Contents

Chapter 3 Culvert Design

3-1 Overview

A culvert is a closed conduit under a roadway or embankment used to maintain flow from a natural channel or drainage ditch. A culvert should convey flow without causing damaging backwater, excessive flow constriction, or excessive outlet velocities.

In addition to determining the design flows and corresponding hydraulic performance of a particular culvert, other factors can affect the ultimate design of a culvert and should be taken into consideration. These factors can include the economy of alternative pipe materials and sizes, horizontal and vertical alignment, environmental concerns, and necessary culvert end treatments.

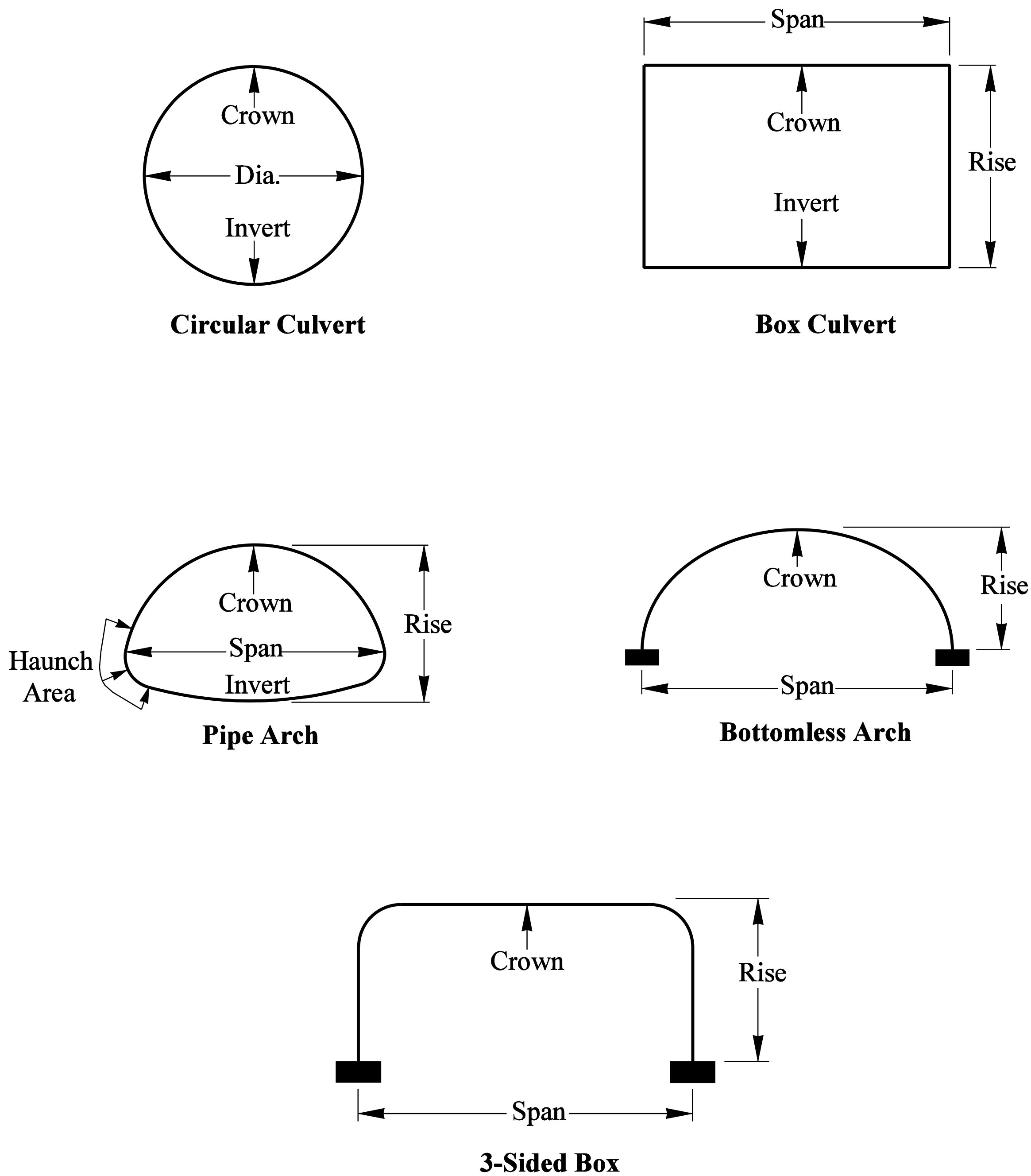
In some situations, the hydraulic capacity may not be the only consideration for determining the size of a culvert opening. Fish passage requirements often dictate a different type of crossing than would normally be used for hydraulic capacity. Wetland preservation may require upsizing a culvert or replacement of a culvert with a bridge. Excessive debris potential may also require an increase in culvert size. In these cases, the designer should seek input from the proper authorities and document this input in the Hydraulic Report in order to justify the larger design.

3-1.1 Metric Units and English Units

When this manual was revised in 1997, WSDOT was in the process of converting to metric units. The 1997 revision included dual units throughout this chapter (and manual) except on charts and graphs. A supplement to this manual was planned that would include Metric charts and graphs, however WSDOT converted back to English units before the supplement was completed. Dual units have been left in this manual to accommodate any redesigns on metric projects. In the event a design requires metric units, it is recommended that the designer complete the form in English units and convert the discharges, controlling HW elevation, and velocity to metric units. All equations related to the charts and graphs are shown in English units only. Elsewhere in the chapter, dual units are provided.

3-2 Culvert Design Documentation

3-2.1 Common Culvert Shapes and Terminology



Common Culvert Shapes and Terminology

Figure 3-2.1

3-2.2 Hydraulic Reports

Culverts 48 inch (1200 mm) or less in diameter or span will be included as part of a Type B Hydraulic Report and will be reviewed by the Region Hydraulics Office/Contact as outlined in Chapter 1. The designer shall collect field data and perform an engineering analysis as described in Sections 3-2.3 and 3-2.4. Culverts in this size range should be referred to on the contract plan sheets as “Schedule ____ Culv. Pipe ____ in (mm) Diam.”. The designer is responsible for listing all acceptable pipe alternates based on site conditions. The decision regarding which type of pipe material to be installed at a location will be left to the contractor. See Chapter 8 for a discussion on schedule pipe and acceptable alternates.

Culverts larger than 48 inch (1200 mm) in diameter or span will be included as part of a Type A Hydraulic Report and will be reviewed by both the Regional Hydraulics Office/Contact and the Headquarters (HQ) Hydraulics Office as outlined in Chapter 1. The designer shall collect field data and perform an engineering analysis as described in Sections 3-2.3 and 3-2.4.

If it is determined that a bottomless arch or three-sided box structure is required at a location, the HQ Hydraulics Office is available to provide assistance in the design. The level of assistance provided by the HQ Hydraulics Office can range from full hydraulic and structural design to review of the completed design. If a project office requests the HQ Hydraulics Office to complete a design, the project office shall submit field data as described in Section 3-2.3. The engineering analysis and footing structural design will be completed by the HQ Hydraulics Office, generally within four to six weeks after receiving field data. Once completed, the design will be returned to the project office and included as part of the Type A Hydraulic Report.

In addition to standard culvert design, the HQ Hydraulics Office is also available to provide assistance in the design of any unique culvert installation. The requirements for these structures will vary, and it is recommended that the HQ Hydraulics Office be contacted early in the design phase to determine what information will be necessary to complete the engineering analysis.

3-2.3 Required Field Data

Information and field data required to complete an engineering analysis for all new culvert installations or draining an area requiring a culvert, should be part of the Type A Hydraulics Report and include the items that follow. Type B reports are further discussed at the end of this section.

1. Topographic map showing contours and the outline of the drainage area.
2. Description of the ground cover of the drainage area.
3. Streambed description and gradation at the proposed site.
4. Soils investigation per Section 510.03(1) of the *Design Manual.*
5. Streambed alignment and profile extending twice the diameter at the proposed site. The distance will vary on size of the culvert and location, if the culvert is 48 inches use 2 times the diameter for the distance in feet. For example, a 48 inch culvert would require 48x2=96ft upstream and downstream for a total of 192ft plus the culvert length for the stream profile.
6. Cross-sections of the stream width extending beyond the limits of the floodplain on each side.
7. Proposed roadway profile and alignment in the vicinity of the culvert.
8. Proposed roadway cross-section at the culvert.
9. Corrosion zone location, pH, and resistivity of the site.
10. Historical information at the site from Maintenance or the locals.
11. Fish passage requirements, if applicable.
12. Any other unique features that can affect design, such as low-lying structures that could be affected by excessive headwater or other consideration discussed in Section 3-5.

Information and field data required to complete an engineering analysis for a Type B Hydraulic Report does not require the same level of information as a Type A Report. If an existing culvert(s) does not have a history of problems, and it only needs to be extended or replaced, it is not necessary to gather all the information to find out the existing culvert's capacity to adequately handle the flows. Therefore, attaining the history of problems at an existing culvert site, would warrant a more detailed review. If the Type B Hydraulic Report has new culverts sites, those will need to follow the Type A guidance. The following Table 3-2.3 is a general outline showing the information and field data requirements for either a Type A or Type B report.

Information and Field Data	**Type A&B New Sites**	**Type B Extending or Replacing**
1. Topographic survey	R	O
2. Ground cover description	R	O
3. Stream descriptions & investigation	R	O
4. Ground soil investigation	R	O
5. Streambed profile & alignment	R	O
6. Streambed cross section	R	O
7. Proposed roadway profile & alignment	R	O
8. Proposed roadway cross section	R	O
9[1]. Corrosion Zone, pH, resistivity	R[1]	O[1]
10. Historical information	R	R
11. Fish passage	R	O
12. Unique features	R	O

1. Only required if replacing with dissimilar material.

R=REQUIRED, O=OPTION UNLESS NEW CULVERT

Field Data Requirements for Type A or B Hydraulic Reports

Figure 3-2.3

3-2.4 Engineering Analysis

Collected field data will be used to perform an engineering analysis. The intent of the engineering analysis is to insure that the designer considers a number of issues, including flow capacity requirements, foundation conditions, embankment construction, run-off conditions, soil characteristics, stream characteristics, construction problems that may occur, estimated cost, environmental concerns, and any other factors that may be involved and pertinent to the design. An additional analysis may be required, if a culvert is installed for flood equalization, to verify that the difference between the floodwater levels is less than 1’ on either side of the culvert. Designers should contact the HQ Hydraulics Office for further guidance on flood equalization. Other miscellaneous design considerations for culverts are discussed in Section 3-5.

Once the engineering analysis is completed, it will be part of the Hydraulic Report and shall include:

1. Culvert hydraulic and hydrology calculations as described in Section 3-3. Approved modeling software, such as HY-8 can also be in lieu of hand calculations. If the designers wish to use different software, HQ approval is required prior to submitting final designs.
2. Proposed roadway stationing of the culvert location.
3. Culvert and stream profile per the distance in Section 3-2.3
4. Culvert length and size. The minimum diameter of culvert pipes under a main roadway shall be 18 inches. Culvert pipe under roadway approaches shall have a minimum diameter of 12 inches.
5. Culvert material (for culverts larger than 48 inch (1200 mm) (with appropriate n values from Appendix 4-1)
6. Headwater depths, water surface elevations (WSEL) and flow rates (Q) for the design flow event (generally the 25-year event and the 100-year flow event), should appear on the plan sheets for future record.
7. Proposed roadway cross-section and roadway profile, demonstrating the maximum and minimum height of fill over the culvert.
8. Appropriate end treatment as described in Section 3-4.
9. Hydraulic features of downstream controls, tailwater or backwater (storage) conditions.

Information to complete an engineering analysis for a Type B Hydraulic Report does not require the same depth of information as a Type A Report. This is true with existing culverts that only need to be extended or replaced as stated in the field data section. If the Type B Hydraulic Report has new culvert sites, those will need to follow the Type A guidance. The following Figure 3-2.4 is a general outline showing the information required for an engineering analysis for either a Type A or Type B report.

Engineering Analysis Items	Type A&B New Sites	Type B Extending or Replacing
1. Culvert hydraulic & hydrology calculations	R	O
2. Roadway stationing at culvert	R	R
3. Culvert & Stream profile	R	O
4. Culvert length & size	R	R
5. Culvert material	R	R
6. Hydraulic details	R	O
7. Proposed roadway details	R	O
8. End treatment	R	R
9. Hydraulic features	R	O

R=REQUIRED, O=OPTION UNLESS NEW CULVERT

Information Required for Type A or B Hydraulics Report

Figure 3-2.4

3-3 Hydraulic Design of Culverts

A complete theoretical analysis of the hydraulics of a particular culvert installation is time-consuming and complex. Flow conditions vary from culvert to culvert and can also vary over time for any given culvert. The barrel of the culvert may flow full or partially full depending upon upstream and downstream conditions, barrel characteristics, and inlet geometry. However, under most conditions, a simplified procedure can be used to determine the type of flow control and corresponding headwater elevation that exist at a culvert during the chosen design flow.

This section includes excerpts from the Federal Highway Administration's *Hydraulic Design Series No. 5 — Hydraulic Design of Highway Culverts (HDS 5)*. The designer should refer to this manual for detailed information on the theory of culvert flow or reference an appropriate hydraulics textbook for unusual situations. The HQ Hydraulics Office is also available to provide design guidance.

The general procedure to follow when designing a culvert, for a span width less than 20ft, is summarized in the steps below. Culvert spans over 20ft are considered bridges and any hydraulic design for bridges is the responsibility of HQ Hydraulics, see section 3-3.1.2 for further guidance.

1. Calculate the culvert design flows (Section 3-3.1).
2. Determine the allowable headwater elevation (Section 3-3.2).
3. Determine the tailwater elevation at the design flow (Section 3-3.3).
4. Determine the type of control that exists at the design flow(s), either inlet control or outlet control (Section 3-3.4).
5. Calculate outlet velocities (Section 3-3.5).

3-3.1 Culvert Design Flows

The first step in designing a culvert is to determine the design flows to be used. The flow from the basin contributing to the culvert can be calculated using the methods described in Chapter 2. Generally, culverts will be designed to meet criteria for two flows: the 25-year event and the 100-year event. If fish passage is a requirement at a culvert location, an additional flow event must also be evaluated for the hydraulic option, the 10 percent exceedence flow (see Chapter 7). Guidelines for temporary culverts are described further below. The designer will be required to analyze each culvert at each of the design flows, insuring that the appropriate criteria are met.

For Circular Pipe, Box Culverts, and Pipe Arches

$Q_{10\%}$: If a stream has been determined to be fish bearing by either Region Environmental staff or Washington Department of Fish and Wildlife (WDFW) personnel and the hydraulic option is selected, the velocity occurring in the culvert barrel during the 10 percent exceedence flow must meet the requirements of Chapter 7.

Q_{25}: The 25-year flow event should not exceed the allowable headwater, which is generally taken as 1.25 times the culvert diameter or rise as described in Section 3-3.2.2. Additionally, the WSEL for the 25-year event should not exceed the elevation of the base course of the roadway (else the base course could be saturated).

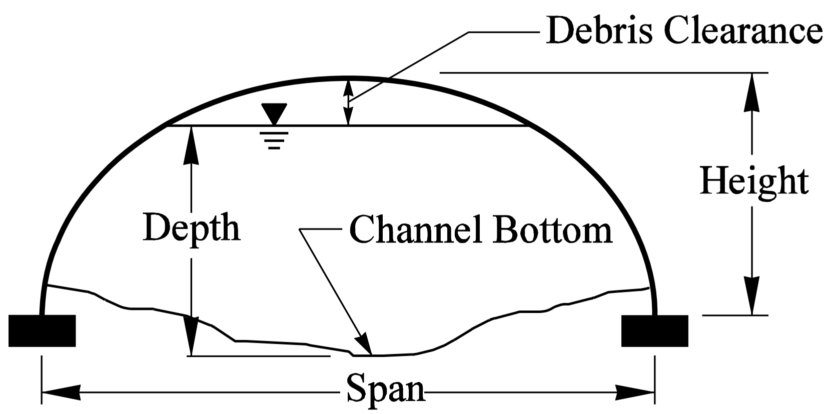
Q_{100}: It is recommended that the culvert be sized such that there is no roadway overtopping during the 100-year flow event. See Section 3-3.2.2 for more discussion on this topic.

For Concrete or Metal Bottomless Culverts

Q10%: If a stream has been determined to be fish bearing by either Region Environmental staff or WDFW personnel and the hydraulic option is selected, the velocity occurring during the 10% exceedance flow through the arch must meet the requirements of Chapter 7.

Q25: 1 foot (0.3 meters) of debris clearance should be provided between the water surface and the top of the arch during the 25-year flow event, as shown in Figure 3.3.1 and discussed in Section 3-3.2.3. Additionally, the WSEL for the 25-year event should not exceed the elevation of the base course of the roadway (else the base course could be saturated).

Q100: The depth of flow during the 100-year flow event should not exceed the height of the arch as described in Section 3-3.2.3.



Typical Bottomless Culvert

Figure 3-3.1

3-3.1.1 Precast Reinforced Concrete Three Sided Structure

When selecting a precast reinforced concrete three-sided structure for the site the following criteria must be determined:

- Span - For a three-sided structure the maximum span is 26ft.
- Cover - A minimum of 2 feet of cover (measured from the bottom of pavement to the top of the culvert) is required when the current ADT is 5000 or greater. For cover less than 2', see Chapter 8 Shallow Cover Installations.
- Footing Slope - The footing slope cannot be greater than 4% in the direction parallel to the channel.

3-3.1.2 Additional Requirement for Culverts over 20’

Once a culvert exceeds a 20’ width, it is defined as a bridge and all hydraulic analysis on bridges are the responsibility of the HQ Hydraulics Office (see Chapter 1 Section 1-2). The federal definition of a bridge is a structure, including supports, erected over a depression or obstruction, such as water, highway, or railway, and having a track or passage way for carrying traffic or other moving loads with a clear span as measured along the center line of the roadway equal to or greater than 20’. The interior cell walls of a multiple box are ignored as well as the distance between the multiple pipes if the distance between pipes is less than D/2 (i.e. a 16’ culvert on a 45 degree skew is a bridge, a 10’ culvert on a 60 degree skew is a bridge, three 6’ pipes two feet apart is a bridge).

The two primary types of hydraulic analysis performed on bridges are backwater and scour. As noted above all hydraulic analysis of bridges is performed by HQ Hydraulics however it is the responsibility of the Project Office to gather field information for the analysis. Chapter 4 Sections 4-5 and 4-6.3.3 contain more information about backwater and scour analysis, along with the PEO list of responsibilities.

3-3.1.3 Alignment and Grade

It is recommended that culverts be placed on the same alignment and grade as the natural streambed, especially on year-round streams. This tends to maintain the natural drainage system and minimize downstream impacts.

In many instances, it may not be possible or feasible to match the existing grade and alignment. This is especially true in situations where culverts are conveying only hillside runoff or streams with intermittent flow. If following the natural drainage course results in skewed culverts, culverts with horizontal or vertical bends, or requires excessive and/or solid rock excavation, it may be more feasible to alter the culvert profile or change the channel alignment up or downstream of the culvert. This is best evaluated on a case-by-case basis, with potential environmental and stream stability impacts being balanced with construction and function ability issues.

3-3.1.4 Allowable Grade

Concrete pipe may be used on any grade up to 10 percent. Corrugated metal pipe and thermoplastic pipe may be used on up to 20 percent grades. For grades over 20 percent, consult with the Region Hydraulics Engineer or the HQ Hydraulics Office for design assistance.

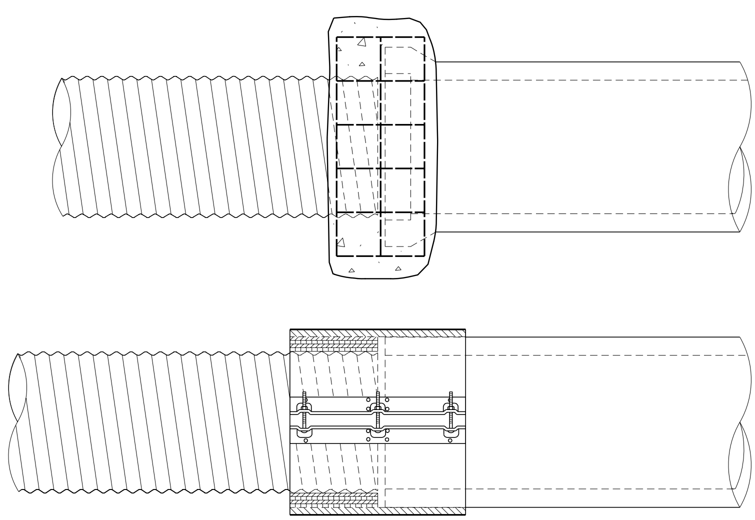
3-3.1.5 Minimum Spacing

When multiple lines of pipe or pipe-arch greater than 48 inches in diameter or span are used, they should be spaced so that the sides of the pipe are no closer than one-half a diameter or 3 feet, which ever is less, so there is space for adequate compaction of the fill material available. For diameters up to 48 inches, the minimum distance between the sides of the pipe should be no less than 2 feet. Utility lines maybe closer, please consult the Region Utilities Office for appropriate guidance.

3-3.1.6 Culvert Extension

Whenever possible culvert extensions should be done in-kind; that is use the same pipe material and size and follow the existing slope. All culvert extension hydraulic reports should follow the guidelines for the culvert sizes noted in section 3-2.2 of Chapter 3 and section 1-3 of Chapter 1. For in-kind extensions, designers should follow the manufacturer's recommendations for joining pipe. For extensions of dissimilar material or box culverts, designers should follow the guidelines below. For situations not listed, contact the Region Hydraulics Engineer or the HQ Hydraulics Office.

- Culvert pipe connections for dissimilar materials must follow standard plan B-60.20 of the WSDOT Standard Plans as shown in Figure 3-3.1.5.
- For cast in place box culvert connections; contact Bridge Design Office for rebar size and embedment.
- Precast box culvert connections must follow ASTM C 1433, and ASHTO M 259, M 273 and Standard Specification 6-02.3(28)



Connection for Dissimilar Culvert Pipe

Figure 3-3.1.5

3-3.1.1 Temporary Culverts

Temporary culverts should be sized for the 2-year storm event, unless the designer can justify a different storm event and receive HQ or Region Hydraulics approval. If the designer should decide to challenge the 2 year storm event, the designer should consider the following: the number of seasons during construction, the construction window, historical rainfall data for at least 10 years (both annually and monthly) and factor in any previous construction experience at the site.

1. Construction Seasons: If the construction season will extend beyond two seasons, the 2-year storm event or greater should be used to size a temporary culvert. If only one season is involved, proceed to number 2.

