CHAPTER-6

Cross-Drainage and Drop Structures

6.1 Aqueducts and canal inlets and outlets

6.1.1 Introduction

The alignment of a canal invariably meets a number of natural streams (drains) and other structures such as roads and railways, and may sometimes have to cross valleys. Cross drainage works are the structures which make such crossings possible. They are generally very costly, and should be avoided if possible by changing the canal alignment and/or by diverting the drains.

6.1.2 Aqueducts

An aqueduct is a cross-drainage structure constructed where the drainage flood level is below the bed of the canal. Small drains may be taken under the canal and banks by a concrete or masonry barrel (culvert), whereas in the case of stream crossings it may be economical to flume the canal over the stream (e.g. using a concrete trough, Fig. 6.1(a)).

When both canal and drain meet more or less at the same level the drain may be passed through an inverted siphon aqueduct (Fig. 6.1(d)) underneath the canal; the flow through the aqueduct here is always under pressure. If the drainage discharge is heavily silt laden a silt ejector should be provided at the upstream end of the siphon aqueduct; a trash rack is also essential if the stream carries floating debris which may otherwise choke the entrance to the aqueduct.

6.1.3 Superpassage

In this type of cross-drainage work, the natural drain runs above the canal, the canal under the drain always having a free surface flow. The Superpassage is called a canal siphon or simply an inverted siphon if the canal bed under the drain is lowered to accommodate the canal flow, which will always be under pressure. The layouts of the Superpassage and canal siphon are similar to those shown in Figs 6.1(a) and 6.1(b), with the canal and drain interchanged.

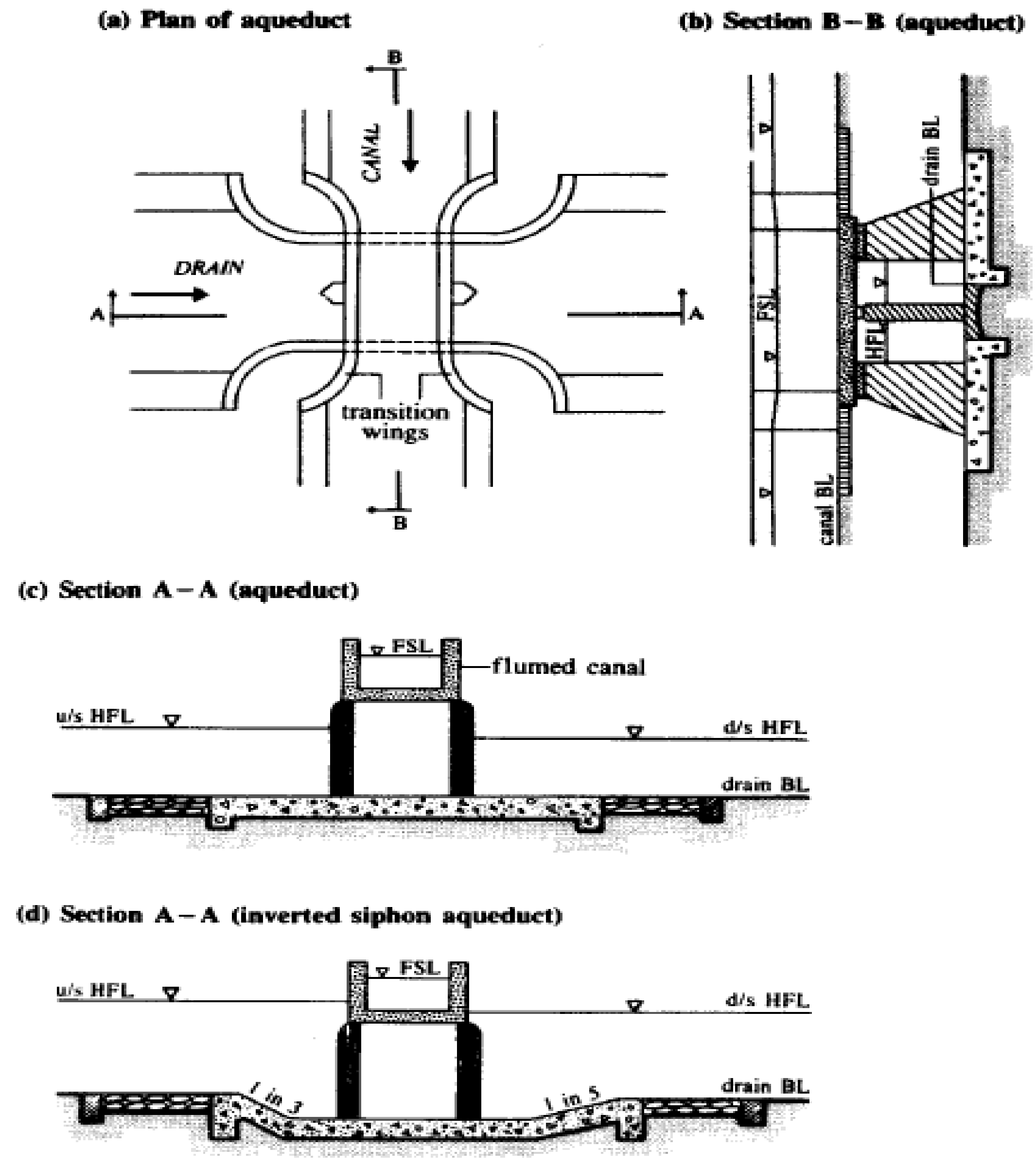


Figure 6.1: Layout of an aqueduct

6.1.4 Level crossing

Level crossing facilities are provided when both the drain and the canal run at more or less the same level. This is more frequently used if either of the flows occurs for a short period (e.g. flash floods in the drain); in addition, the mixing of the two bodies of water must also be acceptable (quality considerations).

The plan layout of a level crossing with two sets of regulators, one across the drain and the other across the canal, is shown in Fig. 6.2. Normally, the canal regulator regulates its flow with the drain regulator kept closed. Whenever the flash floods occur, the canal gates are closed and drainage gates opened to let the flood flow pass.

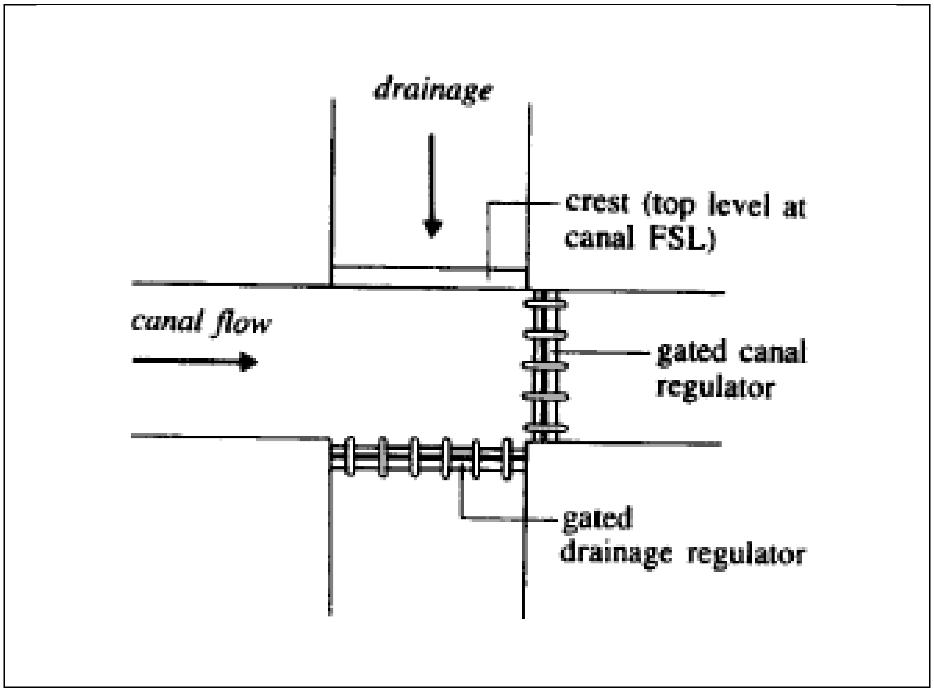


Figure 6.2: Level crossing

6.1.5 Canal inlets and outlets

When the drainage flow is small it may be absorbed into the canal through inlets. The flow in the canal may be balanced, if necessary (in the case of small canals), by providing suitable outlets (or escapes). The inlet and outlet structures must also be provided with energy dissipators wherever necessary.

6.2 Culverts, bridges and dips

6.2.1 Introduction

Highways cross natural drainage channels or canals, and provision must be made for appropriate cross-drainage works. The alignment of a highway along ridge lines (though it may be a circuitous route with less satisfactory gradients) may eliminate the cross-drainage work, thus achieving considerable savings.

