PDHonline Course C287 (4 PDH)

Culvert Design Basics

Instructor: George E. Thomas, PE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone & Fax: 703-988-0088
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George E. Thomas, PE

1.0 INTRODUCTION

The function of a culvert is to convey surface water across a highway, railroad, or other embankments. In addition to the hydraulic function, the culvert must carry construction, highway, railroad, or other traffic and earth loads. Culvert design involves both hydraulic and structural design considerations. The hydraulic aspects of culvert design are provided for in this course.

Culverts are available in a variety of sizes, shapes, and materials. These factors, along with several others, affect their capacity and overall performance. Sizes and shapes may vary from small circular pipes to extremely large arch sections that are sometimes used in place of bridges.

The most commonly used culvert shape is circular. However arches, boxes, and elliptical shapes are used, as well. Pipe arch, elliptical, and rectangular shapes are generally used in place of circular pipe where there is limited cover. Arch culverts have application in locations where less obstruction to a waterway is a desirable feature, and where foundations are adequate for structural support. Box culverts can be designed to pass large flows and to fit nearly any site condition. A box or rectangular culvert lends itself more readily than other shapes to low allowable headwater situations since the height may be decreased and the span increased to satisfy the location requirements.

The material selected for a culvert is dependent upon various factors, such as durability, structural strength, roughness, bedding condition, abrasion and corrosion resistance, and water tightness. The more common culvert materials used are concrete and steel (smooth and corrugated).

Another factor that significantly affects the performance of a culvert is its inlet configuration. The culvert inlet may consist of a culvert barrel projecting from the roadway fill or mitered to the embankment slope. Other inlets have headwalls, wingwalls, and apron slabs or standard end sections of concrete or metal.

A careful approach to culvert design is essential, both in new land development and retrofit situations, because culverts often significantly influence upstream and downstream flood risks, floodplain management and public safety. Culverts can be designed to provide beneficial upstream conditions and to avoid negative visual impact.

The information and references necessary to design culverts according to the procedure given in this course can be found in *Hydraulic Design of Highway Culverts,* Hydraulic Design Series No. 5 (FHWA 1985). Some of the charts and nomographs from that publication covering the more common requirements are given in this course.

1.1 Required Design Information

The hydraulic design of a culvert consists of an analysis of the required performance of the culvert to convey flow from one side of the roadway (or other kind of embankment, such as a railroad) to the other.

The engineer must select a design flood frequency, estimate the design discharge for that frequency, and set an allowable headwater elevation based on the selected design flood and headwater considerations. These criteria are typically dictated by local requirements although state and federal standards will apply to relevant highway projects. The culvert size and type can be selected after the design discharge, controlling design headwater, slope, tailwater, and allowable outlet velocity have been determined.

The design of a culvert will include the determination of the following:

- Impacts of various culvert sizes and dimensions on upstream and downstream flood risks, including the implications of embankment overtopping.
- How will the proposed culvert/embankment fit into the relevant major drainageway master plan, and are there multipurpose objectives that should be satisfied?
- Alignment, grade, and length of culvert.
- Size, type, end treatment, headwater, and outlet velocity.
- Amount and type of cover.
- Public safety issues, to include whether or not to include a safety/debris rack.
- Pipe material.
- Type of coating (if required).
- Need for fish passage measures, in specialized cases.
- Need for protective measures against abrasion and corrosion.
- Need for specially designed inlets or outlets.
- Structural and geotechnical considerations, which are beyond the scope of this course.

1.1.1 Discharge

The discharge used in culvert design is usually estimated on the basis of a preselected storm recurrence interval, and the culvert is designed to operate within acceptable limits of risk at that flow rate. The design recurrence interval should be based on the criteria set by local, state and federal authorities having jurisdiction.

1.1.2 Headwater

Culverts generally constrict the natural stream flow, which causes a rise in the upstream water surface. The elevation of this water surface is termed headwater elevation, and the total flow depth in the stream measured from the culvert inlet invert is termed headwater depth.

In selecting the design headwater elevation, the engineer should consider the following:

- Anticipated upstream and downstream flood risks, for a range of return frequency events.
- Damage to the culvert and the roadway.
- Traffic interruption.
- Hazard to human life and safety.
- Headwater/Culvert Depth (HW/D) ratio.
- Low point in the roadway grade line.
- Roadway elevation above the structure.
- Elevation at which water will flow to the next cross drainage.
- Relationship to stability of embankment that culvert passes through.

The headwater elevation for the design discharge should be consistent with the freeboard and overtopping criteria set by local, state and federal authorities having jurisdiction. The engineer should verify that the watershed divides are higher than the design headwater elevations. In flat terrain, drainage divides are often undefined or nonexistent and culverts should be located and designed for the least disruption of the existing flow distribution.

1.1.3 Tailwater

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

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

1.1.4 Outlet Velocity

The outlet velocity of a highway culvert is the velocity measured at the downstream end of the culvert, and it is usually higher than the maximum natural stream velocity. This higher velocity can cause streambed scour and bank erosion for a limited distance downstream from the culvert outlet. Permissible velocities at the outlet will depend upon streambed type, and the kind of energy dissipation (outlet protection) that is provided.

If the outlet velocity of a culvert is too high, it may be reduced by changing the barrel roughness. If this does not give a satisfactory reduction, it may be necessary to use some type of outlet protection or energy dissipation device. Most culverts require adequate outlet protection, and this is a frequently overlooked issue during design and construction.

Variations in shape and size of a culvert seldom have a significant effect on the outlet velocity. Slope and roughness of the culvert barrel are the governing factors affecting the outlet velocity.

2.0 CULVERT HYDRAULICS

2.1 Key Hydraulic Principles

For purposes of the following, it is assumed that the reader has a basic working knowledge of hydraulics and is familiar with the Manning's, continuity and energy equations.

$$Q = \frac{1.49}{n} AR^{2/3}S^{1/2}$$

$$Q = v_1 A_1 = v_2 A_2$$

$$\frac{v^2}{2g} + \frac{p}{\gamma} + z + \text{losses} = \text{constant}$$

2.1.1 Energy and Hydraulic Grade Lines

Figures 1 and 2 illustrate the energy grade line (EGL) and hydraulic grade line (HGL) and related terms.

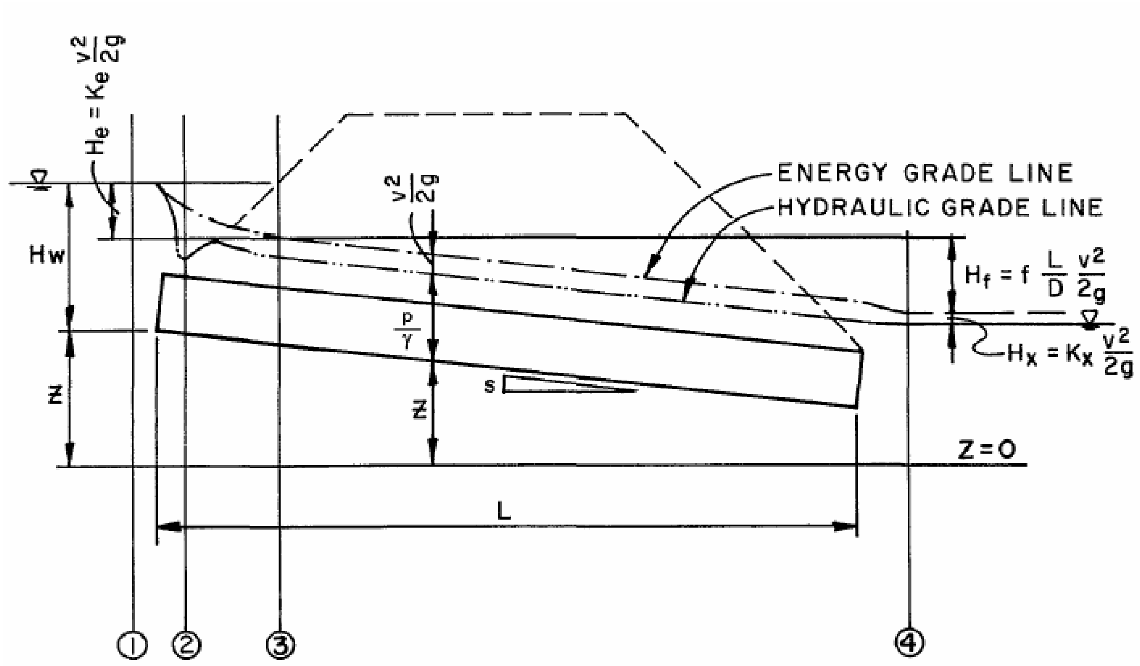


Figure 1—Definition of Terms for Closed Conduit Flow

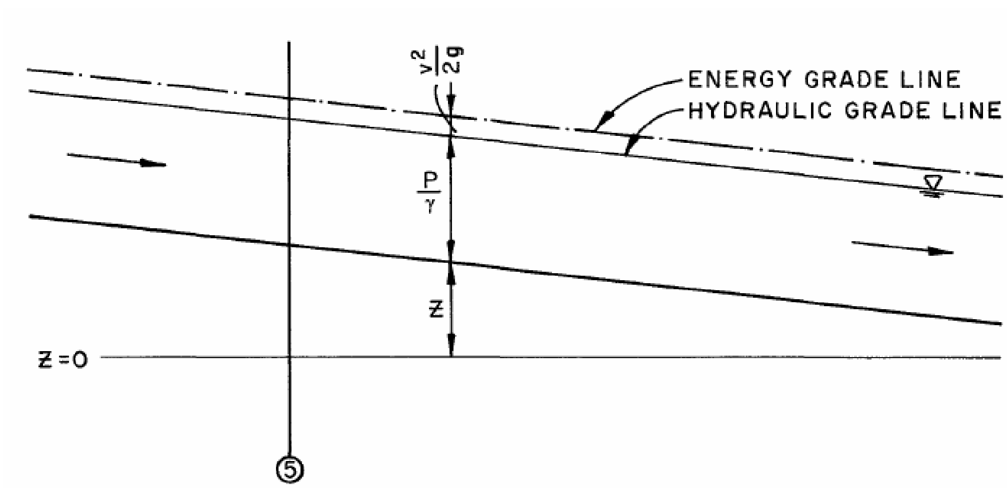


Figure 2—Definition of Terms for Open Channel Flow

The energy grade line, also known as the line of total head, is the sum of velocity head $v^2/2g$, the depth of flow or pressure head p/γ, and elevation above an arbitrary datum represented by the distance z. The energy grade line slopes downward in the direction of flow by an amount equal to the energy gradient *HL*/*L,* where *HL* equals the total energy loss over the distance *L.*

The hydraulic grade line, also known as the line of piezometric head, is the sum of the elevation z and the depth of flow or pressure head p/γ.

For open channel flow, the term p/γ is equivalent to the depth of flow and the hydraulic grade line is the same as the water surface. For pressure flow in conduits, p/γ is the pressure head and the hydraulic grade line falls above the top of the conduit as long as the pressure relative to atmospheric pressure is positive.

Approaching the entrance to a culvert as at Point 1 of Figure 1, the flow is essentially uniform and the hydraulic grade line and energy grade lines are almost the same. As water enters the culvert at the inlet, the flow is first contracted and then expanded by the inlet geometry causing a loss of energy at Point 2. As normal turbulent velocity distribution is reestablished downstream of the entrance at Point 3, a loss of energy is incurred through friction or form resistance. In short culverts, the entrance losses are likely to be high relative to the friction loss. At the exit, Point 4, an additional loss is incurred through turbulence as the flow expands and is retarded by the water in the downstream channel. At Point 5 of Figure 2, open channel flow is established and the hydraulic grade line is the same as the water surface.

There are two major types of flow conditions in culverts: (1) inlet control and (2) outlet control. For each type of control, a different combination of factors is used to determine the hydraulic capacity of a culvert. The determination of actual flow conditions can be difficult; therefore, the engineer must check for both types of control and design for the most adverse condition.

2.1.2 Inlet Control

A culvert operates with inlet control when the flow capacity is controlled at the entrance by these factors:

- Depth of headwater
- Cross-sectional area
- Inlet edge configuration
- Barrel shape

When a culvert operates under inlet control, headwater depth and the inlet edge configuration determine the culvert capacity with the culvert barrel usually flowing only partially full.

Inlet control for culverts may occur in two ways. The least common occurs when the headwater depth is not sufficient to submerge the top of the culvert and the culvert invert slope is supercritical as shown in Figure 3.

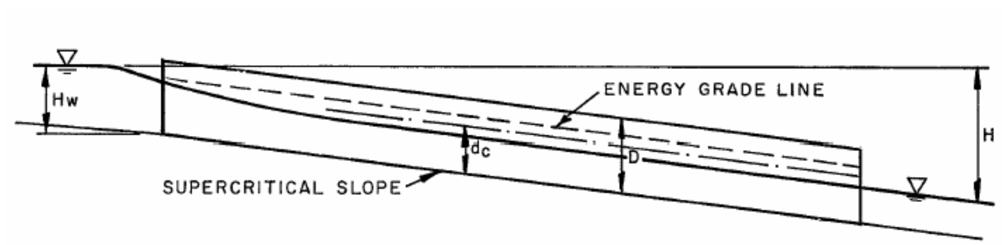


Figure 3, Inlet Control, Unsubmerged Inlet

The most common occurrence of inlet control is when the headwater submerges the top of the culvert (Figure 4), and the pipe does not flow full. A culvert flowing under inlet control is defined as a hydraulically short culvert.

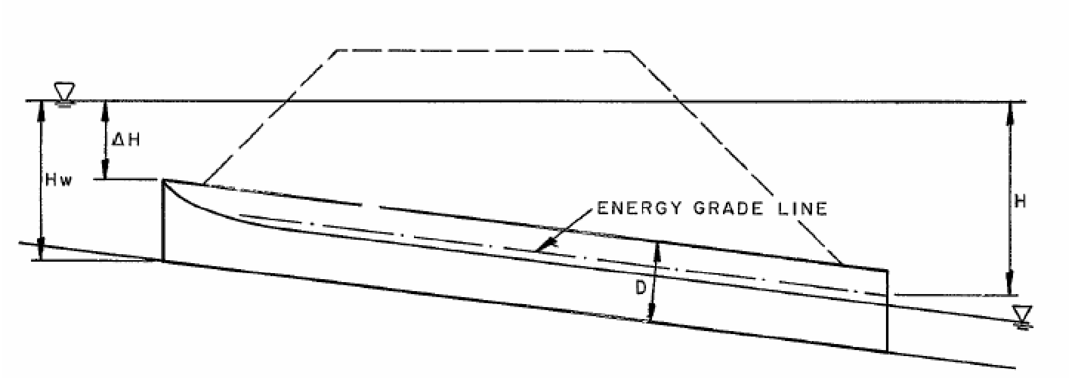


Figure 4, Inlet Control, Submerged Inlet

For a culvert operating with inlet control, the roughness, slope, and length of the culvert barrel and outlet conditions (including tailwater) are not factors in determining the culverts hydraulic performance.

2.1.3 Outlet Control

If the headwater is high enough, the culvert slope sufficiently flat, and the culvert sufficiently long, the control will shift to the outlet. In outlet control, the discharge is a function of the inlet losses, the headwater depth, the culvert roughness, the culvert length, the barrel diameter, the culvert slope, and sometimes the tailwater elevation.

In outlet control, culvert hydraulic performance is determined by these factors:

- Depth of headwater
- Cross-sectional area
- Inlet edge configuration
- Culvert shape
- Barrel slope
- Barrel length
- Barrel roughness
- Depth of tailwater

Outlet control will exist under two conditions. The first and least common is that where the headwater is insufficient to submerge the top of the culvert, and the culvert slope is subcritical (Figure 5). The most common condition exists when the culvert is flowing full (Figure 6). A culvert flowing under outlet control is defined as a hydraulically long culvert.

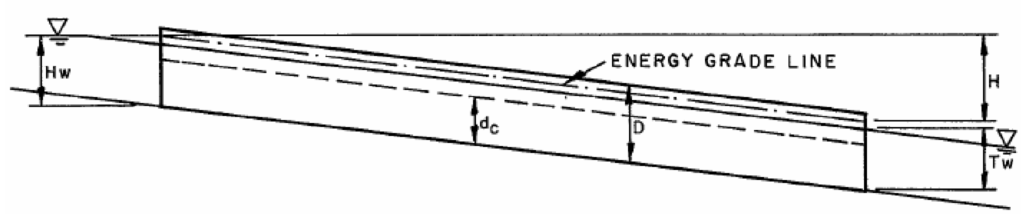


Figure 5, Outlet Control, Partially Full Conduit

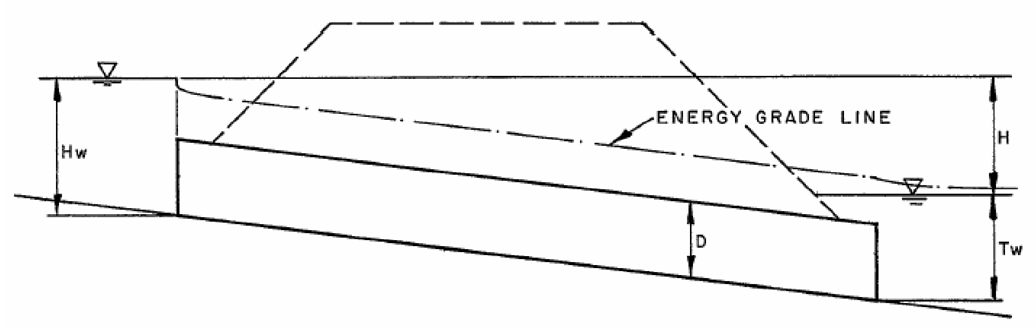


Figure 6, Outlet Control, Full Conduit

Culverts operating under outlet control may flow full or partly full depending on various combinations of the above factors. In outlet control, factors that may affect performance appreciably for a given culvert size and headwater are barrel length and roughness, and tailwater depth.

2.2 Energy Losses

In short conduits, such as culverts, the form losses due to the entrance can be as important as the friction losses through the conduit. The losses that must be evaluated to determine the carrying capacity of the culverts consist of inlet (or entrance) losses, friction losses and outlet (or exit) losses.

2.2.1 Inlet Losses

For inlet losses, the governing equations are:

$$Q = CA\sqrt{2gH}$$

$$H_e = K_e \frac{v^2}{2g}$$

where:

Q = flow rate or discharge (cfs)
C = contraction coefficient (dimensionless) A = cross-sectional area (ft^2)
g = acceleration due to gravity, 32.2 (ft/sec^2) H = total head (ft)
He = head loss at entrance (ft)
Ke = entrance loss coefficient
v = average velocity (ft/sec)

2.2.2 Outlet Losses

For outlet losses, the governing equations are related to the difference in velocity head between the pipe flow and that in the downstream channel at the end of the pipe.

