6.0 CULVERTS

The function of a culvert is to convey water across the highway right-of-way. In addition to this hydraulic function, a culvert should support the loads imposed by the earth cover, highway traffic, and construction equipment. Therefore, culvert design involves both hydraulic and structural design. This section addresses the hydraulic aspects of culvert design. Section 8 addresses structural aspects of culverts.

A structure with a total clear span (including the interior wall thicknesses) greater than 20.0 ft (measured along the project centerline) is classified as a bridge. A multiple-pipe installation is considered a bridge if the spacing between the pipes (measured perpendicular to the centerlines of the pipes) is less than one-half of the pipe diameter and the total clear span (including the spacing between the pipes) is greater than 20.0 ft (measured along the project centerline). Bridge structures are subject to the requirements of the Bridge Design Manual.

A single culvert or a multiple-culvert installation with a total clear span (including the interior wall thicknesses) of 10.0 ft to 20.0 ft (measured along the project centerline) is classified as a 10'-20' structure. A multiple-pipe installation is considered a 10'-20' structure if the spacing between the pipes (measured perpendicular to the centerlines of the pipes) is less than one-half of the pipe diameter and the total clear span (including the spacing between the pipes) is 10.0 ft to 20.0 ft (measured along the project centerline). All 10'-20' structures are assigned a culvert serial number by the KDOT Bridge Management Section. The serial number should be requested prior to final plans.

A Hydraulic Assessment Checklist for Drainage Design should also be completed by the Bureau of Structures and Geotechnical Services for each bridge structure. The designer should coordinate to complete the modified “Hydraulic Assessment Checklist for 10’-20’ Culverts” with the Bureau of Structures and Geotechnical Services.

6.1 TYPES OF CULVERTS

6.1.1 Culvert Shapes

The cross sectional shape of a culvert can be square, rectangular, circular, elliptical, or arch shaped. Reinforced concrete boxes are square or rectangular. Reinforced concrete pipes are available in circular and elliptical shapes. Corrugated metal pipes are manufactured in circular and arch shapes. Pipe-arch, elliptical, and box shapes are appropriate in situations with limited cover or low allowable headwater. Pipe-arch and box shapes can also be used where less obstruction of the waterway is desirable. Round pipes are generally more economical than noncircular pipes due to their greater strength. Therefore, the use of noncircular pipe should be justified by dimensional constraints or unusual AHW constraints.

6.1.2 Reinforced Concrete Boxes

RCB culverts are available in a wide range of sizes with one or more barrels. RCB culverts are typically cast in place in the field by forming and pouring; however, pre-cast RCB sections are permissible in many situations (see Section 2.6.4, "Precast Structures"). The KDOT Automated RCB System generates quantities and detail sheets for single-cell, double-cell and triple-cell box culverts with cell spans from 3.0 ft to 20.0 ft, cell heights from 2.0 ft to 20.0 ft, and fill heights up to 50 ft. The culvert can be a pinned box (RCB) or a rigid frame box (RFB). Box culverts are designed for a specified fill height (up to 50 ft). Designers external to KDOT can request box-culvert detail sheets for KDOT projects by completing the “RCB Details Request Form” and submitting it to the appropriate KDOT unit within the Division of Engineering and Design. For more information on design of reinforced concrete boxes, see the Bridge Design Manual.

6.1.3 Multiple Barrel Culverts

Culverts with multiple barrels are appropriate in situations with limited cover or low allowable headwater. They can be used in wide, shallow channels to limit the constriction of the flow. However, widening a natural channel to accommodate a multiple-barrel culvert often results in sediment and debris accumulation in the widened channel section and in the culvert. A multiple-cell box culvert is generally more economical than a box culvert with a single long span.

6.1.4 End Treatments

The inlets and outlets of culverts should be provided with appropriate end treatments, as stated in Section 2.8, "END TREATMENTS FOR DRAINAGE STRUCTURES". This requirement applies to extensions of existing structures as well as new structures. The inlet and outlet locations and end treatments should comply with the KDOT Roadside Design Guidelines.

Inlet and outlet structures for culverts retain the fill around the culvert and provide some protection against erosion. The design of the inlet can have a major impact on the hydraulic performance of the culvert. Beveling or rounding of the inlet edges can substantially increase a culvert's capacity. A depressed inlet may be hydraulically advantageous for culverts that operate under inlet control. Side-tapered inlets and slope-tapered inlets offer greater hydraulic advantages in certain situations. For more information on the design of depressed, side-tapered and slope-tapered inlets, see FHWA's HDS No. 5, Hydraulic Design of Highway Culverts. A depressed, side-tapered or slope-tapered inlet is economically advantageous if it allows the culvert barrel to be downsized, and if the reduction in the cost of the culvert barrel exceeds the added cost of the inlet. A depressed, side-tapered or slope tapered inlet may be cost-effective for a long culvert that would operate under inlet control with a conventional inlet.

6.1.4.1 End Sections for Pipe Culverts

KDOT has standard drawings for three types of end sections for pipe culverts:

1. Type I end sections are flared end sections made of metal or concrete. They serve to retain the embankment and to control local scour. Type I end sections may be used within the clear zone on crossroad and single parallel pipes of any shape that are 24 in. or less in height.

2. Type III end sections are side-tapered end sections made of concrete or metal. Type III inlets are very efficient hydraulically. They are functionally equivalent to FHWA's standard side-tapered inlets. Type III end sections may be used within the clear zone on crossroad pipes of any shape that are 24 in. or less in height.

3. Type IV end sections are metal end sections with heavy steel bars across the flow opening. Type IV end sections can be traversed by automobiles and, therefore, may be used within the clear zone.

The upstream ends of CMP culverts larger than 48 in. in diameter should be restrained against buoyant uplift with a concrete headwall or tiedown. Table 6.1.4.1-1, "Restraint against Uplift for Upstream Ends of Large CMP Culverts" shows the recommended restraining force and the volume of concrete that would provide this restraint. Temporary installations of large CMP culverts with projecting ends are particularly susceptible to buoyant uplift. A full-length section of pipe should be used at the upstream end of a CMP culvert.

Table 6.1.4.1-1 Restraint against Uplift for Upstream Ends of Large CMP Culverts

Pipe Diameter (in.)	Restraining Force (kips)	Concrete Volume (yd^3)
54	2	0.5
60	3	0.7
66	4	1.0
72	6	1.5
78	8	2.0
84	10	2.5
90	12	3.0
96	15	3.7
102	18	4.4
108	22	5.4
114	26	6.4
120	31	7.7

References: Austin (1990) and Lohnes (1996)

6.1.4.2 End Treatments for Box Culverts

Headwalls and wingwalls are essentially retaining walls located at the ends of culverts. The headwall-wingwall structure can help to inhibit piping and stabilize the ends of the culvert against buoyant uplift and other forces. The wingwalls should be long enough to retain the embankment. Where streambed degradation or the potential for scour are anticipated, the headwall-wingwall structure should include a paved apron at the level of the culvert flowline with a toewall extending below the anticipated depth of scour (not less than 18 in.). Wingwalls are classified as flared and straight. Straight wingwalls are an extension or continuation of the box walls. KDOT has a standard drawing for a “soil saver” for RCB culverts. The soil saver is a depressed entrance that can be used to increase the hydraulic capacity of an RCB culvert that operates under inlet control and reduce the potential for head-cutting in the channel. Soil savers do not provide a means for aquatic organism passage; therefore, they are generally not permitted in a jurisdictional channel.

The Aquatic Organism Passage (AOP) apron is similar to soil saver but is modified to allow for aquatic organism passage. The AOP apron would be used in a jurisdictional channel and basically function as a soil saver. A standard drawing is not available for AOP aprons; therefore, a special design may be required. The design should be coordinated with the Environmental Services Section and the Bureau of Structures and Geotechnical Services.

Standard details for headwalls, wingwalls, aprons and toewalls for standard reinforced concrete box culverts are available through KDOT's "Automated RCB System". Flared wingwalls are available for all box heights. Straight wingwalls are available for box heights of 10.0 ft and less. Flared wingwalls should be used in most situations. However, straight wingwalls may be used where advantageous provided that additional costs are adequately considered. Straight wingwalls may be appropriate at sites where erosion aprons are needed. Flared wingwalls on standard normal (90º crossing) and rotated box culverts are flared at a 45º angle. For the flare angles of wingwalls on standard skewed culverts, see the Bridge Design Manual.

