
27 CULVERTS

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27.1 INTRODUCTION

This Chapter provides guidance on the hydraulic design of culverts, culvert end treatment, the design of scour protection, debris control and an introduction to improved culvert inlets. The procedures for the hydraulic design of culverts are based on "Hydraulic Design of Highway Culverts", Hydraulic Engineering Circular No 5 (US Federal Highway Administration, 1985).

The emphasis in this Chapter is on the design of culverts for urban stormwater drainage. Highway authorities may have different or additional requirements, which are not discussed herein.

27.2 DESIGN CONSIDERATIONS

27.2.1 Headwater

Any culvert that constricts the natural stream flow will cause a rise in the upstream water surface. The total flow depth in the stream measured from the invert of the culvert inlet is termed headwater.

The available headwater will depend on the topography of the site and the vertical road profile in relation to that topography. In flat or undulating country or where a high standard vertical road profile is used the available headwater may be limited by the height of the surrounding ground or the elevation at which the road formation cuts through the hydraulic grade line. Raised levee banks may be necessary to maintain the headwater depth required as indicated in Section 27.2.6.

The most economical culvert is one which utilise all of the available headwater to pass the design discharge, since the discharge increases with increasing head. However, it is not always possible to utilise all of the available headwater, because of constraints, which limit the upstream water level. Selection of the design headwater should be based therefore, on consideration of the following factors :

- Limits on backwater resulting from the presence of buildings upstream and/or the inundation of agricultural land.
- The outlet velocity and the potential for scour.

Potential damage to adjacent property or inconvenience to owners should be of primary concern in the design of all culverts. Expensive court cases and resultant compensation may result, if property owner's rights are neglected. In urban areas, the potential for damage to adjacent property is greater, because of the number and value of properties that can be affected.

Culvert installation under high embankments in rural areas may present the design engineer with an opportunity to adopt a high headwater and allow ponding upstream to

attenuate flood peaks downstream. If deep ponding is considered, the consequences of scour at the outlet and catastrophic failure of the embankment should be investigated. When culverts are installed under high embankments, an appropriate investigation should be made to evaluate the risk of a larger flood occurring or blockage of the culverts by debris.

27.2.2 Culvert in Plan

Ideally, a culvert should be placed in the natural channel (Figure 27.1). A culvert in this location is usually aligned with flow and little structural excavation and channel work are required at the inlet and outlet, especially for shorter culverts. In the case, where location in the natural channel would require an inordinately long culvert, some stream realignment may be required (Figure 27.2). Such modification to reduce skew and shorten culverts should be carefully designed, environmental concerns for stream velocity, flow depth and factors important to the stream ecosystem, and hydraulic concerns for stream bed and bank stability make it advisable not to undertake channel modifications unless there is no practical alternative.

Culvert skew should not generally exceed 45 degrees measured from a line perpendicular to the roadway centreline. If the skew is greater than 45 degrees special consideration needs to be given to the hydraulic efficiency of the wingwalls.

Culvert alignments square to the road centreline are not recommended where severe or abrupt changes in channel alignment are required upstream or downstream of the culvert. Small radius bends are subject to erosion on the concave bank and deposition on the inside of the bend. Such changes, upstream of the culverts, result in poor alignment of the approach flow to the culvert with resulting loss of hydraulic efficiency, subject the embankment to erosion and increase the probability of deposition in the culvert cell. Abrupt changes in channel alignment downstream of culverts may also cause erosion or deposition of material in adjacent properties.

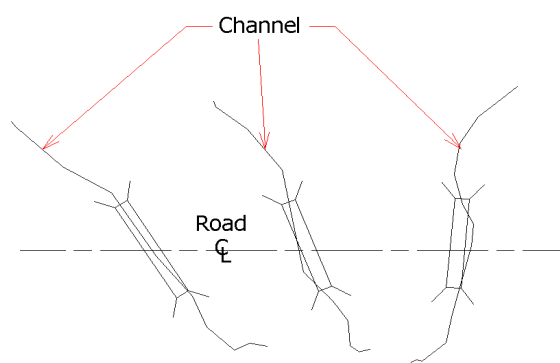


Figure 27.1 Culvert Located in Natural Channel

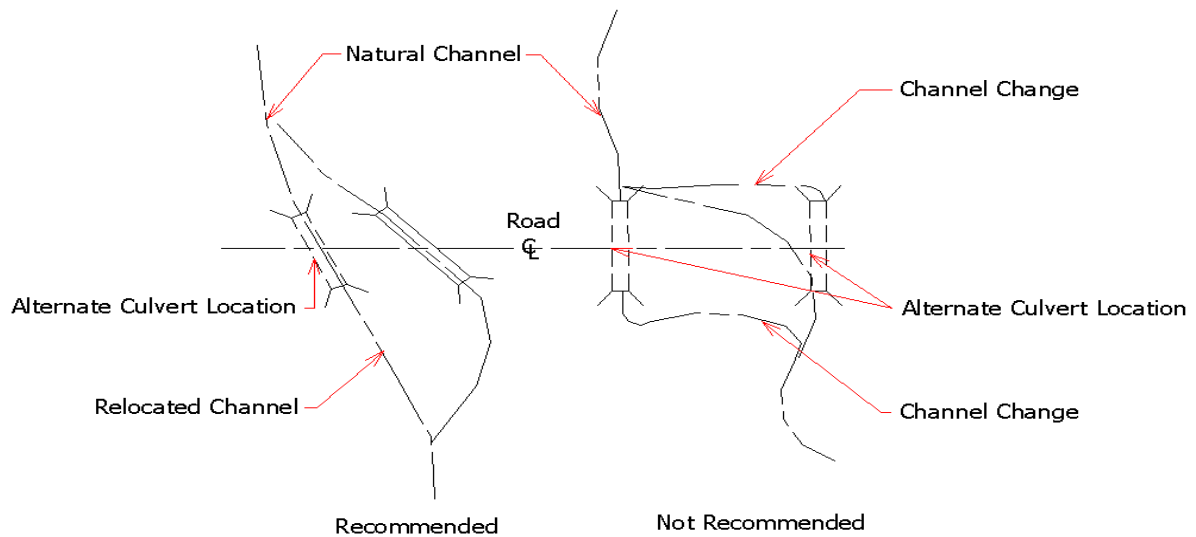


Figure 27.2 Methods of Culvert Location in the Natural Channel to avoid an Inordinately Long Culvert

27.2.3 Vertical Profile

Most longitudinal culvert profiles should approximate the natural stream bed. Other profiles may be chosen for either economic or hydraulic reasons. Modified culvert slopes, or slopes other than that of the natural stream, can be used to prevent stream degradation, minimise sedimentation, improve the hydraulic performance of the culvert, shorten the culvert, or reduce structural requirements. Modified slope can also cause stream erosion and deposition. Slope alterations should, therefore, be given special attention to ensure that detrimental effects do not result from the change.

Channel changes often result in culverts being shorter and steeper than the natural channel. A modified culvert slope can be used to achieve a flatter gradient to prevent channel degradation. Figure 27.3 illustrates possible culvert profiles.

27.2.4 Multiple Cells

It is important to select a culvert shape that will best fit the waterway of the channel or stream. In narrow deep channels, a small number of large diameter pipes or box culverts are usually appropriate. In flat areas having no well defined waterway the flood may be larger in volume, but of shallow depth. A number of separate culverts spread over the width of the flooded area may be more appropriate for these conditions.

Special consideration should be given to multiple cell culverts where the approach flow is of high velocity, particularly if supercritical. These sites are best suited to a single cell or special inlet treatment to avoid adverse hydraulic jump effects.

27.2.5 Increasing Capacity of Culverts

Changed landuse, such as urbanisation upstream from an existing crossing may increase the magnitude of flooding and necessitate increasing the culvert capacity to accommodate additional flow without exceeding a given headwater elevation. Before deciding that the culvert has to be replaced by a larger structure, (assuming relief flow is not feasible), the possibility of improving the inlet of the existing culvert should be investigated (see Section 27.9 for details of improved inlet culverts).

27.2.6 Culverts in Flat Terrain

In flat terrain, drainage channels are often ill-defined or non-existent and culverts should be located and design for least disruption of the existing flow conditions. In these locations multiple culverts can be considered to have a common headwater elevation, although this will not be precisely so. Figure 27.4 illustrates a design technique that can be used to determine the combined capacity of multiple culverts with different invert levels and capacities. The total discharge at any point of the headwater elevation for culverts 1 and 2, on Figure 27.4, is the sum of the discharges Q_1 and Q_2 .

In flat terrain it may be necessary to construct levee banks, as shown on Figure 27.5, to achieve the design headwater at the culvert location. This is only possible if there is no danger of increased flooding of upstream properties. Therefore, approval of the local drainage Authority must be obtained prior to construction of any such levee bank.

27.2.7 Site Investigation

A site investigation must be carried out at each proposed culvert site. The extent and complexity of the investigation will depend on the size, importance and cost of the proposed culvert, site conditions, the height of the embankment and the loading that will be imposed on the foundation material and on the culvert itself.

Survey information should be sufficient to permit the culvert to be located in plan and profile and should include relevant physical features. In flat terrain the elevation of

important buildings upstream, such as houses, commercial property, roads or railways should be recorded, if they are likely to be affected by backwater.

At sites where the stage-discharge curve may have to be calculated by the Slope Area Method, as is often the case in urban or developing areas and for all major culverts, the survey should include a cross-section of the channel and floodplain and a water surface profile extending a sufficient distance upstream and downstream to establish the longitudinal stream gradient.

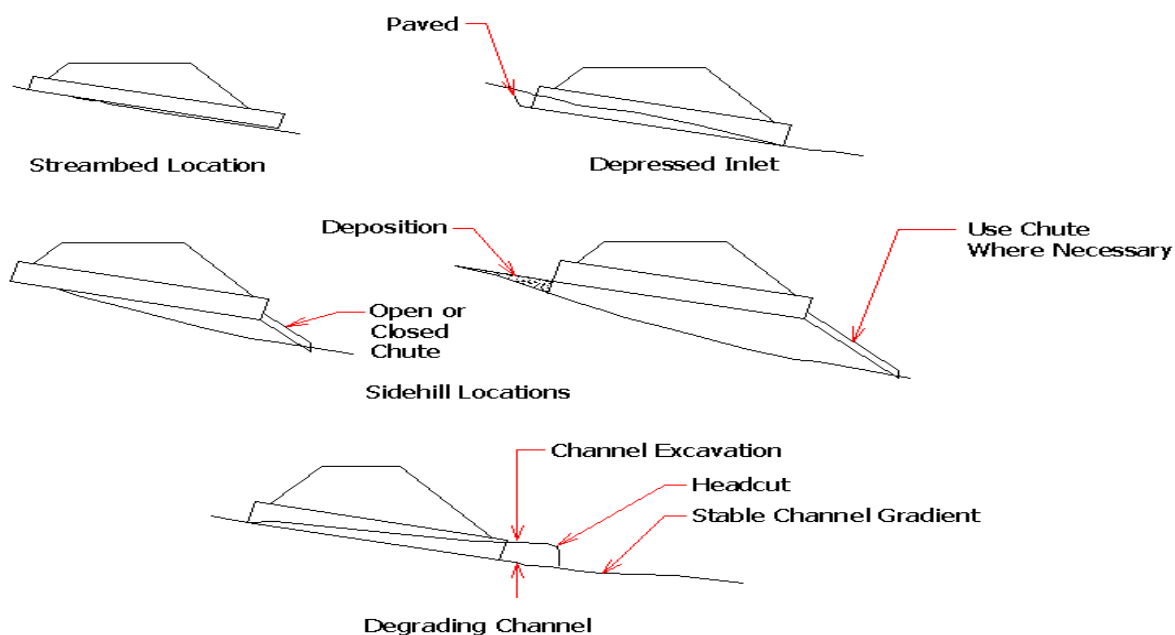


Figure 27.3 Possible Culvert Profiles

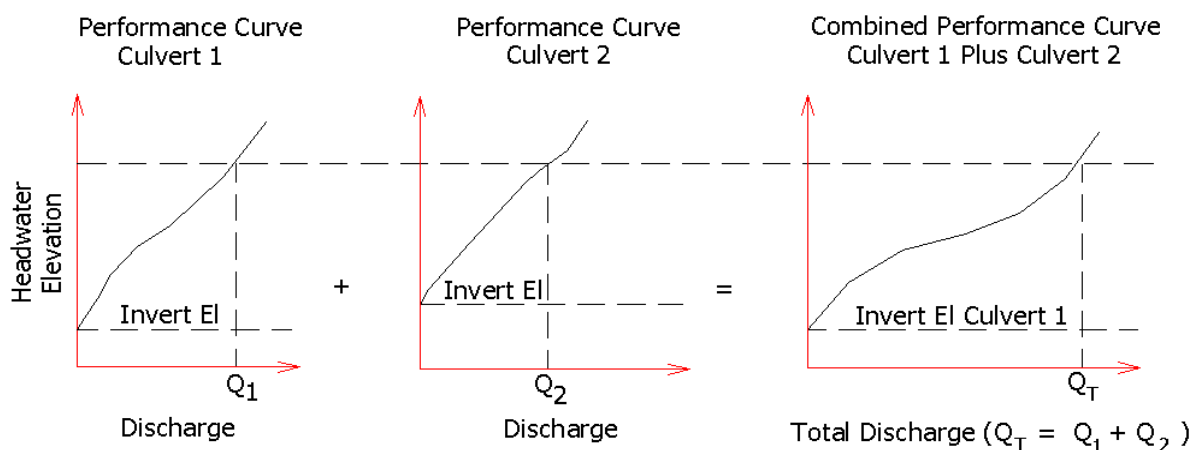


Figure 27.4 Stage-Discharge Curve for Multiple Culverts with Different Invert Levels

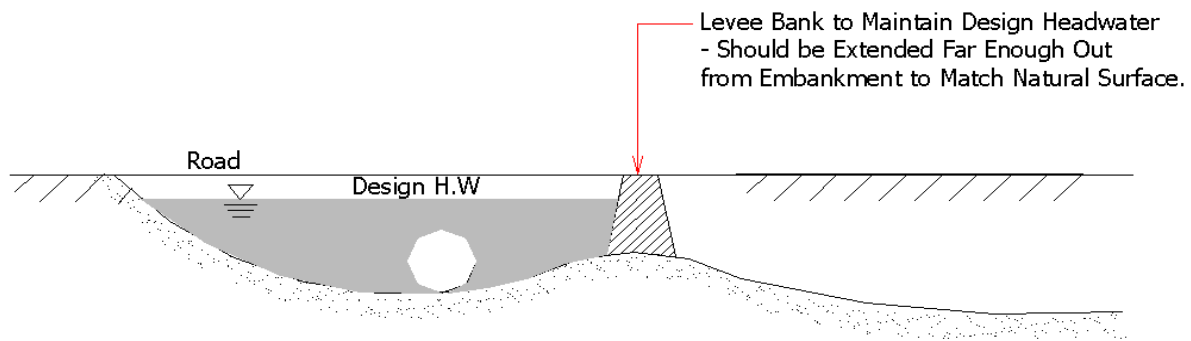


Figure 27.5 Development of Headwater

In scour prone areas, soil characteristics should be assessed to enable stream protection strategies to be formulated. The design engineer should also know the nature of the subsoil material underlying the stream bed, unless it is obvious that it is sound bed-rock or other material, which will not cause foundation problems. Detailed foundation investigations should be carried out for all large culverts, unless it is certain that they will be founded on sound bed-rock.

27.2.8 Safety

Traffic safety – An exposed culvert end (projecting from the plane of the batters) acts as an unyielding obstruction, which is likely to bring an out of control vehicle to an abrupt stop, causing considerable damage to the vehicle and high deceleration forces on the occupants.

Where a road safety barrier is not provided, culvert ends should be designed so that they will not present an obstruction to vehicles running off the road. This can be achieved by covering exposed sides with fill, providing headwalls or wingwalls which will not present an obstruction, or mitreing culvert ends flush with the embankment surface.