2. Construction Window: If construction will occur during one season, the designer should evaluate at least 10 years of rainfall data for that season and then have HQ Hydraulics perform a statistical analysis to determine an appropriate peak rainfall during that season to generate a flow rate for sizing the culvert. If gage data is available for the peak flow rate during the season of construction that should always be used first. The designer should consult the Region Hydraulics Office for further guidance. Steam Flow data can be found at http://nwis.waterdata.usgs.gov/wa/nwis/dvstst.

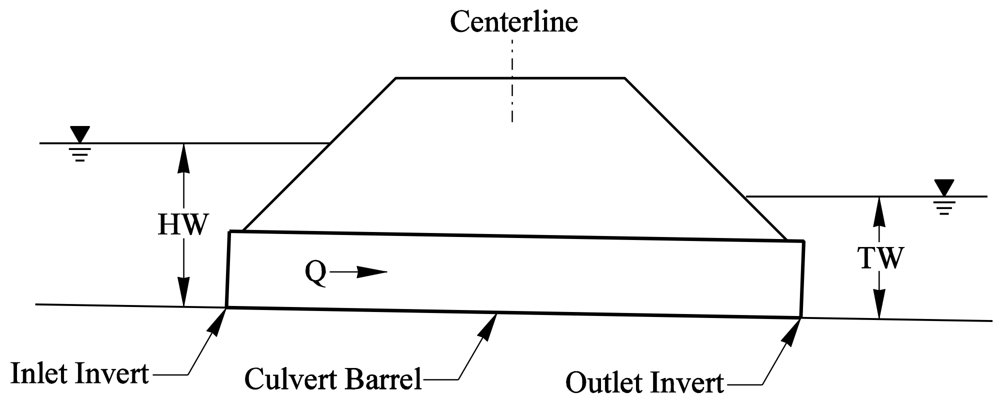
3. Previous Experience: Previous experience sizing temporary culverts at a nearby site can be the best way to size the culvert. If for example, the 2-year event yielded a 36-inch diameter culvert (assuming the same season), but the culvert was only 6-8 inches full, a reduction in the culvert size could be justified.

It is recommended that Region Hydraulics be involved at the beginning of this process. The designer should document the steps followed above in the Hydraulics Report.

3-3.2 Allowable Headwater

3-3.2.1 General

The depth of water that exists at the culvert entrance at a given design flow is referred to as the **headwater (HW).** Headwater depth is measured from the invert of the culvert to the water surface, as shown in Figure 3-3.2.1.



Headwater and Tailwater Diagram

Figure 3-3.2.1

Limiting the amount headwater during a design flow can be beneficial for several reasons. The potential for debris clogging becomes less as the culvert size is increased. Maintenance is virtually impossible to perform on a culvert during a flood event if the inlet is submerged more than a few feet. Also, increasing the allowable headwater can adversely impact upstream property owners by increasing flood elevations. These factors must be taken into consideration and balanced with the cost effectiveness of providing larger or smaller culvert openings.

If a culvert is to be placed in a stream that has been identified in a Federal Emergency Management Agency (FEMA) Flood Insurance Study, the floodway and floodplain requirements for that municipality may govern the allowable amount of headwater. In this situation, it is recommended that the designer contact either the Region Hydraulics Section/Contact or the HQ Hydraulics Office for additional guidance.

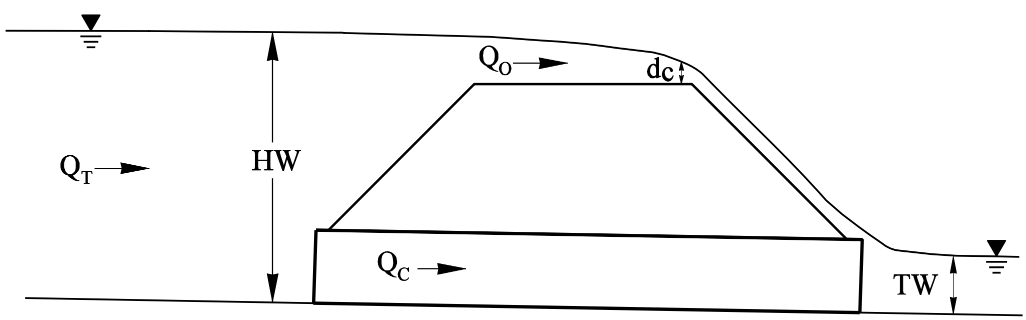
3-3.2.2 Allowable Headwater for Circular and Box Culverts and Pipe Arches

Circular culverts, box culverts, and pipe arches should be designed such that the ratio of the headwater (HW) to diameter (D) during the 25-year flow event is less than or equal to 1.25 ($HW_i/D < 1.25$). HW_i/D ratios larger than 1.25 are permitted, provided that existing site conditions dictate or warrant a larger ratio. An example of this might be an area with high roadway fills, little stream debris, and no impacted upstream property owners. Generally, the maximum allowable HW_i/D ratios should not exceed 3 to 5. The justification for exceeding the HW_i/D ratio of 1.25 must be discussed with either the Region Hydraulics Section/Contact or the HQ Hydraulics Office and, if approved, included as a narrative in the corresponding Hydraulics Report.

The headwater that occurs during the 100-year flow event must also be investigated. Two sets of criteria exist for the allowable headwater during the 100-year flow event, depending on the type of roadway over the culvert:

1. If the culvert is under an interstate or major state route that must be kept open during major flood events, the culvert must be designed such that the 100-year flow event can be passed without overtopping the roadway.
2. If the culvert is under a minor state route or other roadway, it is recommended that the culvert be designed such that there is no roadway overtopping during the 100-year flow event. However, there may be situations where it is more cost effective to design the roadway embankment to withstand overtopping rather than provide a structure or group of structures capable of passing the design flow. An example of this might be a low ADT roadway with minimal vertical clearance that, if closed due to overtopping, would not significantly inconvenience the primary users.

   Overtopping, of the road, will begin to occur when the headwater rises to the elevation of the roadway centerline. The flow over the roadway will be similar to flow over a broad-crested weir, as shown in Figure 3-3.2.2. A methodology is available in HDS 5 to calculate the simultaneous flows through the culvert and over the roadway. The designer must keep in mind that the downstream embankment slope must be protected from the erosive forces that will occur. This can generally be accomplished with riprap reinforcement, but the HQ Hydraulics Office should be contacted for further design guidance. Additionally, the designer should verify the adjacent ditch does not overtop and transport runoff causing damage to either the road or private property.



Roadway Overtopping

Figure 3-3.2.2

3-3.2.3 Allowable Headwater for Bottomless Culverts

Bottomless culverts with footings should be designed such that 1 foot (0.3 meters) of debris clearance from the water surface to the culvert crown is provided during the 25-year flow even, see Figure 3.3.1. In many instances, bottomless culverts function very similarly to bridges. They typically span the main channel and are designed to pass relatively large flows. If a large arch becomes plugged with debris, the potential for significant damage occurring to either the roadway embankment or the culvert increases. Excessive headwater at the inlet can also increase velocities through the culvert and correspondingly increase the scour potential at the footings. Sizing a bottomless culvert to meet the 1 foot (0.3 meter) criteria will alleviate many of these potential problems.

Bottomless culverts should also be designed such that the 100-year event can be passed without the headwater depth exceeding the height of the culvert. Flow depths greater than the height can cause potential scour problems near the footings.

3-3.3 Tailwater Conditions

The depth of water that exists in the channel downstream of a culvert is referred to as the **tailwater (TW)** and is shown in Figure 3-3.2.1. Tailwater is important because it can effect the depth of headwater necessary to pass a given design flow. This is especially true for culverts that are flowing in outlet control, as explained in Section 3-3.4. Generally, one of three conditions will exist downstream of the culvert and the tailwater can be determined as described below.

1. If the downstream channel is relatively undefined and depth of flow during the design event is considerably less than the culvert diameter, the tailwater can be ignored. An example of this might be a culvert discharging into a wide, flat area. In this case, the downstream channel will have little or no impact on the culvert discharge capacity or headwater.

2. If the downstream channel is reasonably uniform in cross section, slope, and roughness, the tailwater may effect the culvert discharge capacity or headwater. In this case, the tailwater can be approximated by solving for the normal depth in the channel using Manning’s equation as described in Chapter 4.

3. If the tailwater in the downstream channel is established by downstream controls, other means must be used to determine the tailwater elevation. Downstream controls can include such things as natural stream constrictions, downstream obstructions, or backwater from another stream or water body. If it is determined

that a downstream control exists, a method such as a backwater analysis, a study of the stage-discharge relationship of another stream into which the stream in question flows, or the securing of data on reservoir storage elevations or tidal information may be involved in determining the tailwater elevation during the design flow. If a field inspection reveals the likelihood of a downstream control, contact either the Region Hydraulics Section/Contract or the HQ Hydraulics Office for additional guidance.

3.3.4 Flow Control

There are two basic types of flow control. A culvert flows in either inlet control or outlet control.

When a culvert is in **Inlet Control,** the inlet is controlling the amount of flow that will pass through the culvert. Nothing downstream of the culvert entrance will influence the amount of headwater required to pass the design flow.

When a culvert is in **Outlet Control** , the outlet conditions or barrel are controlling the amount of flow passing through the culvert. The inlet, barrel, or tailwater characteristics, or some combination of the three, will determine the amount of headwater required to pass the design flow.

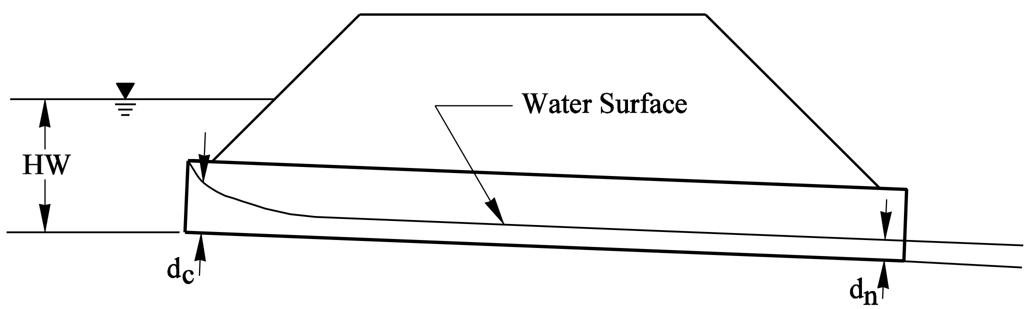
There are two different methods used to determine the headwater, one for inlet control and one for outlet control. If the culvert is flowing in inlet control, the headwater depth is calculated using inlet control equations. If the culvert is flowing in outlet control, the headwater depth is calculated using outlet control equations. Often, it is not known whether a culvert is flowing in inlet control or outlet control before a design has been completed. It is therefore necessary to calculate the headwater that will be produced for both inlet and outlet control, and then compare the results. The larger headwater will be the one that controls and that headwater will be the one that will be used in the design of the culvert. Both inlet control and outlet control will be discussed in the following sections and methods for determining the headwater for both types of control will be given.

3-3.4.1 Culverts Flowing With Inlet Control

In inlet control, the flow capacity of a culvert is controlled at the entrance by depth of headwater and the entrance geometry. The entrance geometry includes the inlet area, shape, and type of inlet edge. Changing one of these parameters, such as increasing the diameter of the culvert or using a hydraulically more efficient opening, is the only way to increase the flow capacity through the culvert for a given headwater.

Changing parameters downstream of the entrance, such as modifying the culvert slope, barrel roughness, or length will not increase the flow capacity through the culvert for a given headwater.

Inlet control usually occurs when culverts are placed on slopes steeper than a 1 percent grade and when there is minimal tailwater present at the outlet end. Figure 3-3.4.1 shows a typical inlet control flow profile. In the figure, the inlet end is submerged, the outlet end flows freely, and the barrel flows partly full over its length. The flow passes through critical depth (d_c) just downstream of the culvert entrance and the flow approaches normal depth (d_n) at the downstream end of the culvert.



Typical Inlet Control Flow Profile

Figure 3-3.4.1

3-3.4.2 Calculating Headwater for Inlet Control

When a culvert is flowing in inlet control, two basic conditions exist. If the inlet is submerged, the inlet will operate as an orifice. If the inlet is unsubmerged, the inlet will operate as a weir. Equations have been developed for each condition and the equations demonstrate the relationship between headwater and discharge for various culvert materials, shapes, and inlet configurations. The inlet control nomographs shown Figures 3-3.4.2A-E utilize those equations and can be used to solve for the headwater.

To Determine Headwater (HW)

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

Step 2 If $\frac{HW}{D}$ scale marked (1) represents entrance type used, read $\frac{HW}{D}$ on scale (1). If some other entrance type is used, extend the point of intersection found in Step 1 horizontally on scale (2) or (3) and read $\frac{HW}{D}$.

Step 3 Compute HW by multiplying $\frac{HW}{D}$ by D.

To Determine Culvert Size (D)

Step 1 Locate the allowable $\frac{HW}{D}$ on the scale for appropriate entrance type. If scale (2) or (3) is used, extend the $\frac{HW}{D}$ point horizontally to scale (1).

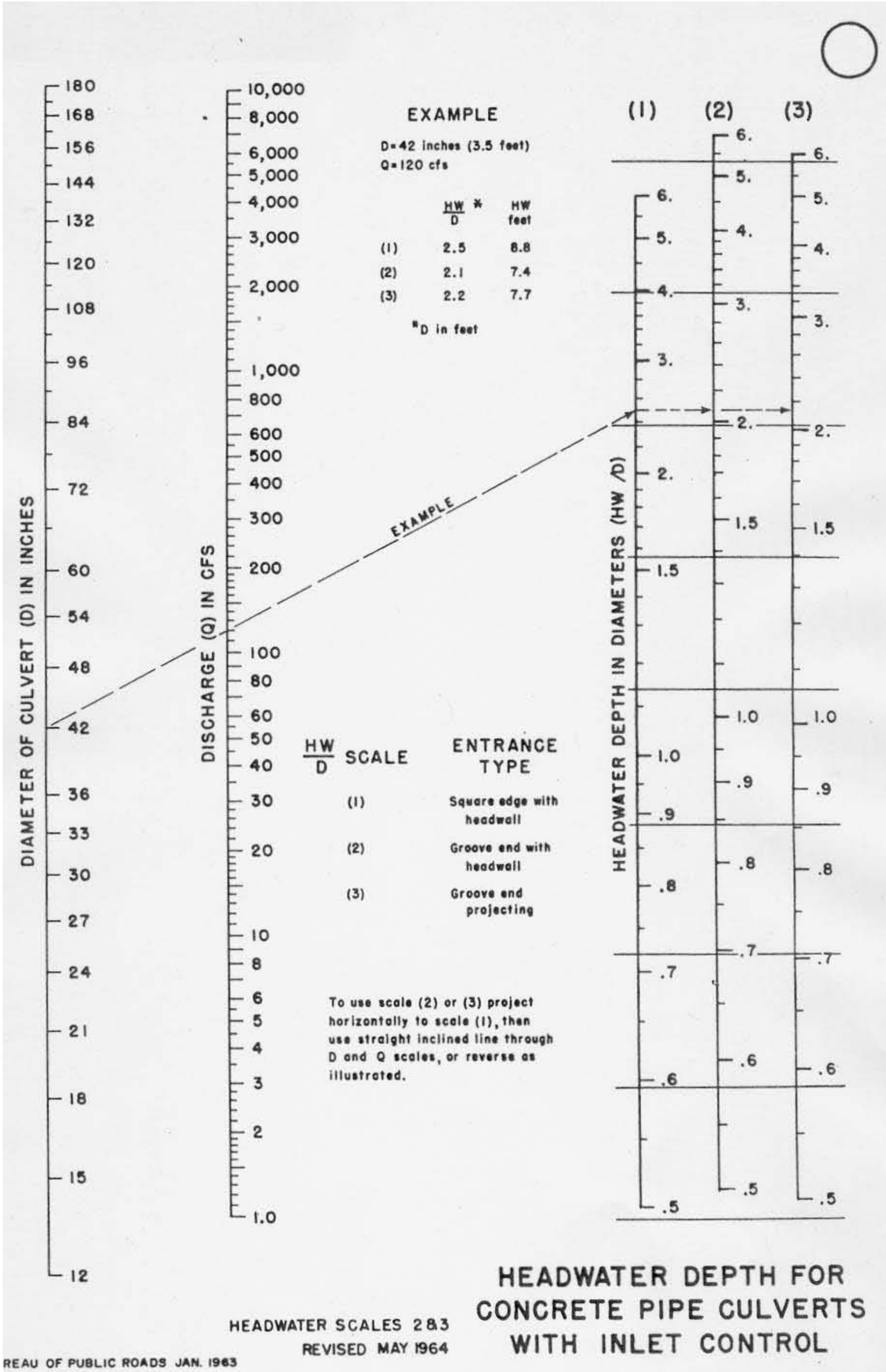
Step 2 Connect the point on $\frac{HW}{D}$ scale (1) as found in Step 1 to the given discharge Q and read diameter, height, or size of culvert required. If this value falls between two sizes, choose the next largest diameter.

To Determine Discharge (Q)

Step 1 Given HW and D, locate $\frac{HW}{D}$ on scale for appropriate entrance type. If scale (2) or (3) is used, extend $\frac{HW}{D}$ point horizontally to scale (1).

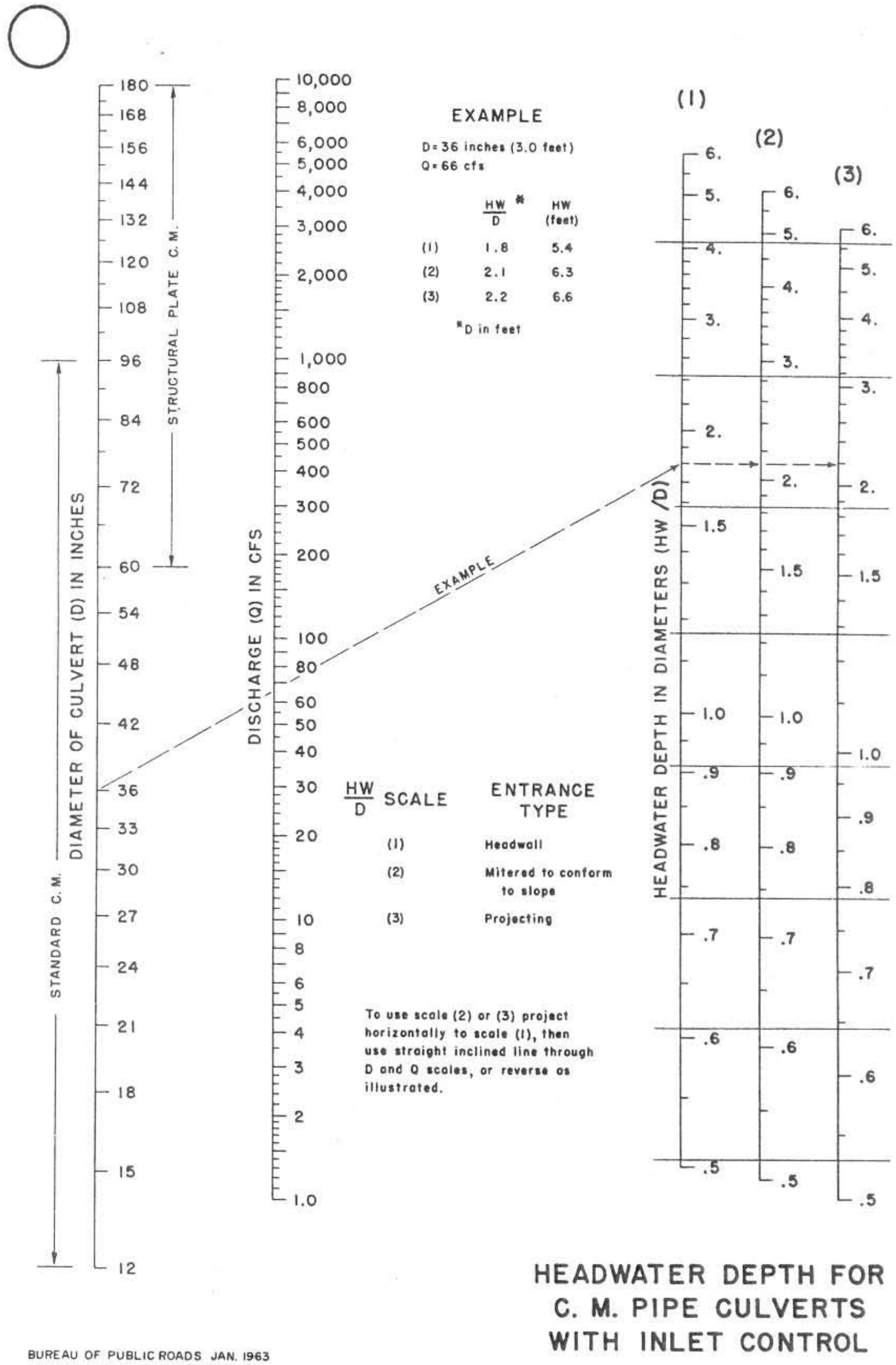
Step 2 Connect point $\frac{HW}{D}$ scale (1) as found in Step 1 and the size of culvert on the left scale. Read Q or $\frac{Q}{B}$ on the discharge scale.

Step 3 If $\frac{Q}{B}$ is read in Step 2, multiply by B to find Q. B is the width of the culvert.