2.2.3 Friction Losses

Friction head loss for turbulent flow in pipes flowing full can be determined from the Darcy-

Weisbach equation.

$$H_f = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right)$$

where:

Hf = frictional head loss (ft)
f = friction factor (dimensionless)
L = length of culvert (ft)
D = Diameter of culvert (ft)
v = average velocity (ft/sec)
g = acceleration due to gravity, 32.2 (ft/sec^2)

The friction factor has been determined empirically and is dependent on relative roughness, velocity, and barrel diameter. Moody diagrams can be used to determine the friction factor. The friction losses for culverts are often expressed in terms of Manning's *n,* which is independent of the size of pipe and depth of flow. Another common formula for pipe flow is the Hazen-Williams formula. Standard hydraulic texts should be consulted for limitations of these formulas

3.0 CULVERT SIZING AND DESIGN

FHWA (1985) Hydraulic Design Series No. 5, *Hydraulic Design of Highway Culvert*s, provides valuable guidance for the design and selection of drainage culverts. This explains inlet and outlet control and the procedure for designing culverts. Culvert design basically involves the trial and error method:

1. Select a culvert shape, type, and size with a particular inlet end treatment.
2. Determine a headwater depth from the relevant charts for both inlet and outlet control for the design discharge, the grade and length of culvert, and the depth of water at the outlet (tailwater).
3. Compare the largest depth of headwater (as determined from either inlet or outlet control) to the design criteria. If the design criteria are not met, continue trying other culvert configurations until one or more configurations are found to satisfy the design parameters.
4. Estimate the culvert outlet velocity and determine if there is a need for any special features such as energy dissipators, riprap protection, fish passage, trash/safety rack, etc.

3.1 Description of Capacity Charts

Figure 7 is an example of a capacity chart used to determine culvert size. Refer to this figure in the following discussion.

Each chart contains a series of curves, which show the discharge capacity per barrel in cfs for each of several sizes of similar culvert types for various headwater depths in feet above the invert of the culvert at the inlet. The invert of the culvert is defined as the low point of its cross section.

Each size is described by two lines, one solid and one dashed. The numbers associated with each line are the ratio of the length, *L,* in feet, to 100 times the slope, *s,* in feet per foot (ft/ft) (100*s*). The dashed lines represent the maximum *L*/(100*s*) ratio for which the curves may be used without modification. The solid line represents the division between outlet and inlet control. For values of $L/(100s)$ less than that shown on the solid line, the culvert is operating under inlet control and the headwater depth is determined from the $L/(100s)$ value given on the solid line. The solid-line inlet-control curves are plotted from model test data. The dashed-line outlet-control curves were computed for culverts of various lengths with relatively flat slopes. Free outfall at the outlet was assumed; therefore, tailwater depth is assumed not to influence the culvert performance.

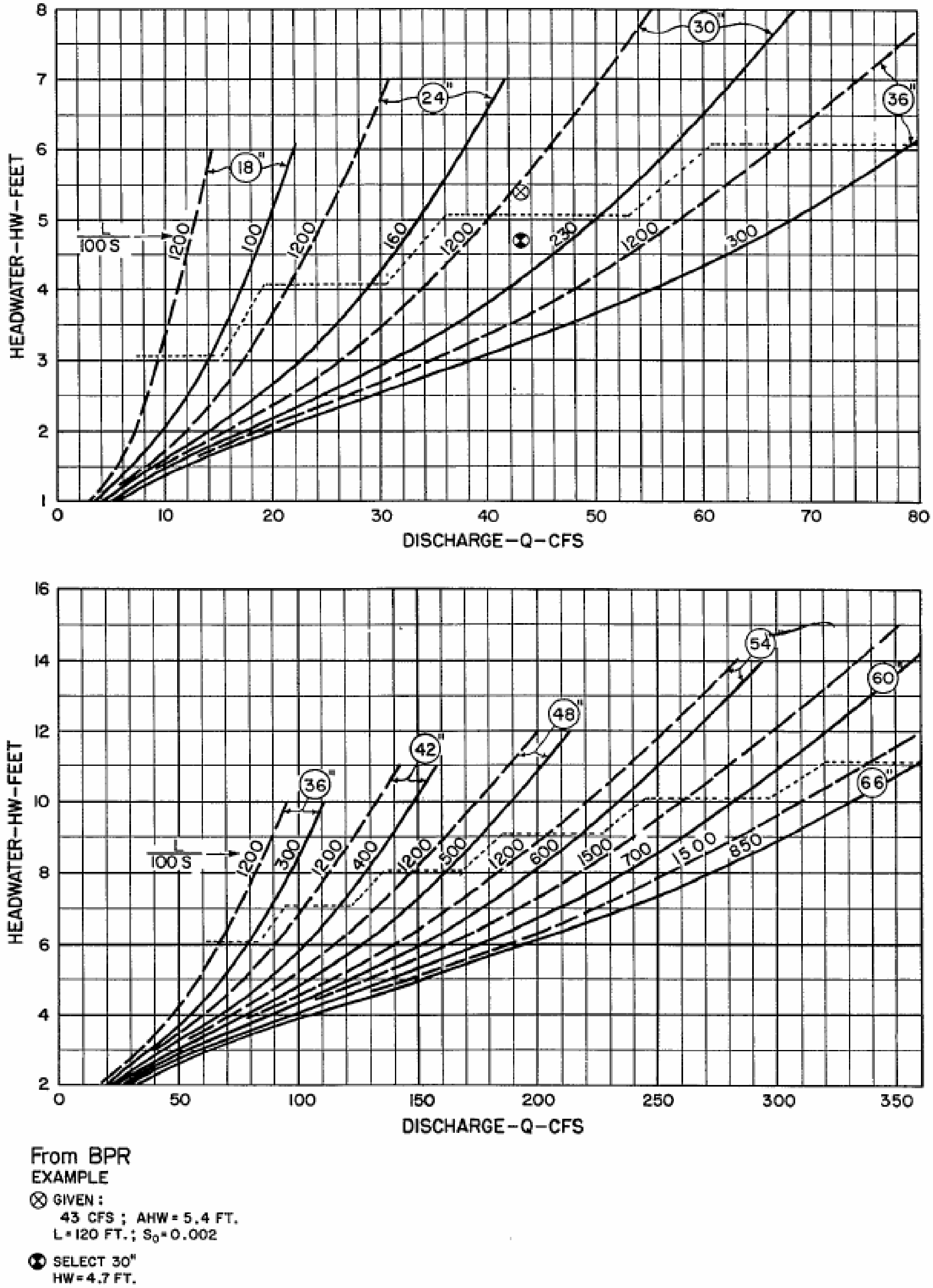


Figure 7, Culvert Capacity Chart Example

For culverts flowing under outlet control, the head loss at the entrance was computed using the loss coefficients previously given, and the hydraulic roughness of the various materials used in culvert construction was taken into account in computing resistance loss for full or part-full flow. The Manning's *n* values used for each culvert type ranged from 0.012 to 0.032.

Except for large pipe sizes, headwater depths on the charts extend to 3 times the culvert height. Pipe arches and oval pipe show headwater up to 2.5 times their height since they are used in low fills. The dotted line, stepped across the charts, shows headwater depths of about twice the barrel height and indicates the upper limit of restricted use of the charts. Above this line the headwater elevation should be checked with the nomographs, which are described in Section 3.3.

The headwater depth given by the charts is actually the difference in elevation between the culvert invert at the entrance and the total head; that is, depth plus velocity head for flow in the approach channel. In most cases, the water surface upstream from the inlet is so close to this same level that the chart determination may be used as headwater depth for practical design purposes. Where the approach velocity is in excess of 3.0 ft/sec, the velocity head must be subtracted from the curve determination of headwater to obtain the actual headwater depth.

3.2 Use of Capacity Charts

1. The procedure for sizing the culvert is summarized below. Data can be tabulated in the Design Computation Form shown in Figure 8.

2. List design data: *Q* = flow or discharge rate (cfs), *L* = length of culvert (ft), allowable *Hw* = headwater depth (ft), *s* = slope of culvert (ft/ft), type of culvert barrel, and entrance.
3. Compute *L*/(100*s*).

4. Enter the appropriate capacity chart in Section 11.0 with the design discharge, *Q*.

5. Find the *L*/(100*s*) value for the smallest pipe that will pass the design discharge. If this value is above the dotted line in Figure 7, use the nomographs to check headwater conditions.

6. If *L*/(100*s*) is less than the value of *L*/(100*s*) given for the solid line, then the value of *Hw* is the value obtained from the solid line curve. If *L*/(100*s*) is larger than the value for the dashed outlet control curve, then special measures must be taken, and the reader is referred to *Hydraulic Design of Highway Culverts* (FHWA 1985).

7. Check the *Hw* value obtained from the charts with the allowable *Hw.* If the indicated *Hw* is greater than the allowable *Hw,* then try the *Hw* elevation from the next largest pipe size.

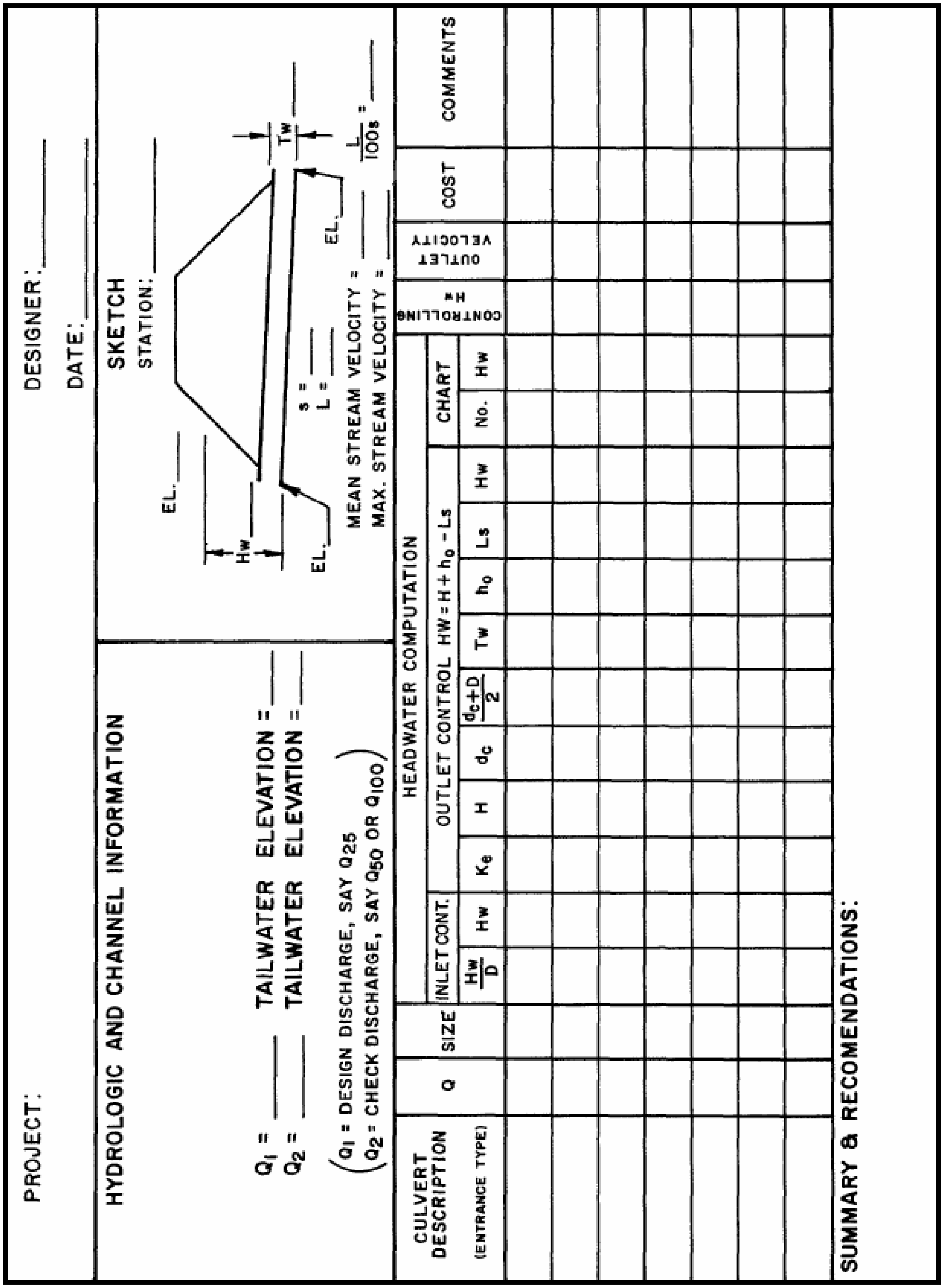


Figure 8, Design Computation Sheet for Culverts

3.3 Use of Nomographs

Examples of two nomographs for designing culverts are presented in Figures 9 and 10. The use of these nomographs is limited to cases where tailwater depth is higher than the critical depth in the culvert. The advantage of the capacity charts over the nomographs is that the capacity charts are direct where the nomographs are trial and error. The capacity charts can be used only when the flow passes through critical depth at the outlet. When the critical depth at the outlet is less than the tailwater depth, the nomographs must be used; however, both give the same results where either of the two methods may be used. The procedure for design requires the use of both nomographs and is as follows (refer to Figures 9 and10):

1. List design data: *Q* (cfs), *L* (ft), invert elevations in and out (ft), allowable *Hw* (ft), mean and maximum flood velocities in natural stream (ft/sec), culvert type and entrance type for first selection.

2. Determine a trial size by assuming a maximum average velocity based on channel considerations to compute the area, $A = Q/V$.

3. Find *Hw* for trial size culvert for inlet control and outlet control. For inlet control, Figure -9, connect a straight line through *D* and *Q* to scale (1) of the *Hw*/*D* scales and project horizontally to the proper scale, compute *Hw* and, if too large or too small, try another size before computing *Hw* for outlet control.

4. Next, compute the *Hw* for outlet control, Figure 10. Enter the graph with the length, the entrance coefficient for the entrance type, and the trial size. Connect the length scale and the culvert size scale with a straight line, pivot on the turning line, and draw a straight line from the design discharge on the discharge scale through the turning point to the head scale (head loss, *H).* Compute *Hw* from the equation:

$$Hw=H+h_o-Ls$$

where:

Hw = headwater depth (ft)
H = head loss (ft)
ho = tailwater depth or elevation at the outlet of a depth equivalent to the location of the hydraulic grade line (ft)
L = length of culvert (ft) *s* =
slope of culvert (ft/ft)

For *Tw* greater than or equal to the top of the culvert, *ho* = *Tw,* and for *Tw* less than the top of the culvert:

where:

dc = critical depth (ft) *Tw* = tailwater depth (ft)

If *Tw* is less than *dc,* the nomographs cannot be used, see *Hydraulic Design of Highway Culverts* (FHWA 1985) for critical depth charts.

5. Compare the computed headwaters and use the higher *Hw* to determine if the culvert is under inlet or outlet control. If outlet control governs and the *Hw* is unacceptable, select a larger trial size and find another *Hw* with the outlet control nomographs. Since the smaller size of

culvert had been selected for allowable *Hw* by the inlet control nomographs, the inlet control for the larger pipe need not be checked.