The location of culvert ends placed flush with the embankment slope should be indicated by markers to reduce hazards to equipment operators and others. High culverts in populated areas should be fenced whenever possible.

The hazard presented by culverts under private and side-road entrances should be minimised by placing them as far as practicable from the roadway and avoiding the use of headwalls.

Child safety – Culverts can also be an attraction for adventurous and inquisitive children. At locations where long culverts could be a hazard, especially in urban areas, fencing, swing gates or grates at upstream ends should be considered to prevent entry. However, this may cause blockages and reduce the efficiency of the culvert.

27.2.9 Culvert as Flow Measuring Device

As stream flow records for small catchments are very scarce, any reliable supplementary data gathered during or after major floods are of considerable value. A convenient way of deriving such data is to measure high water marks at culverts after major floods and then to estimate the actual flood flows, which pass through the culvert (see Section 27.4). The calculated discharge can then be related to the catchment characteristic and used to verify or improve existing runoff estimation methods. Careful identification and measurement of high water marks is essential and should be carried out as soon as possible after the flood, before the evidence disappears.

27.2.10 Design Documentation

Records of culvert designs should be retained for at least the lives of the culverts. The amount and detail of documentation should be related to the importance of the structure. The following data would normally be retained for large culverts:

- Field notes and data
- Site plan, profiles and cross-sections
- Soil data
- Summary of calculations
- Design flood frequency
- Headwater depth
- Outlet velocity
- Culvert drawings
- Rationale for culvert choice
- Photographs of site and developments, if there is a possibility of future claims resulting from the hydraulic performance of the culvert.
- Flood data observed during and after construction of the culvert.

27.3 HYDRAULICS

27.3.1 General

The flow hydraulics in the culvert is normally either under condition of full flow in closed conduit or part full flow under uniform flow or non-uniform flow. The fundamental hydraulic principles under these two flow conditions were described in Chapter 12.

The most important consideration in culvert hydraulics is whether the flow is subject to inlet or outlet control. Figures 27.6 and 27.7 show the range of flow types commonly encountered in culverts. For inlet control two distinct regimes exist, depending on whether the inlet is submerged or not submerged. Outlet control occurs in long culverts, laid on flat grades and with high tailwater depths. In designing culverts, the type of control is determined by the greater of the headwater depths calculated for both inlet control and outlet control.

For the two types of control, different factors and formulae are used to calculate the hydraulic capacity of a culvert. Under inlet control, the cross-sectional area of the culvert cell, the inlet geometry and the amount of headwater or ponding at the entrance are of primary importance. Outlet control involves the additional consideration of the elevation of the tailwater in the outlet channel and the slope, roughness and length of the culvert cell.

27.3.2 Control at Inlet

For culverts subject to inlet control, the important factors are entrance conditions, including the entrance type, existence and angle of headwalls and wingwalls and the projection of the culvert into the headwater pond.

For one dimensional flow, the theoretical relation between discharge and upstream energy can be computed by an iterative process or by the use of nomographs.

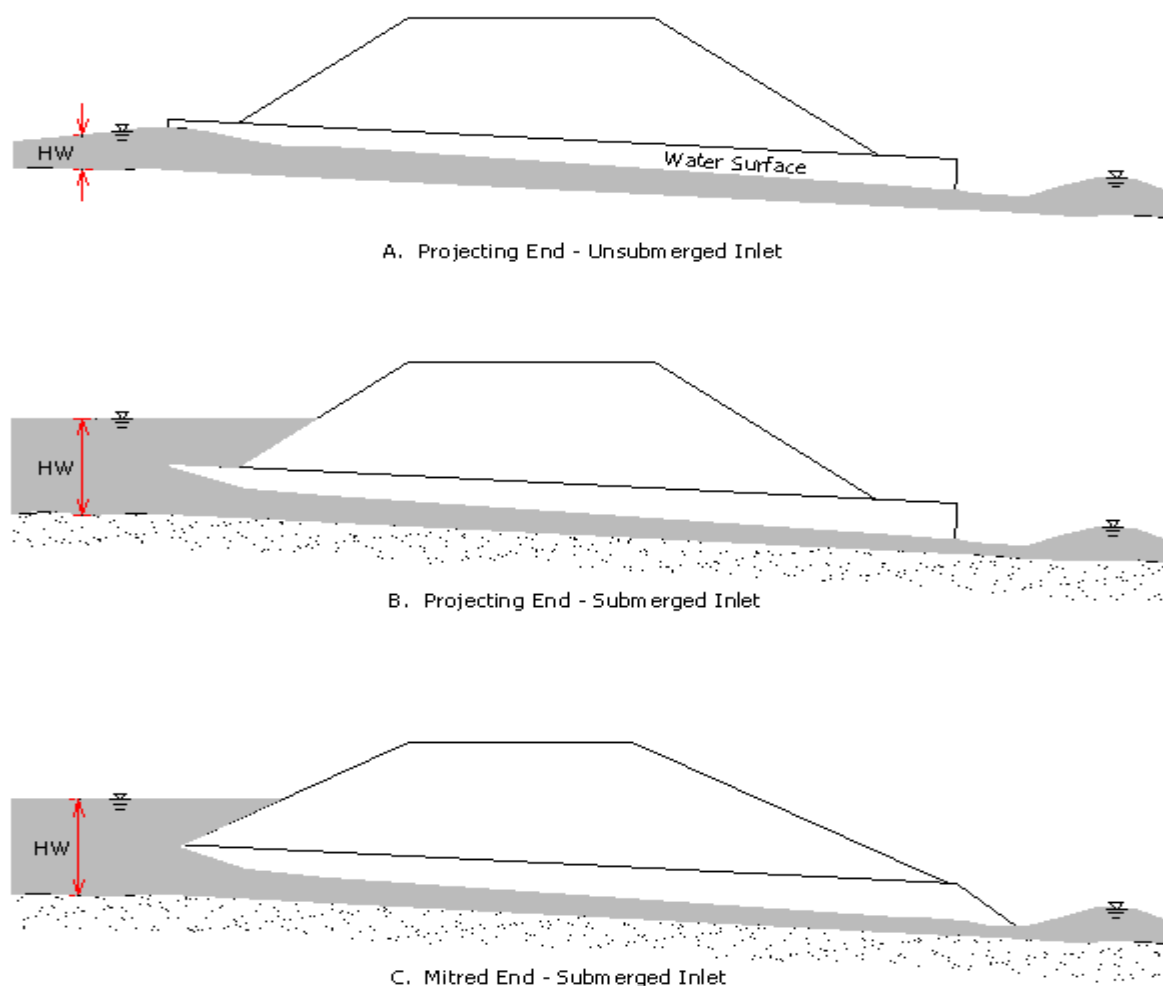


Figure 27.6 Flow Profiles for Culvert under Inlet Control

Inlet control can occur with the inlet submerged and the outlet not submerged (Figure 27.6). Sketches of inlet control flow for both unsubmerged and submerged projecting entrances are shown on Figure 27.6(a) and 27.6(b). Figure 27.6(c) shows a mitred entrance flowing submerged with inlet control. Under inlet control, the flow contracts to a supercritical jet immediately downstream from the inlet. When the tail water depth exceeds critical depth h_c and the culvert is laid on a steep grade, flow remains supercritical in the cell and a hydraulic jump will form near the outlet. If the culvert is laid on a slope less than critical, then a hydraulic jump will form within the culvert.

In inlet control the roughness and length of the culvert cell and the outlet conditions (including depth of tail water) **are not factors in determining culvert capacity**. An increase in the slope of culvert reduces headwater only to a small degree and can normally be neglected for conventional culverts flowing under inlet control.

27.3.3 Control at Outlet

Culverts flowing with outlet control can flow with the culvert cell full or with the cell part full for all of the culvert length. With outlet control and both inlet and outlet submerged (Figure 27.7(a)) the culvert flows full under pressure. The culvert can also flow full over part of its length, then part-full at the outlet (Figure 27.7). The point at which the water surface breaks away from the culvert crown depends on the tailwater depth and culvert grade and can be determined by using backwater calculations. If the culverts is laid on a flat grade, outlet control can occur with both inlet and outlet not submerged (Figure 27.7) and part full flow throughout the cell is subcritical. Minor variations of these main types can occur, depending on the relative value of critical slope, normal depth, culvert height and tailwater depth.

The procedure given in Section 27.4 provides methods or the accurate determination of headwater depths for the full flow condition and for the case of the cell part-full over part of the culvert length. The method given for the condition of the cell part full, over the total length, gives a solution for headwater depth that decreases in accuracy as the headwater decreases.

(a) Determination of Energy Head (H)

The head, H (Figure 27.7) or energy required to pass a given flow through a culvert operating under outlet control is made up of three major parts. These three parts are usually expressed in metres of water and include a velocity head, H_v , an entrance loss, H_e and a friction loss, H_f . The energy head is expressed in equation form as:

$$H = H_v + H_e + H_f \quad (27.1)$$

The velocity head, H_v is given by,

$$H_v = \frac{V^2}{2g} \quad (27.2)$$

where V is the mean velocity in the culvert cell and g is the acceleration due to gravity. The mean velocity is the discharge, Q , divided by the cross-sectional area A of the cell.

The entrance loss is expressed as,

$$H_e = K_e \frac{V^2}{2g} \quad (27.3)$$

The entrance loss coefficient, K_e , depends on the inlet geometry primarily through the effect it has on contraction of the flow. Values of K_e determined from experiment, range from 0.2 for a well rounded entrance, through 0.5 for a square edged inlet in a vertical headwall to 0.9 for a sharp pipe (e.g. corrugated steel) projecting from an embankment. K_e coefficients are given on Design Chart 27.2.

Since most engineers are familiar with Manning's n , the following expression is used to calculate the friction loss, H_f along the conduit:

$$H_f = \frac{2gn^2L}{R^{1.33}} \times \frac{V^2}{2g} \quad (27.4)$$

where,

- n = Manning's friction factor
- L = length (m) of culvert cell
- V = mean velocity (m/s) of flow in culvert cell
- g = acceleration due to gravity
= 9.80 m/s²
- R = hydraulic radius (m) = A/W_p
- A = area (m²) of flow for full cross-section
- W_p = wetted perimeter (m)

Substituting in Equation 27.1 and simplifying, we get for full flow:

$$H = \left[1 + K_e + \frac{2gn^2L}{R^{1.33}} \right] \frac{V^2}{2g} \quad (27.5)$$

Figure 27.8 shows the terms of Equation 27.5, the energy line, the hydraulic grade line and the headwater depth, HW . The energy line represents the total energy at any point along the culvert cell. **The hydraulic grade line is defined as the pressure line to which water would rise in small vertical pipes attached to the culvert wall along its length.** The difference in elevation between these two lines is the velocity head, $\frac{V^2}{2g}$.

By referring to Figure 27.8 and using the culvert invert at the outlet as datum, we get:

$$H = h_1 + \frac{V_1^2}{2g} + LS - h_2 = H_v + H_e + H_f \quad (27.8)$$

$$h_1 + \frac{V_1^2}{2g} + LS = h_2 + H_v + H_e + H_f \quad (27.6)$$

Then,

$$h_1 + \frac{V_1^2}{2g} + LS - h_2 = H_v + H_e + H_f \quad (27.7)$$

and,

Equation 27.5 can be readily solved for H by the use of the full flow nomographs in Design Charts 27.3 to 27.5.

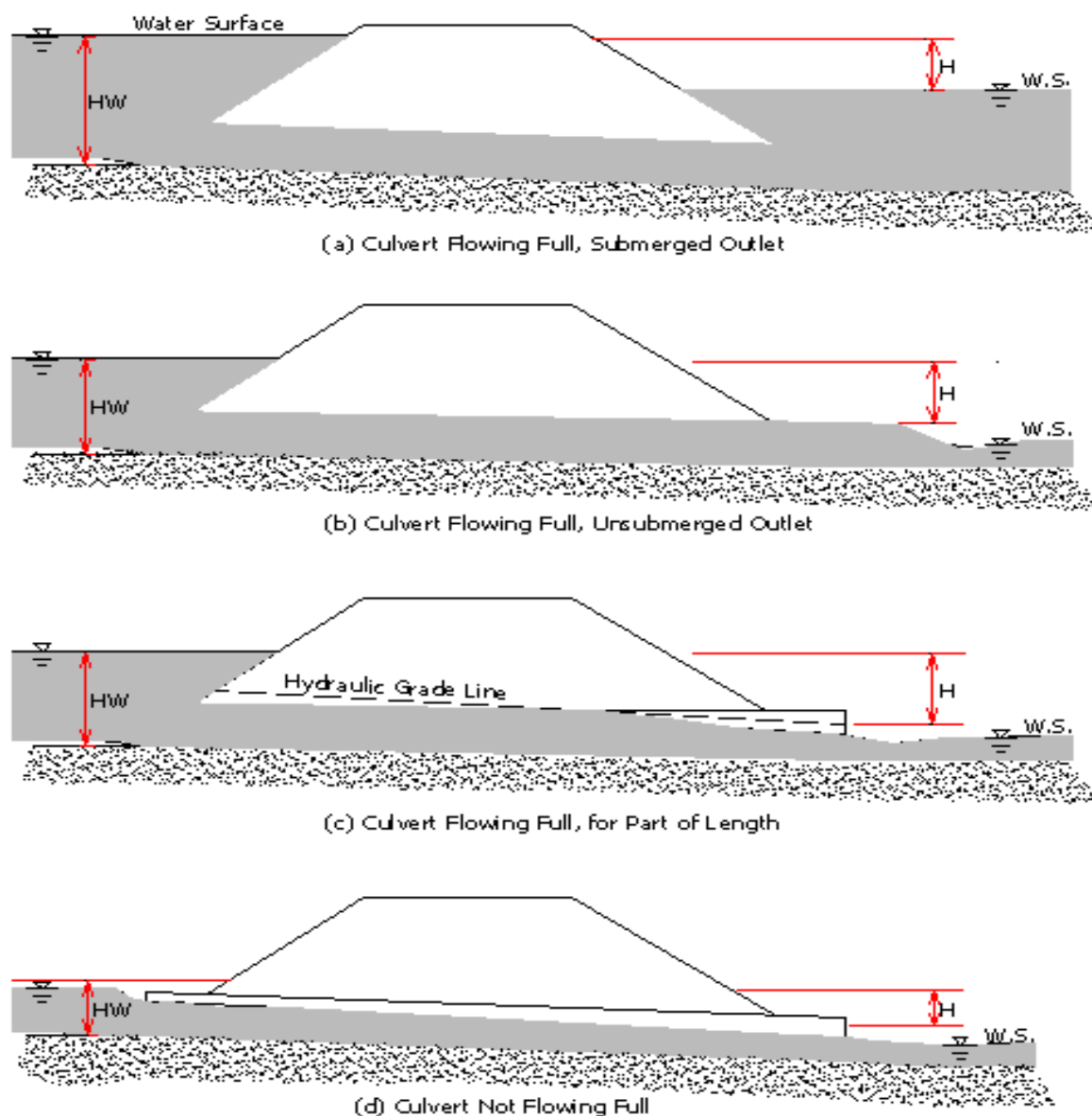


Figure 27.7 Flow Profiles for Culvert under Outlet Control

The head, H can be added to this level in calculating HW_0 . The relationship of h_0 to the other terms in Equation 27.9 for this situation is illustrated on Figure 27.10.

As the discharge decreases the situation approaches that of Figure 27.7(d). For design purposes, this method is satisfactory for calculated headwater depths above $0.75D$. For smaller values of headwater, more accurate result can be obtained by flow profile calculations or by the use of the capacity charts from Hydraulic Engineering Circular No 10 (US Federal Highway Administration, 1972).

27.4 DESIGN PROCEDURE

The design engineer should be familiar with all the equations in the previous Section before using these procedures. Following the design method without an understanding of culvert hydraulics can result in an

inadequate, unsafe, or costly structures. The procedures does not address the effect of storage. The design procedure is summarised on the Culvert Design Flowchart, Figure 27.11.

