5. DESIGN OF CULVERTS

5.1 Overview

Culverts are enclosed conduits used to convey water through embankments such as highways, streets, and driveways. In addition to their hydraulic function, culverts must also support earth loads, traffic, and construction equipment. Therefore, culvert design involves both hydraulic and structural design. They must be designed to protect the traveling public and adjacent property from flood hazards in a reasonable and prudent manner.

Primary considerations for the final selection of any drainage structure are that its design be based on appropriate hydraulic principles, economy, and that it has allowable design storm headwater depth and outlet velocity. The allowable headwater elevation is that elevation above which unacceptable impacts may be caused to adjacent property and/or the roadway. It is this allowable headwater depth that is the primary basis for sizing a culvert. In addition to sound hydraulic design, sound structural design, site design and construction practices are necessary for a culvert to function properly.

Any structure that measures less than 20 feet from the inside face of the exterior wall to the inside face of the exterior wall (including interior walls) along the centerline of the roadway is classified as a culvert. Any structure that measures 20 feet or greater for the same dimensions is classified as a bridge or major structure.

5.2 Engineering Design Criteria

The engineering design criteria described in this chapter are based on the most recent edition of Hydraulic Design Series 5: Hydraulic Design of Highway Culverts (HDS 5). See HDS 5 for additional design procedures not found in this manual.

Hydraulic analysis of culverts includes the computation of:

- Drainage area
- Design flow
- Allowable headwater
- Headwater at design flow
- Outlet velocity

Culvert design also involves the consideration of the following factors:

- Inlet and outlet control
- Culvert shape and cross section
- Culvert length and extensions
- End treatments
- Multiple installations
- Inlet improvement
- Outlet velocity
- Culvert size
- Slope and alignment
- Camber
- Bedding and fill requirements

5.2.1 Return Period

Since it is generally not economically feasible to design culverts for the maximum runoff that a watershed is capable of producing, design storm frequency criteria must be established. The design storm frequency criteria for culverts is 50 years for the major system and 10 years for the minor system. The minor system consists of culverts and open channels that run parallel to the roadway and are used to drain the roadway in lieu of a storm sewer system.

5.2.2 Headwater Elevation

Any culvert that constricts the natural stream flow will cause a rise in the upstream water depth to some extent. The depth of water in the stream measured from the culvert inlet invert (flowline) is termed headwater.

The maximum allowable headwater elevation for culverts will be the lowest of the following:

- One foot below the top of all roadway curbs or edges of roadway pavement.
- One foot above the top of the culvert.
- Elevations that could damage adjacent property.
- Elevations established to delineate floodplain zoning at the culvert.
- Ditch elevation of the terrain that would permit flow to divert around the culvert.

The headwater shall also be checked for the 100-year design storm to ensure compliance with street cross flow criteria established for the major storm in Chapter 3 of this manual, to ensure compliance with floodplain management regulations, and to avoid increasing the water surface elevation on an adjacent property.

5.2.3 Tailwater Elevation

Tailwater is the flow depth in the downstream channel measured from the invert at the culvert outlet. It can be an important factor in culvert hydraulic design because a submerged outlet may cause the culvert to flow full rather than partially full.

A field inspection of the downstream channel should be made to determine whether there are obstructions that will influence the flow depth. Tailwater depth may be controlled by the stage in another stream, headwater from structures downstream of the culvert, reservoir water surface elevations, or other downstream features.

5.2.4 Inlet and Outlet Control

Based on laboratory tests and field observations there are two major types of culvert flow:

