CHAPTER 14

CULVERT HYDRAULICS

DESIGN APPROACH

A culvert is defined here as a structure for conveying stormwater under an embankment. A culvert or a bridge would be constructed over a natural river or man-made channel to assist traffic to pass over the waterway.

The design of culverts to convey stormwater under roads or embankments has been the subject of considerable research and considerable misunderstanding. The difficulty invariably arises in connection with the point of control - either inlet or outlet control is usually the case. However in order to appreciate the problem it is necessary to start a step earlier in the design process. That is to understand why a culvert is a control structure at all. For this we need to consider the aspects of economics and risk.

Economic design

The cost of a culvert is much greater than the cost of the equivalent length of channel. The culvert will have to be designed and built to resist high earth and superimposed loads, both vertical and lateral. The structure will also have to protect the embankment against scour, and provide a passageway for water. The cost of the culvert per unit length is highly dependent on the cross sectional area and shape. The cross sectional area of a culvert is invariably smaller than that of the water in the channel at flood flow in order to reduce the cost of the culvert.

A culvert also has a larger wetted perimeter than a channel as it is closed on top. The head loss and average energy gradient through the culvert is therefore steeper than in the channel without the culvert. If the channel bed is prefixed at a subcritical gradient, the only way this steepening of the hydraulic gradient through the culvert can occur is by raising the headwater level above the normal depth. This causes a backwater in the channel upstream of the embankment. Head is gained by reducing the friction loss in the upstream channel. Inlet conditions into the culvert then control the discharge through the culvert.

If the channel is at a supercritical bed gradient, the culvert will probably be installed at a flatter grade, with the result that the water level will fall towards the discharge end and may reach critical depth. This condition gives rise to outlet control conditions.

Outlet control is more likely to occur for culverts in defined streams or channels. Inlet control is more likely in the case of an embankment across a catchment which collects water towards the culvert crossing. Flow is thereby concentrated at the inlet whereas the outlet will be free.

Risk

The headwater level at the entrance to a culvert cannot be increased indefinitely without consequences. Associated with a depth increase in a river a channel is a backwater effect. Water may rise above the banks of the channel and cause flooding of the surrounding land. The social and economic consequences could be severe.

Of more relevance to the road engineer may be flooding of the embankment through which the culvert passes. A water level rise on the upstream side of the embankment may affect any of the following:

i) The stability of the bank as a whole or either face,
ii) The structural loads on the culvert (lateral and vertical),
iii) Scour of earth embankment and possibly washaway if there is severe overtopping,
iv) Interruption of traffic,
v) Danger to life and vehicles,
vi) Flooding of upstream land,
vii) Erosion of downstream channel.

The culvert cross-sectional area and hydraulic properties are therefore important. Where the consequences of a headwater rise can be evaluated economically they can be balanced against the cost of the culvert and embankment height. The structure with least total cost i.e. of structure and due to flooding, should be selected. Construction and engineering costs could be discounted to a time basis common with the economic losses and a least cost system selected. The resulting culvert will discharge a certain design flood without overtopping the embankment but there may still be some risk of a greater flood occuring.

The probability of the design flood being exceeded could be established or estimated from a hydrological analysis. The cost of a flooding should be multiplied by the probability of a flood occuring in any year in evaluating the average economic cost of flooding. The probable cost of one, two or more floods in any year should be summated in the comparison.

Principle of Controls

An hydraulic device is said to control flow if it limits the flow of water which would otherwise exceed that flow with the prevailing upstream and downstream conditions. If the river flow is specified then neglecting backwater storage the head will adjust across the control section until the inflow equals the discharge.

Flow can be controlled from either the upstream side or the downstream side depending on whether flow is supercritical or subcritical respectively. The velocities of water relative to that of an hydraulic reaction dictate whether flow is supercritical or subcritical. Thus if the flow is supercritical, the water velocity is faster than the velocity of a wave, so that waves cannot pass upstream, and control cannot be effected from downstream. A downstream control or constriction would create a standing wave which may be in the form of an hydraulic jump.

A control from upstream will uniformly affect the downstream flow depth.

On the other hand if the velocity is subcritical waves can travel upstream at a speed faster than the water is flowing, so any control on the flow downstream will back up water until it reaches an equilibrium profile upstream of the control. Flow downstream will be at normal depth.

Supercritical depth occurs when the Froude number, $F = v/\sqrt{gy}$ is greater than unity, i.e. $v>\sqrt{gy}$ where $\sqrt{gy}$ is the celerity of a shallow water wave. If F is less than 1, the flow is subcritical.

The relative gradient of the culvert and channel and the geometry will dictate where the control section is in a culvert section. It can be altered by careful design, and in fact if control can be transferred from the inlet to the outlet, or else if a balanced design is achieved, the possibility of upstream flooding is minimized for any outlet size.