1. Assemble Site Data

- Site survey and locality map.
- Embankment cross-section.
- Roadway profile.
- Photographs, aerial photographs.
- Details from field visit (sediment, debris and scour at existing structure).
- Design data for nearby structures.
- Studies by other authorities near the site, including small dams, canals, weirs, floodplains, storm drains.
- Recorded and observed flood data.

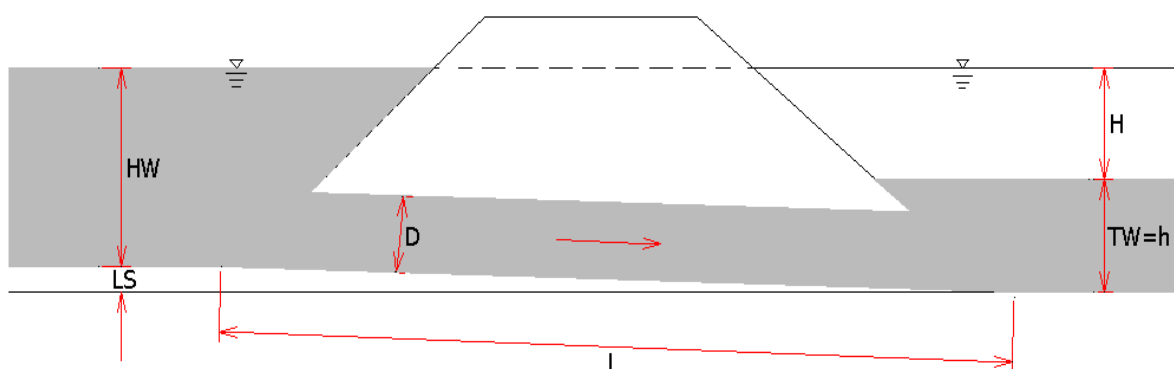


Figure 27.9 Determination of h_0 for High Tailwater

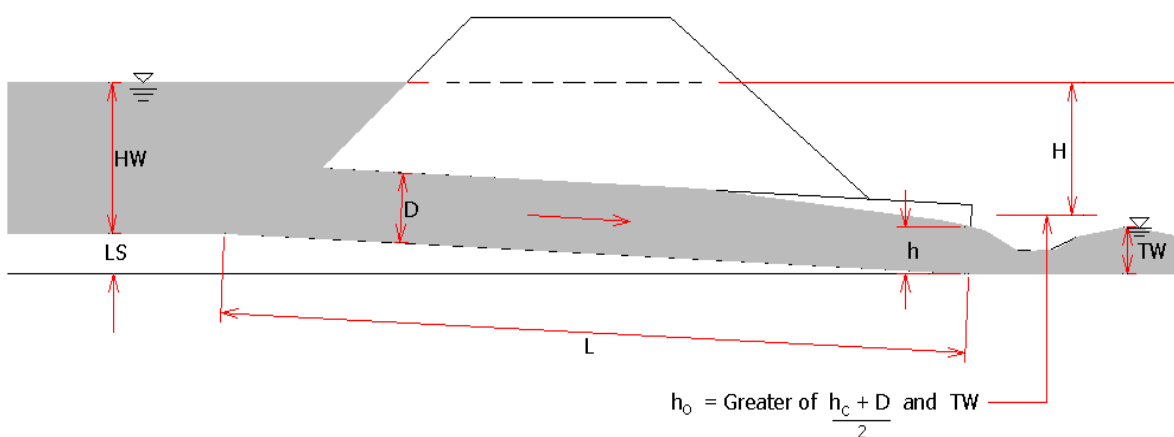


Figure 27.10 Determination of h_0 for Tailwater Below Top of Opening

2. Determine Design Flood Discharge

Determine ARI of design flood – see Chapter 4.
Determine design flood discharge, Q – see Chapter 14.

3. Commence Summarising Data on Design Form

See Design Chart 27.1 in Appendix 27.A.

4. Select Trial Culvert

- (i) Choose culvert material, shape, size and entrance type.
- (ii) Determine the initial trial size of culvert, either by arbitrary selection or by assuming a velocity (say 3 m/s) and calculating a culvert area from $A = Q/V$

5. Determine Inlet Control Headwater Depth, HW_i – Use inlet Control Design Charts 27.3 to 27.5.

The nomographs cover various culvert types and inlet configurations. Each nomograph has an example on it which is self-explanatory. Using the trial culvert size, the relevant nomograph can be used to calculate HW_i given a known Q . They can also be used in reverse to calculate Q given a known HW_i .

It should be noted that where the approach velocity is considerable, the approach velocity head can be calculated and deducted from the calculated HW_i to give the actual physical head required.

6. Determine Depth, h_o for Outlet control

- (i) Calculate both $(h_c + D)/2$ and the tailwater, TW from known flood levels, downstream controlling levels or from the Slope Area Method. If it is clear that the downstream tailwater conditions do not control, take $h_o = (h_c + D)/2$. h_c can be calculated from Design Charts 27.8 or 27.9. If h_c exceeds D then take h_c as D .
- (ii) h_o is the larger of TW or $(h_c + D)/2$

7. Determine Outlet Control Headwater Depth at Inlet, HW_o

- (i) Determine entrance loss coefficient, K_e from Design Chart 27.2.
- (ii) Calculate the losses through the culvert, H using the outlet control nomographs, Design Charts 27.10 to 27.12 (or Equation 27.5 if outside the range). As with the inlet control nomographs, these nomographs cover various culvert types and each nomograph has an self-explanatory example on it.

- (iii) If the Manning's n value of the culvert under consideration differs from the Manning n value shown on the nomograph, this can be allowed for by adjusting the culvert length as follows:

$$L_1 = L \left(\frac{n_1}{n} \right) \quad (27.12)$$

where,

L_1 = adjusted culvert length

L = actual culvert length

n_1 = desired Manning n value

n = Manning n value given on the nomograph

- (iv) Calculate $HW_o = H + h_o - LS$

As with inlet control, where the approach velocity is considerable, the approach velocity head can be calculated and deducted from the calculated HW_o to give the actual physical head required.

- (v) If HW_o is less than $0.75D$ and the culvert is under outlet control, then the culvert may be flowing only part full and using $(h_c + D)/2$ to calculate h_o may not be applicable. If required, more accurate results can be obtained by flow profile calculations or the use of Hydraulic Engineering Circular No 10 (as discussed in Section 27.3.3 under (ii) tailwater depth at or below top of opening).

8. Determine Controlling Headwater, HW_c

Compare HW_i and HW_o and use the higher:

If $HW_i > HW_o$ the culvert is under inlet control and $HW_c = HW_i$

If $HW_o > HW_i$ the culvert is under outlet control and $HW_c = HW_o$

9. Calculate Outlet Velocity, V_o

The average outlet velocity will be the discharge divided by the cross-sectional area of flow at the culvert outlet. The cross-sectional area of flow depends, in turn, on the flow depth at the outlet.

If inlet control is the controlling headwater, the flow depth can be approximated by calculating the normal depth, y_n , for the culvert cross-section using Manning's Equation. The flow area, A is calculated using y_n and the outlet velocity:

$$V_o = \frac{Q}{A} \quad (27.13)$$

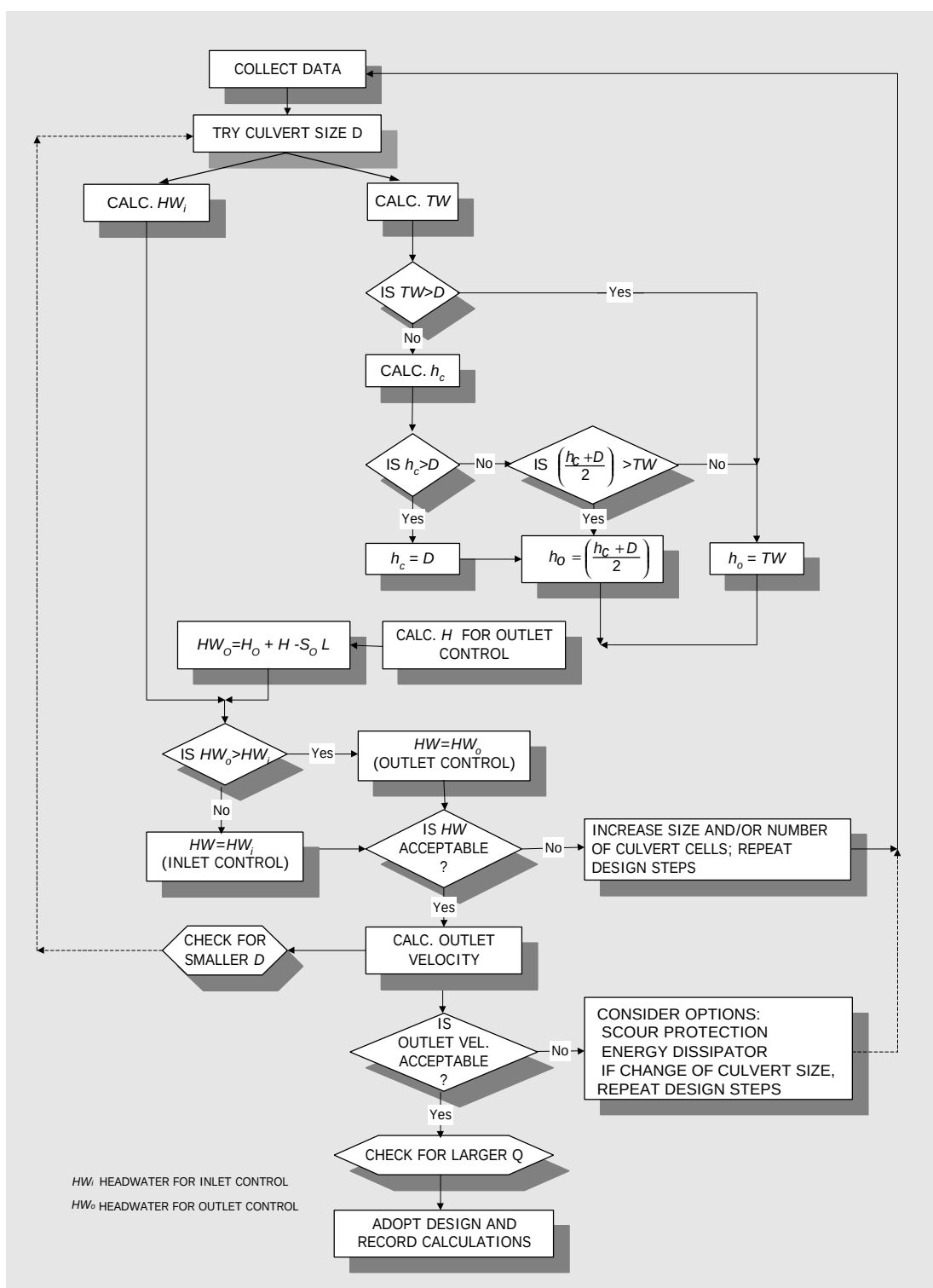


Figure 27.11 Design Flow Chart

The outlet velocity computed utilising the normal depth, y_n , will usually be high, because the normal depth is seldom reached in the relatively short length of average culvert.

If outlet control is the controlling headwater, the flow depth can be either critical depth h_c , the tailwater depth TW (if below the top of the culvert), or the full depth D of the culvert depending on the following relationships:

- Use h_c , if $h_c > TW$
- Use TW , if $h_c < TW < D$
- Use D , if $D < TW$

Calculate flow area using appropriate flow depth and then outlet velocity using Equation 27.13.

10. Review Results

Compare alternative design with the site constraints and assumptions. If any of the following conditions are not met, repeat steps 4 to 9:

- The culvert must have adequate cover.
- The final length of the culvert should be close to the approximate length assumed in design.
- The headwalls and wingwalls must fit the site.
- The allowable headwater should not be exceeded.
- The allowable overtopping flood frequency should not be exceeded.

The performance of the culvert should also be considered, (i) with floods larger than the design flood to ensure such rarer floods do not pose unacceptable risks to life or potential for major damage and (ii) with smaller floods than the design flood to ensure that there will be no unacceptable problems of maintenance.

If outlet velocity is high, scour protection or an energy dissipater (see Section 27.8.5) may be required.

11. Improved Designs

Under certain conditions more economic designs may be achieved by consideration of the following:

- The use of an improved inlet for culverts operating under inlet control (see Section 27.9).
- Allowing ponding to occur upstream to reduce the peak discharge, if a large upstream headwater pool exists.

12. Documentation

Prepare report and file background information. See 'Design Documentation' in Section 27.2.10.

27.5 COMPUTER MODELLING

HEC-2 Water Surface Profiles, (Hydrologic Engineering Centre, US Army Corps of Engineers) is a widely-used general purpose program with advanced culvert design features which is available in the public domain. The revised version, September 1991, includes the hydraulic design of culverts using the US Federal Highway Administration culvert design methods. A commercial development, HEC-RAS, is also available.

Several computer programs have been developed specifically for the hydraulic design of culverts, including:

- XP-Culvert2000, distributed by XP Software, Canberra, Australia.
- Waterflow, Hydraulic Design of Culverts, Distributed by Roads and Traffic Authority, Wagga Wagga, NSW Australia.

Further information on computer modelling is given in Chapter 17.

27.6 DEBRIS CONTROL

27.6.1 General

All too often floods have clearly demonstrated how the performance of culverts can be affected by an accumulation of debris at inlets. This accumulation can cause failure of the drainage structure, possibly resulting in overtopping of the roadway by floodwaters, with ensuing damage to the embankment or to the properties upstream and downstream of the culvert.

Experience has shown that in non-urban areas, the following stream characteristics tend to produce the most serious debris problems:

- Susceptibility of stream to flash flood, i.e. relatively impervious watersheds with moderate or steep gradients.
- Actively eroding banks bordered by trees or large shrubs
- Relatively straight unobstructed stream channels with no sharp bends.
- Cleared land upstream with fallen trees on the ground.

In urban areas there is additional potential for debris to enter waterways and cause blockage. The risk of debris blockage is very high in all urban areas in Malaysia.

Precautions to be taken range from providing freeboard, and taking design precautions to providing elaborate debris control structures.

27.6.2 Freeboard

All culverts with a waterway area of 1.0 m² or more should be designed with a minimum of 300 mm freeboard above the design water level. For large culverts the designer should consider increasing this freeboard to allow for the size of debris anticipated, up to a maximum of 1000 mm.

27.6.3 Design Precautions

Where debris accumulation is considered to be a problem, other design precautions should be taken, such as providing a smooth well designed inlet, avoiding multiple cells and increasing the size of culvert. If multiple cells are unavoidable, provision of a sloping cutwater on the upstream pier (wall) ends may help to align floating debris with the culvert entrance.

27.6.4 Relief Culvert

A relief culvert passing through the embankment at a higher level than the main culvert permits water to by-pass the latter, if it becomes blocked. The relief culvert could also be placed at a low level some distance away from the main culvert where it is not likely to be blocked. As this relief culvert is an additional requirement, the cost of both culverts should be compared with that of a larger culvert that will be less subject to blockage.

27.6.5 Debris Control Structures

These can be costly both to construct and maintain. Details of the various types of debris control structures may be found in Hydraulic Engineering Circular No 9, "Debris Control Structures" (US Federal Highway Administration, 1971). The choice of structure type depends upon size, quantity and type of debris, the cost involved and the maintenance proposed. However, for existing culverts, which are prone to debris clogging, it may be worthwhile to construct a debris control structure rather than replace or enlarge the culvert.

27.7 CULVERT END TREATMENT

27.7.1 Introduction

The term "end treatment" encompasses the shape of the culvert ends, end structures such as wingwalls, cut-offs and anchorages and erosion control measures for the adjoining fill and channel (see Standard Drawings SD F-21 to SD F-24). The design of hydraulically improved inlets is discussed separately in Section 27.9.