6.1.5 Embedded Culverts

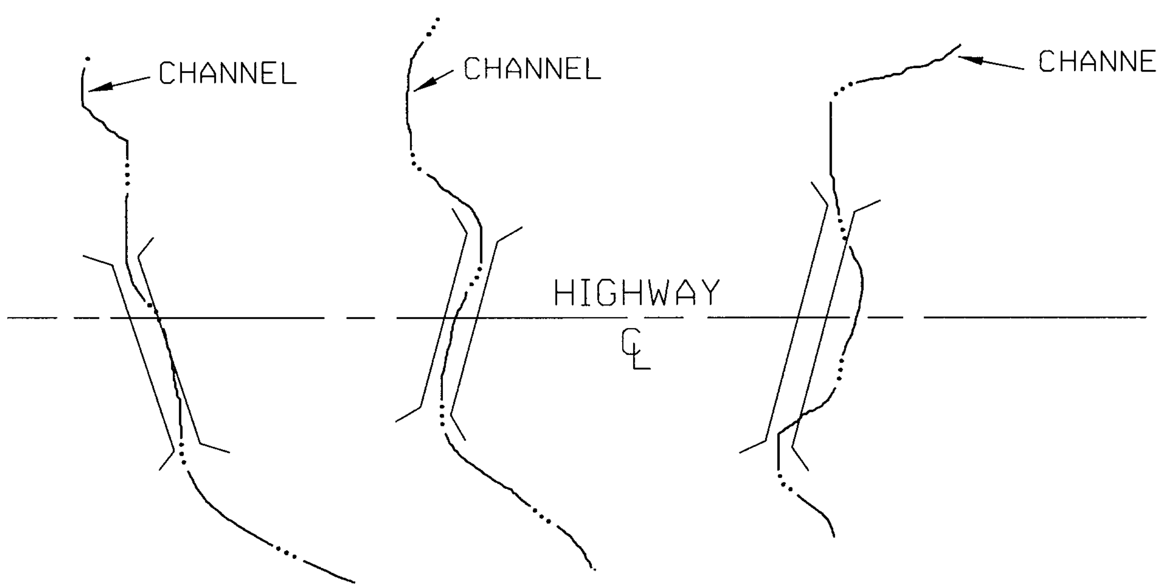
The embedment of culverts may be required when streams and channels are considered jurisdictional as regulated by the U.S. Army Corps of Engineers (USACE). The designer should review Road Memorandum No.16-02, "Embedment of Culverts on Jurisdictional Streams". This memorandum will provide guidance on embedment requirements and establish consistent plan notations and use of bridge base sheet and standard drawing for embedded culverts. In addition, the designer should contact the Environmental Services Section regarding embedment requirements.

6.2 ALIGNMENT OF CULVERTS

6.2.1 Horizontal Alignment

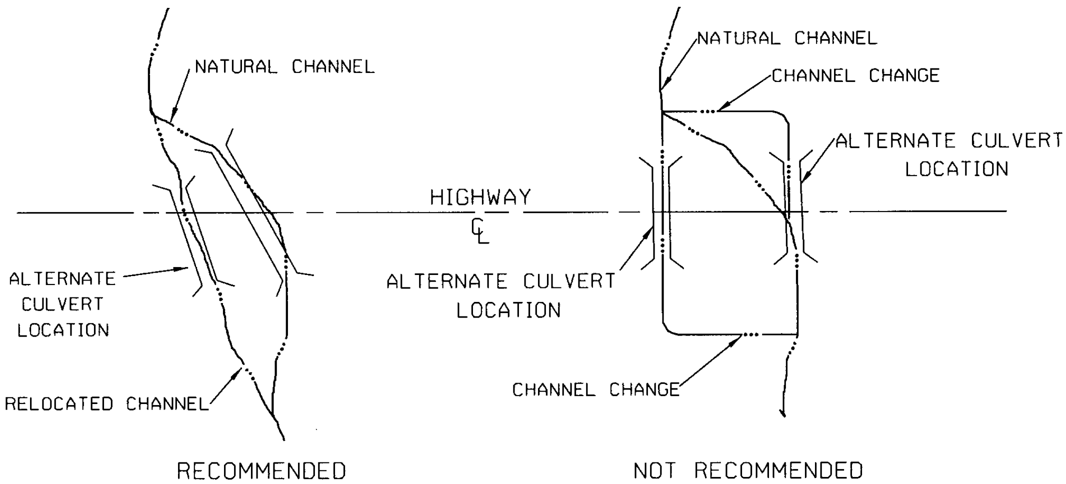
Ideally, a culvert should be placed in the natural channel, as in Figure 6.2.1-1, "Culvert Located in a Natural Channel". This location usually provides good alignment of the natural flow with the culvert inlet and outlet and little excavation and channel work are required. Where location in the natural channel would require an inordinately long culvert, some stream modification may be in order, as illustrated in Figure 6.2.1-2, "Methods of Culvert Location Where Location in the Natural Channel Involves an Inordinately Long Culvert". Such modifications to reduce skew and shorten culverts should be designed carefully to avoid erosion and sedimentation problems. For information regarding lengths of culverts, see the KDOT Roadside Design Guidelines.

Figure 6.2.1-1 Culvert Located in a Natural Channel



Source: AASHTO, *Highway Drainage Guidelines*, Chapter 4, 2007

Figure 6.2.1-2 Methods of Culvert Location Where Location in the Natural Channel Involves an Inordinately Long Culvert



Source: AASHTO, *Highway Drainage Guidelines*, Chapter 4, 2007

Culvert locations normal to the roadway centerline are not recommended where severe or abrupt changes in channel alignment are required upstream or downstream of the culvert. Short-radius bends are subject to erosion on the concave bank and deposition on the inside of the bend. Such changes upstream of the culvert result in poor alignment of the approach flow to the culvert, subject the highway fill to erosion, and increase the likelihood of deposition in the culvert barrel. Abrupt changes in channel alignment downstream of culverts may cause erosion on adjacent properties.

RCB culverts may be rotated or skewed to improve the alignment of the culvert with the stream. A rotated RCB is defined as an RCB that intersects the project centerline at an angle other than 90º and has entrance and exit faces normal to the RCB centerline. A skewed RCB is defined as an RCB that intersects the project centerline at an angle other than 90º and has entrance and exit faces parallel to the project centerline. Ordinary design practice allows normal (90º crossing) box culverts to be rotated up to 15º. Standard skewed boxes with 30º and 45º skew angles may be used at skewed stream crossings.

Channel changes in Kansas streams are regulated by the Division of Water Resources of the Kansas Department of Agriculture. The Environmental Services Section is responsible for obtaining and processing the permits required for channel changes. The designer should inform the Environmental Services Section of proposed channel changes as early as feasible, and promptly provide the design information needed for the permit application. The timely submittal of the permit application is necessary to avoid delays in the project.

6.2.2 Grade

The culvert should be placed on a grade that approximates the natural grade of the stream wherever practical. A minimum slope of 0.3% is recommended for RCB and RCP crossroad structures. A minimum slope of 0.5% is recommended for CMP crossroad structures. An aquatic organism passage (AOP) apron can be used to reduce the slope of an RCB where lower exit velocities are desirable. The designer should contact the Environmental Services Section and the Bureau of Structures and Geotechnical Services for information and examples of an AOP apron.

6.2.3 Embedment of Culverts

Many new and replacement culverts over a certain size may need to be embedded below the streambed to facilitate aquatic organism passage. In general, for permanent crossings, the culvert must be embedded and backfilled below the grade of the stream on both the upstream and downstream sides a minimum of 12 inches for culverts greater than 48 inches in height. Designers should identify culvert locations where embedment may be required based on the flowchart (Attachment B) included in Road Memorandum No. 16-02, "Embedment of Culverts on Jurisdictional Streams".

6.2.4 Hydraulic Geometry of Embedded Culverts

To apply the general equations of culvert hydraulics to an embedded culvert, one must first calculate the area and perimeter of the open cross-section and width of the channel bottom within the culvert. These calculations are simple for an embedded box culvert but more complex for an embedded pipe culvert. The relevant dimensions for an embedded culvert are defined as follows:

D = rise or diameter of culvert, unadjusted for embedment

b = depth of embedment

D_b = rise of embedded culvert

B_b = width of channel bottom within embedded culvert

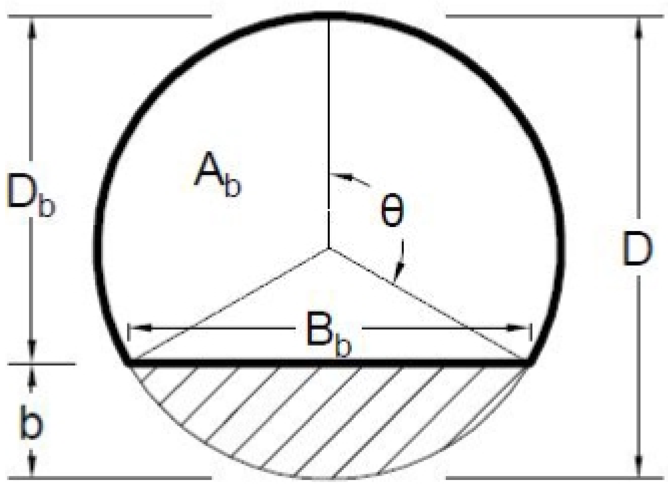
P_c = perimeter of conduit above channel bottom within embedded culvert

P_b = total perimeter of open waterway within embedded culvert

A_b = area of open waterway within embedded culvert

For a culvert installation with multiple barrels or cells, the dimensions defined above apply to a single barrel or cell. Figure 6.2.4-1 shows how these dimensions apply to an embedded pipe culvert.

Figure 6.2.4-1 Dimensions for Embedded Pipe Culvert



The values of D_b, B_b, P_c, P_b, and A_b all depend only on the pipe diameter, D, and the embedment depth, b. However, the relations for B_b, P_b, and A_b can be expressed most compactly in terms of the angle Θ defined in Figure 6.2.4-1. The angle Θ depends only on the ratio b/D. Its value in radians is computed with the equation below.

$$\theta = \cos^{-1}\left(2\frac{b}{D} - 1\right)$$

The values of D_b, B_b, P_b, P_c, and A_b are computed from D, b, and Θ using the following equations:

$$D_b = D - b$$

$$B_b = D \sin\theta$$

$$P_c = D \cdot \theta$$

$$P_b = P_c + B_b$$

$$A_b = \frac{D^2}{4}(\theta - \sin\theta\cos\theta)$$

Table 6.2.4-1 provides values of the required dimensions for standard-size pipes larger than 48 inches embedded to a depth of 12 inches.

