6. Culvert Hydraulics

6.1 General

A culvert is defined as a short conduit used to convey stormwater runoff under an embankment such as a roadway or driveway whose primary purpose is to convey surface water. Alongside the hydraulic capabilities of culverts, a culvert must support the embankment and/or roadway while also protecting traffic and adjacent property owners from flood hazards to the extent practicable.

6.1.1 Criteria for Use of Culverts

Culvert design shall be based upon peak discharges for the appropriate design storm based on roadway type. Requirements are provided in Table 6.1. All computations, hydraulic profiles, and energy transition to channel shall be provided for the design event and the 100-year storm check.

Table 6.1. Culvert and Bridge Sizing Requirements

Roadway Classification	Design Storm Event	Minimum Freeboard (Culvert)	Minimum Freeboard (Bridges)
Principal Arterial Streets	100-year	1 foot	1 foot
Major and Minor Arterial Streets	100-year	1 foot	1 foot
All other streets	25-year	1 foot	1 foot

Note: Freeboard for culverts shall be from top of low point in road. Freeboard for Bridges shall be measured from the low chord.

Route the 100-year frequency storm through all culverts to be sure building structures (i.e., houses, commercial buildings) are not flooded or increased damage does not occur to the roadway or adjacent property for the 100-year storm event. The runoff generated from the 100-year event shall be safely conveyed through drainage easements and/or the Right of Way. Appropriate tailwater conditions shall be used from receiving waters. See section 6.2.5, tailwater considerations.

6.2 Design Criteria

6.2.1 Velocity Requirements

The final design of culverts should consider the minimum and maximum velocities. A minimum velocity of 3 ft/s is required when a culvert is flowing partially full to ensure no siltation occurs. There is no maximum velocity constraint, however; if velocities exceed 10 ft/s, chances of abrasion due to bedload movement and erosion downstream increase significantly. When velocities exceed the permissible velocity for the receiving channel type, energy dissipators are necessary and should be included in the culvert design. Energy dissipators are discussed in Section 6.2.2.

6.2.2 Energy Dissipators

To prevent scour at stormwater outlets, protect the outlet structure, and minimize the potential of downstream erosion, energy dissipators are required to reduce the flow to a non-erosive velocity. Some common types of energy dissipators include:

- **Rock-Protected Outlets**

  Rock is often placed around the outlet of culverts to protect against the erosive action of the water. Typical placement of rock protection is shown in Figure 6.1. The material size used is dependent on the velocity and should be determined using a full flow analysis as noted in Table 6.2. Riprap is required to have a minimum depth of 12 inches.

- **Other Energy-Dissipating Structures**

  Other structures include baffled outlets, plunge pools, internal dissipators, impact basins, and stilling basins designed according to the FHWA's HEC-14, "Hydraulic Design of Energy Dissipators for Culverts and Channels."

Energy dissipators should be analyzed and designed using HY-8 Culvert Hydraulic Analysis Program or an approved equivalent.

Energy dissipators are known to collect debris so the possibility of debris collection should be considered when choosing a dissipator design. Dissipators should be kept open and easily accessible to maintenance crews and provisions should be made to allow water to overtop without causing excessive damage.