Culvert end treatment may be required to perform one or more of the following functions:

- To increase the hydraulic efficiency of the culvert;
- To prevent fill from encroaching on the culvert opening;

- To prevent erosion of the fill and adjacent channel;
- To prevent undermining of culvert ends;
- To inhibit the seepage and piping through the bedding and backfill;
- To meet traffic safety requirements (see Section 27.2.8);
- To improve the appearance of large culverts;
- To resist hydraulic uplift forces on corrugated metal pipe culverts; and/or
- To strengthen the ends of large flexible culverts, especially those with mitred or skewed ends.

Cut-offs in the form of a vertical wall, constructed below the end apron of a culvert, should always be provided at culvert inlets to prevent undermining and piping. For corrugated metal pipe culverts, the cut-off walls also act to counteract uplift at the culvert inlet.

27.7.2 Typical End Treatments

Headwalls and wingwalls – are the most common end treatment in overseas countries. An apron is generally incorporated between the wingwalls to limit scour of the stream bed. They are usually constructed from reinforced concrete, but can be formed from masonry, or rock filled gabions and mattresses, or concrete filled mattresses.

Mitred ends – these are generally limited to corrugated metal pipe culverts, where the end of the pipe is cut parallel to the slope of the embankment. The area of embankment around the ends of the culverts is usually paved with concrete or rock.

Projecting ends – where the ends of the culvert project from the face of the embankment. Although they are the least costly end treatment, they are hydraulically inefficient, do not meet safety requirements and are visually objectionable. For these reasons their use in Malaysia is not recommended.

27.8 FLOW VELOCITY

Culverts usually increase the flow velocity over that in the natural water course. Except when the culverts flow full, the highest velocity occurs near the outlet and this is the point where most erosion damage is likely to occur.

A check on outlet velocity, therefore, must be carried out as part of the culvert design if the outlet discharges to an unlined waterway.

27.8.1 Inlet Control

For a pipe culvert flowing with inlet control the outlet velocity can be determined from Figure 25.B1 to 25.B4 in Chapter 25, Appendix 25.B ($k = 0.6$) in combination with charts for part full flow in Chapter 12.

Figures 25.B1 to 25.B4 were derived from the Colebrook – White equation (in Chapter 12) for $k = 0.06$ to 0.6 . This approach assumes that the depth of flow at the outlet equals the depth corresponding to uniform flow, but the short length of the average culvert mostly precludes this, making this approach conservative.

The depth of flow should be checked against critical depth as determined from Design Charts 27.8 or 27.9. If the flow is supercritical the effect of a hydraulic jump must be considered.

27.8.2 Outlet Control

For outlet control the average outlet velocity will be the discharge divided by the cross-sectional area of flow at the outlet. This flow area can be either that corresponding to critical depth, tailwater depth (if below the crown of the culvert) or the full cross section of the culvert barrel.

27.8.3 Erosion of Conduit

Flow of the water subjects the conduit material to abrasion, and too fast a velocity for a given wall material will cause erosion to the conduit. Very fast flows can cause cavitation unless the conduit surface is very smooth, and this results in erosion taking place at a rapid rate. However, cavitation damage does not occur in full flowing pipes with velocity less than about $7.5 - 8$ m/s and about 12 m/s in open conduits.

The maximum velocity beyond which erosion will take place depends on factors like smoothness of conduit, quantity and nature of debris discharged and frequency of peak velocity. Commonly adopted maximum values based on experience are listed in Table 27.1.

27.8.4 Scour at Inlets

A culvert normally constricts the natural channel, forcing the flow through a reducing opening. As the flow contracts, vortices and areas of high velocity flow impinge against the upstream slopes of the embankment adjacent to the culvert. Scour can also occur upstream of the culvert, as a result of the acceleration of the flow, as it leaves the natural channel and enters the culvert.

Upstream wing walls, aprons, cut-off walls and embankment paving assist protecting the embankment and stream bed at the upstream end of a culvert.

27.8.5 Scour at Outlets

If the flow emerging from a culvert has a sufficiently high velocity and the channel is erodible, the jet will scour a hole in the bed immediately downstream and back eddies will erode the stream banks to form a circular elongated scour hole. Coarse material scoured from the hole will be deposited immediately downstream, often forming a low

bar across the stream, while finer material will be carried further downstream. Depending on the supply of sediment, the scour hole may gradually refill until after the next major flood occurs.

Table 27.1 Maximum Recommended Flow Velocities , (m/s) for various conduit materials

Material	Maximum V (m/s)
Precast concrete pipes	8.0
Precast box culverts	8.0
In situ concrete and hard packed rock (300mm min)	6.0
Beaching or boulders (250mm min)	5.0
Stones (150 – 100mm)	3.0 – 2.5
Grass covered surfaces	1.8
Stiff, sandy clay	1.3 – 1.5
Coarse gravel	1.3 – 1.8
Coarse sand	0.5 – 0.7
Fine sand	0.2 – 0.5

The provision of wing walls, headwall, cut-off wall and apron is generally all the protection that is required at culvert outlets. The judgement of design engineers, working in a particular area is required to determine the need for any further protection. Investigation of scour and outlet protection at similar culverts in the vicinity of the culvert being designed may provide guidance on whether further protection is required. Periodic site visits and inspection after major flood events will also confirm whether the protection is adequate or further protection is required.

In urban areas, the risk of outlet scour is generally unacceptable and therefore a choice must be made as to which type of scour protection is suitable for the site. The options available include the following:

- Local protection of the stream bed material, in the case of unlined drains and waterways.
- Flow expansion structure.
- An energy dissipating structure

Stream bed protection can be achieved with a concrete apron, rock riprap, or rock mattresses, or concrete filled mattresses. It is important that mattresses are anchored to the cut-off wall or apron at the culvert outlet, to stop them moving downstream. A geotextile filter is usually provided under the mattresses and may also be required

under the rock riprap. Scour protection is discussed in detail in Chapter 29.

An important parameter in the selection of an appropriate energy dissipater is the Froude Number, F_r , of the outlet flow. Where an outlet has $F_r < 1.7$, a simple apron structure, riprap, or a flow expansion structure will suffice. Where $1.7 < F_r < 3$ a riprap basin or horizontal roughness elements basin is appropriate. Where $F_r > 3$ a hydraulic jump basin will be required. Energy dissipaters are discussed in detail in Chapter 29.

27.8.6 Siltation

If the flow velocity becomes too low siltation occurs. Flow velocity below about 0.5 m/s will cause settlement of fine to medium sand particles.

To be self-cleansing culverts must be graded to the average grade of the water course upstream and downstream of the culvert, and levels must represent the average stream levels before the culvert was built.

Culvert location in both plan and profile is of particular importance to the maintenance of sediment-free culvert cells. Deposition can occur in culverts when the sediment transport capacity of flow within the culvert is less than in the stream. The following factors may cause deposition in culverts:

- Culverts often provide a wider flow width at low flows than natural streams. This results in the flow depth and sediment transport capacity being reduced.
- Point bars (deposition) form on the inside of stream bends and culvert inlet placed at bends in the stream will be subjected to deposition in the same manner. This effect is most pronounced in multiple-cell culverts with the cell 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 upstream of the culvert will induce deposition. Gravel and sand deposits are common downstream from the break in grade because of the reduced transport capacity in the flatter section.

Deposition usually occurs at flow rates smaller than the design flow rate. The deposits may be removed during larger floods, depending 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.

Siltation can also occur upstream of culverts if they are installed at incorrect levels, creating ponding areas. Such grading should generally be avoided.

27.9 IMPROVED INLET CULVERTS

27.9.1 General

The capacity of a culvert operating under inlet control can be significantly increased by providing a more efficient inlet, which reduces the flow concentration at the entrance and increases the flow depth in the cell. In outlet control, the entrance losses form only a minor part of the total head losses and major inlet improvement are not justified.

Various types of inlet improvements are discussed in this Section. A number of these are aimed merely at improving the inlet efficiency by reducing the entrance loss, K_e . These focus on headwalls, wingwalls and the end of the culvert cell. Other major types of improvement, include the provision of a fall (or steep slope) in the bed of the inlet, or tapers in the end section of the cell, or combination of these improvements. The aim of these major improvements is to increase the velocity head or the effective headwater depth.

The material in this Section is based on "Hydraulic Design of Improved Inlets for Culverts", Hydraulic Engineering Circular No. 13, (US Federal Highway Administration, 1972) and the "Hydraulic Design of Culverts" (Ontario Ministry of Transportation and Communications, 1985, which includes metric design nomographs). These references may need to be consulted for further information when undertaking the design of improved inlet culverts.

27.9.2 Bevelled Inlets

Adding bevels to a conventional culvert design with a square-edge at the periphery of the inlet opening increases culverts capacity by 5 to 20 percent. The greatest benefit occurs with high headwaters.

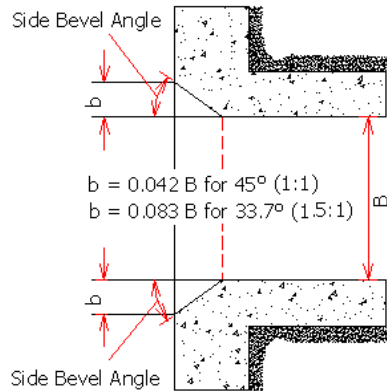
Bevelled inlets increase the hydraulic efficiency of the culvert ($K_e = 0.2$). Details of typical bevels are shown on Figure 27.12. They should be considered for all box culvert installations, which operate under inlet control. Bevelled inlets can be provided on both pre-cast and cast in-situ culverts.

The 1.5:1 bevel (33.7 degrees) is more efficient than the 1:1 bevel (45 degrees), but the latter is easier to construct and more practical. Bevels should be provided on the top and side edges of the opening.

27.9.3 Provision of Depressed Inlet

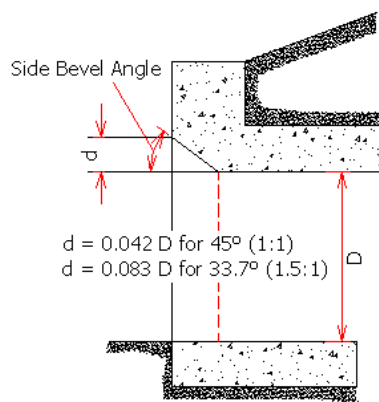
Provision of a fall or steep slope upstream from the culvert inlet may improve the capacity of a culvert operating under inlet control by increasing the velocity head. The fall may be achieved by flattening the cell slope. This may tend to induce sedimentation during low flows, but the deposit will in most cases be washed out during floods.

PLAN



(a) Side Bevels

LONGITUDINAL SECTION



(b) Top Bevel

NOTE:

1. Dimensions of Bevels Shall Not be Less than Shown.
2. Dimensions b and d are Based on the Square Dimensions of the Opening.
3. To Obtain Bevel Termination in One Plan on a Rectangular Box, either Increase d to Equal b , or Decrease the Top Bevel Angle.
4. For Multiple Cells Calculate b from Total Clear Width or $3D$, whichever is Smaller.

Figure 27.12 Bevelled Inlet for Box Culvert

The fall may be constructed within the limits of the flared wingwalls, as illustrated in Figure 27.13. The drop may also form an integral part of a slope-tapered inlet.

The fall slope should be paved to prevent upstream bed degradation and an upstream cut-off wall provided.

27.9.4 Tapered Inlets

A tapered inlet is a culvert inlet with a side-taper or a slope taper within the end section of the culvert cell. This results in an enlarged face section and a hydraulically efficient throat section. A tapered inlet may have a fall, incorporated into the inlet structure. The fall is used to provide more head on the throat section for a given headwater elevation.

A tapered inlet can sometimes greatly improve the performance of a culvert operating under inlet control. This may permit the use of a cell size considerably smaller than would be required for a conventional culvert. The greatest savings are achieved with long culverts, but the possibility of increasing the capacity of an existing undersized culvert by adding an improved inlet should not be overlooked, since it may eliminate the need for a costly replacement structure.

A disadvantage of a tapered inlet culvert is the high outlet velocity, which in some cases may necessitate an expensive outlet structure or downstream channel erosion control works. Cost comparisons between various improved inlet designs and conventional designs should be made to select that with the least overall cost.

Side Tapered Inlet – Side tapered inlets are illustrated in Figure 27.14. In some cases, they may increase flow capacity by 25 to 40 percent over that of conventional culverts with a square edge-inlet. The side tapered inlet has an enlarged face area with a tapered transition to the constant culvert cell section. The inlet face has the same height as the cell and its top and bottom are extensions of the top and bottom of the cell. The intersection of the sidewall tapers and the cell is defined as the throat section. Side-tapers may range from 6:1 to 4:1 taper being recommended as it results in a shorter inlet.

For a side-tapered inlet, there are two possible control sections the face and the throat. H_f shown on Figure 27.14, is the headwater depth measured from the face section invert and H_t is the headwater depth measured from the throat section invert. The weir crest is a third possible control section when a fall is used.

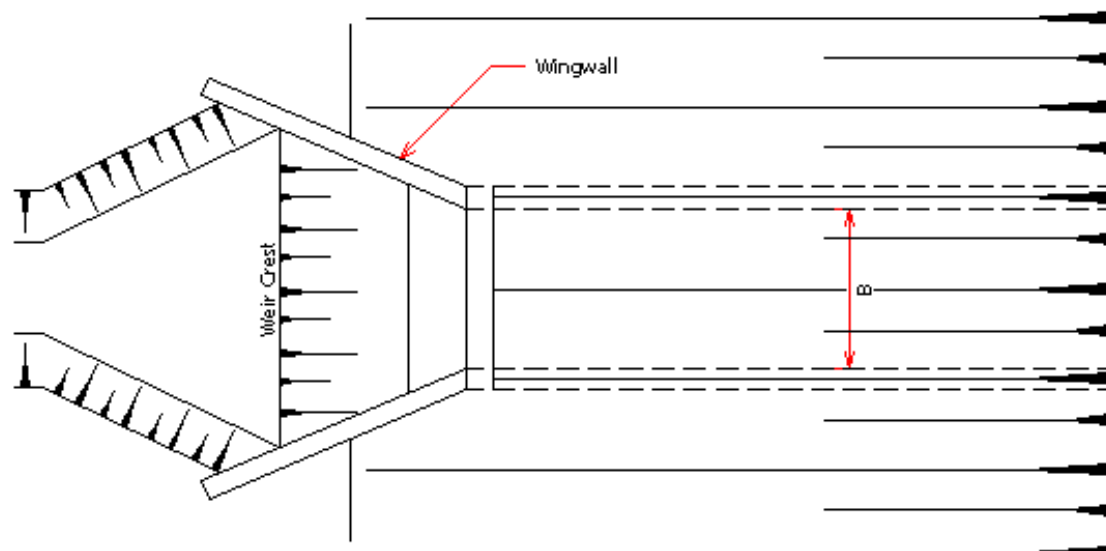
Slope Tapered Inlet – The slope tapered inlet, like the side-tapered inlet, has an enlarged face section with tapered side walls at the throat section (Figure 27.15). In addition, a steep fall is incorporated into inlet between the face and throat section. This fall concentrates more head on the throat section. At the location where the steeper slope of the inlet intersects the flatter slope of the cell, a third section, designated the bend section, is formed.

The slope-tapered inlet is the most complex inlet improvement. This type of inlet can in some instances provide a capacity more than 100% greater than that of a conventional culvert with square edges. The increase in

capacity depends largely upon the amount of fall available between the invert at the face and invert at the throat section. Construction difficulties are inherent, but the benefits in increased performance can be great. With proper design, a slope tapered inlet passes more flow at a given headwater elevation than any other configuration.

Slope-tapered inlets can be applied to both box culverts and circular pipe culverts. For the latter application, a square or round transition is normally used to connect the rectangular slope-tapered inlet to the circular pipe.

PLAN



NOTE :

Weir Slope to be Paved to Prevent Upstream Degradation where Necessary.