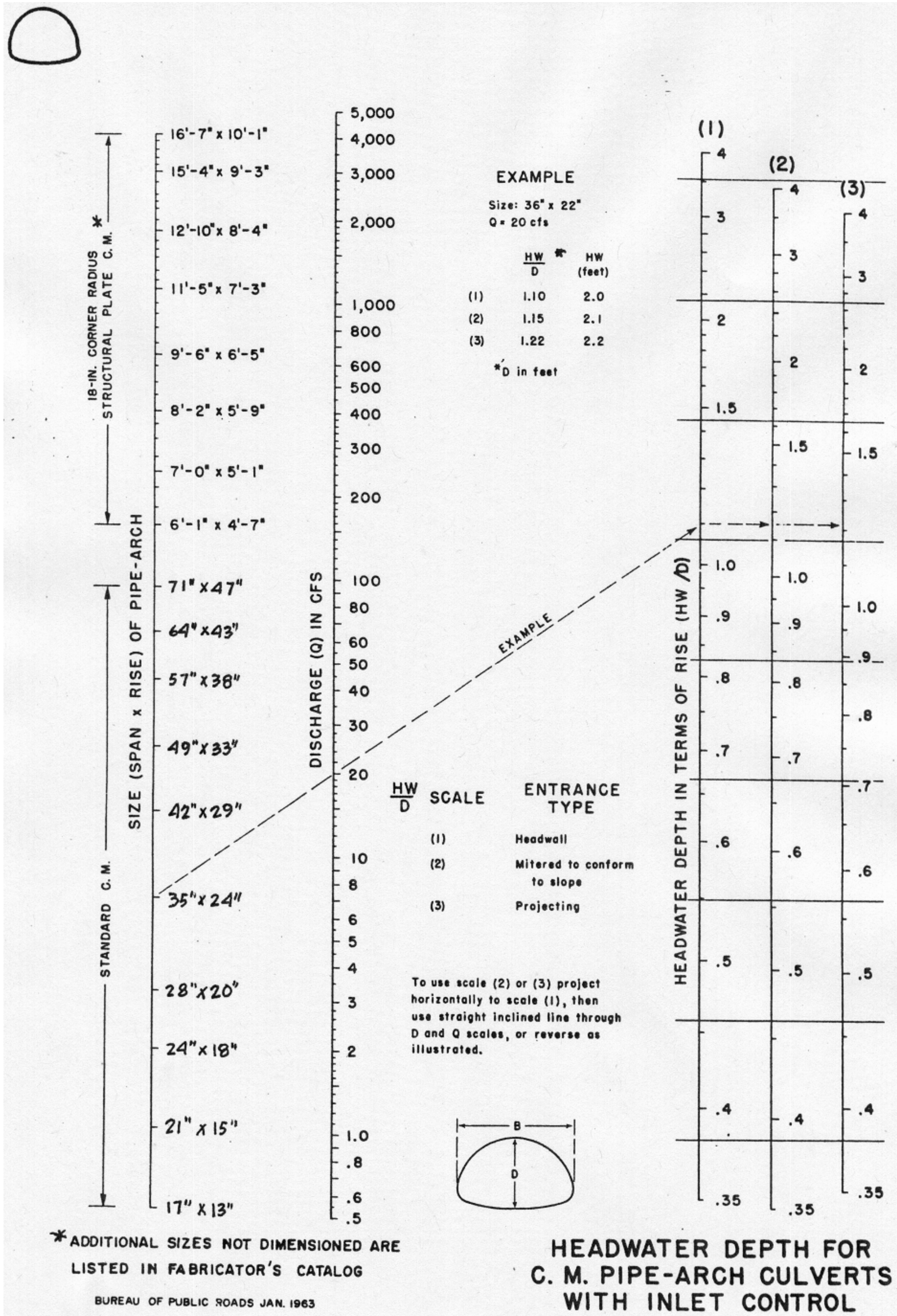
Concrete Pipe Inlet Control Nomograph

Figure 3-3.4.2A



Corrugated Metal and Thermoplastic Pipe Inlet Control Nomograph

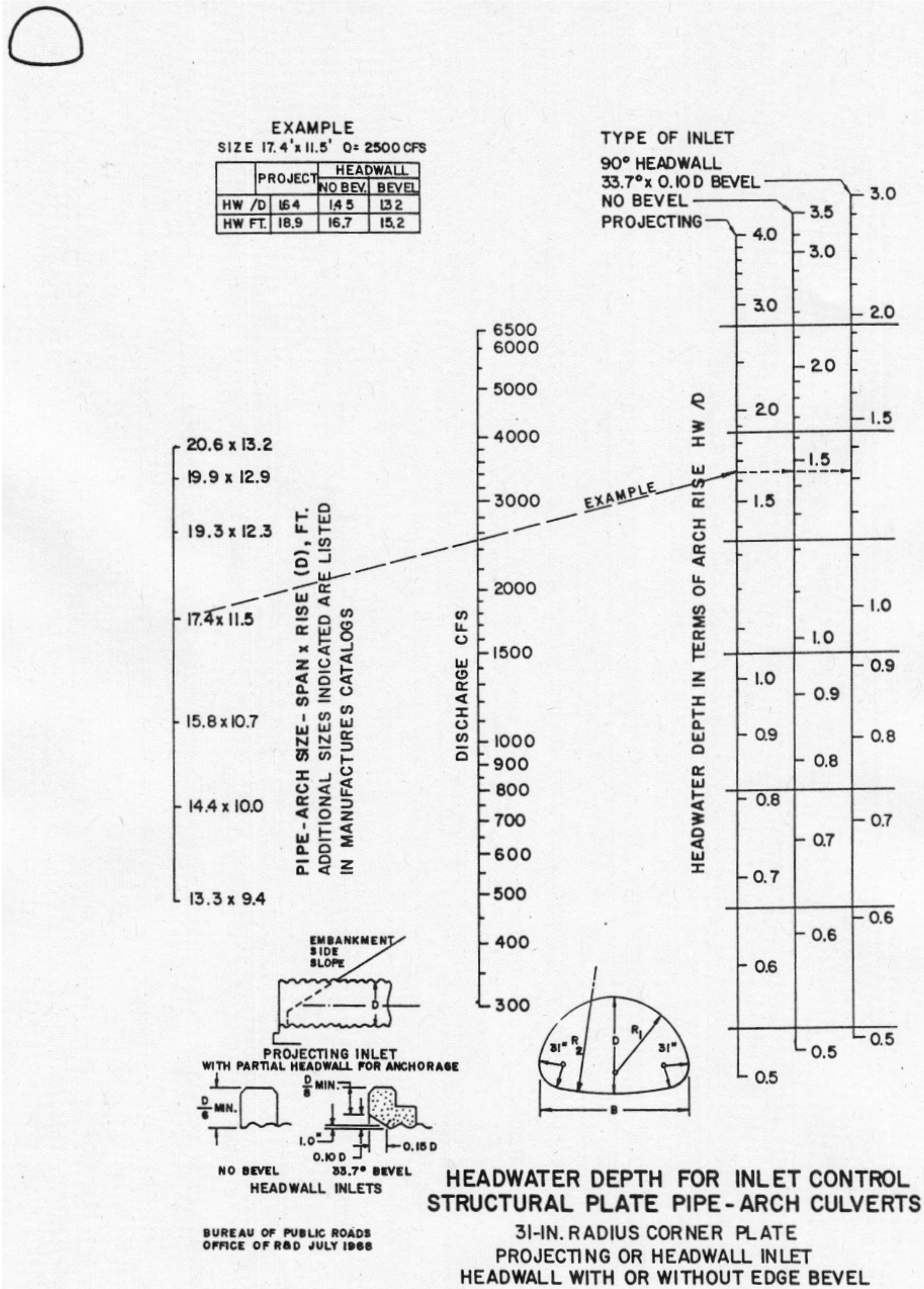
Figure –3-3.4.2B



Corrugated Metal Pipe-Arch Inlet Control Nomograph

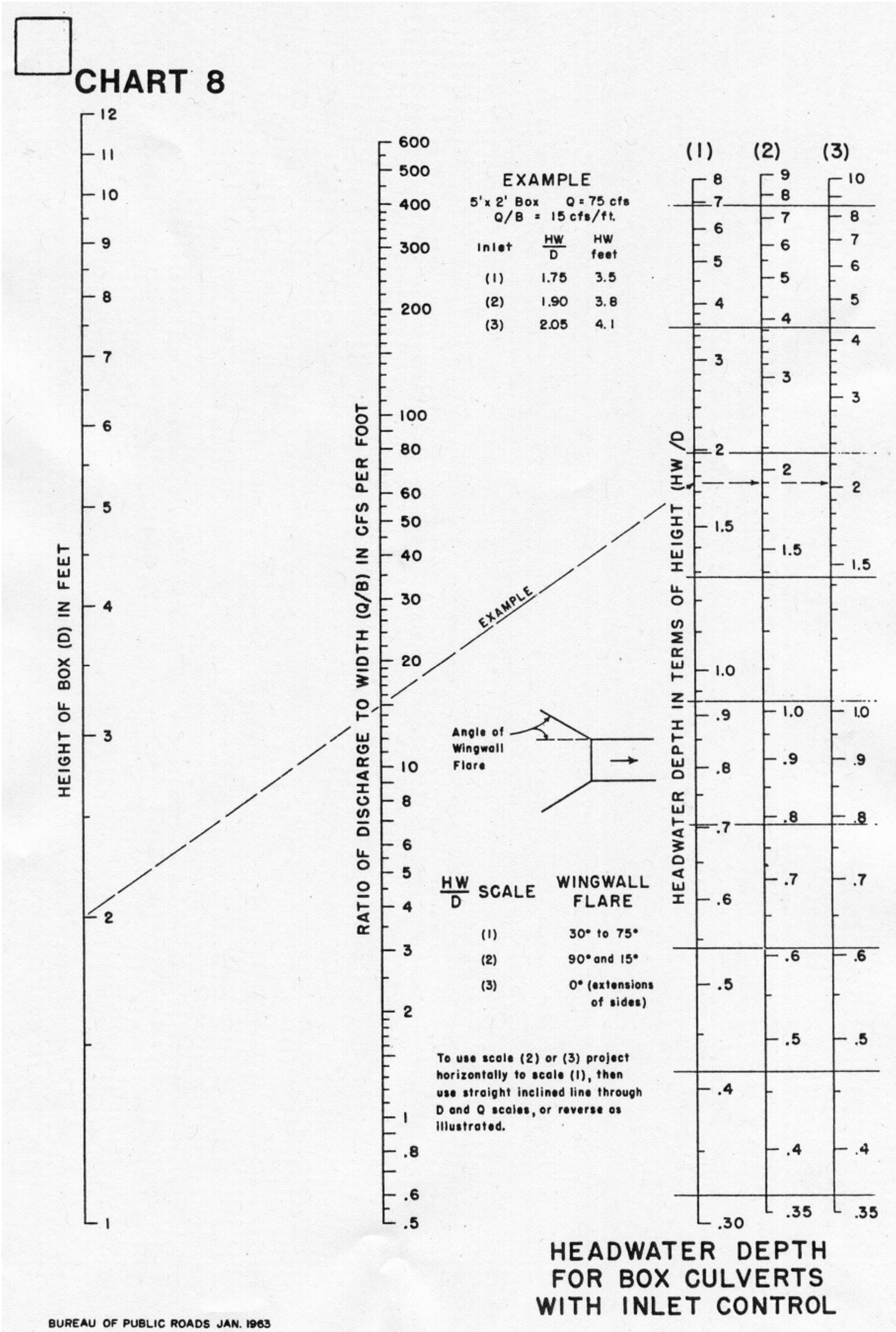
Standard Sizes and 18-Inch Corner Radius

Figure-3-3.4.2C



Corrugated Metal Pipe-Arch Inlet Control Nomograph Large Sizes

Figure-3-3.4.2D



Box Culvert Inlet Control Nomograph

Figure-3-3.4.2E

3-3.4.3 Culverts Flowing With Outlet Control

In outlet control, the flow capacity of a culvert is controlled by the inlet, barrel, or tailwater conditions, or some combination of the three. Changing any parameter, such as the culvert size, entrance configuration, slope, roughness, or tailwater condition can have a direct impact on the headwater required to pass the design flow.

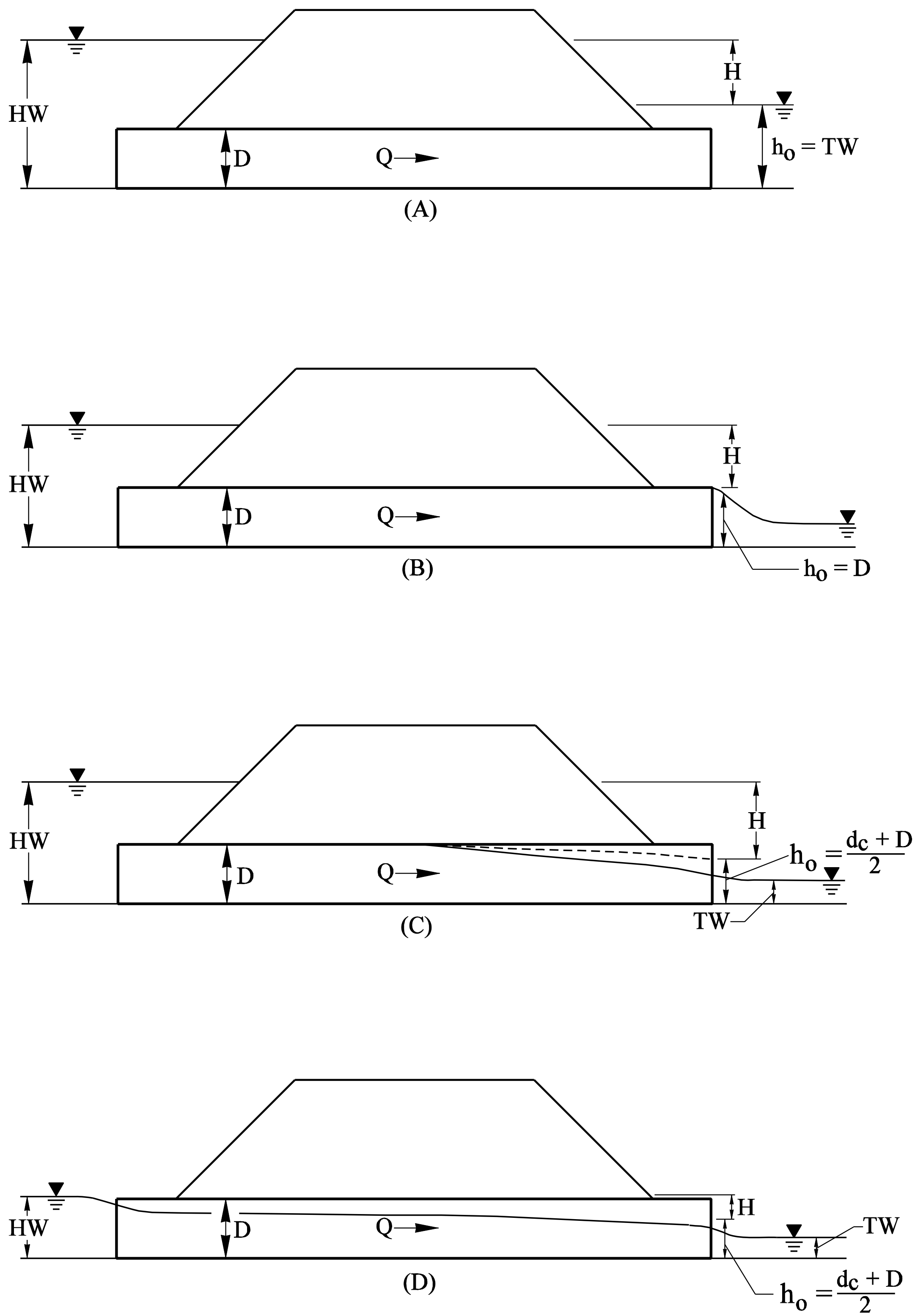
Outlet control usually occurs when a culvert is placed on a relatively flat slope, generally less than a 1 percent grade, or when the depth of tailwater is significant. Figure 3-3.4.3 demonstrates several typical outlet control flow profiles that can occur in a culvert. The method for computing the headwater for each of the profiles is the same and is described in Section 3-3.4.4. However, the method used to calculate outlet velocities for outlet control can vary as described in Section 3-3.5.2. Figure 3-3.4.3 can be useful for visually representing some of the concepts discussed in that section.

Figure 3-3.4.3(A) shows a full flow condition, with both the inlet and outlet submerged. The culvert barrel is in pressure flow throughout the entire length. This condition is often assumed in calculations but seldom actually exists.

Figure 3-3.4.3(B) shows the entrance submerged to such a degree that the culvert flows full throughout the entire length. However, the exit is unsubmerged by tailwater.This is a rare condition because it requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are unusually high under this condition.

Figure 3-3.4.3(C) is more typical. The culvert entrance is submerged by the headwater and the outlet flows freely with a low tailwater. For this condition the barrel flows partly full over at least part of its length and the flow passes through critical depth just upstream of the outlet.

Figure 3-3.4.3(D) is also typical, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partly full over its entire length. The procedure described in Section 3-3.4.4 for calculating headwater for outlet control flow does not give an exact solution in this case. However, the procedure is considered accurate when the headwater is .75D and greater, where D is the height or rise of the culvert barrel.



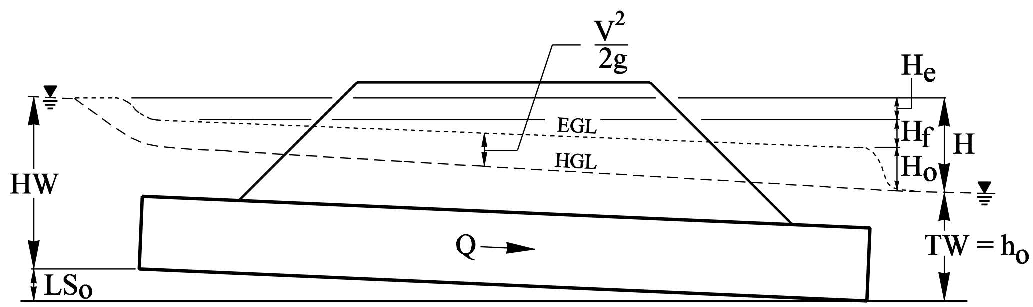
Outlet Control Flow Profiles

Figure 3-3.4.3

3-3.4.4 Calculating Headwater For Outlet Control

Outlet control headwater (HW) cannot be solved for directly. Rather, HW can be found by utilizing the relationship shown in Equation (3-1) and Figure 3-3.4.4A.

$$HW = H + h_o - LS_o \qquad (3\text{-}1)$$



Outlet Control Flow Relationships

Figure 3-3.4.4A

Where:

- HW = Headwater (ft)
- H = Total head loss through the culvert, including entrance, barrel, and exit losses
- h_o = Approximation of the hydraulic grade line at the outlet of the culvert (ft)
- LS_o = Product of the culvert length multiplied by the culvert slope (ft)
- EGL = Energy Grade Line. The EGL represents the total energy at any point along the culvert barrel.
- HGL = Hydraulic Grade Line. Outside of the culvert, the HGL is equal to the water surface elevation. Inside the culvert, the HGL is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel.

H, h_o, and LS_o can be calculated as described below, then used in conjunction with Equation 1 to determine HW.

H: H is the total head loss through the culvert, generally expressed in units of feet. It is made up of three major parts: an entrance loss H_e, a friction loss through the barrel H_f, and an exit loss at the outlet H_o. Expressed in equation form, the total head loss is shown in equation (3-2):

$$H = H_e + H_f + H_o \qquad (3\text{-}2)$$

Each of the losses are a function of the velocity head in the barrel. The velocity head is the kinetic energy of the water in the culvert barrel. The velocity head is equal to $V^2/2g$, where V is the mean velocity in the culvert barrel. The mean velocity is found by dividing the discharge by the cross-sectional area of the flow.

The entrance loss H_e is found by multiplying the velocity head by an entrance loss coefficient k_e and is shown by Equation (3-3). The coefficient k_e for various types of culvert entrances can be found in Figure 3-3.4.5H.

$$H_e = k_e \frac{V^2}{2g} \qquad (3\text{-}3)$$

The friction loss H_f is the energy required to overcome the roughness of the culvert barrel. It is found by multiplying the velocity head by an expression of Manning's equation and is given by Equation (3-4).

$$H_f = \left[\frac{29n^2L}{R^{1.33}}\right]\frac{V^2}{2g} \qquad (3\text{-}4)$$

Where:
- n = Manning's roughness coefficient
- L = Length of culvert barrel (ft)
- V = Mean velocity of flow in culvert barrel (ft/s)
- R = Hydraulic radius (ft)
  (R = D/4 for full flow pipe, see section 4-4)

The exit loss at the outlet H_o occurs when flow suddenly expands after leaving the culvert. It is found by multiplying the velocity head by an exit loss coefficient, generally taken as 1.0, and is given by Equation (3-5).

$$H_o = 1.0\frac{V}{2g} \qquad (3\text{-}5)$$

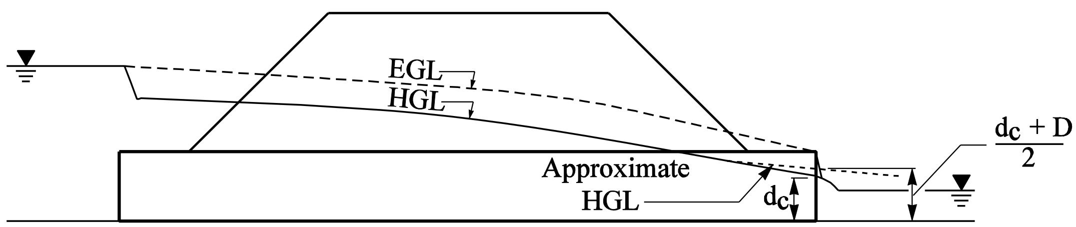
Combining Equations (3), (4), and (5) and substituting back into (2), the total head loss H can be expressed as shown in equation (3-6):

$$H = \left[1 + k_e + \frac{29n^2L}{R^{1.33}}\right]\frac{V^2}{2g} \qquad (3\text{-}6)$$

The outlet control nomographs shown in Section 3-3.4.5 provide graphical solutions to Equation (3-6) and should be utilized to solve for H.

h_o: h_o is an approximation of the hydraulic grade line at the outlet of the culvert and is equal to the tailwater or $(d_c + D)/2$, whichever is greater. The term $(d_c + D)/2$ represents an approximation of the hydraulic grade line at the outlet of the culvert, where d_c is equal to the critical depth at the outlet of the culvert and D is the culvert diameter or rise. When free surface flow occurs in a culvert operating in outlet control, the most accurate method for determining the HW elevation is to perform a backwater analysis through the culvert. This, however, can be a tedious and time-consuming process. Making the assumption that $(d_c + D)/2$ represents the hydraulic grade line simplifies the design procedure. The approximate method will produce reasonably accurate results when the headwater is 0.75 D and greater, where D is the culvert diameter or rise. In situations where the headwater is less than 0.75 D, the culvert should be designed using a computer software program, as discussed in Section 3-3.7. Most programs will perform a backwater analysis through the culvert and arrive at a more accurate solution for the headwater elevation than the approximate method.

As shown in Figure 3-3.4.4B, $(d_c + D)/2$ does not represent the actual water surface elevation at the outlet of the culvert and therefore should not be used for determining the corresponding outlet velocity. The method for determining the outlet velocity is discussed in Section 3-3.5.2



Hydraulic Grade Line Approximation

Figure 3-3.4.4B

LS_o: LS_o is the culvert length (L) multiplied by the culvert slope (S_o), expressed in feet.

3-3.4.5. Outlet Control Nomographs

The outlet control nomographs presented in this section allow the designer to calculate H, the total head loss through the culvert, as discussed in Section 3-3.4.4. The nomographs should be used in conjunction with Figure 3-3.6, Culvert Hydraulic Calculations Form.

Figure 3-3.4.5A shows a sample outlet control nomograph. The following set of instructions will apply to all of the outlet control nomographs in this section. To determine H for a given culvert and discharge:

Step 1: Locate the appropriate nomograph for type of culvert selected.