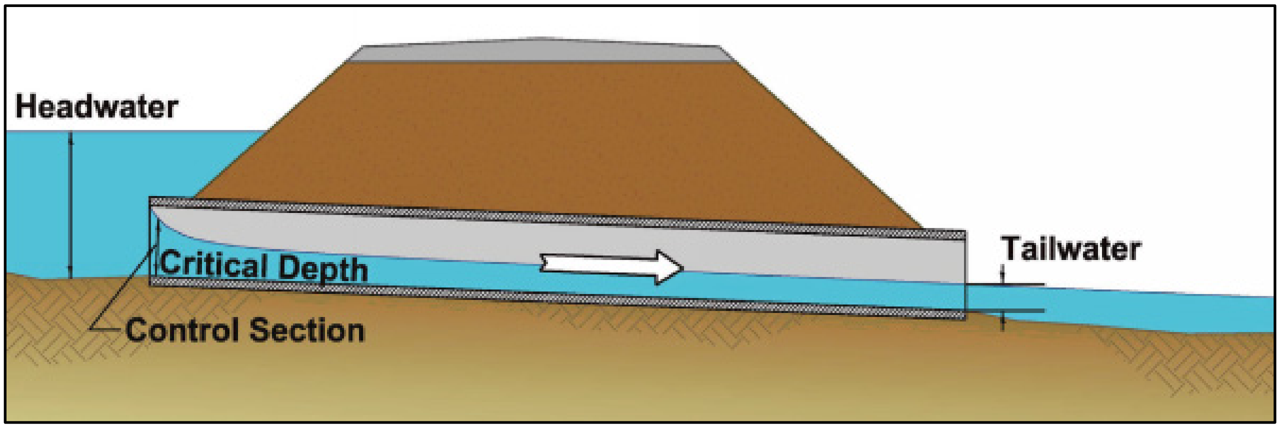
- Flow with inlet control
- Flow with outlet control

For each type of control, different factors and formulas are used to compute the hydraulic capacity of a culvert. Hydraulic analysis of a culvert design includes determining the headwater elevation at the design discharge. This is done by comparing the inlet control headwater elevation against the outlet control headwater elevation and selecting the higher value. For additional information, see HDS 5.

5.2.4.1 Inlet Control

In inlet control, the discharge capacity of a culvert is controlled by the conditions at the culvert entrance. Inlet control generally occurs when the culvert opening is not capable of accepting as much flow as the culvert barrel is able to convey. Flow passes through critical depth shortly after entering the culvert, becoming high-velocity, shallow (supercritical) flow in the culvert. Under inlet control, the cross-sectional area of the culvert opening, the inlet shape, entrance configuration (projecting, headwalls, wingwalls) and depth of the headwater at the entrance are of primary importance. Hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. The efficiency of the culvert inlet can be enhanced by beveling or tapering the opening (see Section 5.2.11, Culvert Inlet Configurations and HDS 5).

Figure 5-1. Example Inlet Control Flow Condition



5.2.4.2 Outlet Control

In outlet control, the discharge capacity of a culvert is controlled by the barrel exit or downstream conditions. Outlet control generally occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. Water flows through the culvert as low-velocity, deep (subcritical) flow, or pressure flow. The culvert may flow completely or partially full. Under outlet control, in addition to the parameters affecting inlet control, the barrel slope, length, and roughness are important. Also of importance is the tailwater elevation of the outlet.

