

ECONOMIC AND INNOVATIVE DESIGN OF A CANAL DROP

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ABSTRACT

In the conventional practice of design of canal drops, long length of inlet and outlet transitions are provided for improving performance. They are very costly and their hydraulic performance too is not satisfactory. Analytical and experimental studies were undertaken by the author to find an economic and innovative method of design. Optimum fluming ratio and optimum length of transitions are found both for economy as well as good performance. An innovative and economic stilling basin with rapidly diverging side walls and adversely sloping floor which act simultaneously as energy dissipater and expanding transition has been recommended. An example has been worked out to illustrate the design procedure of a typical canal drop.

Keywords: Canal drop, Fluming , Transition, Energy Dissipation, Optimum Length , Efficiency

INTRODUCTION

Large numbers of canal drops are to be provided to negotiate with a terrain sloping faster than the design bed slope of the canal. Without the requisite numbers of drops, the cost of canal becomes excessive and the flow velocity will be very high. This may often result in supercritical flow which is not permissible in a canal except in selected reaches where concrete chutes are to be provided to prevent erosion.

In the conventional design of drop structures, it is customary to flume the canal by restricting the normal waterway. Extent of fluming will be governed by Froude's number of incoming flow (F_1) in the normal canal section and the desired value of Froude's number of flow in the flumed/contracted section (F_0) as illustrated in Fig.1 (Mazumder¹). Any fluming/contraction beyond a critical limit (known also as choking limit, when $F_0 = 1$) will cause excessive afflux resulting in a long backwater reach where the canal regime and proportional flow condition i.e the normal depth-discharge relation (Mazumder & DebRoy²) is lost. Excessive restriction of normal waterway has many other problems. (Mazumder et al³).

Apart from hydraulic problems, the cost of connecting the flumed section with the normal canal section by providing classical transition structures becomes excessively high. Demerits of conventional design of energy dissipaters, conventional type inlet and outlet transitions with long length and complicated shapes have been discussed earlier (Mazumder^{4,5}). In this paper, author has suggested an innovative, economic and efficient design of a canal drop employing the recent advances in hydraulics.

FLUMING OF NORMAL WATERWAY IN CANAL DROPS

(i) Hydraulic and Economic Aspects

If B_1 and B_0 are the mean widths of flow at the normal and flumed sections of a canal respectively, it can be proved that the fluming ratio (B_0/B_1) may be expressed as

$$B_0/B_1 = (F_1 / F_0) [(2+F_0^2) / (2+F_1^2)]^{3/2} \quad (1)$$

Where F_1 and F_0 are the Froude's number of flow at the normal and flumed sections respectively. Fig.1 shows the functional relation between B_0/B_1 and F_0 for different values of F_1 for approaching flow. It may be seen that higher the F_1 -value, less is the opportunity of fluming to avoid flow choking. F_1 - values indicated in the figure were found corresponding to mean width of flow (B_1) for four different canals with varying bed slope and discharge. There is hardly any advantage /economy if fluming is made such that F_0 exceeds approximately 0.70. Also, flow surface becomes wavy when $F_0 > 0.70$, with highest degree of wave amplitude at critical flow at $F_0 = 1$ Excessive fluming also causes higher loss in head due to higher velocity of flow at the flumed section resulting in higher afflux.

(ii) Regime / Proportional Flow Aspects

Canal drops are control structures which can be used also for measuring flow through the canal. In case the fluming is too high, crest height above the canal bed, Δ (shown in Fig.2) will be low. On the other hand, if