HYDRAULIC PROFILES

Some of the different water surface profiles with the corresponding control sections, are indicated in Figs. 14.1 and 14.2. In the case of inlet control, the tailwater level will be relatively low so that the culvert runs part full for some or all of its length. The slope of the bed may be supercritical in which case depth will pass through critical at the entrance (case A). It may even occur that the headwater is higher than the barrel soffit without the water touching it if there were an inlet taper. H/D should exceed approximately 1.2 for submergence,

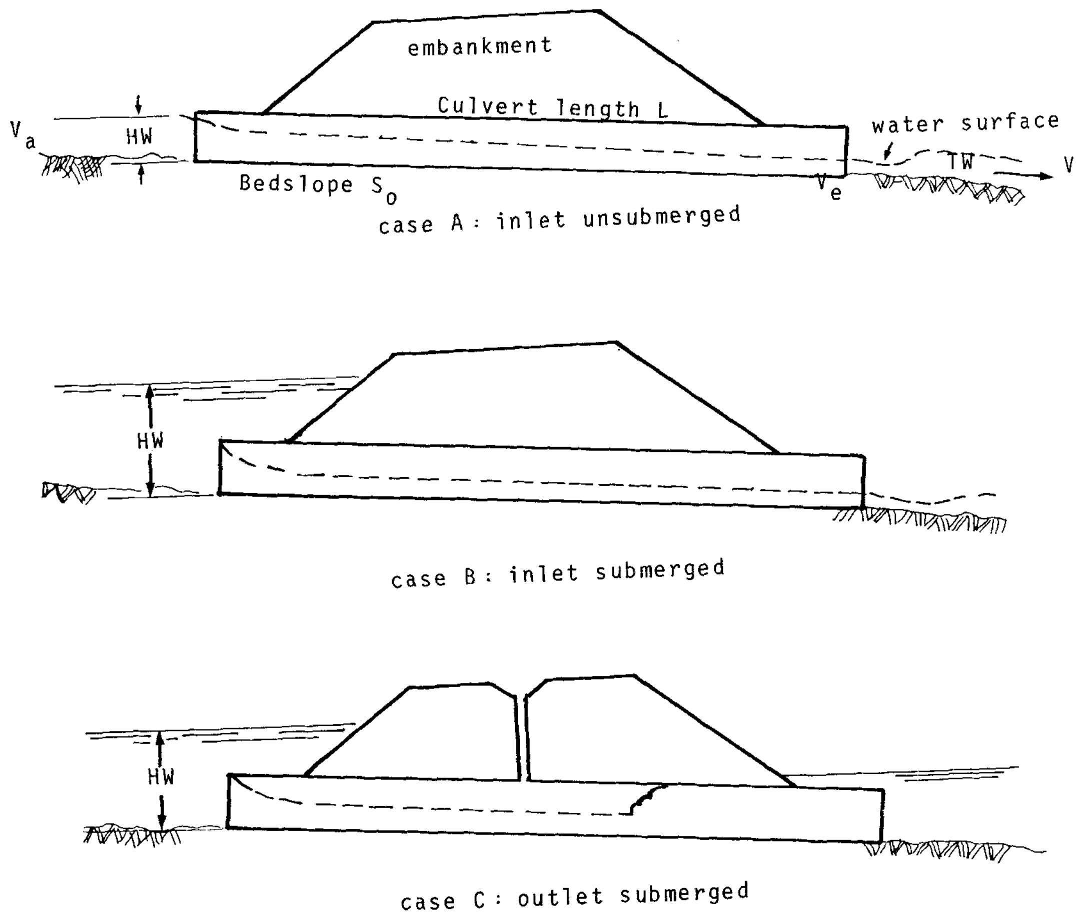


Fig. 14.1 Culvert longitudinal sections illustrating inlet control conditions

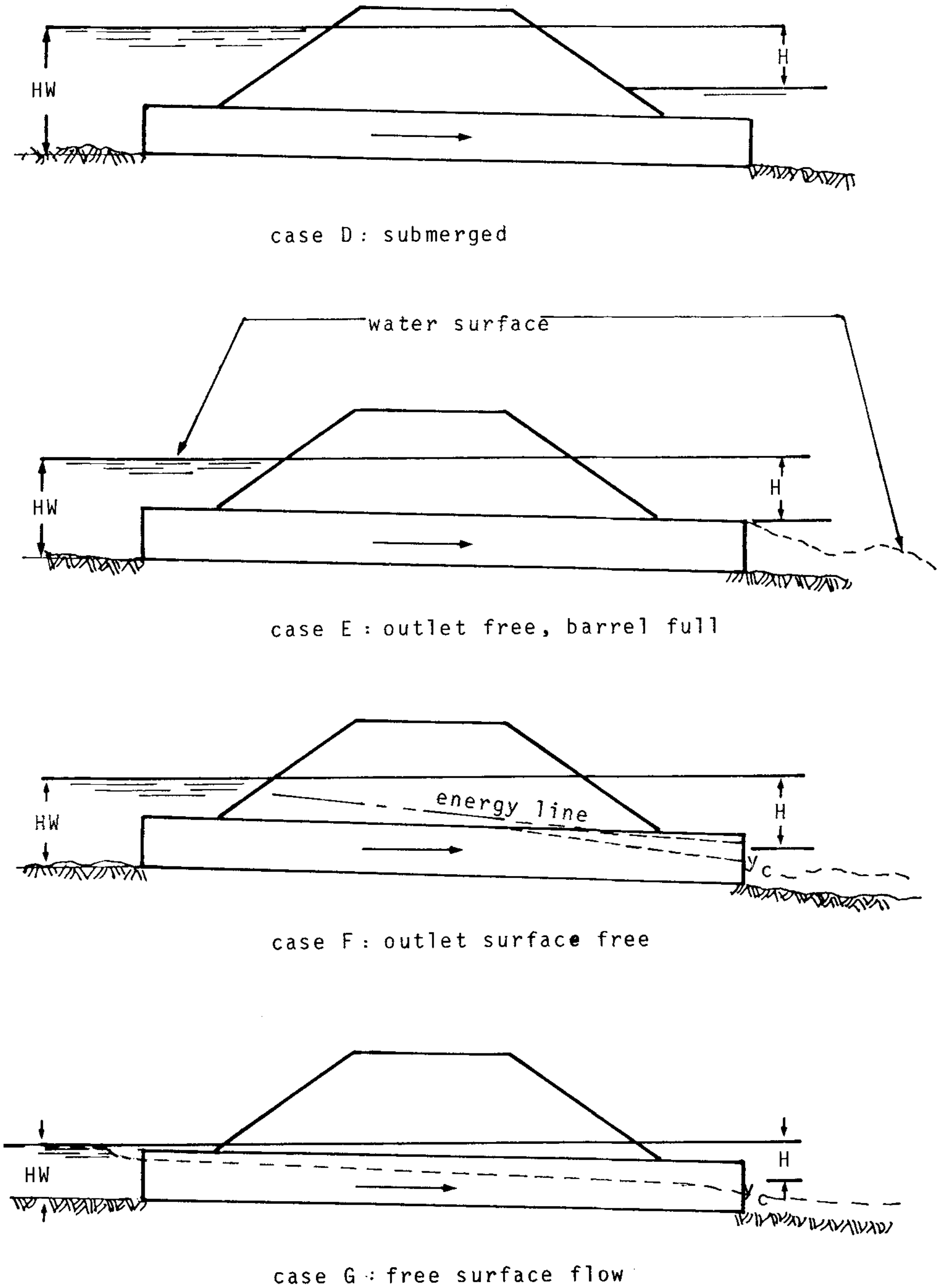


Fig. 14.2 Culvert longitudinal sections illustrating outlet control conditions

(USBR, 1960). If discharge were higher, the headwater may cover the entrance in which case the situation would be case B for a low tailwater. Critical depth could be induced at this inlet either by a steep downstream slope, or a high headwater H, creating a high velocity and large contraction. Case C where a hydraulic jump occurs is possible for a high tailwater. Observe that for case C to be stable the culvert barrel upstream of the jump would have to be vented. Kalinske and Bliss (1943) indicate a jump would evacuate air at a rate $0.006\ Q(F_1-1)^{1.4}$ where Q is the water discharge and F_1 the upstream Froude number $v_1/\sqrt{gy_1}$. With no ventilation the jump would move upstream creating subatmospheric pressures and possible instability at the entrance.

In each of the inlet control cases the barrel size beyond the inlet could be reduced without affecting the discharge. Conversely if the inlet conditions were improved the capacity of the culvert for any limiting headwater could be increased.

For a tailwater level so high that it drowned the culvert completely, the discharge would be controlled by the difference between entrance and exit water levels. This is a form of outlet control (case D).

Assuming the barrel was reduced in capacity until it limited the flow or increased the headwater, control would transfer to the barrel (but this is classified as one form of outlet control, Case E).