Figure 5-2. Typical Outlet Control Flow Conditions

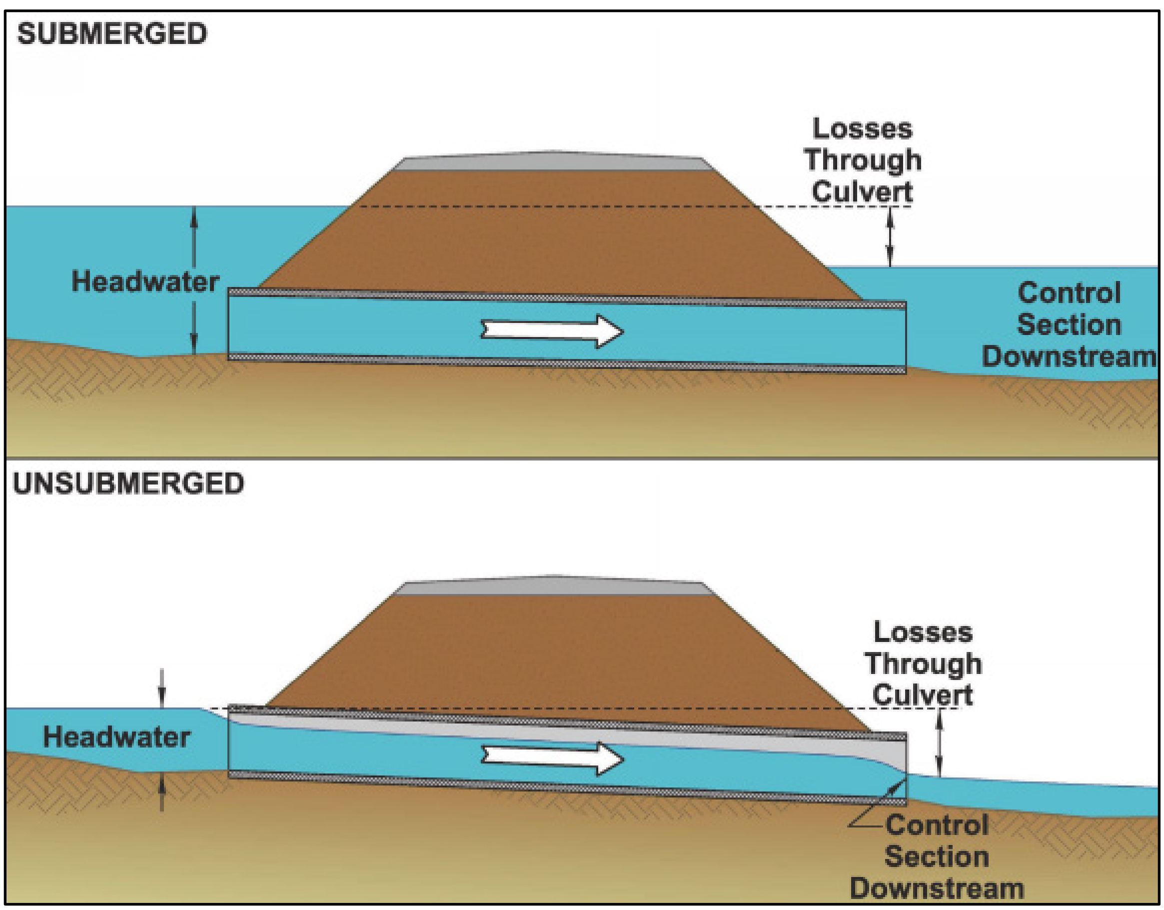


Table 5-1 summarizes factors affecting inlet and outlet control conditions at a culvert.

Table 5-1. Factors Affecting Inlet and Outlet Control

Inlet Control	Outlet Control
Headwater Depth	Headwater Depth Tailwater Depth
Inlet Edge Cross Sectional Area Shape	Inlet Edge Cross Sectional Area Shape
n/a	Slope Length Roughness

5.2.5 Culvert Shape, Cross Section, and Material

Culvert type selection includes the shape and cross section, choice of materials, and number of culvert barrels or spans. The following shapes and cross sections are acceptable for culverts:

- Circular: Most common; standard lengths and strength classes are available.
- Pipe Arch and Elliptical: Typically used where cover is limited.
- Box or Rectangle: Typically used for larger culverts where pipes are not adequate. A longer construction time is required for cast-in-place construction; precast construction may be considered.

Table 5-2 shows equivalent pipe cross sections.

Table 5-2. Equivalent Pipe Cross Sections

Circular Pipe		Concrete Pipe Horizontal – Elliptical			Concrete Pipe Arch			Corrugated Metal Pipe Arch (2 2/3 in x 1/2 in)		
Diameter (in)	Area (ft²)	Span (in)	Rise (in)	Area (ft²)	Span (in)	Rise (in)	Area (ft²)	Span (in)	Rise (in)	Area (ft²)
15	1.23	—	—	—	—	—	—	—	—	—
18	1.77	23	14	1.84	22	13 1/2	1.6	—	—	—
21	2.41	—	—	—	—	—	—	25	16	2.16
24	3.14	30	19	3.28	28 1/2	18	2.8	29	18	2.83
27	3.98	34	22	4.14	—	—	—	—	—	—
30	4.91	38	24	5.12	36 1/4	22 1/2	4.4	36	22	4.42
33	5.94	42	27	6.31	—	—	—	—	—	—
36	7.07	45	29	7.37	43 3/4	26 5/8	6.4	43	27	6.36
42	9.62	53	34	10.21	51 1/8	31 5/16	8.8	50	31	8.65
48	12.57	60	38	12.92	58 1/2	36	11.4	58	36	11.30
54	15.90	68	43	16.6	65	40	14.3	65	40	14.34
60	19.64	76	48	20.5	73	45	17.7	72	44	17.7
66	23.76	83	53	24.8	88	54	25.6	—	—	—
72	28.27	91	58	29.5	—	—	—	—	—	—