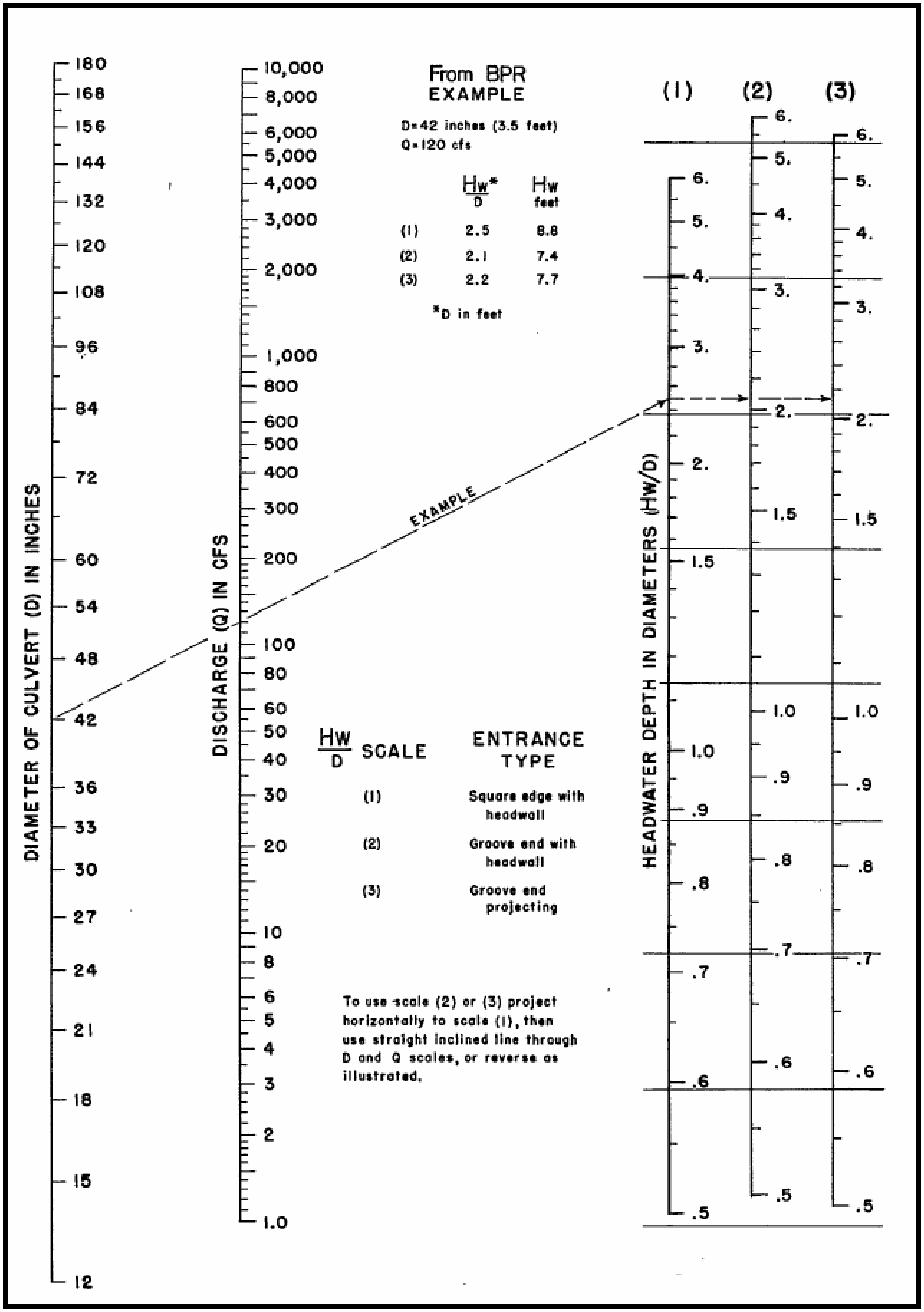


Figure 9, Inlet Control Nomograph Example

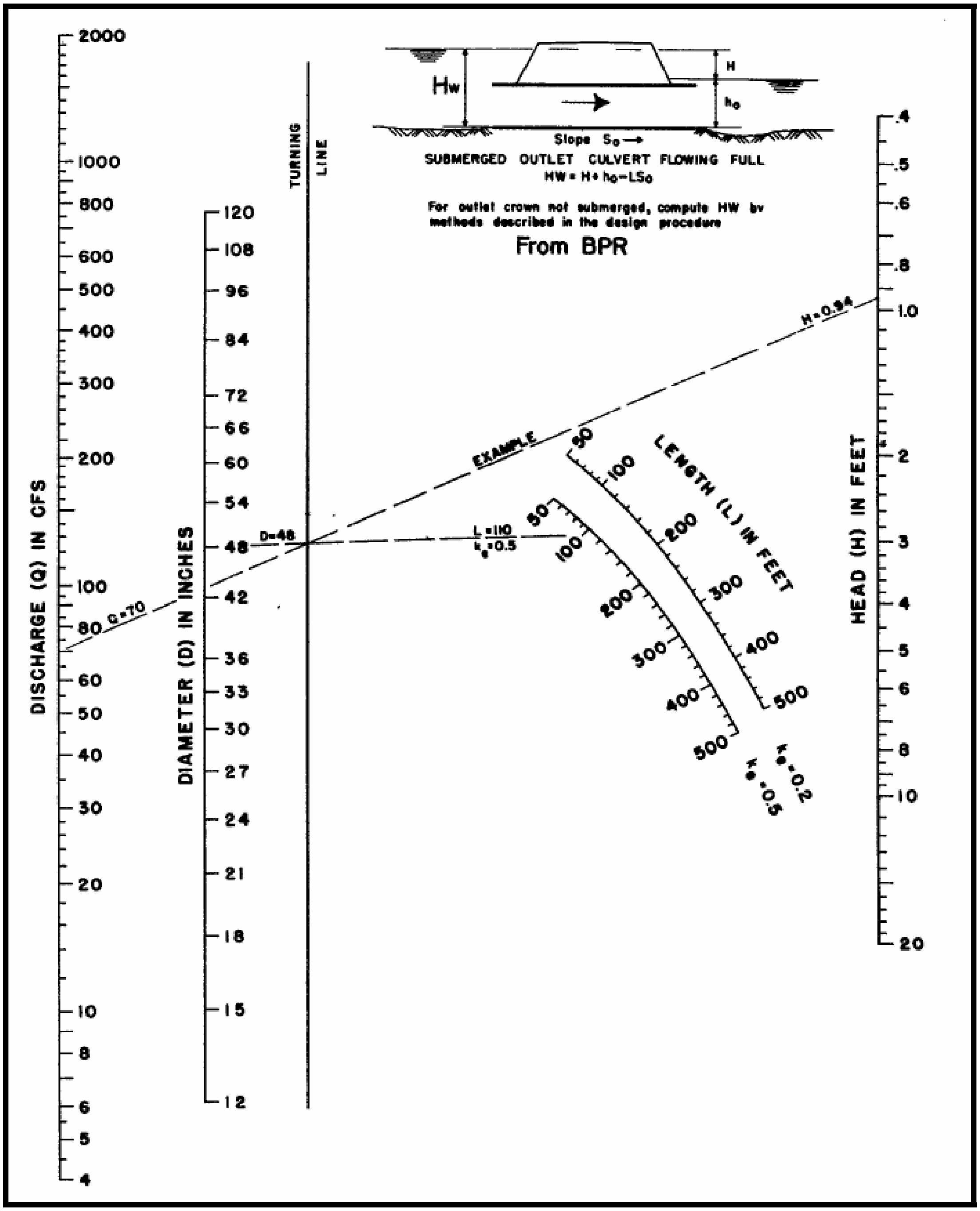


Figure 10, Outlet Control Nomograph Example

3.4 Computer Applications, Including Design Spreadsheet

Although the nomographs discussed in this course are still used, engineers are increasingly designing culverts using computer applications. Among these applications are the FHWA's HY8 Culvert Analysis

(Ginsberg 1987) and numerous proprietary applications.

3.5 Design Considerations

Due to problems arising from topography and other considerations, the actual design of a culvert installation is more difficult than the simple process of sizing culverts. The information given in this course in the procedure for design is only a guide since the problems encountered are too varied and too numerous to be generalized. However, the actual process presented should be followed to insure that something is not overlooked. Several combinations of entrance types, invert elevations, and pipe diameters should be tried to determine the most economic design that will meet the conditions imposed by topography and engineering.

3.5.1 Design Computation Forms

The use of design computation forms is a convenient method to use to obtain consistent designs and promote cost-effectiveness. An example of such a form is Figure 8.

3.5.2 Invert Elevations

After determining the allowable headwater elevation, the tailwater elevation, and the approximate length, invert elevations must be assumed. Scour is not likely in an artificial channel such as a roadside ditch or a major drainage channel when the culvert has the same slope as the channel. To reduce the chance of failure due to scour, invert elevations corresponding to the natural grade should be used as a first trial.

For natural channels, the flow conditions in the channel upstream from the culvert should be investigated to determine if scour will occur.

3.5.3 Culvert Diameter

After the invert elevations have been assumed and using the design computation forms (e.g., Figure 8), the capacity charts (e.g., Figure 7), and the nomographs, the diameter of pipe that will meet the headwater requirements should be determined. Since small diameter pipes are often plugged by sediment and debris, it is recommended that pipe smaller than 18 inches not be used for any drainage. Since the pipe roughness influences the culvert diameter, both concrete and corrugated metal pipe should be considered in design, if both will satisfy the headwater requirements.

3.5.4 Limited Headwater

If there is insufficient headwater elevation to obtain the required discharge, it is necessary to oversize the culvert barrel, lower the inlet invert, use an irregular cross section, or use any combination of the preceding.

If the inlet invert is lowered, special consideration must be given to scour. The use of gabions or concrete drop structures, riprap, and headwalls with apron and toe walls should be investigated and compared to obtain the proper design.

3.6 Culvert Outlet

The outlet velocity must be checked to determine if significant scour will occur downstream during a major storm. Do not short-change outlet protection to economize during design and construction because downstream channel degradation can be significant and the culvert outlet can be undermined.

3.7 Minimum Slope

To minimize sediment deposition in the culvert, the culvert slope must be equal to or greater than the slope required to maintain a minimum velocity set by the authority having jurisdiction. The slope should be checked for each design, and if the proper minimum velocity is not obtained, the pipe diameter may be decreased, the slope steepened, a smoother pipe used, or a combination of these may be used.

4.0 CULVERT INLETS

A fact often overlooked is that a culvert cannot carry any more water than can enter the inlet. Frequently culverts and open channels are carefully designed with full consideration given to slope, cross section, and hydraulic roughness, but with little or no regard to the inlet limitations. Culvert designs using uniform flow equations rarely can carry their design capacity due to limitations imposed by the inlet.

The design of a culvert, including the inlet and the outlet, requires a balance between cost, hydraulic efficiency, purpose, and topography at the proposed culvert site. Where there is sufficient allowable headwater depth, a choice of inlets may not be critical, but where headwater depth is limited, where erosion is a problem, or where sedimentation is likely, a more efficient inlet may be required to obtain the necessary discharge for the culvert.

The primary purpose of a culvert is to convey flows. A culvert may also be used to restrict flow, that is, to discharge a controlled amount of water while the area upstream from the culvert is used for detention storage to reduce a storm runoff peak. For this case, an inefficient inlet may be the most desirable choice.

The inlet types described in this chapter may be selected to fulfill either of the above requirements depending on the topography or conditions imposed by the designer. The entrance coefficient, *Ke,* is a measure of the hydraulic efficiency at the inlet, with lower valves indicating greater efficiency. Inlet coefficients recommended for use are given in Table 1.

Table 1, Inlet Coefficients For Outlet Control

Type of Entrance	Entrance Coefficient, *Ke*
1. Pipe entrance with headwall	
Grooved edge	0.20
Rounded edge (0.15*D* radius)	0.15
Rounded edge (0.25*D* radius)	0.10
Square edge (cut concrete and CMP)	0.40
2. Pipe entrance with headwall & 45° wingwall	
Grooved edge	0.20
Square edge	0.35
3. Headwall with parallel wingwalls spaced 1 .25*D* apart	
Grooved edge	0.30

Square edge	0.40
4. Special inlets—see Section 4.3	
5. Projecting Entrance	
Grooved edge	0.25
Square edge	0.50
Sharp edge, thin wall	0.90

4.1 Projecting Inlets

Projecting inlets vary greatly in hydraulic efficiency and adaptability to requirements with the type of pipe material used. Figure 11 illustrates this type of inlet.

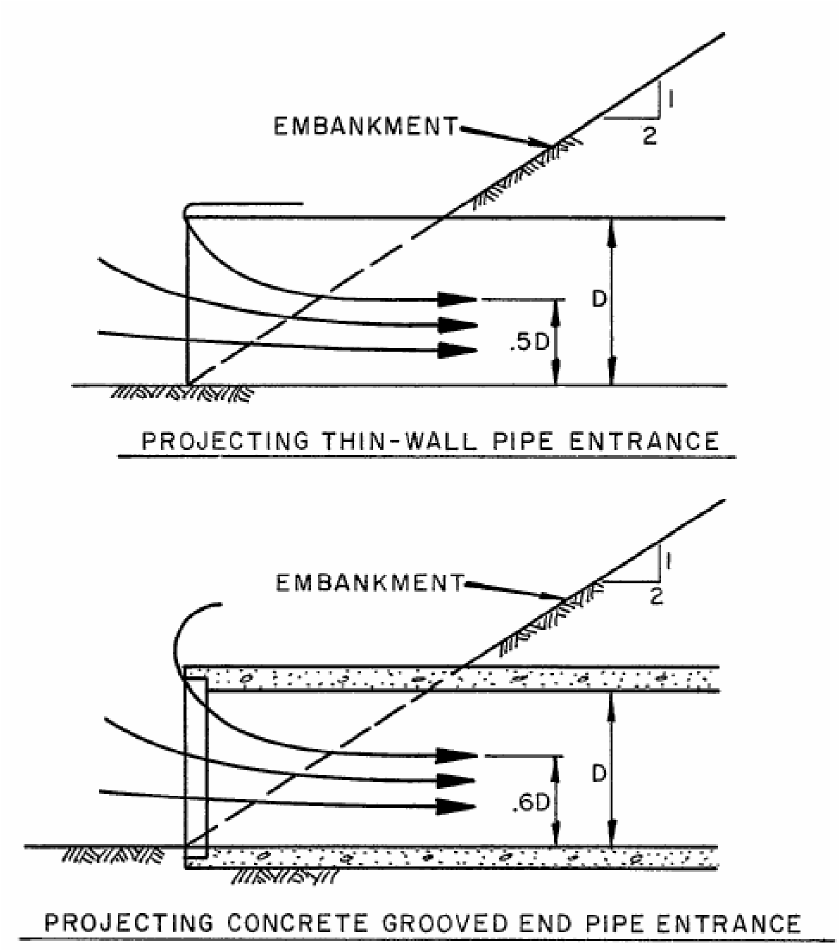


Figure 11, Common Projecting Culvert Inlets

The primary advantage of projecting inlets is relatively low cost. Because projecting inlets are susceptible to damage due to maintenance of embankment and roadways and due to accidents, the adaptability of this type of entrance to meet the engineering and topographical demands varies with the type of material used.

Corrugated metal pipe projecting inlets have limitations which include low efficiency, damage which may result from maintenance of the channel and the area adjacent to the inlet, and restrictions on the ability of maintenance crews to work around the inlet. The hydraulic efficiency of concrete-grooved or bell-end pipe is good and, therefore, the only restriction placed on the use of concrete pipe for projecting inlets is the requirement for maintenance of the channel and the embankment surrounding the inlet. Where equipment will be used to maintain the embankment around the inlet, it is not recommended that a projecting inlet of any type be used.

4.1.1 Corrugated Metal Pipe

A projecting entrance of corrugated metal pipe is equivalent to a sharp-edged entrance with a thin wall and has an entrance coefficient of about 0.9.

4.1.2 Concrete Pipe

Bell-and-spigot concrete pipe or tongue-and-groove concrete pipe with the bell end or grooved end used as the inlet section are quite efficient hydraulically, having an entrance coefficient of about 0.25. For concrete pipe that has been cut, the entrance is square edged, and the entrance coefficient is about 0.5.

4.2 Inlets with Headwalls

Headwalls may be used for a variety of reasons, including increasing the efficiency of the inlet, providing embankment stability, and providing embankment protection against erosion. The relative efficiency of the inlet varies with the pipe material used. Figure 12 illustrates a headwall with wingwalls.

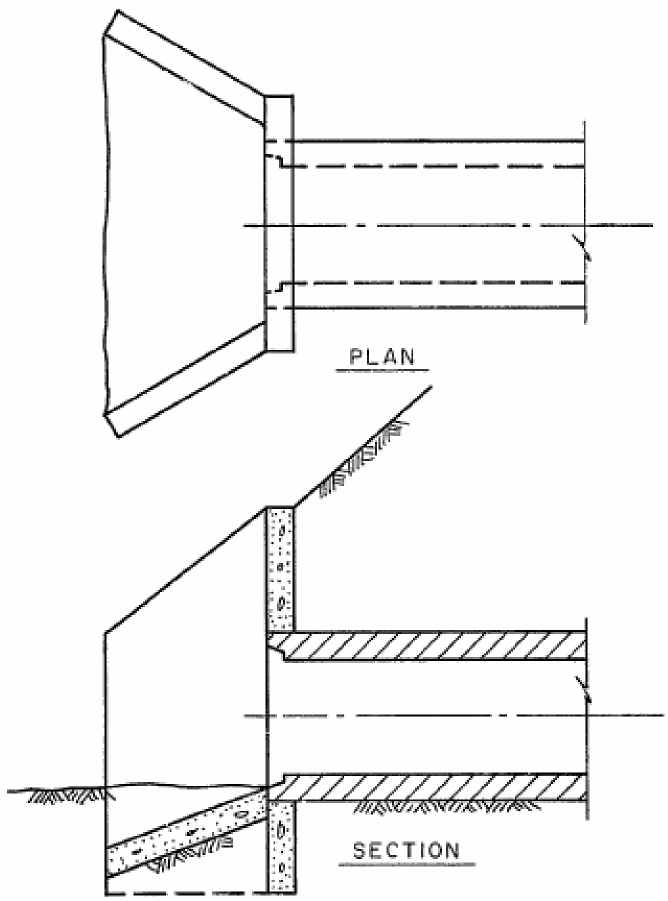


Figure 12, Inlet with Headwall and Wingwalls

4.2.1 Corrugated Metal Pipe

Corrugated metal pipe in a headwall is essentially a square-edged entrance with an entrance coefficient of about 0.4. The entrance losses may be reduced by rounding the entrance. The entrance coefficient may be reduced to 0.15 for a rounded edge with a radius equal to 0.15 times the culvert diameter, and to 0.10 for rounded edge with a radius equal to 0.25 times the diameter of the culvert.

4.2.2 Concrete Pipe

For tongue-and-groove or bell-end concrete pipe, little increase in hydraulic efficiency is realized by adding a headwall. The primary reason for using headwalls is for embankment protection and for ease of maintenance. The entrance coefficient is equal to about 0.2 for grooved and bell-end pipe, and equal to 0.4 for cut concrete pipe.

4.2.3 Wingwalls

Wingwalls are used where the side slopes of the channel adjacent to the entrance are unstable and where the culvert is skewed to the normal channel flow. Little increase in hydraulic efficiency is realized with the use of wingwalls, regardless of the pipe material used and, therefore, the use should be justified for reasons other than an increase in hydraulic efficiency. Figure 13 illustrates several cases where wingwalls are used. For parallel wingwalls, the minimum distance between wingwalls should be at least 1.25 times the diameter of the culvert pipe.

4.2.4 Aprons

If high headwater depths are to be encountered, or if the approach velocity of the channel will cause scour, a short channel apron should be provided at the toe of the headwall. This apron should extend at least one pipe diameter upstream from the entrance, and the top of the apron should not protrude above the normal streambed elevation.

Culverts with wingwalls should be designed with a concrete apron extending between the walls. Aprons must be reinforced to control cracking. As illustrated in Figure 13, the actual configuration of the wingwalls varies according to the direction of flow and will also vary according to the topographical requirement placed upon them.

For conditions where scour may be a problem due to high approach velocities and special soil conditions, such as alluvial soils, a toe wall is often desirable for apron construction.

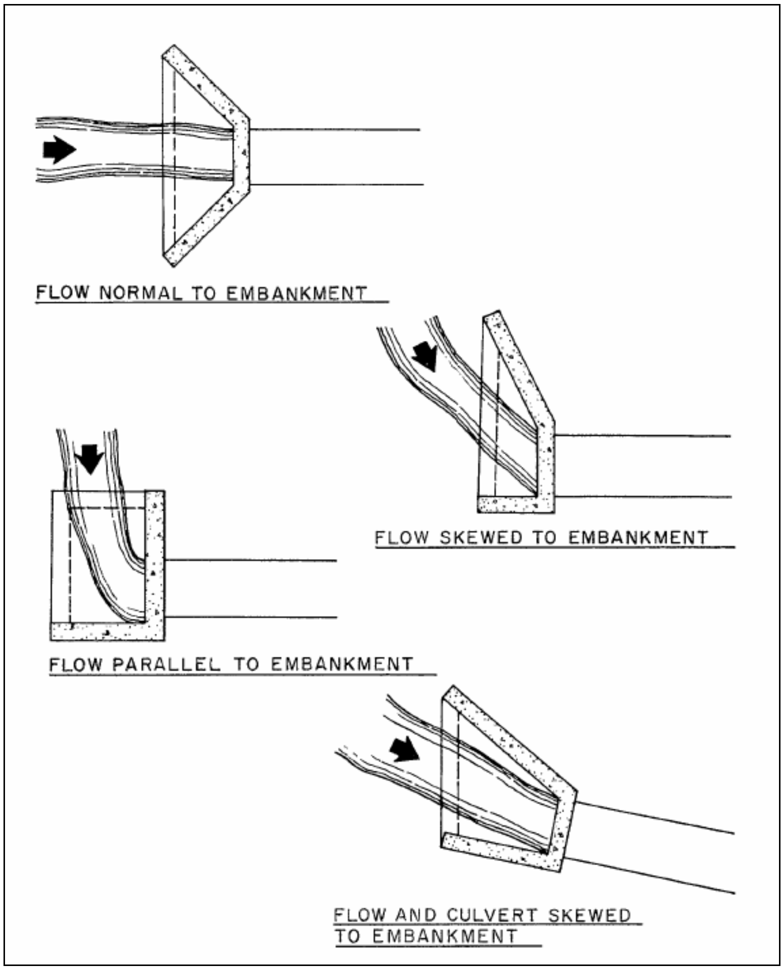


Figure 13, Typical Headwall Wingwall Configurations

4.3 Special Inlets

There is a great variety of inlets other than the common ones described. Among these are special end-sections, which serve as both outlets and inlets and are available for both corrugated metal pipe and concrete pipe. Because of the difference in requirements due to pipe materials, the special end-sections will be discussed independently according to pipe material, and mitered inlets will also be considered.

