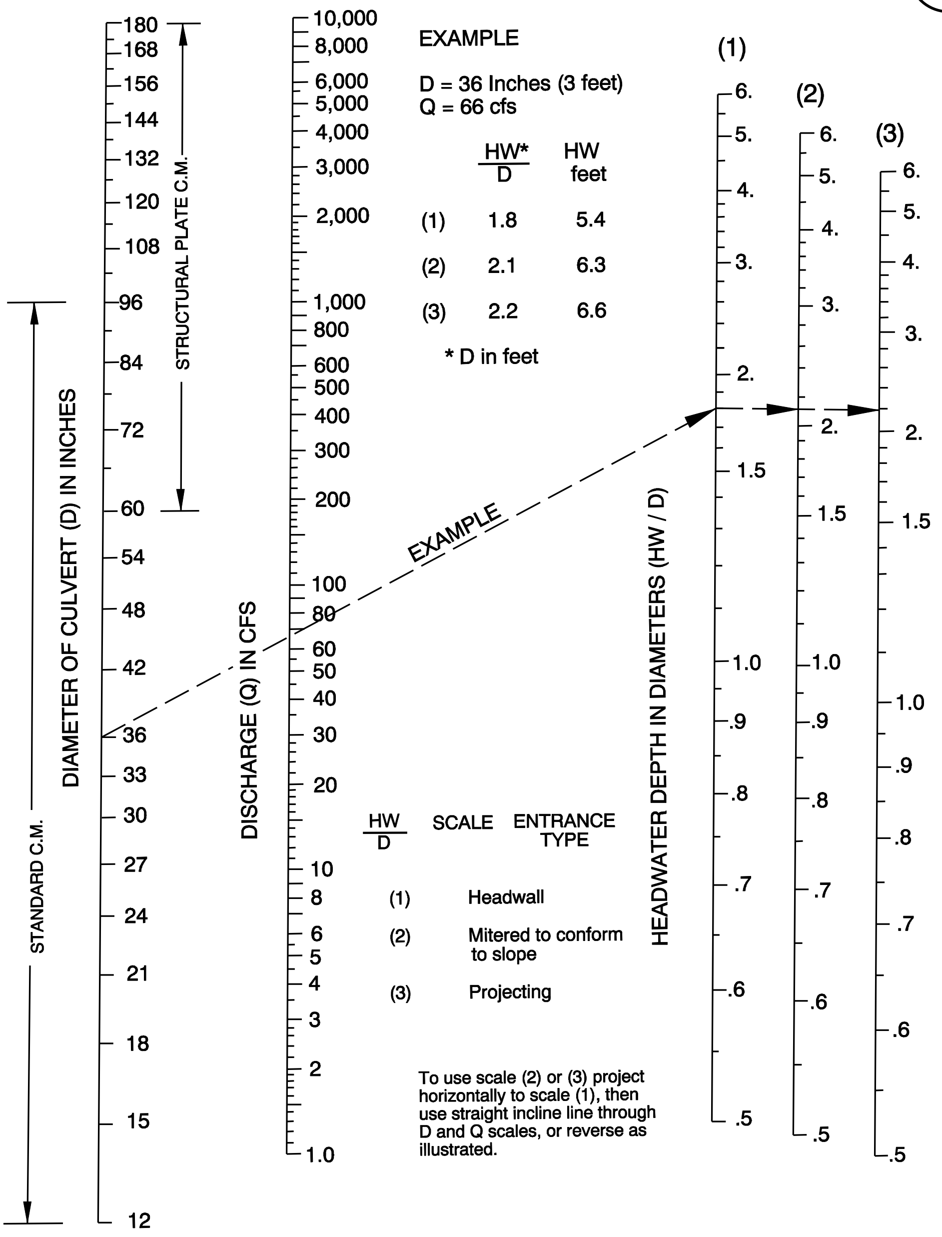
Department of Transportation
Report No. K-TRAN:KU-94-4

CHART 3

HEADWATER DEPTH FOR C.M. CULVERTS WITH INLET CONTROL



EXAMPLE

D = 36 Inches (3 feet)
Q = 66 cfs

	$\frac{HW^*}{D}$	HW feet
(1)	1.8	5.4
(2)	2.1	6.3
(3)	2.2	6.6

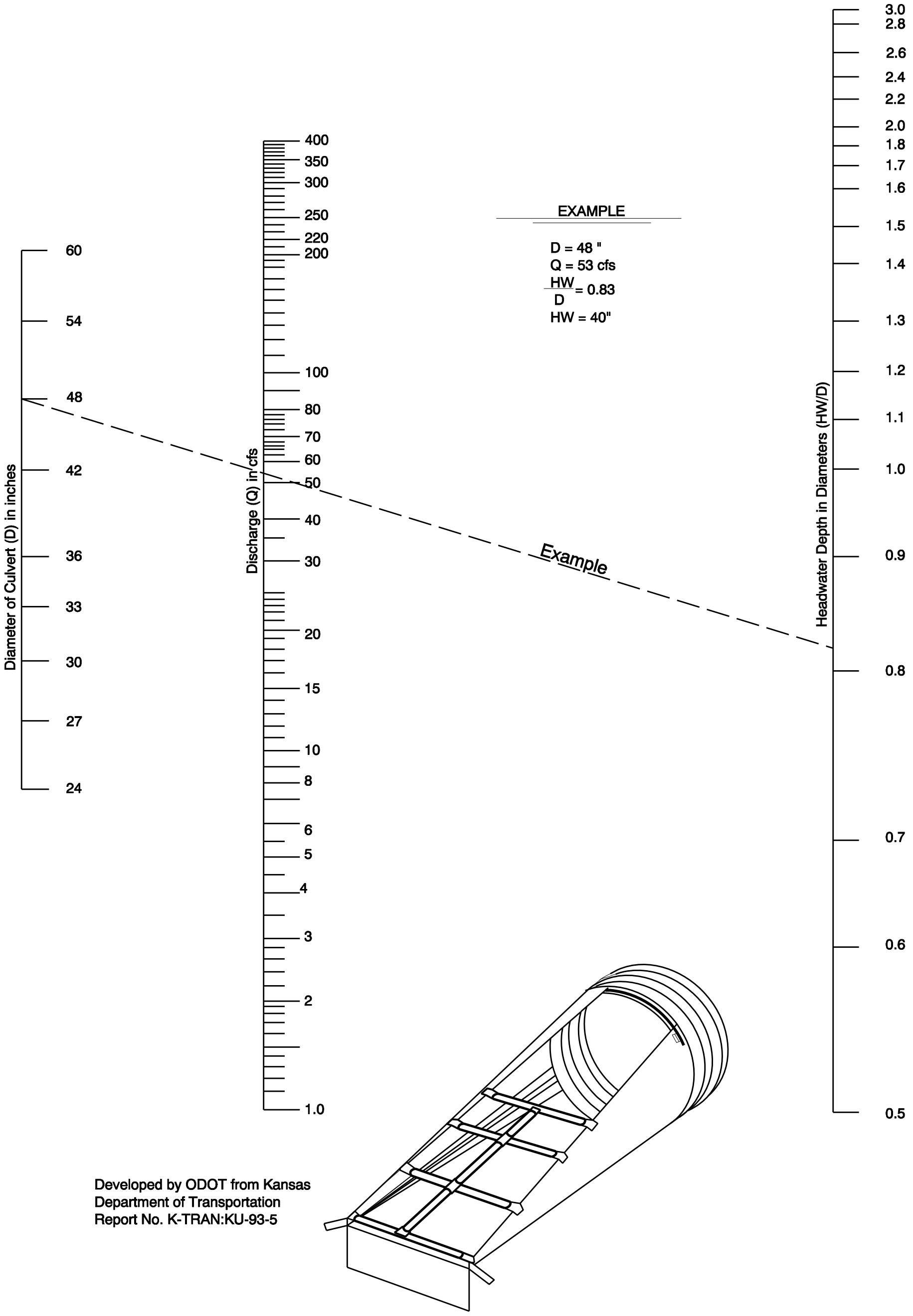
* D in feet

$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Headwall
(2)	Mitered to conform to slope
(3)	Projecting

To use scale (2) or (3) project horizontally to scale (1), then use straight incline line through D and Q scales, or reverse as illustrated.

CHART 4

HEADWATER DEPTH FOR SAFETY END SECTIONS WITH SAFETY BARS IN INLET CONTROL



EXAMPLE

D = 48 "
Q = 53 cfs
$\frac{HW}{D}$ = 0.83
HW = 40"

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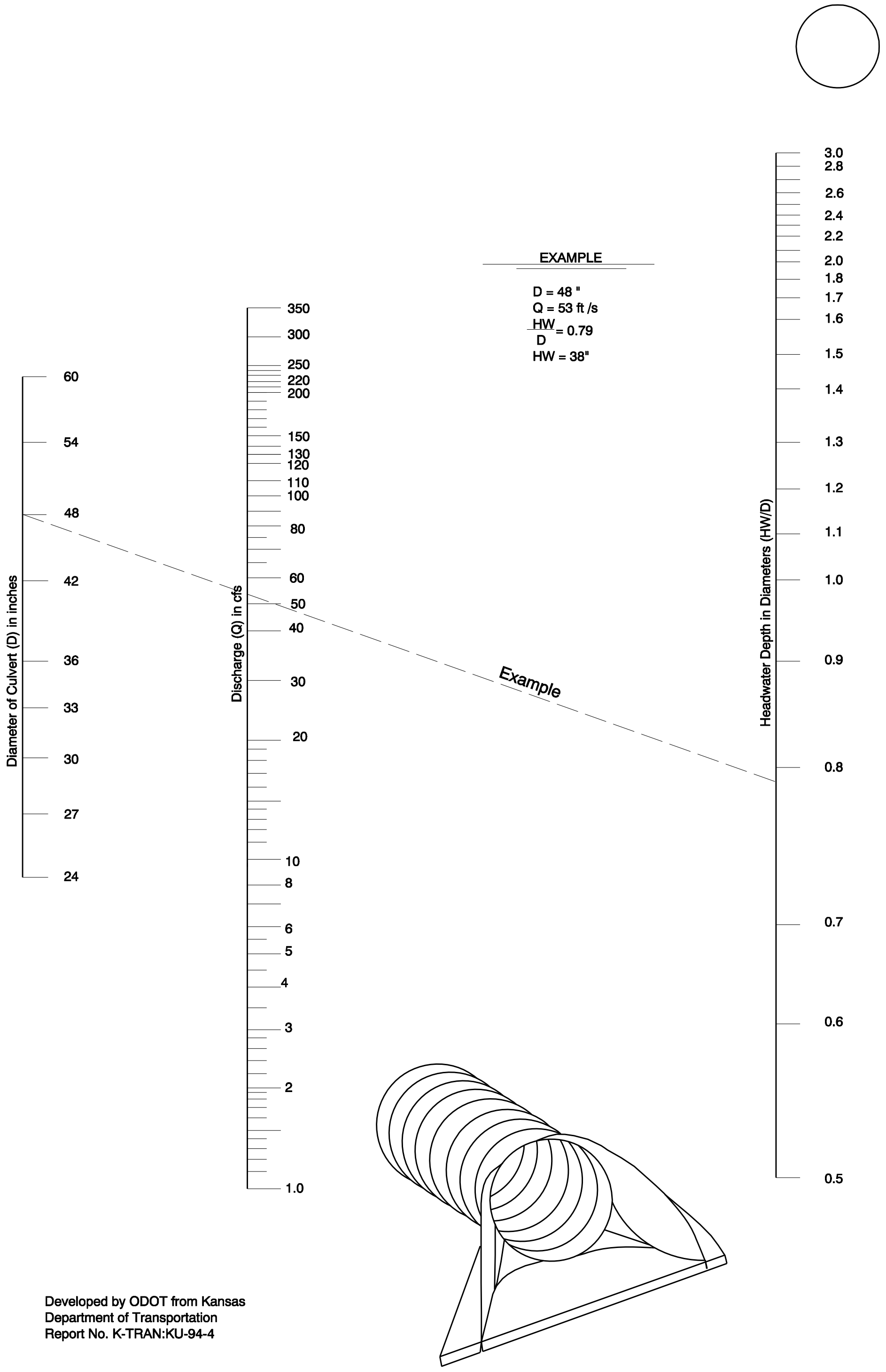
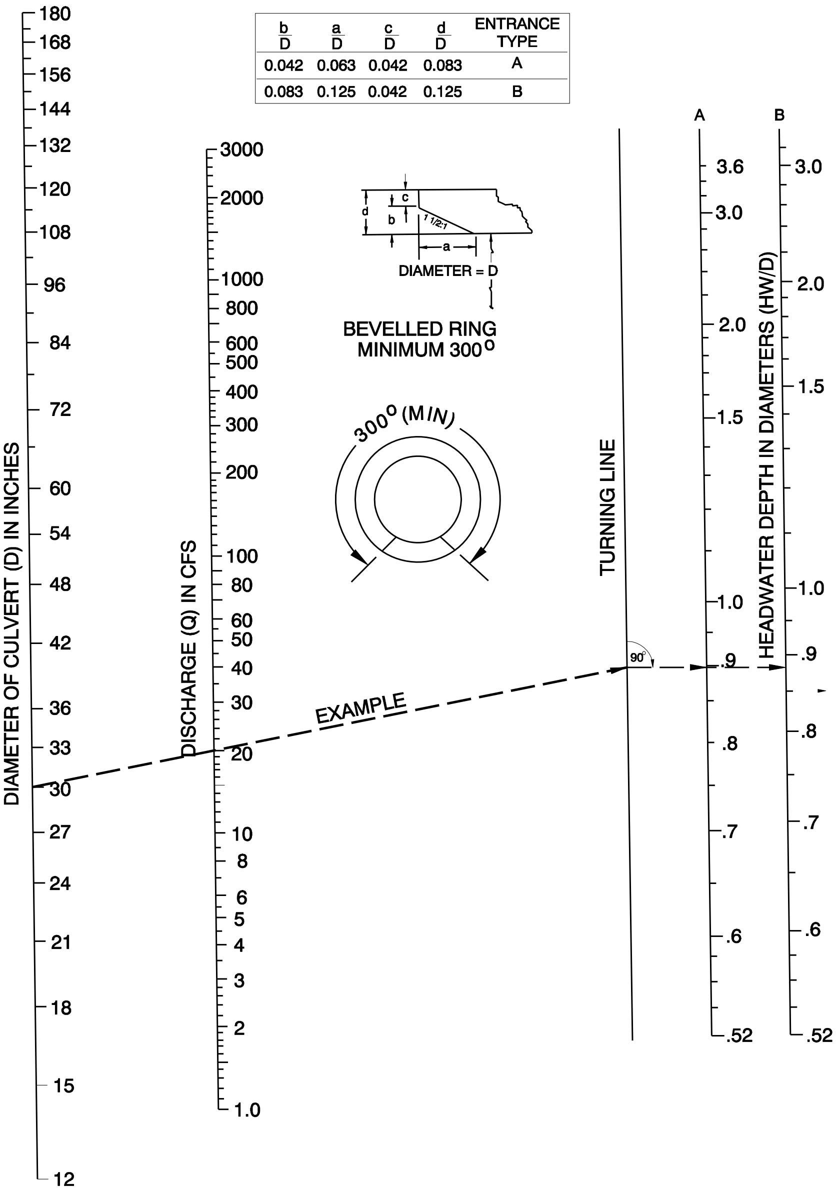
CHART 5
HEADWATER DEPTH FOR PREFABRICATED METAL END SECTIONS IN INLET CONTROL



Developed by ODOT from Kansas
Department of Transportation
Report No. K-TRAN:KU-94-4