Allowable materials for culverts, most commonly reinforced concrete, smooth or corrugated metal, and smooth or corrugated PVC or HDPE, can be found in the City's Standard Specifications.

5.2.6 Velocity

A minimum velocity of 2 feet per second should be maintained in the culvert to preclude settlement of silts and other solids. Velocities greater than 10 feet per second should be avoided when possible. See Chapter 6 of this manual for energy dissipation measures for outlet velocities greater than 10 feet per second.

5.2.7 Culvert Sizes

Culvert sizes will be determined in accordance with the charts and methods contained in HDS 5 or from computer programs based on HDS 5, such as FHWA's HY-8 culvert analysis program. Minimum culvert sizes shall be as follows:

- 18-inch pipes for roadways
- 15-inch pipes for driveways
- 4-feet by 4-feet for box culverts

5.2.8 Manning's n Values

The recommended Manning's n value for design purposes when using corrugated pipe is 0.024. The recommended Manning's n value for smooth interior pipes is 0.012. When it is necessary to determine the true magnitude of the pipe outlet flow velocity, designers should use the actual Manning's n value recommended by the manufacturer to perform computations. When both corrugated and smooth pipe are selected as options, the designer shall use a Manning's n value of 0.024. A Manning's n value of 0.012 shall be used when only smooth interior pipe is specified.

5.2.9 Length, Slope, and Alignment

Since the capacity of culverts in outlet control will be affected by the length of the culvert, their length should be kept to a minimum and existing facilities shall not be extended without determining the decrease in capacity that may occur. In addition, the culvert length and slope should be chosen to generally match existing topography.

To the degree practicable, the culvert invert should be aligned with the channel bottom and the skew angle of the stream. The culvert entrance should fit with the geometry of the roadway embankment. Culvert skews shall not exceed 45 degrees as measured from a line perpendicular to the roadway centerline without approval of the City.

5.2.10 Multiple Barrels and Spans

In the case of box culverts, it is usually more economical to use a multiple span structure than a wide single span, due to a reduction in the thickness of the top slab. In some locations, multiple spans tend to catch debris and clog the waterway. They are also susceptible to ice jams and the deposition of silt in one or more spans. Alignment of the culvert face normal to the approach flow and installation of debris control structures can help to alleviate these problems.

In the case of pipe culverts, multiple pipe installations often exhibit settlement after construction. Use of multiple pipes should be avoided whenever possible. However, if multiple pipes are used, sufficient space between pipes must be provided to allow proper backfill and compaction to eliminate the settlement problem. Multiple pipe installations should desirably have 5 feet or greater clearance from outside of pipe to outside of pipe. Backfill material for the minimum clear spacing of one foot shall be flowable fill. Proper indigenous soils may be used for backfill material where spacing is greater than 5 feet.

Headwalls are preferred to flared end sections for multiple pipe installations where the headwall does not present an obstacle, (e.g., is outside the clear zone). Flared end sections are also available that permit one foot minimum clear spacing between pipes.

5.2.11 End Treatments

Flared end sections are preferred over a headwall for single pipe culverts from a safety standpoint and shall be used whenever feasible. The material of the flared end section generally shall match the pipe material unless plastic pipe is used, which requires a metal flared end section. Flared end sections may prove to be unsatisfactory for skewed culverts with low fills and the use of a headwall may be necessary. Installation of flared end sections on multiple pipe installations is preferred over cast-in-place concrete headwalls within the clear zone.

Headwalls may be used for:

- Multiple pipe installations.
- Culverts with skews of 30° or more.
- Culverts with slopes too steep for flared end sections.
- Broken-back culverts where the possibility of slippage exists (e.g., drop pipes in backslopes).