The latter two cases are equivalent to pipe flow, with the head drop being consumed primarily in conduit friction. The slope could be subcritical or supercritical. For relatively long culverts the inlet end only may be surcharged and the discharge end may run with a free surface. This case (F) will only occur with a low tailwater level and subcritical slope. In some extremes with a flat culvert bed gradient and large cross-section the flow may be free-surface and subcritical the entire length, which is illustrated as case G.

INLET DESIGN

If the culvert cross sectional area is to be fully utilized or conversely is to be minimized the culvert should run full or nearly full. In the case of low tailwater levels or steep gradients this may be a problem. It was indicated that for these cases the control is often at the inlet. Careful attention is therefore necessary in the design of the inlet to ensure minimum contraction of the flow (French, 1969). The objective is to ensure that flow rounds the edges of the inlet with minimum of separation, thereby filling the barrel cross section as much as possible. The discharge coefficient is there maximized. Full design details and nomographs for the design of improved inlets were given by the U.S. Department of Transport (1972) from which much of the following is abstracted.

The improvement may be obtained with a steep throat, a drop inlet, wing walls, a hood, or just bevelled edges. The shape of the top entrance appears to be the most important, and the bottom or invert the least important since flow there is horizontal. Thus an inlet meeting the battered embankment is highly conducive to flow contraction and results in a low discharge coefficient.

A taper should be in straight sections for ease of construction and rounded edges are found to have little improvement over plane bevels. Nevertheless there are shaped precast concrete inlets available for circular culverts in the smaller sizes. It is always good policy to lay pipes with the barrel end facing upstream as this provides something of a transition.

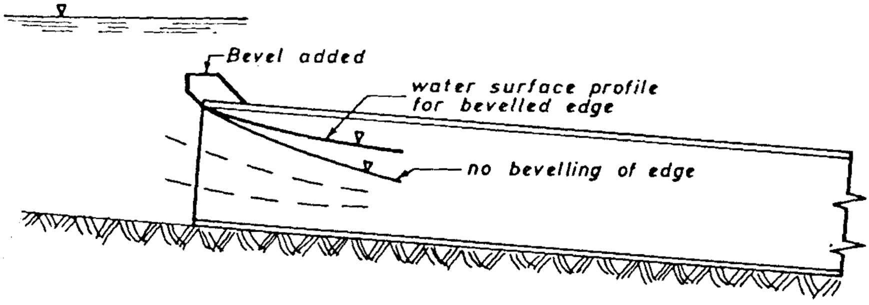
Fig. 14.3 illustrates some possible inlet arrangements. The simplest type of improvement is a vertical head-wall on top of the entrance to the culvert in the case of a battered embankment. This eliminates the re-entrant angle. The next step would be to bevel the top of the inlet. The bevel should be at least 10% of the culvert height at 33° to 45° to the axis of the culvert. In the case of skew culverts, the acute approach edge should also be bevelled. This will increase flow by up to 20%.