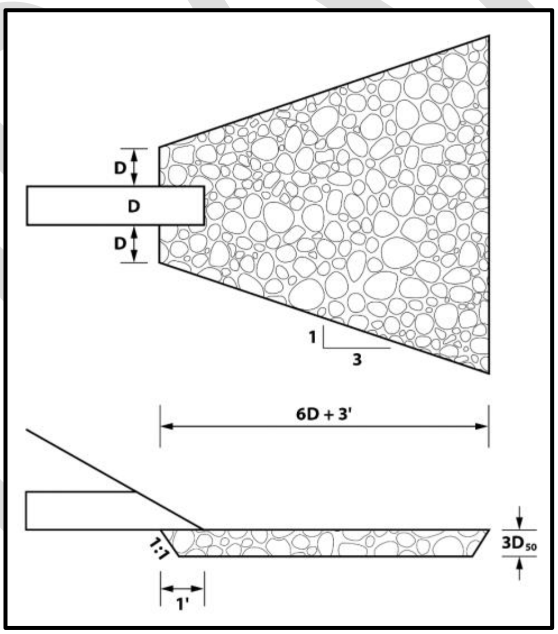

Figure 6.1. Typical Rock Protection Placement

Table 6.2. Outlet Protection Material Size

Outlet Velocity (ft/s)	Material
Up to 10	Dumped Riprap
>10	Foundation Protection Riprap

Note: All rock protection shall be designed in accordance with ARDOT Standard Specifications for Highway Construction Section 816.

6.2.3 Length and Slope

The maximum culvert slope using a reinforced concrete pipe shall be 10%. For culverts with a slope greater than 10%, the culvert must be approved by the Director of Planning and Development or Design Review Engineer to ensure proper pipe restraints. while the minimum slope for standard construction procedures shall be 0.5% when possible. Maximum drop in a drainage structure or junction box is 10 feet unless approved by the Director of Planning and Development or Design Review Engineer.

6.2.4 Headwater Limitations

Headwater is the water above the culvert invert at the entrance of the culvert. Headwater will be non-damaging to adjacent property and/or roadways. The maximum permissible headwater is determined from an evaluation of the land use upstream of the culvert and the proposed or existing roadway elevation and is the primary basis for sizing a culvert.

The following headwater criteria apply to culvert design:

- The allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design flood.
- Headwater shall have no adverse impact on upstream property.
- Maximum headwater depth for the design storm shall be 1 foot lower than the top of road or curb.
- Ponding depth shall be no greater than the elevation where flow diverts around the culvert.
- For drainage facilities with a cross-sectional area equal to or less than 30 sq.ft., headwater to depth ratio (HW/D) should be equal to or less than 1.5.
- For drainage facilities with a cross-sectional area greater than 30 sq.ft., HW/D should be equal to or less than 1.2.
- The headwater should be checked against the 100-year flood (base flood) elevation to ensure compliance with floodplain management criteria.
- The culvert should be sized to maintain flood-free conditions on principal and minor arterials with 1-foot freeboard from the low point of the road.
- Identify the maximum acceptable outlet velocity, based on receiving channel conditions. Reference Section 5.2.1 to determine acceptable velocities based on channel type.
- The constraint that gives the lowest allowable headwater elevation establishes the criteria for the hydraulic calculations.
- Bridges require 1 foot of freeboard from the low chord.

6.2.5 Tailwater Considerations

The hydraulic conditions downstream of the culvert site must be evaluated to determine tailwater depth for a range of discharge for the appropriate design storm and the 100-yr storm. At times, there may be a need for calculating backwater curves to establish the tailwater conditions. When evaluating the tailwater, the following must be considered:

- If the culvert outlet is operating with a freefall outfall, the critical depth and hydraulic grade line shall be determined.
- For culverts that discharge into an open channel, the water surface elevation in the open channel for the relevant design storm event. Recommend checking a range (more frequent events will sometimes result in lower tailwater and higher velocities) for the culvert should be evaluated as a part of the culvert capacity computations. See Chapter 5, Open Channel Design.
- If an upstream culvert outlet is located near a downstream culvert inlet, the headwater elevation of the downstream culvert may establish the design tailwater depth for the upstream culvert.
- If the culvert discharges to a lake, pond, or other major water body, the expected high-water elevation for the design storm of the water body may establish the culvert tailwater.

6.2.6 Culvert End Treatments

The culvert inlet often has a significant impact on the culvert's hydraulic capacity, efficiency, and cost. The inlet coefficient, $K_{e,}$ is a measure of the hydraulic efficiency of the inlet, with lower values indicating greater efficiency. Table 6.3 provides recommended inlet coefficients.