4.3.1 Corrugated Metal Pipe

Special end-sections for corrugated metal pipe add little to the overall cost of the culvert and have the following advantages:

1. Less maintenance around the inlet.
2. Less damage from maintenance work and from accidents compared to a projecting entrance.
3. Increased hydraulic efficiency. When using design charts, as discussed in Section 3.0, charts for a square-edged opening for corrugated metal pipe with a headwall may be used.

4.3.2 Concrete Pipe

As in the case of corrugated metal pipe, these special end-sections may aid in increasing the embankment stability or in retarding erosion at the inlet. They should be used where maintenance equipment must be used near the inlet or where, for aesthetic reasons, a projecting entrance is considered too unsightly.

The hydraulic efficiency of this type of inlet is dependent on the geometry of the end-section to be used. Where the full contraction to the culvert diameter takes place at the first pipe section, the entrance coefficient, *Ke,* is equal to 0.5, and where the full contraction to the culvert diameter takes place in the throat of the end-section, the entrance coefficient, *Ke,* is equal to 0.25.

4.3.3 Mitered Inlets

The use of this entrance type is predominantly with corrugated metal pipe and its hydraulic efficiency is dependent on the construction procedure used. If the embankment is not paved, the entrance, in practice, usually does not conform to the side slopes, giving essentially a projecting entrance with *Ke* = 0.9. If the embankment is paved, a sloping headwall is obtained with *Ke* = 0.60 and, by beveling the edges, *Ke* = 0.50.

Uplift is an important factor for this type entrance. It is not good practice to use unpaved embankment slopes where a mitered entrance may be submerged to an elevation one-half the diameter of the culvert above the top of the pipe.

4.3.4 Long Conduit Inlets

Inlets are important in the design of culverts for road crossings and other short sections of conduit; however, they are even more significant in the economical design of long culverts and pipes. Unused capacity in a long conduit will result in wasted investment. Long conduits are costly and require detailed engineering, planning, and design work. The inlets to such conduits are extremely important to the functioning of the conduit and must receive special attention.

Most long conduits require special inlet considerations to meet the particular hydraulic characteristics of the conduit. Generally, on larger conduits, hydraulic model testing will result in better and less costly inlet construction.

4.4 Improved Inlets

Inlet edge configuration is one of the prime factors influencing the performance of a culvert operating under inlet control. Inlet edges can cause a severe contraction of the flow, as in the case of a thin edge, projecting inlet. In a flow contraction, the effective cross-sectional area of the barrel may be reduced to about one-half of the actual available barrel area. As the inlet configuration is improved, the flow contraction is reduced, thus improving the performance of the culvert.

A tapered inlet is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section. Tapered inlets improve culvert performance by providing a more efficient control section (the throat). However, tapered inlets are not recommended for use on culverts flowing under outlet control because the simple beveled edge is of equal benefit. The two most common improved inlets are the side-tapered inlet and the slope-tapered inlet (Figure 14). FHWA (1985) *Hydraulic Design of Highway Culverts* provides guidance on the design of improved inlets.

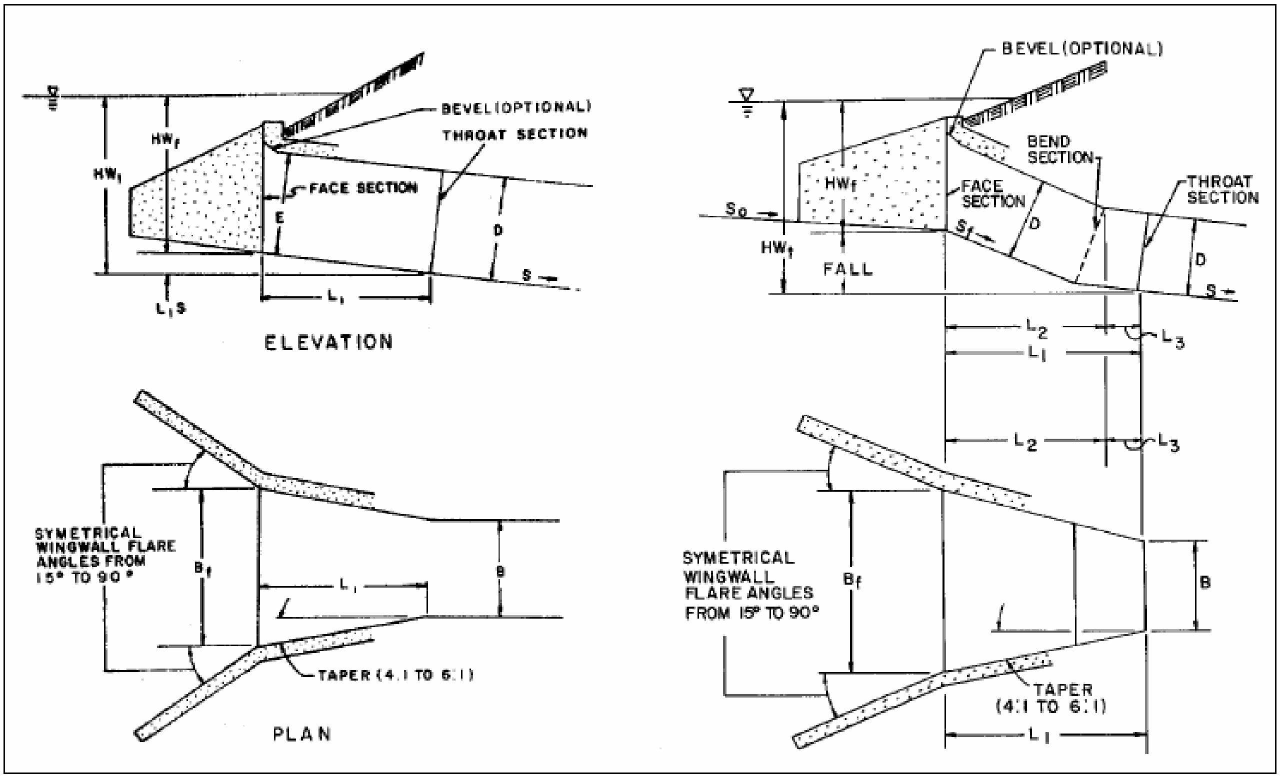


Figure14, Side-Tapered and Slope-Tapered Improved Inlets

5.0 INLET PROTECTION

Inlets on culverts, especially on culverts to be installed in live streams, should be evaluated relative to debris control and buoyancy. These topics are addressed in this section, while broader discussion of the advantages and disadvantages of trash/safety racks is provided in Section 8.0.

5.1 Debris Control

Accumulation of debris at a culvert inlet can result in the culvert not performing as designed. The consequences may be damages from inundation of the road and upstream property. The designer has three options for coping with the debris problem:

1. Retain the debris upstream of the culvert.
2. Attempt to pass the debris through the culvert.
3. Install a bridge.

If the debris is to be retained by an upstream structure or at the culvert inlet, frequent maintenance may be required. The design of a debris control structure should include a thorough study of the debris problem.

The following are among the factors to be considered in a debris study:

- Type of debris
- Quantity of debris
- Expected changes in type and quantity of debris due to future land use
- Stream flow velocity in the vicinity of culvert entrance
- Maintenance access requirements
- Availability of storage

- Maintenance plan for debris removal
- Assessment of damage due to debris clogging, if protection is not provided

Hydraulic Engineering Circular No. 9, *Debris Control Structure*s (FHWA 1971), should be used when designing debris control structures.

5.2 Buoyancy

The forces acting on a culvert inlet during flows are variable and indeterminate. When a culvert is functioning with inlet control, an air pocket begins just inside the inlet that creates a buoyant effect when the inlet is submerged. The buoyancy forces increase with an increase in headwater depth under inlet control conditions. These forces, along with vortexes and eddy currents, can cause scour, undermine culvert inlets, and erode embankment slopes, thereby making the inlet vulnerable to failure, especially with deep headwater.

In general, installing a culvert in a natural stream channel constricts the normal flow. The constriction is accentuated when the capacity of the culvert is impaired by debris or damage.

The large unequal pressures resulting from inlet constriction are in effect buoyant forces that can cause entrance failures, particularly on corrugated metal pipe with mitered, skewed, or projecting ends. The failure potential will increase with steepness of the culvert slope, depth of the potential headwater, flatness of the fill slope over the upstream end of the culvert, and the depth of the fill over the pipe.

Anchorage at the culvert entrance helps to protect against these failures by increasing the deadload on the end of the culvert, protecting against bending damage, and by protecting the fill slope from the scouring action of the flow. Providing a standard concrete headwall or endwall helps to counteract the hydrostatic uplift and to prevent failure due to buoyancy.

Because of a combination of high head on the outside of the inlet and the large region of low pressure on the inside of the inlet due to separation, a large bending moment is exerted on the end of the culvert, which may result in failure. This problem has been noted in the case of culverts under high fills, on steep slopes, and with projecting inlets. Where upstream detention storage requires headwater depth in excess of 20 feet, reducing the culvert size is recommended rather than using the inefficient projecting inlet to reduce discharge.

6.0 OUTLET PROTECTION

Scour at culvert outlets is a common occurrence and must be accounted for. The natural channel flow is usually confined to a lesser width and greater depth as it passes through a culvert barrel. An increased velocity results with potentially erosive capabilities as it exits the barrel. Turbulence and erosive eddies form as the flow expands to conform to the natural channel. However, the velocity and depth of flow at the culvert outlet and the velocity distribution upon reentering the natural channel are not the only factors that need consideration.

The characteristics of the channel bed and bank material, velocity, and depth of flow in the channel at the culvert outlet, and the amount of sediment and other debris in the flow are all contributing factors to scour potential. Due to the variation in expected flows and the difficulty in evaluating some of these factors, scour prediction is not a very exact science.

Scour in the vicinity of a culvert outlet can be classified into two separate types called local scour and general stream degradation.

6.1 Local Scour

Local scour is typified by a scour hole produced at the culvert outlet. This is the result of high exit velocities, and the effects extend only a limited distance downstream.

Coarse material scoured from the circular or elongated hole is deposited immediately downstream, often forming a low bar. Finer material is transported further downstream. The dimensions of the scour hole change due to sedimentation during low flows and the varying erosive effects of storm events. The scour hole is generally deepest during passage of the peak flow. Methods for predicting scour hole dimensions are found in *Hydraulic Design of Energy Dissipators for Culverts and Channels* (FHWA 1983 and 2000).

6.2 General Stream Degradation

General stream degradation is a phenomenon that is independent of culvert performance. Natural causes produce a lowering of the streambed over time. The identification of a degrading stream is an essential part of the original site investigation.

Both local and general scour can occur simultaneously at a culvert outlet. Protection against scour at culvert outlets varies from limited riprap placement to complex and expensive energy dissipation devices. At some locations, use of a rougher culvert material may alleviate the need for a special outlet protection device. Pre-formed scour holes (approximating the configuration of naturally formed holes) dissipate energy while providing a protective lining to the streambed.

Riprapped channel expansions and concrete aprons protect the channel and redistribute or spread the flow. Barrel outlet expansions operate in a similar manner. Headwalls and cutoff walls protect the integrity of the fill. When outlet velocities are high enough to create excessive downstream problems, consideration should be given to more complex energy dissipation devices. These include hydraulic jump basins, impact basins, drop structures, and stilling wells. Design information for the general types of energy dissipators can be found in *Hydraulic Design of Energy Dissipators for Culverts and Channels* (FHWA 1983 and 2000).

7.0 GENERAL CONSIDERATIONS

7.1 Culvert Location

Culvert location is an integral part of the total design. The main purpose of a culvert is to convey drainage water across the roadway section expeditiously and effectively. The designer should identify all live stream crossings, springs, low areas, gullies, and impoundment areas created by the new roadway embankment for possible culvert locations. Note that environmental permitting constraints will often apply for new culverts or retrofits, such as permits that regulate construction activities in jurisdictional wetlands and "Waters of the United States."

Culverts should be located on existing stream alignments and aligned to give the stream a direct entrance and a direct exit. Abrupt changes in direction at either end may retard the flow and make a larger structure necessary. If necessary, a direct inlet and outlet may be obtained by means of a channel change, skewing the culvert, or a combination of these. The choice of alignment should be based on economics, environmental concerns, hydraulic performance, and/or maintenance considerations.
If possible, a culvert should have the same alignment as its channel. Often this is not practical and where

the water must be turned into the culvert, headwalls, wingwalls, and aprons with configurations similar to those in Figure 13 should be used as protection against scour and to provide an efficient inlet.

7.2 Sedimentation

Deposits usually occur within the culvert barrels at flow rates smaller than the design flow. The deposits may be removed during larger floods dependent upon the relative transport capacity of flow in the stream and in the culvert, compaction and composition of the deposits, flow duration, ponding depth above the culvert, and other factors.

Culvert location in both plan and profile is of particular importance to the maintenance of sediment-free culvert barrels. Deposits occur in culverts because the sediment transport capacity of flow within the culvert is often less than in the stream.

Deposits in culverts may also occur due to the following conditions:

- At moderate flow rates the culvert cross section is larger than that of the stream, so the flow depth and sediment transport capacity is reduced.
- Point bars form on the inside of stream bends. Culvert inlets placed at bends in the stream will be subject to deposition in the same manner. This effect is most pronounced in multiple-barrel culverts with the barrel on the inside of the curve often becoming almost totally plugged with sediment deposits.
- Abrupt changes to a flatter grade in the culvert or in the channel adjacent to the culvert will induce sedimentation. Gravel and cobble deposits are common downstream from the break in grade because of the reduced transport capacity in the flatter section.

7.3 Fish Passage

At some culvert locations, the ability of the structure to accommodate migrating fish is an important design consideration. For such sites, state fish and wildlife agencies should be consulted early in the roadway planning process. Some situations may require the construction of a bridge to span the natural stream. However, culvert modifications can often be constructed to meet the design criteria established by the fish and wildlife agencies.

7.4 Open Channel Inlets

Entrances to open channels often require the same careful planning and design as is needed for culverts and long conduits if the necessary hydraulic balance is to be achieved. The energy grade line should be analyzed by the designer to insure proper provision for balanced energy conversion, velocity control, energy loss, and other factors controlling the downstream flow. Channel confluences, in particular, require careful hydraulic design to eliminate scour, reduce oscillating waves, and minimize upstream backwater effects.

7.5 Transitions

Transitions from pipe flow to open channels, between different rigid channels, and from slow flow to supercritical flow must be designed using the concepts of conservation of energy and open channel hydraulics. Primarily, a transition is necessary to change the shape or cross section of flowing water.

Normally, the designer will have as an objective the avoidance of excessive energy losses, cross waves, and turbulence. It is also necessary to provide against scour and overtopping.

Supercritical flow transitions must receive more attention than is usually due subcritical flow transitions. Care must be taken to insure against unwanted hydraulic jumps or velocities causing critical depth. Froude numbers between 0.9 and 1.1 should be avoided.

In general, the rate at which the flow prism may be changed should not exceed perhaps 5 to 12 1/2 degrees, depending upon velocity. Sharp angles should be avoided. The water surface hydraulic grade line should normally be smooth.

7.6 Large Stormwater Inlets

The functioning of large stormwater inlets, which collect major storm surface runoff at points of concentration, is dependent upon careful planning and design. Due regard must be given to debris, hail, and safety hazards.

7.6.1 Gratings

The design of gratings should focus on (1) public safety, (2) hydraulic function and (3) debris control. See Section 8.0 of this course for further discussion.

7.6.2 Openings

The hydraulic openings for large storm inlets need to be designed in general accordance with the guides given in Section 4.0. Inadequate openings are easily plugged when needed most, and give a false sense of security. Clear vertical openings should be at least 6 inches. For greater inlet flows, the length of opening needed may be so large that special design approaches are needed for shape and function.

7.6.3 Headwater

The required headwater over large inlets must be computed and kept within acceptable limits to avoid excessive ponding on streets and damage to adjacent property.

7.7 Culvert Replacements

When installing or replacing an existing culvert, careful consideration should be taken to ensure that upstream and downstream property owners are not adversely affected by the new hydraulic conditions. The potential upstream flooding impacts associated with the backwater from the calculated headwater depth must be considered and the determination of the available headwater should take into account the area inundated at the projected water surface elevation. If a culvert is replaced by one with more capacity, the downstream effects of the additional flow must be factored into the analysis. Assuring consistency with all existing major drainageway master plans and/or outfall studies is important.

7.8 Fencing for Public Safety

Culverts are frequently located at the base of steep slopes. Large box culverts, in particular, can create conditions where there is a significant drop, which poses risk to the public. In such cases, fencing (guardrails) is recommended for public safety.

8.0 TRASH/SAFETY RACKS

The use of trash/safety racks at inlets to culverts and long underground pipes should be considered on a case-by-case basis. While there is a sound argument for the use of racks for safety reasons, field experience has clearly shown that when the culvert is needed the most, that is, during the heavy runoff, trash racks often become clogged and the culvert is rendered ineffective. A general rule of thumb is that a trash/safety rack will not be needed if one can clearly "see daylight" from one side of the culvert to the other, if the culvert is of sufficient size to pass a 48" diameter object and if the outlet is not likely to trap or injure a person. By contrast, at entrances to longer culverts and long underground pipes and for culverts not meeting the above-stated tests, a trash/safety rack is necessary.

The trash/safety rack design process is a matter of fully considering the safety hazard aspects of the problem, defining them clearly, and then taking reasonable steps to minimize these hazards while protecting the integrity of the water carrying capability of the culvert.