Step 2: Find the Manning's n value for the culvert from Appendix 4-1. If the Manning's n value given in the nomograph is different than the Manning's n for the culvert, adjust the culvert length using equation (3-7):

$$L_1 = L\left[\frac{n_1}{n}\right] \quad (3\text{-}7)$$

Where:
L_1 = Adjusted culvert length (ft)

L = Actual culvert length (ft)

n_1 = Actual Manning's n value of the culvert

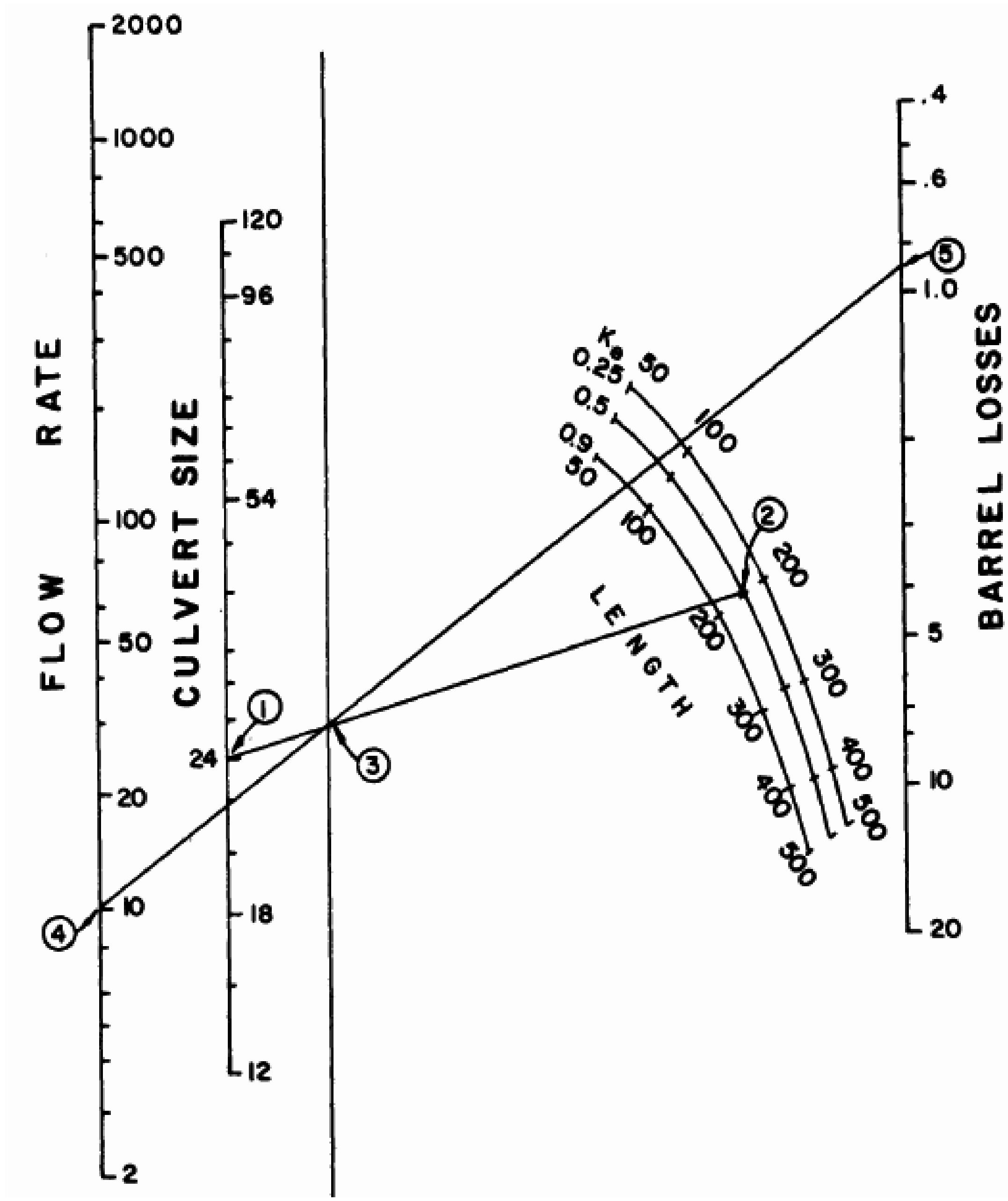
n = Manning's n value from the nomograph

Step 3: Using a straightedge, connect the culvert size (point 1) with the culvert length on the appropriate k_e curve (point 2). This will define a point on the turning line (point 3). If a k_e curve is not shown for the selected k_e, interpolate between the two bounding k_e curves. Appropriate k_e factors are shown in Figure 3-3.4.5H.

Step 4: Again using a straightedge, extend a line from the discharge (flow rate) (point 4) through the point on the turning line (point 3) to the head loss H (barrel losses) scale (point 5). Read H.

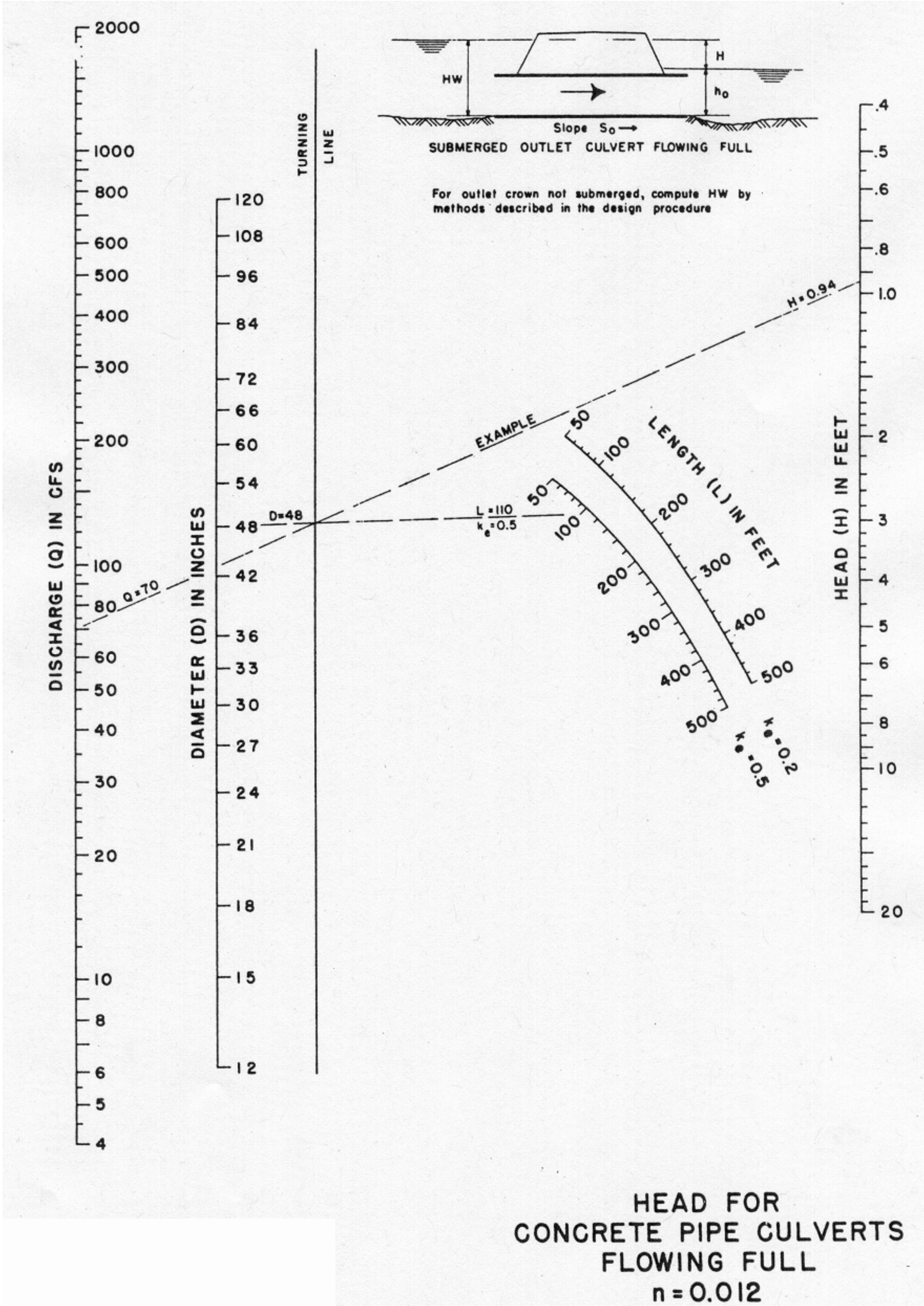
Note: Careful alignment of the straightedge is necessary to obtain accurate results from the nomographs.

Figure 3-3.4.5G is the outlet control nomograph to be used for square box culverts. The nomograph can also be used for rectangular box culverts by calculating the cross-sectional area of the rectangular box and using that area as point 1 described in Step 3 above.



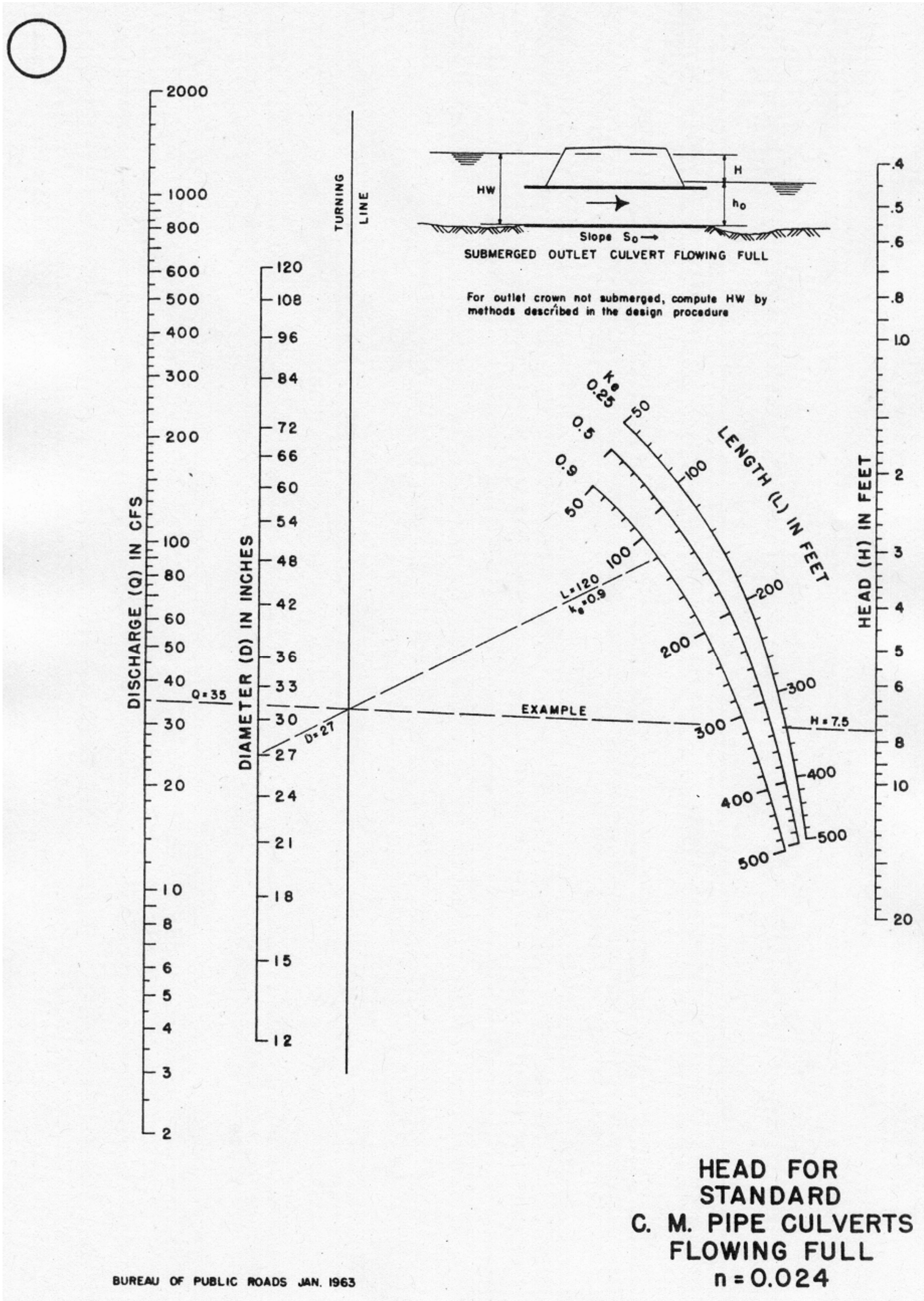
Sample Outlet Control Nomograph

Figure 3-3.4.5A



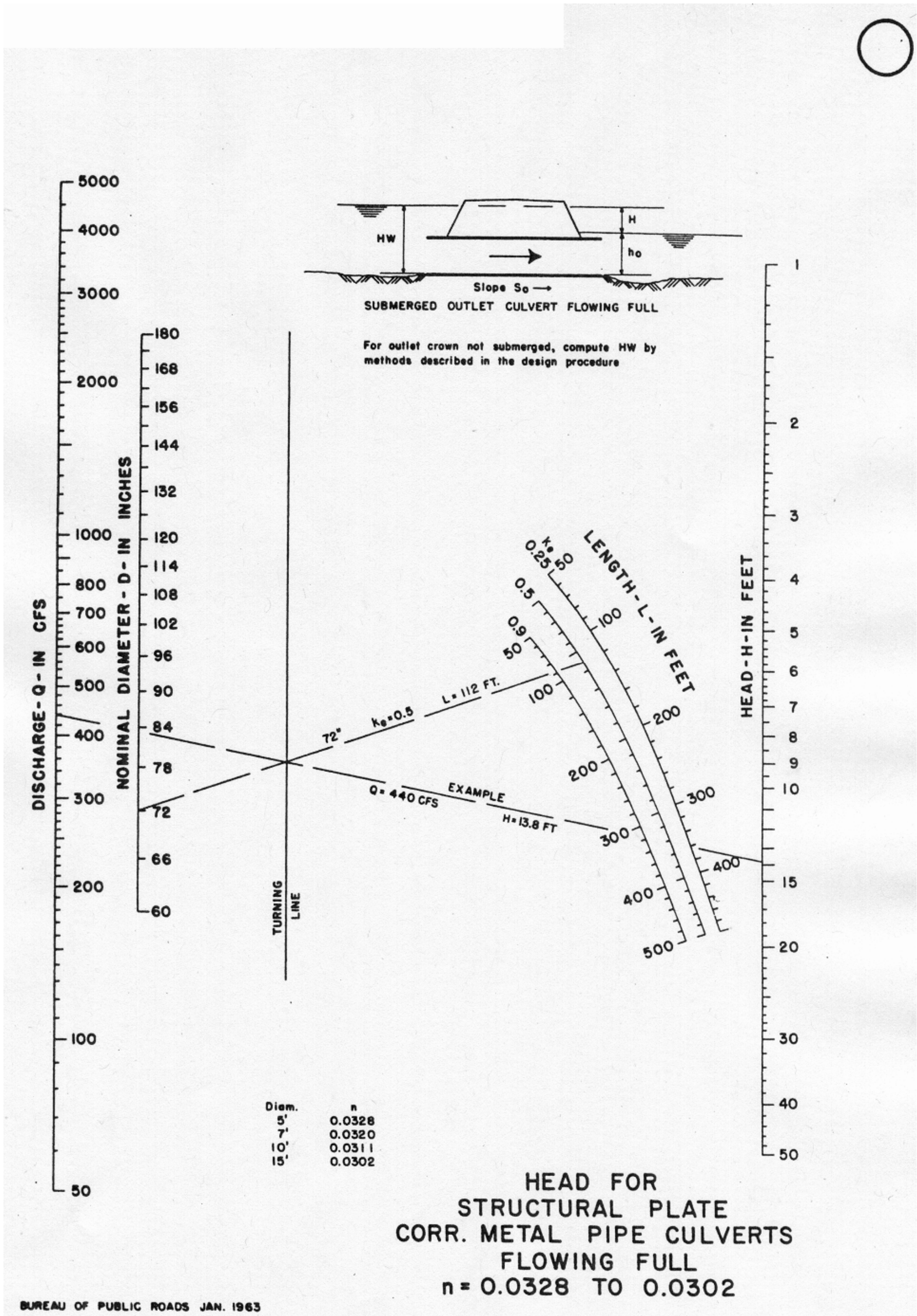
Concrete and Thermoplastic Pipe Outlet Control Nomograph

Figure 3-3.4.5B



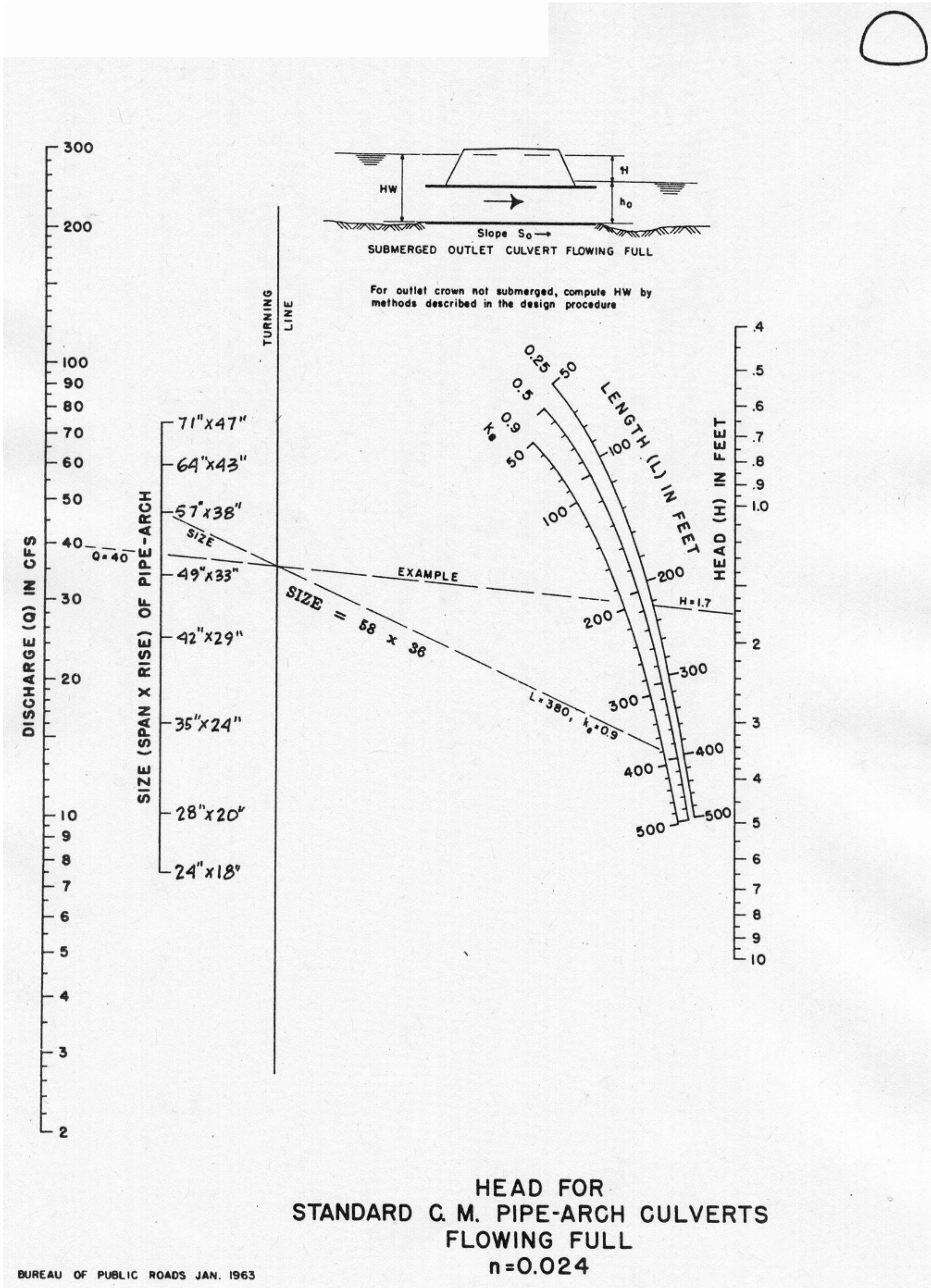
Corrugated Metal Pipe Outlet Control Nomograph

Figure 3-3.4.5C



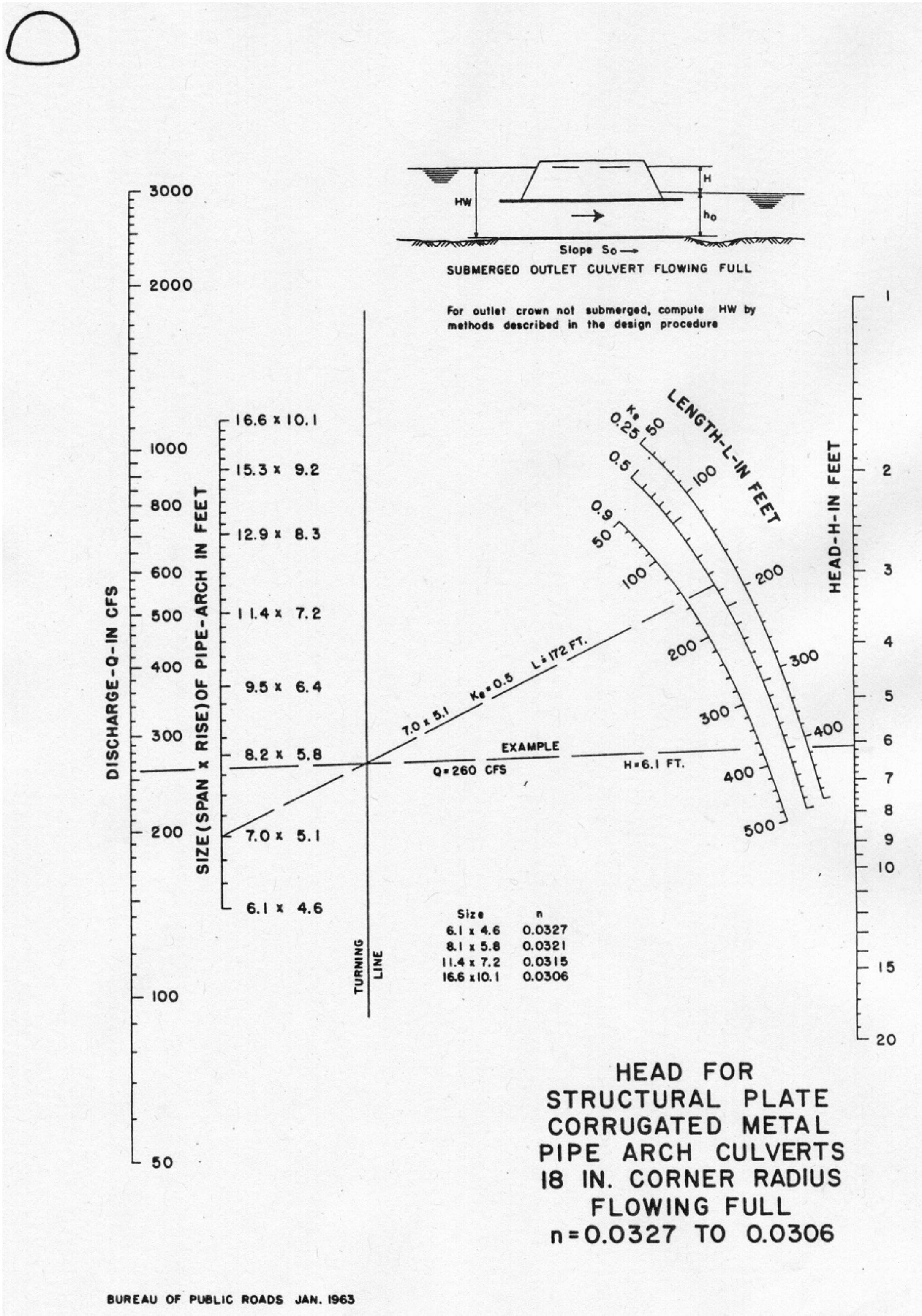
Structural Plat Corrugated Metal Pipe Outlet Control Nomograph