Highway cross-drainage is provided by culverts, bridges and dips. Culverts are usually of shorter span (less than 6m), with the top not normally forming part of the road surface like in a bridge structure. They are submerged structures buried under a high-level embankment. On the other hand, if the embankment is a low-level one, appropriate armouring protection works against overtopping during high floods have to be provided. Such a low-level structure (sometimes called a ʹdipʹ) in the absence of the culvert is often economical if the possible traffic delays do not warrant a costly high-level structure such as a bridge, keeping the road surface above all flood levels. A culvert combined with a dip (lowered road surface) is an attractive solution for small perennial streams with occasional flash floods; however, appropriate traffic warning systems/signs have to be incorporated.

Bridges are high-level crossing structures which can be expensive for large rivers. It is therefore essential to protect them even from rare floods. It is often advantageous to allow overtopping of part of the approach embankment, which may act as a fuse plug, to be replaced if necessary, after the flood event. Such an alternative route for the water avoids the overtopping of the bridge deck and, in addition, reduces the scouring velocities which may otherwise undermine the foundations of the structure.

6.2.2 Culverts

The culvert consists essentially of a pipe barrel (conveyance part) under the embankment fill, with protection works at its entrance and exit. At the entrance a head wall, with or without wing walls, and a debris barrier are normally provided. If necessary, an end wall with energy-dissipating devices is provided at the exit.

The culvert acts as a constriction and creates a backwater effect to the approach flow, causing a pondage of water above the culvert entrance. The flow within the barrel itself may have a free surface with subcritical or supercritical conditions depending on the length, roughness, gradient, and upstream and downstream water levels of the culvert. If the upstream head is sufficiently large the flow within the culvert may or may not fill the barrel, and its hydraulic performance depends upon the combination of entrance and friction losses, length of barrel, and the downstream backwater effects (Fig.6.3).

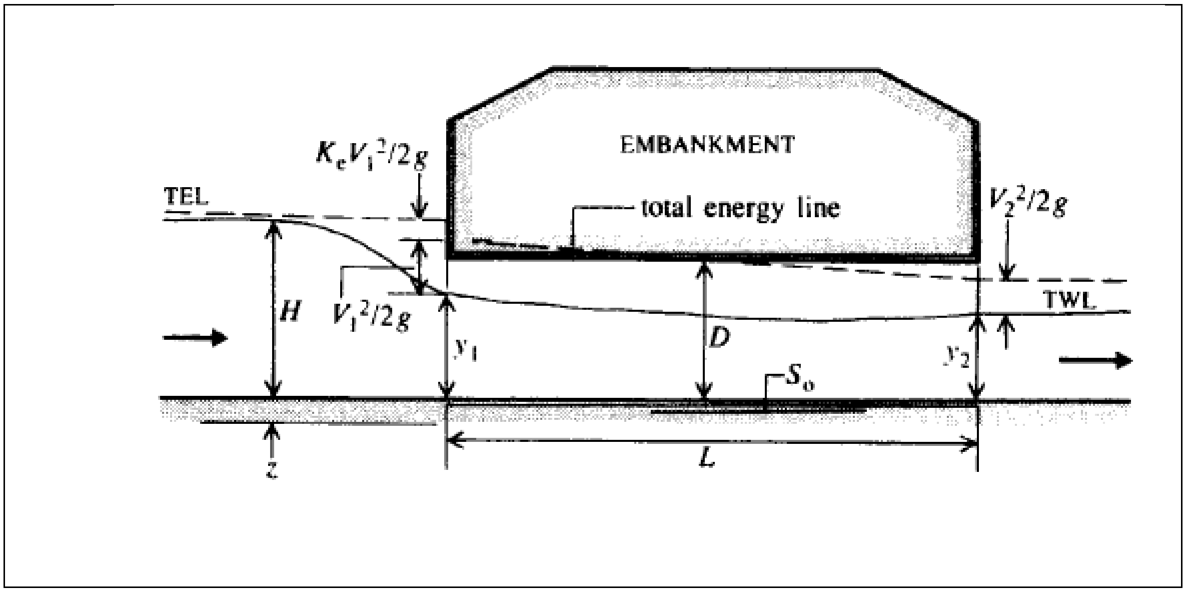
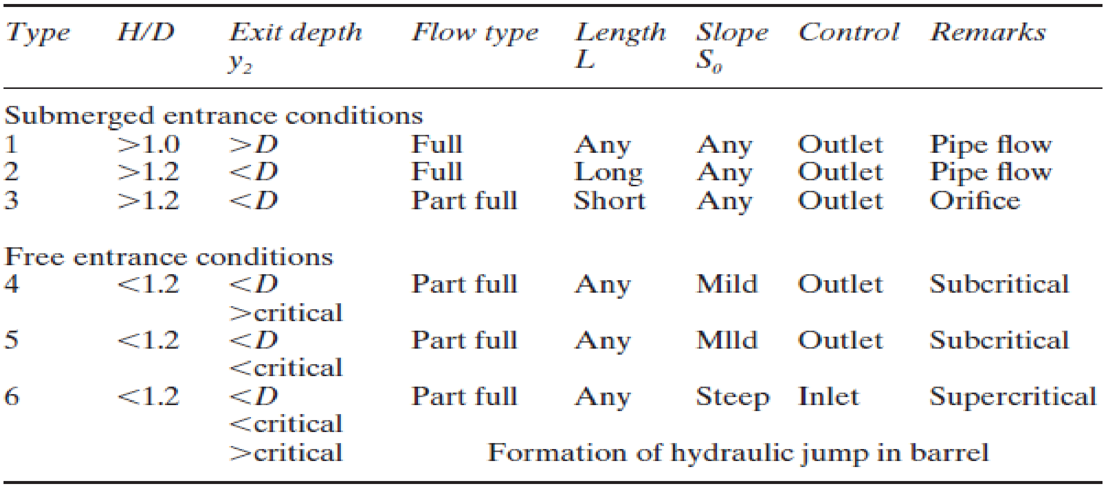


Figure 6.3: Flow through a culvert

The various flow types that can exist in the pipe barrel of a culvert are shown in Table 6.1 below.



Type	*H/D*	*Exit depth y_2*	*Flow type*	*Length L*	*Slope S_o*	*Control*	*Remarks*
Submerged entrance conditions							
1	>1.0	>*D*	Full	Any	Any	Outlet	Pipe flow
2	>1.2	<*D*	Full	Long	Any	Outlet	Pipe flow
3	>1.2	<*D*	Part full	Short	Any	Outlet	Orifice
Free entrance conditions							
4	<1.2	<*D* >critical	Part full	Any	Mild	Outlet	Subcritical
5	<1.2	<*D* <critical	Part full	Any	Mlld	Outlet	Subcritical
6	<1.2	<*D* <critical	Part full	Any	Steep	Inlet	Supercritical
		>critical	Formation of hydraulic jump in barrel				

The hydraulic performance of a culvert can be improved by the adoption of the following guidelines.

a) Culvert alignment

As a general rule, the barrel should follow the natural drainage alignment and its gradient, in order to minimize head losses and erosion. This may lead to a long skew culvert which will require more complex head and end walls. However, it is sometimes more economical to place the culvert perpendicular to the highway with certain acceptable changes in the channel alignment (see Linsley and Franzini, 1979).

b) Culvert entrance structures

Properly designed entrance structures prevent bank erosion and improve the hydraulic characteristics of the culvert. The various types of entrance structures (end walls and wing walls) recommended are shown in Fig. 6.4.