Table 6.2.4-1 Hydraulic Dimensions for Pipe Culverts Embedded to 12-inch Depth

D (in.)	**D_b (ft)**	**B_b (ft)**	**P_c (ft)**	**P_b (ft)**	**A_b (ft^2)**
54	3.5	3.74	9.72	13.46	13.27
60	4.0	4.00	11.07	15.07	16.84
66	4.5	4.24	12.43	16.68	20.81
72	5.0	4.47	13.80	18.28	25.18
78	5.5	4.69	15.18	19.87	29.95
84	6.0	4.90	16.56	21.46	35.11
90	6.5	5.10	17.96	23.05	40.68
96	7.0	5.29	19.35	24.64	46.64
102	7.5	5.48	20.75	26.23	53.00
108	8.0	5.66	22.16	27.81	59.75
114	8.5	5.83	23.57	29.40	66.90
120	9.0	6.00	24.98	30.98	74.45

6.3 HYDRAULIC ANALYSIS OF CULVERTS

The hydraulic analysis procedures in this section apply to RCP and CMP culverts with standard Type I, Type III or Type IV end sections, and to RCB culverts with standard 45º or straight wingwalls. For guidance on hydraulic analysis of other types of culverts or end treatments, see FHWA's HDS No. 5, *Hydraulic Design of Highway Culverts*. For guidance on detention-storage analysis of culverts, see Section 6.5, "ANALYSIS AND DESIGN OF CULVERTS FOR DETENTION STORAGE".

Certain types of culverts cannot be analyzed fully by the methods in this manual or HDS No. 5. These cases may include culverts with a change in alignment, a change in cross section or a junction within the culvert, and may need a more detailed analysis.

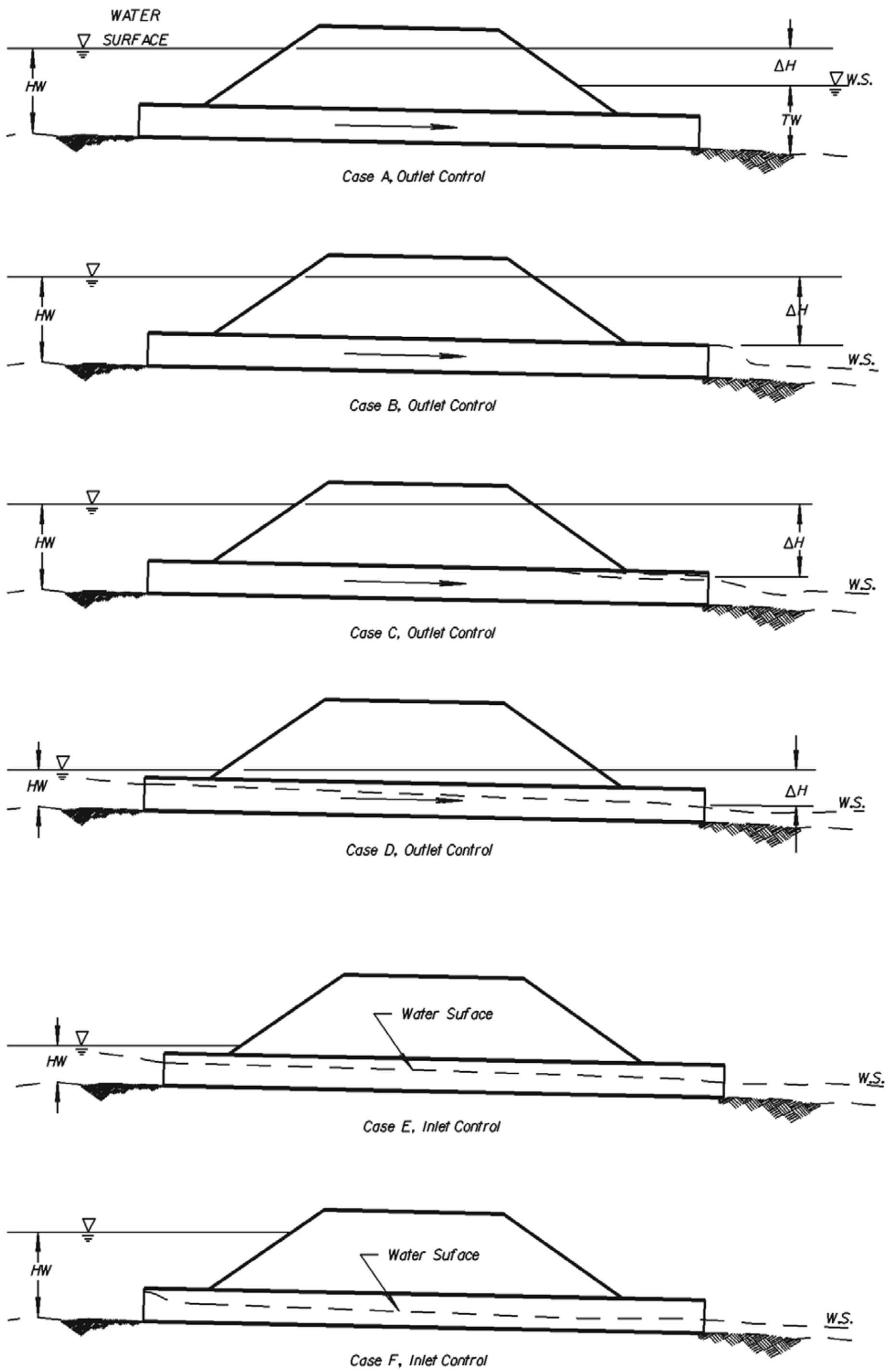
6.3.1 Types of Flow in Culverts

Water can flow through culverts in several different ways. If the culvert outlet is submerged by tailwater, the culvert will flow full, as in Case A of Figure 6.3.1-1. Cases B through F of Figure 6.3.1-1 are the five types of flow that can occur when the outlet is not submerged by tailwater. Cases A through D are types of outlet control, and Cases E and F are types of inlet control. Under outlet control, the headwater level depends on the discharge, the size and design of the culvert entrance; the length, slope and roughness of the culvert barrel; and the tailwater level. Under inlet control, the headwater level depends only on the discharge and the size and design of the culvert entrance.

6.3.2 General Procedure for Culvert Analysis

The usual objective of culvert analysis is to determine the headwater level for a specified discharge, Q. The first step is to determine the tailwater depth, TW (see Section 6.3.3). If $TW \geq D$ (where D is the inside height of the culvert), the culvert is certain to flow full, and the headwater level should be computed using the procedure for outlet control. If $TW < D$, the culvert could operate under outlet control or inlet control. In this case, two different headwater levels should be computed using the procedures for outlet control and inlet control, and the higher level should be used for design.

Figure 6.3.1-1 Types of Flow through Culverts



Source: HDS No. 5 (FHWA, 1985)

6.3.3 Tailwater Level

The tailwater level at a given discharge depends on the hydraulic characteristics of the channel and floodplain downstream of the culvert. If the tailwater level would not be affected significantly by backwater from a downstream feature, compute the depth of flow with Manning's equation for uniform flow (Equation 4-1). If the flow cannot be conveyed within the banks of the channel, compute the discharges in the main channel and the left and right overbank regions separately. If the tailwater level would be affected by backwater from a downstream feature, a backwater analysis may be used to determine the tailwater depth.

Tailwater calculations require Manning's roughness coefficients for the downstream channel and overbank regions. Table 3.5.6-1, "Manning's Roughness Coefficients for Minor Streams and Floodplains" provides guidance for estimation of Manning's n values for streams and floodplains.

6.3.4 Outlet Control

Use the following procedure to find the headwater depth at a specified discharge for a culvert operating under outlet control.

1. Determine the tailwater depth, TW (see Section 6.3.3).

2. Determine the entrance-loss coefficient, K_e, for the culvert entrance from Table 6.3.4-1.

3. If the culvert is embedded, determine the hydraulic dimensions defined in Section 6.2.4. For pipe culverts embedded to a 12-inch depth, use Table 6.2.4-1.

4. Determine the Manning's n value for the culvert barrel from Table 6.3.4-2. If the culvert is embedded, compute the average Manning's n value for the open waterway with Equation 6-1.

$$\bar{n} = \left(\frac{P_c n_c^{\frac{3}{2}} + B_b n_b^{\frac{3}{2}}}{P_c + B_b} \right)^{\frac{2}{3}} \qquad (6\text{-}1)$$

where:

$\bar{n}$ = average Manning n value for embedded culvert

n_c = Manning n value for conduit

n_b = Manning n value for embedment (streambed) material in conduit and P_c and B_b are defined in Section 6.2.

5. Compute the velocity for full flow:

$$V = \frac{Q}{mA} \tag{6-2}$$

where: V = velocity (ft/s)

Q = discharge (cfs)

m = number of barrels or cells

A = cross-sectional area of one barrel or cell (ft^2)

Note: If the culvert is embedded, use A_b in place of A in Equation 6-2.