The second degree of improvement would be to taper the sides of the inlet. A taper angle of 45° (angle measure from the culvert axis) is perhaps the best compromise between hydraulic efficiency and length of approach. This will increase flow 25 to 40% over a square-edged inlet. Associated with side taper is usually a bevelled soffit, or a drop inlet to ensure the soffit height is not the control.

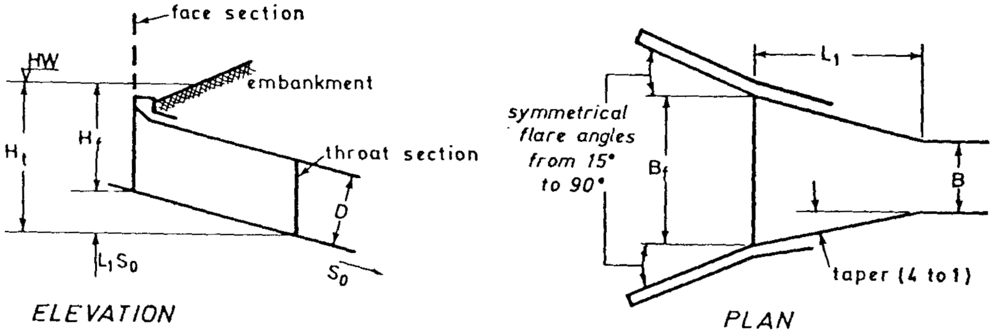
A slope-tapered section (see Fig. 14.3c) is the third degree of improvement (Southwood, 1978). This form of design increases the head on the barrel as well as tapering the inlet and 100 percent improvement in flow is possible. There are many different possible combinations of side-taper and throat taper, and the position of the control section within the inlet will have to be determined by trial.

Inlet control equations for box culverts

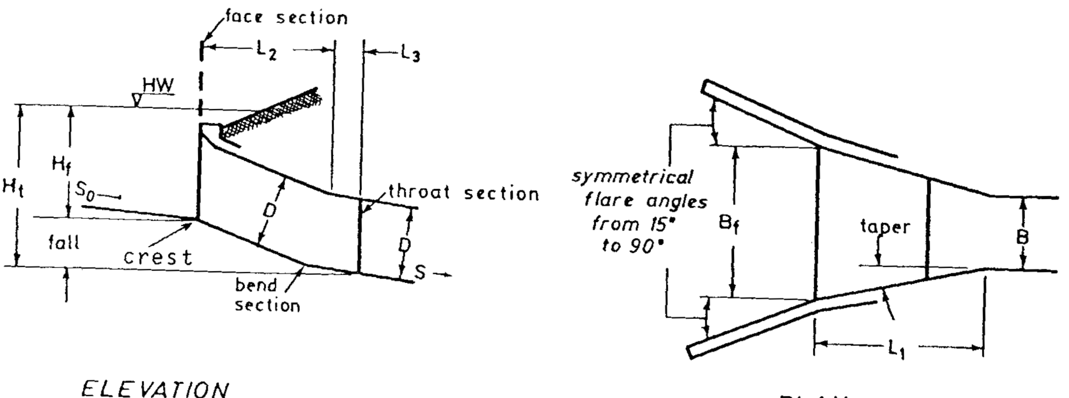
The position of the control section in a box culvert will depend on the type of inlet. In the case of composite designs, e.g. with wing walls, a slope taper or a drop inlet, the necessary headwater at each



a. BEVELED TOP



b. SIDE-TAPERED INLET



c. SLOPE-TAPERED INLET

Fig. 14.3 Inlet Details.

change in section should be determined. The type of flow at the relevant section will depend on whether the soffit (top of barrel) is submerged or there is a free surface.

If the inlet control is due to a drop or a narrow entrance and flow is free, then the depth at the entrance is critical depth and weir flow occurs. This occurs for H/D less than about 1.2. Thus

$$Q = C_B B g^{\frac{1}{2}} (\tfrac{2}{3}H)^{3/2} \qquad (14.1)$$

where B is the width at that point and H is the headwater level above the invert or effective weir crest. Strictly H is the energy level of the headwater, not the water level, but in most cases the approach velocity is negligible. Values of the discharge coefficient C_B are tabulated in Table (14.1).

Where the water touches the soffit, the culvert acts as an orifice. Discharge is related to head according to an equation of the form:

$$Q = C_c BD\{2g(H-C_h D)\}^{1/2} \qquad (14.2)$$

It is implied that the remaining head loss between the control section and headwater is negligible. This is the case for crest control or face control. By assuming throat or head control it is implied the crest and face are sufficiently wide to avoid separation and near to the control section to eliminate friction. It may be necessary in some situations to add the head loss for each section.

Multiple-barrel rectangular culverts

A set of rectangular culverts in parallel can be treated as a single culvert ignoring the dividing walls, for the purpose of selecting wingwalls. The noses of the dividing walls should, however, have a bevel. Practical considerations may limit the side taper on very wide culvert sets.

Circular pipe culverts

A circular cross section has better hydraulic characteristics than a rectangular one. Head losses are lower. The structural resistance is good as arching is induced. A higher headwater may however be needed for any cross sectional area owing to the shape if it is to run full at the entrance. For this reason the inlets are often rectangular with a subsequent transition to a circular section (see Fig. 14.4).