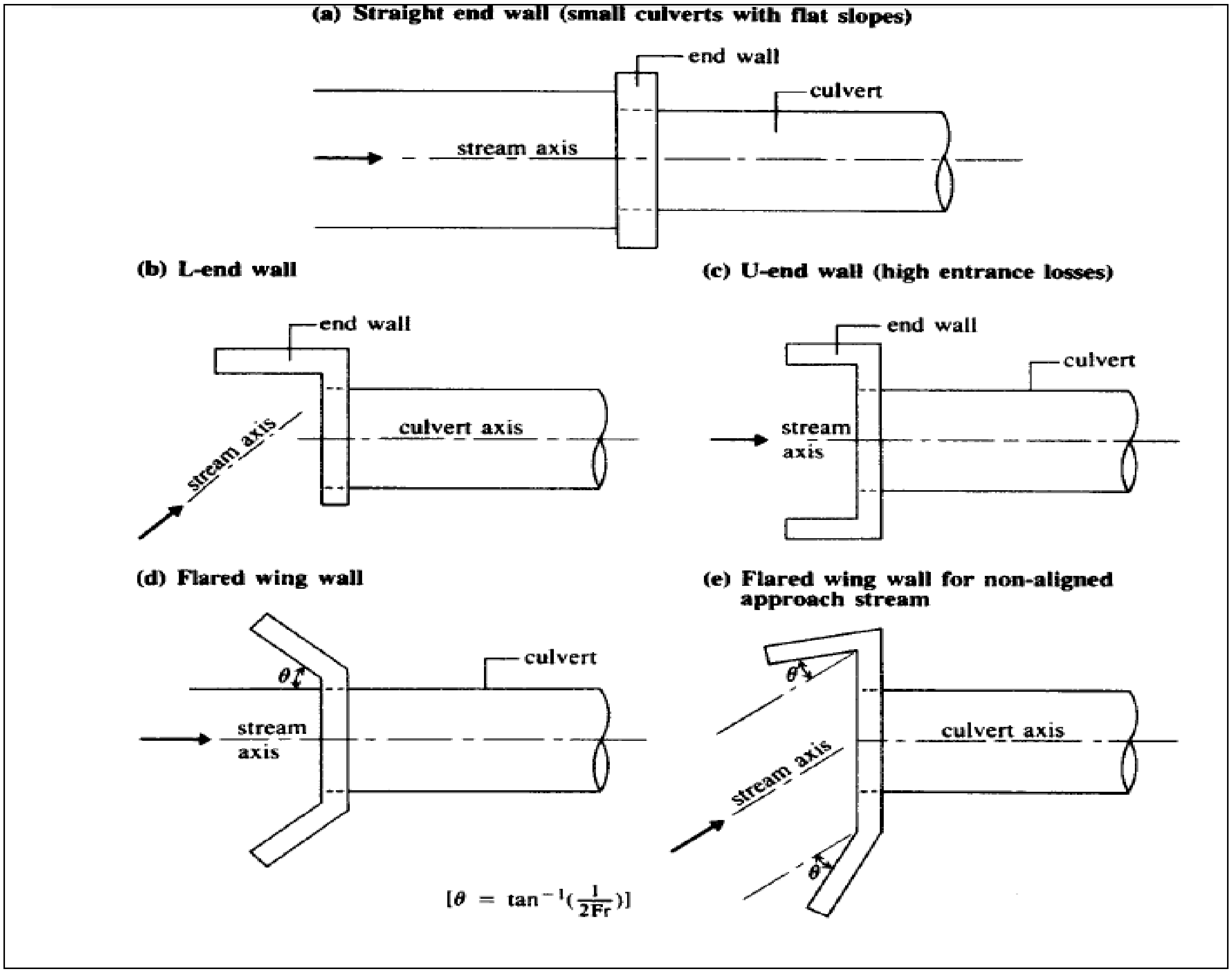


Figure 6.4: Culvert entrance structures; plan views

A debris barrier (trash rack) must also be provided upstream of the culvert entrance to prevent the blockage of the barrel entrance.

In the case of a culvert with a submerged entrance, flaring the entrance will increase its capacity under a lower head for a given discharge. Such an arrangement for a box culvert (square or rectangular concrete barrel), the entrance area being double the barrel area over a length of 1.2*D*, where *D* is the height of the barrel, is shown in Fig. 10.5.

A drop inlet structure with a necessary debris barrier (timber or concrete cribs) has to be provided whenever the culvert entrance is at the bed level (highway drainage facilities) of the drainage, requiring an abrupt break in the channel slope. Various arrangements of drop inlet culverts are shown in Fig. 10.6. The culvert sill length must be sufficient to discharge the design flow with a reasonably low-head water level. For high discharges, the entrance may be flared so as to increase the crest length. A flared entrance with a back wall (to prevent vortex action) considerably increases the inlet capacity. De-aeration chambers may have to be provided if a jump forms in the barrel of the culvert.

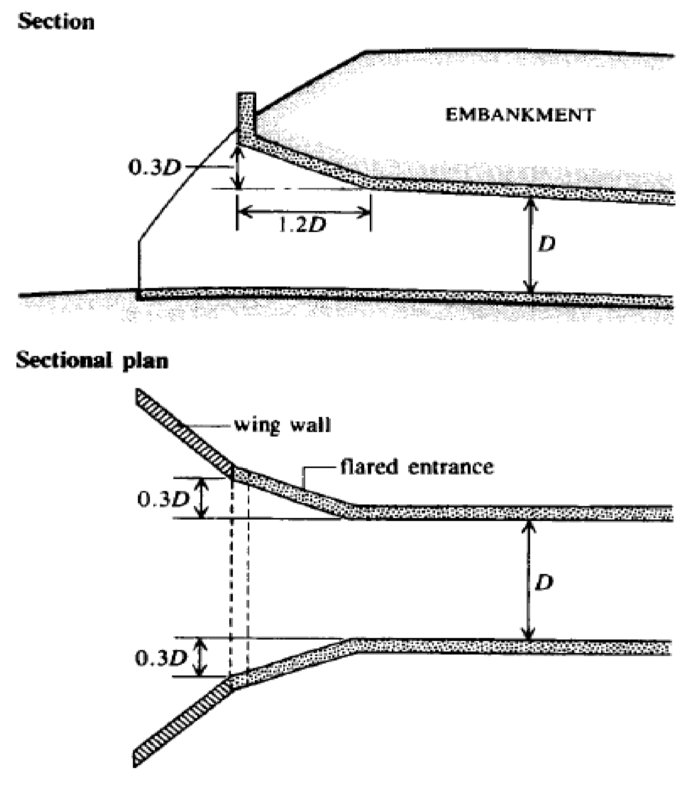


Figure 6.5: Box culvert with flared entrance

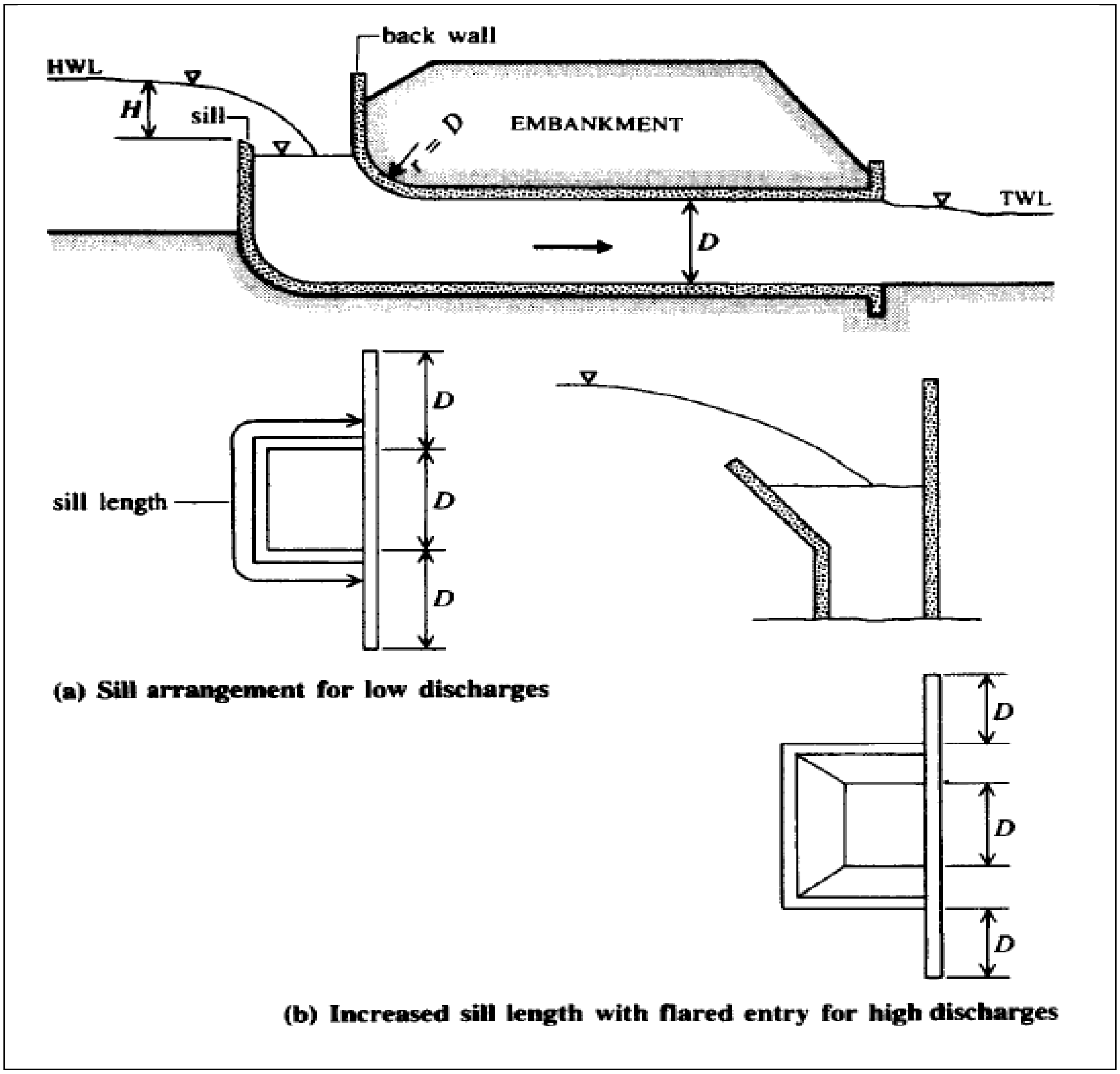


Figure 6.6: Drop inlet culvert

c) Culvert outlet structures

Proper device has to be provided at the outlet of a culvert to prevent the downstream erosion of the bed and the slopes of the embankment. For small discharges a straight or U-shaped end wall is sufficient. For moderate flows a flaring wing-walled outlet connecting the much wider downstream channel will reduce the scouring of the embankment and channel banks. The suggested flare angle for supercritical flows should be under 1 in 2, decreasing linearly with the flow Froude number. For subcritical flows it may be larger than 1 in 2.

d) Scour below culvert outlets

The flow through a culvert may cause undesirable erosion (scour) at its unprotected outlet which can lead to undermining of the culvert structure.