CHART 6

HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL



b/D	a/D	c/D	d/D	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B

CHART 7

HEAD FOR
CONCRETE PIPE CULVERTS
FLOWING FULL IN OUTLET CONTROL
n = 0.012

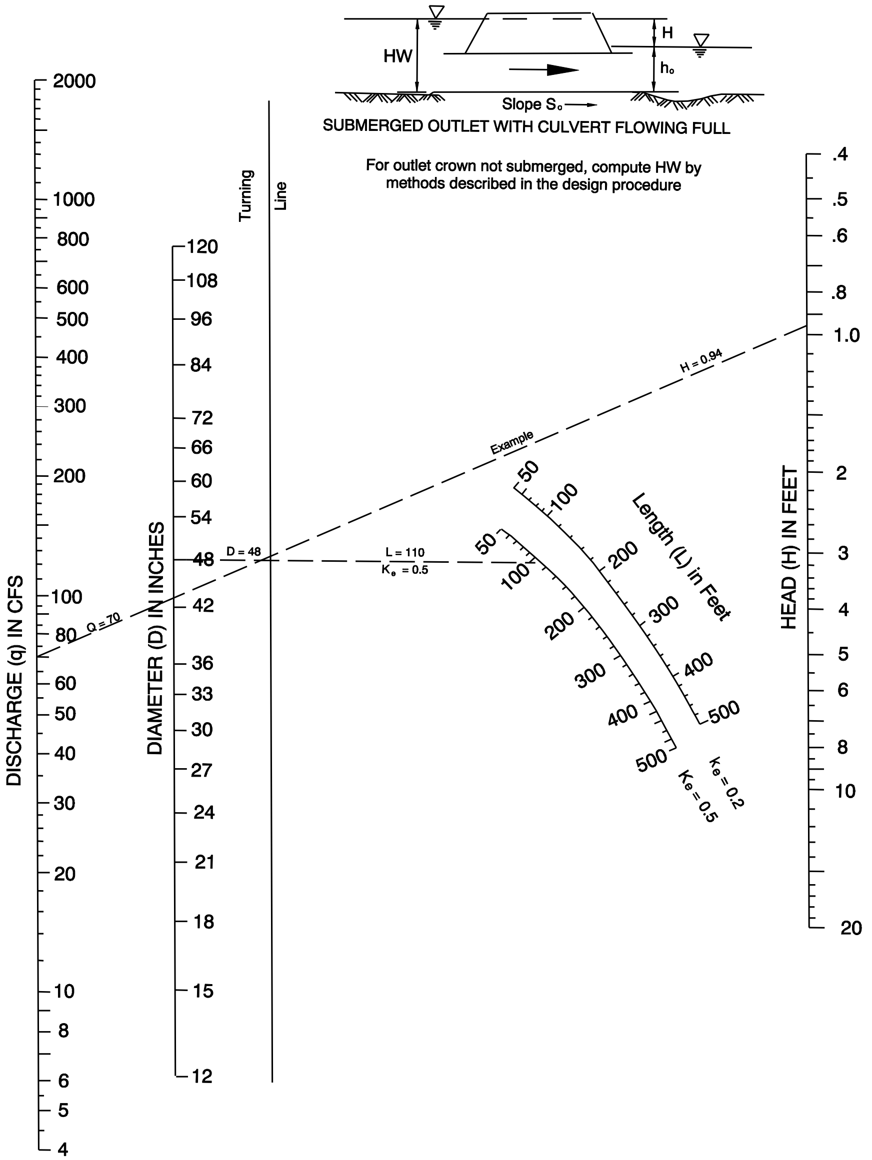
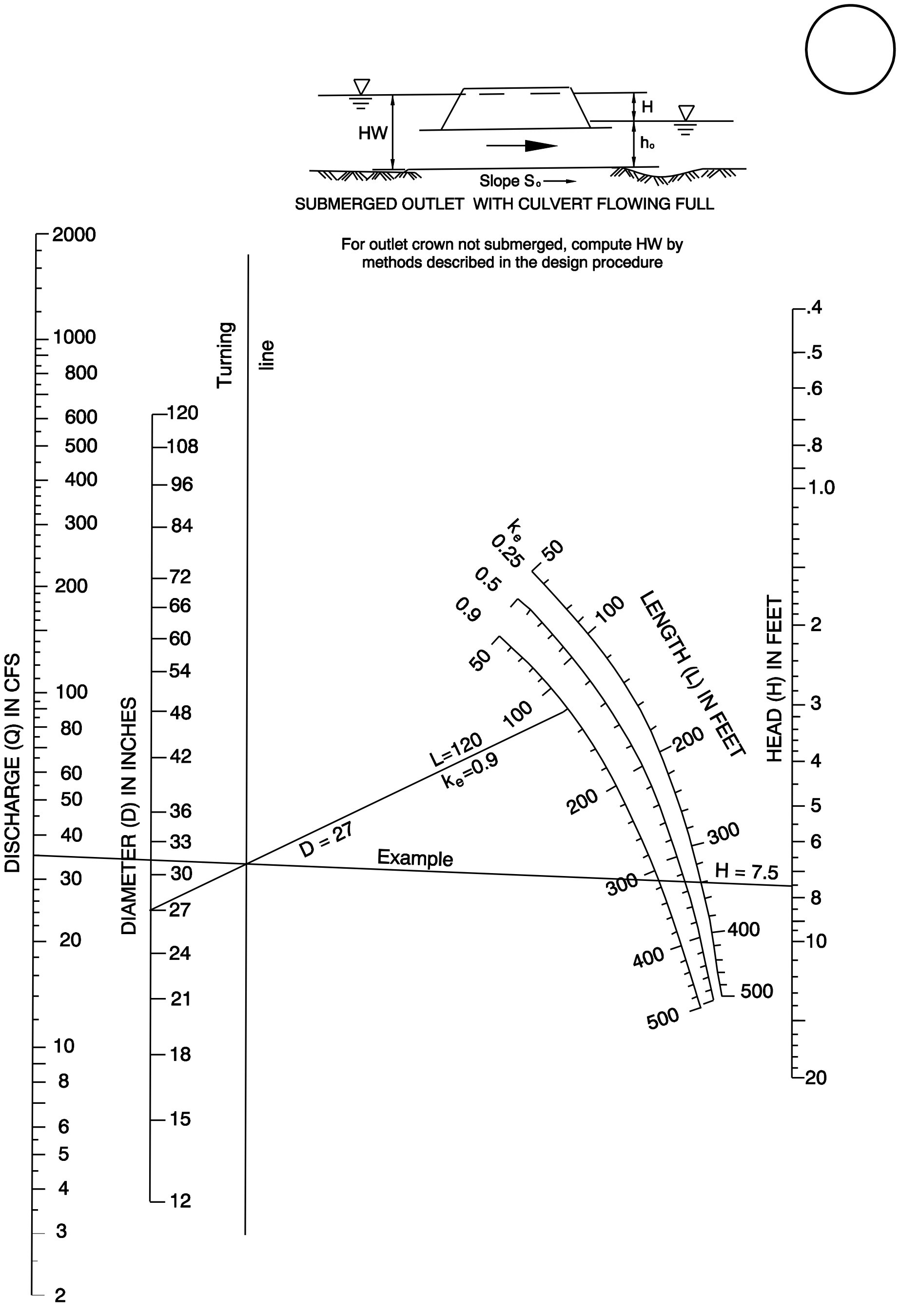


CHART 8

HEAD FOR STANDARD
C.M. PIPE CULVERTS
FLOWING FULL IN OUTLET CONTROL
n = 0.024

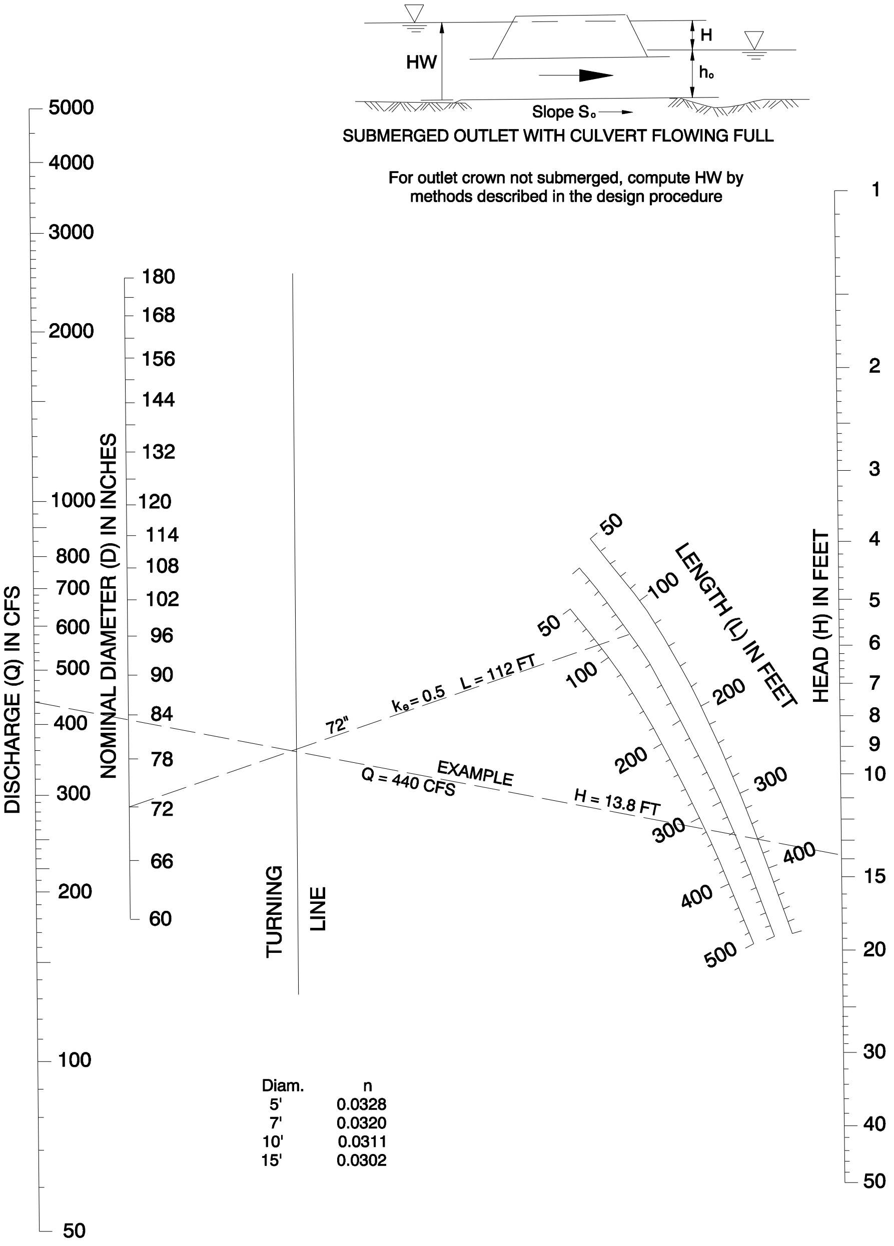


SUBMERGED OUTLET WITH CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure

CHART 9

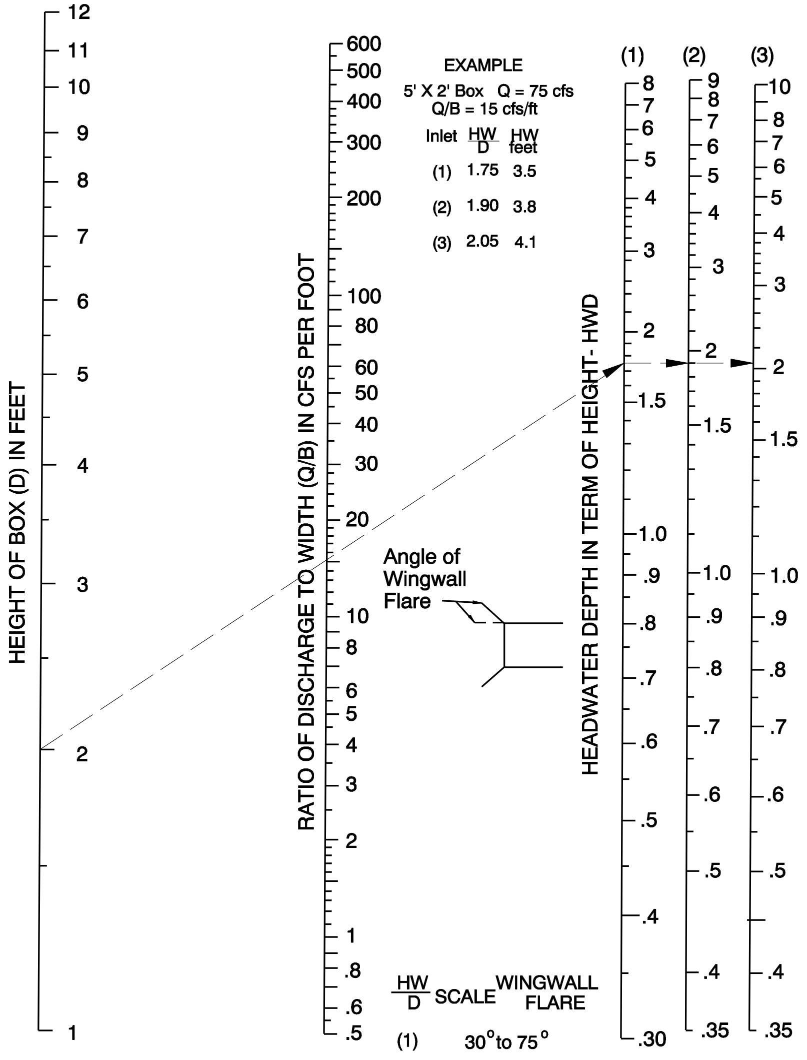
HEAD FOR STRUCTURAL PLATE CORR. METAL PIPE CULVERTS FLOWING FULL IN OUTLET CONTROL N = 0.0328 TO 0.0302



Diam.	n
5'	0.0328
7'	0.0320
10'	0.0311
15'	0.0302

CHART 10

HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL



EXAMPLE

5' X 2' Box Q = 75 cfs
Q/B = 15 cfs/ft

Inlet	$\frac{HW}{D}$	HW feet
(1)	1.75	3.5
(2)	1.90	3.8
(3)	2.05	4.1

$\frac{HW}{D}$ SCALE	WINGWALL FLARE
(1)	30° to 75°
(2)	90° and 15°
(3)	0° Extensions of side

To use scale (2) (3) project hoizontally to (1) then use straight inclined line through D and Q scales, or reverse as illustrated.

CHART 11

HEADWATER DEPTH FOR RECTANGULAR BOX CULVERTS WITH INLET CONTROL FLARED WINGWALLS 18° TO 33.7° AND 45° WITH BEVELED EDGE AT TOP OF INLET