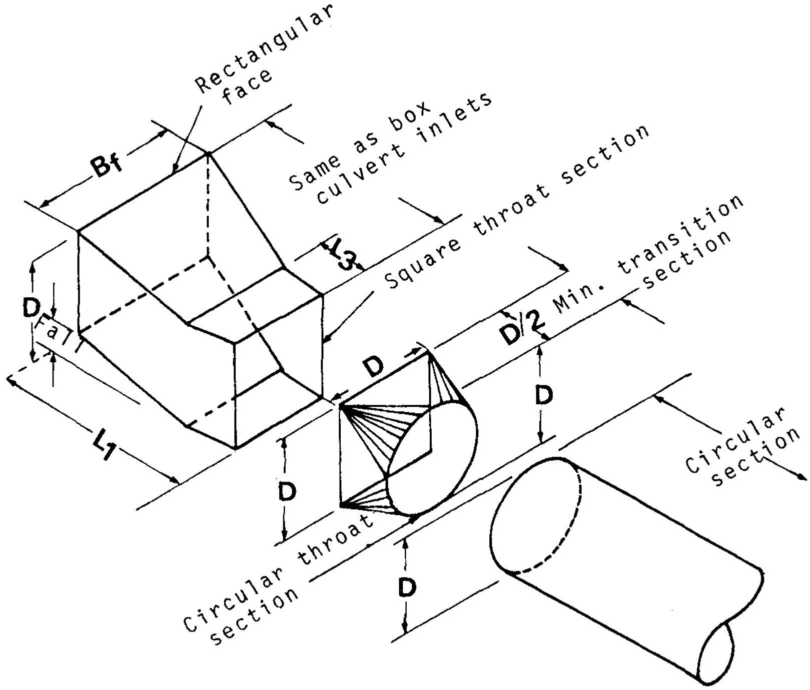


Fig. 14.4 Slope-tapered inlet transition for circular pipe

Where rectangular section inlets are provided, the discharge control equations are similar to those for box culverts. In circular sections, the type of control is generally similar to that for rectangular sections and similar equations apply in the case of submerged flow. The inlet is normally submerged if H/D is greater than 1.25.

For free surface discharge a control section will occur where the depth is critical depth. Direct derivation of an expression for critical depth is difficult for circular conduits (see chapter 10), but the principle of minimum specific energy is used to derive the relationship as for rectangular sections. The resulting expression for all shapes is

$$A_c{}^3/B = \frac{Q^2}{g} \qquad (14.3)$$

where A_c is the cross sectional area of flow at critical depth, B is the width of surface and Q is the discharge rate. This expression cannot be solved directly for critical depth y_c as a function of diameter D, and the relationship must be derived numerically (see chapter 10). The relationship between discharge and critical specific energy,

E_c, can be approximated over the range E_c/D less than 0.8 by the expression

$$Q = 0.48 C_B g^{1/2} D^{5/2} (E_c/D)^{1.9} \quad (14.4)$$

As a guide the discharge coefficients C_B in Table 14.1 for box culverts could be used, although Henderson (1966) indicates they are sensitive to slope. There are difficulties in evaluating specific energy or discharge at any particular depth in non-rectangular conduits. Diskin (1962) produced dimensionless charts of use for circular conduits running part full.

For submerged inlets, the discharge equation is the orifice equation

$$Q = C_c A\{2g\ (H - C_h D)\}^{1/2} \quad (14.5)$$

Blaisdell (1960) indicated that a considerable improvement in inlet capacity of circular culverts was possible with a hood and vortex suppressor over the entrance.

TABLE 14.1 Discharge coefficients for culverts.

Control position	Flow condition	Coefficient	Box culverts Side taper	Box culverts Slope taper	Circular Culverts	
Crest	Unsubmerged	C_B	0.92	0.92		
Face	Unsubmerged	C_B	0.77	0.92		
15-26° wingwalls + top bevel		C_c	0.59	0.59	Square edge	0.57
or 26-90° wingwalls, no bevel		C_h	0.84	0.64	Square edge	0.79
26-45° wingwalls with top bevel		C_c	0.64	0.64	Bevel edge	0.65
or 45-90° with top and side bevel		C_h	0.86	0.70	Bevel edge	0.83
Bend	Unsubmerged	C_B	-	-		
	Submerged	C_c	0.80	0.8		
	Submerged	C_h	0.87	0.87		
Throat	Unsubmerged	C_B	1.00	1.00		
	Submerged	C_c	0.94	0.93		0.89
	Submerged	C_h	0.95	0.96		0.89

OUTLET CONTROL

The outlet may be free-discharging in which case the depth in the culvert at the outlet will be critical, or submerged in which case the culvert will flow full. Alternatively the tailwater depth may be above critical depth in the culvert but below the soffit of the culvert. In either case of free surface discharge the downstream water level is known in which case one can backwater (using the direct step method) to determine the point beyond which the culvert will run full.

In all cases where the culvert runs full the head loss along the culvert can be determined from a friction formula, eg. Darcy-Weisbach

$$S_f = \frac{\lambda}{4R}\frac{V^2}{2g} \tag{14.6}$$

where R is the hydraulic radius A/P, and λ is a friction factor which for most culvert cases is the fully developed turbulent factor and is obtainable from a Moody diagram. Alternatively the Manning resistance equation can be employed. The head losses at the entrance may be evaluted from an equation of the form

$$h_L = K_e \frac{V^2}{2g} \tag{14.7}$$

where the coefficient K_e may be determined from Table 14.2.