Headwalls with a deeper footing are needed for culverts placed on steep grades or in areas of potential head cutting.

5.2.12 Culvert Inlet Configurations

The culvert inlet configuration is the cross-sectional area and shape of the culvert face and the type of inlet edge. When a culvert operates in inlet control, headwater depth and the inlet configuration determine the culvert capacity and the culvert barrel usually flows only partially full. Inlet geometry refinements or inlet improvements can be used to reduce the contraction losses at the inlet and to increase the capacity of the culvert without increasing the headwater depth.

Culverts operating in outlet control usually flow full at the design flow rate. Therefore, inlet improvements on these culverts only reduce the entrance loss coefficient, which results in only a small decrease in the required headwater elevation.

Common conventional culvert inlets include projecting inlets, groove-end projecting inlets, square-edge inlets in a headwall with wingwalls, mitered inlets with slope paving and flared end inlets. Recommended entrance loss coefficients for inlets can be found in Table 5-2.

Table 5-3. Entrance Loss Coefficients, Outlet Control

Type of Structure and Design of Entrance		Coefficient, K_e
Pipe, Concrete	Projecting from Fill, Socket End (Groove-end)	0.2
	Project from Fill, Square Cut End	0.5
	Headwall or Headwall and Wingwalls	
	Socket End (Groove-End)	0.2
	Square-edge	0.5
	Rounded (Radius = D/12)	0.2
	Mitered to Conform to Fill Slope	0.7
	*Flared End Section Conforming to Fill Slope	0.5
	Beveled Edges, 33.7° or 45° Bevels	0.2
	Side- or Slope-tapered Inlets	0.2
Pipe or Pipe-Arch, Corrugated Metal	Projecting from Fill	0.9
	Headwall or Headwall and Wingwalls, Square-edge	0.5
	Mitered to Conform to Fill Slope, Paved or Unpaved	0.7
	*Flared End Section Conforming to Fill Slope	0.5
	Beveled Edges, 33.7° or 45° Bevels	0.2
	Side- or Slope-Tapered Inlet	0.2
Box, Reinforced Concrete	Headwall Parallel to Embankment (No Wingwalls)	
	Square-edge on 3 Edges	0.5
	Rounded on 3 Edges to Radius of D/12 or B/12 or Beveled Edge on 3 Sides	0.2
	Wingwalls at 30° to 75° to Barrel	
	Square-edge at Crown	0.4
	Crown Edge Rounded to Radius of D/12 or Beveled	0.2
	Wingwalls at 10° to 25° to Barrel, Squared-edge at Crown	0.5
	Wingwalls Parallel (Extension of Sides)	
	Square-edge at Crown	0.7
	Side- or Slope-tapered Inlet	0.2

*Note: Flared end sections conforming to fill slope, made of either metal or concrete, are the section commonly available from manufacturers. From limited hydraulic tests, they are equivalent in operation to a headwall in both inlet and outlet control. Some flared end sections incorporating a closed taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.

5.2.12.1 Improved Inlets

Even though the construction of an improved inlet will increase the labor and material costs for the inlet portion of a new culvert, a substantial savings may be attained by a reduction in the size of the barrel that represents the major portion of the structure. Improved inlets may also be installed on existing culverts with inadequate flow capacity, thus avoiding the replacement of the entire structure or the addition of a new parallel structure. The greatest savings usually result from the use of improved inlets on culverts with long barrels. Short barrels, however, should also be checked, especially when an improved inlet might increase the capacity sufficiently to avoid replacement of an existing structure.

Improved inlets include bevel-edged, side-tapered, and slope-tapered inlets. Additional information and design procedures for improved inlets can be found in HDS 5.

5.2.13 Broken-back Culverts

Abrupt changes in slope or direction are not typically desirable from a maintenance and construction standpoint. However, at locations where the inlet is substantially higher than the outlet, culverts referred to as "broken-back" (with either one or two breaks in the vertical alignment), are commonly constructed to effectively control the drop in flow line and the outlet velocity.