6.2.3 Bridges

The presence of a bridge across a stream creates constricted flow through its openings because of (a) the reduction in the width of the stream due to piers and their associated end contractions and (b) the fluming of the stream itself (in the case of wide streams with flood plains) to reduce the costs of the structure.

Apart from (local) scour around the piers and bridge abutments and possible bed erosion, there is a considerable backwater effect of the bridge. The corresponding afflux (rise in upstream water level) depends on the type of flow (subcritical or supercritical). As most bridges are designed for subcritical flow conditions in order to minimize scour and choking problems, further discussions here are mainly confined to subcritical flow.

The establishment of afflux levels is extremely important for the design of upstream dykes and other protective works and also for the location of safe bridge deck levels (to avoid the flooding of the deck and any consequent structural damage). It is equally important to determine the minimum clear length of span (economic considerations) which will not cause undesirable afflux levels. In order to establish permissible upstream stage levels, detailed investigations of the properties along the stream have to be investigated. Downstream of the bridge the water levels are only influenced by the nearest control section below the bridge. These levels can therefore be established by backwater computation (for further information see Hamill, 1999).

Backwater levels

SHORT CONTRACTIONS

In flow through a relatively short contracted section (narrow bridge without approach fluming) with only a few piers, the backwater problem may be relatively less important. Referring to Fig. 6.7, the change in water level, Δh can be obtained by the energy equation between sections 1 and 2 (Kindsvater, Carter and Tracy, 1953) as:

$$\Delta h = K_B V_2^2/2g + S_0 L/\sigma - \alpha_1 V_1^2/2g$$

Where *K*B is the bridge loss coefficient (Table 10.2), expressed as a function of the conveyance ratio,

$$\sigma = k_b/k_B,$$

Bridge loss coefficient, *K*B

σ	K_B
1.0	1.00
0.8	1.36
0.6	1.67
0.4	1.88
0.2	1.92

Kb being the conveyance of the gross contracted section with the same normal depth and roughness characteristics as the upstream approach section whose conveyance is kB.

LONG CONTRACTIONS

In the case where the bridge has a number of large piers and/or long approach embankments contracting the water width, the backwater effect is considerable. Referring to the flow profile shown in Fig. 6.7, through such a long contracting section, Δy is the afflux entirely created by the presence of piers and channel contraction.

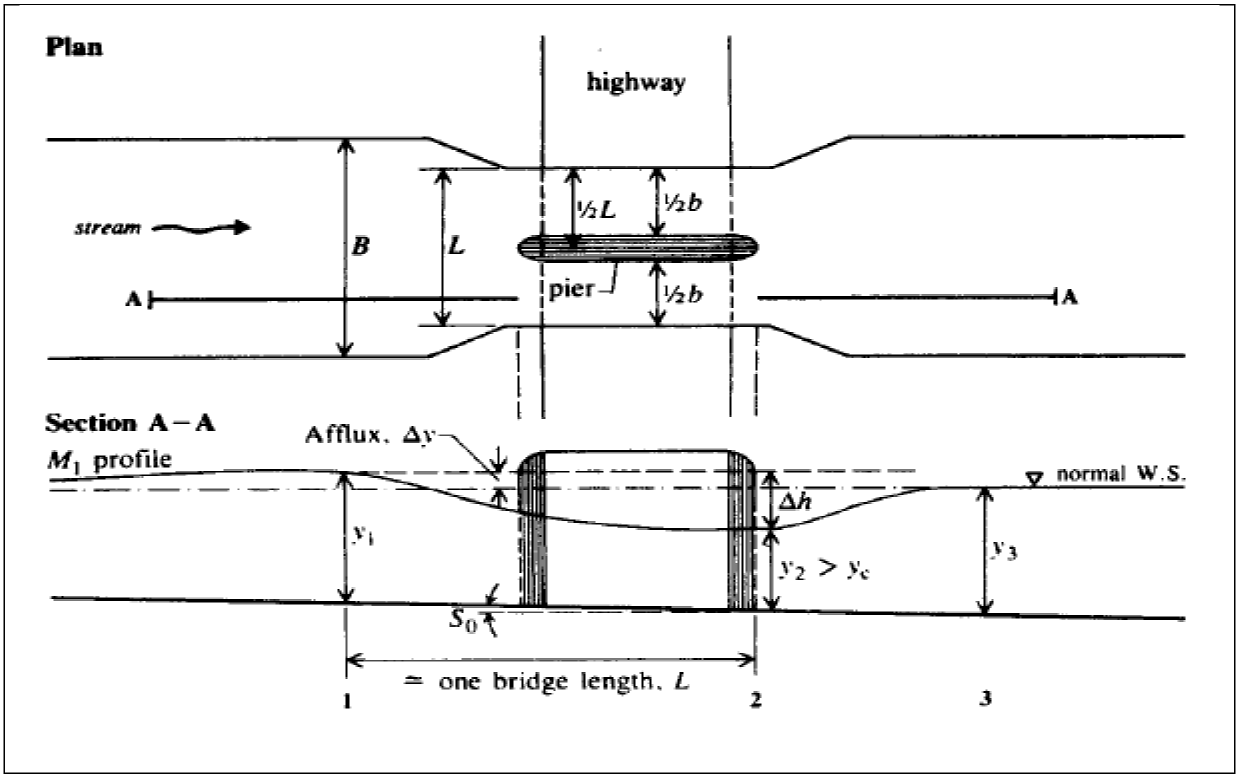


Figure 6.7: Flow profile through bridge with contracted channel of relatively short length (subcritical flow)

6.2.4 Dips

The dip is a shallow structure without excessive approach gradients. In arid regions, streams with infrequent flash floods and shallow depths (less than 0.3 m) may be allowed to flow through the dipped area. The upstream road edge should not be discontinuous with the stream bed in order to avoid scour, and at the downstream edge protection works such as a cutoff wall, concrete, or riprap paving must be provided. Also, the profile of the dip should, as far as possible, conform to the profile of the stream to minimize local disturbances to the flow.

6.3 Drop structures

6.3.1 Introduction

A drop (or fall) structure is a regulating structure which lowers the water level along its course. The slope of a canal is usually milder than the terrain slope as a result of which the canal in a cutting at its headworks will soon outstrip the ground surface. In order to avoid excessive infilling the bed level of the downstream canal is lowered, the two reaches being connected by a suitable drop structure (Fig. 6.8).

The drop is located so that the fillings and cuttings of the canal are equalized as much as possible. Wherever possible, the drop structure may also be combined with a regulator or a bridge. The location of an offtake from the canal also influences the fall site, with offtakes located upstream of the fall structure.

Canal drops may also be utilized for hydropower development, using bulb- or propeller-type turbines. Large numbers of small and medium sized drops are desirable, especially where the existing power grids are far removed from the farms. Such a network of micro-installations is extremely helpful in pumping ground water, the operation of agricultural equipment, village industries, etc. However, the relative economy of providing a large number of small falls versus a small number of large falls must be considered. A small number of large falls may result in unbalanced earthwork but, on the other hand, some savings in the overall cost of the drop structures can be achieved.

Drops are usually provided with a low crest wall and are subdivided into the following types: (i) the vertical drop, (ii) the inclined drop and (iii) the piped drop.