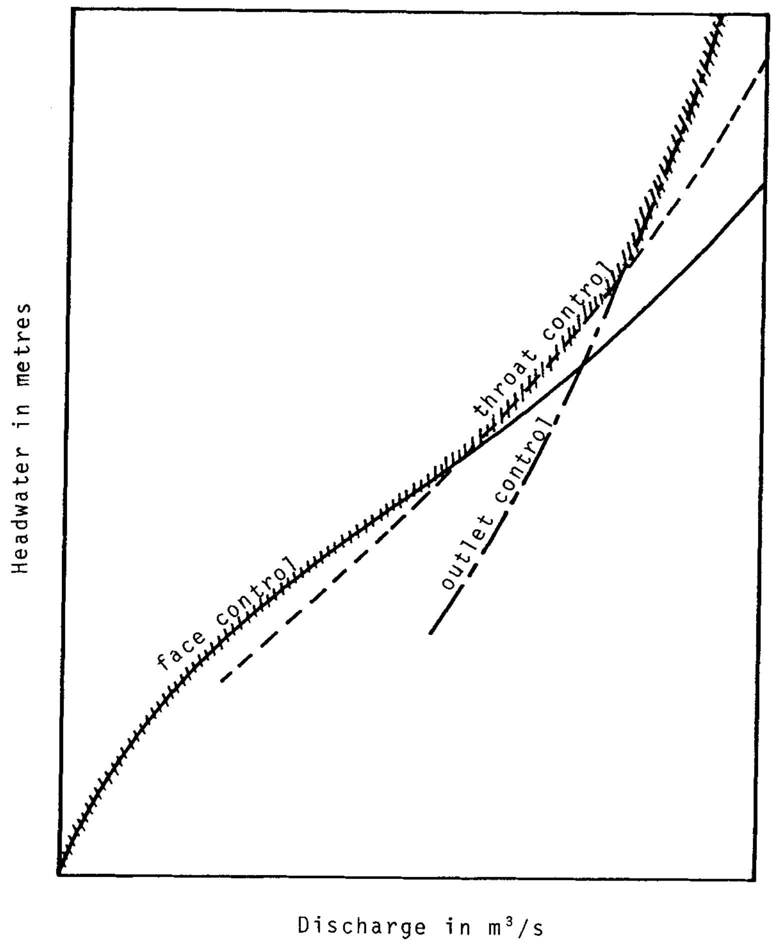


Fig. 14.5 Culvert performance curves for locating control section

The discharge characteristics as a function of headwater for each section of a culvert will differ with the type of flow. Thus flow into the inlet is usually orifice-type flow (Q proportional to $H^{1/2}$). Barrel control may be similar (Q proportional to $H^{1/2}$) while outlet conditions may be weir flow (Q proportional to $H^{3/2}$). Under different headwaters different sections may control the flow. It is therefore useful to plot the discharge characteristics of each section on a common chart, such as Fig. 14.5. It will be seen that at lower headwater levels, the inlet conditions limit the flow, while at higher heads, the outlet conditions may limit the flow.

The optimum design will be that for which inlet and outlet conditions give a similar discharge (the design flow) for the required maximum headwater permitted. Inlet control curves should be plotted for different inlet configurations (Fig. 14.6). The required inlet configuration for any headwater and barrel size can then be read off the plot.

TABLE 14.2 Entrance Loss Coefficients

Outlet Control, Full or Partly Full

Entrance head loss $H_e = K_e \frac{V^2}{2g}$

Type to Structure and Entrance Design	Coefficient K_e
Pipe	
Projecting from fill, socket end	0.2
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe or rounded	0.2
Square-edge	0.5
Mitered to conform to fill slope	0.7
End-Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side-or slope-tapered inlet	0.2
Metal pipe projecting from fill, no headwall	0.9
Reinforced Concrete Box Section	
Headwall parallel to embankment, no wingwalls	
Square on 3 edges	0.5
Round 3 edges to radius 1/12 barrel or beveled 3 sides	0.2
Wingwalls 30° to 75° to barrel. Square edged at crown	0.4
Crown edge rounded to radius 1/12 barrel or beveled top	0.2
Wingwall 10° to 25° to barrel. Square-edged at crown	0.5
Wingwalls paralled (extension of sides). Square at crown	0.7
Side-or slope-tapered inlet	0.2