6. Compute the hydraulic radius for full flow:

$$R = \frac{A}{P} \tag{6-3}$$

where: R = hydraulic radius (ft)

P = perimeter of one barrel or cell (ft)

Note: If the culvert is embedded, use A_b and P_b in place of A and P in Equation 6-3.

7. Compute the total head loss through the culvert:

$$\Delta H = \left(1 + K_e + \frac{29.0n^2L}{R^{4/3}}\right)\frac{V^2}{2g} \tag{6-4}$$

where: ΔH = total head loss through culvert (ft) n = Manning's roughness coefficient for culvert barrel

L = length of culvert barrel (ft)

g = gravitational constant (32.2 ft/s^2)

Note: If the culvert is embedded, use $\bar{n}$ from Step 4 in place of n in Equation 6-4.

8. If TW < D, then compute the critical depth in the culvert, d_{cr}

For non-embedded pipe culverts, use the following procedure:

(1) Compute the value of $Q/D^{2.5}$, for Q in cfs and D in ft.

(2) Find the corresponding value of d_{cr}/D by interpolation in Table 6.3.4-3.

(3) $d_{cr} = (d_{cr}/D) \cdot D$

For pipe culverts embedded to a 12-inch depth, the critical depth can be found by interpolation in Table 6.3.4-4.

For RCB culverts, use Equation 6-5:

$$d_{cr} = \left(\frac{Q^2}{B^2 g}\right)^{\frac{1}{3}} \qquad (6\text{-}5)$$

where: d_{cr} = critical depth (ft)

Q = discharge (total for all cells) (cfs)

B = width of culvert (total for all cells) (ft)

g = gravitational constant (32.2 ft/s^2)

9. Compute HW using Equation 6-6 or 6-7. If TW ≥ D or TW ≥ $(D+d_{cr})/2$, use Equation 6-6. If TW < $(D+d_{cr})/2$, use Equation 6-7. If the culvert is embedded, substitute D_b for D in these instructions.

$$HW = TW - L \cdot S + \Delta H \qquad (6\text{-}6)$$

where: L = length of culvert barrel (ft)

S = slope of culvert barrel (ft/ft)

ΔH = total head loss through the culvert (ft)

$$HW = \frac{D + d_{cr}}{2} - L \cdot S + \Delta H \qquad (6\text{-}7)$$

D = inside culvert height (ft)where: d_{cr} = critical depth (ft)

This procedure yields satisfactory estimates of HW provided that HW > 0.75 D. For lower headwaters, backwater calculations are recommended to obtain more accurate headwater elevations; refer to HDS No. 5. FHWA's HY-8 computer program performs the necessary backwater calculations.

Table 6.3.4-1 Entrance-Loss Coefficients for Culvert Entrances

Entrance Type	K_e	
	Non-Embedded	Embedded
KDOT Standard End Treatments		
Type I metal or concrete end section (54 in. or smaller)	0.35	0.45
Type I metal or concrete end section (60 in. or larger)	0.30	0.40
Type III metal end section	0.16	0.20
Type III (or Type III alternate) concrete end section	0.10	0.15
Type IV end section (24 in.)	0.65	0.75
Type IV end section (30 in.)	0.70	0.80
Type IV end section (36 in.)	0.75	0.85
Type IV end section (42 and 48 in.)	0.80	0.90
Type IV section (54 and 60 in.)	0.85	0.95
Concrete headwall and structural steel grate (for medians)	0.30	---
RCB with flared wingwalls	0.20	0.20
RCB with straight wingwalls	0.40	0.40
Other End Treatments		
RCP projecting from fill (socket end)	0.20	0.30
RCP projecting from fill (square-cut end)	0.50	0.60
CMP projecting from fill	0.90	1.00
RCP or CMP mitered to conform to fill slope	0.70	0.90
RCP with headwall, or headwall and wingwalls		
Socket end of pipe	0.20	0.30
Square inlet edges	0.50	0.55
Beveled or rounded inlet edges	0.20	0.35
CMP with headwall, or headwall and wingwalls		
Square inlet edges	0.50	0.55
(Table continued on next page)		

Table 6.3.4-1 Entrance-Loss Coefficients for Culvert Entrances

Entrance Type	K_e	
	Non-Embedded	Embedded
Beveled or rounded inlet edges	0.20	0.35
CMP Mitered to conform to fill slope	0.70	0.90
RCB with headwall parallel to embankment (no wingwalls)		
Square edges on crown and sides	0.50	0.50
Beveled or rounded edges on crown and sides	0.20	0.20
RCB with wingwalls at 30º to 75º to barrel, crown edge square	0.40	0.40
RCB with wingwalls at 10º to 25º to barrel, crown edge square	0.50	0.50
RCB with straight wingwalls, crown edge square	0.70	0.70
Side-tapered or slope-tapered inlet (FHWA standard design)	0.20	0.20

Sources: HDS No. 5 and KDOT Reports K-TRAN: KU-93-5, KU-94-4 and KU-16-2

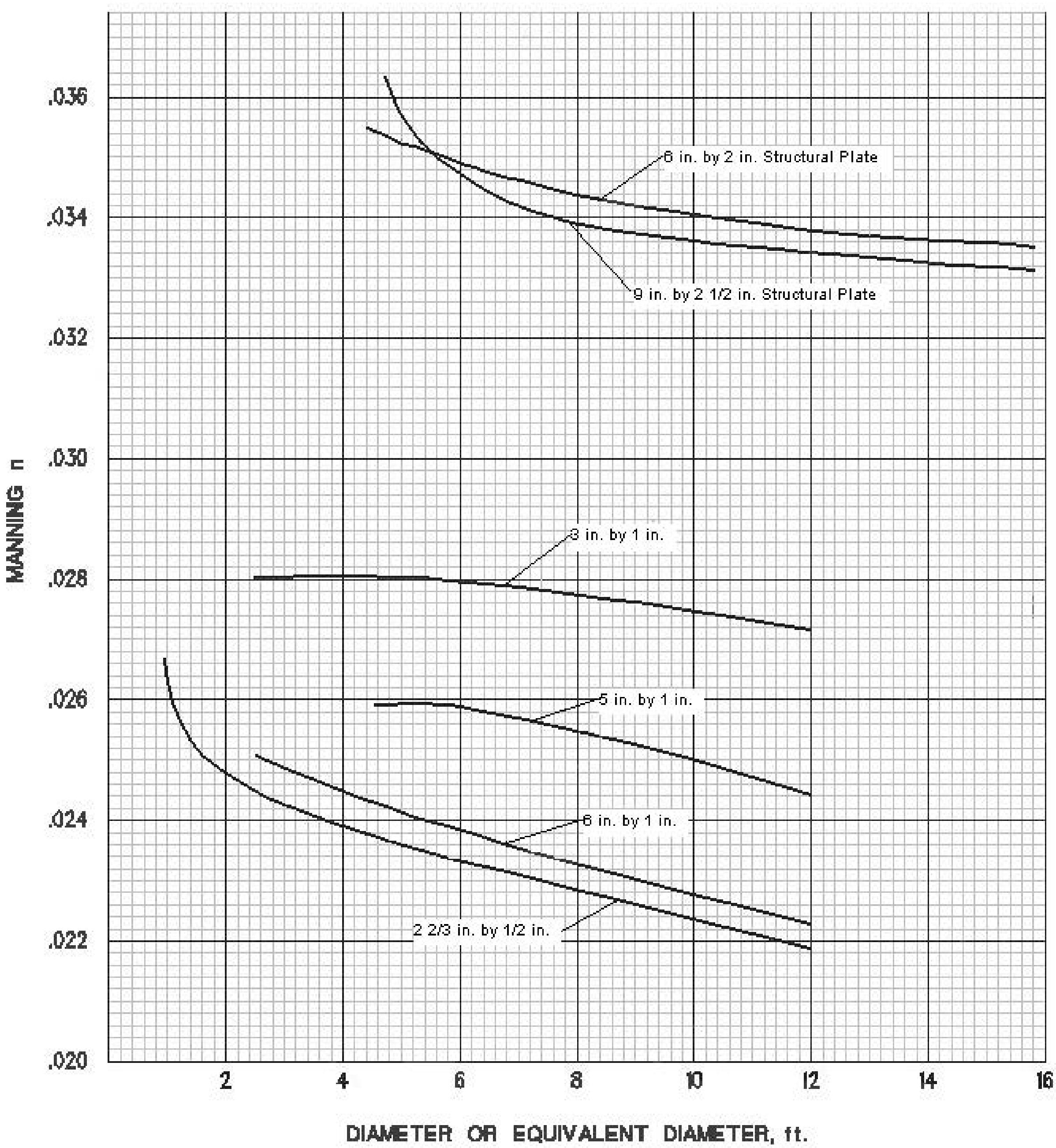
Table 6.3.4-2 Manning's Roughness Coefficients for Culverts

Culvert Type	Manning's n
Reinforced Concrete Pipe	
New and existing installations with smooth walls and good joints	0.012
Existing installations with rough walls or poor joints	0.013 - 0.017
Reinforced Concrete Box	
New and existing installations with smooth walls and good joints	0.013
Existing installations with rough walls and poor joints	0.014 - 0.018
*Corrugated Metal Pipe (good condition, $2^2/_3$" x $^1/_2$" corrugations)	0.024
Spiral Rib Steel Pipe (good condition)	0.012
Polyethylene Pipe (smooth wall)	0.012
Polyvinyl Chloride Pipe	0.010

Source: HDS No. 5

* See Figure 6.3.4-1 for other corrugations. For CMPs with helical corrugations and diameter less than 24", see K-TRAN Report Number KU-07-05, "Hydraulic Resistance of Small Diameter Helically Corrugated Metal Pipe".