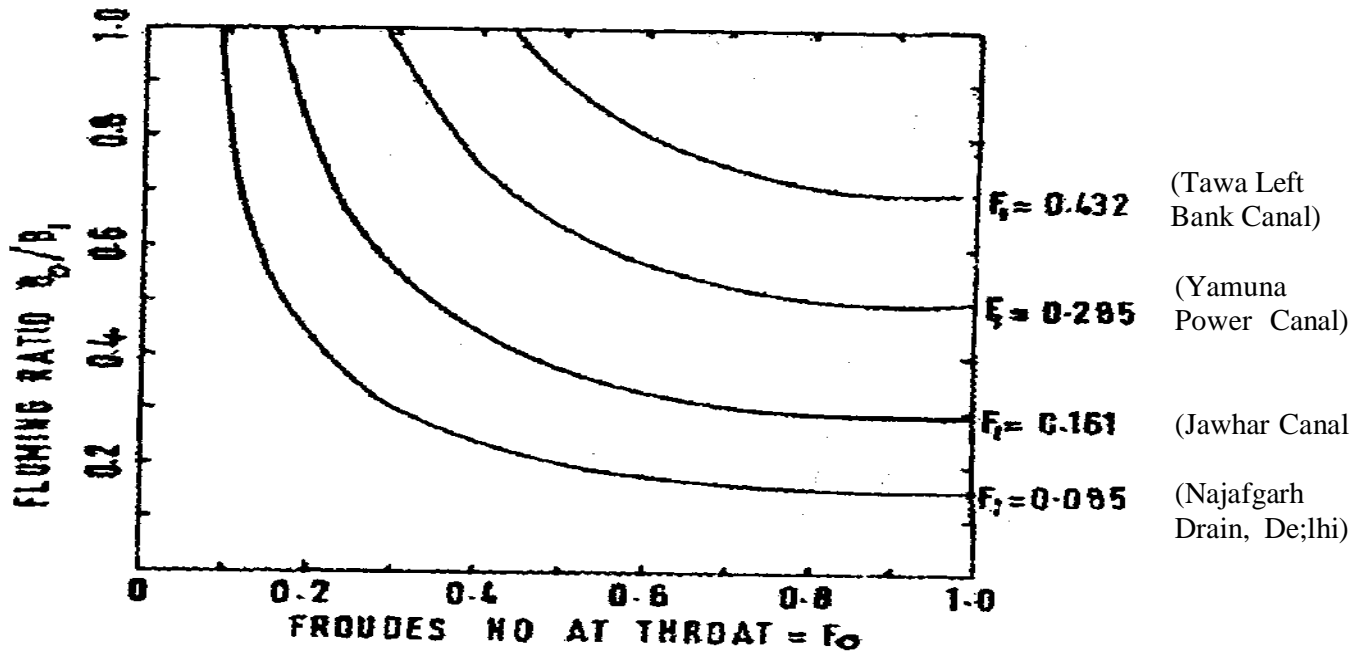


Fig.1 Showing Interrelation between F_1 , F_0 , and B_0/B_1

the fluming is too low, the crest height will be more. An optimum width of throat (B_0) and corresponding crest height (Δ) were determined theoretically (Mazumder et al²) such that the proportionality of flow with negligible afflux will occur. Equation (2) gives the optimum width at throat (B_0) and equation (3) gives the corresponding crest height (Δ) for maintaining proportionality of flow for all discharges passing through the canal.

$$B_0 = [0.7 (Q_{\max}^2 - Q_{\min}^2) / (E_{1\max} - E_{1\min})]^{3/2} \quad (2)$$

$$\Delta = E_{1\max} - 3/2 [(Q_{\max} / B_0)^2 / g]^{1/3} \quad (3)$$

where Q_{\max} and Q_{\min} are the maximum and minimum flow through the canal ; $E_{1\max}$ and $E_{1\min}$ are the corresponding maximum and minimum specific energy of flow given by

$$E_{1\max} = Y_{1\max} + V_{1\max}^2/2g \text{ and } E_{1\min} = Y_{1\min} + V_{1\min}^2/2g \quad (4)$$

where $Y_{1\max}$ and $Y_{1\min}$ are the normal flow depths and $V_{1\max}$ and $V_{1\min}$ are the mean velocities of flow in the canal upstream of the drop corresponding to Q_{\max} and Q_{\min} respectively. The various symbols used in the equations, the flumed drop, the inlet and outlet transition structures etc. are illustrated in Fig.2.