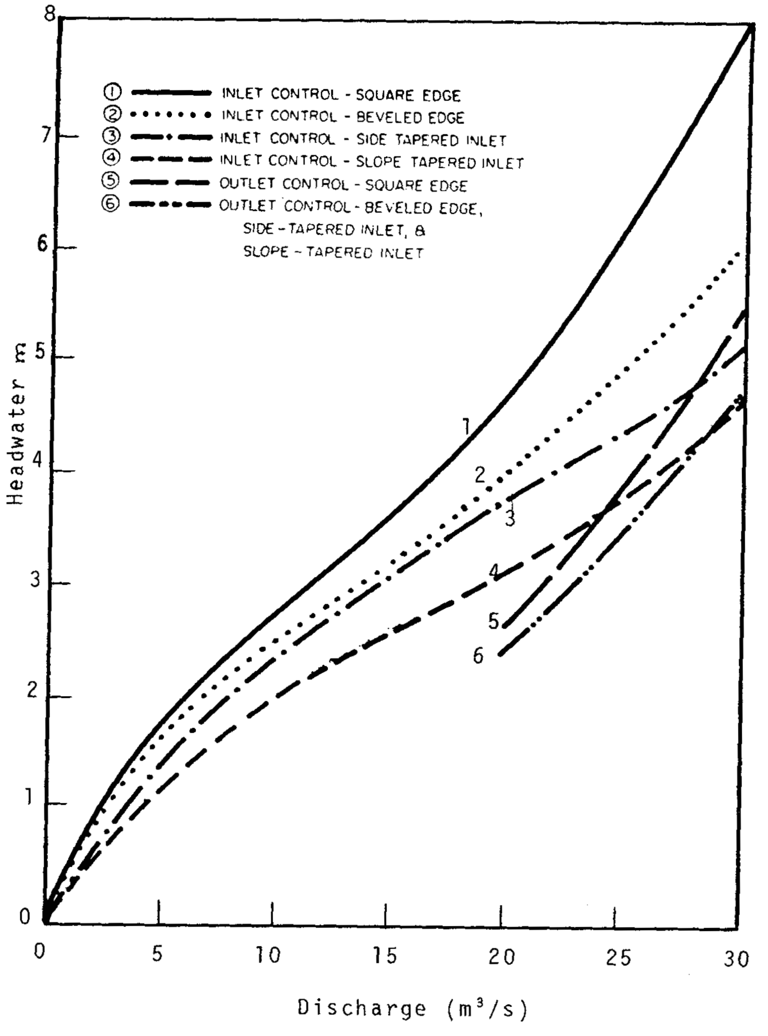


Fig. 14.6 Performance curves for single 2m box culvert with alternative inlets

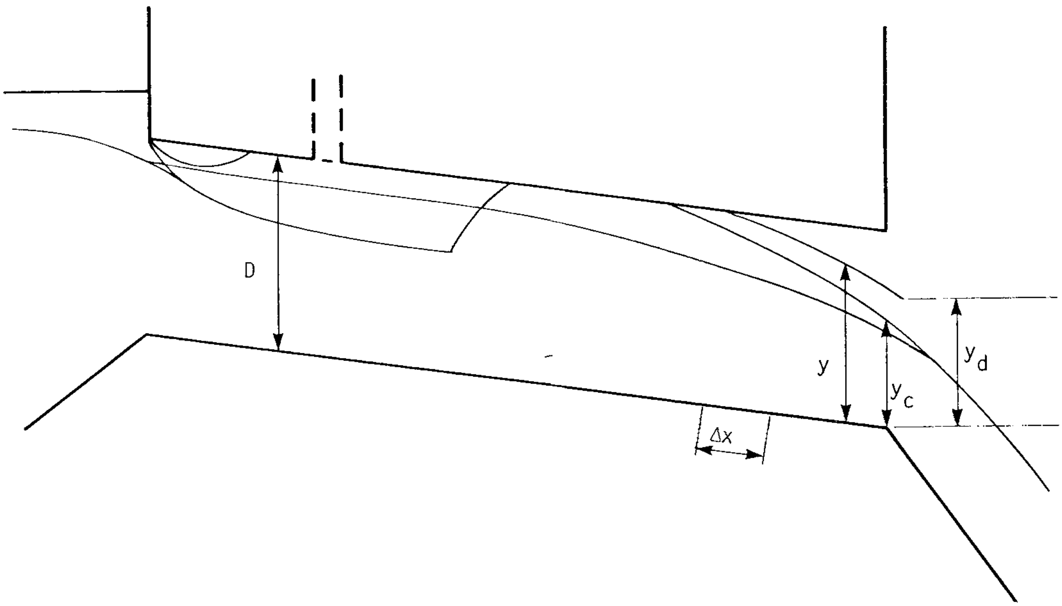


Fig. 14.7 Alternative water profiles

COMPUTER PROGRAM FOR CALCULATION OF FLOW PROFILES IN RECTANGULAR CULVERTS

The number of possible flow profiles in a culvert is obviously vast. Careful analytical procedures can however isolate the possibilities and enable the flow profile to be established for any condition. The analytical procedure can be programmed for a computer.

The engineer should, however, establish his objectives in order to minimize the trial and error approach. There are three problems the engineer is likely to encounter:

1) Design of a culvert to discharge a given flow with a specified headwater and tailwater level: The most economical solution is to select a practical inlet and barrel such that they are both equal in capacity ie equal to the design flow. As the barrel is usually the most expensive component this should be designed to run full, so that the inlet should be carefully designed to prevent control there.

2) For any given culvert design and headwater conditions to determine the discharge capacity: If the control section cannot be readily identified, it will be necessary to consider a number of alternative flow rates. The rating curve can be plotted as in Fig. 14.6 in order to

establish which condition controls the flow at the prescribed headwater level.

3) For a given culvert and discharge rate, determine the water surface profile: This is a confirmatory measure but a recommended step in the design process.

The latter analytical procedure can most readily be programmed for a computer. The procedure is summarized below for a box culvert with a simple inlet.

1) Start at the downstream end, knowing the water level in the channel or pool downstream of the culvert. If the water surface downstream is below critical depth in the culvert the depth then will be critical depth. Otherwise the energy level is set equal to that in the channel plus exit losses.

2) Calculate the water surface and energy levels at suitable intervals proceeding upstream. A backwater procedure is used for free surface flow and a friction gradient equation for full flow.

3) If the depth at any section works out to be less than critical depth ($y_c = \sqrt[3]{q^2/g}$) proceed to the inlet and set $y = y_c$ at the control section there.