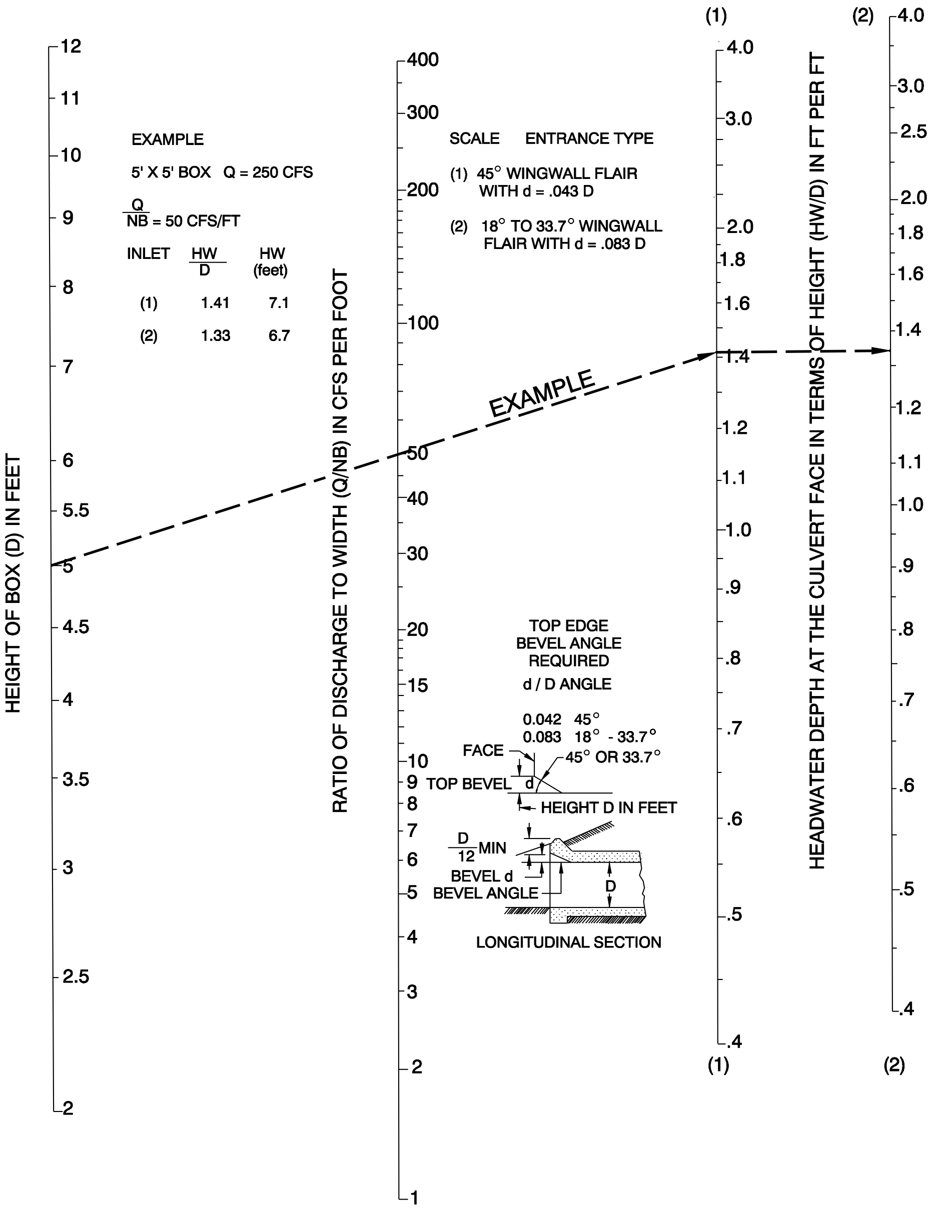
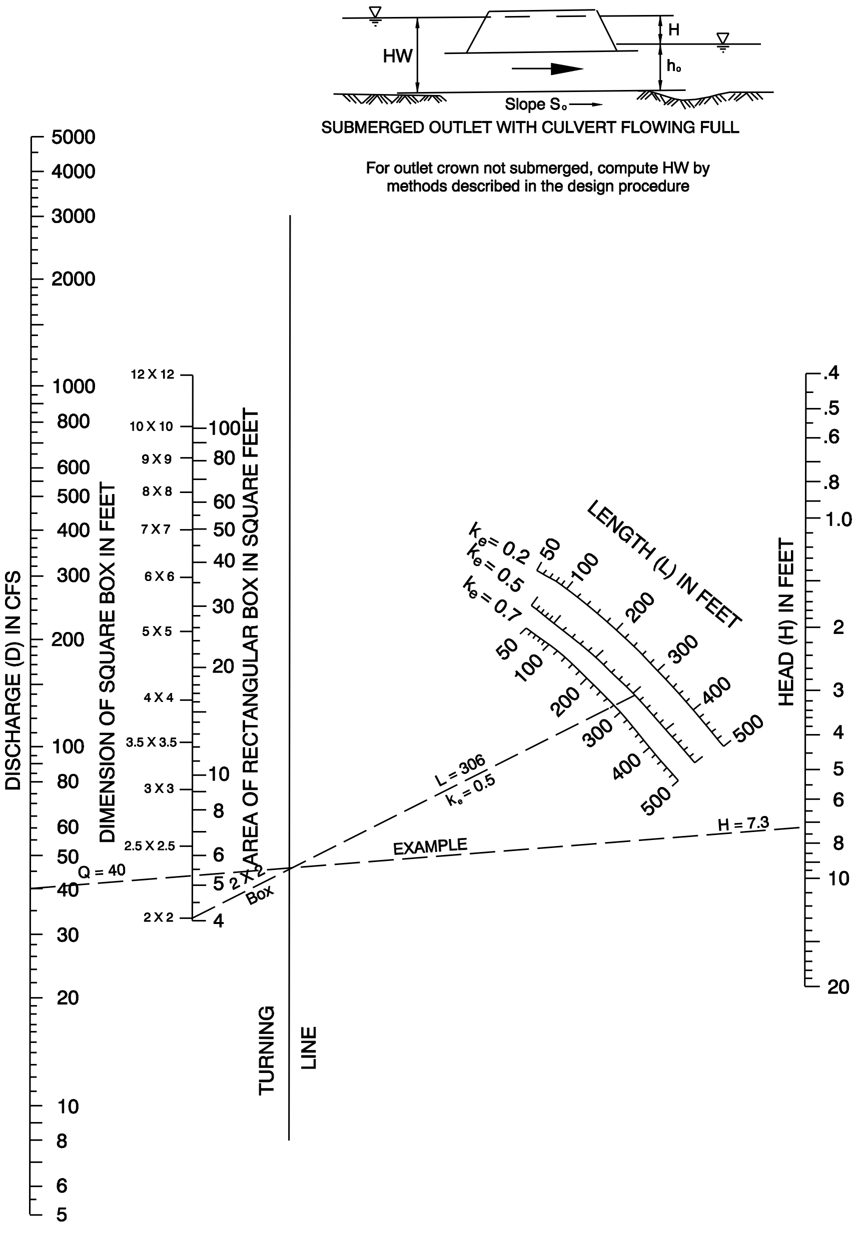


CHART 12

HEAD FOR
CONCRETE BOX CULVERTS
FLOWING FULL IN OUTLET CONTROL
n = 0.012

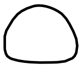


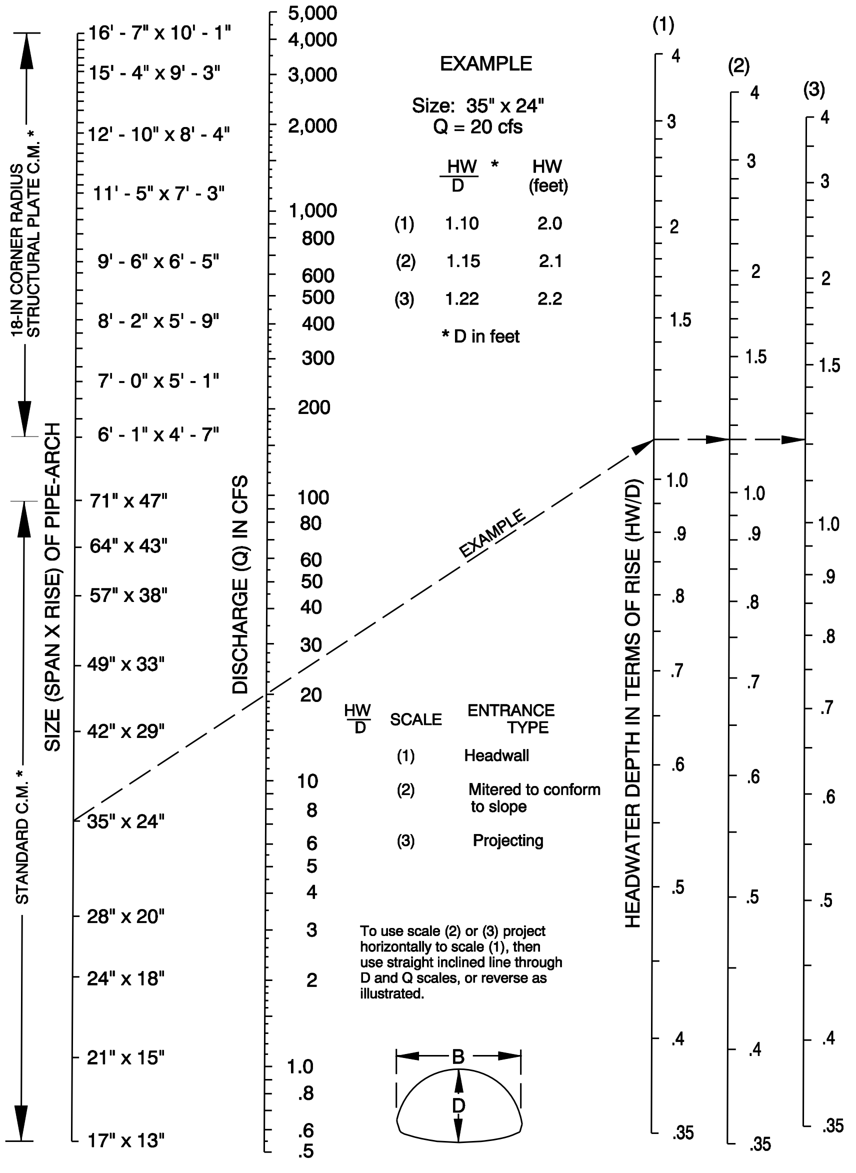
SUBMERGED OUTLET WITH CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure

CHART 13

HEADWATER DEPTH FOR C.M. PIPE-ARCH CULVERTS WITH INLET CONTROL

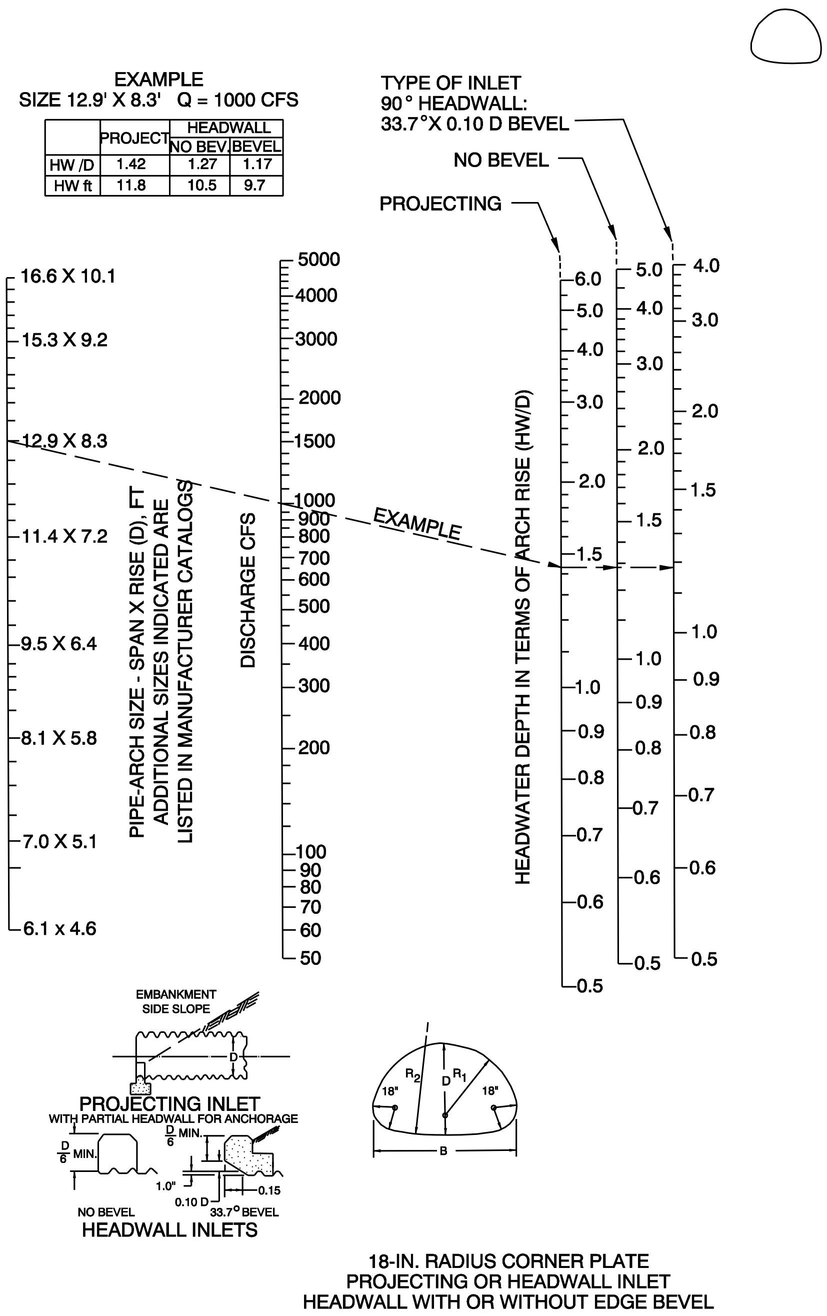




* ADDITIONAL SIZES NOT DIMENSIONED ARE LISTED IN FABRICATOR'S CATALOG

CHART 14

HEADWATER DEPTH FOR STRUCTURAL PLATE PIPE-ARCH CULVERTS WITH INLET CONTROL

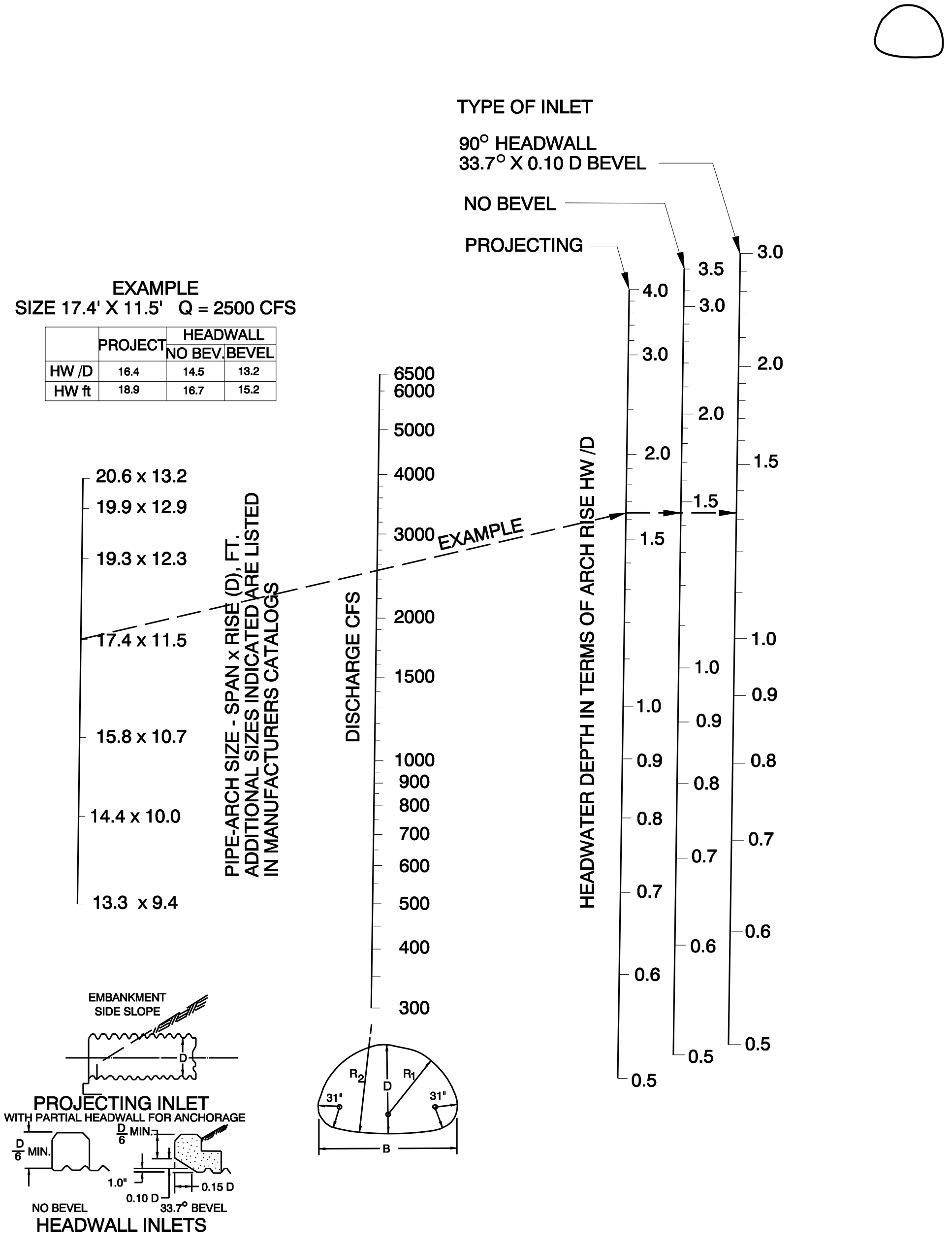


EXAMPLE
SIZE 12.9' X 8.3' Q = 1000 CFS

	PROJECT	HEADWALL NO BEV.	HEADWALL BEVEL
HW /D	1.42	1.27	1.17
HW ft	11.8	10.5	9.7

CHART 15

HEADWATER DEPTH FOR STRUCTURAL PLATE PIPE-ARCH CULVERTS WITH INLET CONTROL



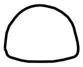
EXAMPLE
SIZE 17.4' X 11.5' Q = 2500 CFS

	PROJECT	HEADWALL	
		NO BEV.	BEVEL
HW /D	16.4	14.5	13.2
HW ft	18.9	16.7	15.2

31-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

CHART 16

HEAD FOR
STANDARD C.M. PIPE-ARCH CULVERTS
FLOWING FULL IN OUTLET CONTROL
n = 0.024



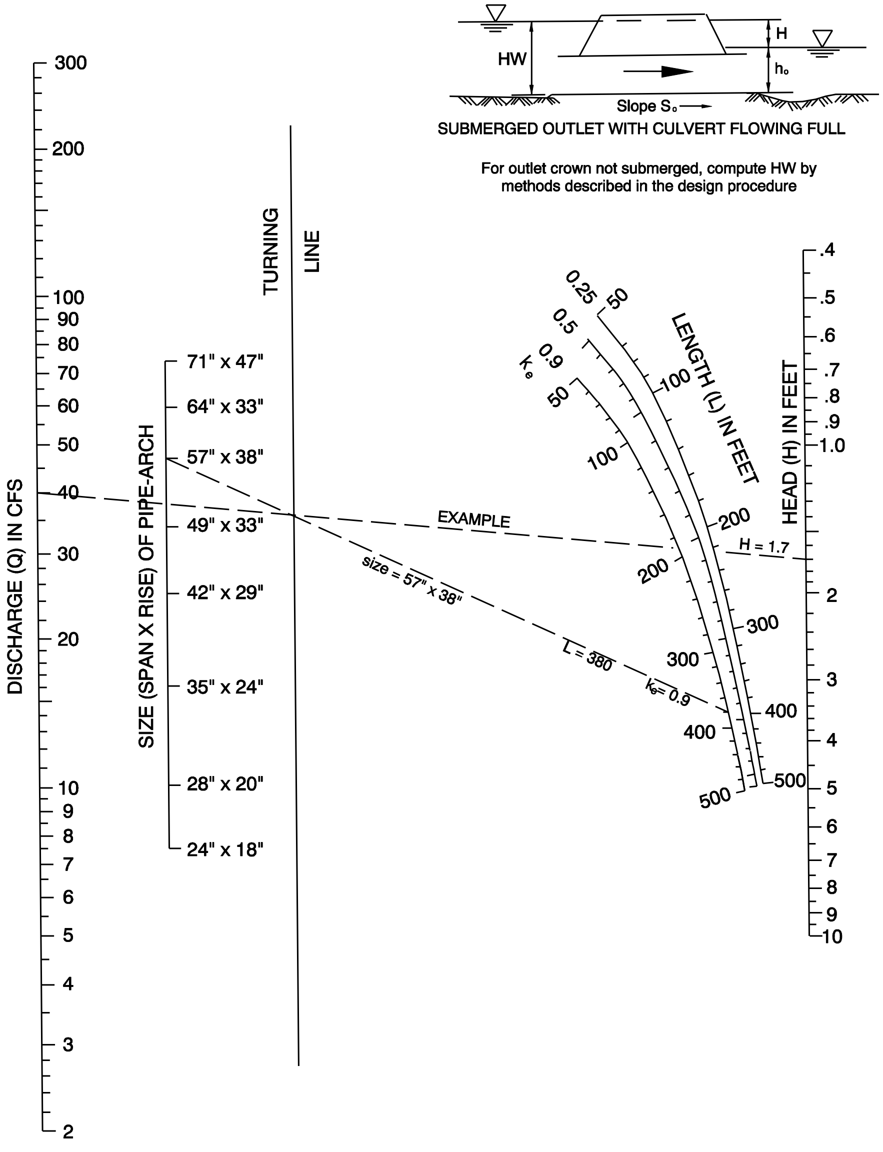
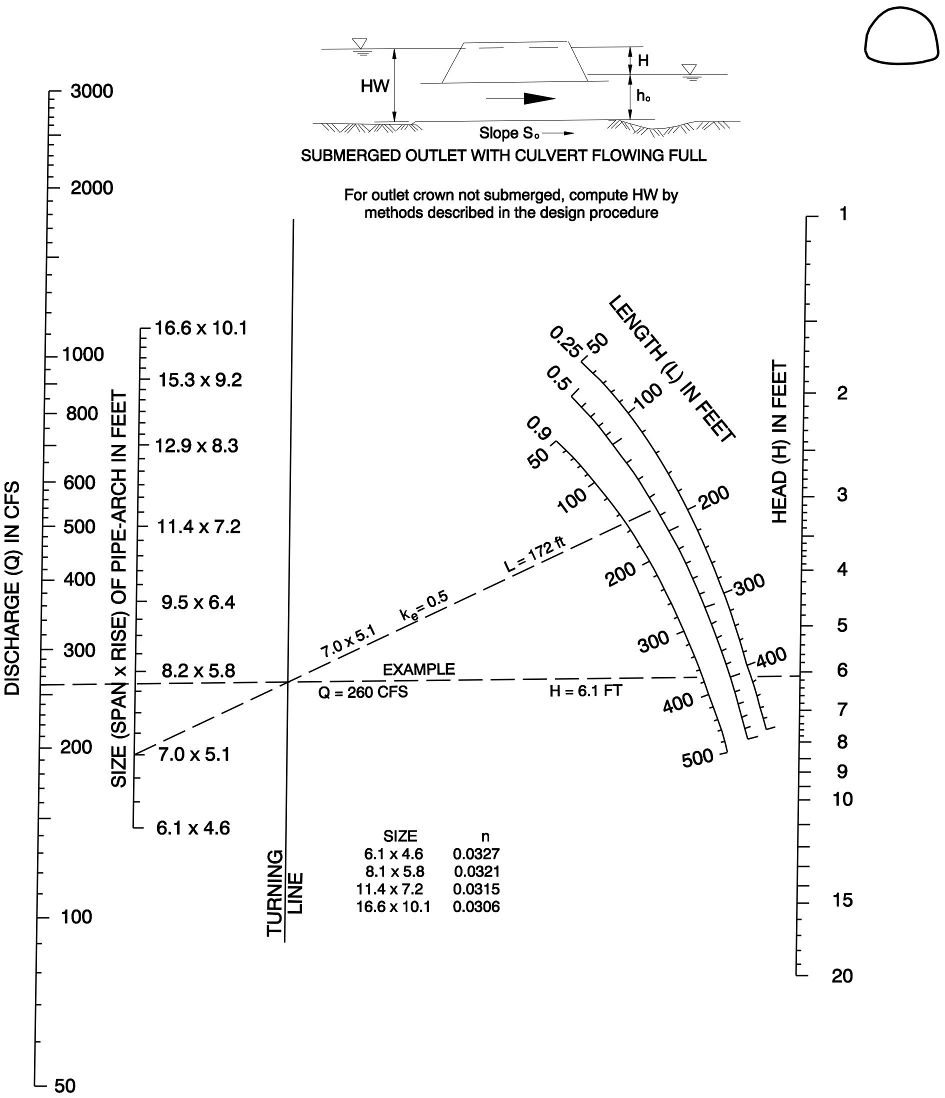


CHART 17

HEAD FOR STRUCTURAL PLATE CORRUGATED METAL PIPE ARCH CULVERTS 18 IN. CORNER RADIUS FLOWING FULL IN OUTLET CONTROL n= 0.0327 TO 0.0306



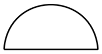
SUBMERGED OUTLET WITH CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure

SIZE	n
6.1 x 4.6	0.0327
8.1 x 5.8	0.0321
11.4 x 7.2	0.0315
16.6 x 10.1	0.0306

CHART 18

HEADWATER DEPTH FOR C.M. ARCH CULVERTS 0.3 ≤ RISE / SPAN <0.4 WITH INLET CONTROL



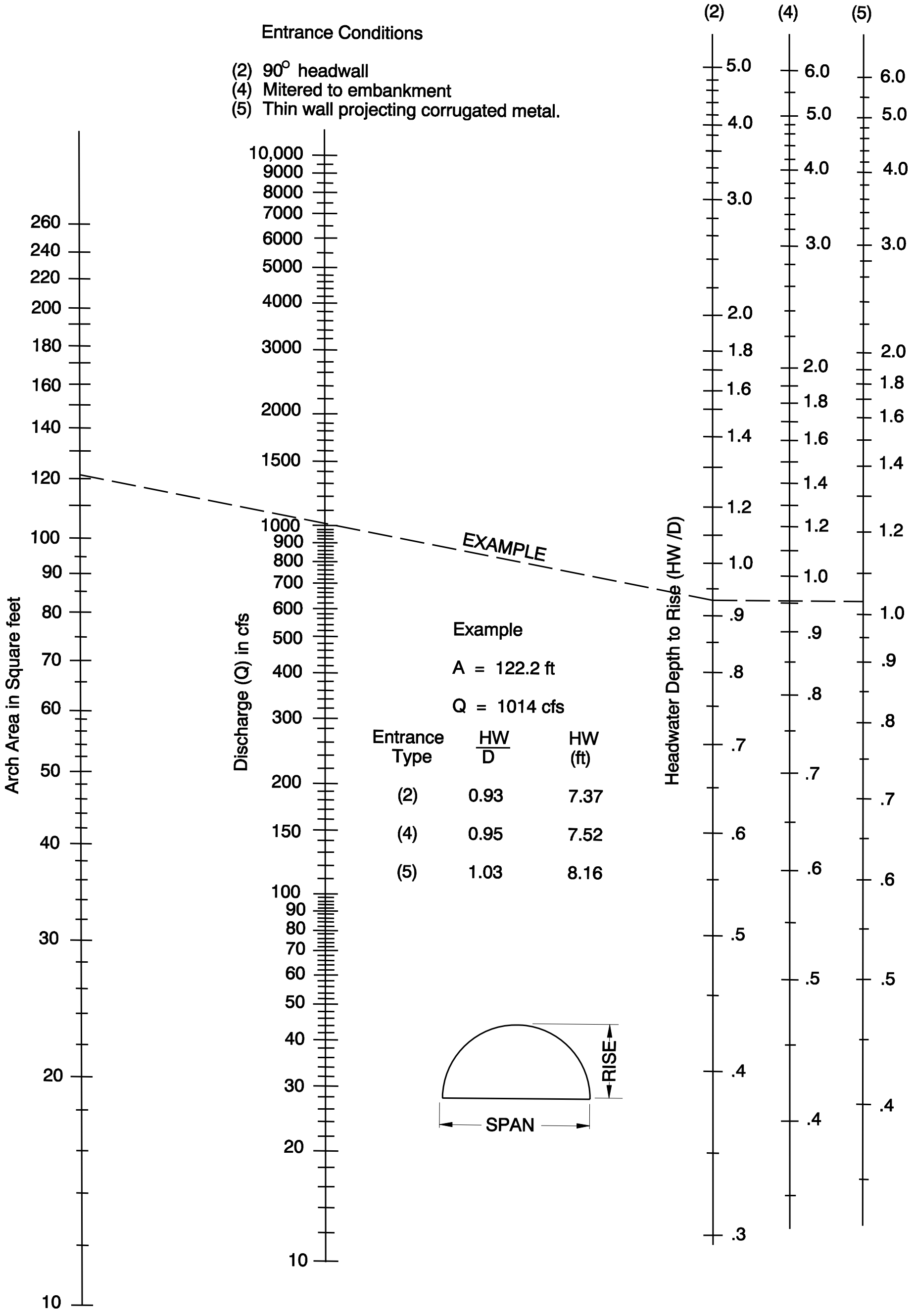


CHART 19

HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.4 ≤RISE / SPAN <0.5
WITH INLET CONTROL

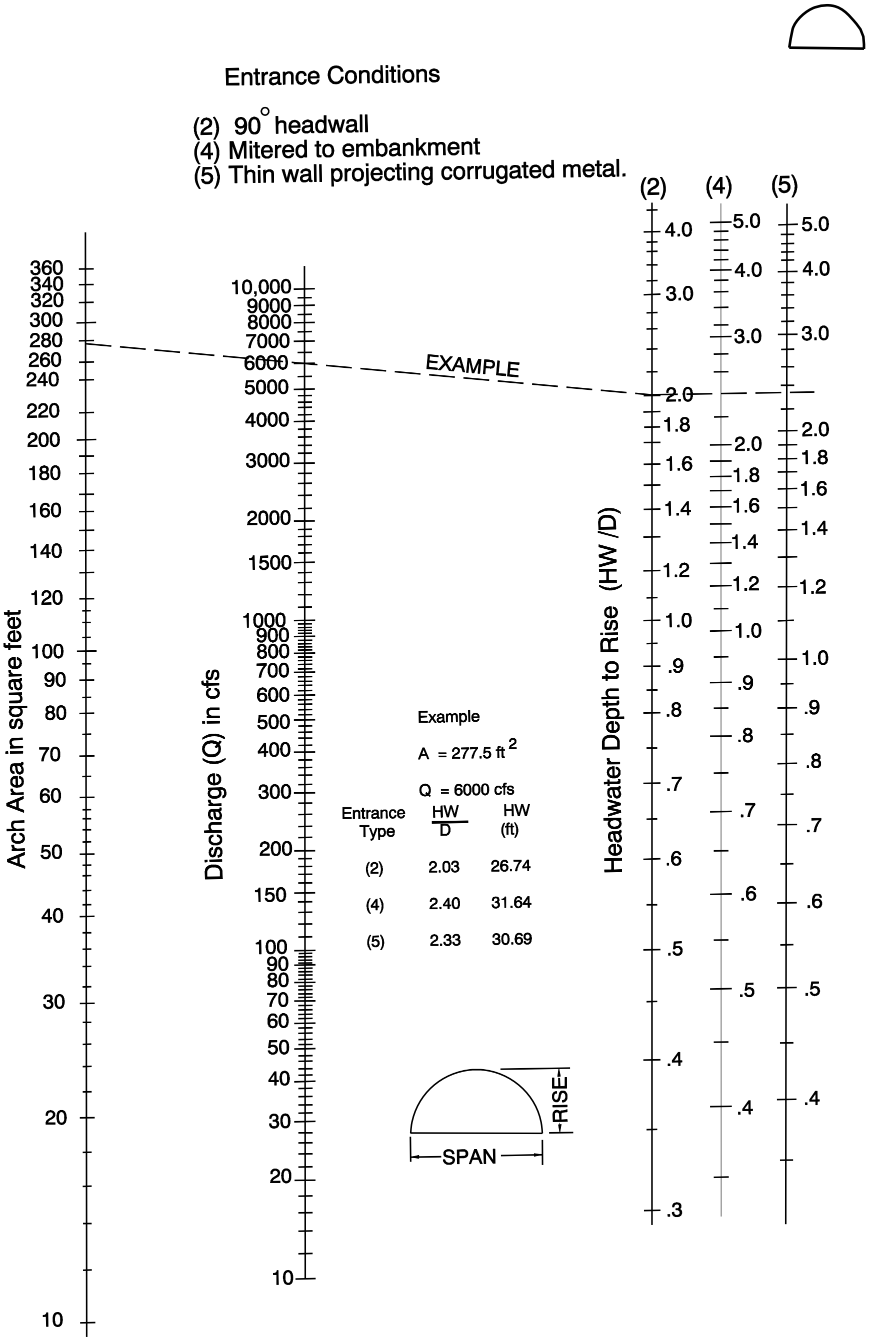
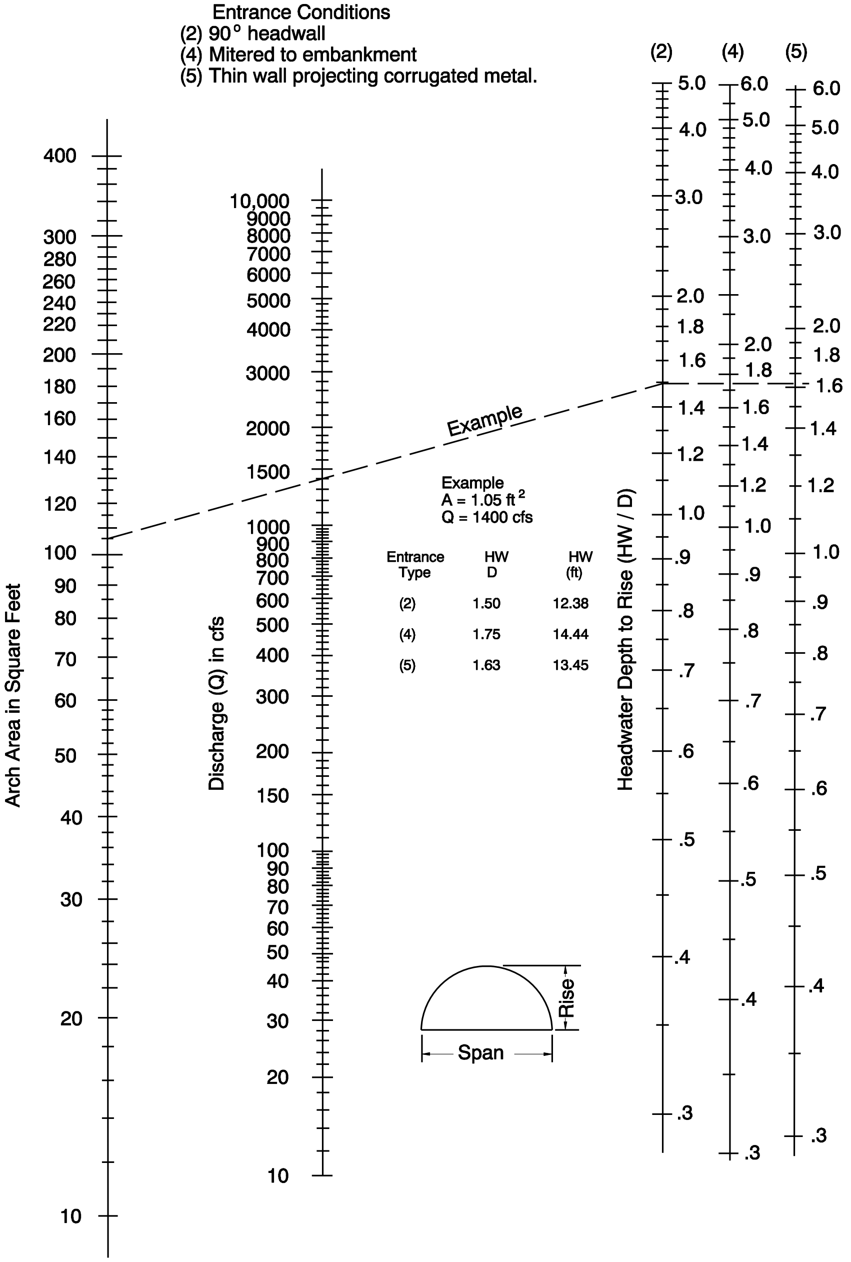