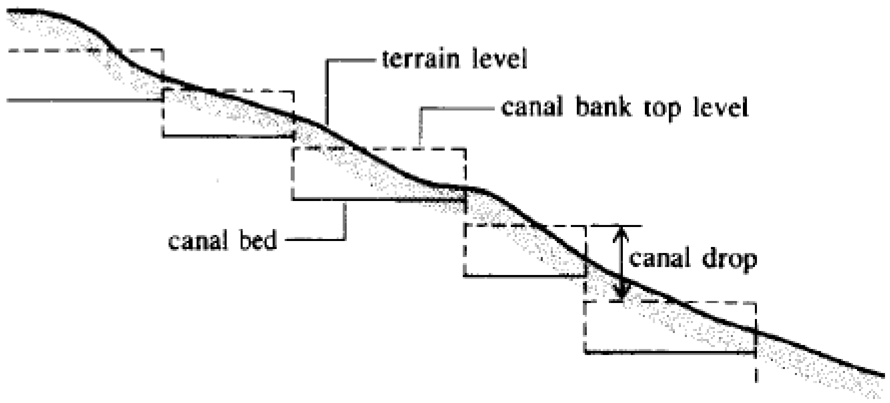


Figure 6.8: Location of canal drops

6.3.2 Vertical drop structures

a) Common (straight) drop

The common drop structure, in which the aerated free-falling nappe (modular flow) hits the downstream basin floor, and with turbulent circulation in the pool beneath the nappe contributing to energy dissipation, is shown in Fig. 6.9.

The following equations fix the geometry of the structure in a suitable form for steep slopes:

drop number, $D_r = q^2/g^{d3}$

where q is the discharge per metre width;

basin length, $L_B/d = 4.3D_r^{0.27} + L_j/d$;

pool depth under nappe, $Y_P/d = D_r^{0.22}$;

sequent depths, $y_1/d = 0.54D_r^{0.425}$;

$y_2/d = 1.66D_r^{0.27}$;

Here d is the height of the drop crest above the basin floor and Lj the length of the jump.

A small upward step, *h* (around 0.5<*h*/*y*1<4), at the end of the basin floor is desirable in order to localize the hydraulic jump formation. Forster and Skrinde (1950) developed design charts for the provision of such an abrupt rise.

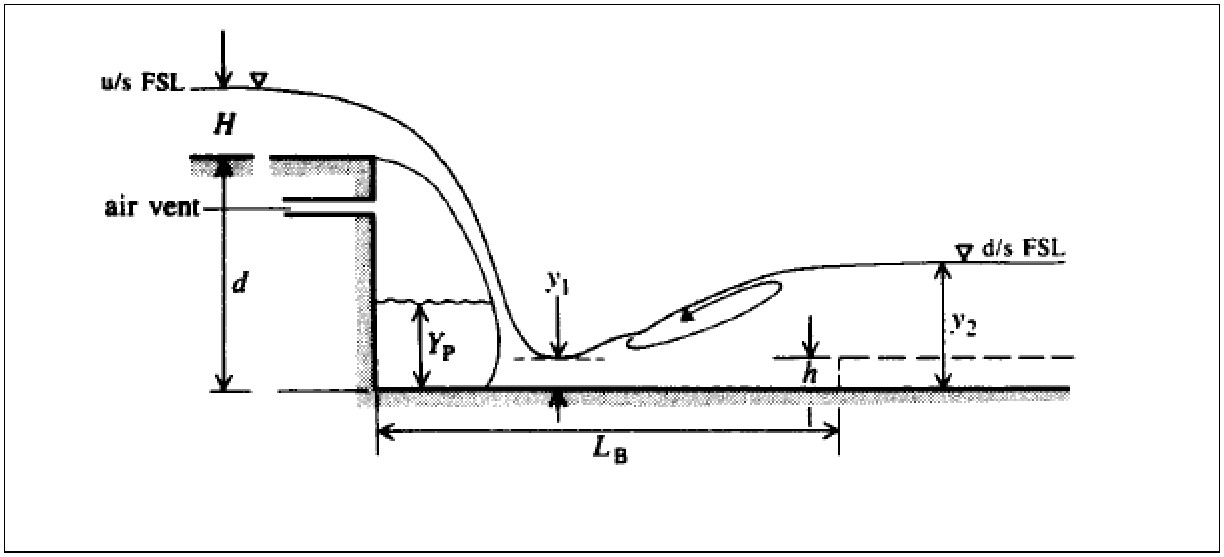
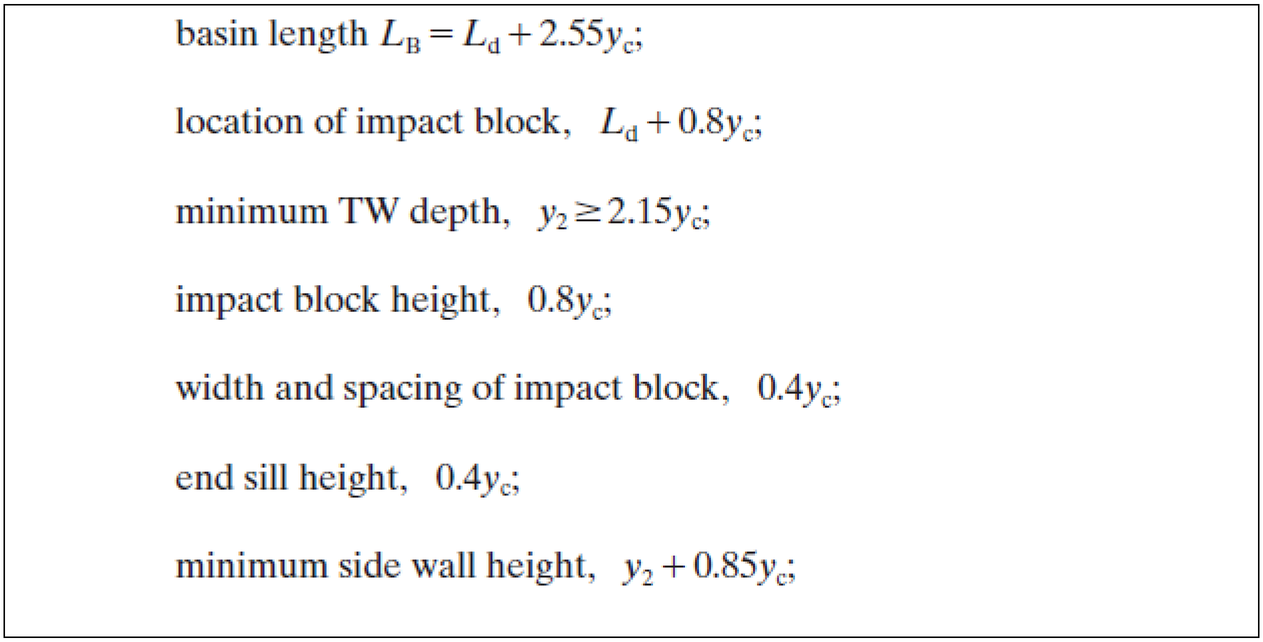


Figure 6.9: Common drop structure (after Bos, 1976)

The USBR (Kraatz and Mahajan, 1975) impact block type basin also provides good energy dissipation under low heads, and is suitable if the tailwater level (TWL) is greater than the sequent depth, y2. The following are the suggested dimensions of such a structure (Fig. 6.10):



basin length $L_B = L_d + 2.55y_c$;

location of impact block, $L_d + 0.8y_c$;

minimum TW depth, $y_2 \geq 2.15y_c$;

impact block height, $0.8y_c$;

width and spacing of impact block, $0.4y_c$;

end sill height, $0.4y_c$;

minimum side wall height, $y_2 + 0.85y_c$;

Here *y*c is the critical depth. The values of *L*d can be obtained from Fig. 6.11.