ELEVATION

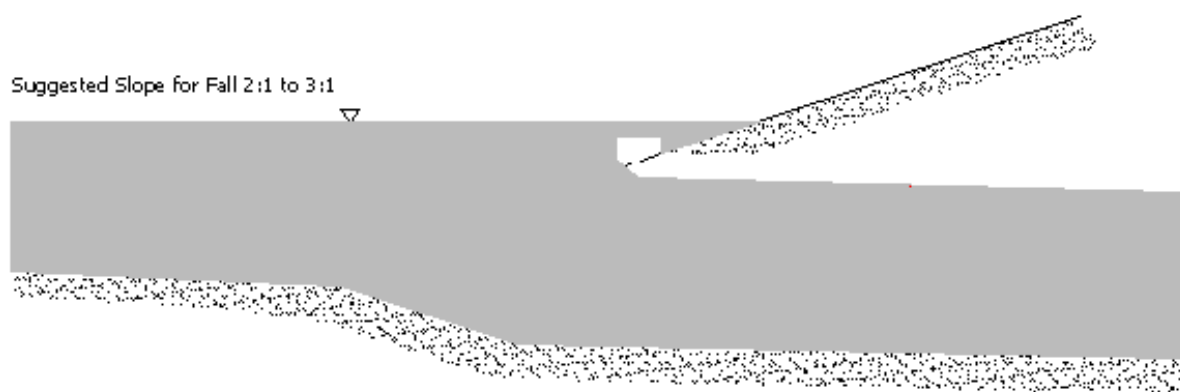


Figure 27.13 Fall for Conventional Culvert with Flared Wingwalls

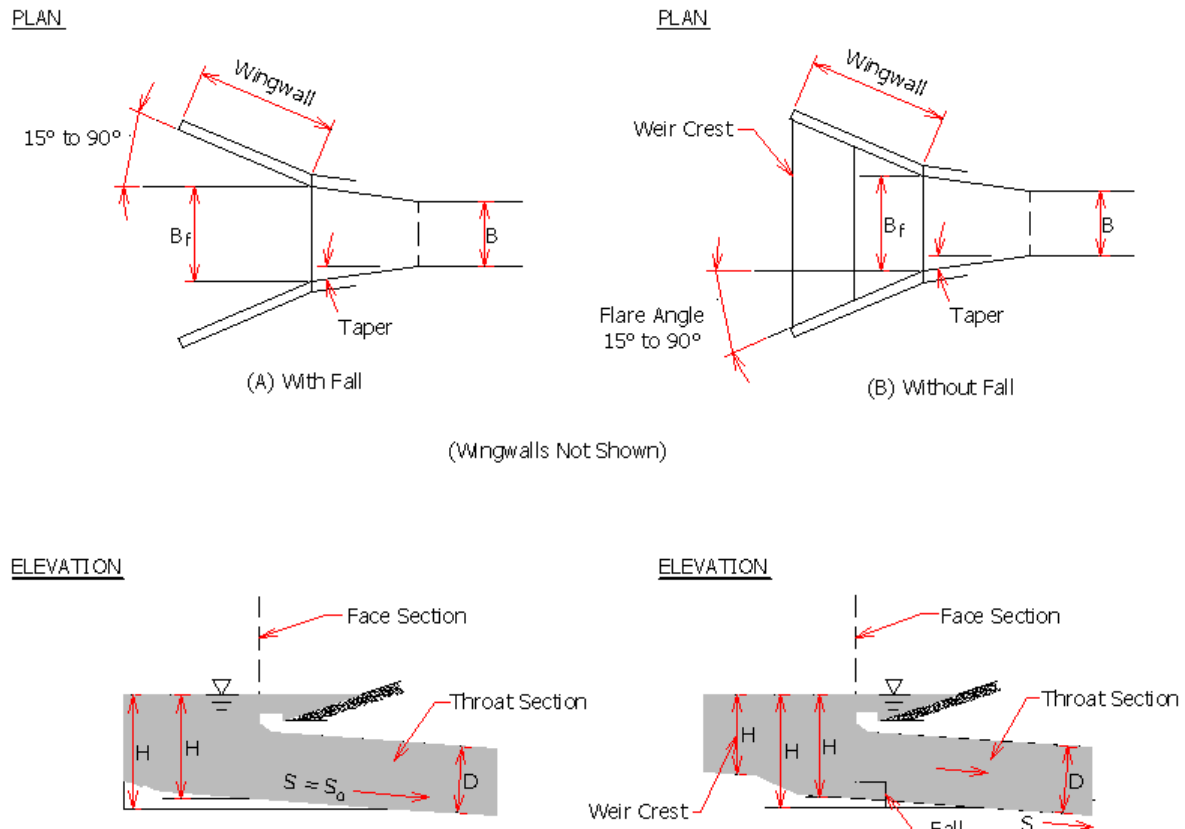


Figure 27.14 Side-Tapered Improved Inlet

27.10 MINIMUM ENERGY CULVERTS

In the coastal plains the natural slope of the land is often little more than a fraction one per thousand, which in concrete conduits laid on natural grade, grass covered channels and natural water courses results in tranquil flow (see Chapter 12).

To reduce the costs of bridging these waterways the concept of the "The Minimum Energy Culvert" was developed.

The aim of "The Minimum Energy Culvert" concept is to concentrate the flow in a narrow, deep cross section flowing with critical velocity under maximum design flow thus taking advantage of the minimum specific energy under critical flow condition (see Chapter 12). This maximises the flow per unit length of waterway crossing. By keeping the flow outside the supercritical region the designer avoids the energy loss in a hydraulic jump and the cost of having to protect against the erosion associated with the jump.

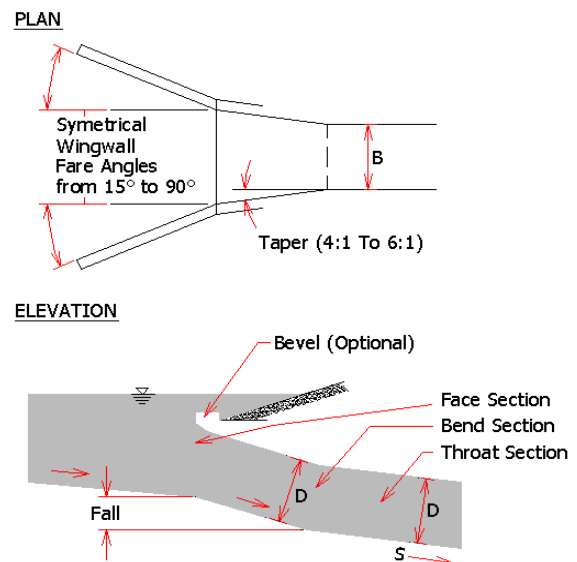


Figure 27.15 Slope-Tapered Improved Inlets for Box Culverts

The design requires knowledge of:

- Design discharge
- Average natural slope of terrain
- Flood levels
- Survey details of floodplain adjacent to culvert

On the basis of this information a plan and longitudinal section of the culvert is drawn up. (Figure 27.16). In doing so the following assumptions are made :

- The energy line parallels the natural fall of the terrain
- Energy losses at entry and exit of culvert are disregarded

The justification for the latter assumption is that losses at smooth transitions are generally small.

In this context it is worth noting that the exit expansion of the stream bed needs to progress at a smaller angle than the entry angle if the formation of standing eddies is to be avoided.

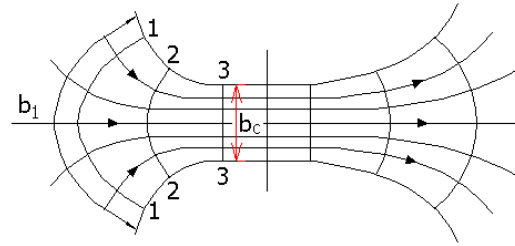
Using the equations:

$$H_{s,c} = 1.5 d_c \text{ and}$$

$$Q = b d_c \sqrt{g d_c} \quad (27.14)$$

corresponding values of b , d_c and H_s can be tried and compared.

PLAN



ELEVATION

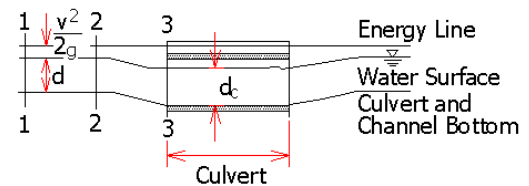


Figure 27.16 Characteristic Flow Line of Minimum Energy Culvert

One problem with minimum-energy culverts is that they are located in a dip below the drain or waterway invert, creating a potential site for ponding and sediment deposition. The potential for ponding can sometimes be minimised by a small diameter pipe drain or a channel connecting the culvert to a suitable point downstream. However this approach is not feasible if there are high sediment loads.

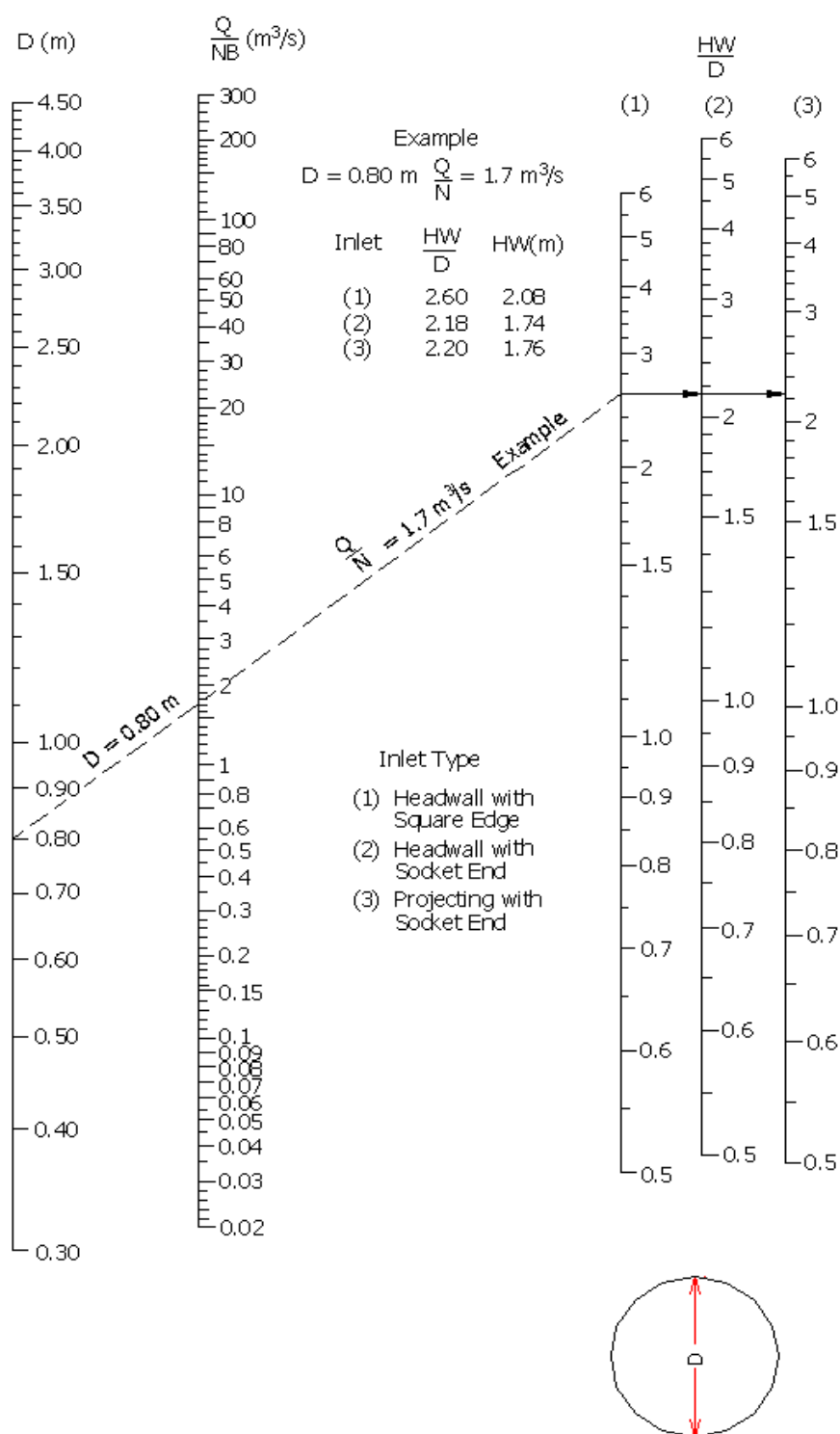
APPENDIX 27.A DESIGN FORM, CHARTS AND NOMOGRAPHS

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Coefficient K_e to apply velocity head $V^2/2g$ for determination of head loss at entrance to a culvert operating under outlet control. Entrance head loss $H_e = K_e V^2/2g$

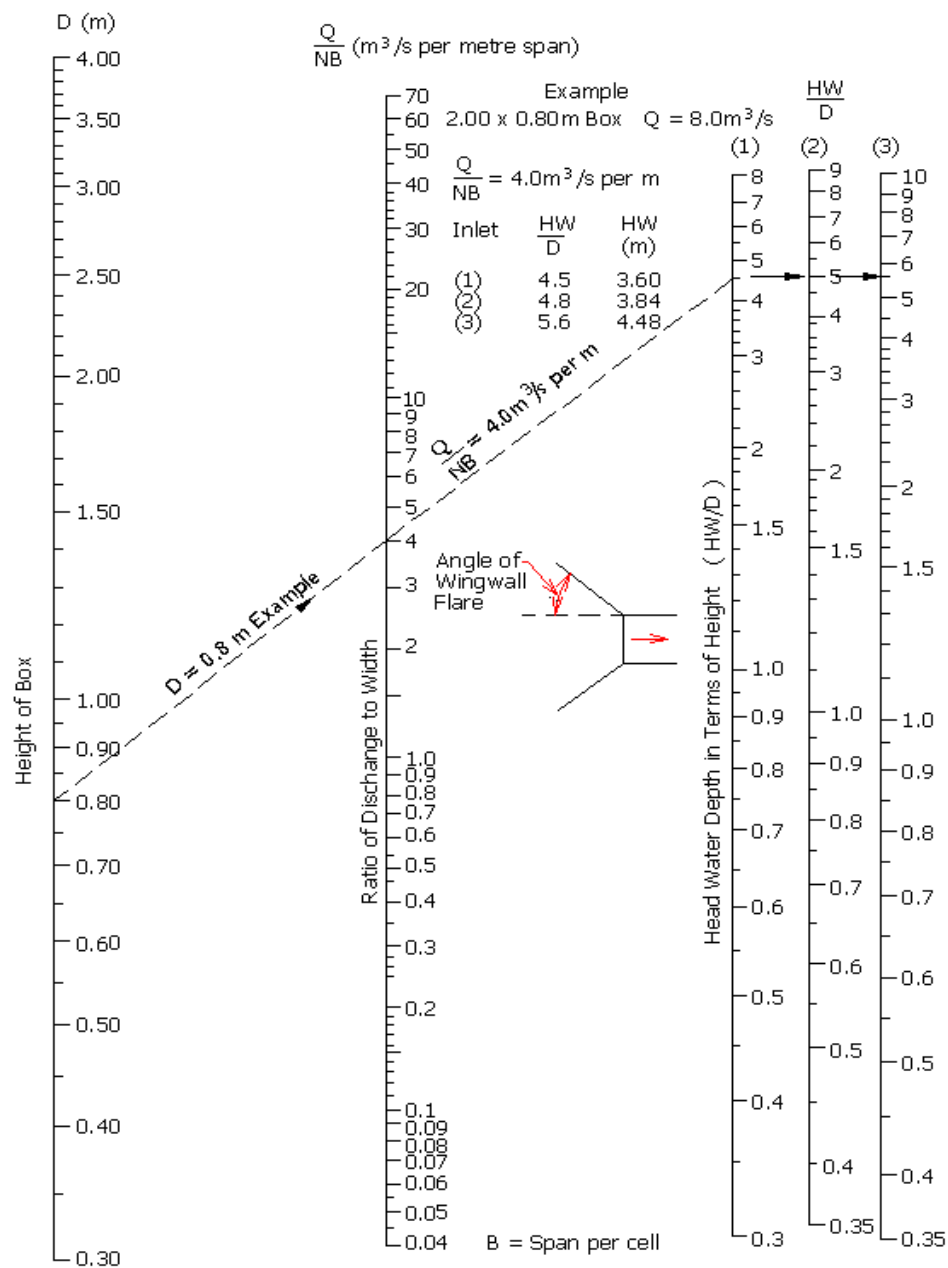
TYPE OF BARREL AND INLET	
Pipe, Concrete	K_e
Projecting from fill, socket end	0.2
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe	0.2
Square-edge	0.5
Rounded (radius = 1/12 D)	0.2
Mitred to conform to fill slope	0.7
End-section conforming to fill slope (standard precast)	0.5
Bevelled edges, 33.7° or 45° bevels	0.2
Side-tapered or slope-tapered inlets	0.2
Pipe, or Pipe-Arch, Corrugated Steel	
Projecting from fill	0.9
Headwall or headwall and wingwalls, square edge	0.5
Mitred to conform to fill slope	0.7
End-section conforming to fill slope (standard prefab)	0.5
Bevelled edges, 33.7° or 45° bevels	0.25
Side-tapered or slope-tapered inlets	0.2
Box, Reinforced Concrete	
Headwall	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, Or bevelled edges on 3 sides	0.2
Wingwalls at 30° to 75° to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of 1/12 barrel dimension Or bevelled top edge	0.2
Wingwalls at 10° to 25° to barrel	
Square-edged at crown	0.5
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Side-tapered or slope-tapered inlet	0.2
Projecting	
Square-edged	0.7*
Bevelled edges, 33.7° or 45° bevels	0.2*
* Estimated	