In reviewing potential hazards to the public of a possibility of a person being swept into the culvert, it is also necessary to consider depth and velocity of upstream flow, the local currents in the vicinity of the culvert entrance, the general character of the neighborhood and whether it has residential population nearby, the length and size of the culvert, and other factors affecting safety and culvert capacity. Furthermore, in the event that someone was carried to the culvert with the storm runoff, the exposure hazard may in some cases be even greater if the person is pinned to the grating by the hydraulic pressures of the water rather than being carried through the culvert. Large, oversized racks positioned well in front of the culvert entrance can reduce the risk of pinning.

Where debris potential and/or public safety indicate that a rack is required, if the pipe diameter is more than 24 inches, the rack's open surface area must be, at the absolute minimum, at least four times larger. For smaller pipes, the factor increases significantly. For culverts larger than 24 inches (i.e., in the smallest dimension), in addition to the trash rack having an open area larger than four times the culvert entrance, the average velocities at the rack's face shall be less than 2.0 feet per second at every stage of flow entering the culvert. The rack needs to be sloped no steeper than 3H:1V (the flatter the better) and have a clear opening at the bottom of 9 to 12 inches to permit debris at lower flows to go through. The bars on the face of the rack should be generally paralleling the flow and be spaced to provide 4 1/2- to 5-inch clear openings between them. Transverse support bars need to be as few as possible, but sufficient to keep the rack from collapsing under full hydrostatic loads.

The District strongly recommends against the installation of trash racks at culvert outlets, because debris or a person carried into the culvert will impinge against the rack, thus leading to pressurized conditions within the culvert, virtually destroying its flow capacity and creating a greater hazard to the public or a person trapped in the culvert than not having one.

8.1 Collapsible Gratings

On larger culverts where a collapsible grating is deemed necessary by a local jurisdiction or an engineer, such gratings must be carefully designed from the structural standpoint so that collapse is achieved with a hydrostatic load of perhaps one-half of the maximum backwater head allowable. Collapse of the trash rack should be such that it clears the waterway opening adequately to permit the inlet to function properly without itself contributing to potential plugging of the culvert.

8.2 Upstream Trash Collectors

Where a safety hazard exists, a large trash rack situated diagonally across a stream a reasonable distance upstream from the culvert inlet offers an alternative. This type of rack may consist of a series of vertical pipes or posts embedded in the approach channel bottom with horizontal bars to deflect the debris to one side. If partial blocking of a properly designed rack occurs, it should be designed so that the backwater flow over the top of the rack is minimal. The rack must not cause the water to rise higher than the maximum allowable flood elevation. A trash rack at the culvert entrance can then provide a backup for safety.

9.0 DESIGN EXAMPLE

The following example problem illustrates the culvert design procedures using the FHWA nomographs and using Culvert Spreadsheet application.

9.1 Culvert Under an Embankment

Given: *Q*5-yr = 20 cfs, *Q*100-yr = 35 cfs, *L* = 95 feet
The maximum allowable headwater elevation is 5288.5. The natural channel invert elevations are 5283.5 at the inlet and 5281.5 at the outlet. The tailwater depth is computed as 2.5 feet for the 5-year storm, and 3.0 feet for the 100-year storm.
Solution:

Step 1: Fill in basic data (Figure 15)
*Q*5-yr = discharge for 5-year storm
*Q*100-yr = discharge for 100-year storm
Headwater and tailwater elevations

Step 2: Set invert elevations at natural channel invert elevations to avoid scour. Compute *s* and *L*/(100*s*).

Step 3: Start with an assumed culvert size for the 5-year storm by adopting a velocity of 6.5 ft/sec. In this case, first size is estimated by adopting a velocity of 6.5 ft/sec and computing $A = 20/6.5 = 3.1$ ft^2, giving a culvert diameter, $D = 24$ inches.

Step 4: For this example, two inlets are considered: square edge with headwall (*Ke* = 0.4) and groove end with headwall (*Ke* = 0.2). Also, assume concrete pipe will be used with a Manning's *n* of 0.012 (Note: the District recommends a minimum *n* of 0.013; however, 0.012 is used in this example to correspond to the FHWA nomograph.)

Step 5: Using the inlet control nomograph (Figure 16), the ratio of the headwater depth to diameter (Hw/D) is 1.47 for the square edge and 1.32 the culvert for the groove end. Thus, the inlet control headwater depths are 2.94 feet and 2.64 feet, respectively.

Step 6: The outlet control headwater depth is determined using the method described in Section 3.0. The head is determined from the nomograph (Figure 17). The resulting outlet control headwater depths are 2.13 feet for the square edge and 1.90 feet for the grove end inlet.

Step 7: Comparing the headwater depths for inlet control (2.94 feet and 2.64 feet) and outlet control (2.13 feet and 1.90 feet) shows that the culvert is inlet controlled with either inlet configuration. Furthermore, the calculated headwater depths are less than the allowable headwater depth. These results can also be determined using the UD-Culvert Spreadsheet.

Step 8: The next step is to evaluate the culvert for the 100-year flow of 35 cfs and tailwater depth of 3.0 feet. Using the same procedure, the culvert continues to be inlet controlled with the square-edge inlet and switches to outlet control with the more efficient groove-end inlet. However, both of the calculated headwater depths exceed the allowable headwater depth and, consequently, are not viable alternatives.

Step 9: Increase the pipe diameter to 27 inches and repeat the process. The resulting headwater depths are less than the allowable.

Step 10: Compute outlet velocities for each acceptable alternate.

Step 11: Compute cost for each alternate Step

Step 12: Make recommendations

PROJECT: Drainage Criteria Manual
Culvert Design Example

DESIGNER: ____

DATE: February 2001

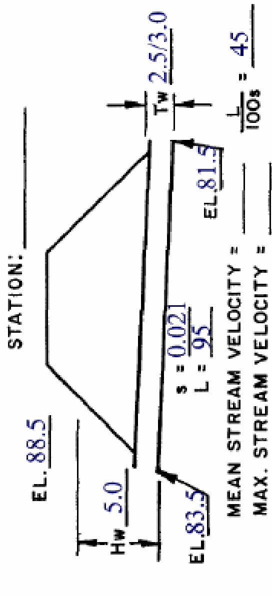
HYDROLOGIC AND CHANNEL INFORMATION

Q_1 = 20 cfs TAILWATER ELEVATION = 84.0
Q_2 = 35 cfs TAILWATER ELEVATION = 84.5

(Q_1 = DESIGN DISCHARGE, SAY Q_{25}
Q_2 = CHECK DISCHARGE, SAY Q_{50} OR Q_{100})

SKETCH

STATION: ____



MEAN STREAM VELOCITY = ____
MAX. STREAM VELOCITY = ____

$\frac{L}{100s}$ = 45

CULVERT DESCRIPTION w/ Headwall (ENTRANCE TYPE)	Q	SIZE	HEADWATER COMPUTATION: INLET CONT.		OUTLET CONTROL HW = H + h_o − Ls								CHART		CONTROLLING HW	OUTLET VELOCITY	COST	COMMENTS
			$\frac{Hw}{D}$	Hw	K_e	H	d_c	$\frac{d_c+D}{2}$	Tw	h_o	Ls	Hw	No.	Hw				
RCP w/ sq edge	20	24	1.47	2.94	0.4	1.63	0.80	1.40	2.5	2.5	2.0	2.13			2.94	6.4		Inlet Control
RCP w/ groove	20	24	1.32	2.64	0.2	1.40	0.80	1.40	2.5	2.5	2.0	1.90			2.64	6.4		Inlet Control
RCP w/ sq edge	35	24	3.08	6.16	0.4	4.90	0.96	1.48	3.0	3.0	2.0	5.90			6.16	11.1		Inlet Control HW>allowable
RCP w/ groove	35	24	2.50	5.00	0.2	4.40	0.96	1.48	3.0	3.0	2.0	5.40			5.40	11.1		Outlet Control HW>allowable
RCP w/ sq edge	35	27	2.03	4.57	0.4	2.85	1.01	1.63	3.0	3.0	2.0	3.85			4.57	8.8		Inlet Control
RCP w/ groove	35	27	1.71	3.85	0.2	2.50	1.01	1.63	3.0	3.0	2.0	3.50			3.85	8.8		Inlet Control

SUMMARY & RECOMENDATIONS: Choose 27-inch RCP to pass the 100-year flow within the allowable headwater.
Either entrance type will work; allow cost to determine.
Design outlet protection based on velocity of 8.8 ft/sec.

Figure 15, Design Computation Form for Culverts Example 9.1

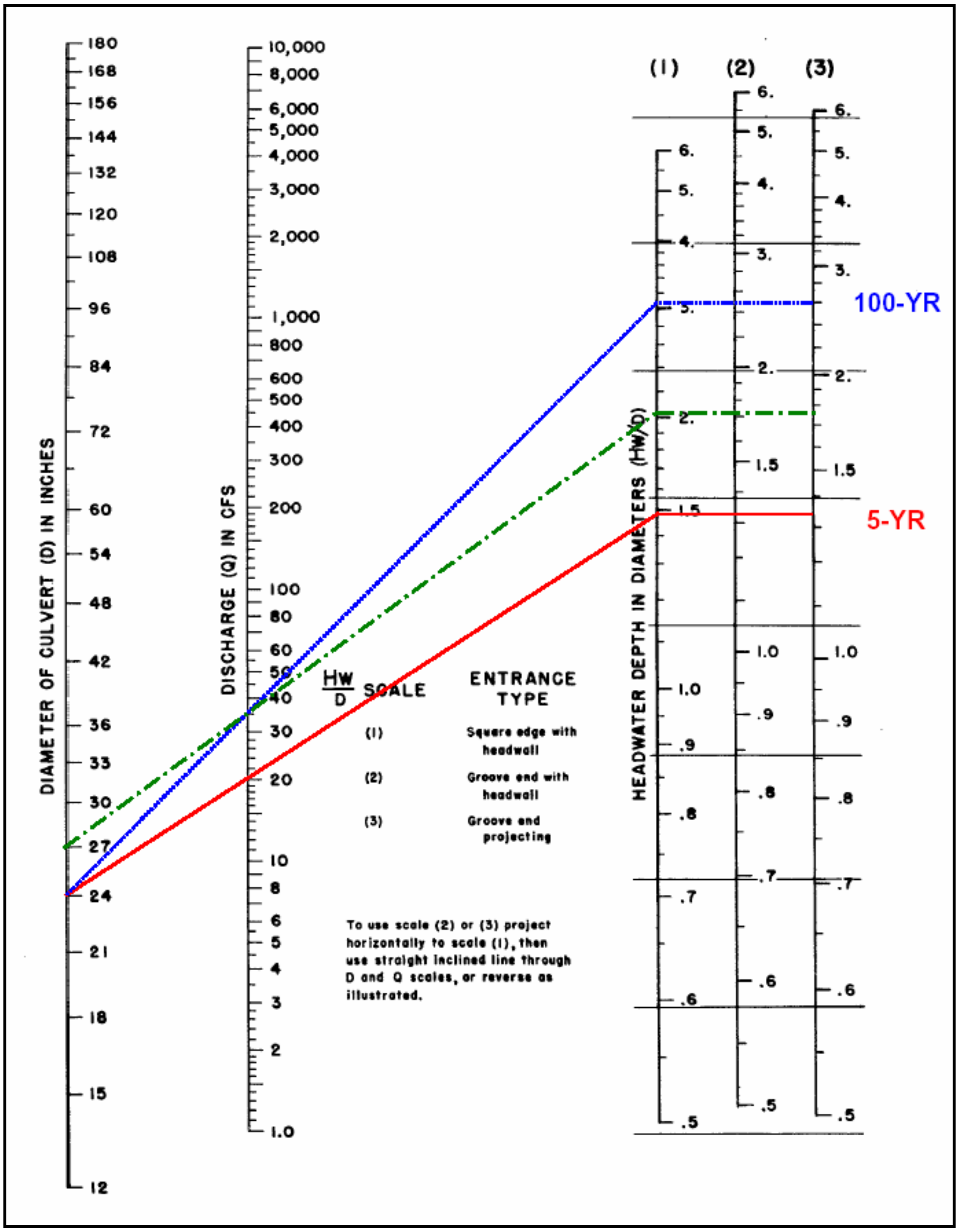


Figure 16, Headwater Depth for Concrete Pipe Culverts with Inlet Control Example 9.1

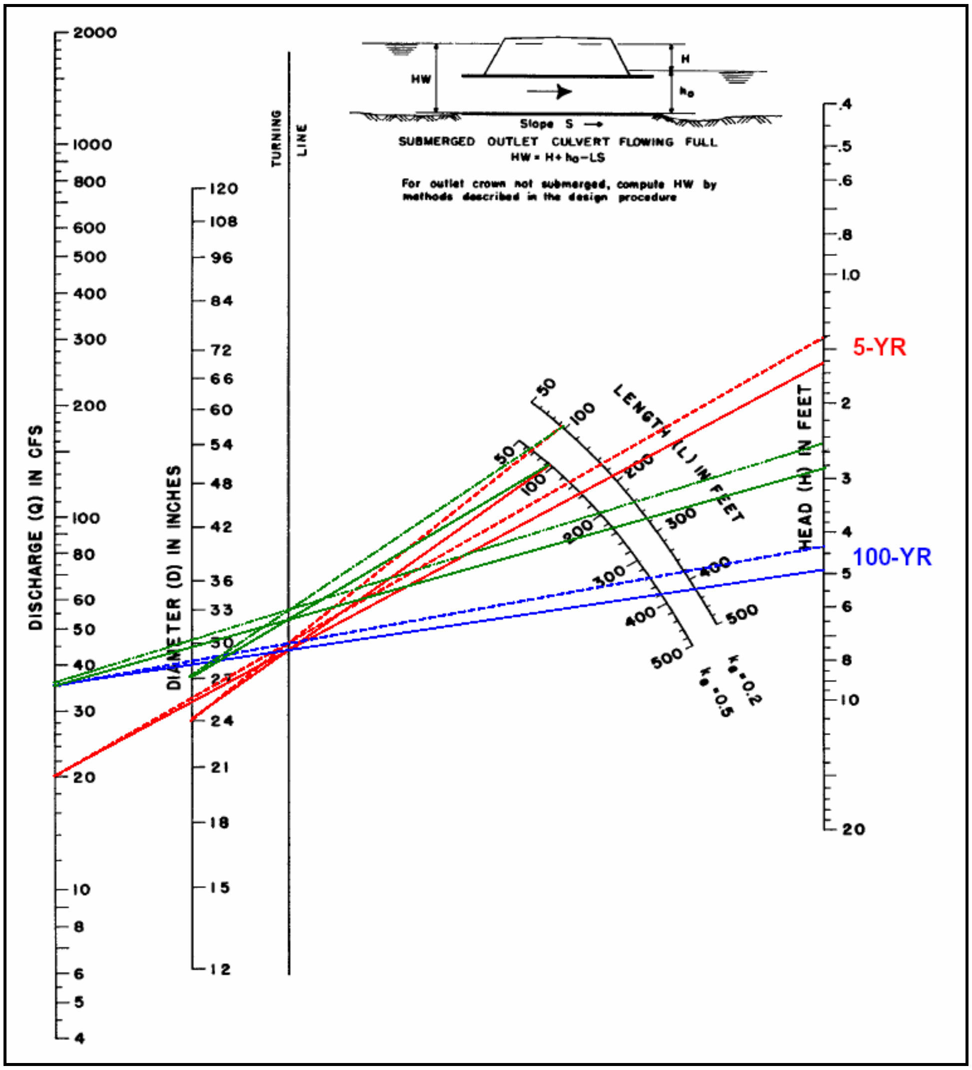


Figure 17, Head for Concrete Pipe Culverts Flowing Full (*n* = 0.012) Example 9.1

9.2 Culvert Sizing Using Nomograhs

The example problem is as follows: Size a culvert given the following design conditions (this following example problem requires the use of nomographs).

Given: Discharge for 10-year flood = 70 cfs. Discharge for 100-year flood = 176 cfs. Allowable H_w for 10-year discharge = 4.5 feet. Allowable H_w for 100-year discharge = 7.0 feet. Length of culvert = 100 feet. Natural channel invert elevations – inlet = 15.50 feet, outlet = 15.35 feet. Culvert slope = 0.00 15 feet per feet. Tailwater depth for 10-year discharge = 3.0 feet. Tailwater depth for 100-year discharge = 4.0 feet. Tailwater depth is the normal depth in downstream channel. Entrance type = groove end with headwall

STEP 1: Assume a culvert velocity of 5 feet per second
Required flow area = 70 cfs/5 feet per second = 14 sq ft (for the 10-year flood).

STEP 2: *The corresponding culvert diameter is about 48 inches. This can be calculated by using* the formula for area of a circle:
Area = (3.14 D^2)/4 or D = (Area times 4/3.14)$^{0.5}$

Therefore: $D = [(14 \text{ sq ft} \times 4) / 3.14]^{0.5} \times 12$ inches per feet = 50.7 inches

STEP 3: A grooved-end culvert with a headwall is selected for the design. Using the inlet-control nomograph, with a pipe diameter of 48 inches and a discharge of 70 cfs; read an HW/D value of 0.93.

STEP 4: The depth of headwater (HW) is (0.93) x (4) = 3.72 feet, which is less than the allowable headwater of 4.5 feet.

STEP 5: The culvert is checked for outlet control. With an entrance loss coefficient K_e of 0.20, a culvert length of 100 feet, and a pipe diameter of 48 inches, an H value of 0.77 feet is determined. The headwater for outlet control is computed by the equation: $HW = H + h_o - LS$

For the tailwater depth lower than the top of culvert, $h_o = T_w$ or 1/2 (critical depth in culvert + D), whichever is greater.
h_o = 3.0 feet or h_o = 1/2 (2.55 + 4.0) = 3.28 feet

The headwater depth for outlet control is: $HW = H + h_o - LS$

HW = 0.77 + 3.28 – (100) x (0.0015) = 3.90 feet

STEP 6: Because HW for outlet control (3.90 feet) is greater than the HW for inlet control (3.72 feet), outlet control governs the culvert design. Thus, the maximum headwater expected for a 10-year recurrence flood is 3.90 feet, which is less than the allowable headwater of 4.5 feet.

STEP 7: The performance of the culvert is checked for the 100-year discharge. The allowable headwater for a 100-year discharge is 7 feet; critical depth in the 48-inch diameter culvert for the 100-year discharge is 3.96 feet. For outlet control, an H value of 5.2 feet is read from the outlet-control nomograph. The maximum headwater is:

$HW = H + h_o - LS$

HW = 5.2 + 4.0 – (100) x (0.0015) = 9.05 ft

This depth is greater than the allowable depth of 7 feet; thus, a larger size culvert must be selected. Repeat steps 1-7 as necessary.