4) Backwater downstream from the control at the inlet to determine the supercritical water surface profile.

5) Establish the position of the hydraulic jump if any at the point where the depth computed from the downstream end is equal to the sequent depth to the supercritical depth calculated from the upstream end.

6) If the hydraulic jump is not ventilated negative pressures (down to vapour pressure) may be assumed in the barrel in which case the effective water level is higher.

7) The headwater energy level is calculated by adding entrance losses to the energy level in the inlet.

REFERENCES

Blaisdell, F.W., May 1960. Hood inlet for closed conduit spillways. Proc, ASCE, 86 (HY5), p7.

Diskin, M.H., July 1962. Specific energy in circular channels, Water Power, 14, p270.

French, J.L., Nov. 1969. Nonenlarged box culvert inlets. Proc. ASCE 95(HY6), 6928, p2115-2137.

Henderson, F.M., 1966. Open Channel Flow, Macmillan, N.Y., 522pp.

Kalinske, A.A., and Bliss, P.H., Oct. 1943. Removal of air from pipelines by flowing water. Civil Engineering, ASCE, 13(10) p480.

Southwood, S.R., 1978. Culvert Hydraulics. Course on Urban Hydrology and Drainage, SAICE, Durban.

U.S. Bureau of Reclamation, 1960. Design of Small Dams. 611pp.

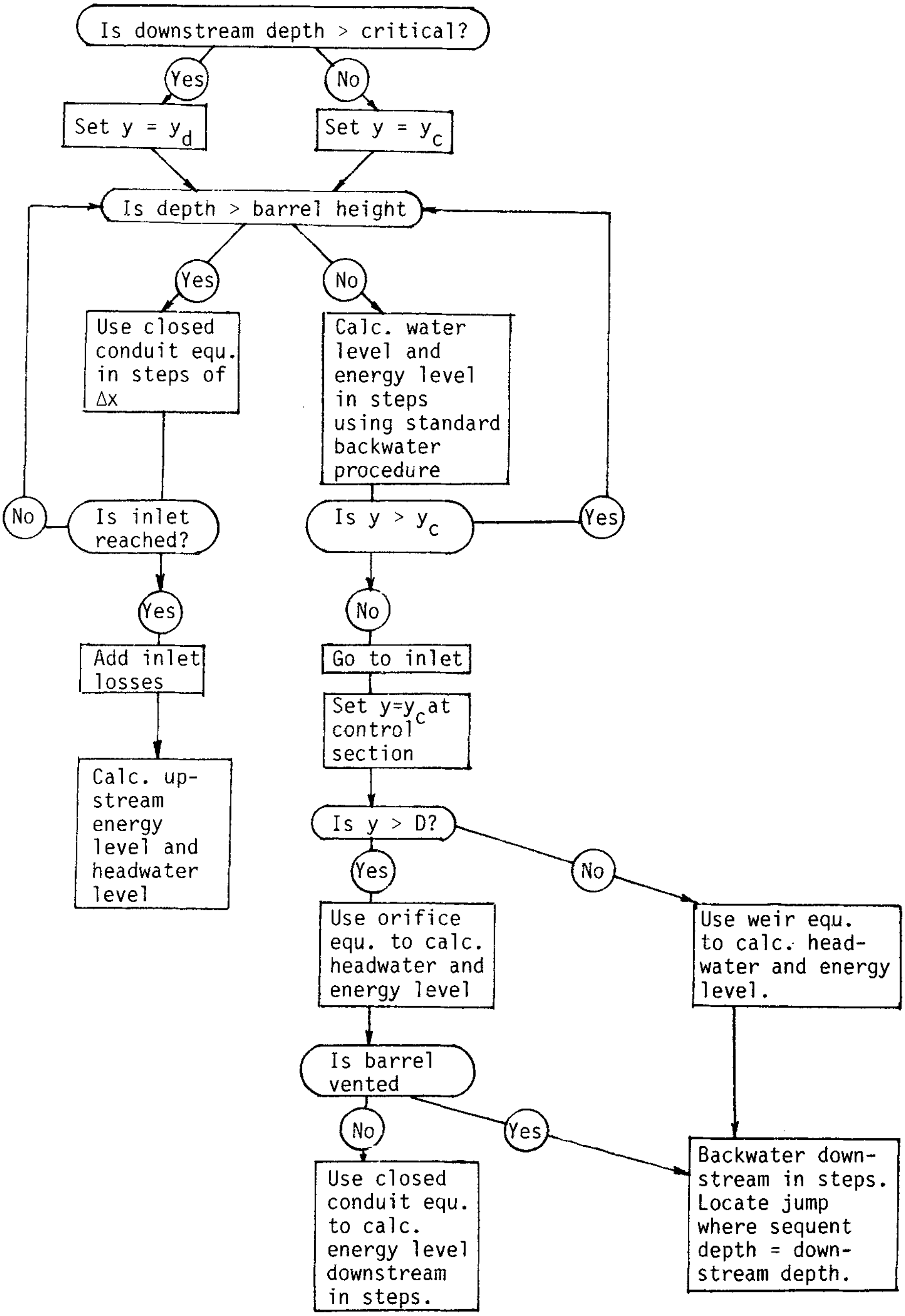


Fig. 14.8 Computation of flow profile in simple rectangular culvert

U.S. Department of Transport, Aug. 1972. Federal Highway Commission, Hydraulic Design of Improved Inlets for Culverts, Hydraulic Eng. Circular 13, 172pp.