Figure 3-3.4.5D



Corrugated Metal Pipe-Arch Outlet Control Nomograph

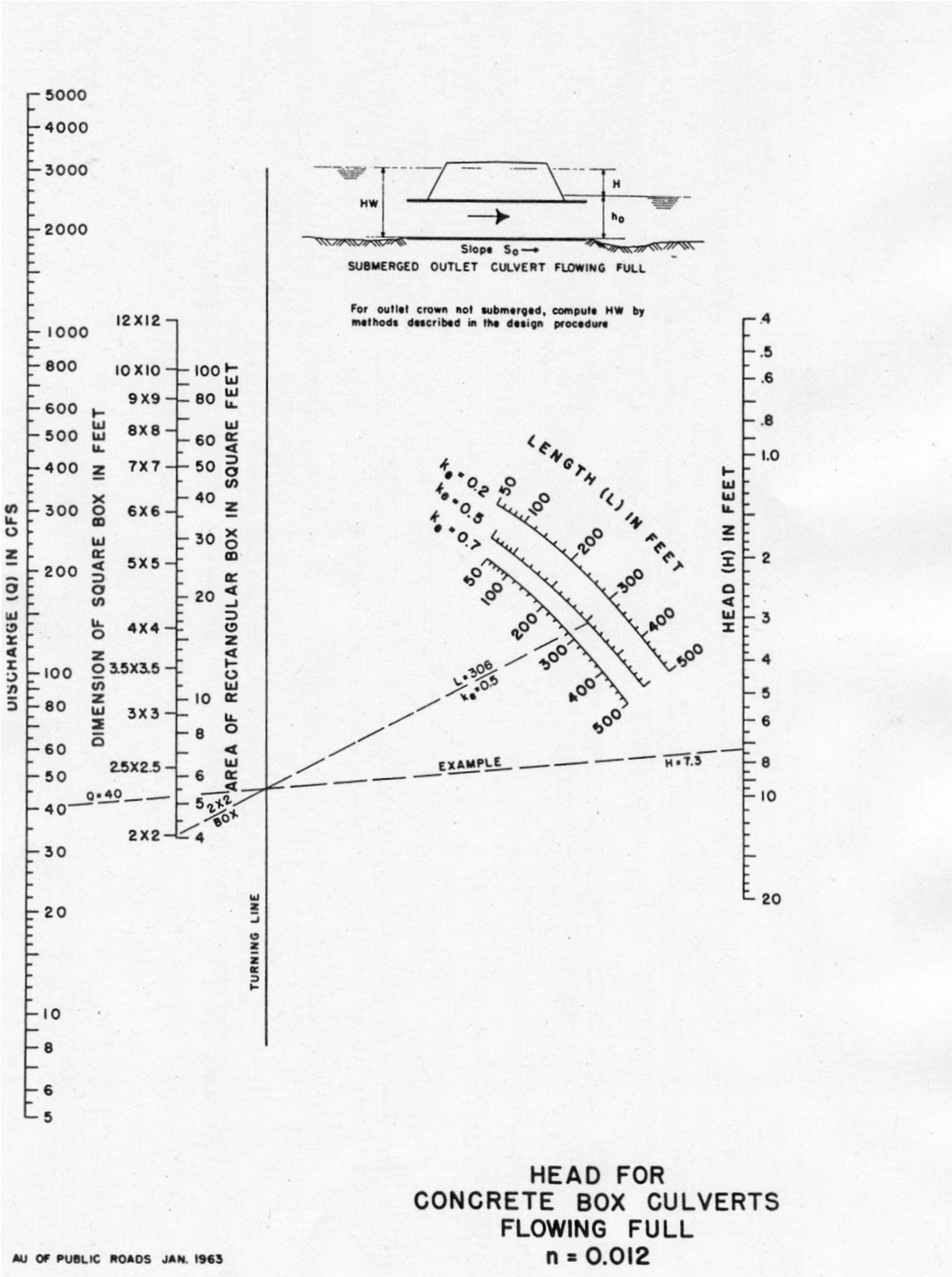
Figure 3-3.4.5E



Corrugated Metal Pipe-Arch Outlet Control Nomograph

18 Inch Corner Radius

Figure 3-3.4.5F



Box Culvert Outlet Control Nomograph

Figure 3-3.4.5G

Type of Structure and Entrance Design	ke	Standard Plan
Concrete Pipe		
Projecting from fill, no headwall, socket (groove) end	0.2	
Projecting from fill, no headwall Square cut end	0.5	
Mitered to conform to fill slope (beveled end section)	0.7	B-70.20
Mitered to conform to fill slope, with concrete headwall	0.7	B-75.20
Flared end sections, metal or concrete	0.5 B-70.60	Design B
Vertical headwall with wingwalls		
Socket end (groove end)	0.2 B	
Square cut end	0.5	
Rounded (radius = 1/12 D)	0.2*	
Metal and Thermoplastic Pipe or Pipe Arch		
Projecting from fill, no headwall	0.9	
Tapered end section	0.9	B-80.20, B-80.40
Mitered to conform to fill slope (beveled end section)	0.7	B-70.20
Mitered to conform to fill slope, with concrete headwall	0.7	B-75.20
Flared metal or thermoplastic end sections	0.5 B-70.60	Design A
Vertical headwall with wingwalls	0.5	
Any headwall with beveled inlet edges	0.2*	
Reinforced Concrete Box		
Mitered concrete headwall to conform to fill slope		
Square-edged on 3 edges	0.5	
Rounded or beveled edges on 3 sides	0.2	
Wingwalls at 30 degrees to 75 degrees to barrel		
Square edge at crown	0.4	
Rounded or beveled edge at crown	0.2*	
Wingwalls at 10 degrees to 25 degrees to barrel		
Square edge at crown	0.5	
Wingwalls parallel to barrel		
Square edge at crown	0.7	
Side or slope tapered inlet	0.2*	

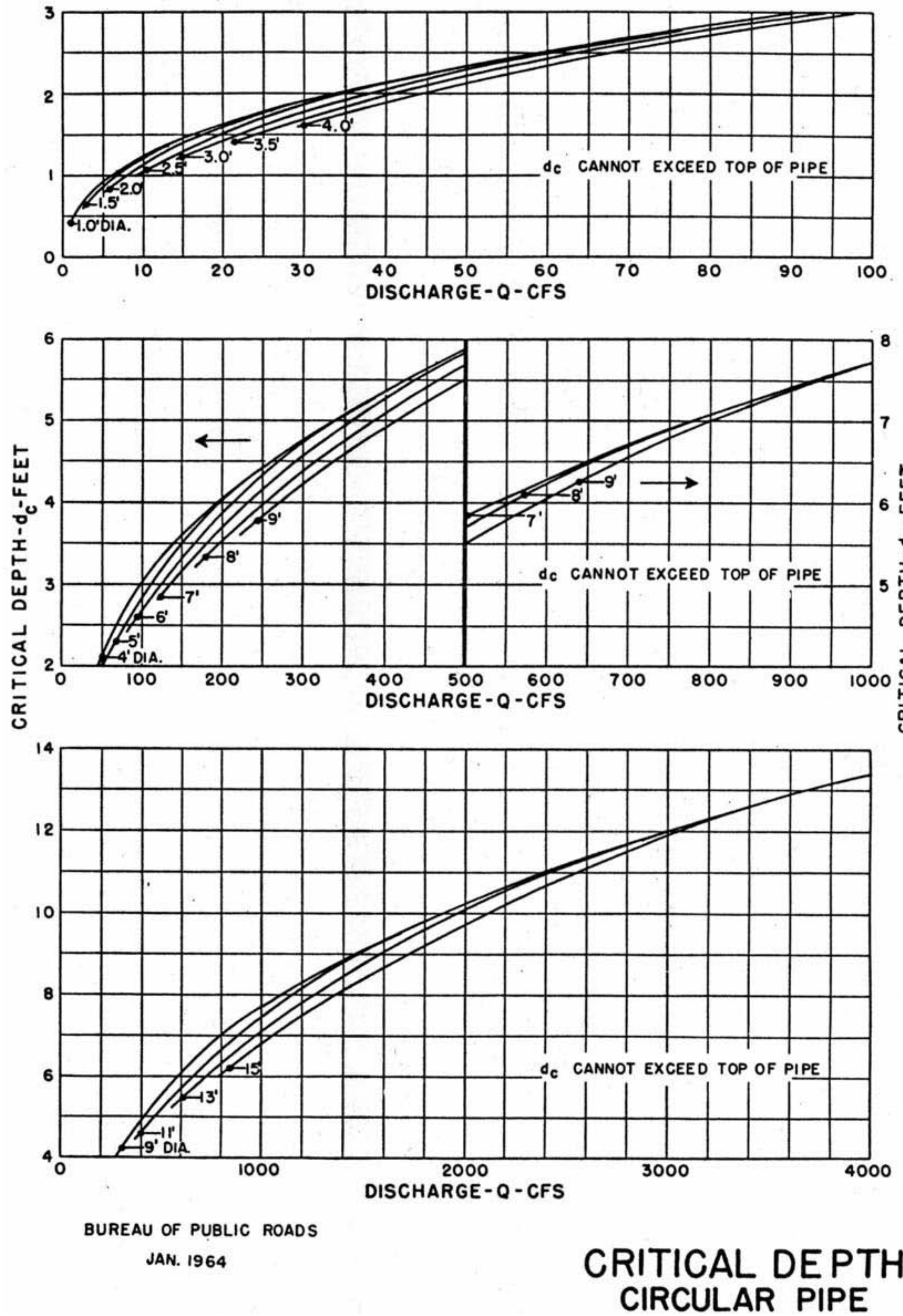
*Reference Section 3-4.6 for the design of special improved inlets with very low entrance losses

**Modified for round pipe.

Entrance Loss Coefficient k_e

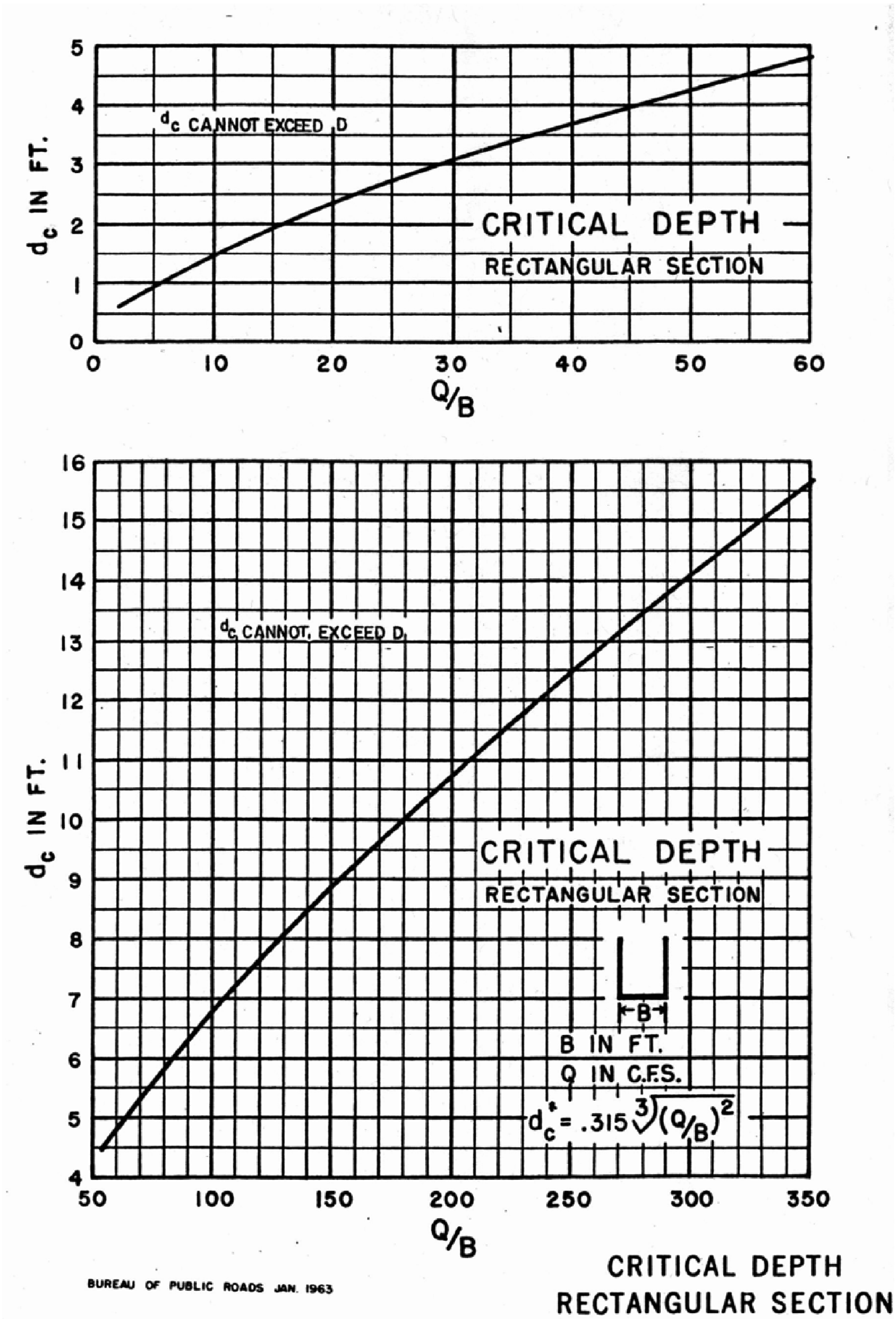
Outlet Control

Figure 3-3.4.5H



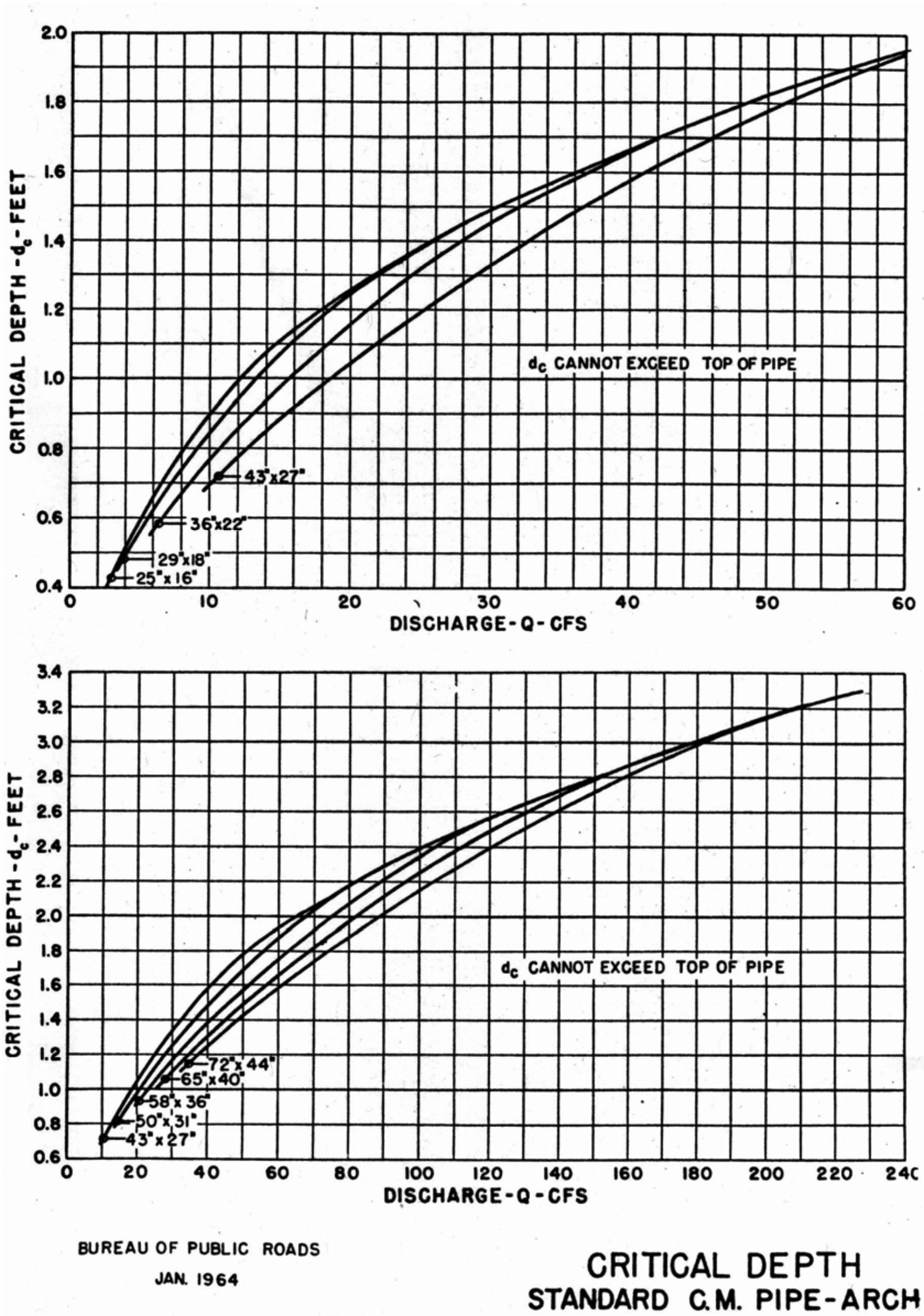
Critical Depth for Circular Pipe

Figure 3-3.45I



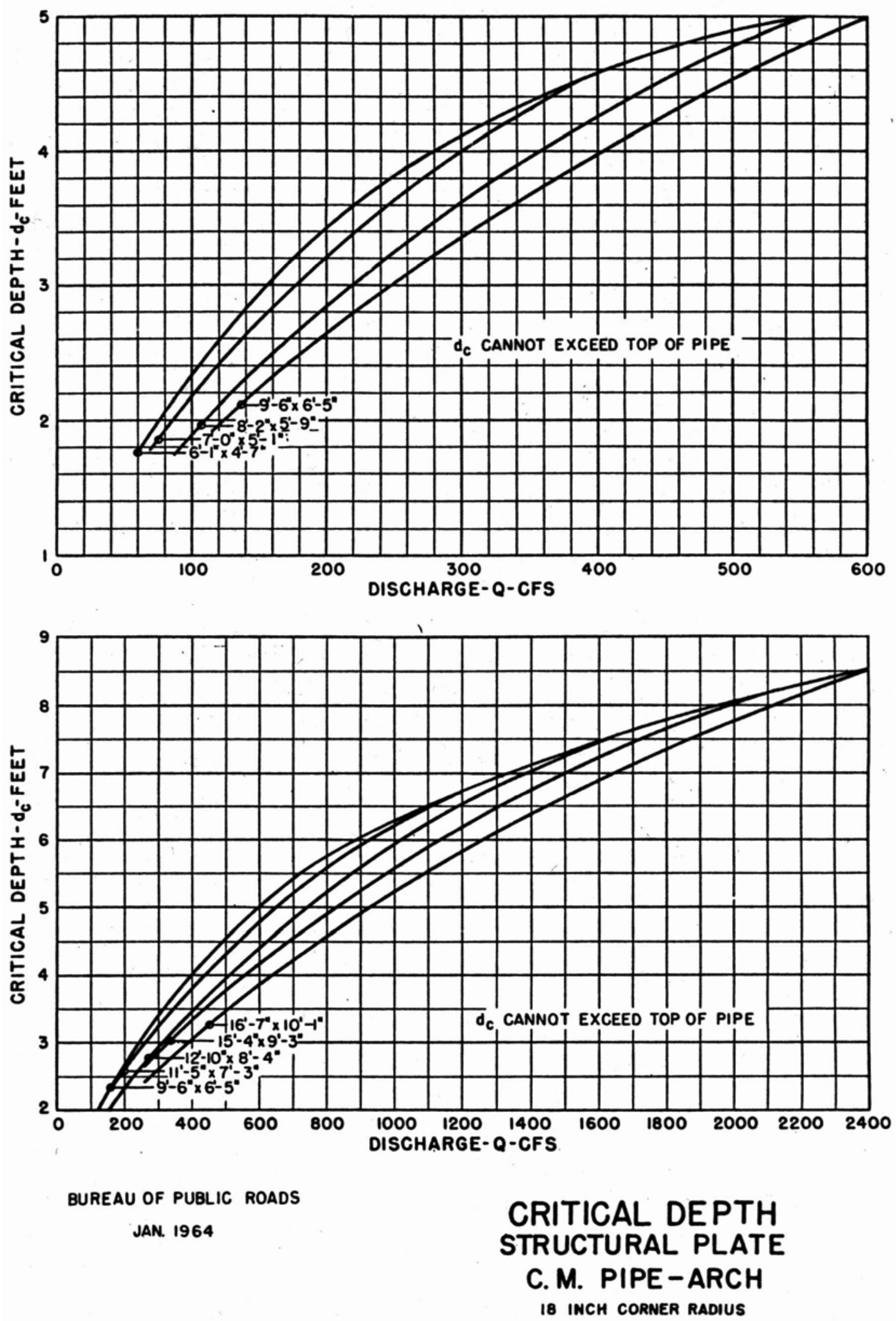
Critical Depth for Rectangular Shapes

Figure 3-3.4.5J



Critical Depth for Standard Corrugated Metal Pipe Arch

Figure 3-3.4.5K



Critical Depth for Structural Plate Corrugated Metal Pipe Arch

Figure 3-3.4.5L

3-3.5 Velocities in Culverts — General

A culvert, because of its hydraulic characteristics, generally increases the velocity of flow over that in the natural channel. High velocities are most critical just downstream from the culvert outlet and the erosion potential from the energy in the water must be considered in culvert design.