Culvert end treatments are required for all culverts installed in public right of ways or drainage easements. Some common end treatments include:

Headwalls
Headwalls shall be constructed with reinforced concrete. Straight, flared, and warped headwalls are all permissible depending on site conditions. Headwalls are required to be included in the culvert design when culverts cross the embankments at angle of 15-degrees or greater.

Wingwalls
Wingwalls are required when the side slopes of the channel adjacent to the entrance are unstable or where the culvert is skewed to the normal channel flow.

Aprons
If the approach velocity in the channel will cause scour, channel aprons at the toe are required to be included in the culvert design. Aprons shall extend a minimum of one pipe diameter upstream from the culvert entrance. The top of apron elevation shall not protrude above the normal streambed elevation.

6.2.7 Size and Material Selection

Reinforced concrete pipe (RCP) is to be used in roadway areas including under curbs. Sections where other material is used must be approved by the City Design Review Engineer. Polyvinyl chloride pipe (PVC) and high-density polyethylene pipe (HDPE) may be used in non-roadway areas. Galvanized CMP is not permissible and shall not be used in any culvert design. Coated CMP and HDPE flared end sections are prohibited within right of ways and drainage easements. All pipes shall be installed according to the standard details provided by the City of Little Rock including bedding, backfill, and compaction. Details for bedding, backfill, and compaction must be included in the Plans and Specifications.

The minimum allowable circular pipe diameter shall be 18 inches for culverts.

6.3 Design Procedure

6.3.1 Flow Type

Inlet and outlet control are the two basic types of flow control defined by the FHWA. The characterization of pressure, subcritical, and supercritical flow regimes play an important role in determining the control type. The control type also plays a significant role in determining the hydraulic capacity of a culvert. Proper culvert design requires checking for both inlet and outlet control to determine which will govern culvert designs.

Inlet Control

Inlet control occurs when the culvert barrel can convey more flow than the inlet will accept. In this control, critical depth occurs just inside the entrance of the culvert and the flow regime immediately downstream is supercritical. The upstream water surface elevation and the inlet geometry represent the major flow controls. Figure 6.2 depicts a typical inlet control flow section.

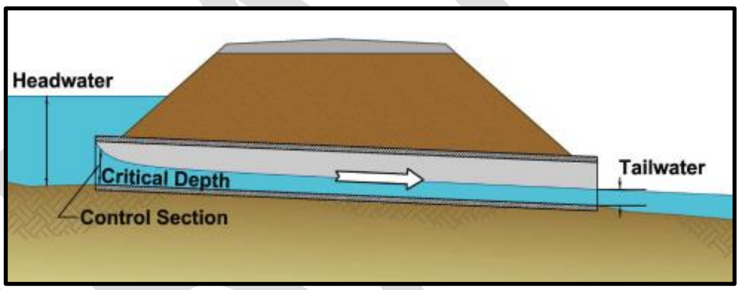

Figure 6.2. Typical Inlet Control Flow Section

Outlet Control

Outlet control flow occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. The control section for outlet control flow is located at the barrel exit or further downstream. Either subcritical or pressure flow exists in the culvert barrel under these conditions. All geometric and hydraulic control characteristics, including all factors governing inlet control, water surface elevation at the outlet, and barrel characteristics, play a role in determining the culvert's capacity. Figure 6.3 depicts two typical outlet control flow sections.