STEP 8: A 54-inch diameter culvert is tried and found to have a maximum headwater depth of 3.74 feet for the 10-year discharge and of 6.97 feet for the 100-year discharge. These values are acceptable for the design conditions.

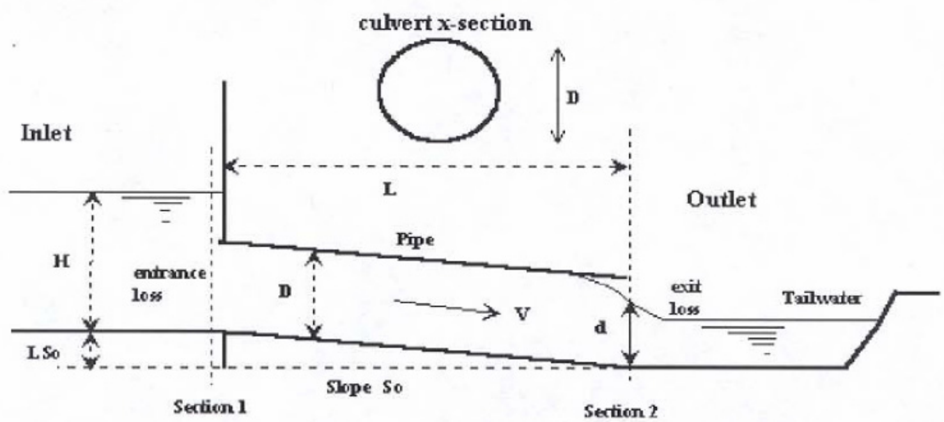
STEP 9: Estimate outlet exit velocity. Because this culvert is on outlet control and discharges into an open channel downstream, the culvert will be flowing full at the flow depth in the channel. Using the 100-year design peak discharge of 176 cfs and the area of a 54-inch or 4.5-foot diameter culvert, the exit velocity will be Q = VA. Therefore:
$V = 176 / (\pi(4.5)^2 /4 = 11.8$ ft/s.

With this high velocity, some energy dissipater may be needed downstream from this culvert for streambank protection.

STEP 10: The engineer should check minimum velocities for low-frequency flows if the larger storm event (100-year) controls culvert design.

Headwater Depth For Circular Culvert

Project: Drainage Criteria Manual
Pipe ID: Example 9.1



Design Information (input)

Design Discharge	**Q =**	**20.0**	**cfs**
Pipe Diameter	D =	2.00	ft
Inlet Edge Type (choose from pull-down list)	Inlet Type =	Square End with Headwall	
Inlet Invert Elevation	I_e =	83.50	ft
Outlet Invert Elevation	O_e =	81.50	ft
Pipe Length	L =	95.0	ft
Manning's Roughness N-Value	N =	0.012	*
Bend Loss Coefficient	K_b =	0.00	
Exit Loss Coefficient	K_x =	0.00	
Tailwater Water Surface Elevation	El. Y_t =	84.00	ft

Calculations (output)

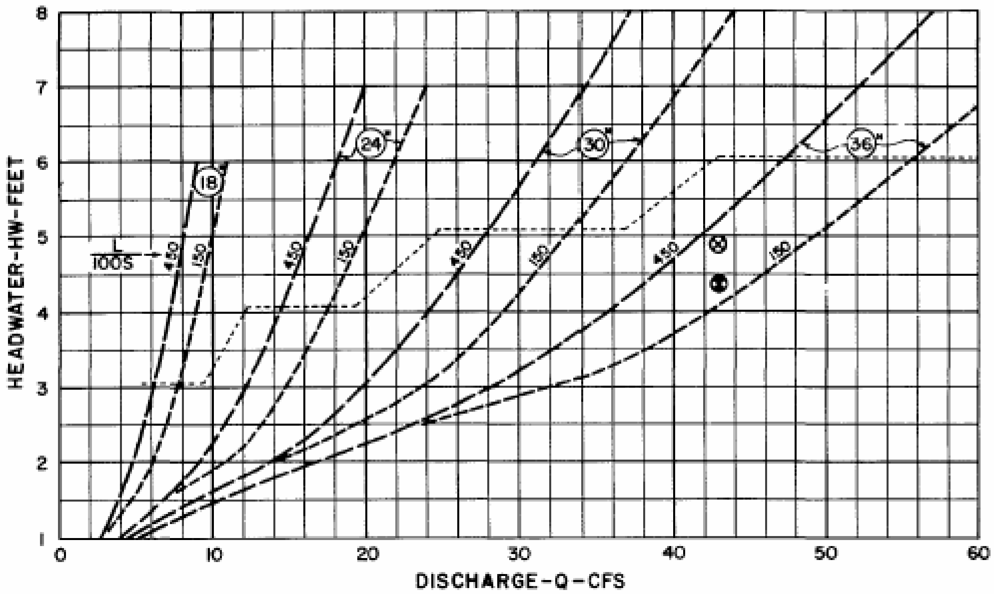
Pipe Cross Sectional Area	A_o =	3.14	sq ft
Culvert Slope	S_o =	0.0211	ft/ft
Normal Flow Depth	Y_n =	0.54	ft
Critical Flow Depth	Y_c =	0.80	ft
Headwater Depth by Inlet Control			
Headwater Depth by Inlet Control	**HW-inlet=**	**2.92**	**ft**
Headwater Depth by Outlet Control			
Tailwater Depth for Design	d =	2.50	ft
Friction Loss Coefficient over Culvert Length	K_f =	1.00	
Sum of All Loss Coefficients	K_s =	1.50	
Headwater Depth by Outlet Control	**HW-outlet=**	**2.07**	**ft**
Design Headwater Depth	**HW=**	**2.92**	**ft**
HW/D Ratio =	**HW/D=**	**1.46**	

10.0 CHECKLIST

Criterion/Requirement	✓
Culvert diameter should be at least 18 inches.	
Evaluate the effects of the proposed culvert on upstream and downstream water surface elevations.	
When retrofitting or replacing a culvert, evaluate the changes in the upstream and downstream flood hazard.	
Review any proposed changes with local, state, and federal regulators.	
When a culvert is sized such that the overlying roadway overtops during large storms, check the depth of cross flow with Table DP-3 in the POLICY chapter.	
Provide adequate outlet protection in accordance with the energy dissipator discussion in the MAJOR DRAINAGE and HYDRAULIC STRUCTURES chapters.	

11.0 CAPACITY CHARTS AND NOMOGRAPHS

Capacity charts and nomographs covering the range of applications commonly encountered in drainage are contained in this section. These charts are from the FHWA, which also contains detailed instructions for their use. For situations beyond the range covered by these charts, reference should be made to FHWA publications.



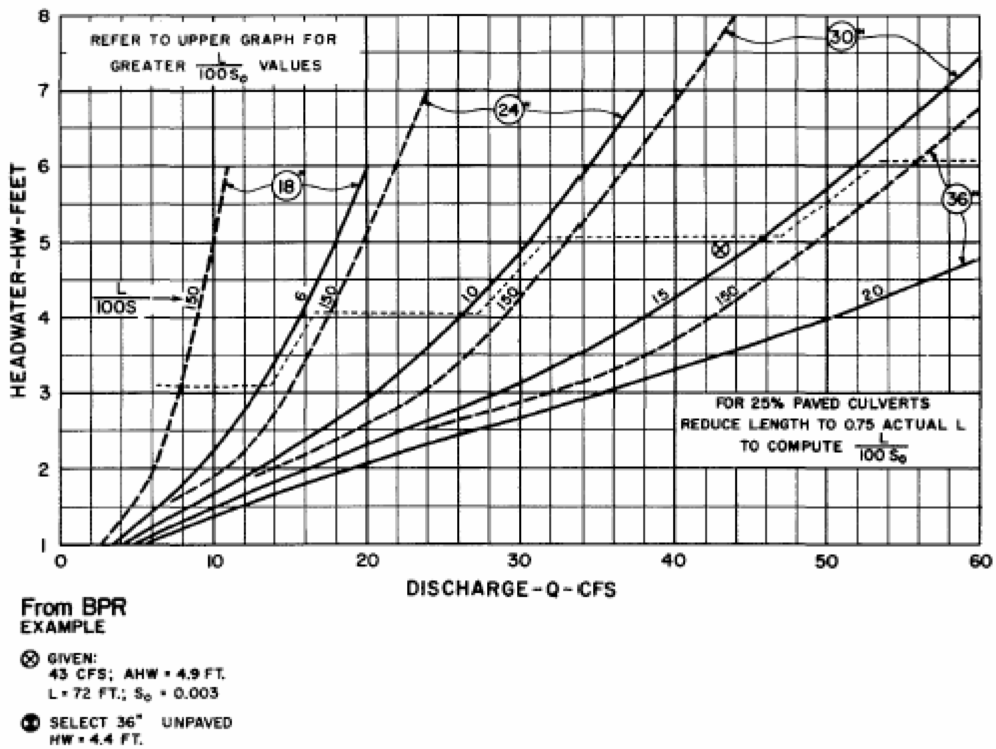
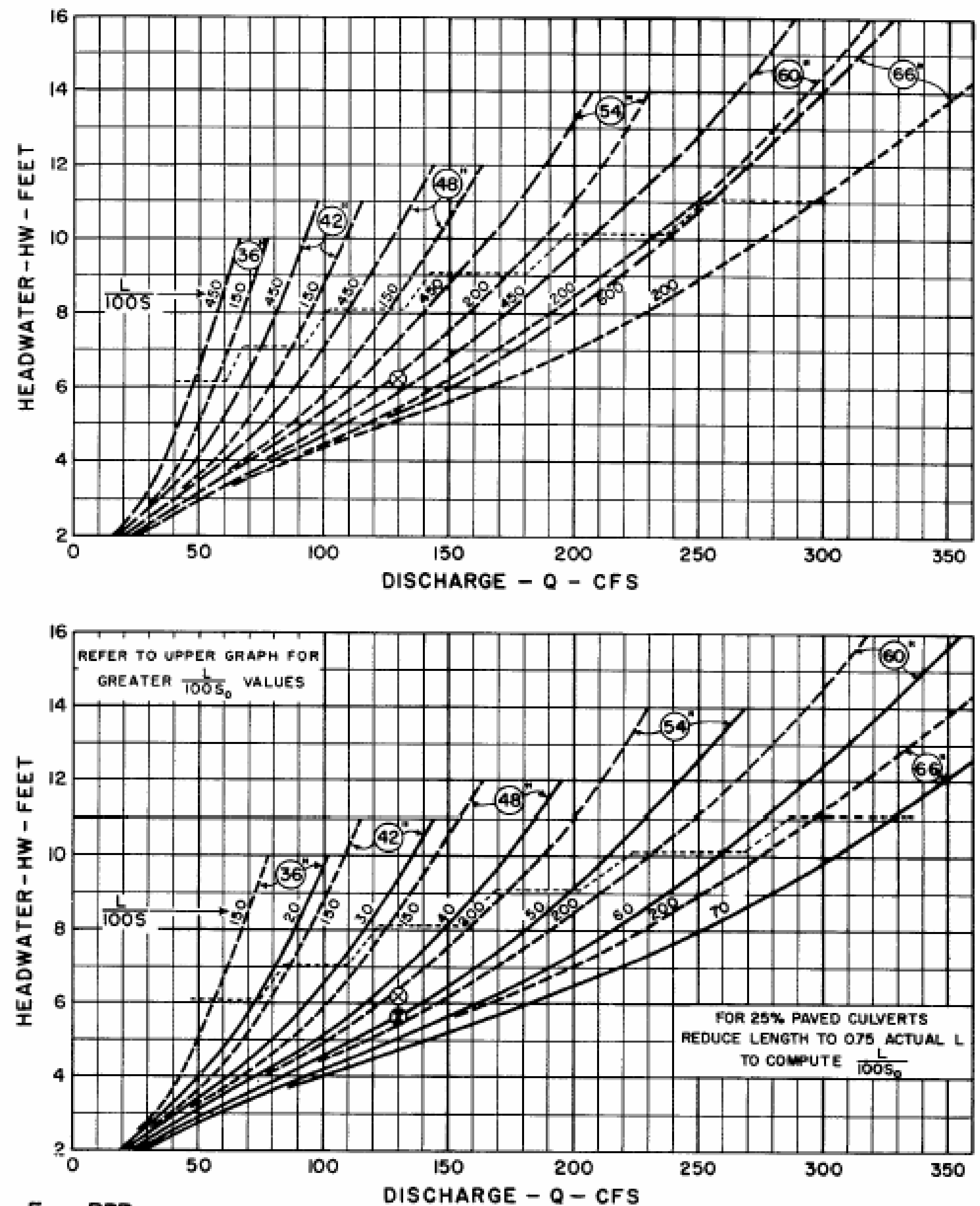


Figure 18, Culvert Capacity Standard Circular Corrugated Metal Pipe Headwall Entrance 18" to 36"



From BPR

EXAMPLE

⊗ GIVEN:
130 CFS; AHW = 6.2 FT.
L = 120 FT.; S_0 = 0.025

SELECT 54" UNPAVED
HW = 5.6 FT.

Figure 19, Culvert Capacity Standard Circular Corrugated Metal Pipe Headwall Entrance 36" to 66"

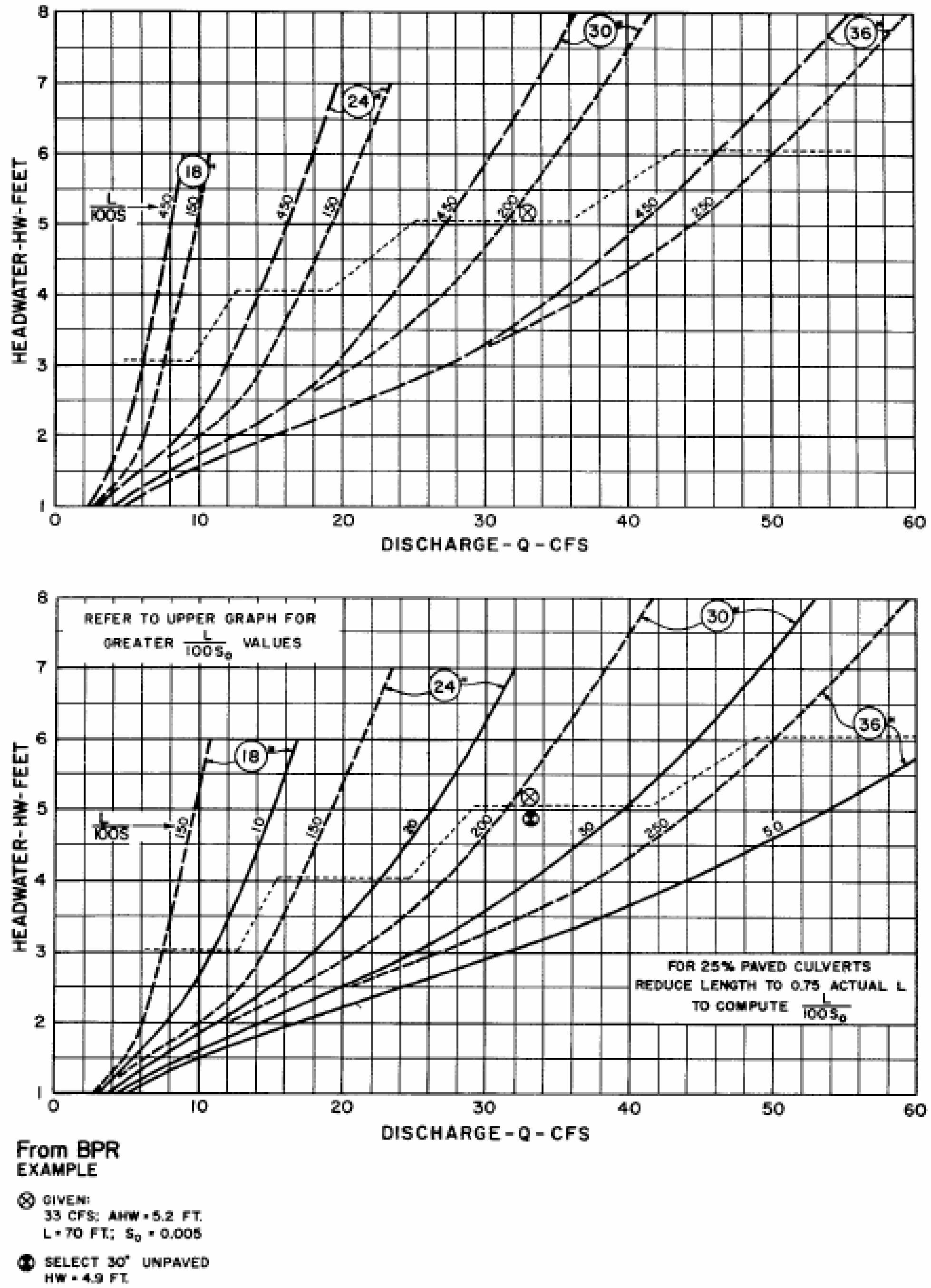


Figure 20, Culvert Capacity Standard Circular Corrugated Metal Pipe Projecting Entrance 18" to 36"