Culverts that produce velocities in the range of 3 to 10 ft/s (1 to 3 m/s) tend to have fewer operational problems than culverts that produce velocities outside of that range. Varying the grade of the culvert generally has the most significant effect on changing the velocity, but since many culverts are placed at the natural grade of the existing channel, it is often difficult to alter this parameter. Other measures, such as changing the roughness characteristics of the barrel, increasing or decreasing the culvert size, or changing the culvert shape should be investigated when it becomes necessary to modify the outlet velocity.

If velocities are less than about 3 ft/s (1 m/s), siltation in the culvert may become a problem. In those situations, it may be necessary to increase the velocity through the culvert or provide a debris basin upstream of the inlet. A debris basin is an excavated area upstream of the culvert inlet that slows the stream velocity and allows sediments to settle out prior to entering the culvert. See Section 3-4.8 for additional information on debris basins. If the velocity in the culvert cannot be increased and if a debris basin cannot be provided at a site, another alternative is to provide oversized culverts. The oversized culverts will increase siltation in the culvert, but the larger size may prevent complete blocking and will facilitate cleaning. It is recommended that the designer consult with the Region Hydraulics Engineer to determine the appropriate culvert size for this application.

If velocities exceed about 10 ft/s (3 m/s), abrasion due to bed load movement through the culvert and erosion downstream of the outlet can increase significantly. Abrasion is discussed in more detail in Section 8-6. Corrugated metal culverts may be designed with extra thickness to account for possible abrasion. Concrete box culverts and concrete arches may be designed with sacrificial steel inverts or extra slab thicknesses to resist abrasion. Thermoplastic pipe exhibits better abrasion characteristics than metal or concrete; see Figure 8-6 for further guidance. Adequate outlet channel or embankment protection must be designed to insure that scour holes or culvert undermining will not occur. Energy dissipators can also be used to protect the culvert outlet and downstream property, as discussed in Section 3-4.7. The designer is cautioned that energy dissipators can significantly increase the cost of a culvert and should only be considered when required to prevent a large scour hole or as remedial construction.

3-3.5.1 Calculating Outlet Velocities for Culverts in Inlet Control

When a culvert is flowing in inlet control, the water surface profile can be assumed to converge toward normal depth as flow approaches the outlet. The average outlet velocity for a culvert flowing with inlet control can be approximated by computing the normal depth and then the normal velocity for the culvert cross-section using Manning's equation, as shown below.

The normal depth approximation is conservative for short culverts and close to actual for long culverts. When solving for velocity using computer programs, a different velocity will be obtained. This occurs because the program does not make the normal depth approximation but rather computes a standard step backwater calculation through the pipe to develop the actual depth and velocity. Equation (3-8) is for full flow (80% to 100%):

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \quad \text{(English Units)} \qquad (3\text{-}8)$$

or

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad \text{(Metric Units)}$$

Where:
- V = Mean full velocity in channel, m/s (ft/s)
- n = Mannings roughness coefficient (see Appendix 4-1)
- S = Channel slope, m/m (ft/ft)
- R = Hydraulic radius, m (ft)
- A = Area of the cross section of water, m^2 (ft^2)
- P = Wetted perimeter, m (ft)

Manning's equation should be used to solve for the outlet velocity in non-circular culverts. The procedure for determining the velocity is discussed in Chapter 4-3.

For circular culverts, a simplified version of Manning's equation can be used to calculate the velocity in the culvert. The simplified equation for partial flow (10%-80%) is given by equation (3-9):

$$V_n = \frac{0.863 S^{0.366} Q^{0.268}}{D^{0.048} n^{0.732}} \qquad (3\text{-}9)$$

Where: S = Pipe slope (ft/ft)

Q = Flow rate (cfs)

D = Pipe diameter (ft)

N = Manning's roughness coefficient

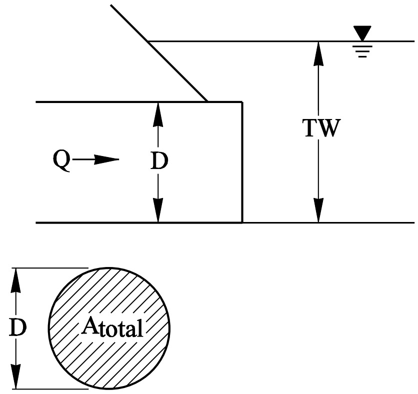
V_n = Normal velocity for partial flow (ft/s)

The above equation was developed from the proportional flow curves shown in Figure 3-3.5.2 and is based on a constant Manning's roughness coefficient. When compared to normal velocities, as calculated by a complete normal depth analysis, the results of this equation are accurate to within ± 5 percent.

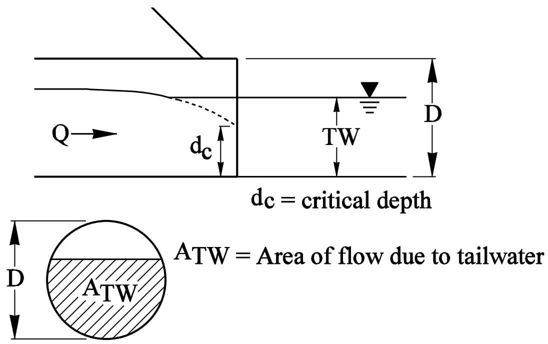
In some circumstances, a culvert can be flowing in inlet control but the outlet may be submerged. In that situation, the outlet velocity can be found by $V_{out} = Q/A_{total}$, where A_{total} is the full area of the culvert. This condition is rare, and should only be assumed when the outlet is fully submerged and the velocities in the pipe have had a chance to reduce before the outlet.

3-3.5.2 Calculating Outlet Velocities for Culverts in Outlet Control

When a culvert is flowing in outlet control, the average outlet velocity can be found by dividing the discharge by the cross-sectional area of flow at the outlet. There are three general water surface conditions that can exist at the outlet and affect the cross-sectional area of flow. The designer must determine which one of the three conditions exist and calculate the outlet velocity accordingly.



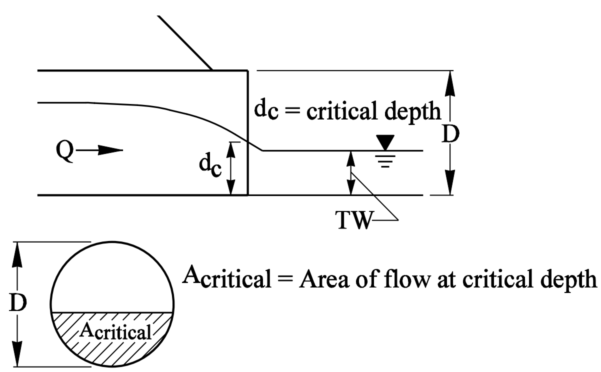
Condition 1: If the tailwater is greater than the diameter of the culvert, the total area of the culvert is used to calculate the outlet velocity.



Condition 2: If the tailwater is greater than critical depth but less than the diameter of the culvert, the tailwater depth is used to calculate the area of flow in the pipe and the corresponding outlet velocity.

In culverts flowing with outlet control, the flow profile tends to converge toward critical depth as flow approaches the outlet. In Condition 2, the flow profile is converging to critical depth near the outlet, but a tailwater depth exists that is greater than the critical depth. Therefore, the tailwater depth will dictate the corresponding area of flow to be used in the velocity calculation.

Condition 3: If the tailwater is equal to or less than critical depth, critical depth is used to calculate the area of flow and corresponding outlet velocity.



Condition 3 represents a situation where a culvert flowing with outlet control is allowed to freely discharge out of the end of the culvert. The tailwater in this case has no effect on the depth of flow at the outlet. Instead, critical depth is used to determine the flow area and corresponding outlet velocity. Critical depth for various shapes can be calculated from the equations shown in Section 4-5 or read from the critical depth charts shown in Figures 3-3.4.5I to L.

Once it has been determined which of the three outlet conditions exist for a given design, the corresponding area of flow for the outlet depth can be determined. The geometrical relationship between the depth of flow and area of flow can range from very simple for structures such as box culverts to very complex for structures such as pipe arches and bottomless culverts. Generally, utilizing a computer program, as discussed in Section 3-3.7, is the most accurate method for completing a culvert design that includes complex shapes.

For circular culverts, the area of flow for a given outlet depth can be determined using the proportional flow curves shown in Figure 3-3.5.2. The curves give the proportional area, discharge, velocity and hydraulic radius of a circular culvert when the culvert is flowing less than full. Once the area has been calculated, the corresponding outlet velocity can be determined. The following example illustrates how to use the chart:

3-3.5.2.1 Example - Calculating Outlet Velocities for Culverts in Outlet Control

Assume that a design was completed on a 6 ft (1800 mm) diameter pipe with a flow of 150 cfs (4.3 cms). The pipe was found to be in outlet control and a tailwater of 5 ft (1.5 m) was present. Determine the flow condition that exists and calculate the outlet velocity.

Step 1 From Figure 3-3.4.5I, critical depth d_c was found to be 3.6 ft (1.1 m).

Step 2 Determine the flow condition.

D = 6 ft (1.8 m)

TW = 5 ft (1.5 m)

d_c = 3.6 ft (1.1 m)

Since $d_c < TW < D$, Condition 2 exists. Therefore, the area of flow caused by the tailwater depth will be used.

Step 3 Find the ratio of the depth of flow (d) to the diameter of the pipe (D), or d/D.

d = tailwater depth = 5 ft (1.5 m)

D = pipe diameter = 6 ft (1.8 m)

d/D = 5/6 = 0.83

Step 4 Go to the proportional flow curves of Figure 3-3-5.2. Locate 0.83 on the vertical axis. Extend a line horizontally across the page and intercept the point on the "Proportional Area" curve.

Step 5 From the point found on the "Proportional Area" curve, extend a line vertically down the page and intercept the horizontal axis. The value read from the horizontal axis is approximately 0.89. This value represents the ratio of the proportional flow area (A_{prop}) to the full flow area (A_{full}), or A_{prop}/A_{full} = 0.89.

Step 6 Find the proportional flow area. The equation A_{prop}/A_{full} = 0.89 can be rearranged to:

$$A_{prop} = 0.89A_{full} \quad (3\text{-}10)$$

$$A_{full} = \frac{\pi D^2}{4} = \frac{\pi(6)^2}{4} = 28.6ft^2(2.54m^2) \quad (3\text{-}11)$$

$$A_{prop} = 0.89(28.6) = 25.2ft^2(2.26m^2)$$

Step 7 A_{prop} is equal to A_{TW}. Use A_{prop} and Q to solve for the outlet velocity.

$$V_{outlet} = \frac{Q}{A_{prop}} = \frac{150}{25.2} = 6\frac{ft}{s}(1.9\frac{m}{s}) \quad (3\text{-}12)$$

The previous example was solved by first determining the proportional area from Figure 3-3.5.2. Utilizing the "Proportional Velocity" curve from the same figure could also have solved the example. Picking up on

Step 3 from above, the ratio of d/D would remain the same, 0.83.

Step 4 Go to the proportional flow curves of Figure 3-3.5.2. Locate 0.83 on the vertical axis. Extend a line horizontally across the page and intercept the point on the "Proportional Velocity" curve.

Step 5 From the point found on the “Proportional Velocity” curve, extend a line vertically down the page and intercept the horizontal axis. The value read from the horizontal axis is approximately 1.14. This value represents the ratio of the proportional velocity (V_{prop}) to the full flow velocity (V_{full}), or $V_{prop}/V_{full} = 1.14$.

Step 6 Rearrange $\frac{V_{prop}}{V_{full}} = 1.14$ to

$$V_{prop} = 1.14 V_{full} \qquad (3\text{-}13)$$

Step 7 Find V_{full} by solving the equation $V_{full} = \frac{Q}{A_{full}}$

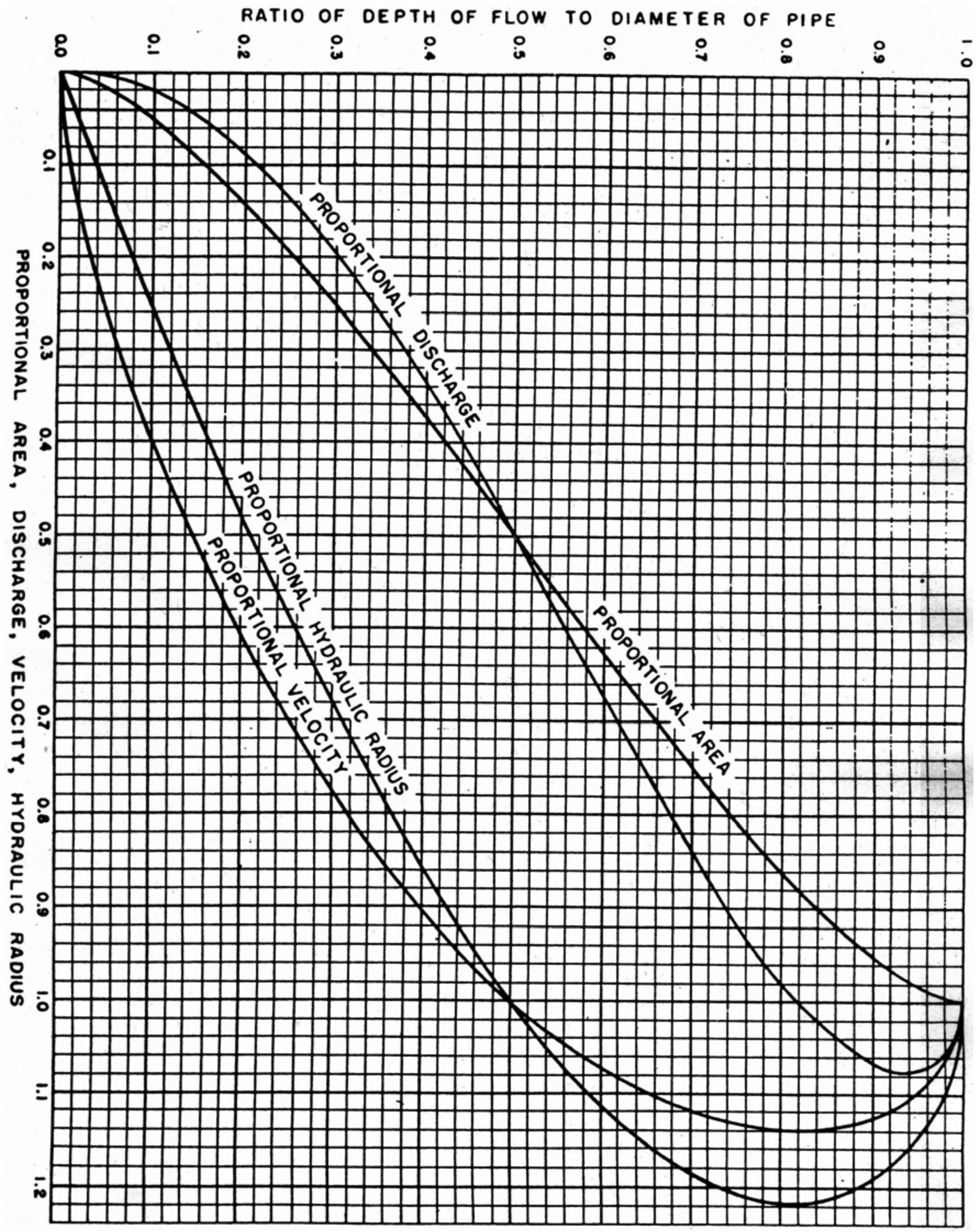
$$Q = 150 \frac{ft^3}{s} (4.3 \frac{m^3}{s})$$

$$A_{full} = \frac{\pi D^2}{4} = \frac{\pi (6)^2}{4} = 28.3 ft^2 (2.54 m^2)$$

$$V_{full} = \frac{150}{28.3} = 5.3 \frac{ft}{s} (1.69 \frac{m}{s})$$

Step 8 Solve for V_{prop} using equation (3-13) which is the outlet velocity.

$$V_{prop} = 1.14 V_{full} = 1.14(5.3 \frac{ft}{s}) = 6 \frac{ft}{s} (1.9 \frac{m}{s})$$



Proportional Flow Curve

Figure 3-3-5.2

3-3.6 Culvert Hydraulic Calculations Form

A "Culvert Hydraulic Calculations" form has been developed to help organize culvert hydraulic computations. The form is shown in Figure 3-3.6A and B and should be used in all Hydraulic Reports that involve culvert designs utilizing hand calculations. If a culvert is designed using a computer program, it is not necessary to include the form in the Hydraulic Report, provided that all design information is included in the input and output files created by the program. Included in this section is an explanation of each of the components of the form and the corresponding chapter section that provides additional information. Figure 3-3.6A has been labeled with either alpha or numeric characters to facilitate discussion for each component on the form. A second form, Figure 3-3.6B, is a blank copy of the culvert hydraulic calculations form. The blank copy should be used by the designer and included as part of the hydraulic report.

From Figure 3-3.6A:

A, A' and A": Design flow(s) Q, in cfs — Section 3-3.1

B, B', and B": Depth of tailwater (TW) in feet, using the corresponding design flow values — Section 3-3.3

C: Elevation of the centerline of the roadway. This is the elevation used to determine roadway overtopping.

D: Allowable headwater depth (AHW), in feet, as discussed in Section 3-3.2 Any significant features upstream that are susceptible to flood damage from headwater should be identified. The elevation at which damage would occur should be identified and incorporated into the design process.

E and E': Inlet and outlet invert elevations, in feet.

F: Slope of culvert (S_o), in feet/feet.

G: Approximate length (L) of culvert, in feet.

Column 1: Culvert Type

Include barrel material, barrel cross-sectional shape, and entrance type.

Column 2: Q - Section 3-3.1

Indicate which design flow from A, A', or A" is being evaluated.
Separate calculations must be made for each design flow.

Project: Example

Designer:

SR:

Date

Hydrologic and Channel Information

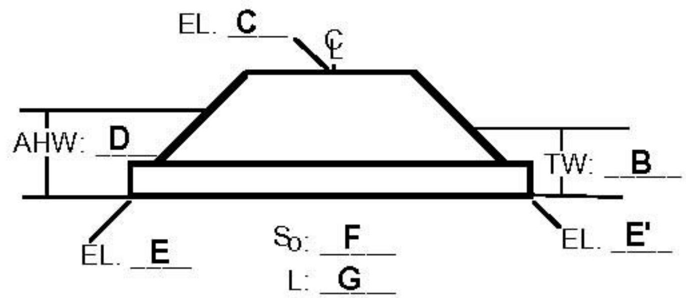
Q_1: A TW$_1$: B

Q_2: A' TW$_2$: B'

Q_3: A" TW$_3$: B"

Sketch

Station:



			Headwater Computations											
			Inlet Control		Outlet Control									
Column 1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Culvert Type	Q	Size	$\frac{HW}{D}$	HW	k_e	d_c	$\frac{d_c + D}{2}$	h_0	H	LS_o	HW	Cont. HW	Outlet Vel.	Comments

Summary and Recommendations:

Culvert Hydraulic Calculations Form (Instructional Form)

Figure 3-3.6A

(WSDOT form 235-006)

Project: ______________________________ Designer: ______________

SR: ______________________________ Date ______________

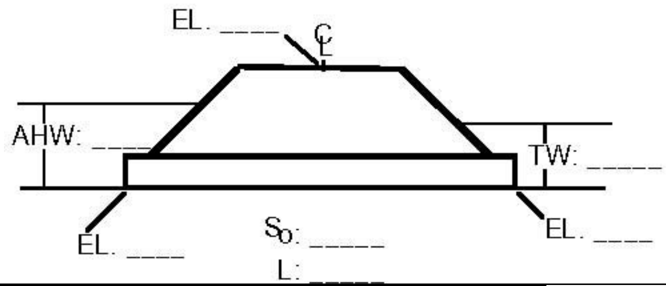
Hydrologic and Channel Information

Q_1: _____ TW_1: _____

Q_2: _____ TW_2: _____

Q_3: _____ TW_3: _____

Sketch



Station: ____________

			Headwater Computations											
			Inlet Control		Outlet Control									
Culvert Type	Q	Size	$\frac{HW}{D}$	HW	k_e	d_c	$\frac{d_c + D}{2}$	h_0	H	LS_o	HW	Cont. HW	Outlet Vel.	Comments

Summary and recommendations:

Culvert Hydraulic Calculations Form

Figure 3-3.6B

(WSDOT form 235-006)

Column 3: Size

Pipe diameter or span and rise, generally indicated in feet.

Column 4: HW_i/D (inlet control)

The headwater to diameter ratio is found from the appropriate nomographs 3-3.4.2A to E.

Column 5: HW (inlet control) — Section 3-3.4.2

This value is found by multiplying Column 3 by Column 4. This is the headwater caused by inlet control. If the inlet control headwater is greater than the allowable headwater as shown in D, the pipe size should be increased. If the headwater is less than allowable, then proceed with the next step. Once the inlet control headwater has been determined, it will be compared with the outlet control headwater in Column 12. The larger of the two values will be the controlling headwater and that value will be entered in Column 13.

Column 6: k_e

This is the entrance loss coefficient for outlet control taken from Figure 3-3.4.5H.

Column 7: Critical Depth

Critical depth can be determined for circular and rectangular shapes by using either the equations shown in Section 4-4 or read from the critical depth charts shown in Figures 3-3.4.5I to L. The critical depth for pipe arches can only be determined by the use of Figures 3-3.4.5K and L.

If critical depth is found to be greater than the pipe diameter or rise, set the critical depth equal to the diameter or rise.

Column 8: $\frac{d_c + D}{2}$ **-** Figure 3-3.4.4B (3-14)

Equation (3-14) represents an approximation of the hydraulic grade line at the outlet of the culvert, where d_c is equal to the critical depth at the outlet of the culvert and D is the culvert diameter or rise. It is used to help calculate headwater during outlet control computations. As shown in Figure 3-3.4.4B, $(d_c + D)/2$ does not represent the actual water surface elevation at the outlet of the culvert and therefore should not be used for determining the corresponding outlet velocity. The method for determining the outlet velocity is discussed in Section 3-3.5.2

Column 9: h_o — Section 3-3.4.4

h_o is equal to either the tailwater or the term $(d_c + D)/2$, whichever is greater.

Column 10: H — Section 3-3.4.4

H is the total amount of head loss in the barrel of the pipe including the minor losses at the entrance and the exit of the pipe.