CHART 20

HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.5 ≤ RISE /SPAN
WITH INLET CONTROL

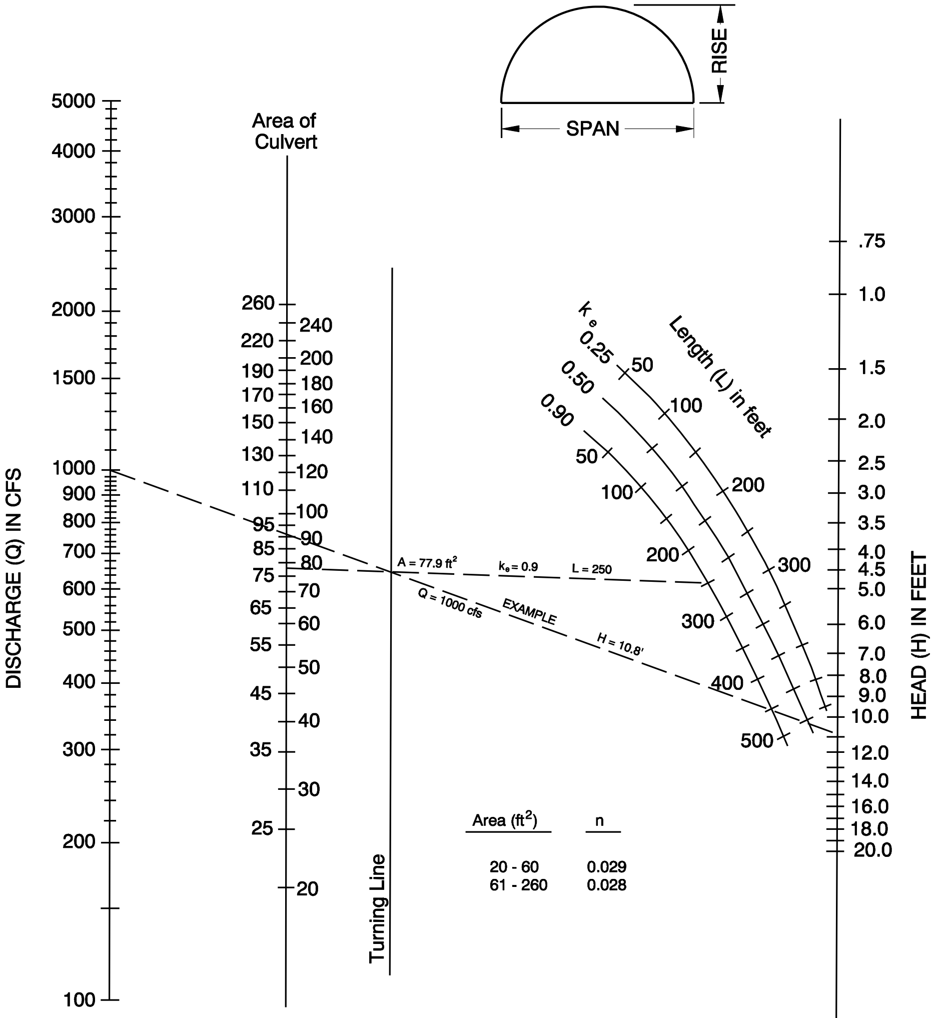


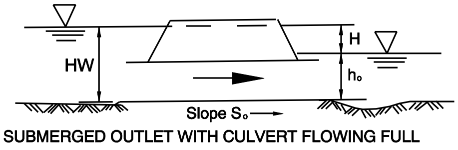
Example
A = 1.05 ft^2
Q = 1400 cfs

Entrance Type	HW D	HW (ft)
(2)	1.50	12.38
(4)	1.75	14.44
(5)	1.63	13.45

CHART 21

HEAD FOR C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM ($n_b = 0.022$)
$0.3 \leq$ RISE / SPAN <0.4



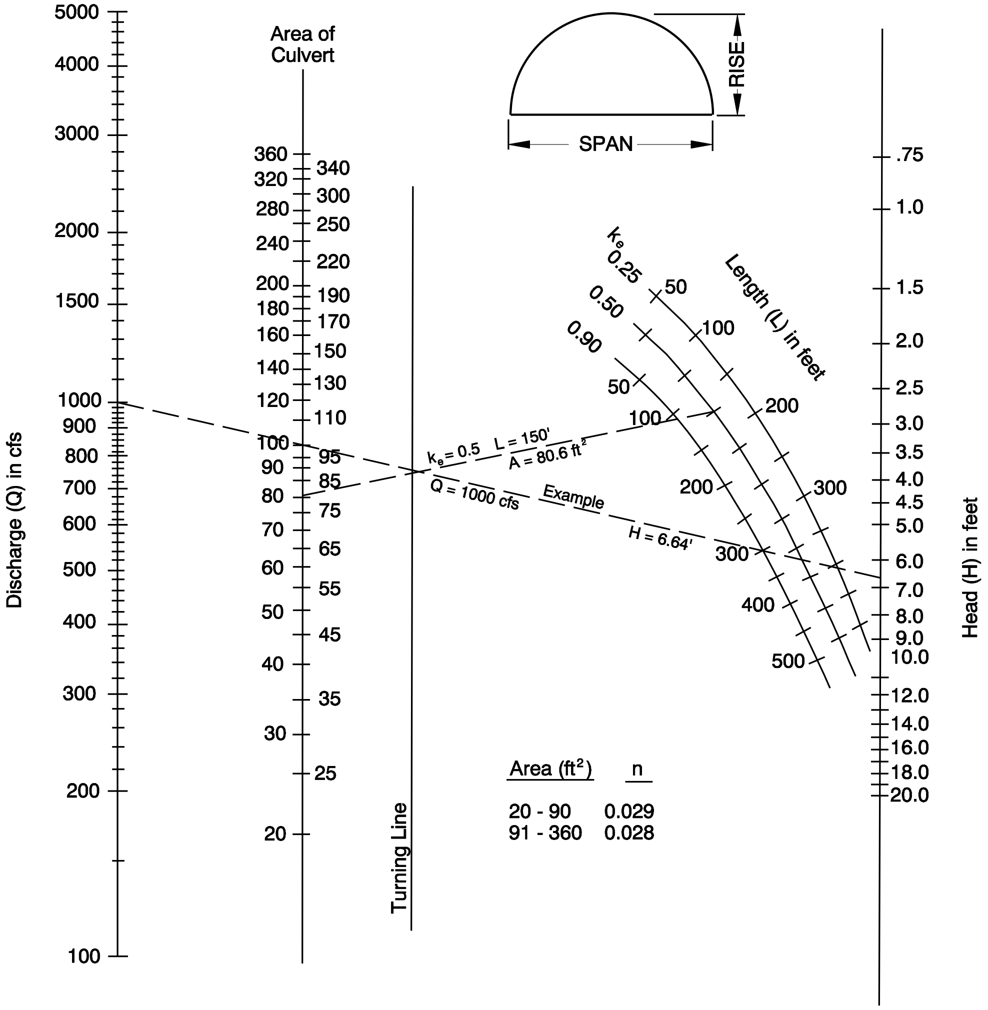


SUBMERGED OUTLET WITH CULVERT FLOWING FULL

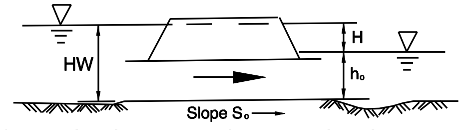
For outlet crown not submerged, compute HW by methods described in the design procedure

CHART 22

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL IN OUTLET CONTROL EARTH BOTTOM (n_b =0.022) 0.4 ≤ RISE / SPAN < 0.5



Area (ft²)	n
20 - 90	0.029
91 - 360	0.028

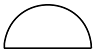


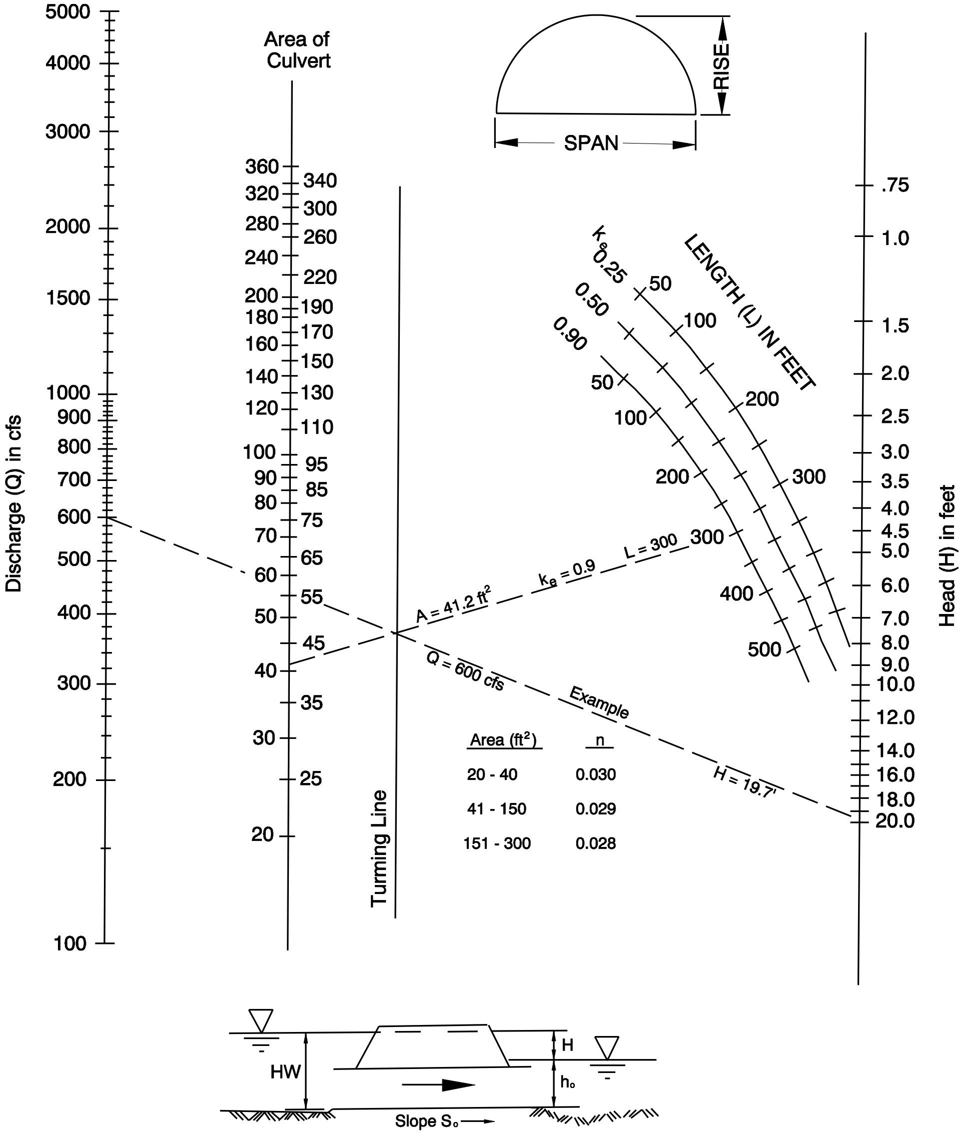
SUBMERGED OUTLET WITH CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure

CHART 23

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL IN OUTLET CONTROL EARTH BOTTOM (n_b=0.022) 0.5 ≤ RISE / SPAN





Area (ft²)	n
20 - 40	0.030
41 - 150	0.029
151 - 300	0.028

SUBMERGED OUTLET WITH CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure

APPENDIX B – CULVERT DESIGN SHEET

Oregon Department of Transportation (01/99)

CULVERT DESIGN SHEET

PROJECT	STATION	DESIGNER	DATE	SHEET OF

HYDROLOGICAL DATA

METHOD: ____________________

DRAINAGE AREA: ______________ (acres)

STREAM SLOPE: ______________ (ft/ft)

CHANNEL SHAPE: ____________________

DESIGN AND CHECK FLOWS / TAILWATER

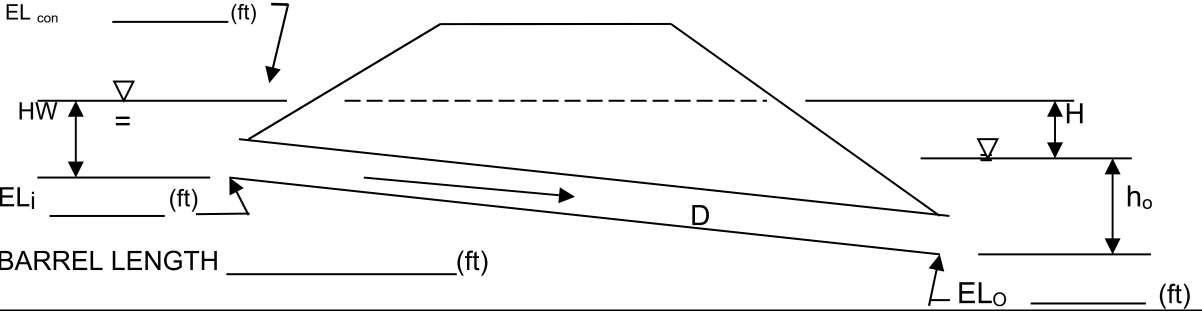
	R.I. (years)	Q (cfs)	TW (ft)
DES	________	________	________
CHK	________	________	________

CHECK FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION ____________________ (ft)

DESIGN FLOOD MAXIMUM ALLOWABLE HEADWATER ELEVATION ____________________ (ft)

CHK EL con ________ (ft)

DES EL con ________ (ft)



EL_i ________ (ft)

BARREL LENGTH ______________ (ft)

EL_O ________ (ft)

TECHNICAL FOOTNOTES:

(1) USE INLET CONTROL NOMOGRAPH **(2)** $El_{hi} = HW + El_i$ **(3)** TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL

(4) $h_o = TW$ or $\frac{d_c+D}{2}$ (WHICHEVER IS GREATER) **(5)** $H = [1 + k_e + (29n^2L / R^{1.33})](V^2/2g)$ OR USE OUTLET CONTROL NOMOGRAPH

(6) $El_{ho} = El_o + H + h_o$ **(7)** USE HIGHER OF El $_{hi}$ or El $_{ho}$ FOR EL_{con}

CULVERT DESCRIPTION MATERIAL – SHAPE – SIZE – ENTRANCE	FLOW PER BARREL Q/N (cfs)	HEADWATER CALCULATIONS												COMMENTS
		INLET CONTROL			OUTLET CONTROL									
		(1) $\frac{HW}{D}$	HW (ft)	(2) EL_{hi} (ft)	(3) TW (ft)	d_c (ft)	$\frac{d_c + D}{2}$ (ft)	(4) h_o (ft)	k_e	(5) H (ft)	(6) EL_{ho} (ft)	(7) EL_{con} (ft)	V (fps)	

COMMENTS/DISCUSSION:

VARIABLE / SUBSCRIPT DEFINITIONS

D = Diameter or Rise of Barrel (ft)
D_c = Critical Depth at Culvert Outlet (ft)
EL_{con} = Control Headwater Elevation
EL_{hd} = Design Headwater Elevation (ft)
EL $_{hi}$ = Inlet Control Headwater Elevation (ft)
EL_{ho} = Outlet Control Headwater Elevation (ft)
EL_i = Inlet Invert Elevation (ft)
EL_o = Outlet Invert Elevation (ft)
G = Acceleration of Gravity (32.2 ft/s^2)
H = Total Outlet Control Head Loss (ft)
h_o(ft) See Technical Footnote 4
HW = Inlet Control Headwater Depth (ft)
k_e = Outlet Control Entrance Loss Coefficient
N = Number of Barrels
n = Manning's Roughness Coefficient
Q = Discharge (ft^3/s)
R = Hydraulic Radius (ft)
R.I. = Recurrence Interval (Years)
TW = Tailwater Depth (ft)
V = Average Velocity in Barrel (ft/s)

INVERT ABRASION PROTECTION

☐ YES TYPE ______________________________
☐ NO ______________________________

CULVERT BARREL SELECTED

SIZE ______________ SHAPE: ______________

MATERIAL: ______________ n= ______________ ENTRANCE: ______________

APPENDIX C – DEBRIS CONTROL STRUCTURES

FHWA Hydraulics Engineering Circular #9 Debris-Control Structures

This circular provides information on debris accumulation and the various debris control countermeasures available for culvert and bridge structures. This circular presents various problems associated with debris accumulation at culvert and bridge structures and provides general guidelines for analyzing and modeling debris accumulation on a bridge structure to determine the impacts that the debris would have on the water surface profile through the bridge structure and the hydraulic loading on the structure. Various types of debris countermeasures for culvert and bridge structures are discussed with in this circular. General criteria for selection of these countermeasures and general design guidelines for some of the structural measures are also included in this FHWA manual.