Design Chart 27.2 Entrance Loss Coefficients

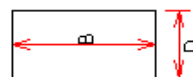


Inlet Control Nomograph - Concrete Pipe Culvert

Design Chart 27.3 Inlet Control Nomograph – Concrete Pipe Culvert

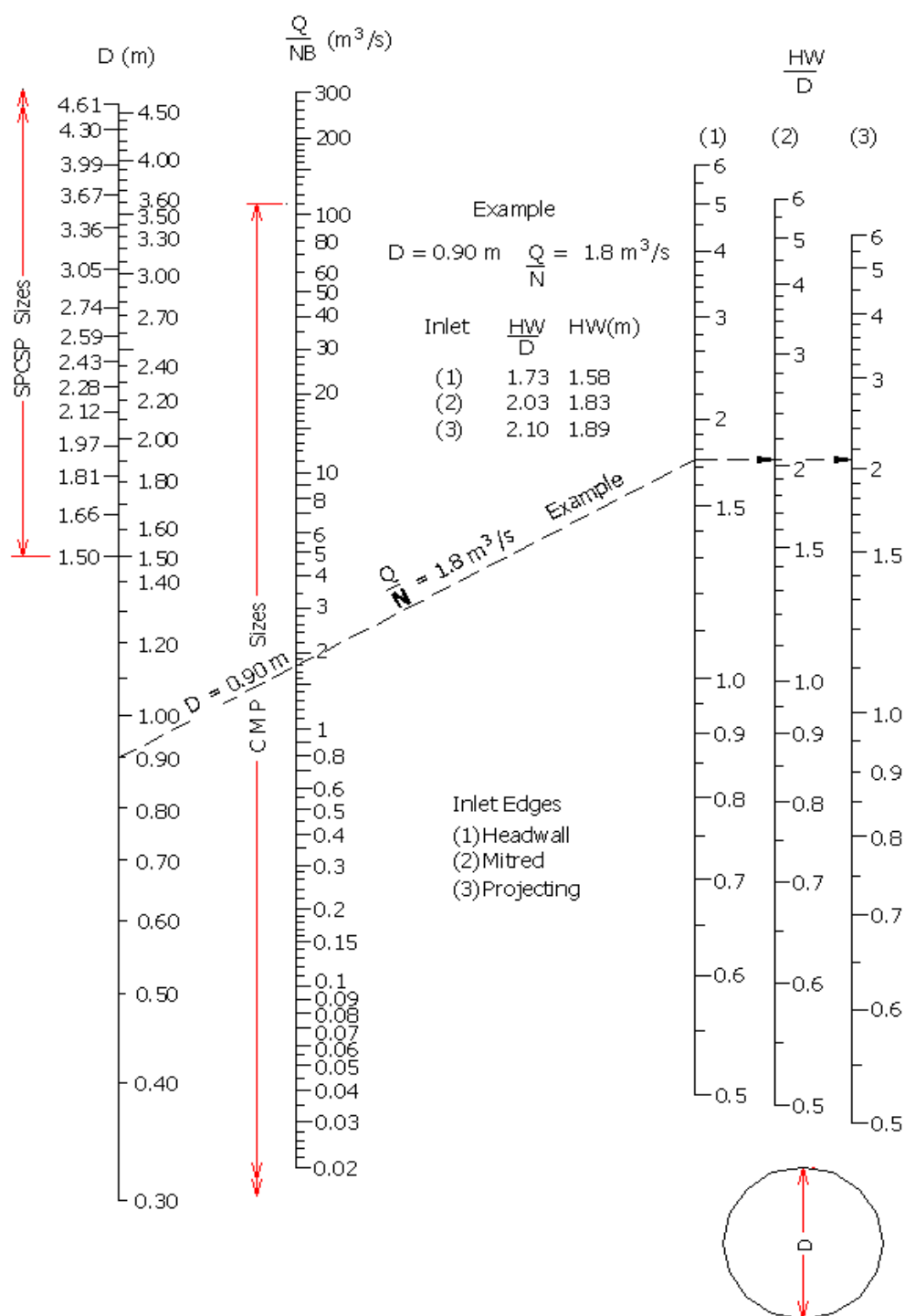


Wingwall Flare	HW/D Scale
30° - 75°	1
90° (headwall)	2
0° (parallel)	3



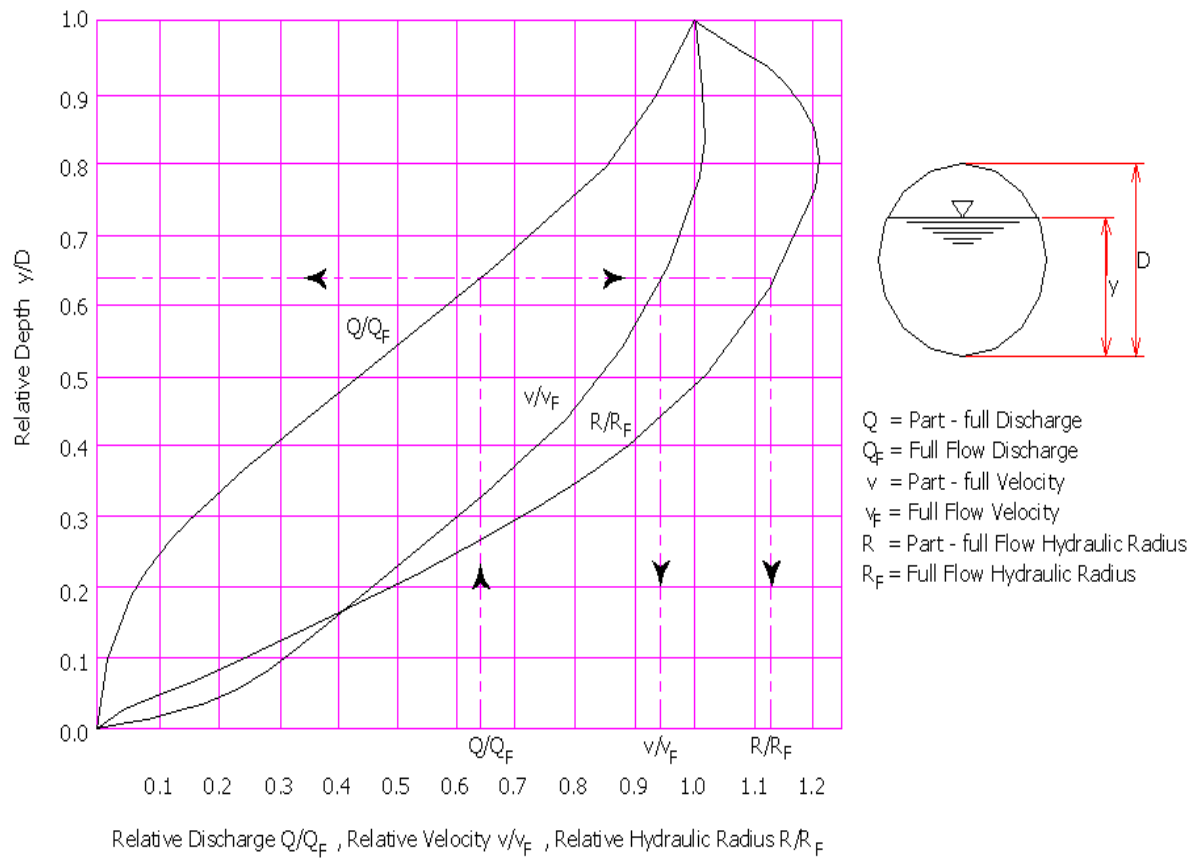
Inlet Control Nomograph - Box Culvert

Design Chart 27.4 Inlet Control Nomograph – Box Culvert

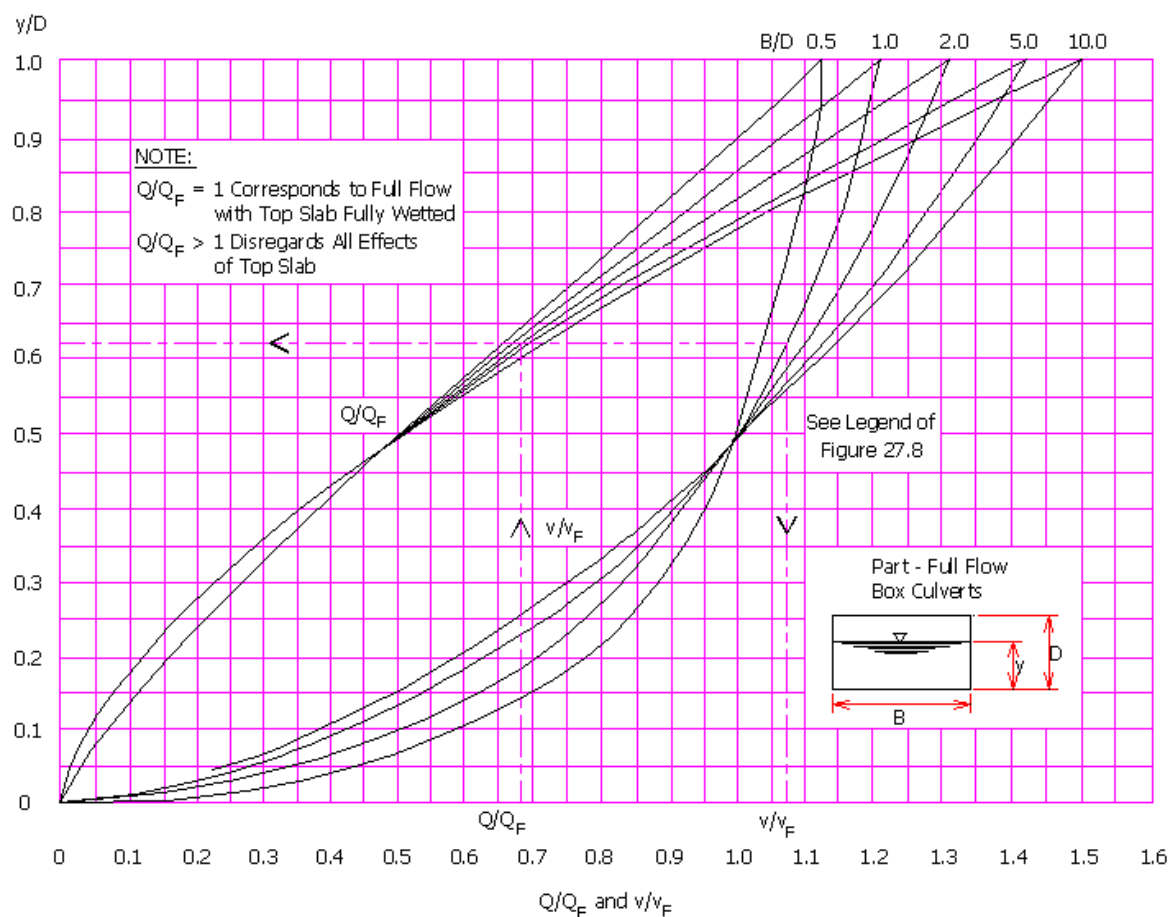


Inlet Control Nomograph - Corrugated Metal Pipe (CMP) and Standard Plate Corrugated Steel Pipe (SPCSP) Culvert

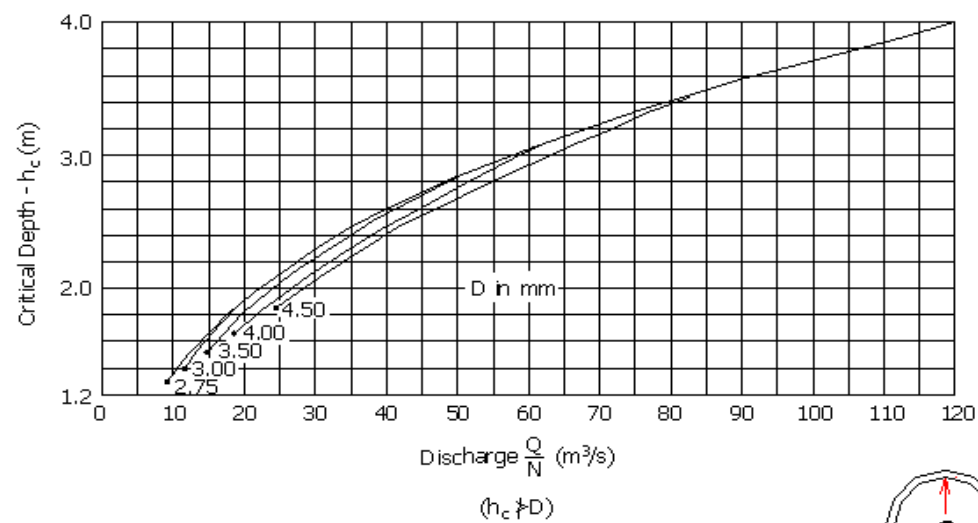
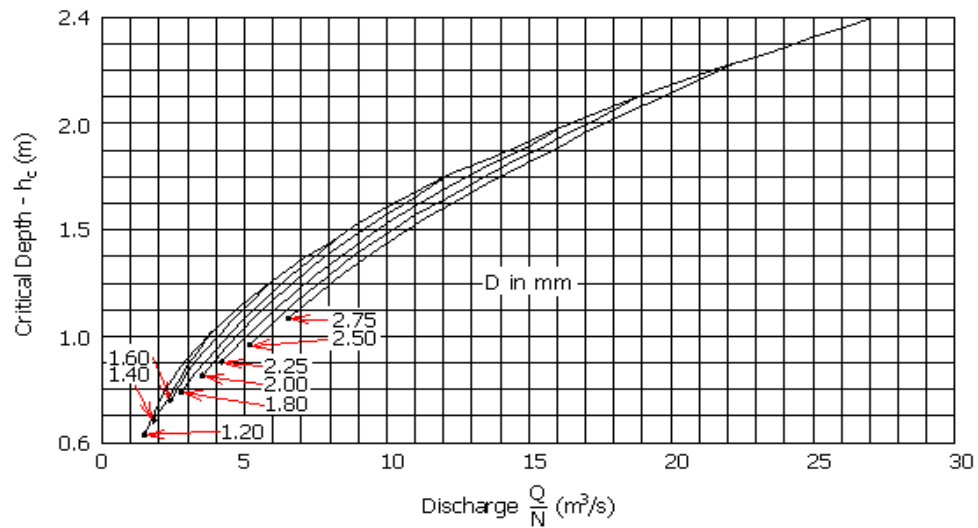
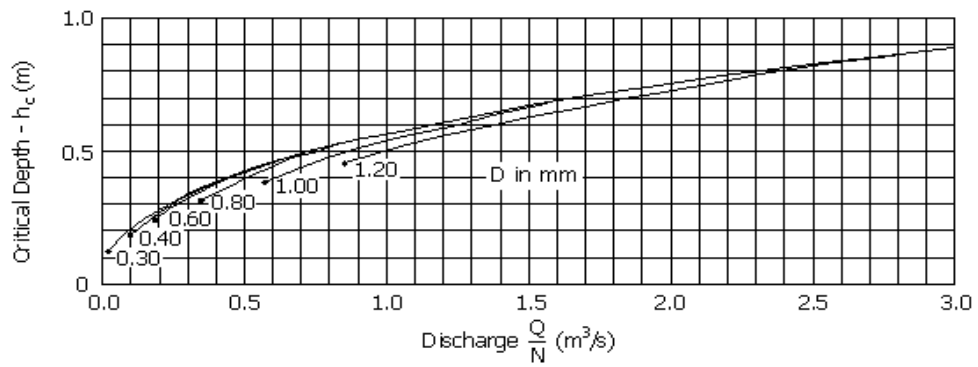
Design Chart 27.5 Inlet Control Nomograph – Corrugated Metal Pipe (CMP) Culvert



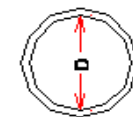
Design Chart 27.6 Relative Discharge, Velocity and Hydraulic Radius in Part-full Pipe Flow.