DESIGN OF CREST PROFILE

Depending upon the drop height, either straight or curved profiles may be adopted connecting the upstream and downstream aprons as shown in Fig.2. In case curved profile is adopted for d/s glacis (in case of high drop), Creager's ogee type profile (USBR⁶) may be adopted for the downstream glacis to ensure smooth flow over the glacis free from any separation.. Co-ordinates of Creager's profile can be obtained from the following equation with crest as origin.

$$Y/H_0 = K (X/H_0)^n \quad (5)$$

where X and Y are the co-ordinates at any point on the profile, H_0 is the energy head above crest, K and n are coefficients governed by approach velocity head and shape of u/s geometry of the profile. K and n - values can be obtained from USBR⁶ publication on Design of small dams.

When the canal drop is used for regulating flow (acting as cross regulator), it is necessary to provide gates above the crest. In such situations, the crest profile should be designed for partial gate opening, say 1m or so. To prevent flow separation, the crest profile should conform to the trajectory of the jet issuing from an orifice. For a vertical orifice, the co-ordinates of the jet is given by the relation

$$Y = X^2/ 4H_0 \quad (6)$$

where H_0 is the head measured from the center of gate opening to the upstream energy line.

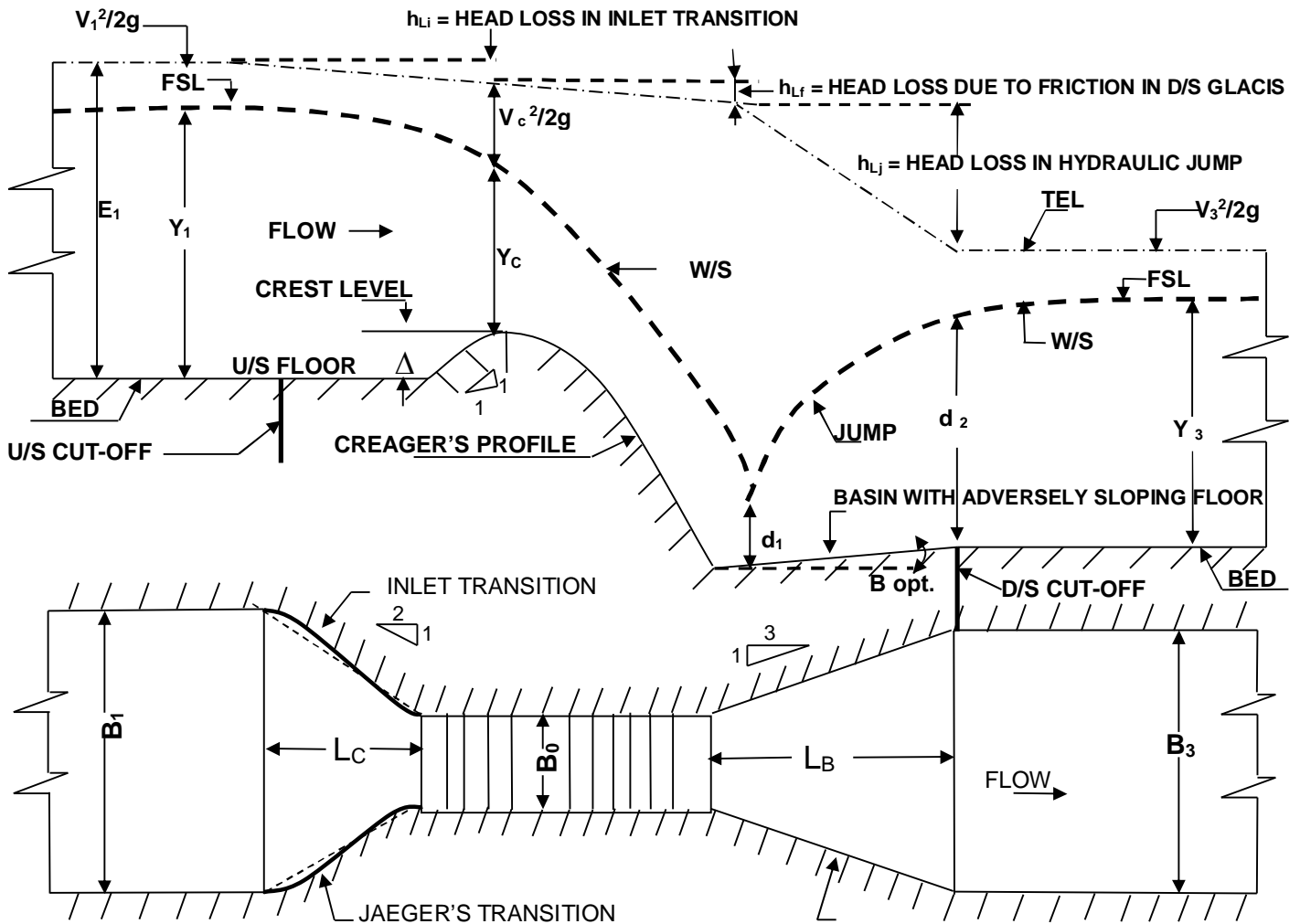


FIG.2 PLAN & SECTION OF A CANAL DROP
 (Showing control section, crest, u/s & d/s glacis, Inlet transition, Basin etc.)

DESIGN OF CONVENTIONAL INLET AND OUTLET TRANSITION

(a) Inlet Contracting Transition

As shown in Fig.2, inlet contracting transition connect the throat (flumed section) with the normal section of the canal. In a contracting transition, potential energy is converted to kinetic energy of flow. Afflux upstream of a drop structure is solely governed by the head loss in the inlet transition. More is the head loss, more will be the afflux. Relation between head loss and efficiency of an inlet transition (η_i) can be expressed as

$$\eta_i = 1 / (1+C_i) \tag{7}$$

where C_i is inlet head loss coefficient given by the relation

$$C_i = h_{Li} / (V_c^2 - V_1^2) / 2g \quad (8)$$