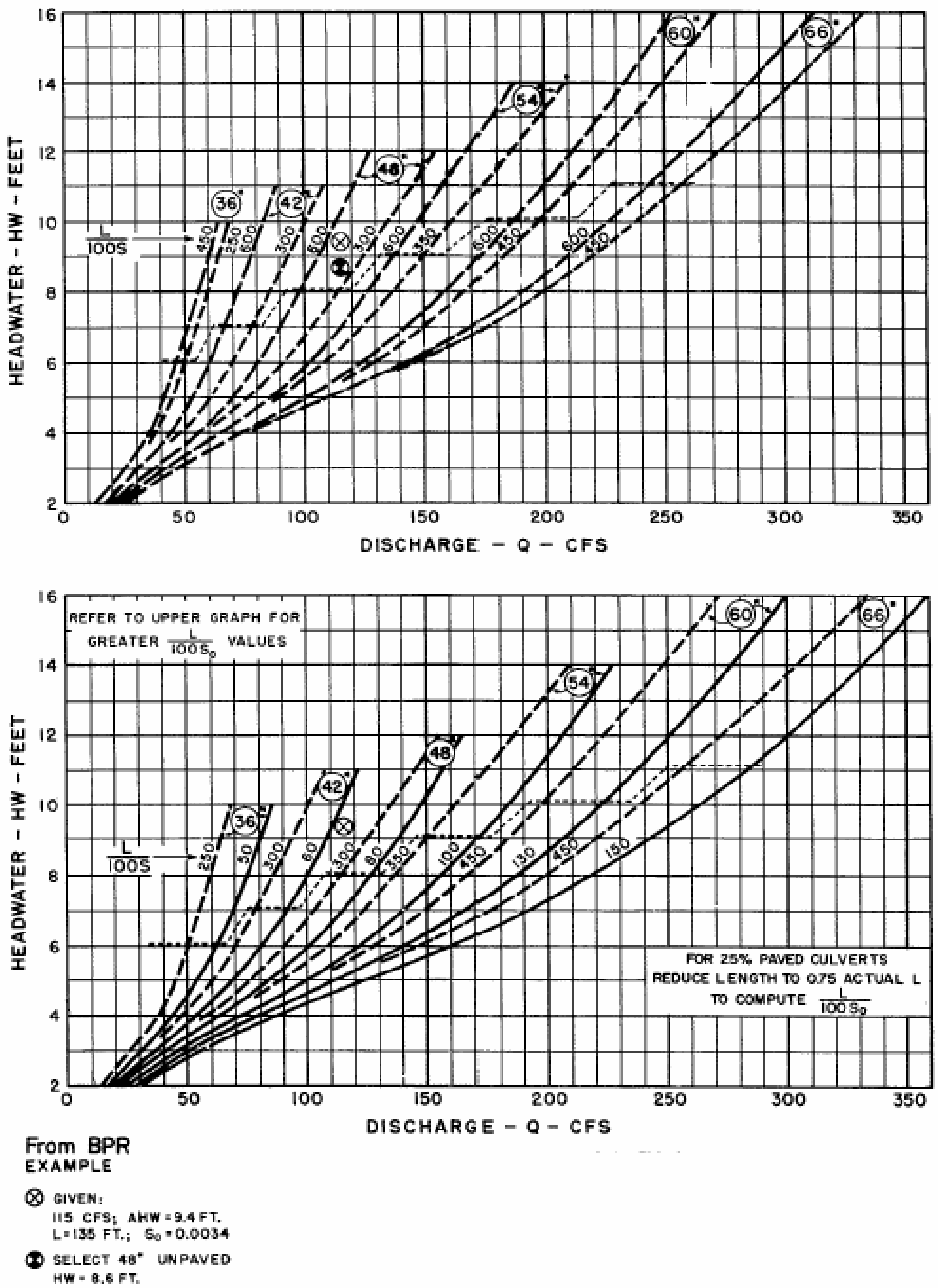


Figure 21, Culvert Capacity Standard Circular Corrugated Metal Pipe Projecting Entrance 36" to 66"

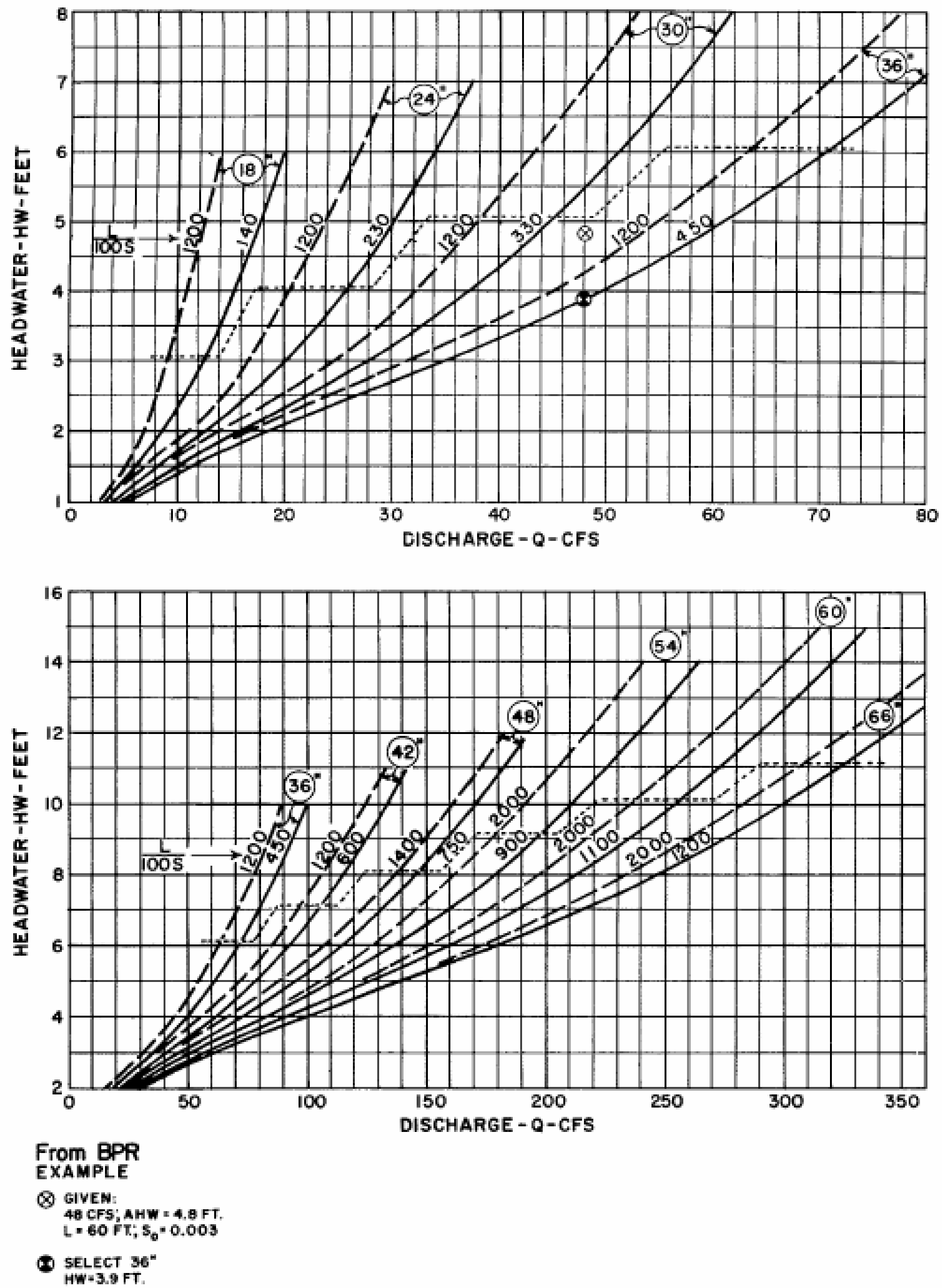


Figure 22, Culvert Capacity Circular Concrete Pipe Square-Edged Entrance 18" to 66"

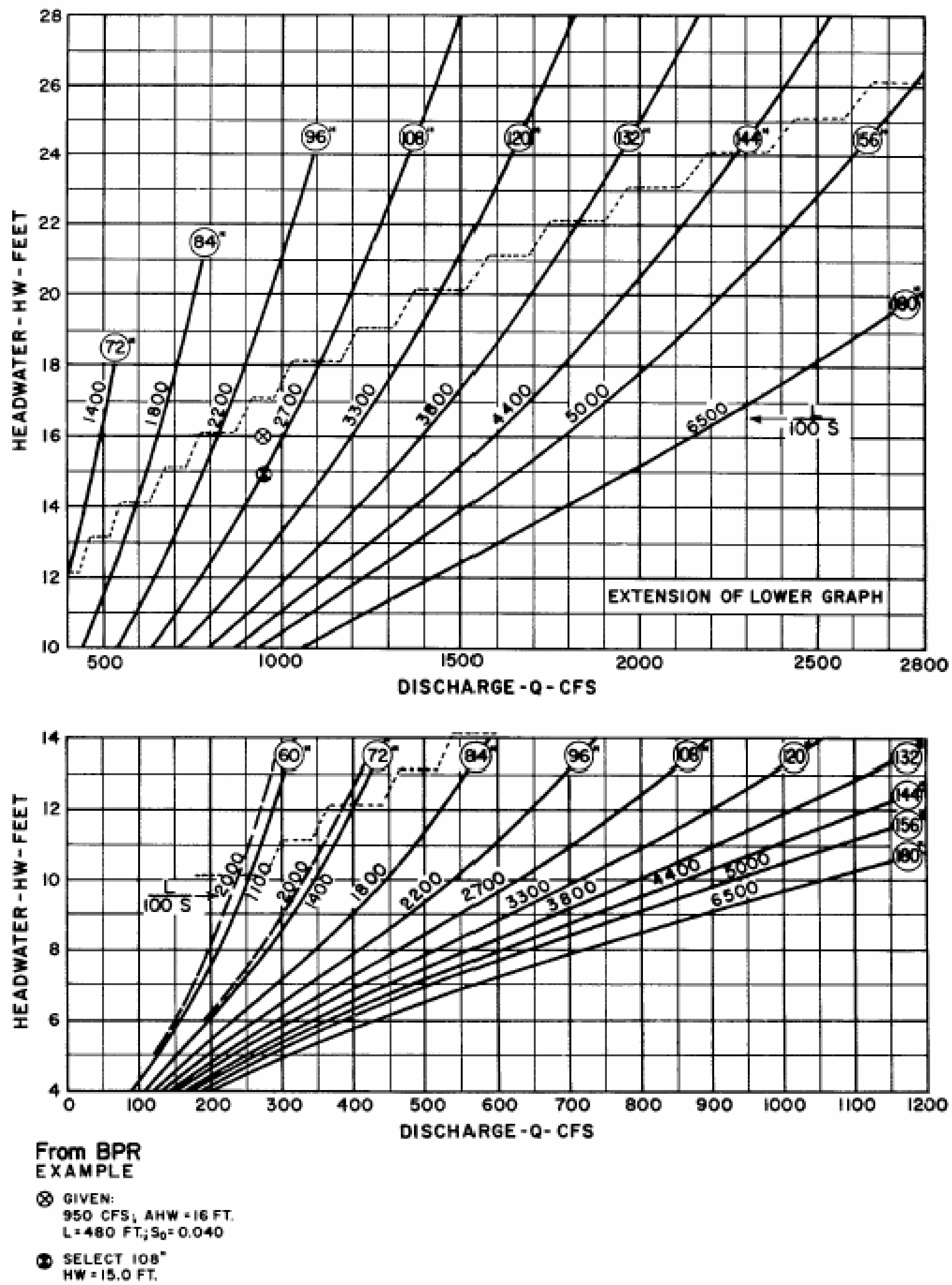


Figure 23, Culvert Capacity Circular Concrete Pipe Square-Edged Entrance 60" to 180"

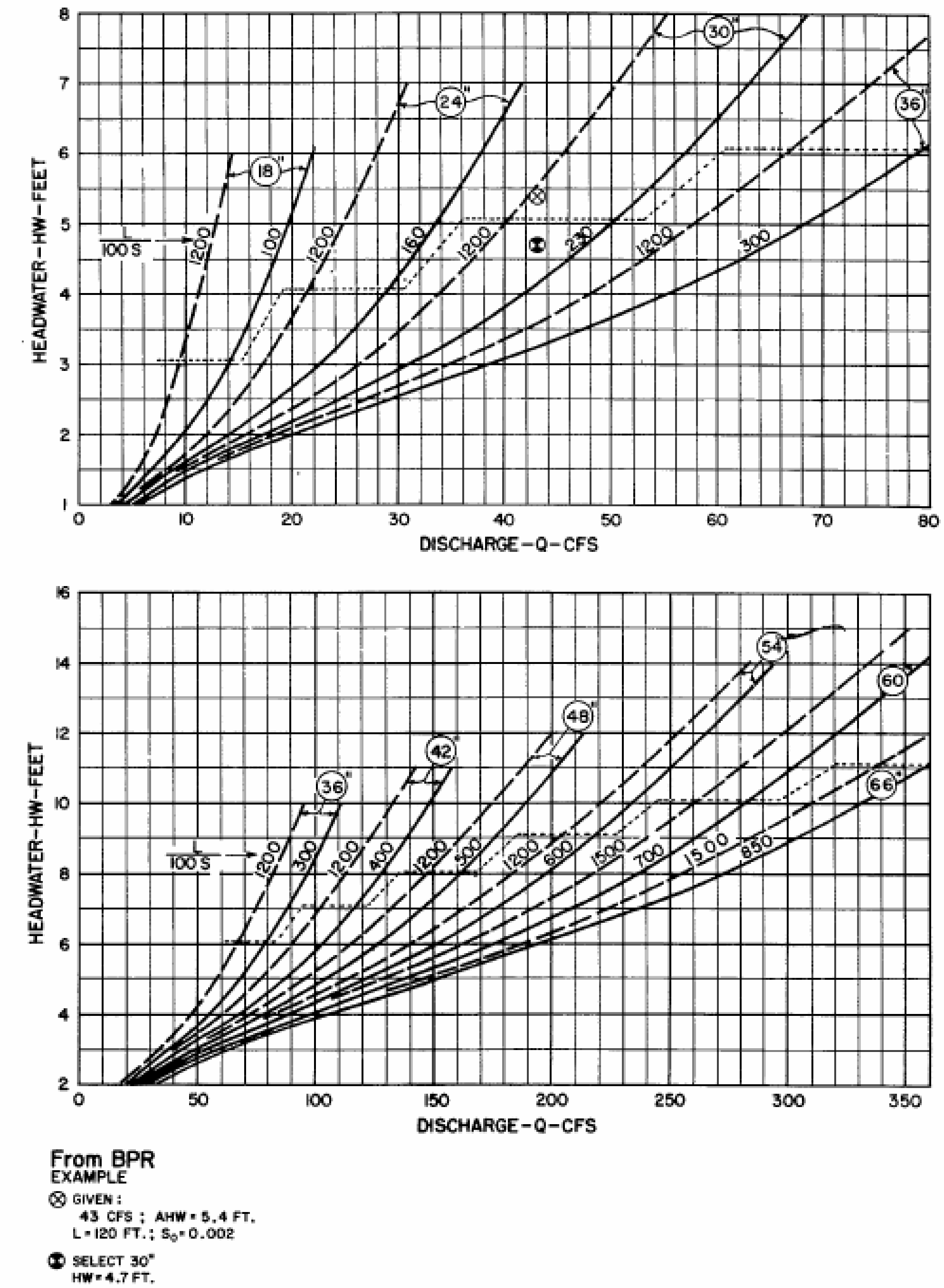


Figure 24, Culvert Capacity Circular Concrete Pipe Groove-Edged Entrance 18" to 66"

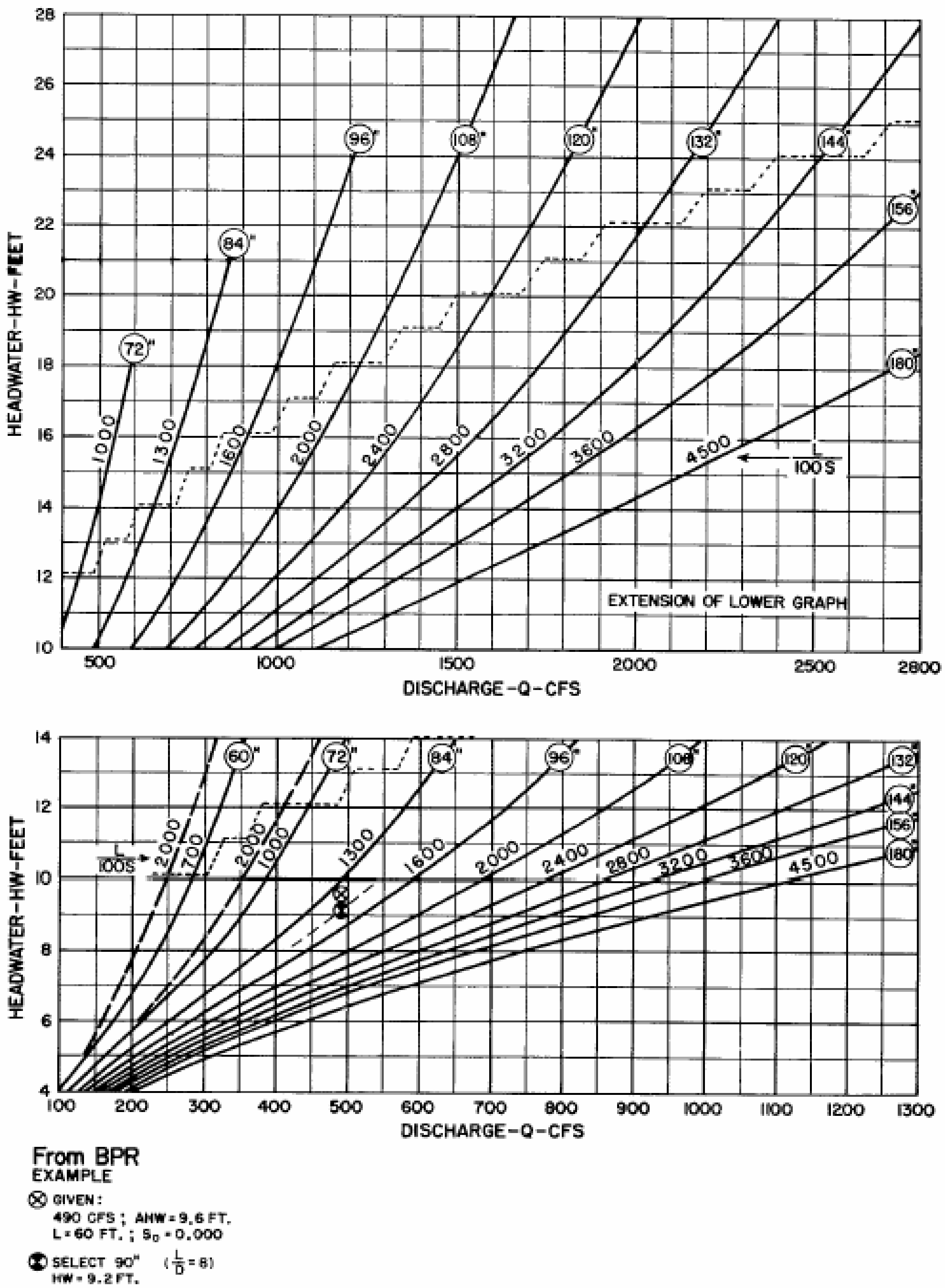


Figure 25, Culvert Capacity Circular Concrete Pipe Groove-Edged Entrance 60” to 180”