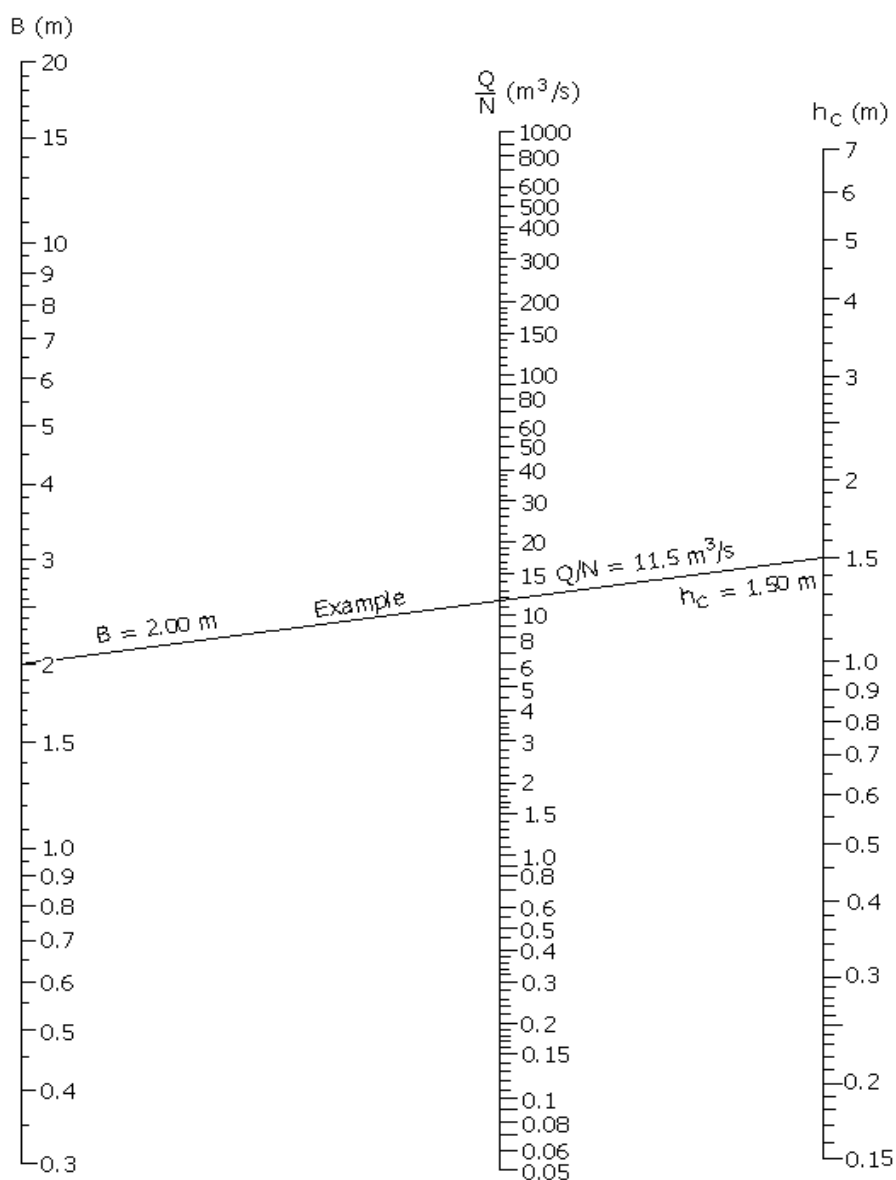
Design Chart 27.7 Relative Discharge, Velocity and Hydraulic Radius in Part-full Box Culvert Flow.



Critical Depth in a Circular Pipe

Critical Depth
Circular Pipe

Design Chart 27.8 Critical Depth in a Circular Pipe

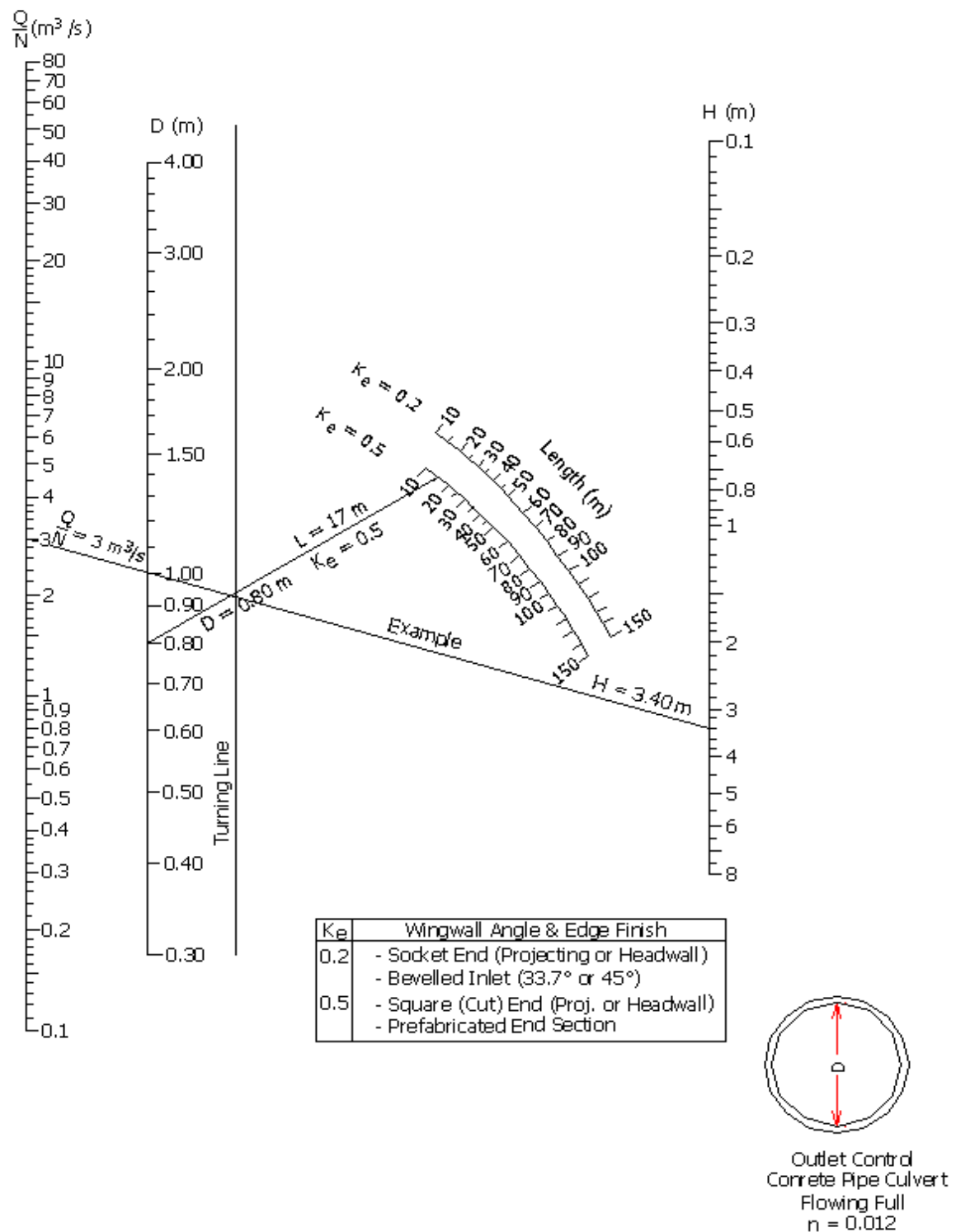


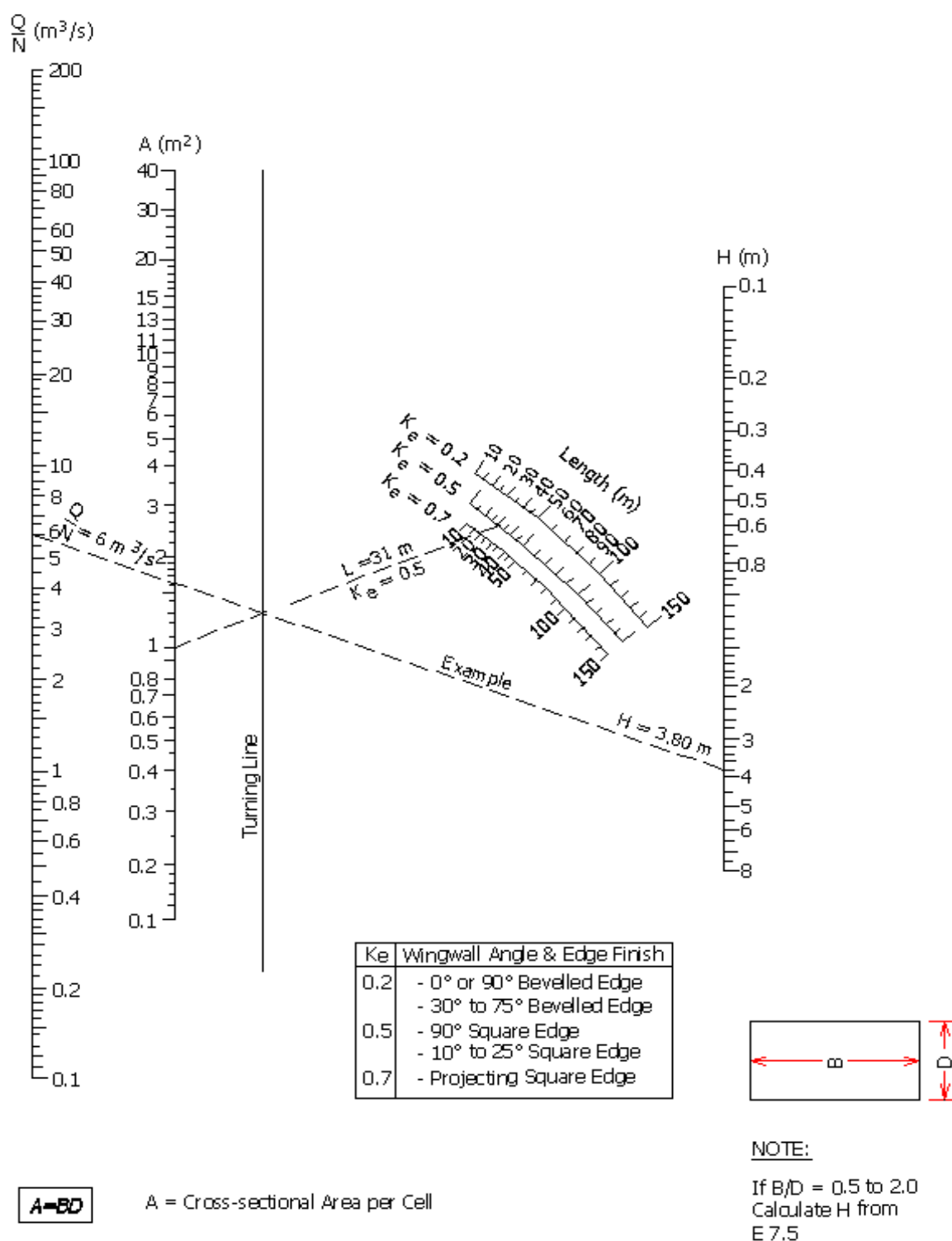
$$h_c = 0.467 \left(\frac{Q}{NB} \right)^{2/3} \quad (h_c \neq D)$$

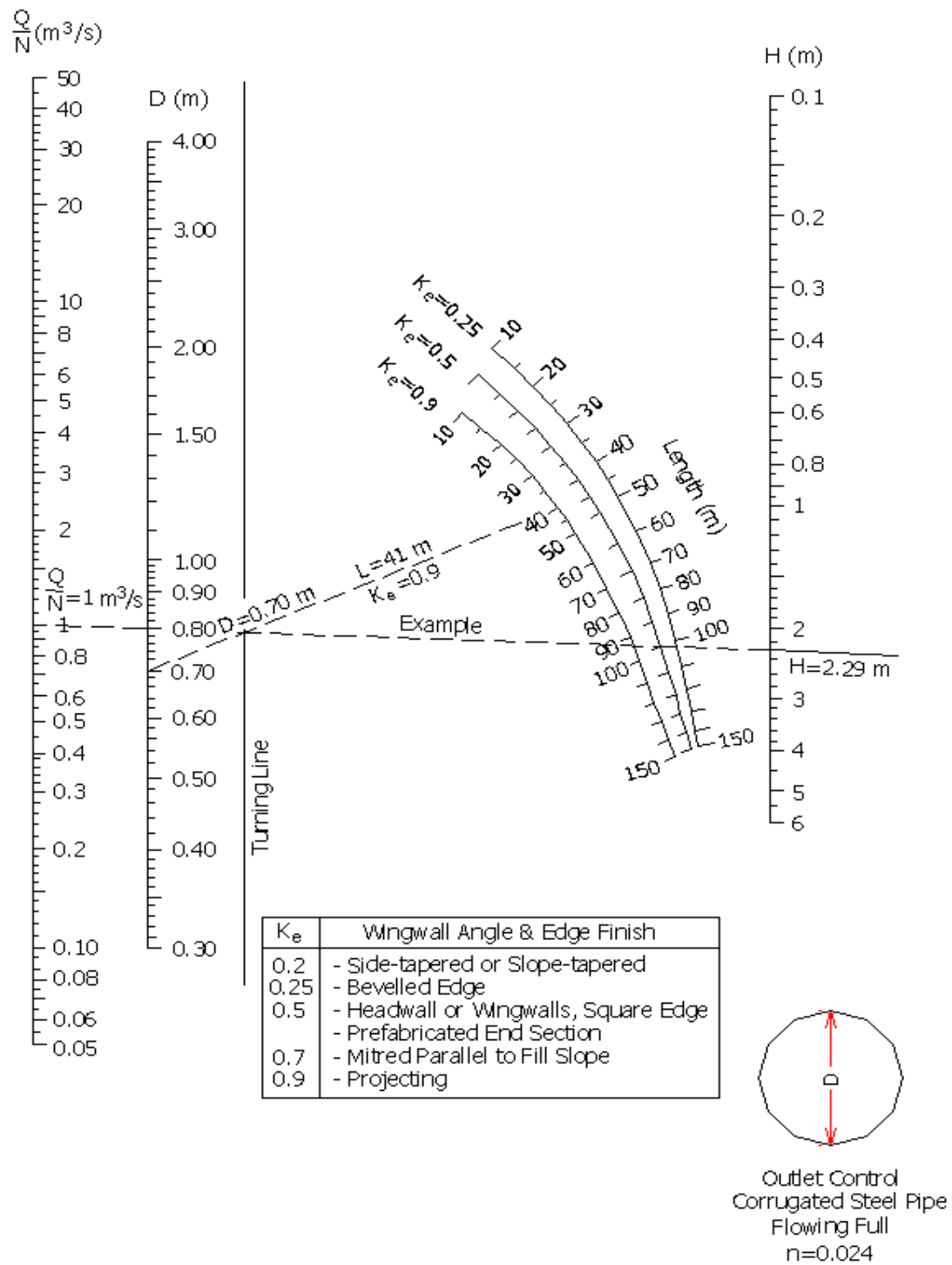
Critical Depth
Rectangular Section

Critical Depth in a Rectangular Section

Design Chart 27.9 Critical Depth in a Rectangular (Box) Section

Outlet Control Nomograph - Concrete Pipe Culvert Flowing Full with $n=0.012$ Design Chart 27.10 Outlet Control Nomograph – Concrete Pipe Culvert Flowing Full with $n = 0.012$

Outlet Control Nomograph - Concrete Box Culvert Flowing Full with $n = 0.012$ Design Chart 27.11 Outlet Control Nomograph – Concrete Box Culvert Flowing Full with $n = 0.012$

Outlet Control Nomograph - Corrugated Metal Pipe (CMP) Flowing Full with $n=0.024$ Design Chart 27.12 Outlet Control Nomograph – Corrugated Metal Pipe (CMP) Flowing Full with $n=0.024$

APPENDIX 27.B WORKED EXAMPLE

27.B.1 Pipe Culvert (Inlet Control)

Given the following data, calculate a suitable culvert size and check the outlet velocity to see if erosion will be a problem.