Figure 6.3.4-1 Manning's Roughness Coefficients for Corrugated Metal Conduits with Annular Corrugations



Source: HDS No. 5, with modification as result of K-TRAN Report Number KU-07-5.

Table 6.3.4-3 Critical Depth in a Circular Pipe

d_{cr}/D	$Q/D^{2.5}$	d_{cr}/D	$Q/D^{2.5}$	d_{cr}/D	$Q/D^{2.5}$
0.00	0.0000	0.27	0.4262	0.54	1.6175
0.01	0.0006	0.28	0.4574	0.55	1.6752
0.02	0.0025	0.29	0.4896	0.56	1.7338
0.03	0.0055	0.30	0.5229	0.57	1.7935
0.04	0.0098	0.31	0.5572	0.58	1.8542
0.05	0.0153	0.32	0.5925	0.59	1.9158
0.06	0.0220	0.33	0.6288	0.60	1.9785
0.07	0.0298	0.34	0.6661	0.61	2.0423
0.08	0.0389	0.35	0.7045	0.62	2.1071
0.09	0.0491	0.36	0.7438	0.63	2.1730
0.10	0.0605	0.37	0.7841	0.64	2.2400
0.11	0.0731	0.38	0.8254	0.65	2.3081
0.12	0.0868	0.39	0.8677	0.66	2.3775
0.13	0.1017	0.40	0.9109	0.67	2.4480
0.14	0.1177	0.41	0.9551	0.68	2.5198
0.15	0.1348	0.42	1.0003	0.69	2.5928
0.16	0.1531	0.43	1.0465	0.70	2.6673
0.17	0.1725	0.44	1.0936	0.71	2.7432
0.18	0.1930	0.45	1.1417	0.72	2.8205
0.19	0.2145	0.46	1.1907	0.73	2.8995
0.20	0.2372	0.47	1.2407	0.74	2.9801
0.21	0.2610	0.48	1.2917	0.75	3.0626
0.22	0.2859	0.49	1.3436	0.76	3.1469
0.23	0.3118	0.50	1.3964	0.77	3.2334
0.24	0.3388	0.51	1.4502	0.78	3.3221
0.25	0.3669	0.52	1.5050	0.79	3.4133
0.26	0.3960	0.53	1.5608	0.80	3.5072

Table 6.3.4-3 Critical Depth in a Circular Pipe

d_{cr}/D	$Q/D^{2.5}$	d_{cr}/D	$Q/D^{2.5}$	d_{cr}/D	$Q/D^{2.5}$
0.81	3.6041	0.88	4.4083	0.95	5.8154
0.82	3.7044	0.89	4.5514	0.96	6.1825
0.83	3.8085	0.90	4.7062	0.97	6.6735
0.84	3.9168	0.91	4.8755	0.98	7.4108
0.85	4.0301	0.92	5.0634	0.99	8.8315
0.86	4.1491	0.93	5.2758	1.00	∞
0.87	4.2748	0.94	5.5217		

Note:D and d_{cr} in ft, Q in cfs

Table 6.3.4-4 Critical Flow in a Circular Pipe Embedded to 12-inch Depth

d_{cr} (ft)	Q (cfs) for critical flow at depth d_{cr} in pipe of stated diameter, embedded 12 inches.											
	54-in. dia.	60-in. dia.	66-in. dia	72-in. dia.	78-in. dia	84-in. dia	90-in. dia.	96-in. dia.	102-in. dia.	108-in. dia	114-in. dia	120-in. dia.
0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	8	8	9	9	10	10	11	11	12	12	12	13
1.0	23	25	26	28	29	31	32	33	35	36	37	38
1.5	44	47	50	53	56	59	61	64	66	69	71	73
2.0	70	75	80	85	90	94	98	102	106	110	113	117
2.5	102	109	116	123	129	136	142	148	153	159	164	169
3.0	146	149	157	166	175	184	192	200	208	216	223	230
3.5	---	206	208	217	227	238	249	259	270	279	289	298
4.0	---	---	280	278	288	300	313	325	338	350	363	374
4.5	---	---	---	368	362	371	384	399	414	429	444	458
5.0	---	---	---	---	471	458	467	482	498	515	532	549
5.5	---	---	---	---	---	590	570	577	592	610	629	649
6.0	---	---	---	---	---	---	726	696	701	716	736	757

Table 6.3.4-4 Critical Flow in a Circular Pipe Embedded to 12-inch Depth

d_{cr} (ft)	Q (cfs) for critical flow at depth d_{cr} in pipe of stated diameter, embedded 12 inches.											
	54-in. dia.	60-in. dia.	66-in. dia	72-in. dia.	78-in. dia	84-in. dia	90-in. dia.	96-in. dia.	102-in. dia.	108-in. dia	114-in. dia	120-in. dia.
6.5	---	---	---	---	---	---	---	880	838	840	855	876
7.0	---	---	---	---	---	---	---	---	1053	997	995	1010
7.5	---	---	---	---	---	---	---	---	---	1246	1173	1166
8.0	---	---	---	---	---	---	---	---	---	---	1460	1367
8.5												1695

6.3.4.1 Example: Culvert Analysis for Outlet Control

Problem:

A new 48-in. RCP culvert has Type IV end sections. The length is 100 ft and the slope is 0.5%. The flowline elevation at the entrance is 1134.09 ft. At a discharge of 150 cfs, the tailwater depth is 1.95 ft. Find the headwater elevation for outlet control at Q = 150 cfs.

Solution:

Determine the total head loss for full flow.

Obtain the entrance-loss coefficient for the 48-in. Type IV end section from Table 6.3.4-1.

$$K_e = 0.80$$

Obtain the Manning's n value for the RCP culvert from Table 6.3.4-2.

$$n = 0.012$$

Compute the velocity for full flow at a discharge of 150 cfs with Equation 6-2.

$$V = \frac{Q}{A} = \frac{Q}{\left(\frac{\pi}{4}D^2\right)} = \frac{150}{\left[\frac{\pi}{4}\left(\frac{48}{12}\right)^2\right]} = 11.94 \text{ ft/s}$$

Compute the hydraulic radius for full flow with Equation 6-3.

$$R = \frac{A}{P} = \frac{\left(\frac{\pi}{4}D^2\right)}{\pi D} = \frac{D}{4} = \frac{(48/12)}{4} = 1.00 \text{ ft}$$

Compute the total head loss with Equation 6-4.

$$\Delta H = \left(1 + K_e + \frac{29.0n^2L}{R^{4/3}}\right)\frac{V^2}{2g} = \left[1 + 0.80 + \frac{29.0(0.012)^2(100)}{(1.00)^{4/3}}\right]\frac{(11.94)^2}{2(32.2)} = 4.91 \text{ ft}$$

The tailwater is below the outlet crown (TW < D), so determine the critical depth.

Compute the quantity $Q/D^{2.5}$ (for Q in cfs and D in ft) for use in Table 6.3.4-3.

$$Q/D^{2.5} = 150 / (4.00)^{2.5} = 4.69$$

Obtain d_{cr}/D from Table 6.3.4-3 by interpolation.

$$d_{cr}/D = 0.899$$

Compute the critical depth.

$$d_{cr} = (d_{cr}/D)\, D = (0.899)\, 4.00 = 3.60 \text{ ft}$$

Compute $(D+d_{cr})/2$

$$(D+d_{cr})/2 = (4.00 + 3.60) / 2 = 3.80 \text{ ft}$$

$(D+d_{cr})/2$ exceeds the actual tailwater depth, so compute the headwater depth with Equation 6-7.

$$HW = \frac{D + d_{cr}}{2} - L \cdot S + \Delta H = 3.80 - 100(0.005) + 4.91 = 8.21 \text{ ft}$$

The headwater elevation is the sum of the flowline elevation at the entrance and the headwater depth.

HWE = 1134.09 + 8.21 = 1142.30 ft

6.3.4.2 Example: Embedded Pipe Culvert under Outlet Control

Problem:

A new 60-inch RCP culvert with Type IV end sections is embedded to a depth of 12 inches. The length is 100 ft and the slope is 0.5%. The flowline elevation at the entrance is 1134.09 ft. The Manning n value for the streambed material is 0.035. At a discharge of 150 cfs, the tailwater depth is 3.10 ft. Find the headwater elevation at a discharge of 150 cfs with the culvert operating under outlet control.

Solution:

Obtain the hydraulic dimensions for the embedded pipe culvert from Table 6.2.4-1

D_b = 4.00 ft

B_b = 4.00 ft

P_c = 11.07 ft

P_b = 15.07 ft

A_b = 16.84 ft^2

Determine the total head loss for full flow.

Obtain the entrance-loss coefficient for the 60-in. Type IV end section from Table 6.3.4-1.