Note: Project environmental personnel should be contacted if it is proposed to install these structures when fish passage is a concern. They can tell you if they are allowed and if there are any environmental concerns.

The following web address is the Federal Highway Administration's Publications site which has the Circular "Debris Control Structures, HEC 9" (latest edition).

http://www.fhwa.dot.gov/engineering/hydraulics/library_listing.cfm

Oregon
Department
of Transportation

Chapter 9
Fish Passage

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Chapter 9

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9.1 Introduction

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

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

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

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

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

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

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

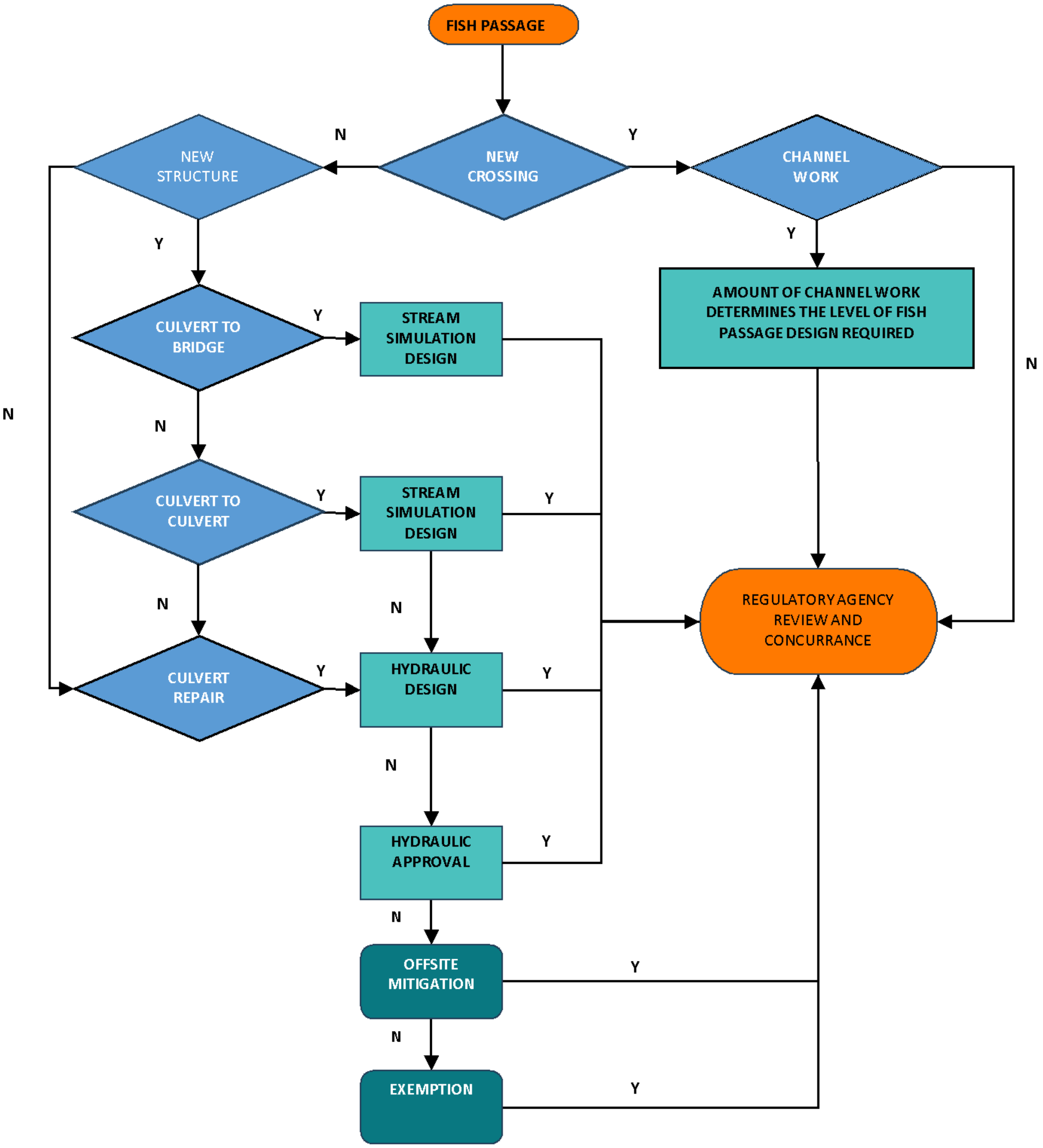


Figure 9.1-1: Fish Passage Project Flow Chart

9.2 Documentation

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

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

9.3 Regulatory Compliance

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

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

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

9.4 Fish Passage Triggers

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

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

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

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

9.5 Hydraulic Approvals

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

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

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

9.6 Fish Passage Hydrology

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

♦ Design Hydrology

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

Base Flood

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

Design Discharge

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

High and Low Fish Passage Design Flows

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

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

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

Table 9.6-1: Fish Passage Design flows

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

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

9.7 Ecological Approach for Stream Crossings

9.7.1 Ecological Concepts

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

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

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

9.7.2 Importance of Movement

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

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

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

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

◆ Stream Crossing Effects on Habitats

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

♦ Upstream Aggradation

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

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

♦ Downstream Degradation

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

9.7.3 Stream Crossing Effects on Fish Passage

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

♦ Outlet Drop

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

Figure 9.7-1: Outlet drop

♦ Physical Barriers

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

Figure 9.7-2: Inlet sediment accumulation

♦ High Water Velocities

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

Figure 9.7-3: High velocities

♦ Insufficient Water Depth

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

Figure 9.7-4: Insufficient water depth

♦ Inlet Transition Velocity

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

9.7.4 Summary of Ecological Considerations

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

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

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

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

9.8 Stream Simulation Concepts

9.8.1 Introduction

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

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

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

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

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

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

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

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

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

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

9.8.2 Key Elements of Stream Simulation

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

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

9.8.3 Stream Reach and Site Assessment

♦ Steps and Considerations for a Site Assessment

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

    - ii) Long term aggradation potential
- d) General channel stability
    - i) Entrenchment ratio

9.8.4 Data Collection

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

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

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

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

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

♦ Channel Types and Bed Mobility

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

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

♦ Site Considerations

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

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

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

9.8.5 Interpreting Site Data

♦ Sediment Process and Mobility

Site assessment documentation for bed mobility should include:

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

Information for the reference reach should include:

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

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

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

♦ Analyzing the Long Profile

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

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

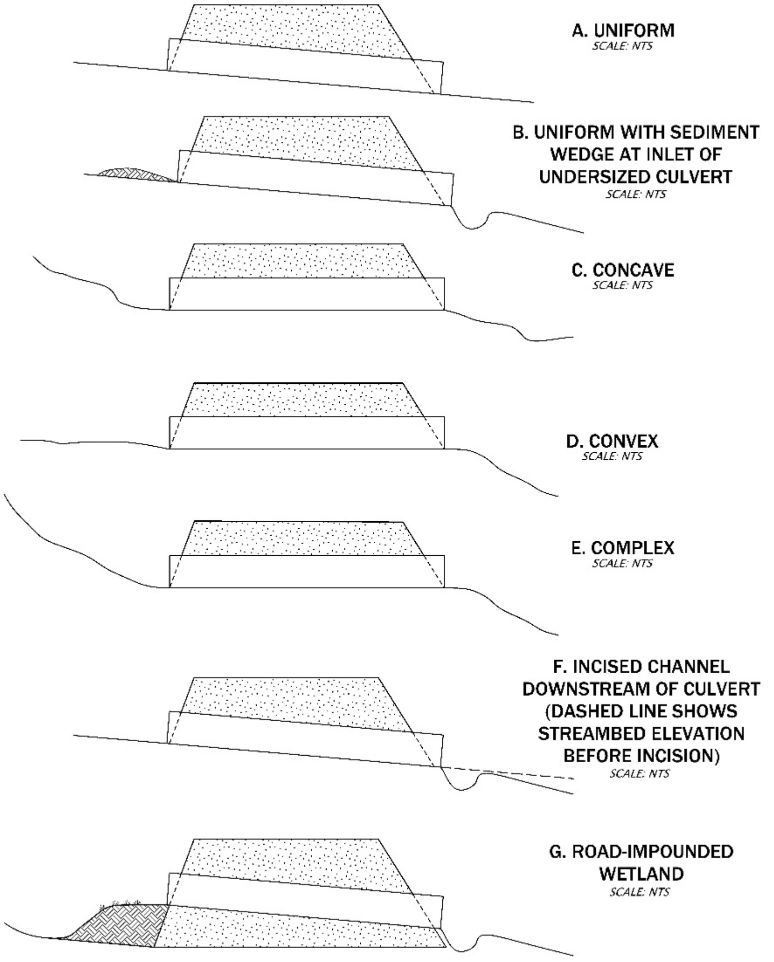


Figure 9.8-1: Road crossing profiles (Forest Service Stream-Simulation Working Group 2008)

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

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

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

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

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

♦ Potential Vertical Adjustment

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

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

- Channel incision caused by downstream base-level change.

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

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

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

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

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

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

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

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

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

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

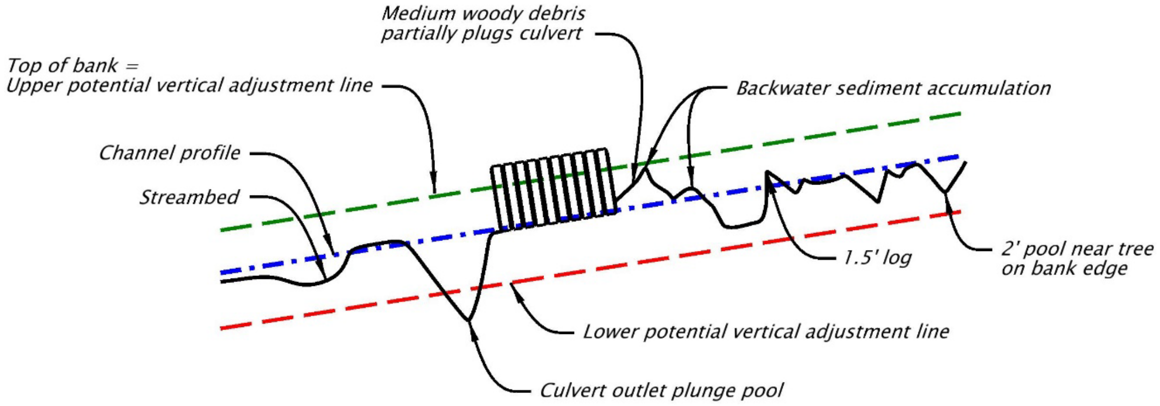


Figure 9.8-2: Uniform Profile

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

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

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

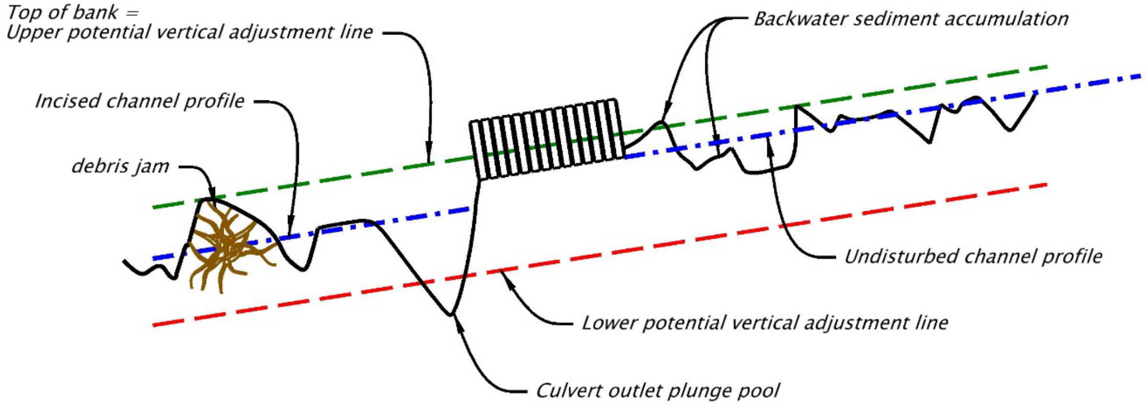


Figure 9.8-3: Incised Channel Profile

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

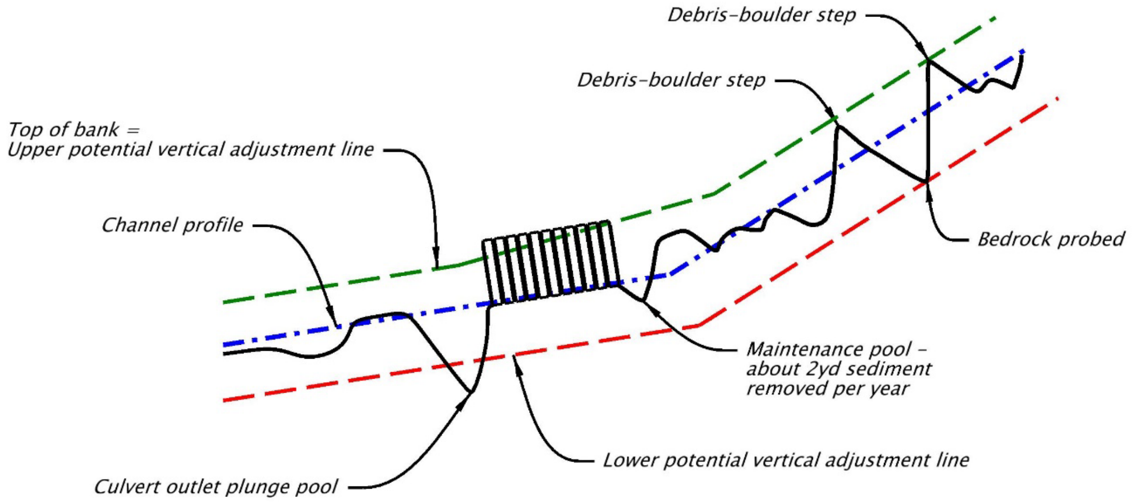


Figure 9.8-4: Concave Slope Transition

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

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

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

9.8.6 Site Risk Assessment

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

♦ Flood Conveyance

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

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

♦ Potential for Lateral Movement

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

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

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

♦ Potential for Head-cutting

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

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

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

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

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

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

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

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

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

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

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

♦ Potential for Wood Debris

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

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

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

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

Table 9.8-1: Risks for Woody debris

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

♦ Unstable Channels

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

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

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

9.8.7 Selecting the Reference Reach

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

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

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

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

The following considerations go into selecting a reference reach:

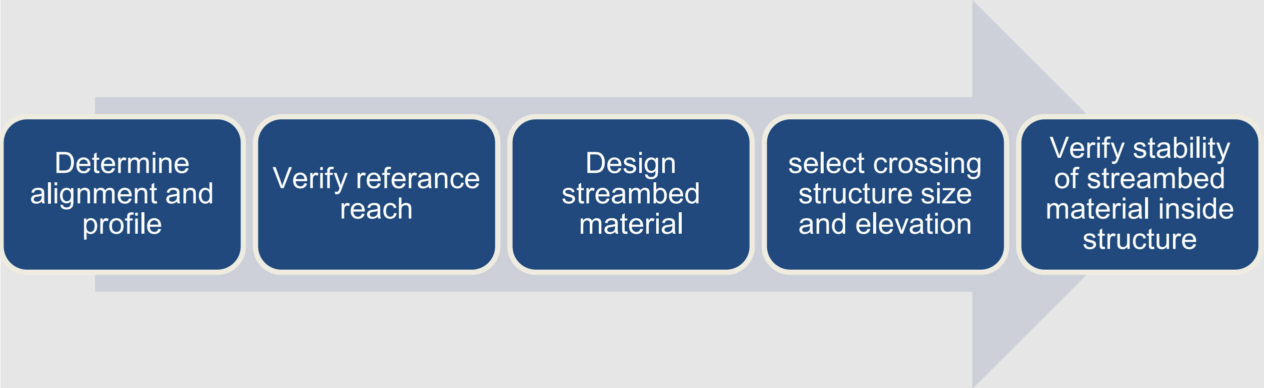
- The reference reach should be out of the area of influence of the existing crossing. Generally, it is upstream of the crossing to avoid any downstream channel changes the crossing may have caused. However, it can also be downstream if crossing effects are localized, and channel dimensions and slope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

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

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

9.9 Stream Simulation Design

9.9.1 Steps and Considerations in Design



9.9.2 Crossing Alignment and Profile

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

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

◆ Alignment

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

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

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

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

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

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

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

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

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

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

♦ Crossing Alignment

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

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

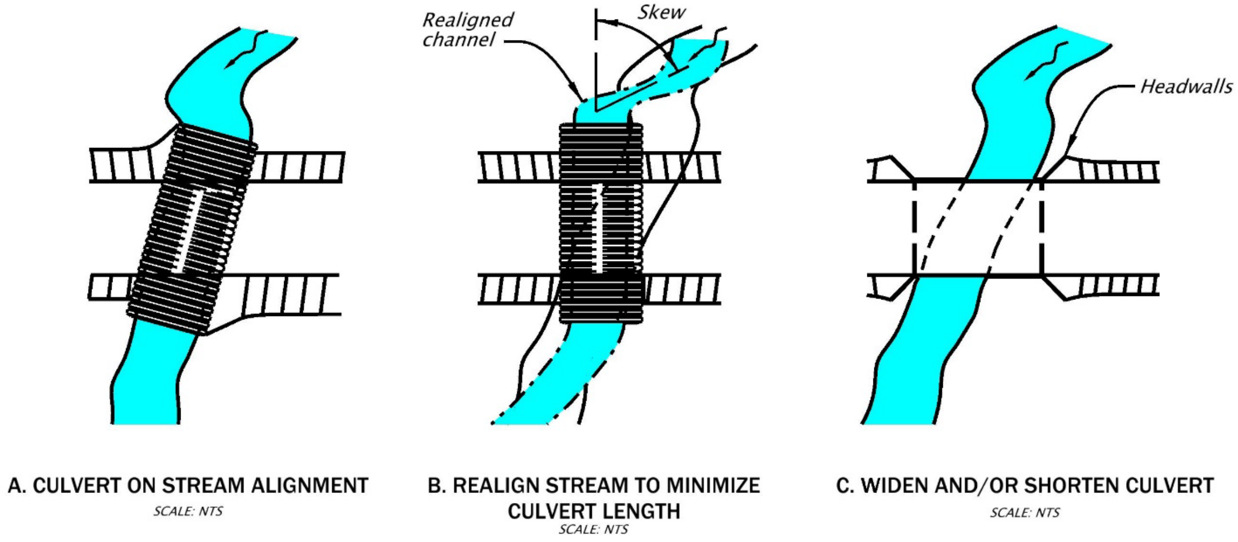


Figure 9.9-1: Crossing alignment options for crossing vs. channel skew.

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

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

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

♦ Profile

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

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

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

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

Designing the project profile involves the following steps.

1. Identify stable endpoints for the project profile.

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

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

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

2. Delineate possible project profiles.

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

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

3. Verify the reference reach.

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

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

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

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

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

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

4. Adjust the profile lines if necessary.

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

5. Locate key bed features.

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

9.9.3 Crossing Channel

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

This section describes design of the following streambed elements:

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

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

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

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

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

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

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

9.9.4 Channel Cross Section

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

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

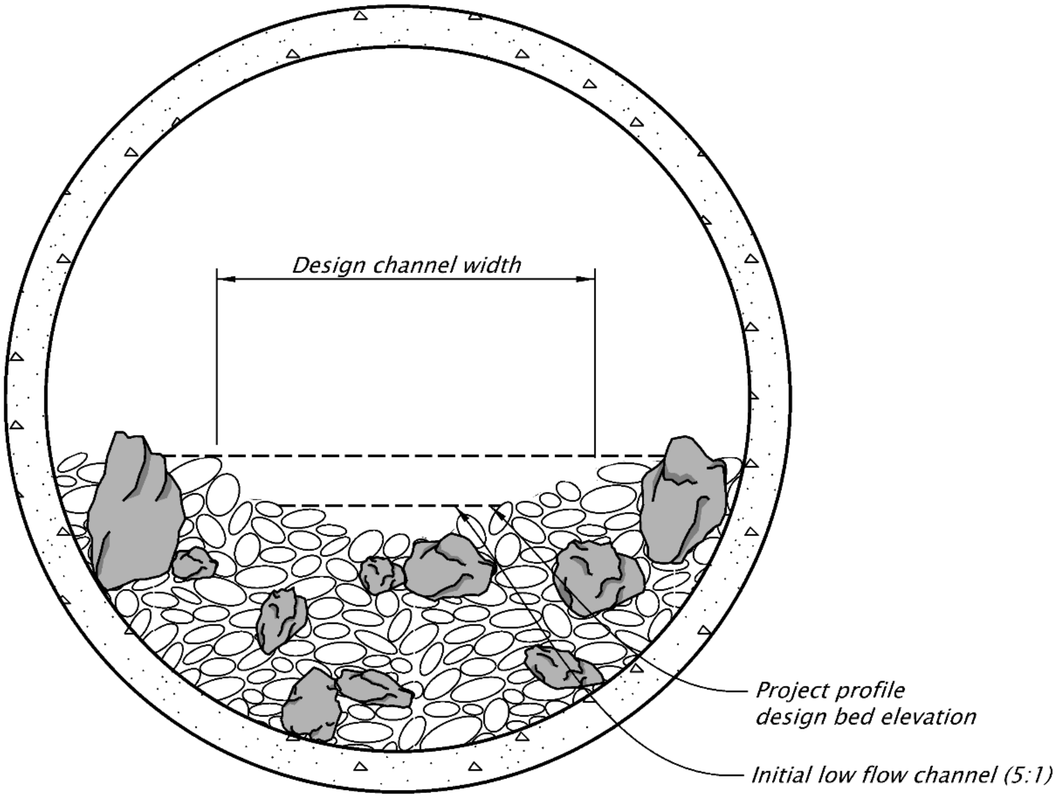


Figure 9.9-2: Channel Section within culvert

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

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

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

9.9.5 Channel Bank and Margin Features

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

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

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

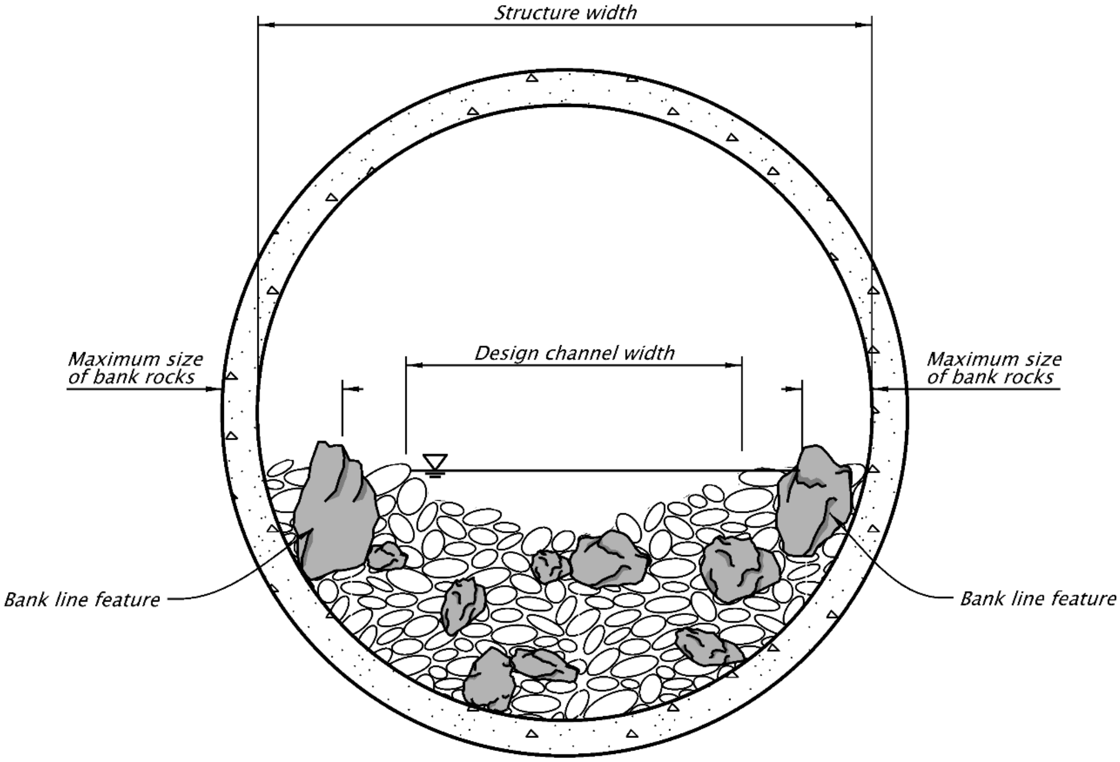


Figure 9.9-3: Bank line features

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

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

9.9.6 Engineered Streambed Material

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

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

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

The Fuller-Thompson equation is:

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

Where: d is any particle size of interest

P is the percentage of the mixture smaller than d,

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

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

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

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

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

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

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

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

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

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

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

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

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

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

9.9.7 Structure Dimensions and Type

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

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

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

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

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

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

♦ Structure Width

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

In Oregon, the minimum required agency widths are:

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

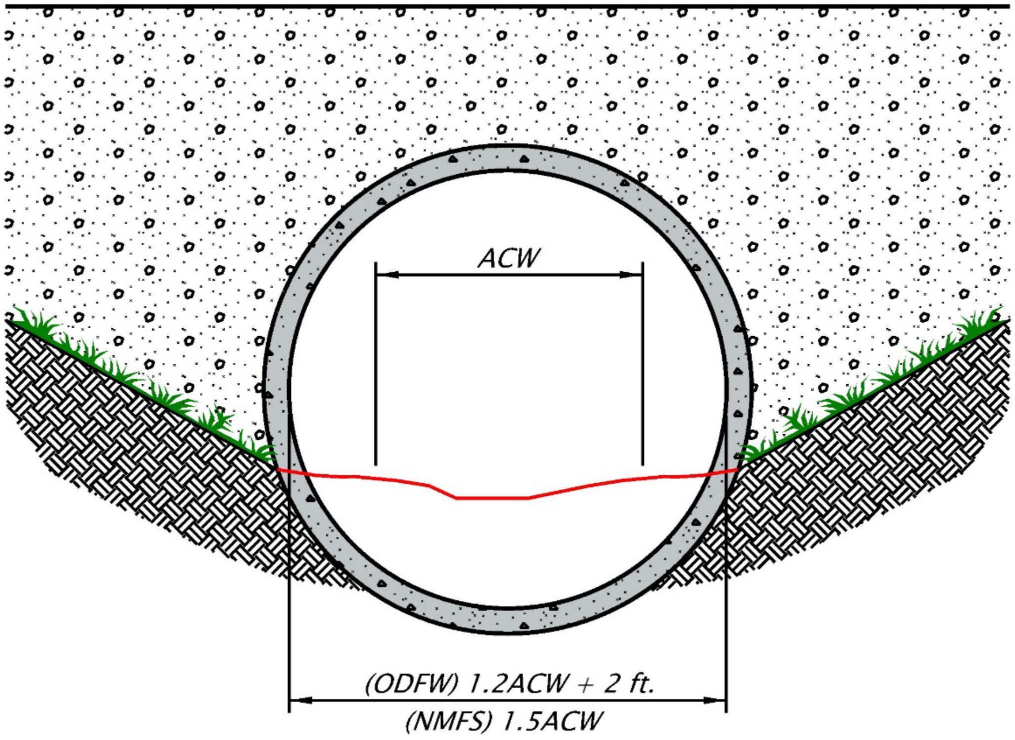


Figure 9.9-4: Circular culvert

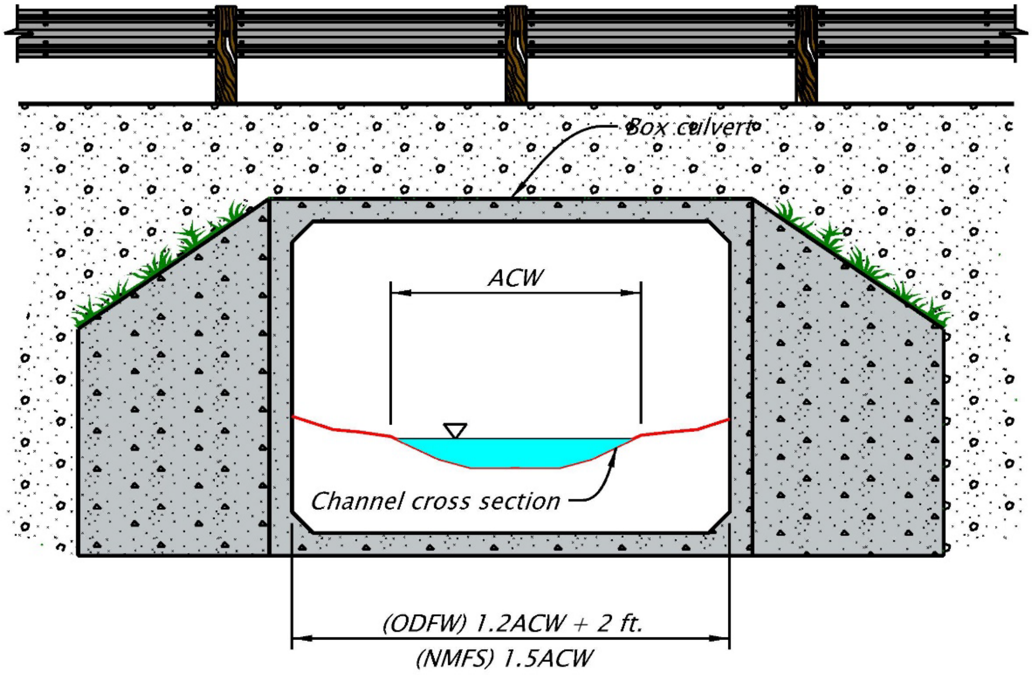


Figure 9.9-5: Box culvert

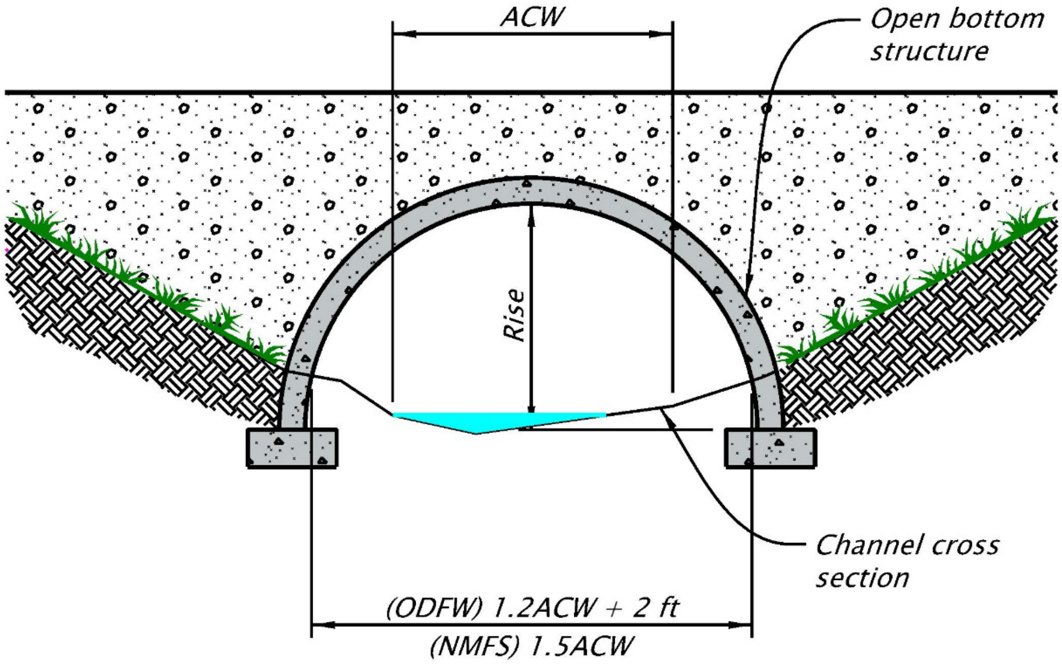


Figure 9.9-6: Open Bottom Structure width

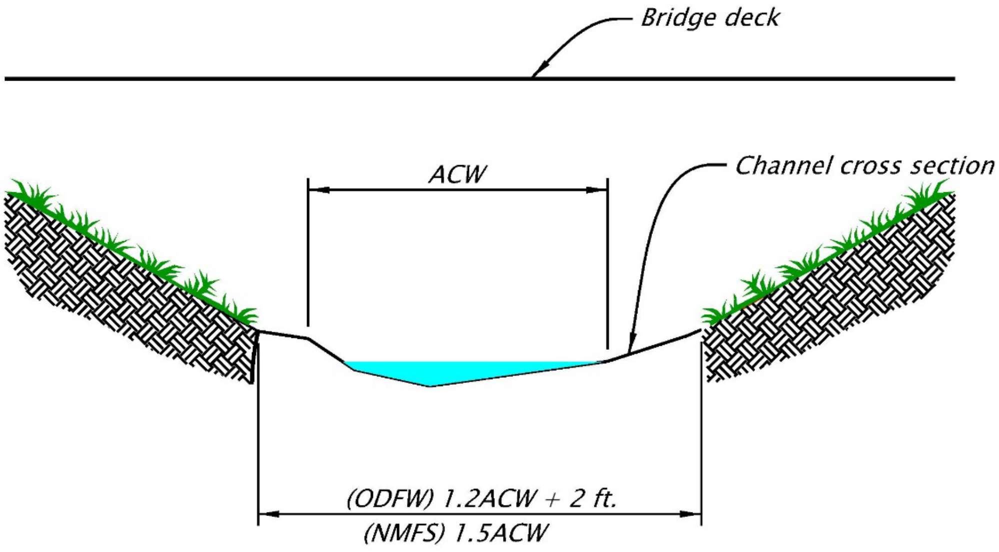


Figure 9.9-7: Bridge Width

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

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

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

♦ Culvert Width

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

The minimum width required is as stated above.

Based on project objectives:

- Stability of the simulated streambed.

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

Based on site characteristics:

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

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

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

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

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

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

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

♦ Culvert Height and Elevation

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

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

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

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

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

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

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

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

♦ Culvert Shape and Material

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

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

9.9.8 Managing Risk Factors

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

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

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

♦ Potential Failure Risks

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

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

Table 9.9-2: Mitigating Potential Risks

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

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

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

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

♦ Flood-plain Constriction

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

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

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

- Minimize flow concentration.

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

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

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

- Conduct a hydraulic and bed mobility/stability analysis.

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

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

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

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

- Increase crossing structure width.

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

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

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

- Increase bed material particle size.

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

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

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

◆ Rapid lateral channel migration

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

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

◆ Steepened channel

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

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

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

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

♦ Downstream channel instability

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

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

♦ Inlet control

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

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

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

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

♦ Initial lack of streambed consolidation

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

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

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

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

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

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

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

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

♦ Excessive infiltration into streambed

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

9.10 Hydraulic Design Method

9.10.1 Description and Application

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

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

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

9.10.2 Criteria and Guidelines

♦ Width

Refer to Section 9.9.7 Structure Width.

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

♦ Fish Passage Design Flows

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

♦ Vertical Clearance

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

♦ Slope

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

♦ Culvert Embedment

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

♦ Water Velocity

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

In Oregon, the maximum average water velocities are:

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

♦ Hydraulic Drop Height

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

ODFW:

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

NMFS:

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

♦ Minimum Flow Depth

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

ODFW:

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

NMFS:

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

9.11 Backwater Control Structures

9.11.1 Rock Sizing

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

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

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

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

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

9.11.2 Boulder Cluster Design Method

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

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

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

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

9.11.3 Hydrostatic (Overturning Moment) Method

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

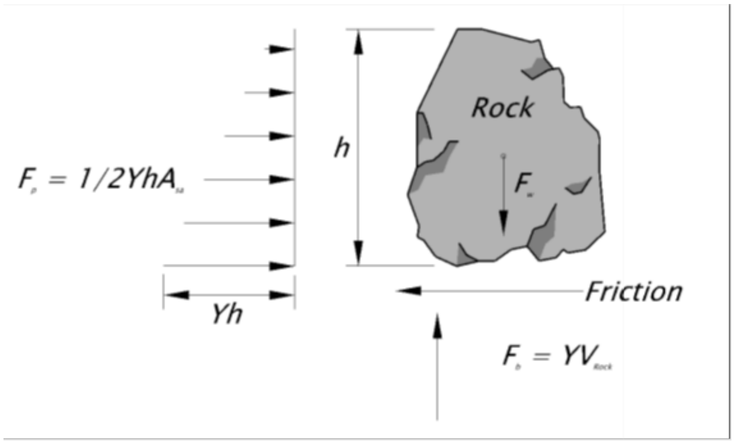


Figure 9.11-1: Rock free body diagram

Equation 9.10-1 $F_P = ½ ϒhA_{sa}$

Equation 9.10-2 $Fw = ϒV_{rock}$

Where:

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

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

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

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

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

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

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

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

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

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

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

9.11.4 Boulder Weir Design

◆ Weir Embedment

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

◆ Toe Scour Estimation Method

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

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

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

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

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

Equation 9.10-3

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

Where:

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

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

Equation 9.10-4

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

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

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

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

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

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

Crest Width = 2 x (Boulder Weir D50)

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

Equation 9.10-5

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

Where:

R = boulder weir radius (ft.)

L = chord length (ft.)

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

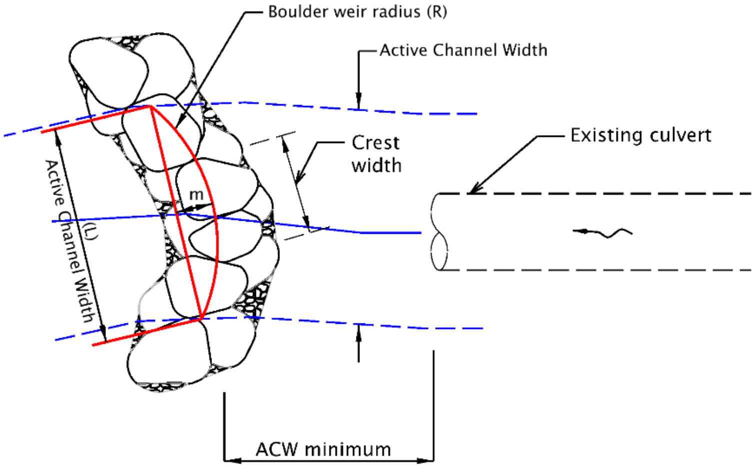


Figure 9.11-2: Boulder Weir Plan section

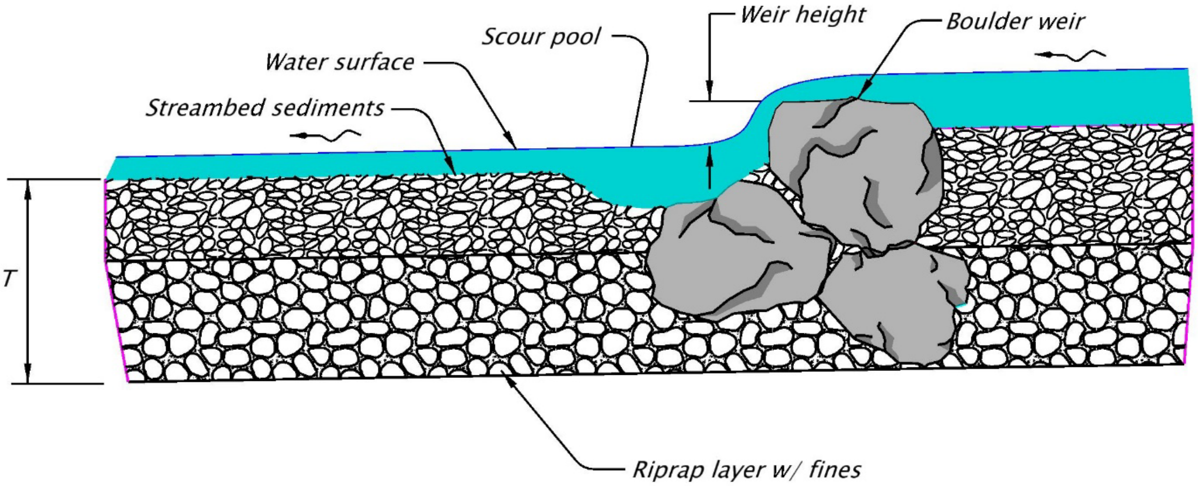


Figure 9.11-3: Boulder weir profile section

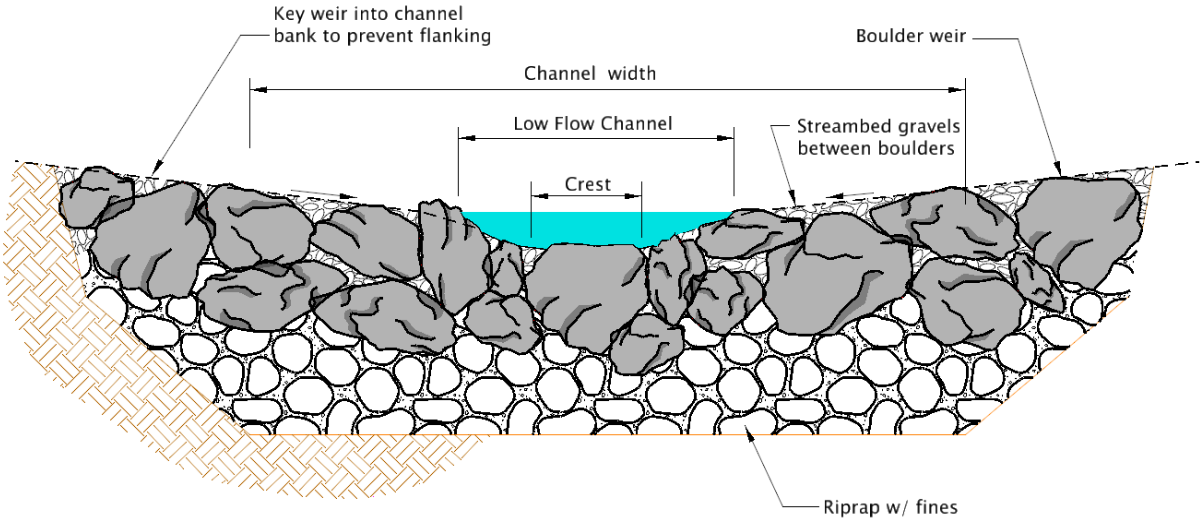


Figure 9.11-4: Boulder weir section

9.11.5 Step Pool Composition

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

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

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

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

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

9.11.6 Boulder Weir and Step Pool Layout

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

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

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

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

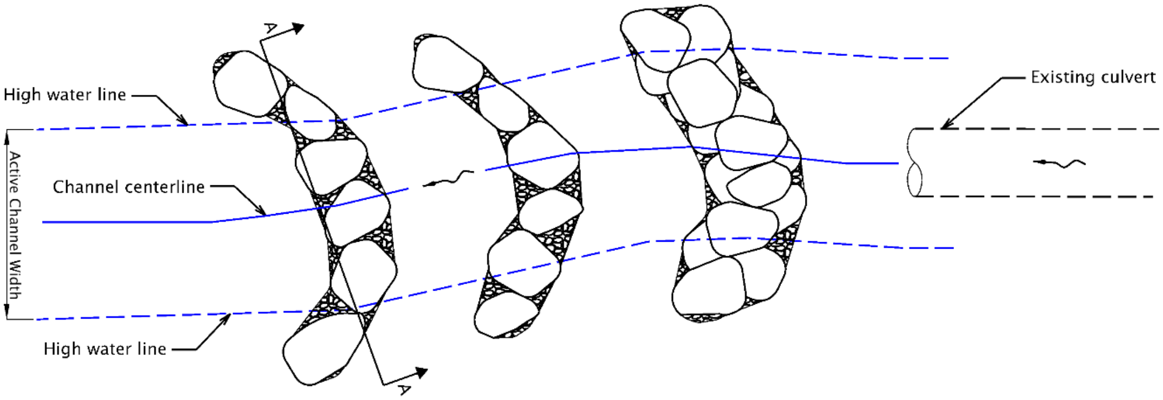


Figure 9.11-5: Step Pool Layout

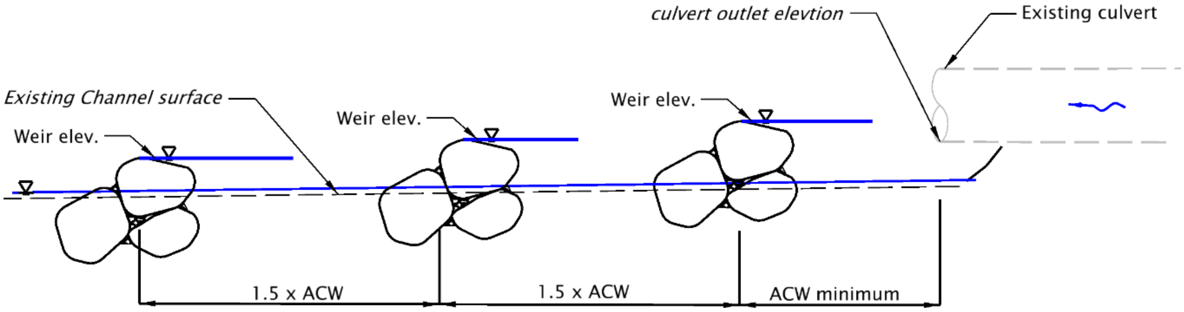


Figure 9.11-6: Step Pool Profile

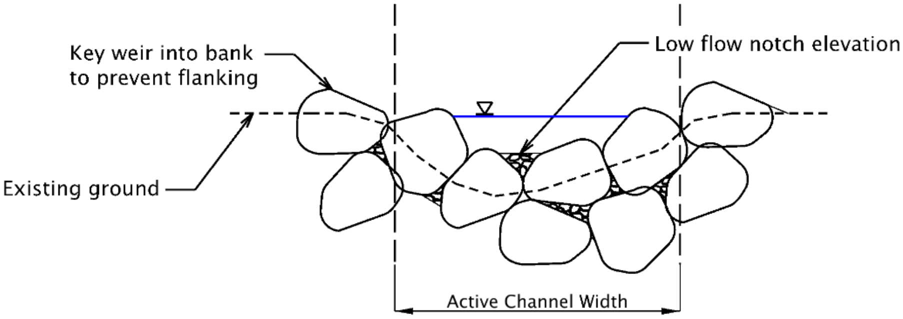


Figure 9.11-7: Weir Section

9.12 Additional Fish Passage Considerations

9.12.1 Tide Gates

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

9.12.2 Beaver Dam Analog and beaver associated projects

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

9.12.3 Fish Passage during construction

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

9.12.4 Fish Ladders (Fishways)

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

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Figure 9.13-1: Who needs a crossing structure.