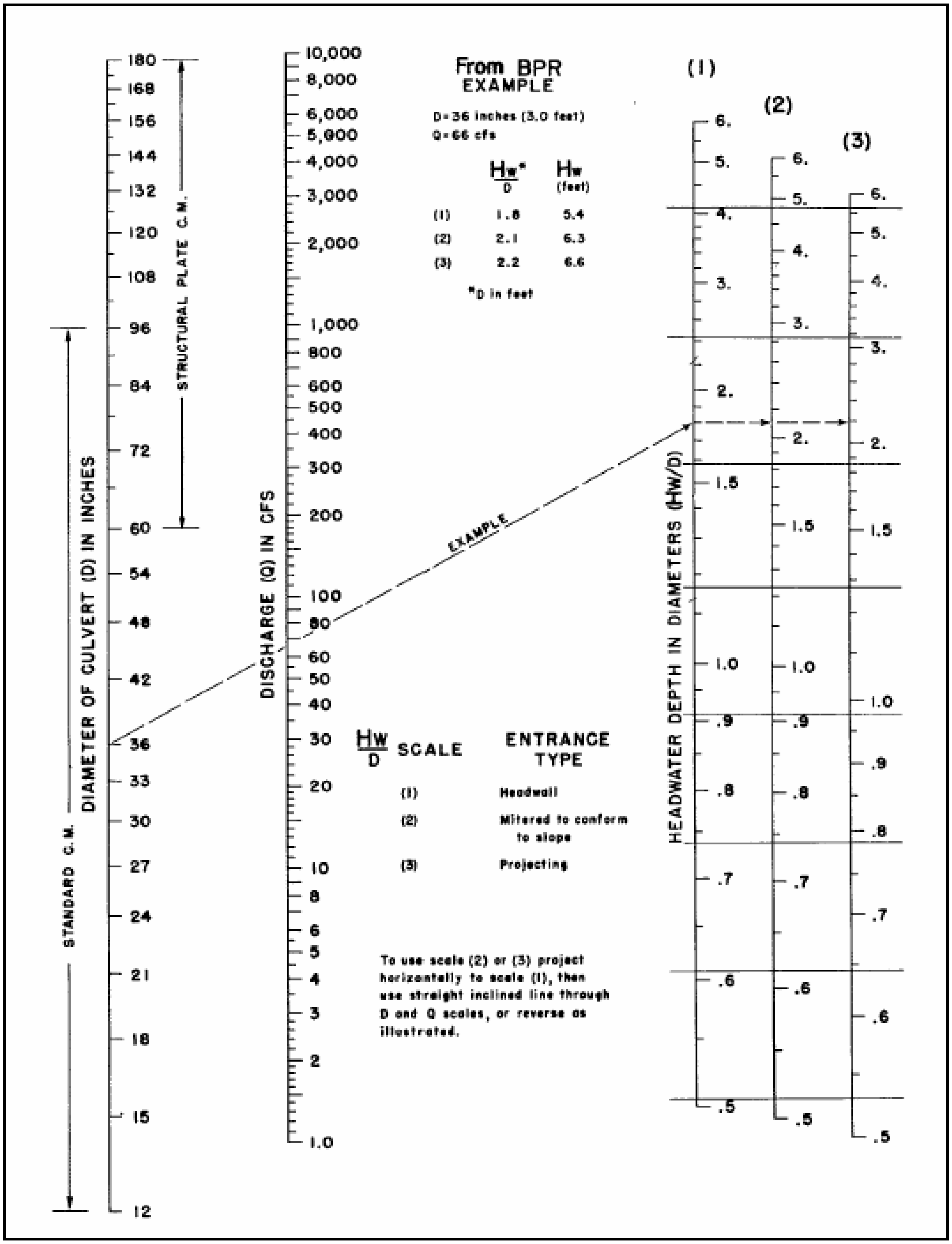


Figure 26, Headwater Depth for Corrugated Metal Pipe Culverts With Inlet Control

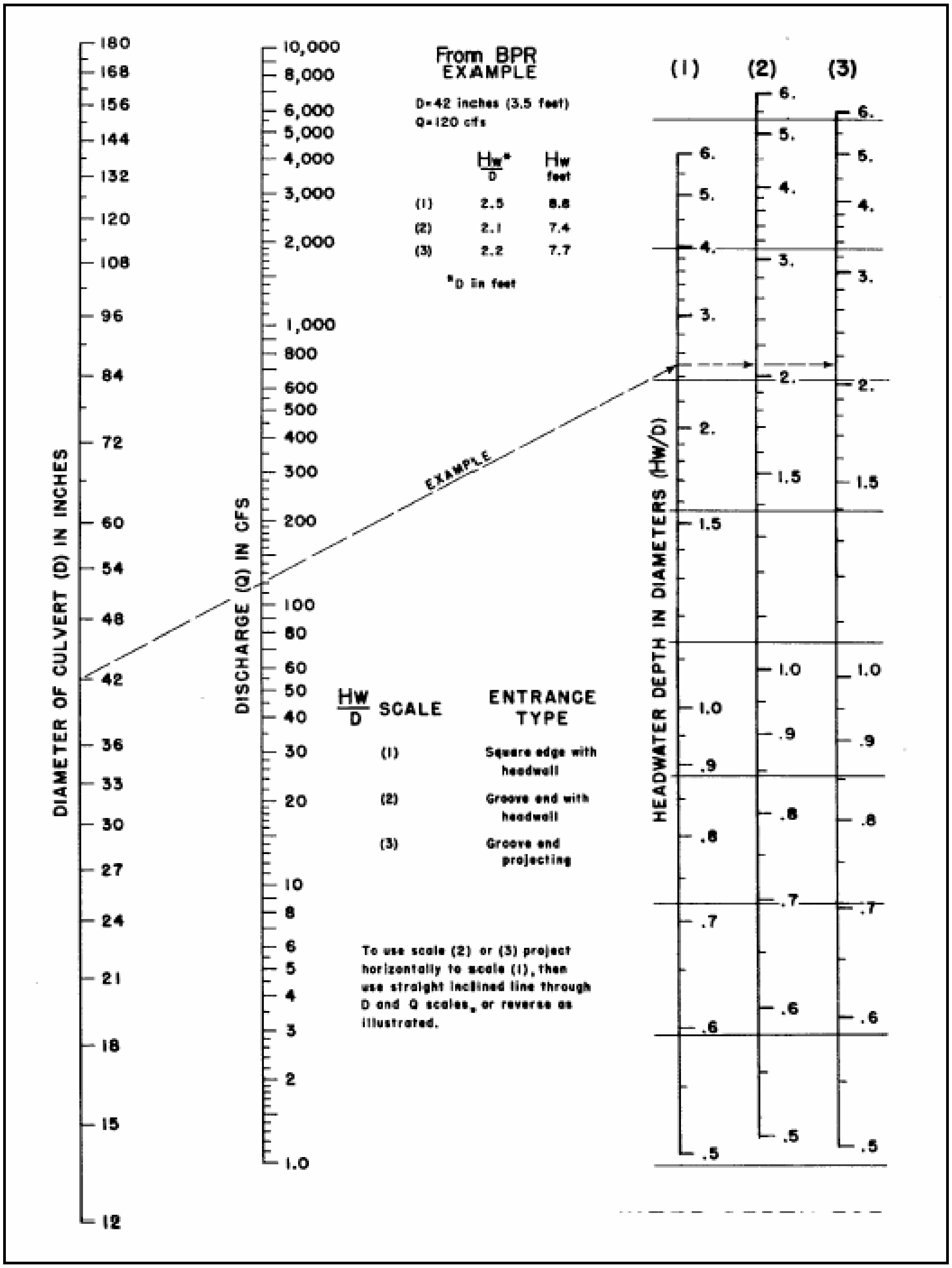


Figure 27, Headwater Depth for Concrete Pipe Culverts With Inlet Control

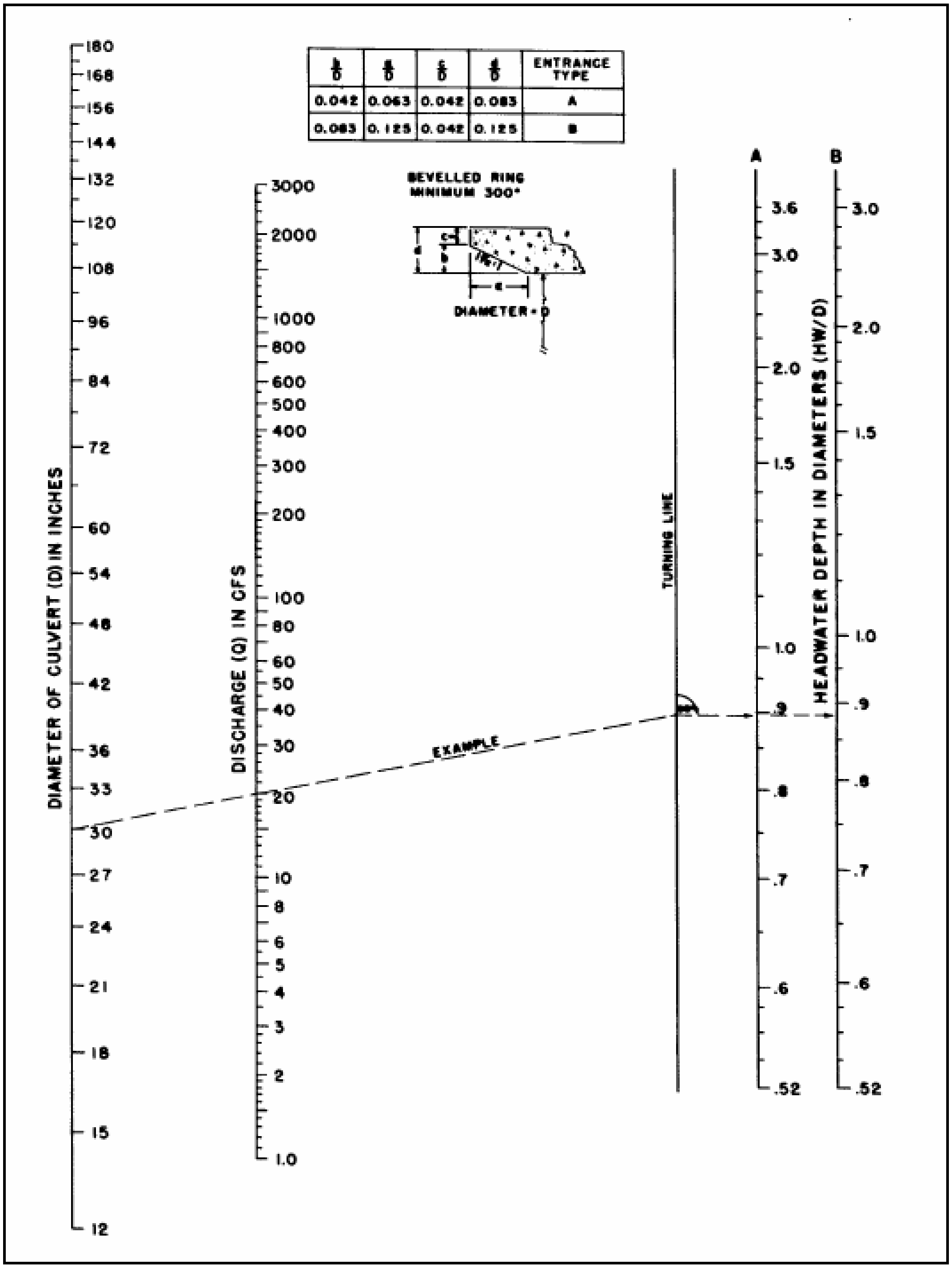


Figure 28, Headwater Depth for Circular Pipe Culverts With Beveled Ring Inlet Control

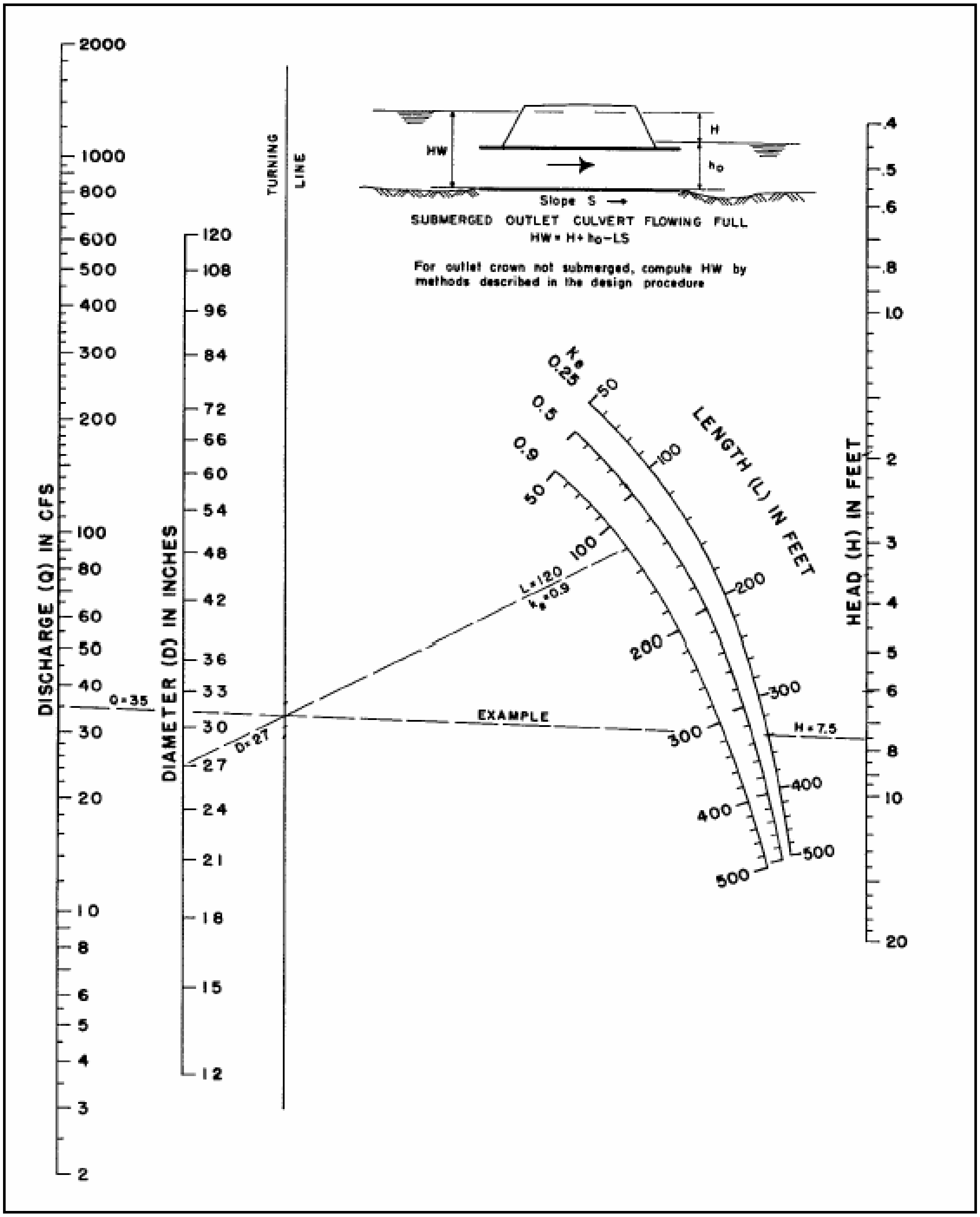


Figure 29, Head for Standard Corrugated Metal Pipe Culverts Flowing Full n = 0.024

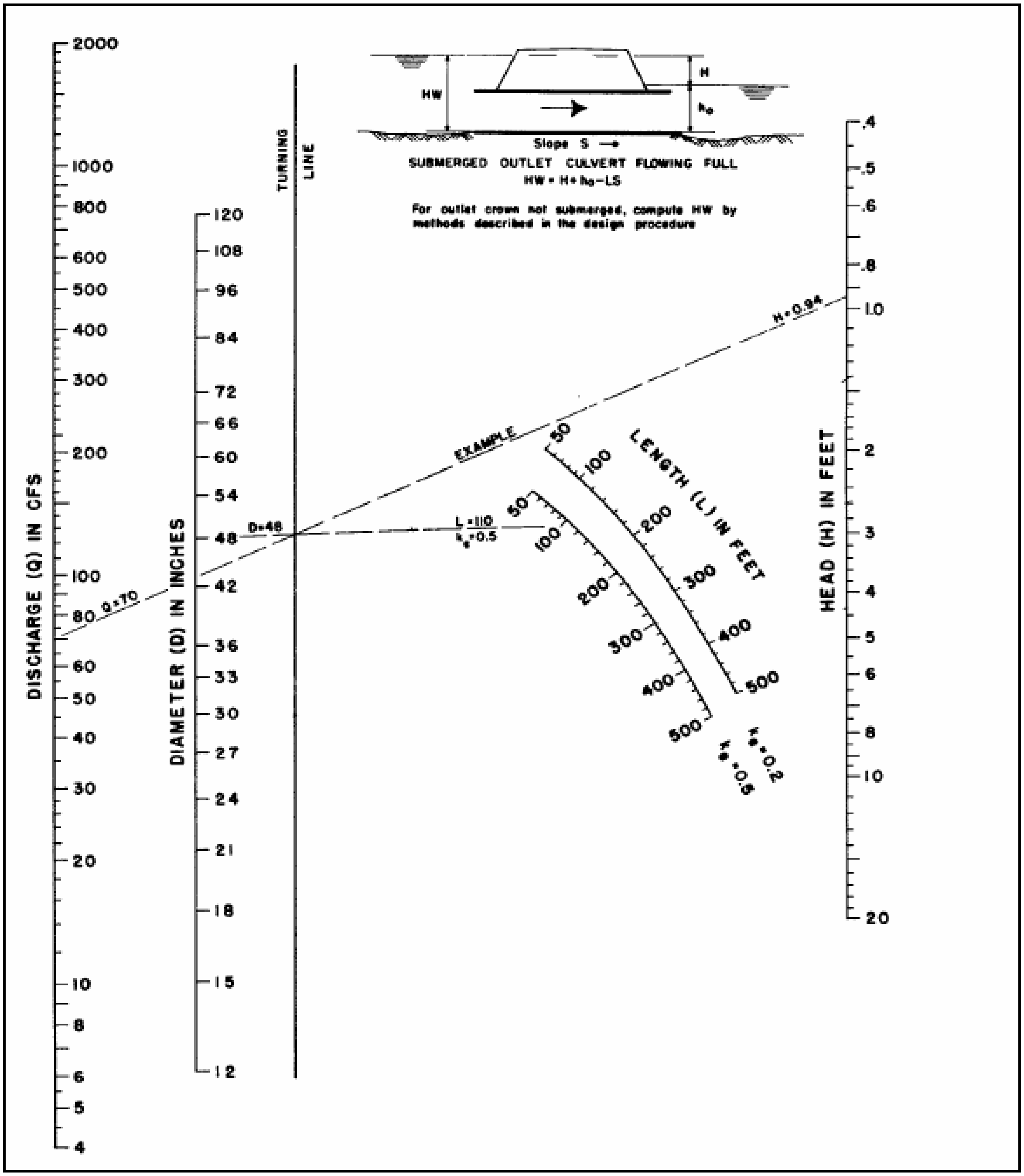


Figure 30, Head for Concrete Pipe Culverts Flowing Full *n* = 0.012