K_e = 0.95

Obtain the Manning n value for the RCP culvert from the Table 6.3.4-2.

n_c = 0.012

Compute the average Manning n value over the perimeter of the embedded pipe ($\bar{n}$) with Equation 6-1.

$$\bar{n} = \left(\frac{P_c n_c^{\frac{3}{2}} + B_b n_b^{\frac{3}{2}}}{P_c + B_b} \right)^{\frac{2}{3}} = \left(\frac{11.07 \times 0.012^{\frac{3}{2}} + 4.00 \times 0.035^{\frac{3}{2}}}{11.07 + 4.00} \right)^{\frac{2}{3}} = 0.0194$$

Compute the velocity for full flow at a discharge of 150 cfs with Equation 6-2, substituting A_b for A and setting m = 1, where m is the number of barrels or cells.

$$V = \frac{Q}{mA_b} = \frac{150}{1(16.84)} = 8.91 \text{ ft/s}$$

Compute the hydraulic radius for full flow in the embedded culvert with Equation 6-3.

$$R = \frac{A_b}{P_b} = \frac{16.84}{15.07} = 1.12 \text{ ft.}$$

Compute the total head loss with Equation 6-4, substituting $\bar{n}$ for n.

$$\Delta H = \left(1 + K_e + \frac{29.0(\bar{n})^2 L}{R^{4/3}} \right) \frac{V^2}{2g} = \left[1 + 0.95 + \frac{29.0(0.0194)^2(100)}{(1.12)^{4/3}} \right] \frac{(8.91)^2}{2(32.2)} = 3.56 \text{ ft.}$$

The tailwater depth is below the outlet crown ($TW < D_b$) so determine the critical depth.

Interpolate in Table 6.3.4-4 for D = 60 in. and Q = 150 cfs.

$d_{cr} = 3.01$ ft

Compute $(D_b+d_{cr})/2$.

$$\frac{D_b + d_{cr}}{2} = \frac{4.00 + 3.01}{2} = 3.50 \text{ ft.}$$

$(D_b+d_{cr})/2$ exceeds the actual tailwater depth, so compute the headwater depth with Equation 6-7.

$$HW = \frac{D_b + d_{cr}}{2} - L \times S + \Delta H = 3.50 - 100\,(0.005) + 3.56 = 6.56 \text{ ft}$$

The headwater elevation is the sum of the flowline elevation at the entrance and the headwater depth.

$$HWE = 1134.09 + 6.56 = 1140.65 \text{ ft.}$$

6.3.5 Inlet Control

6.3.5.1 Pipe Culverts

Use the following procedure to find the headwater depth at a specified discharge for a pipe culvert with a standard end section operating under inlet control.

1. If the culvert is not embedded, compute the quantity $Q/(AD^{0.5})$, with Q in cfs, D in ft and A in ft^2. If the culvert is embedded, compute the dimensions D_b and A_b as directed in Section 18.2.4, and then compute the quantity $Q/(A_b\,D_b^{0.5})$. For multiple pipe installations, Q represents the discharge through a single pipe, and A and A_b are the open cross-sectional areas for single non-embedded and embedded pipes."

   For multiple pipe installations, divide Q by the number of pipes. (Assumes pipes are all the same size)

2. Determine HW/D or HW/D_b by interpolation in the appropriate table listed below.

End Section Type	**Table**
Metal Type I	6.3.5.1-1
Concrete Type I	6.3.5.1-2*
Metal Type III	6.3.5.1-3
Concrete Type III	6.3.5.1-4
Type IV	6.3.5.1-5

*Table 6.3.5.1-2 is also applicable to KDOT’s concrete headwall and structural steel grate for median applications.

3. HW = (HW/D) D or HW= $(HW/D_b)D_b$ if culvert is embedded.

The tables for the Type I end sections cover the range $0 \leq HW/D \leq 4$. The tables for the Type III and Type IV end sections cover the range $0 \leq HW/D \leq 2$. Hydraulic model tests have shown that the pipe culverts with Type III and Type IV end sections do not operate under inlet control for HW/D > 2.0. Information regarding the development of these tables may be found in KDOT Report No. K-TRAN: KU-94-4 (McEnroe and Johnson, 1994), KU-93-5 (McEnroe and Bartley, 1993) and KU-16-2 (McEnroe and Hoffman, 2017).

Table 6.3.5.1-1 Headwater-Discharge Relationship for Pipe Culverts with Metal Type I End Sections under Inlet Control

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
0.00	0.000	1.35	4.294	2.70	7.428
0.05	0.022	1.40	4.456	2.75	7.510
0.10	0.071	1.45	4.635	2.80	7.591
0.15	0.140	1.50	4.801	2.85	7.671
0.20	0.226	1.55	4.958	2.90	7.750
0.25	0.328	1.60	5.106	2.95	7.827
0.30	0.444	1.65	5.248	3.00	7.904
0.35	0.575	1.70	5.384	3.05	7.980
0.40	0.718	1.75	5.514	3.10	8.055
0.45	0.874	1.80	5.640	3.15	8.129
0.50	1.041	1.85	5.762	3.20	8.202
0.55	1.221	1.90	5.880	3.25	8.274
0.60	1.411	1.95	5.994	3.30	8.345
0.65	1.612	2.00	6.105	3.35	8.416
0.70	1.824	2.05	6.214	3.40	8.485
0.75	2.047	2.10	6.319	3.45	8.554
0.80	2.279	2.15	6.422	3.50	8.623
0.85	2.522	2.20	6.523	3.55	8.690
0.90	2.774	2.25	6.621	3.60	8.757
0.95	3.000	2.30	6.718	3.65	8.823
1.00	3.162	2.35	6.812	3.70	8.889
1.05	3.324	2.40	6.905	3.75	8.954

Table 6.3.5.1-1 Headwater-Discharge Relationship for Pipe Culverts with Metal Type I End Sections under Inlet Control (Continued)

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
1.10	3.485	2.45	6.996	3.80	9.018
1.15	3.647	2.50	7.085	3.85	9.082
1.20	3.809	2.55	7.173	3.90	9.146
1.25	3.971	2.60	7.259	3.95	9.208
1.30	4.133	2.65	7.344	4.00	9.270

Note: HW, D, and D_b in ft, Q in cfs, A and A_b in ft^2

Table 6.3.5.1-2 Headwater-Discharge Relationship for Pipe Culverts with Concrete Type I End Sections under Inlet Control*

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
0.00	0.000	1.35	4.191	2.70	7.678
0.05	0.014	1.40	4.353	2.75	7.768
0.10	0.051	1.45	4.515	2.80	7.856
0.15	0.106	1.50	4.749	2.85	7.942
0.20	0.178	1.55	4.932	2.90	8.028
0.25	0.268	1.60	5.104	2.95	8.112
0.30	0.373	1.65	5.266	3.00	8.195
0.35	0.494	1.70	5.421	3.05	8.277
0.40	0.629	1.75	5.569	3.10	8.357
0.45	0.780	1.80	5.711	3.15	8.437
0.50	0.944	1.85	5.847	3.20	8.516
0.55	1.123	1.90	5.979	3.25	8.594
0.60	1.316	1.95	6.106	3.30	8.671
0.65	1.522	2.00	6.230	3.35	8.747
0.70	1.741	2.05	6.349	3.40	8.822
0.75	1.974	2.10	6.466	3.45	8.896
0.80	2.219	2.15	6.580	3.50	8.970
0.85	2.478	2.20	6.690	3.55	9.043
0.90	2.750	2.25	6.798	3.60	9.115
0.95	2.896	2.30	6.904	3.65	9.186
1.00	3.058	2.35	7.008	3.70	9.256
1.05	3.220	2.40	7.109	3.75	9.326
1.10	3.382	2.45	7.208	3.80	9.395
1.15	3.544	2.50	7.306	3.85	9.464
1.20	3.706	2.55	7.401	3.90	9.532
1.25	3.867	2.60	7.495	3.95	9.599
1.30	4.029	2.65	7.587	4.00	9.666

Note: HW, D, and D_b in ft, Q in cfs, A and A_b in ft^2

*This table is also applicable to KDOT's concrete headwall and structural steel grate for median applications.