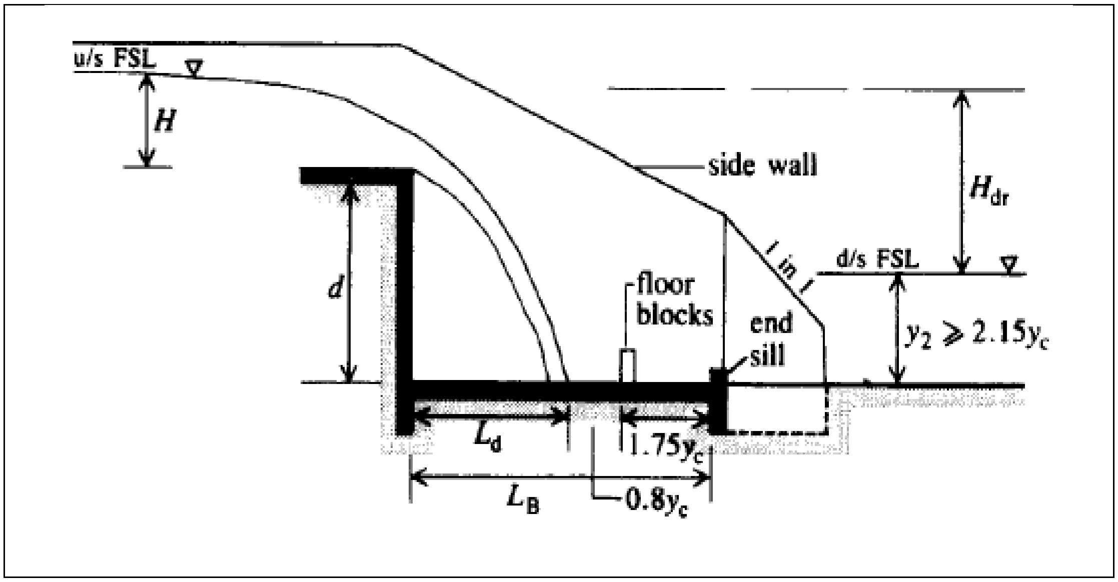


Figure 6.10: Impact block type basin (after Bos, 1976)

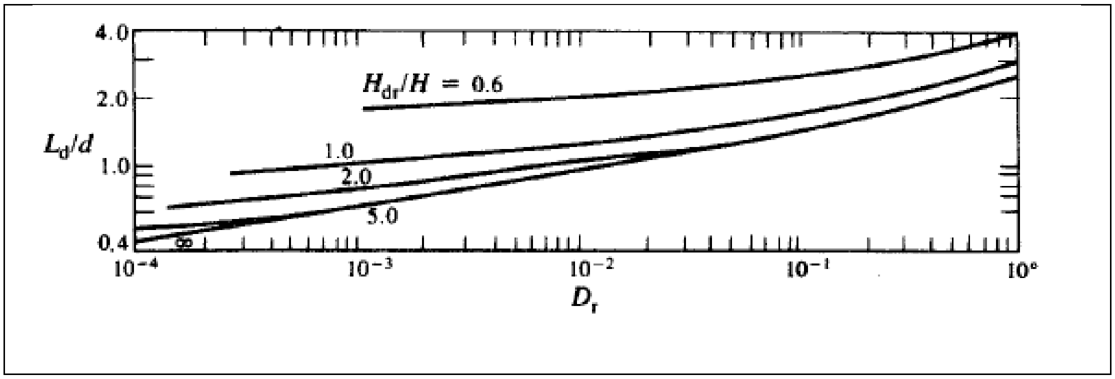


Figure 6.11: Values of *L*d/*d* (after Bos, 1976)

b) Sarda-type fall

This is a raised-crest fall with a vertical impact, consisting of a crest wall, upstream and downstream wing walls, an impervious floor and a cistern, and downstream bank and bed protection works (Fig. 6.12).

The crest design is carried out as follows. The crest length is normally kept equal to the bed width of the canal; however, an increase in length by an amount equal to the flow depth takes into account any future increase in discharge. Fluming may be provided to reduce the cost of construction of the fall. A flumed fall with a fluming ratio equal to 2*F*1, where *F*1 is the approach flow Froude number, creates no choking upstream of the fall. A canal is not usually flumed beyond 50%. Whenever the canal is flumed, both upstream (contracting) and downstream (expanding) transitions have to be provided

The crest level must be so fixed that it does not create changes in upstream water levels (backwater or drawdown effects). If the reduced level (RL) of the full supply level (FSL) is *Y*, the RL of the total energy line (TEL) is:

$$E = Y + V_a^2/2g$$

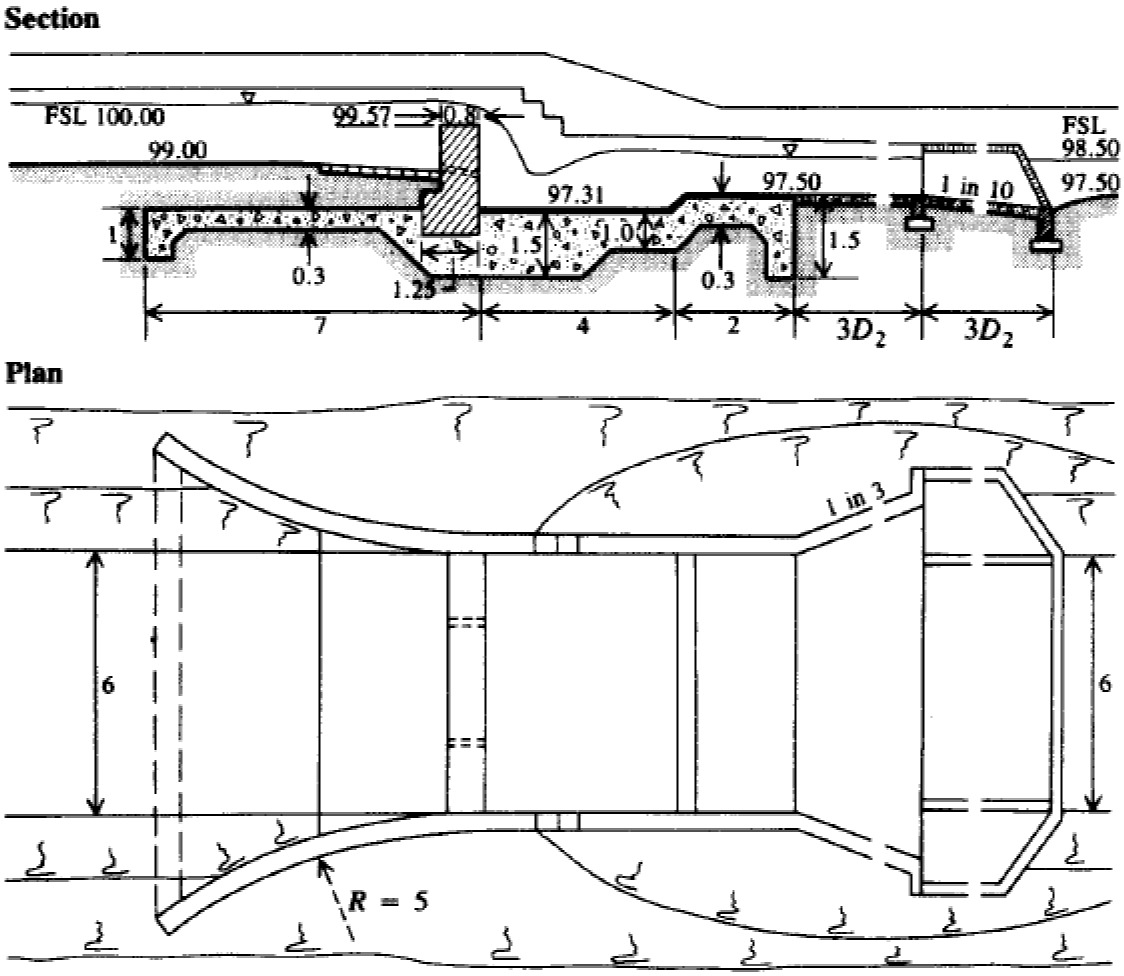


Figure 6.12: Sarda fall layout (dimensions in meters)

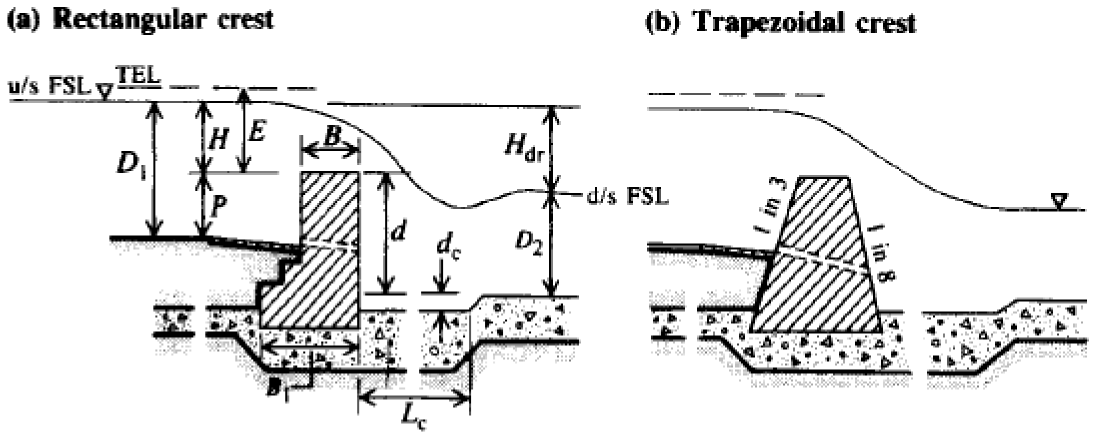


Figure 6.13: Sarda fall crests

c) YMGT-type drop

This type of drop is generally used in flumed sections suitable for small canals, field channels, etc., with discharges up to 1m3/s (Fig. 10.19). The following are the recommended design criteria:

a) Sill height, *P* varies from 0.06 m to 0.14 m with the unit discharge *q* between 0.2 and 1.0m3 s/m;

b) Depth of cistern, dc=1/2(EcHdr)$^{1/2}$;

c) Length of cistern, Lc=2.5Ld,

$$\text{where } L_d = L_{d1} + L_{d2} \text{ and}$$

$$L_{d1}/E_c = 1.155[(P'/E_c) + 0.33]^{1/2},$$

$$L_{d2} = (D_2 + d_c)\cot\alpha,$$

$$\cot\alpha = y_c/L_{d1}.$$

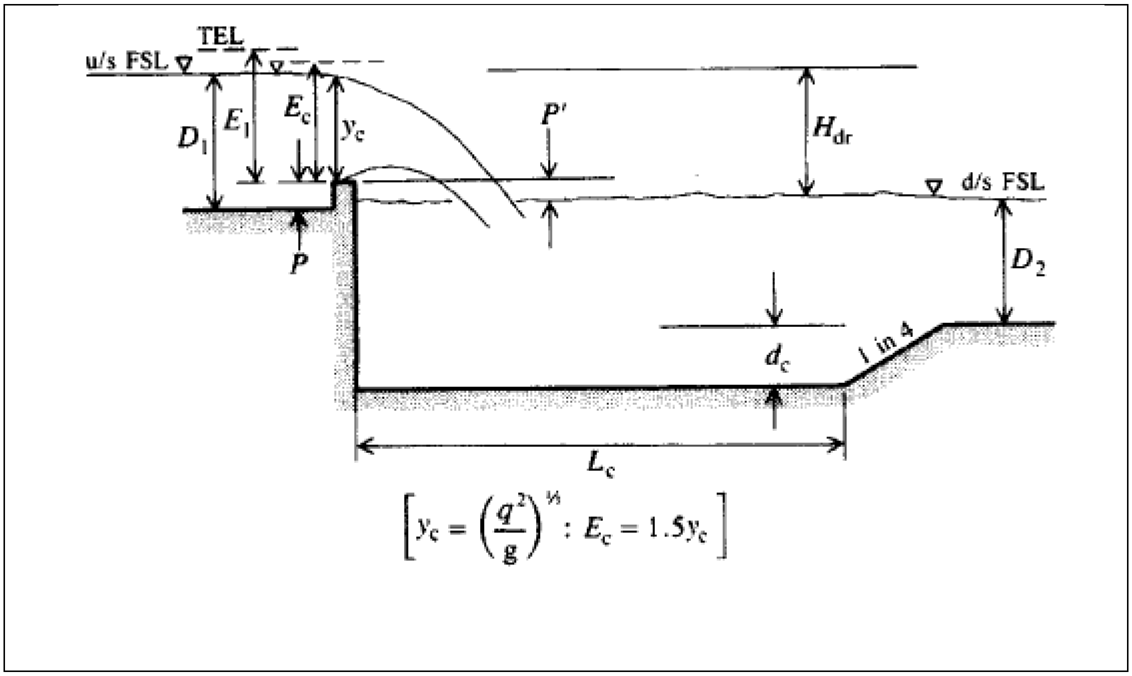


Figure 6.14: YMGT-type drop, Japan (Kraatz and Mahajan, 1975)

d) Rectangular weir drop with raised crest

SOGREAH (Kraatz and Mahajan, 1975) have developed a simple structure suitable for vertical drops of up to 7m (for channel bed widths of 0.2–1 m with flow depths (at FSL) of 0.1–0.7 m): Fig. 6.15 shows its design details.

1) For the design of crest,

$$\text{discharge,} \quad Q = CL(2g)^{1/2}H^{3/2},$$

Where C=0.36 for the vertical upstream face of the crest wall and 0.40 for the rounded upstream face (5–10 cm radius). The crest length, L=LB-0.10 m for a trapezoidal channel and is B1 (the bed width) for rectangular channels.

2) For the design of cistern,

$$\text{volume of basin,} \quad V = QH_{dr}/150 \ (\text{m}^3),$$

$$\text{width of basin,} \quad W_B = V/[L_B(D_2 + d_c)],$$

Where the depth of the basin, dc=0.1–0.3m.

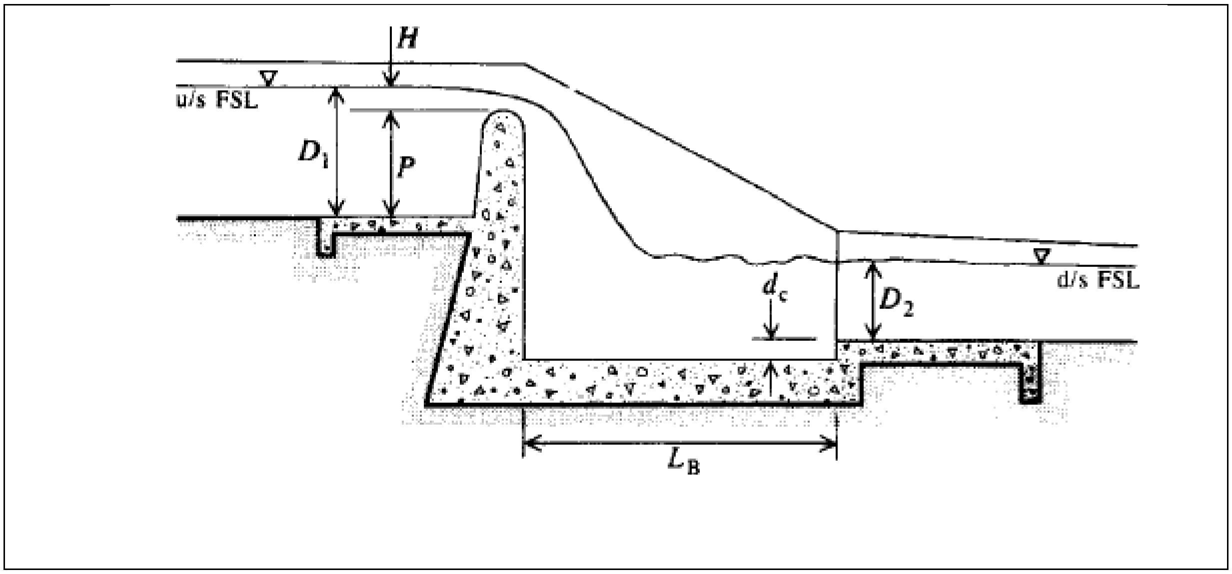


Figure 6.15: Rectangular weir drop with raised crest, France (Kraatz and Mahajan, 1975)

6.3.3 Inclined drops or chutes

a) Common chute

This type of drop has a sloping downstream face (between 1/4 and 1/6, called a glacis) followed by any conventional type of low-head stilling basin; e.g. SAF or USBR type III (Chapter 5). The schematic description of a glacis-type fall with a USBR type III stilling basin, recommended for a wide range of discharges and drop heights, is shown in Fig. 6.16.

b) Rapid fall type inclined drop

This type of fall is cheap in areas where stone is easily available, and is used for small discharges of up to 0.75m3/s with falls of up to 1.5 m. It consists of a glacis sloping between 1 in 10 and 1 in 20. Such a long glacis assists in the formation of the hydraulic jump, and the gentle slope makes the uninterrupted navigation of small vessels (timber traffic, for example) possible.

c) Stepped or cascade-type fall

This consists of stone-pitched floors between a series of weir blocks which act as check dams and are used in canals of small discharges; e.g. the tail of a main canal escape. A schematic diagram of this type of fall is shown in Fig. 6.17.