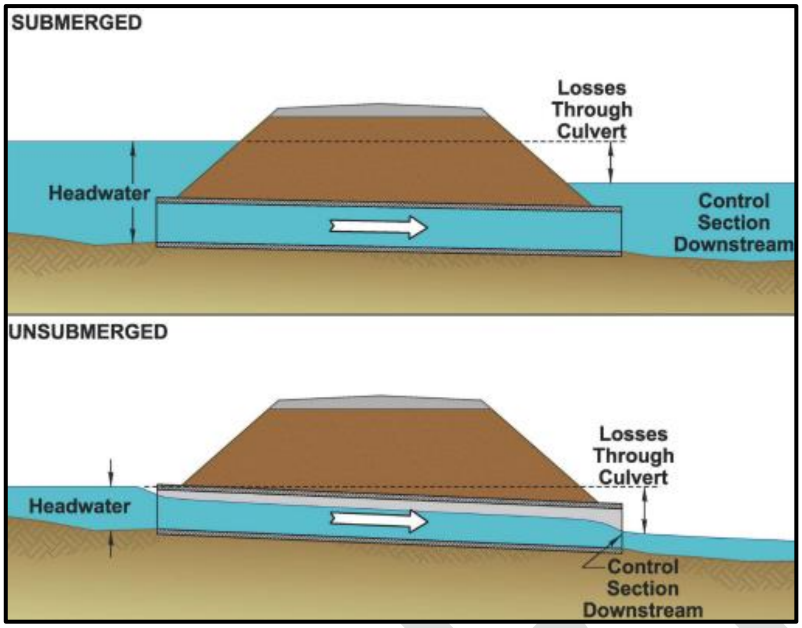

Figure 6.3. Typical Outlet Control Flow Sections

6.4 Design Software

It is recommended to use HY-8 Culvert Hydraulic Analysis Program developed by the Federal Highway Administration for all culvert design and analysis. Additional software may be accepted for use by the City Design Review Engineer provided it is shown to be equivalent to HY-8.

6.4.1 Design Procedure

The following design procedure should be conducted using HY-8 or an approved equivalent.

Step 1. – List Design Input Data.

Q = discharge (cfs)	L = culvert length (ft)
S = culvert slope (ft/ft)	TW = tailwater depth (ft)
V = velocity for trial diameter (ft/s)	K_e = inlet loss coefficient
Material Type	HW = allowable headwater depth (ft)

Step 2. – Determine Trial Size.

Assume a trial velocity of 3-5 ft/s and compute the culvert area using A = Q/V. Determine the culvert shape, open size (diameter or span and rise), and number of barrels.

Step 3. – Calculate HW for Inlet and Outlet Control

For inlet control, enter inlet control data into the software with D and Q and find HW/D for the entrance type. If HW is too large, adjust the opening size and recompute until the HW is acceptable.

For outlet control, enter the outlet control data into the software with the culvert length, entrance loss coefficient, and trial culvert diameter. Use Equation 6.1 to compute the HW elevation.

$$HW = H + h_0 - LS \quad \textbf{Eq. 6.1}$$

Where: h_0 = ½ (critical depth + D) or tailwater depth, whichever is greater.

Step 4. – Determine if the culvert is under Inlet or outlet control.

Compare the computed headwaters and use the higher HW to determine if the culvert is under inlet or outlet control.

If inlet control governs, then the design is complete, and no further analysis is required.

If outlet control governs and the HW is unacceptable, select a larger trial size and repeat the steps. Unless material or entrance conditions change, the inlet control conditions for the larger pipe does not need to be rechecked.

Step 5. – Check Potential Scour.

Calculate the exit velocity and if erosion problems are expected. Modify the culvert size to eliminate the erosion problems. If erosion problems cannot be eliminated, refer to section 6.2.2 for appropriate energy dissipation design.

6.4.2 Multi-barrel Installations

For culverts installations with multiple barrels exceeding a 3:1 width to depth ratio, the side bevels become excessively large when proportioned on the basis of the total clear width. For these structures, it is recommended that the side bevel be sized in proportion to the total clear width, B, or three times the height, whichever is smaller.

The top bevel dimension should always be based on the culvert height.

The shape of the upstream edge of the intermediate walls of a multi-barrel culvert is not as important to the hydraulic performance of a culvert as the edge condition of the top and sides. Therefore, the edges of these walls may be square, rounded with a radius of one-half their thickness, chamfered, or beveled. The intermediate walls may also project from the face and slope downward to the channel bottom to help direct debris through the culvert. Multi-barrel pipe culverts should be designed as a series of single barrel installations since each pipe requires a separate bevel.