The head loss is determined by equation (3-4):

$$H = \left[1 + K_e + \frac{29n^2L}{R^{1.33}}\right]\frac{V^2}{2g} \qquad (3\text{-}4)$$

or it may be determined by the outlet control nomographs shown in Figures 3-3.4.5B to G. Both the nomographs and the equation are based on the assumption that the barrel is flowing completely full or nearly full. This is usually the case with most outlet control pipes, but some exceptions do occur. When the barrel is partially full, solving for H using either the nomographs or the equation will tend to overestimate the actual headlosses through the culvert. This will result in a higher, and more conservative, headwater value. A more accurate headwater can be obtained by designing a culvert using a computer program, as described in Section 3-3.7.

Column 11: LS_o

This column is the product of the culvert length (L) multiplied by culvert slope (s_o) or it is equal to the inlet elevation minus the outlet elevation of the culvert.

Column 12: HW— Section 3-3.4.4

This column shows the amount of headwater resulting from outlet control. It is determined by equation (3-15):

$$HW_o = H + h_o - L\,S_o \qquad (3\text{-}15)$$

Column 13: Controlling HW

This column contains the controlling headwater, which is taken from Column 5 or Column 12 whichever is greater. This value is the actual headwater caused by the culvert for the particular flow rate indicated in Column 2.

Column 14: Outlet Velocity

If the culvert was determined to be in inlet control, velocity at the outlet can be determined using the method described in Section 3-3.5.1. If the culvert was determined to be in outlet control, the outlet velocity can be determined using the method described in Section 3-3.5.2.

Column 15: Comments

As appropriate.

Column 16: Summary and Recommendations

As appropriate.

3-3.7 Computer Programs

Once familiar with culvert design theory as presented in this chapter, the designer is encouraged to utilize one of a number of commercially available culvert design software programs. The Federal Highway Administration has developed a culvert design program called HY-8 that utilizes the same general theory presented in this chapter. HY-8 is DOS menu-driven and easy to use, and the output from the program can be printed out and incorporated directly into the Hydraulic Report. HY-8 is copyright protected but the copyright allows for free distribution of the software. It is available by contacting either the Region Hydraulic Office/Contact or Office on the web at http://www.wsdot.wa.gov/eesc/design/hydraulics/downloads.htm.

In 2002, the FHWA developed a window interface to HY8, called HY8InpGen and HY8PCViewer. To attain this new software contact your Region IT or MIS support group. It is level playing field software and more user friendly than the DOS version. The HY8InpGen is the input file generator it stores all the data information and it uses the DOS engine to run the computation that creates a PC file. The HY8PCViewer is the output file viewer, to view the created PC file in different formats.

In addition to ease of use either software, HY-8 is advantageous in that the headwater elevations and outlet velocities calculated by the program tend to be more accurate than the values calculated using the methods presented in this chapter. HY-8 computes an actual water surface profile through a culvert using standard step-backwater calculations. The methods in this chapter approximate this approach but make several assumptions in order to simplify the design. HY-8 also analyzes an entire range of flows input by the user. For example, the program will simultaneously evaluate the headwater created by the $Q_{10\%}$, Q_{25}, and Q_{100} flow events, displaying all of the results on one screen. This results in a significantly simplified design procedure for multiple flow applications. The basic Hydrology and Hydraulic training manual contains a section that has a step-by-step guidance on how to use HY8 DOS version. The manual can be found at the following web link:

http://www.wsdot.wa.gov/eesc/design/hydraulics/training.htm

3-3.8 Example

A hydrological analysis was completed for a basin above a proposed roadway and culvert crossing. The analysis found that the 25-year flow event was 300 cfs and the 100-year flow event was 390 cfs. In the vicinity of the culvert, the preferable roadway profile would place the centerline at elevation 1,530 feet, about 10 feet higher than the existing channel bottom. The tailwater depth was found to be 5 feet during the 25-year flow event and 5.5 feet during the 100-year flow event. Also, there are no fish passage concerns at this location. Assume that the culvert will be 100 ft long and will match the existing channel slope of 0.005 ft/ft. Then determine the appropriate culvert material and size, and calculate the controlling headwater elevation and corresponding outlet velocity for both the 25- and 100-year events.

Step 1: The designer must choose an initial type of culvert material to begin the design. Once the culvert is analyzed, the designer may go back and choose a different type of material or pipe configuration to see if the hydraulic performance of the culvert can be improved. In this case, assume that a circular concrete culvert was chosen.

Step 2: Use the hydraulic calculation form shown in Figure 3-3.6 and fill out the known information (see Figure 3-3.8A the complete form for this example). This would include the design flows, tailwater, roadway and culvert elevations, length, slope, and material type. Two design flows were given, one for the 25-year flow event and one for the 100-year flow event. The designer should first analyze the 25-year flow event.

Step 3: The next piece of information needed is the culvert size. In some cases, the culvert diameter is already known and the size can be entered in the appropriate column. In this example, the diameter was not given. In order to determine the appropriate diameter, go to the inlet control nomograph for concrete pipe, Figure 3-3.4.2A.

Step 4: On the nomograph, there are three entrance types available. Assume that in this case, the culvert end will be out of the clear zone and aesthetics are not a concern. Entrance type (3) is an end condition where the pipe is left projecting out of the fill, with the bell or grooved end facing upstream. Choose this entrance type.

Step 5: Because of the relatively low embankment height in this example, it is recommended that the culvert be designed using an HW/D ratio during the 25-year event equal to or less than 1.25. On the right hand side of the nomograph, find 1.25 on the vertical HW/D scale representing entrance type (3).

Step 6: Using a straightedge, extend that point horizontally to the left and mark the point where it intercepts scale (1). The point marked on scale (1) should be about 1.37.

Step 7: Connect the point just found on scale (1) with 300 cfs on the discharge scale and read the required culvert size on the diameter scale. The value read should be about 75 inches. Since culverts are typically fabricated only in the sizes shown on the nomograph, choose the next largest diameter available, which in this case is 84 inches (7 feet).

Step 8: The 7-feet diameter culvert is slightly larger than the required size. Therefore, the actual HW/D ratio will be less than the 1.25 used to begin the design. To find the new HW_iD ratio, line up the 84-inch mark on the diameter scale and 300 cfs on the discharge scale, and then mark the point where the straightedge intersects scale (1). This value should be about 1.05.

Step 9: Extend that point horizontally to the right to scale (3) and find an HW/D ratio of about 0.98. This is the actual HW/D ratio for the culvert.

Step 10: Find the inlet control headwater by multiplying the HW/D ratio just found by the culvert diameter. $HW = 0.98 \times 7' = 6.86'$. The previous steps found the headwater for inlet control. The next several steps will be used to find the headwater for outlet control.

Step 11: Go to Figure 3-3.4.5H and find the entrance loss coefficient for the culvert. As discussed in Step 4, the grooved end is projecting; therefore, choose an entrance loss coefficient of 0.2.

Step 12: Find the critical depth-using Figure 3-3.4.5I. d_c = 4.6 ft

Step 13: Use equation (3-14) to find the value for:

$(d_c + D)/2 = (4.6 + 7)/2 = 5.8$ ft

Step 14: The value for h_o is equal to the value found from equation (3-14) or the tailwater, whichever is greater. In this case, the tailwater was given as 5 ft, therefore, h_o is equal to 5.8 ft.

Step 15: The value for H can be found by using the outlet control nomograph for concrete pipe shown in Figure 3-3.4.5B. With a straightedge, connect the 84-inch point on the diameter scale with the 100-foot length on the 0.2 k_e scale. This will define a point on the turning line. Mark that point.

Step 16: Again with a straightedge, go to the discharge scale and line up 300 cfs with the point just found on the turning line. Extend the line across the page to the head loss scale and find a value of about 1.3 ft.

Step 17: The value for LS_o can be found by multiplying the culvert length times the slope. $LS_o = 100 \times .005 = 0.5$ ft.

Step 18: The outlet control headwater can be found by solving equation (4-15):

$$HW_o = H + h_o - LS_o = 1.3 + 5.8 - 0.5 = 6.6 \text{ ft.}$$

The controlling headwater is the larger value of either the inlet control or the outlet control headwater. In this example, the inlet control headwater was found to be 6.86 feet. This value is greater than the 6.6 ft calculated for the outlet control headwater and therefore will be used as the controlling headwater.

Step 19: Using the equation shown in Section 3-3.5.1, the outlet velocity was found to be 13.2 ft/s. This velocity could cause erosion problems at the outlet, so the designer may want to consider protecting the outlet with riprap, as discussed in Section 3-4.7

The 100-year event must also be checked, using the same procedure. The results of the analysis are summarized below:

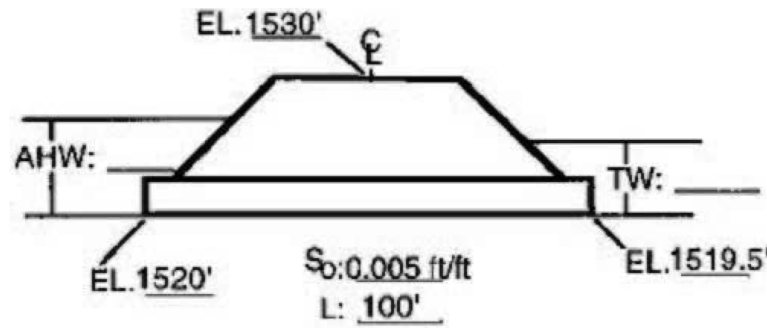
HW_i/D:	1.18 ft
HW_i:	8.26 ft
k_e	0.2
d_c	5.1 ft
$(d_c + D)/2$	6.05 ft
h_o	6.05 ft
H	2.2 ft
LS_o	0.5 ft
HW_o	7.75 ft
Cont. HW	8.26 ft
Out. Vel.	14.1 ft/s

Figure 3-3.8A shows a complete culvert hydraulic calculation form for this example. Figure 3-3.8B shows the controlling headwater elevations and outlet velocities for both flow events in English and metric units.

Project: ______________________________ Designer: ______________

SR: Date

Hydrologic and Channel Information	Sketch
Q_1: 300 cfs TW_1: 5 ft Q_2: 390 cfs TW_2: 5.5 ft Q_3: ____ TW_3: ____	Station: ______________



AHW – shown as HW_i below

Culvert Type	Q	Size	Headwater Computations – Inlet Control: $\frac{HW_i}{D}$	Inlet Control: HW_i	Outlet Control: k_e	d_c	$\frac{d_c+D}{2}$	h_0	H	LS_o	HW_o	Cont. HW	Outlet Vel.	Comments
Circ. Concrete	300	7'	0.9	6.86	0.2	4.6	5.80	5.80	1.3	0.5	6.60	6.86	13.2	25-yr, Inlet control
Circ. Concrete	390	7'	1.18	8.26	0.2	5.1	6.05	6.05	2.2	0.5	7.75	8.26	14.1	100-yr, Inlet control

Summary and recommendations: The 100-year headwater is less than 2 feet below the roadway centerline. This may or may not present a problem, depending on the accuracy of the basin flow calculations, the amount of debris in the stream, and the importance of keeping the roadway open during a large event. The designer may want to consider evaluating a different culvert shape, such as a box culvert or low profile arch. These structures tend to provide a larger flow area for a given height, and could potentially pass the design flows without creating as much headwater.

Completed Culvert Hydraulic Calculations Form

Figure 3-3.8A

Flow Event	Controlling Headwater Elevation		Outlet Velocity	
	ft	m	ft/s	m/s
25-year	1526.86	465.386	13.2	4.0
100-year	1528.26	465.81	14.1	4.3

Example Problem

Figure 3-3.8B

3-4 Culvert End Treatments

The type of end treatment used on a culvert depends on many interrelated and sometimes conflicting considerations. The designer must evaluate safety, aesthetics, debris capacity, hydraulic efficiency, scouring, and economics. Each end condition may serve to meet some of these purposes, but none can satisfy all these concerns. The designer must use good judgment to arrive at a compromise as to which end treatment is most appropriate for a specific site. Treatment for safety is discussed in Section 640.03(4) of the *Design Manual*.

A number of different types of end treatments will be discussed in this section. The type of end treatment chosen for a culvert shall be specified in the contract plans for each installation.

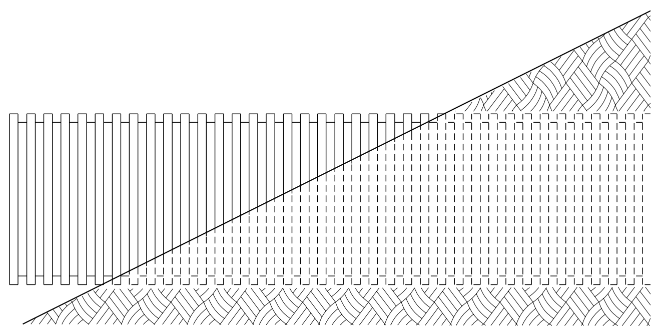
3-4.1 Projecting Ends

A projecting end is a treatment where the culvert is simply allowed to protrude out of the embankment, see Figure 3-4.1. The primary advantage of this type of end treatment is that it is the simplest and most economical of all treatments. Projecting ends also provide excellent strength characteristics since the pipe consists of a complete ring structure out to the culvert end.

There are several disadvantages to projecting ends. For metal, the thin wall thickness does not provide flow transition into or out of the culvert, significantly increasing head losses (the opposite is true for concrete, the thicker wall provides a more efficient transition). From an aesthetic standpoint, projecting ends may not be desirable in areas exposed to public view. They should only be used when the culvert is located in the bottom of a ravine or in rural areas.

Modern safety considerations require that no projecting ends be allowed in the designated clear zone. See the *Design Manual* (M 22-01) for details on the clear zone and for methods, which allow a projecting end to be used close to the traveled roadway.

Projecting ends are also susceptible to flotation when the inlet is submerged during high flows. Flotation occurs when an air pocket forms near the projecting end, creating a buoyant force that lifts the end of the culvert out of alignment. The air pocket can form when debris plugs the culvert inlet or when significant turbulence occurs at the inlet as flow enters culvert. Flotation tends to become a problem when the diameter exceeds 6 feet (1800 mm)for metal pipe and 2 feet (610 mm)for thermoplastic pipe. It is recommended that pipes that exceed those diameters be installed with a beveled end and a concrete headwall or slope collar as described in Sections 3-4.2 and 3-4.4. Concrete pipe will not experience buoyancy problems and can be projected in any diameter. However, because concrete pipe is fabricated in relatively short 6 to 12 feet (2 to 4 meter) sections, the sections are susceptible to erosion and corresponding separation at the joint.

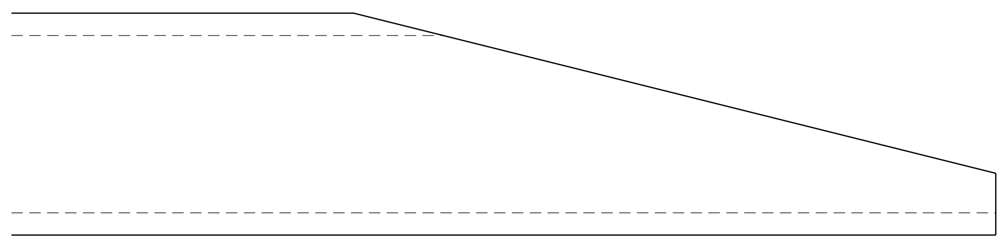


Projecting End

Figure 3-4.1

3-4.2 Beveled End Sections

A beveled end treatment consists of cutting the end of the culvert at an angle to match the embankment slope surrounding the culvert. A schematic is shown on Standard Plan B-70.20 and in Figure 3-4.2. A beveled end provides a hydraulically more efficient opening than a projecting end, is relatively cost effective, and is generally considered to be aesthetically acceptable. Beveled ends should be considered for culverts about 6 feet (1800 mm) in diameter and less. If culverts larger than about 6 feet (1800 mm) in diameter are beveled but not reinforced with a headwall or slope collar, the structural integrity of the culvert can be compromised and failure can occur. The standard beveled end section should not be used on culverts placed on a skew of more than 30 degrees from the perpendicular to the centerline of the highway, however a standard beveled end section can be considered if the culvert is rotated until it is parallel with the highway. Cutting the ends of a corrugated metal culvert structure to an extreme skew or bevel to conform to the embankment slope destroys the ability of the end portion of the structure to act as a ring in compression. Headwalls, riprap slopes, slope paving, or stiffening of the pipe may be required to stabilize these ends. In these cases, special end treatment shall be provided if needed. The Region Hydraulics Section/Contact or the HQ Hydraulics Office can assist in the design of special end treatments.



Beveled End Section

Figure 3-4.2

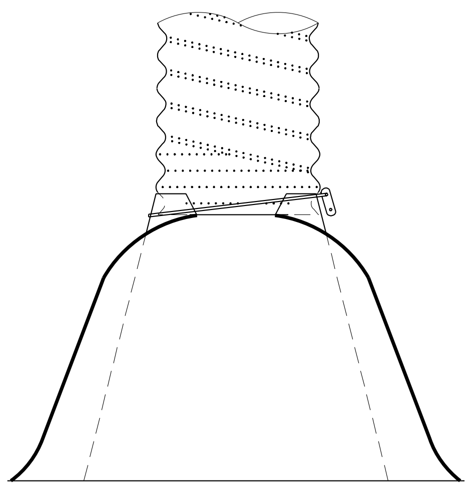
3-4.3 Flared End Sections

A metal flared end section is a manufactured culvert end that provides a simple transition from culvert to streambed. Flared end sections allow flow to smoothly constrict into a culvert entrance and then spread out at the culvert exit as flow is discharged into the natural stream or watercourse. Flared ends are generally considered aesthetically acceptable since they serve to blend the culvert end into the finished embankment slope.

Flared end sections are typically used only on circular pipe or pipe arches. The acceptable size ranges for flared ends, as well as other details, are shown on Standard Plan B-70.60 and a detail is shown in Figure 3-4.3. Flared ends are generally constructed out of steel and aluminum and should match the existing culvert material if possible. However, either type of end section can be attached to concrete or thermoplastic pipe and the contractor should be given the option of furnishing either steel or aluminum flared end sections for those materials.

A flared end section is usually the most feasible option in smaller pipe sizes and should be considered for use on culverts up to 48 inch (1800 mm) in diameter. For diameters larger than 48 inch (1800 mm), end treatments such as concrete headwalls tend to become more economically viable than the flared end sections.

The undesirable safety properties of flared end sections generally prohibit their use in the clear zone for all but the smallest diameters. A flared end section is made of light gage metal and because of the overall width of the structure; it is not possible to modify it with safety bars. When the culvert end is within the clear zone and safety is a consideration, the designer must use a tapered end section with safety bars as shown on Standard Plan B-80.20 and B-80.40. The tapered end section is designed to match the embankment slope and allow an errant vehicle to negotiate the culvert opening in a safe manner.



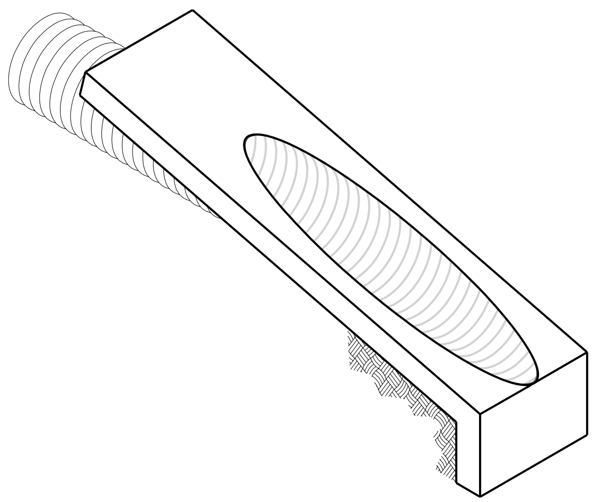
Flared End Section

Figure 3-4.3

3-4.4 Headwalls and Slope Collars

A headwall is a concrete frame poured around a beveled culvert end. It provides structural support to the culvert and eliminates the tendency for buoyancy. A headwall is generally considered to be an economically feasible end treatment for metal culverts that range in size from 6 to 10 feet (1800 to 3050 mm). Metal culverts smaller than 6 feet (1800 mm) generally do not need the structural support provided by a headwall. Headwalls should be used on thermoplastic culverts larger than 2 feet (600 mm). A typical headwall is shown on Standard Plan B-75.20 or in Figure 3-4.4. When the culvert is within the clear zone, the headwall design can be modified by adding safety bars. Standard Plan B-75.50

and B-75.60 provide the details for attaching safety bars. The designer is cautioned not to use safety bars on a culvert where debris may cause plugging of the culvert entrance even though the safety bars may have been designed to be removed for cleaning purposes. When the stream is known to carry debris, the designer should provide an alternate solution to safety bars, such as increasing the culvert size or providing guardrail protection around the culvert end. Headwalls for culverts larger than 10 feet (3000 mm)tend to lose cost-effectiveness due to the large volume of material and forming cost required for this type of end treatment. Instead, a slope collar is recommended for culverts larger than 10 feet (3000 mm). A slope collar is a reinforced concrete ring surrounding the exposed culvert end. The HQ Hydraulics Office generally performs the design of the slope during the structural analysis of the culvert.

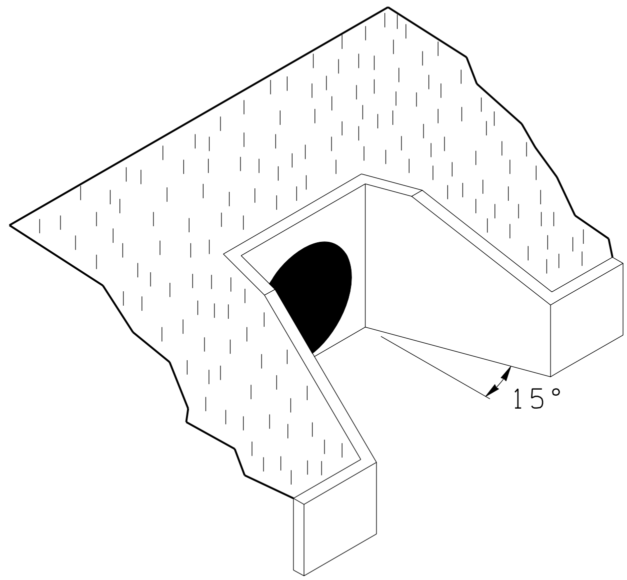


Headwall

Figure 3-4.4

3-4.5 Wingwalls and Aprons

Wingwalls and aprons are intended for use on reinforced concrete box culverts. Their purpose is to retain and protect the embankment, and provide a smooth transition between the culvert and the channel. Normally, they will consist of flared vertical wingwalls, a full or partial apron, and bottom and side cutoff walls (to prevent piping and undercutting). Wingwalls may also be modified for use on circular culverts in areas of severe scour problems. The apron will provide a smooth transition for the flow as it spreads to the natural channel. When a modified wingwall is used for circular pipe the designer must address the structural details involved in the joining of the circular pipe to the square portion of the wingwall. The HQ Hydraulics Office can assist in this design.