Figure 5-3. Single Broken-back Culvert

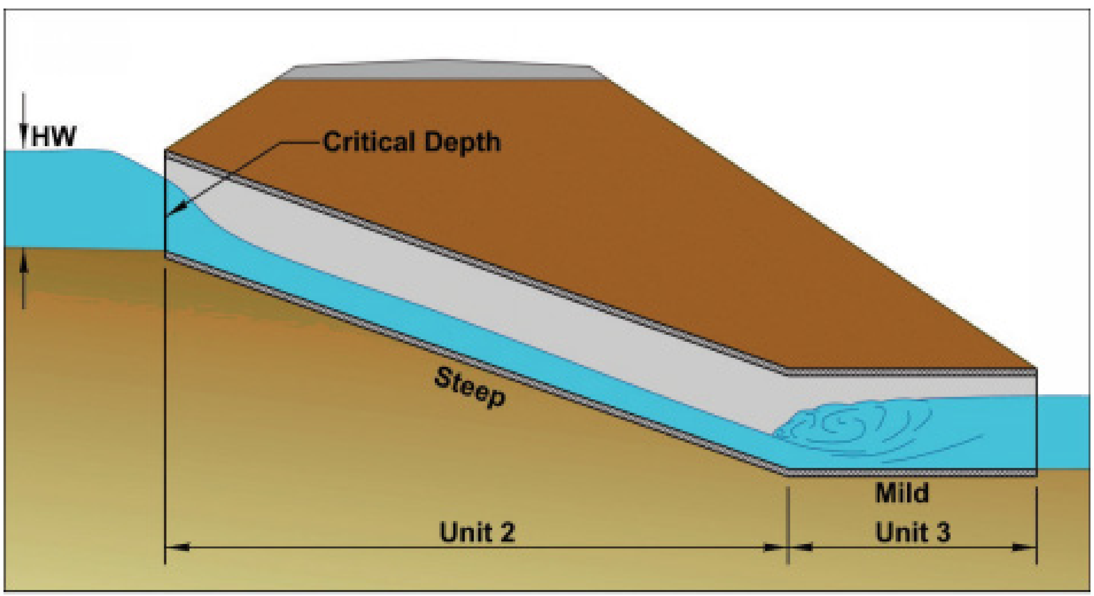
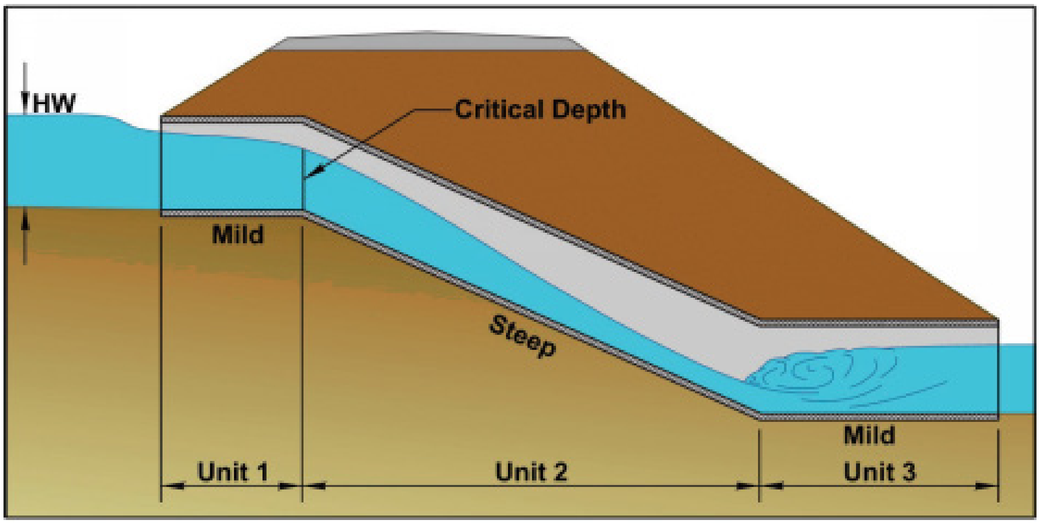


Figure 5-4. Double Broken-back Culvert



The total hydraulic performance of these culverts is difficult to analyze without the aid of a computer program written for such a purpose. The hydraulics of circular and rectangular broken-back culverts can be analyzed using the FHWA HY-8 software or the Broken-back Culvert Analysis Program (BCAP) software from the Nebraska Department of Transportation.