For multi-barrel culvert installations, one culvert in the middle of the channel should be set at the elevation of the existing flowline and the remaining culverts should be set at the elevation of the bank full channel. Figure 6.4 provides an example of a multi-barrel culvert installation.

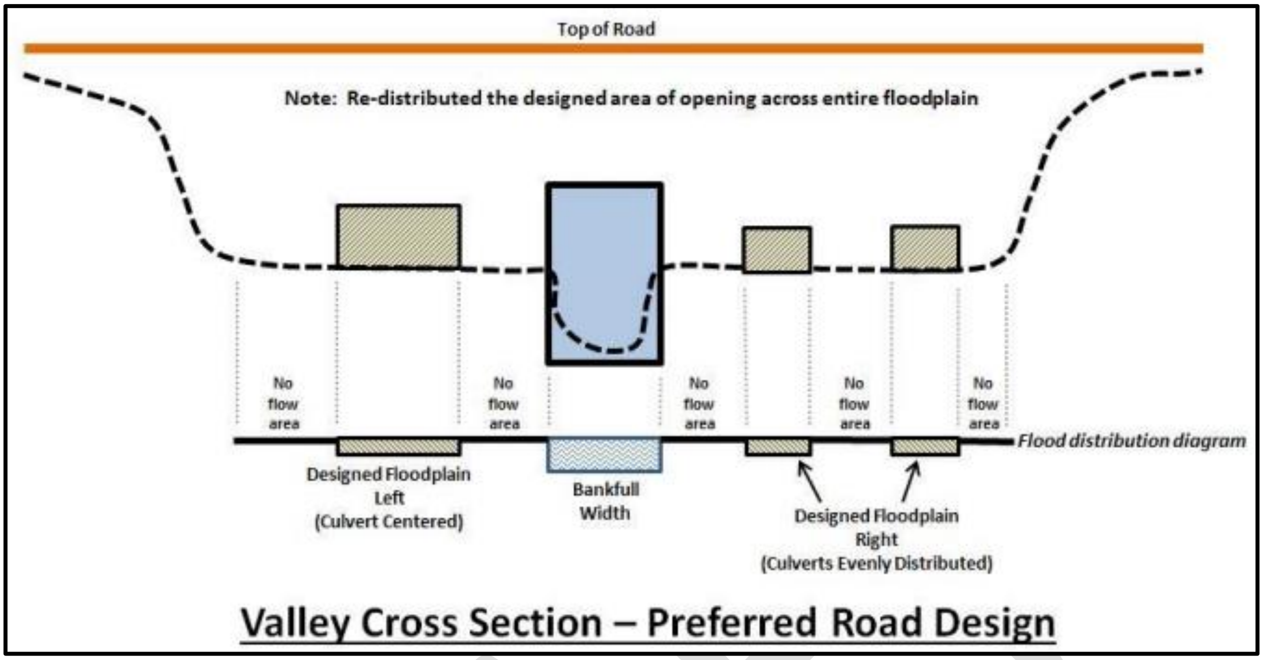

Figure 6.4. Road bisecting the floodplain with floodplain culverts.

Table 6.3. Inlet Coefficients

Type of Structure and Design of Entrance	Coefficient Ke[1]
Pipe, Concrete	
Projecting from fill, socket end (grove-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 = 1/12(D)]	0.2
Mitered to conform to fill slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7o or 45 o bevels	0.2
Side- or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal[1]	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to fill slope, paved or unpaved slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7 o or 45 o 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(D)] or beveled edges on 3 sides	0.2
Wingwalls at 30^{o} to 75^{o} to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of [1/12(D)] or beveled top edge	0.2
Wingwalls at 10^{o} or 25^{o} 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

1. The K_e values for corrugated metal pipes are also recommended for HDPE pipes.

Source: HDS No. 5, 1985.

6.5 References

https://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf

https://wsdot.wa.gov/publications/manuals/fulltext/m23-03/chapter3.pdf