Step 1 : Data

Flow = $Q = 5.00 \text{ m}^3/\text{s}$

Culvert length = $L = 90\text{m}$

Natural waterway invert levels :

Inlet : R.L.50.00m

Outlet : R.L.49.00m

Acceptable upstream flood level: R.L.52.50

Desirable road pavement level : R.L. 52.00

Minimum height of pavement above head water : 0.30

Estimated downstream tailwater level : R.L. 49.80

Maximum headwater height, HW , is the lesser of:

- i) Maximum practical culvert height:

$$52.00 - 0.30 - 50.00 = 1.70\text{m, and}$$

- ii) Acceptable u/s flood level

$$52.50 - 50.00 = 2.50\text{m}$$

Therefore maximum $HW = 1.70\text{m}$

Step 2 : Assume Inlet Control

Estimate required waterway area assuming $V = 2.0 \text{ m/s}$

$$\text{Estimated area } A = Q/V = 2.5 \text{ m}^2$$

- i) Try 1650mm pipe, $D = 1.65\text{m}$

Enter Design Chart 27.3 with $Q = 5.00\text{m}^3/\text{s}$.

Draw line 1 and obtain

$$HW/D = 1.09$$

$$HW = 1.80 > 1.70\text{m maximum. Not acceptable}$$

- ii) Try 1800mm pipe, $D = 1.8\text{m}$

Draw line 2 and obtain $HW/D = 0.93$

$$HW = 1.67\text{m}$$

But max. culvert height available is only 1.70m

- iii) Try twin lines, 2/1050mm

$$D = 1.05\text{m} \quad Q/N = 2.5\text{m}^3/\text{s}$$

Draw line 3 and obtain $HW/D = 1.62$

$$HW = 1.70\text{m}$$

Use 2/1050mm diameter pipes

Step 3 : Check for Outlet Control

Height of tailwater above invert:

$$TW = 49.80 - 49.00 = 0.80 < \text{proposed pipe diameter of } 1.05\text{m}$$

Diagram in Figure 27.7(c) depicts actual conditions, flowing full for part of the length.

Now enter Design Chart 27.8 to determine critical depth

$$d_c = 0.83\text{m}$$

$$\frac{d_c + D}{2} = \frac{0.83 + 1.05}{2} = 0.94 > TW = 0.80$$

as outlined in Section 27.3.3 enter Design Chart 27.10 with

$$L = 90\text{m}$$

$$D = 1.05\text{m}$$

$$K_e = 0.2 \text{ (socket end of pipe upstream)}$$

Then use $Q/N = 2.50 \text{ m}^3/\text{s}$ to draw line 2 and obtain $H = 1.15\text{m}$

Fall of culvert invert, $L_s = 50.00 - 49.00 = 1.00$ hence:

$$HW = \left(\frac{d_c + D}{2} \right) + H - L_s = 0.94 + 1.15 - 1.00 = 1.09\text{m}$$

HW (inlet control) = 1.70m greater than

HW (outlet control) = 1.09m

Therefore inlet control governs.

Step 4 : Flow Velocity

For 1050mm diameter pipes:

$$A = \frac{pD^2}{4} = 0.87 \text{ and } s = 1/90 = 0.0111$$

From Colebrook-White's Chart for $k = 0.6\text{mm}$ (Figure 25.B4 in Chapter 25, Appendix 25.B):

$$Q_f = 3.1 \text{ m}^3/\text{s}$$

$$V_f = 3.6 \text{ m/s}$$

Because the culvert does not flow full it is necessary to use the part-full flow relationships plotted in Design Chart 27.6.

$$Q/Q_f = 2.5/3.1 = 0.81 \text{ and from Design Chart 27.6,}$$

$$V/V_f = 1.0 \text{ and } v = 1.0 \times 3.6 = 3.6 \text{ m/s}$$

$$y/D = 0.75 \text{ and } y = 0.75 \times 1.05$$

$$= 0.79 < d_c = 0.83$$

Unless the drain, which receives the culvert discharge, flows at supercritical flow a hydraulic jump will form at the culvert outlet.

Step 5 : Summary

Use 2/1050 mm diameter concrete pipes with socket end facing upstream.

Pipes will flow with inlet control with a headwater height of 1.70m and headwater R.L. = 51.70m.

Outlet velocity = 3.6 m/s and the possibility of scour or the formation of a hydraulic jump at the outlet must be checked.

27.B.2 Box Culvert (Inlet Control)

Step 1 :

Using the same data as provided for the previous pipe culvert, calculate a suitable box culvert size and check for the effects of the outlet velocity.

Step 2 : Assume Inlet Control

Estimate required waterway area assuming $V = 2.0$ m/s

$$\text{Estimated area } A = Q/V = 2.5 \text{ m}^2$$

Try 1800 (wide) x 1200 (high) box culvert.

Enter Design Chart 27.4 with $Q = 5.00 \text{ m}^3/\text{s}$.

$$\frac{Q}{NB} = 2.78$$

Draw line and obtain $HW/D = 1.30$

$HW = 1.30 \times 1.2 = 1.56 < 1.70\text{m}$, which is acceptable

Step 3 : Check for Outlet Control

$TW = 0.8 < 1.2\text{m}$

Enter Design Chart 27.9 with

$$d_c = 0.92\text{m}$$

$$\frac{d_c + D}{2} = \frac{0.92 + 1.20}{2} = 1.06, \text{ which exceeds the}$$

tailwater depth of 0.80m

As outlined in section 27.3.3 enter Design Chart 27.11 with

$$L = 90\text{m}$$

$$A = 1.2 \times 1.8 = 2.16\text{m}^2$$

$$k_e = 0.5$$

Draw line with $Q = 5.0\text{m}^3/\text{s}$ then draw the other line to obtain $H = 0.45\text{m}$

Fall of culvert invert, $L_s = 50.00 - 49.00 = 1.00\text{m}$ hence:

$$HW = \frac{d_c + D}{2} + H - L_s$$

$$= 1.06 + 0.45 - 1.00 = 0.51\text{m}$$

HW (inlet control) = 1.56m which is greater than

HW (outlet control) = 0.51m

Therefore inlet control governs.

Step 4 : Flow Velocity

Hydraulic radius $R = \frac{\text{area}}{\text{wetted perimeter}}$

$$R = \frac{2.16}{2(1.8 + 1.2)} = 0.36\text{m}$$

Equivalent $D = 4 \times 0.36 = 1.44\text{m}$ and $s = 1/90 = 0.011$

From Colebrook–White's Chart for $k = 0.6\text{mm}$ (Figure 25.B4 in , Appendix 25.B) we get:

$$V_f = 4.4\text{m/s}$$

$$Q_f = 2.16 \times 4.4 = 9.5 \text{ m}^3/\text{s}$$

Because the culvert does not flow full it is necessary to use the part-full flow relationships plotted in Design Chart 27.7.

$$\frac{Q}{Q_f} = \frac{5.0}{9.5} = 0.526,$$

and from Design Chart 27.7 for $B/D = 1.5$

$$\frac{V}{V_f} = 1.02 \quad \text{and} \quad v = 1.02 \times 4.4 = 4.5 \text{ m/s}$$

$$\frac{y}{D} = 0.53 \quad \text{and} \quad y = 0.53 \times 1.2 = 0.64 < d_c = 0.92\text{m}$$

Hence the same remark about hydraulic jump applies as made for pipes (see example 1: step 4).

Step 5 : Summary

Use 1800 x 1200mm concrete box culvert with square edges.

Culvert will flow with inlet control with a headwater height of 1.5m and headwater R.L. = 51.5m

Outlet velocity = 4.5 m/s and the possibility of erosion or a hydraulic jump must be checked.

27.B.3 Pipe Culvert (Outlet Control)

Given the following data calculate a suitable pipe size and check the outlet velocity for the possibility of erosion.

Step 1 : Data

Flow $Q = 0.5 \text{ m}^3/\text{s}$

Culvert length, $L = 120\text{m}$

Natural waterway invert levels : inlet R.L. = 100.0m

: outlet R.L. = 99.0m

Acceptable upstream flood level : R.L. = 103.0m

Desirable road pavement level : R.L. = 102.5m
 Minimum height of road above headwater level : 0.5m
 Required freeboard : Nil
 Estimated downstream tailwater level : R.L. = 100.5m
 Maximum headwater height, HW , is the lesser of:
 iii) Maximum practical culvert height:
 $102.5 - 0.5 - 100.0 = 2.0\text{m}$, and
 iv) Acceptable u/s flood level
 $103.0 - 100.00 = 3.0\text{m}$
 Therefore Maximum $HW = 2.0\text{m}$

Step 2 : Assume Inlet Control

Estimate required waterway area assuming $V = 2.0 \text{ m/s}$

$$\text{Estimated area } A = Q/V = 0.25 \text{ m}^2$$

Try 450mm pipe, $D = 0.45\text{m}$

Enter Design Chart 27.3 with $Q/N = 0.5 \text{ m}^3/\text{s}$

Draw line and obtain for Inlet Type 2:

$$HW/D = 2.8$$

$$HW = 2.8 \times 0.45 = 1.26\text{m for inlet control}$$

This depth is less than the limit of 2.0m.

Step 3 : Check for Outlet Control

Height of tailwater above invert:

$$TW = 100.5 - 99.0 = 1.50 > 0.45\text{m}$$

Diagram in Figure 27.7(a) depicts flow condition, i.e. pipe is flowing full with a submerged outlet. Now enter Design Chart 27.10 with:

$$D = 450\text{mm}$$

$$L = 120\text{m}$$

$$k_e = 0.2 \text{ (socket end of pipe upstream)}$$

Then use $Q = 0.5 \text{ m}^3/\text{s}$ to draw line 2 and obtain

$$H = 3.4\text{m}$$

Fall of culvert invert, $L_s = 100.0 - 99.0 = 1.00$ hence:

$$HW = TW + H - L_s = 1.5 + 3.4 - 1.0 = 3.9\text{m}$$

Note that because $3.9\text{m} > HW$ for inlet control (1.26m), the culvert is under outlet control.

However the design is unacceptable because $HW_{\max} = 2.0\text{m}$.

Return to step 2 using 525mm pipe diameter in Design Chart 27.3 and obtain $HW/D = 1.62$

$$HW = 1.62 \times 0.525 = 0.85\text{m for inlet control}$$

Now check for outlet control. Re-enter Design Chart 27.10 with $D = 0.525\text{m}$ and obtain $H = 1.5\text{m}$ hence:

$$HW = 1.5 + 1.5 - 1.0 = 2.0\text{m}$$

This headwater depth is acceptable.

and since $2.0\text{m} > 0.85\text{m} = HW$ (inlet control) outlet control governs.

With HW and TW both well above the crown of the pipe and a moderate slope of $1.0/120 = 0.0083$ the pipe will flow full hence:

$$v = Q/A$$

$$v = \frac{4 \times 0.5}{\pi \times 0.525^2} = 2.3\text{m/s}$$

This velocity must be checked against erosion danger at outlet (Table 27.1).

Step 4 : Summary

Use a single line of 525mm diameter concrete pipes with socket end upstream.

The pipe will flow full under outlet control and with a HW height of 1.3m giving a HW R.L. of 101.3m and an outlet velocity of 2.3m/s.

27.B.4 Box Culvert (Outlet Control)

Step 1 : Using the same data as provided for the previous pipe culvert calculate a suitable box culvert size and check for the effects of the outlet velocity.

Step 2 : Assume Inlet Control

Using the previous estimate of required area, try 600mm x 300mm box culvert.

Enter Design Chart 27.4 with $Q = 0.5 \text{ m}^3/\text{s}$

$$Q/NB = 0.5/0.6 = 0.83 \text{ m}^3/\text{s/m}$$

Draw line as shown and obtain $HW/D = 4.3$

$$HW = 4.3 \times 0.30 = 1.29\text{m} < 2.0\text{m}$$

Step 3 : Check for Outlet Control

$TW = 1.50\text{m}$ (see example 3) $> 0.30\text{m}$ hence diagram in Figure 27.7(a) depicts flow condition, i.e. culvert is flowing full with a submerged outlet.

$$A = 0.6 \times 0.3 = 0.18\text{m}^2$$

Calculate H from Design Chart 27.11, noting that $B/D = 2.0$ so the chart is applicable.

$$H = 1.4\text{m}$$

$$\text{then } HW = TW + H - L_s = 1.5 + 1.4 - 1.0 = 1.9\text{m}$$

Note that $1.9\text{m} > 1.29\text{m}$, the headwater depth for inlet control, so outlet control applies.

However the design is not acceptable because of the risk of clogging of the 300mm deep culvert due to debris.

Try 600mm x 375mm box culvert.

$$A = 0.225\text{m}^2$$

Repeating the above steps gives:

$$HW/D = 2.7 \text{ and } HW = 1.01\text{m for inlet control, and}$$

$$H = 0.95\text{m and } HW = 1.45\text{m for outlet control.}$$

This is acceptable because $1.45 < HW_{\text{max}} = 2.0$

And the culvert flows with outlet control since:

$$1.45\text{m} > 0.9\text{m} = HW \text{ (inlet control)}$$

As the culvert flows full,

$$v = Q/A = \frac{0.5}{0.225} = 2.2 \text{ m/s}$$

Step 4 : Summary

Use a single 600 x 375 concrete box culvert with square edges.

The culvert will flow with outlet control with a HW height of 1.45m giving a HW R.L. of 101.45 and an outlet velocity of 2.2 m/s.

27.B.5 Minimum Energy Culvert

Given a required design flow of $25 \text{ m}^3/\text{s}$ and referring to Figure 27.16 with chosen widths b as set out in the following table, calculate suitable levels for the bottom profile of the flared culvert entry at the given sections to achieve critical flow through the culvert. Choose an appropriate box culvert size for the culvert.

The widths b are chosen with regard to the survey data, and then q and d_c can be calculated for each section as shown in the table below.

Section	1-1	2-2	3-3
width b	14	9	4
$q = Q/b$	1.79	2.78	6.25
$d_c = \sqrt[3]{q^2 / g}$	0.69	0.92	1.59
trial depth D	1.10	1.30	1.58
$v = Q/A$	1.62	2.14	3.96
$v^2/2g$	0.13	0.23	0.80
$H_s = D + v^2/2g$	1.23	1.53	2.38

The depth of flow is required to be critical in the culvert and unchanged subcritical at the start of the flared entry. Intermediate depths are interpolated.

For chosen values of d , H_s can be calculated and the bottom level of the culvert and approach is located H_s metre below the energy line in each section.

From the table it will be noted that a box culvert flow area of $4\text{m} \times 1.58\text{m}$ is required hence a 4.0m wide x 1.8m high culvert with a flow area of 7.2m^2 will be suitable. This culvert must then be checked for the risk of debris blockage and sediment deposition in the depressed section.