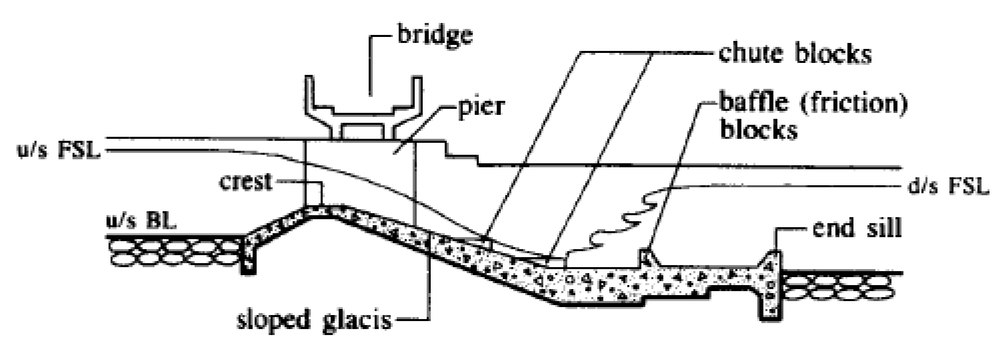


Figure 6.16: Sloping glacis type fall with USBR type III stilling basin

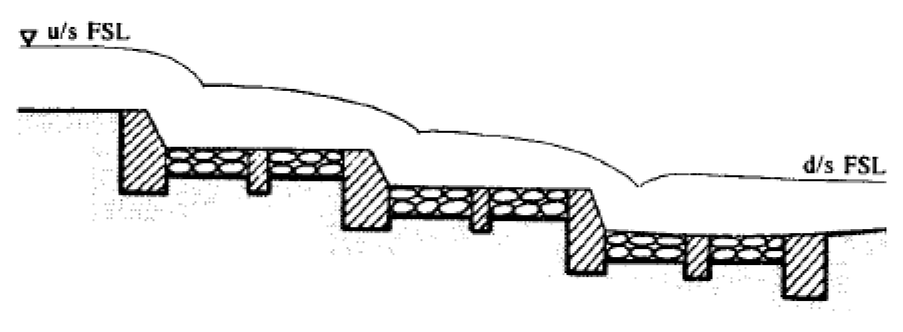


Figure 6.17: Stepped or cascade-type fall

6.3.4 Piped drops

A piped drop is the most economical structure compared with an inclined drop for small discharges of up to 50 l/s. It is usually equipped with a check gate at its upstream end, and a screen (debris barrier) is installed to prevent the fouling of the entrance.

a) Well drop structure

The well drop (Fig. 6.18) consists of a rectangular well and a pipeline followed by a downstream apron. Most of the energy is dissipated in the well, and this type of drop is suitable for low discharges (up to 50 l/s) and high drops (2–3 m), and is used in tail escapes of small channels.

b) Pipe fall

This is an economical structure generally used in small channels. It consists of a pipeline (precast concrete) which may sometimes be inclined sharply downwards (USBR and USSR practice) to cope with large drops. However, an appropriate energy dissipater (e.g. a stilling basin with an end sill) must be provided at the downstream end of the pipeline.

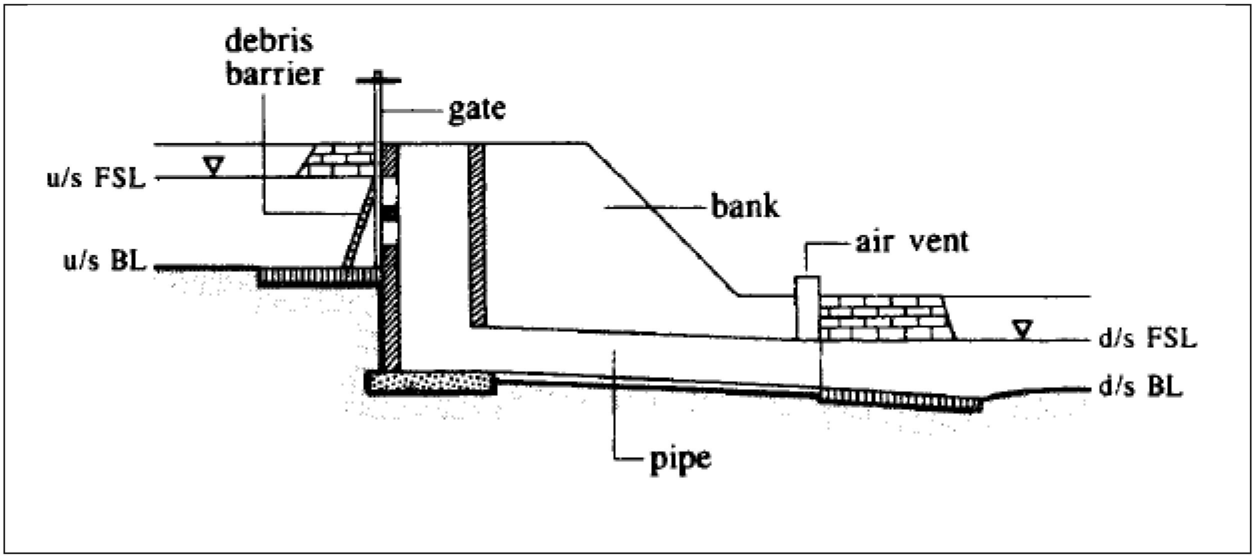


Figure 6.18: Well drop structure

6.3.5 Farm drop structures

Farm channel drops are basically of the same type and function as those in distribution canals, the only differences being that they are smaller and their construction is simpler.

The notch fall type of farm drop structure (precast concrete or timber) consists of a (most commonly) trapezoidal notch in a crested wall across the canal, with the provision of appropriate energy-dissipation devices downstream of the fall. It can also be used as a discharge measuring structure.

The details of a concrete check drop with a rectangular opening, widely used in the USA, are shown in Fig. 6.19. Up to discharges of about 0.5m3/s, the drop in the downstream floor level (*C*) is recommended to be around 0.2 m and the length of the apron (*L*) between 0.75 m and 1.8m over a range of drop (*D*) values of 0.3–0.9m.

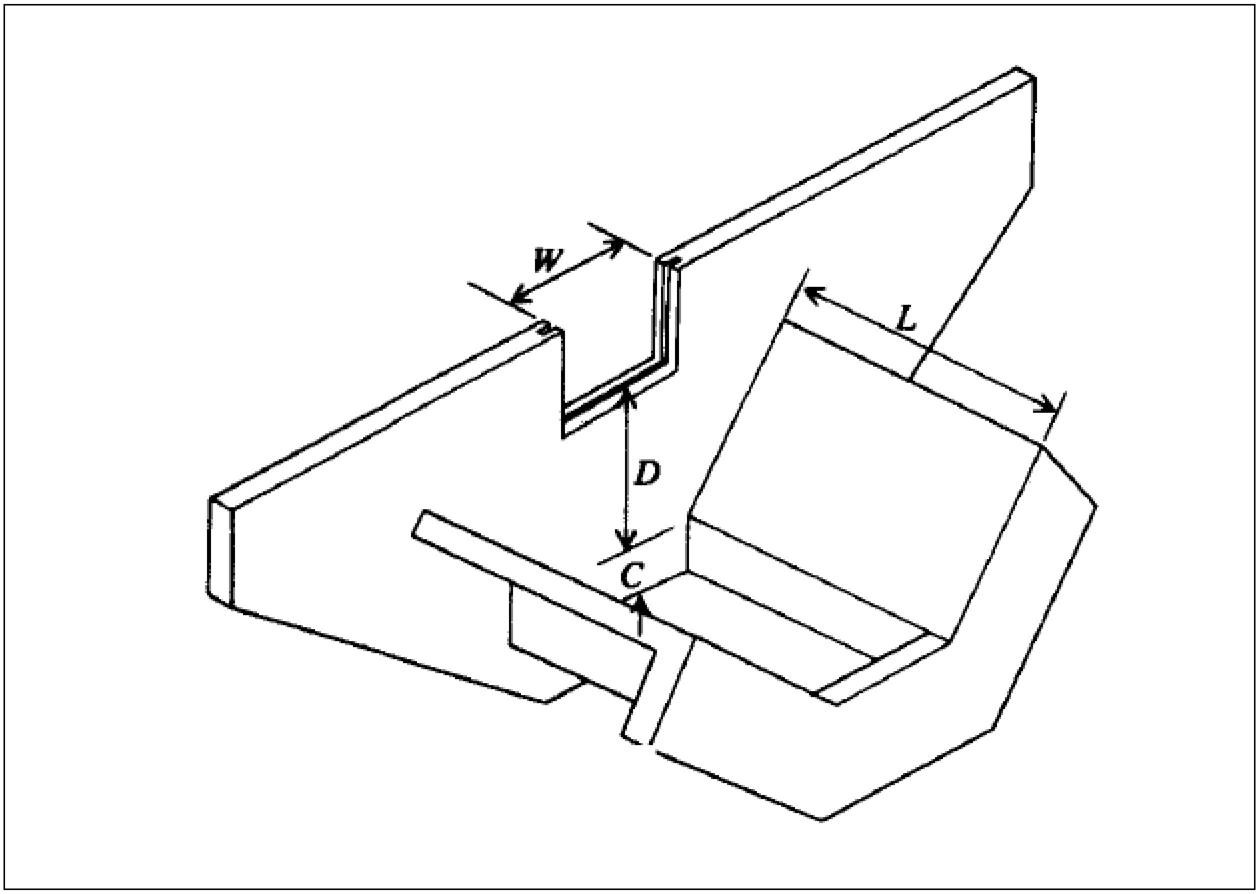


Figure 6.19: Notch fall: concrete check drop (USA)