Table 6.3.5.1-3 Headwater-Discharge Relationship for Pipe Culverts with Metal Type III End Sections under Inlet Control

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
0.00	0.000	1.05	3.398
0.05	0.021	1.10	3.672
0.10	0.067	1.15	3.955
0.15	0.133	1.20	4.228
0.20	0.214	1.25	4.482
0.25	0.311	1.30	4.727
0.30	0.421	1.35	4.965
0.35	0.545	1.40	5.196
0.40	0.680	1.45	5.421
0.45	0.828	1.50	5.639
0.50	0.987	1.55	5.853
0.55	1.157	1.60	6.061
0.60	1.337	1.65	6.265
0.65	1.528	1.70	6.464
0.70	1.729	1.75	6.659
0.75	1.940	1.80	6.851
0.80	2.160	1.85	7.038
0.85	2.390	1.90	7.223
0.90	2.628	1.95	7.404
0.95	2.876	2.00	7.581
1.00	3.133		

Note: HW, D, and D_b in ft, Q in cfs, A and A_b in ft^2

Table 6.3.5.1-4 Headwater-Discharge Relationship for Pipe Culverts with Concrete Type III End Sections under Inlet Control

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
0.00	0.000	1.05	3.661
0.05	0.023	1.10	3.948
0.10	0.073	1.15	4.246
0.15	0.143	1.20	4.529
0.20	0.231	1.25	4.801
0.25	0.335	1.30	5.062
0.30	0.454	1.35	5.313
0.35	0.587	1.40	5.555
0.40	0.733	1.45	5.790
0.45	0.892	1.50	6.017
0.50	1.063	1.55	6.238
0.55	1.246	1.60	6.453
0.60	1.440	1.65	6.663
0.65	1.646	1.70	6.867
0.70	1.862	1.75	7.067
0.75	2.089	1.80	7.262
0.80	2.327	1.85	7.453
0.85	2.574	1.90	7.640
0.90	2.831	1.95	7.824
0.95	3.098	2.00	8.004
1.00	3.375		

Note: HW, D, and D_b in ft, Q in cfs, A and A_b in ft^2

Table 6.3.5.1-5 Headwater-Discharge Relationship for Pipe Culverts with Type IV End Sections under Inlet Control

HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$	HW/D or HW/D_b	$Q/(AD^{0.5})$ or $Q/(A_bD_b^{0.5})$
0.00	0.000	1.05	3.244
0.05	0.020	1.10	3.448
0.10	0.065	1.15	3.630
0.15	0.128	1.20	3.795
0.20	0.206	1.25	3.949
0.25	0.299	1.30	4.092
0.30	0.405	1.35	4.227
0.35	0.524	1.40	4.355
0.40	0.654	1.45	4.477
0.45	0.796	1.50	4.594
0.50	0.949	1.55	4.706
0.55	1.112	1.60	4.814
0.60	1.286	1.65	4.919
0.65	1.469	1.70	5.020
0.70	1.662	1.75	5.118
0.75	1.865	1.80	5.213
0.80	2.077	1.85	5.306
0.85	2.298	1.90	5.397
0.90	2.527	1.95	5.485
0.95	2.766	2.00	5.571
1.00	3.008		

Note: HW, D, and D_b in ft, Q in cfs, A and A_b in ft^2

6.3.5.2 Example: Analysis of a Pipe Culvert for Inlet Control

Problem:

A 48-in. RCP culvert has concrete Type I end sections. Find the headwater depth for inlet control at Q = 100 cfs.

Solution:

Compute the quantity $Q/(AD^{0.5})$ (for Q in cfs, D in ft and A in ft^2).

$$\frac{Q}{AD^{0.5}} = \frac{100}{12.57(4.00)^{0.5}} = 3.978$$

Obtain HW/D for the concrete Type I end section from Table 6.3.5.1-2 by interpolation.

HW/D = 1.28

Compute the headwater depth.

HW = (HW/D) D = (1.28) 4.0 = 5.12 ft

6.3.5.3 Example: Embedded Pipe Culvert under Inlet Control

Problem:

A 60-inch RCP culvert with concrete Type I end sections is embedded to a depth of 12 inches. Find the headwater depth for inlet control at a discharge of 150 cfs.

Solution:

Obtain D_b and A_b for the embedded pipe culvert from Table 6.2.4-1.

D_b = 4.00 ft

A_b = 16.84 ft^2

Compute the quantity $Q/(A_bD_b^{0.5})$ for Q in cfs, D_b in ft, and A_b in ft^2.

$$\frac{Q}{A_b(D_b)^{0.5}} = \frac{150}{16.84(4.00)^{0.5}} = 4.454$$

Obtain HW/Db for the concrete Type I end section from Table 6.3.5.1-2.

$$HW/D_b = 1.43$$

Compute the headwater depth.

$$HW = (HW/D_b)\ D_b = (1.43)\ 4.00 = 5.72 \text{ ft}$$

6.3.5.4 RCB Culverts

Use the following procedure to find the headwater depth at a specified discharge for an RCB culvert with a standard wingwalls (45º or straight) operating under inlet control. If the RCB is embedded, use D_b in place of D.

1. Compute the quantity $Q/(BD^{1.5})$, with Q in cfs and B (span) and D (rise) in ft.

   For multiple cell structures, B is the total span of all the cells.

2. Determine HW/D by interpolation in Table 6.3.5.4-1.

3. $HW = (HW/D) \cdot D$

Table 6.3.5.4-1 applies to RCB culverts with end treatments as shown on KDOT's standard drawings. The standard end treatments include a beveled top edge at the entrance. Table 6.3.5.4-1 does not apply to RCB culverts with square inlet edges. For the RCB culverts with non-standard end treatments, see HDS No. 5.

Table 6.3.5.4-1 Headwater-Discharge Relationship for RCB Culverts under Inlet Control

$Q/(BD^{1.5})$	HW/D		$Q/(BD^{1.5})$	HW/D	
	45° wingwalls	Straight Wingwalls		45° wingwalls	Straight Wingwalls
0.0	0.00	0.00	5.2	1.63	1.78
0.2	0.17	0.19	5.4	1.70	1.86
0.4	0.28	0.30	5.6	1.76	1.94
0.6	0.36	0.39	5.8	1.83	2.03
0.8	0.44	0.47	6.0	1.91	2.12
1.0	0.51	0.55	6.2	1.98	2.21
1.2	0.58	0.62	6.4	2.06	2.31
1.4	0.64	0.68	6.6	2.14	2.40
1.6	0.70	0.74	6.8	2.22	2.51
1.8	0.75	0.80	7.0	2.31	2.61
2.0	0.81	0.86	7.2	2.40	2.72
2.2	0.86	0.92	7.4	2.49	2.83
2.4	0.91	0.97	7.6	2.58	2.94
2.6	0.96	1.02	7.8	2.67	3.06
2.8	1.01	1.07	8.0	2.77	3.17
3.0	1.06	1.12	8.2	2.87	3.30
3.2	1.11	1.17	8.4	2.98	3.42
3.4	1.15	1.22	8.6	3.08	3.55
3.6	1.20	1.27	8.8	3.19	3.68
3.8	1.24	1.32	9.0	3.30	3.82
4.0	1.29	1.36	9.2	3.41	3.95
4.2	1.34	1.43	9.4	3.53	4.09
4.4	1.39	1.49	9.6	3.64	4.24
4.6	1.45	1.56	9.8	3.76	4.38
4.8	1.51	1.63	10.0	3.89	4.53
5.0	1.57	1.70	10.2	4.01	4.68

Note: HW, D and B in ft; Q in cfs; If RCB is embedded, use D_b in place of D

6.3.5.5 Example: Analysis of an RCB Culvert for Inlet Control

Problem:

An RCB culvert has a 10-ft span and an 8-ft rise with standard 45^o wingwalls. Find the headwater depth for inlet control at Q = 1000 cfs.

Solution:

Compute the quantity $Q/(B\ D^{1.5})$ for Q in cfs and B and D in ft.

$$Q/(B\ D^{1.5}) = 1000 / [10\ (8)^{1.5}] = 4.419$$

Obtain HW/D for the RCB culvert with standard 45^o wingwalls from Table 6.3.5.4-1 by interpolation.

$$HW/D = 1.40$$

Compute the headwater depth.

$$HW = (HW/D)\ D = (1.40)\ 8 = 11.2 \text{ ft}$$

6.3.6 Use of Computer Programs for Culvert Analysis

The methods in HDS No. 5 have been implemented in FHWA's HY-8 computer program. KDOT encourages computer-aided hydraulic analysis of culverts with HY-8 or a similar program based on HDS No. 5.

Computer programs for culvert analysis typically provide default values of Manning's n, which may differ from the values recommended in this section. Computer-aided analyses should be performed with Manning's n values in this section rather than the default values provided by the computer program.

KDOT's standard end sections for pipes are not identical to the end treatments in FHWA's HDS No. 5. The hydraulic characteristics of KDOT end sections have been determined experimentally (Reports K-TRAN: KU-93-5 & K-TRAN: KU-94-4, KDOT). Table 6.3.6-1 shows which FHWA end treatment is most similar hydraulically to each KDOT end section.

Table 6.3.6-1 Hydraulic Characteristics of KDOT End Sections for Pipes

KDOT end section	Hydraulically similar end treatment in HDS No. 5
Concrete Type I	RCP with groove end projecting
Metal Type I	CMP with headwall
Concrete Type III	RCP with side-tapered inlet
Metal Type III	CMP with side-tapered inlet
Type IV	CMP mitered to slope

6.4 DESIGN OF CULVERTS FOR PEAK FLOW

Culvert design typically requires hydraulic analyses of several alternative configurations. The designer should select the most economical configuration that meets the design criteria. The general procedure is as follows:

1. Determine the AHW (Section 2.3) and recurrence interval (Section 2.4) that govern the design of the culvert.

2. Compute the design flow for the culvert using the appropriate hydrologic method (Section 3.1).

3. Determine the tailwater elevation at the design flow (Section 6.3.3).

4. Select an appropriate horizontal alignment (Section 6.2.1) and grade (Section 6.2.2) for the culvert. Determine the approximate length of the culvert and select preliminary flowline elevations for the inlet and outlet.

5. Determine the maximum diameter or rise for the culvert, considering the roadway profile, the required minimum cover, need for embedment, and the requirements in the KDOT Roadside Design Guidelines.