Modified Wingwall for Circular Pipe

Figure 3-4.5A

3-4.6 Improved Inlets

When the head losses in a culvert are critical, the designer may consider the use of a hydraulically improved inlet. These inlets provide side transitions as well as top and bottom transitions that have been carefully designed to maximize the culvert capacity with the minimum amount of headwater; however, the design and form construction costs can become quite high for hydraulically improved inlets. For this reason, their use is not encouraged in routine culvert design. It is usually less expensive to simply increase the culvert diameter by one or two sizes to achieve the same or greater benefit.

Certain circumstances may justify the use of an improved inlet. When complete replacement of the culvert is too costly, an existing inlet controlled culvert may have its capacity increased by an improved inlet. Improved inlets may also be justified in new construction when the length of the new culvert is very long (over 500 feet) and the headwater is controlled by inlet conditions. Improved inlets may have some slight advantage for barrel or outlet controlled culverts, but usually not enough to justify the additional construction costs. If the designer believes that a particular site might be suitable for an improved inlet, the HQ Hydraulics Office should be contacted. Also, HDS 5 contains a significant amount of information related to the design of improved inlets.

3-4.7 Energy Dissipators

When the outlet velocities of a culvert are excessive for the site conditions, the designer may consider the use of an energy dissipator. Energy dissipators can be quite simple or very complex, depending on the site conditions. Debris and maintenance problems should be considered when designing energy dissipators. Typical energy dissipators include:

1. Riprap Protected Outlets

   Hand placed riprap is frequently placed around the outlet end of culverts to protect against the erosive action of the water. The size of material at the outlet is dependant on the outlet velocity as noted in Figure 3-4.7.1. The limits of this protection would typically cover an area that would normally be vulnerable to scour holes. See Section 3-4.5 for details on wingwalls and aprons.

Outlet Velocity (ft/sec)	**Material**
6-10	Quarry Spalls
10-15	Light Loose Riprap
>15	Heavy Loose Riprap

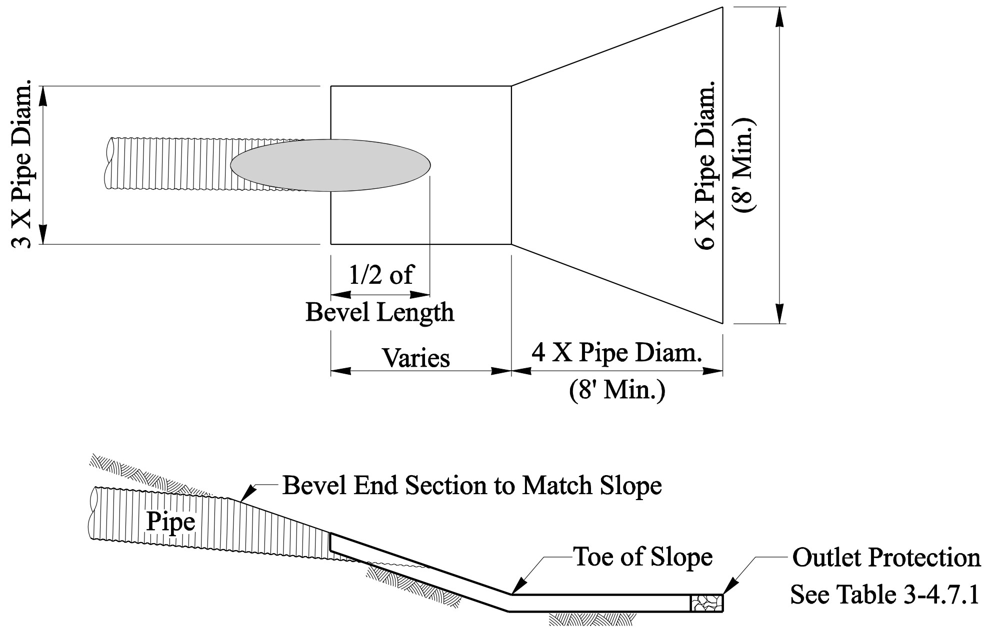
Designers should provide geotextile or filter material between any outlet material and the existing ground for soil stabilization, see section 4-6.3.2 for information..

Outlet Protection Material Size

Figure 3-4.7.1

2. Splash Pads

   Concrete splash pads are constructed in the field at the culvert outlet and used to prevent erosion. Splash pads should be a minimum of three times the diameter wide and four times the diameter long as shown in Figure 3-4.7.2.



Splash Pad Detail

Figure 3-4.7.2

3. Other Energy Dissipating Structures

   Other structures include impact basins and stilling basins/wells designed according to the *FHWA Hydaulic Engineering Circular No. 14*, "Hydraulic Design of Energy Dissipators for Culverts and Channels." These structures may consist of baffles, posts, or other means of creating roughness to dissipate excessive velocity. It is recommended that the HQ Hydraulics Office be consulted to assist in the design of these type of structures.

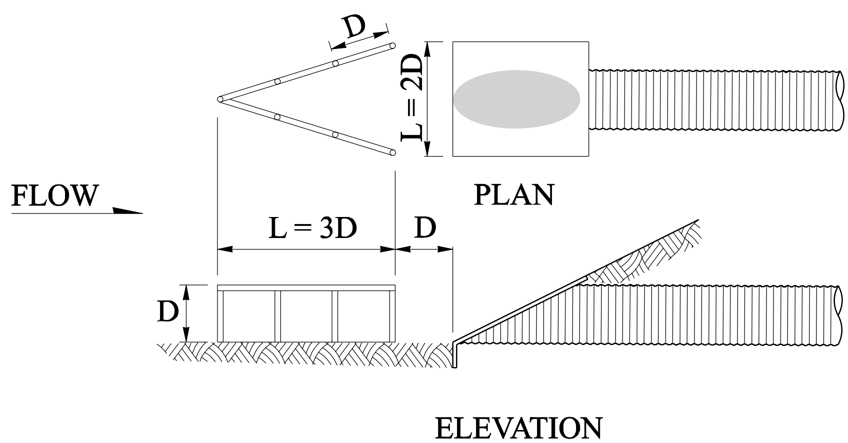
   Energy dissipators have a reputation for collecting debris on the baffles, so the designer should consider this possibility when choosing a dissipator design. In areas of high debris, the dissipator should be kept open and easily accessible to maintenance crews. Provisions should be made to allow water to overtop without causing excessive damage.

3-4.8 Culvert Debris

Debris problems can cause even an adequately designed culvert to experience hydraulic capacity problems. Debris may consist of anything from limbs and sticks or orchard pruning, to logs and trees. Silt, sand, gravel, and boulders can also be classified as debris. The culvert site is a natural place for these materials to settle and accumulate. No method is available for accurately predicting debris problems. Examining the maintenance history of each site is the most reliable way of determining potential problems. Sometimes, upsizing a culvert is necessary to enable it to more effectively pass debris. Upsizing may also allow a culvert to be more easily cleaned. Other methods for protecting culverts from debris problems are discussed below.

1. Debris Deflector (see Figure 3-4.8A)

   A debris deflector is V-shaped and designed to deflect heavy floating debris or boulders carried as a bed load in the moderate to high velocity streams usually found in mountains or steep terrain. It is located near the entrance of the culvert with the vortex of the V placed upstream. The horizontal spacing(s) of the vertical members should not exceed “D,” where D is the diameter or the smallest dimension of a non-circular culvert. The length should be 3D, the width 2D, and the height equal to D.

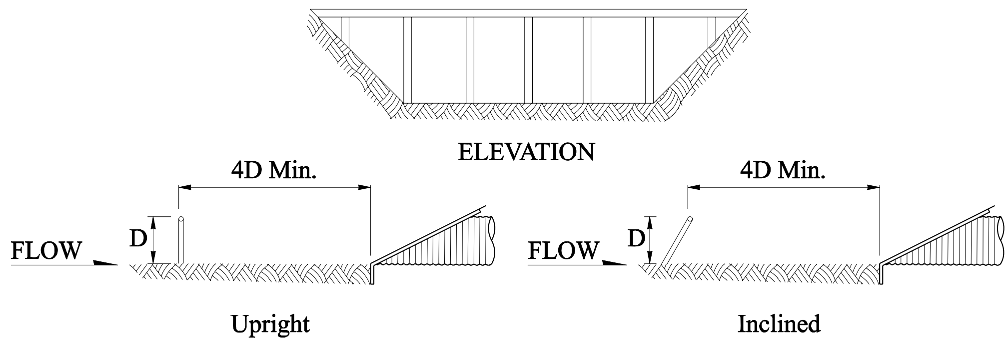


Debris Deflector

Figure 3-4.8A

2. Debris Rack

   The debris rack is placed across the channel of the stream. It should be constructed as shown in Figure 3-4.8 B with bars in an upright or inclined position. The bars should be spaced at one-half “D,” where D is the diameter or the smallest dimension of a non-circular culvert. Debris racks should be placed far enough away (approximately 4D) from the culvert entrance so that debris will not block the pipe itself. The debris will frequently become entangled in the rack making removal very difficult, so some thought must be given to placing the rack so it is accessible for necessary maintenance.

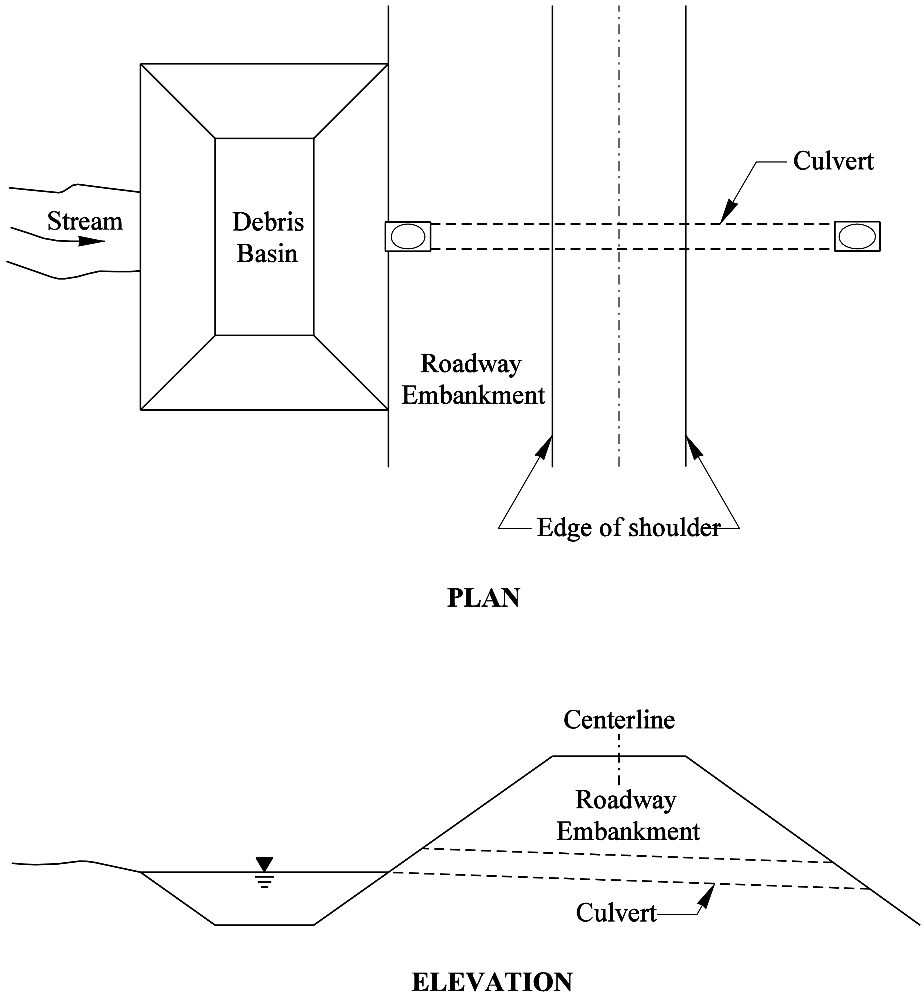


Debris Rack

Figure 3-4.8B

3. Debris Basin (see Figure 3-4.8C)

   A debris basin decreases the stream velocity immediately upstream of a culvert inlet, allowing transported sediments to settle out while providing a location for floating debris is collected. A debris basin is generally constructed by excavating a volume of material from below the culvert inlet, as shown in Figure 3-4.8C. The dimensions of a debris basin will vary, depending on the debris history of a site, the potential for future debris, and topographical constraints. It is recommended that the designer consult with the Region Hydraulics Section/Contact to determine the appropriate basin size for a given location. The periodic cleaning of a debris basin is made much easier by providing an access road for maintenance equipment. The cleaning interval needs to be determined from experience depending on the size of the basin provided and the frequency of storms. Debris basins can be quite effective when adequately sized, however, continual maintenance is required regardless of how large they are made.



Debris Basin

Figure 3-4.8C

4. Emergency Bypass Culvert

In situations where a culvert is placed with a very high fill (over 40 feet (12 m)) on a stream with significant debris problems, it may be necessary to install an emergency bypass culvert. A plugged culvert in a high embankment can impound a large amount of water. A sudden failure of a high fill is possible, which can result in danger to the downstream property owners and the roadway users. An emergency bypass culvert will limit the level of impounded water to a reasonable amount. The diameter of the bypass culvert should be about 50 percent to 60 percent of the diameter of the main culvert. If possible, the bypass culvert should be placed out of the main flow path so that the risk of it also plugging due to debris is minimized. The invert of the bypass culvert should be placed no more than 5 to 10 feet above the crown of the main culvert, or to the elevation of an acceptable ponding level.

5. Debris Spillway

   Regardless of the efforts made to divert debris from entering a culvert, failures do occur and water could eventually overflow the roadway causing a complete washout of the embankment. The designer should always provide an ample primary culvert system, and in problem areas (e.g., high debris, steep side slopes), some consideration should be given to a secondary or auxiliary drainage facility. This might consist of allowing water to flow over the roadway and spilling over a more stable portion of the embankment without causing complete loss of the embankment.

   These spillways should be constructed on, or lined with, material capable of resisting erosion. At some sites the overflow water may have to be directed several hundred feet from its origin in order to find a safe and natural place to spill the water without harm. These secondary drainage paths should always be kept in mind as they can sometimes be utilized at little or no additional cost.

3-5 Miscellaneous Culvert Design Considerations

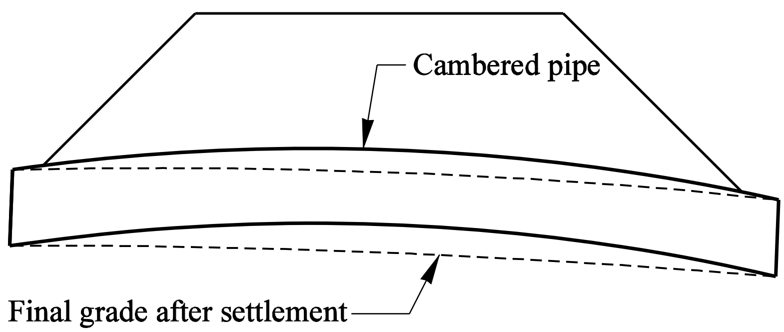
3-5.1 Multiple Culvert Openings

The use of multiple culvert openings is discouraged. It has been observed that this type of system rarely functions as designed because one or more barrels tend to plug with debris. This decreases the effective conveyance capability of the system and can result in failure. Multiple openings have generally been used in situations where very little vertical distance was available from the roadway to the culvert invert. In order to pass the design flow, several identical culverts would have to be placed side by side. New products, such as low profile arches and three-sided box structures, are now available that can provide significant horizontal span lengths while minimizing the necessary vertical rise. The HQ Hydraulics Office recommends low profile arches or three-sided box structures be considered for use in those type of situations. See Chapter 8 for more information related to arches and three-sided box structures. It is permissible to design a culvert system such that there is a primary conveyance culvert and an emergency bypass culvert placed at a different elevation and to one side of the main channel. This type of design can be effective in situations where significant amounts of woody debris are expected.

3-5.2 Camber

When a culvert is installed under moderate to high fills 30 to 60 feet (10 to 20 m) or higher, there may be greater settlement of the fill under the center of the roadway than at the sides. This occurs because at the culvert ends there is very little fill while at the centerline of the roadway, the maximum fill occurs. The difference in surcharge pressure at the elevation of the culvert may cause differential settlement of the fill and can create a low point in the culvert profile. In order to correct for the differential settlement, a culvert can be constructed with a slight upward curve in the profile, or camber, as shown in Figure 3-5.2.

The camber is built into the culvert during installation by laying the upstream half of the culvert on a flat grade and the downstream half on a steeper grade in order to obtain the design grade after settlement. The amount of expected camber can be determined by the HQ Materials Lab and must be shown on the appropriate profile sheet in the contract plans.



Camber Under High Fills

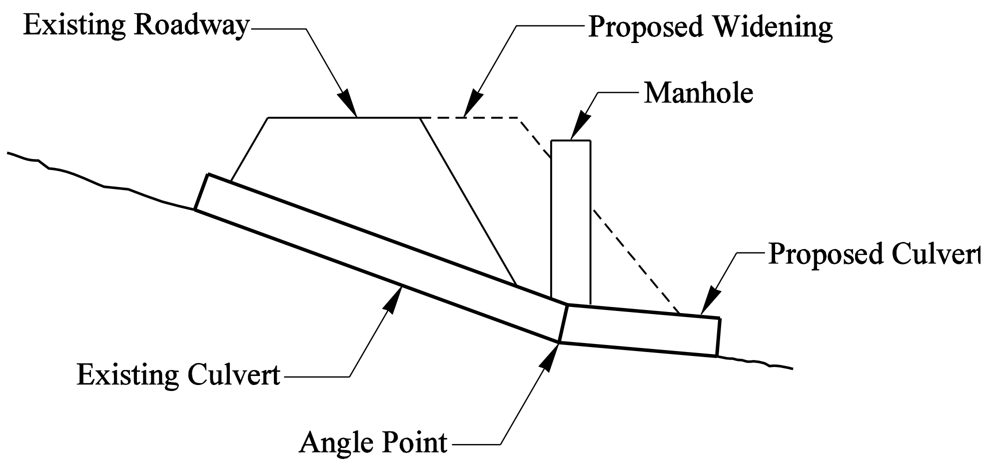
Figure 3-5.2

3-5.5 Angle Points

It is recommended that the slope of a culvert remain constant throughout the entire length of the culvert. This is generally easy to accomplish in new embankments. However, in situations where existing roadways are to be widened, it may be necessary to extend an existing culvert at a different slope. The location where the slope changes is referred to as the angle point.

If the new culvert is to be placed at a flatter grade than the existing culvert, it is recommended that a manhole be incorporated into the design at the angle point as shown in Figure 3-5.5A. The change in slope tends to create a location in the culvert that will catch debris and sediment. Providing access with a manhole will facilitate culvert maintenance.

If the new culvert is to be placed at a steeper slope than the existing culvert, the manhole can be eliminated at the angle point if debris and sedimentation have not historically been a concern at the existing culvert.



Culvert Angle Point

Figure 3-5.5

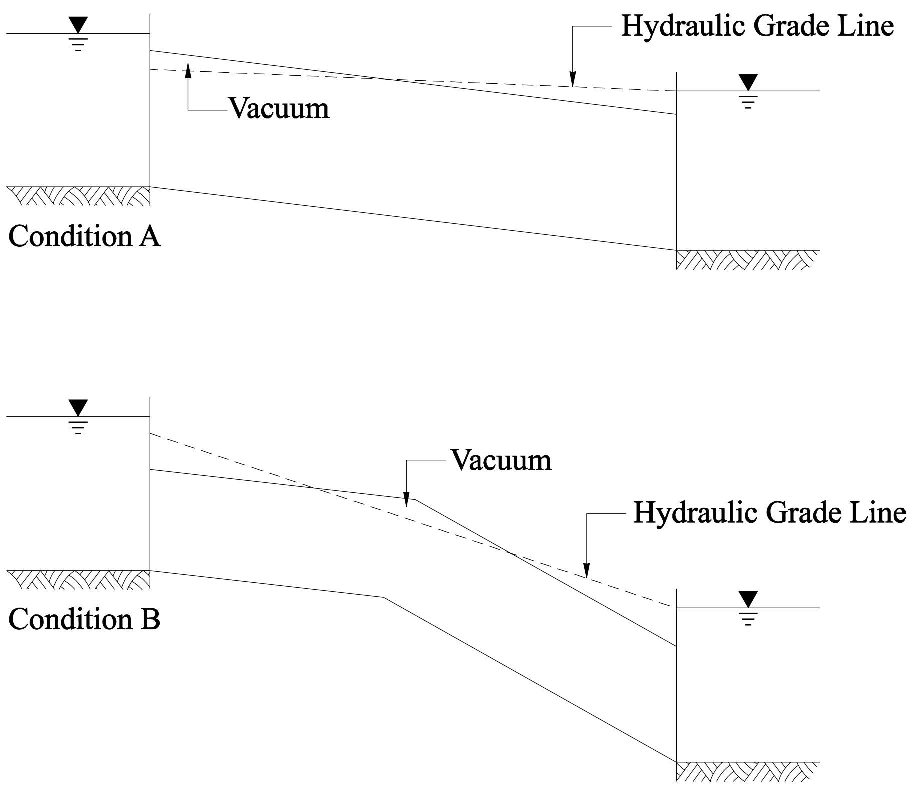
3-5.6 Upstream Ponding

The culvert design methodology presented in Section 3-3 makes the assumption that the headwater required to pass a given flow through a culvert will be allowed to fully develop upstream of the culvert inlet. Any peak flow attenuation provided by ponding upstream of the culvert inlet is ignored. In reality, if a large enough area upstream of the inlet is available for ponding, the design headwater will not occur and the culvert will not pass the full design flow. However, by ignoring any ponding effects, the culvert design is simplified and the final results are conservative. Most culverts should be designed using these assumptions.

If it is determined that the ponding characteristics of the area upstream of the inlet need to be taken into consideration, the calculation of flow becomes a flood routing problem which entails a more detailed study. Essentially, the area upstream of the inlet acts as a detention pond and the culvert acts as an outlet structure. The culvert can be designed utilizing flood routing concepts similar to designing a storm water detention pond, but that methodology is beyond the scope of this manual. Since the need for this type of culvert design is rare, the Region Hydraulics Engineer or HQ Hydraulics Office should be contacted for further assistance.

3-5.7 Misc Design Considerations - Siphons

A siphon is a water conveyance conduit, which operates at subatmospheric pressure over part of its length. Some culverts act as true siphons under certain headwater and tailwater conditions, but culverts are rarely designed with that intention. Figure 3-5.7.1 shows two culverts acting as true siphons. If a designer determines a siphon is appropriate for a project, the designer should contact the Region Hydraulics Office for further guidance.



Culverts Acting as Siphons

Figure 3-5.7.1