where h_{Li} is the loss in head in the inlet transition, V_c and V_1 are the mean velocities of flow at crest and at normal sections of the canal upstream of the drop respectively.

Hinds ⁷, Mitra ⁸, Chaturvedi ⁹, Vittal et al ¹⁰, Swamee et al¹¹, Garde and Nasta ¹², Mazumder ¹³ have proposed different types of curves for efficient design of inlet and outlet transitions. Efficiency (η_i) of Jaeger's ¹⁴ type inlet transitions (given by equations 9 to 13 below) having different axial lengths (governed by average rate of flaring varying from 0:1 to 5:1) as measured by Mazumder¹ are given in Fig.3.

$$V_x = V_1 + a (1 - \cos\Phi) \quad (9)$$

$$\Phi = \pi x / L_c \quad (10)$$

$$y_x = y_1 - a/g [(a+V_1) (1 - \cos\Phi) - 1/2 a \sin^2 \Phi] \quad (11)$$

$$a = 1/2 (V_0 - V_1) \quad (12)$$

$$V_x B_x y_x = Q = V_1 B_1 y_1 \quad (13)$$

where V_x , y_x and B_x are the mean velocity, flow depth and mean flow width at any distance 'x' from the end of inlet transition (i.e. throat section) respectively, L_c is the axial length of inlet contracting transition. and V_0 is the mean flow velocity at throat/flumed section at the exit of inlet transition. Width of flow section (B_x) at any axial distance 'X' from exit end of inlet transition can be found from the continuity equation (13)

(b) Outlet Expanding Transition

Whenever a canal is flumed, a pair of symmetric outlet expanding transition is to be provided connecting the flumed /throat section with the normal canal section. as illustrated in Fig.2. In the conventional design, outlet transition starts from the end of classical stilling basin and ends in the normal canal section. This is necessary since the sub-critical mean velocity of flow [$V_2 = Q/(B_0 \cdot d_2)$] at the exit end of flumed basin (of width, B_0) is substantially higher than the normal mean velocity (V_3) in the canal. Main function of the outlet transition is to diffuse the sub-critical flow from V_2 to V_3 so that there is no scour in the tail channel downstream of the drop. Since the sub-critical flow in an expanding transition is subjected to an adverse or positive pressure gradient, the flow tends to separate if the axial length of transition is insufficient. It has