Many broken-back culverts are constructed to control head cut erosion, when there is great differential between the inlet and outlet elevations. In broken-back culverts, velocity of flow is greatest at the lower break due to acceleration in the steeply sloped segment; however, subcritical flow is desirable at the culvert outlet to reduce the erosive potential of the flow as it exits the culvert. A hydraulic jump will occur within a broken-back culvert when there is sufficient roughness within the culvert barrel, sufficient tailwater at the outlet, or both. It is often advantageous to specify corrugated interior pipes for these culverts to help reduce velocity between the lower break point and the culvert outlet. In many cases, HY-8 or BCAP can be used to optimize the length of the outlet section and provide for velocity reduction between the lower break point and the culvert outlet.

5.2.14 Debris Control

The need for debris control should be considered for each culvert, but in general, debris control shall not be used on entrances for culverts unless approved by the City and should never be installed at the outlet of a culvert. Upstream property management is generally preferred over a debris control structure. See HDS 5 for design of debris control structures.

5.2.15 Anchorage

Anchorage at the culvert entrance or at the outlet of the culvert may be necessary for the following:

- Protect the inlet and especially the outlet from undermining by scour.
- Protect against buoyant forces or uplift.
- Protect against separation of concrete pipe joints.

End anchorage can be in the form of headwalls, slope paving, or piling. These techniques protect the slope from scour and preclude undermining of the culvert end. The culvert barrel, however, must be anchored to the end treatment to be effective.

Buoyant forces are produced when the pressure outside the culvert is greater than the pressure in the barrel. This condition can occur in a culvert in inlet control with a submerged upstream end and in culverts placed in areas of high groundwater.

Culvert ends projected through levees are also susceptible to failure from buoyant forces if flap gates are used on the end. Generally, flexible barrel materials are most vulnerable to this type of failure because of their light weight and lack of resistance to longitudinal bending. Installation of headwalls and wingwalls will increase the dead load on the end of the culvert and protect it from uplift.

Rigid concrete pipe susceptible to separation of the pipe joints can be protected by installation of pipe couplers.

5.2.16 Fill Heights and Loading Requirements

Fill height over a culvert determines the amount of dead or live loads imposed on the culvert structure. Minimum fill height is defined as the vertical fill distance measured from the top of the conduit to the bottom of the pavement or the shoulder surface at its lowest point. Maximum fill height is defined as the vertical distance measured from the top of the conduit to the top of the pavement at its highest. Minimum fill height for all culverts is one foot.

All culverts shall be designed, as a minimum, for HS20 live load with the appropriate impact factor and dead load. Dead load shall be based on the depth of earth cover plus pavement above the top of the culvert.

5.2.17 Storage Routing

A significant storage capacity behind a roadway embankment may attenuate a flood hydrograph. Because of the reduction of the peak discharge associated with such attenuation, the required capacity of the culvert, and its size, may be reduced. If significant storage is anticipated behind a culvert, the design may be checked by routing the design hydrographs through the culvert to determine the discharge and stage behind the culvert. If credit for storage attenuation is taken during culvert design, the facility should be designed as a storage facility according to Chapter 7 of this Manual and measures should be taken to ensure the area inundated by floodwater is not encroached upon in the future. Additional routing procedures are also outlined in HDS 5. No roadway embankment shall be designed as a storage facility without prior approval of the City.

5.3 References

- City of Lincoln Public Works and Utilities Department, 2000. *Drainage Criteria Manual.*
- City of Omaha Environmental Quality Control Division, 2014. *Omaha Regional Stormwater Design Manual.*
- Federal Highway Administration, 2012. *Hydraulic Design Series Number 5, Third Edition, Hydraulic Design of Highway Culverts.*
- Nebraska Department of Transportation, 2006. *Drainage Design and Erosion Control Manual.*