6. Select an appropriate type of culvert (Section 6.1).

7. Select a preliminary size for the culvert (diameter or span x rise and number of cells).

8. Compute the headwater elevation, HWE, at the design flow (Section 6.3).

9. If the HWE at the design flow exceeds the AHW, increase the size of the culvert (or the number of barrels) and repeat the analysis. If the HWE at the design flow is significantly lower than the AHW, decrease the size of the culvert (or the number of barrels) for economy and repeat the analysis. Select the smallest size for which HWE $\leq$ AHW.

10. Determine the required culvert length and flowline elevations for the selected size.

If the HW/D ratio for the preliminary design is large, then detention-storage effects may be substantial and it may be desirable to consider these effects in the design (see Section 6.5, "ANALYSIS AND DESIGN OF CULVERTS FOR DETENTION STORAGE"). Because culverts with large HW/D ratios can have high exit velocities, the need for scour protection should also be assessed (see Section 6.6, "SCOUR PROTECTION AT CULVERT OUTLETS"). If the preliminary design would require expensive scour protection or an engineered energy dissipator, alternative designs should be considered for economy. A larger culvert, which would have a lower exit velocity, might not require scour protection or energy dissipation.

6.5 ANALYSIS AND DESIGN OF CULVERTS FOR DETENTION STORAGE

Consideration of the detention storage upstream of a culvert may allow for a more economical design in appropriate locations. General practice on design of culverts for detention storage is presented in Section 2.5.

Detention-storage analysis of a culvert requires considerably more effort than the analysis of a culvert for a single discharge. The general procedure is as follows:

1. Develop the stage-area relationship (headwater elevation versus inundated area) for the storage zone. Inundated areas should be computed at stage intervals of 2.0 ft or less. Accurate determination of the stage-area relationship requires a topographic map of the storage zone with a contour interval of 2.0 ft or less. Normal field survey data are not sufficiently detailed. Additional stream cross sections, parallel cross sections, and ground elevations are needed.

2. Develop a rating curve for the culvert by computing headwater elevations for approximately ten discharges ranging from zero to a maximum value with a headwater elevation that exceeds the AHW. Use HY-8 or a similar computer program based on HDS No. 5 that performs backwater calculations for low flows. By interpolation, determine the discharges at the stages in the stage-area table.

3. Compute the design-flood hydrograph as directed in Section 2.5 and route this hydrograph through the storage zone to determine the peak headwater elevation. Use the HEC-HMS computer program or the HEC-1 computer program of the U. S. Army Corps of Engineers to perform the flood hydrograph simulation and the reservoir routing.

The design of a culvert for detention storage typically requires hydraulic analyses of several alternative configurations. The designer should select the most economical configuration with a headwater elevation that does not exceed the AHW.

Culverts designed for detention storage require additional documentation in the Hydraulics section of the Drainage Data Sheet. Document the flood hydrograph calculations in the Hydrology section as directed in Section 2.5. In the “Q” column, report the peak inflow to the storage zone. In the Remarks column of the Hydraulics section, note “Detention storage design” and list the peak flow in the culvert and the required storage volume at the AHW (e.g., “culvert Q = 205 cfs; required storage at AHW = 9.1 ac-ft”).

6.5.1 Example: Detention Storage Analysis of a Culvert

Problem:

An RCP culvert installation in rural Shawnee County has the characteristics listed below. Determine the headwater elevation for the 25-year recurrence interval.

Culvert data:

Diameter = 60 in.

Length = 138 ft

Flowline elevation at entrance = 951.77 ft

Flowline elevation at exit = 950.95 ft

Concrete Type I end sections

AHW = 959.65 ft

Recurrence interval = 25 years

Tailwater conditions:

Uniform flow (no backwater)

Channel shape = trapezoidal

Channel depth = 5.0 ft

Bottom width = 10.0 ft

Side slopes = 1:1

Bottom slope = 0.006 ft/ft

Manning's n = 0.035

Watershed characteristics:

Drainage area = 98.8 ac

Basin lag time = 15 minutes

Runoff curve number = 80 (for AMC 2)

Table 6.5.1-1 Stage-Area Data for Storage Site

Headwater Elevation (ft)	Inundated Area (ac)
951.77	0
952	0.08
953	0.43
954	0.75
955	1.04
956	1.31
957	1.55
958	1.77
959	1.96
960	2.13

Solution:

1. The stage-discharge relationship for the culvert is developed with FHWA's HY-8 computer program. The concrete Type I end section is modeled as an RCP with the groove end projecting (see Table 6.3.6-1).

Table 6.5.1-2 Headwater Elevations at Selected Discharges

Culvert Discharge (cfs)	Headwater Elevation (ft)
0	951.77
25	953.57
50	954.52
75	955.25
100	955.87
125	956.46
150	957.06
175	957.73
200	958.49
225	959.35
250	960.33

2. The culvert discharges at the stages in Table 6.5.1-1 are computed from the data in Table 6.5.1-2 by linear interpolation.

Table 6.5.1-3 Culvert Discharges at Selected Headwater Elevations

Headwater Elevation (ft)	Culvert Discharge (cfs)
951.77	0
952	3
953	17
954	36
955	66
956	106
957	148
958	184
959	215
960	242

3. The flood hydrograph simulation and reservoir routing are performed as directed in Section 3.5, using the HEC-HMS computer program of the U. S. Army Corps of Engineers. The results are:

    Peak headwater elevation = 958.77 ft

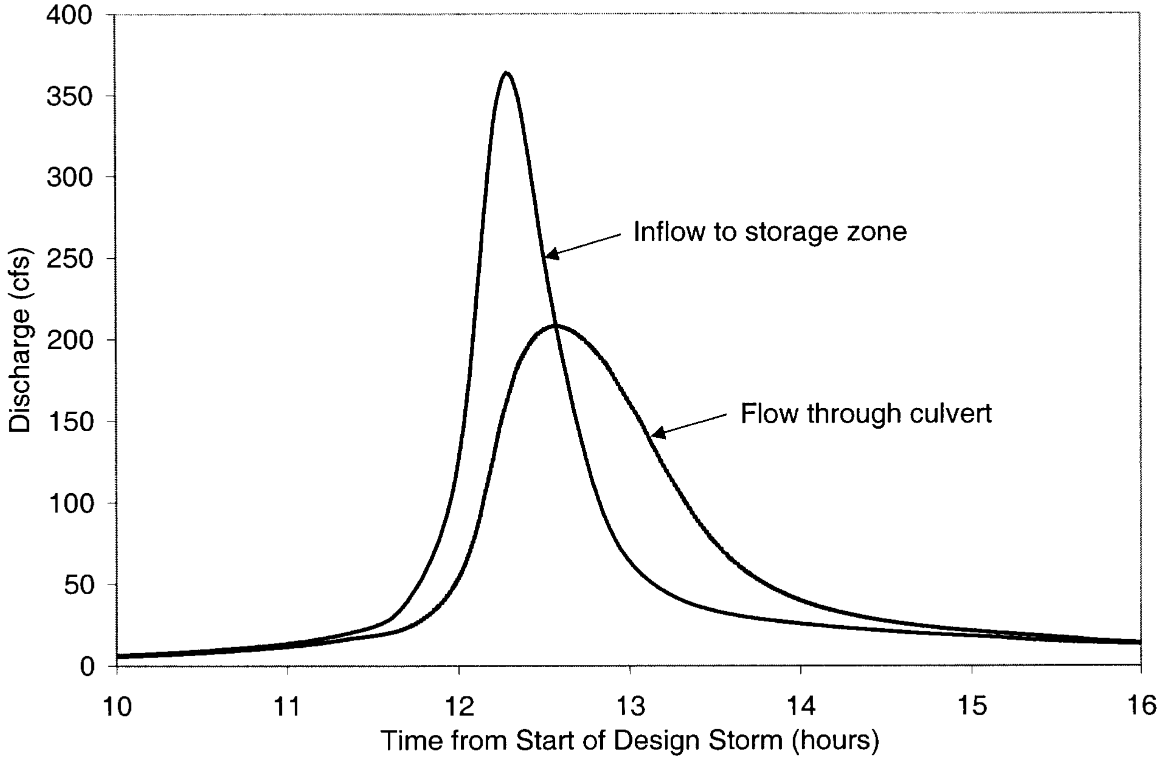
    Peak storage volume = 7.41 ac-ft

    Peak inflow to storage site = 363 cfs

    Peak flow in culvert = 208 cfs

Figure 6.5.1-1 shows the inflow and outflow hydrographs for the central part of the 24-hour period of rainfall. The peak headwater elevation is slightly below the AHW, so the design is satisfactory.

Figure 6.5.1-1 Inflow and Outflow Hydrographs



6.6 SCOUR PROTECTION AT CULVERT OUTLETS

Culvert design should include an assessment of the need for scour protection at the culvert outlet. An inspection of outlet conditions at other culverts in the vicinity will provide an indication of the potential for scour and the protection needed. Scour holes tend to develop naturally downstream of some unprotected culvert outlets. Most scour holes are harmless and serve as natural energy dissipators. A scour hole may be a concern if it threatens to undermine the culvert end section. Where the potential for scour is anticipated, the culvert design should include appropriate scour protection. Common protective measures include rock riprap and concrete aprons with deep toewalls. Where substantial scour is likely, an engineered energy dissipator may be appropriate. FHWA's HEC No. 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels*, provides guidance for the design of several types of engineered energy dissipators. Where no scour is expected, no protection should be provided.

6.7 REFERENCES

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