been established (Kline¹⁵, Gibson¹⁶) that if the total angle of expansion exceeds about 10^0 to 12^0 , flow will separate from the boundary resulting in poor efficiency ($\eta_0 = 1 - C_0$) and non-uniform distribution of velocity at the exit end of expansion. Mazumder¹⁷ tested eddy shaped (Ishbash & Lebedev¹⁸) expanding transition of different lengths and found that for maximum hydraulic efficiency, the axial length of transition must be about 7 to 8 times the offset $[1/2(B_3 - B_0)]$ in order to ensure separation-free uniform flow at the end of transition. (Fig.3)

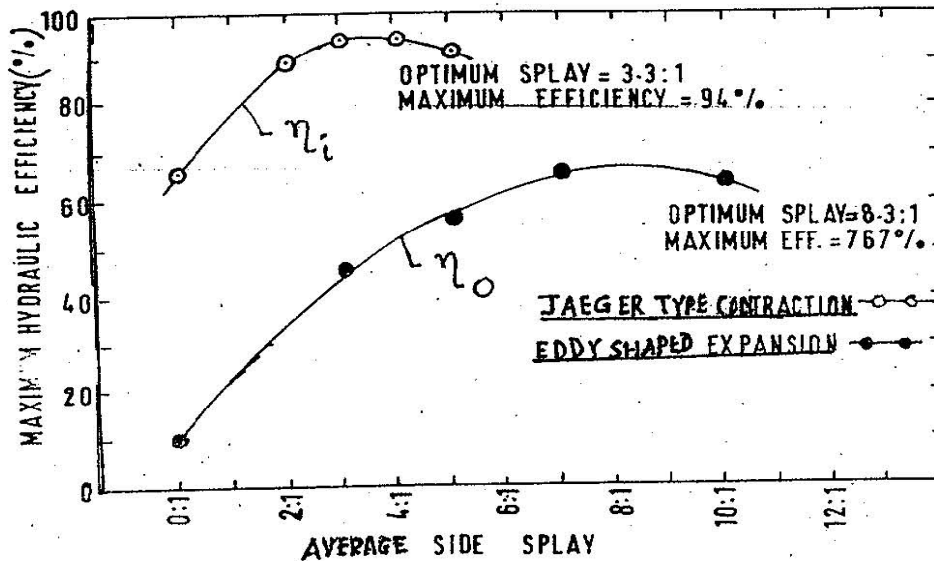


Fig.3 Variation of Efficiency for Inlet and Outlet Transition with Length

DESIGN OF CLASSICAL STILLING BASIN

In most of the canal drops, stilling basins are provided to ensure that the kinetic energy of water falling over the downstream glacis is dissipated within the stilling basin. In a classical basin, width of the basin is kept the same as the width of flumed structure (B_0) up to the end of the basin, length of which is usually fixed by the length of a classical hydraulic jump in the rectangular basin. Different steps for design of a classical stilling basin are:

- (i) Determine the discharge intensity $q = Q/B_0$
- (ii) Determine the pre-jump velocity of supercritical flow at the foot of downstream glacis, U_1
- (iii) Determine the pre-jump flow depth $d_1 = q / U_1$ and corresponding Froude's no. $F_{t1} = U_1 / (gd_1)^{1/2}$
- (iv) Determine the conjugate depth, $d_2 = d_1/2 [(8F_1^2 + 1)^{1/2} - 1]$
- (v) Determine the basin floor level = TWL - d_2 where TWL stands for tail water level

- (vi) Determine the basin length = $K_1 d_2$ where K_1 may vary from 4 to 6 depending on type of stilling basin determined by F_{t1} and U_{t1} -values. where U_{t1} and F_{t1} are the velocity and Froude's number of flow at the toe of d/s glacis respectively.

Further details of design of classical hydraulic jump type stilling basins are given in several text books e.g. (Chow¹⁹, Ranga Raju²⁰, USBR⁶, Hager²¹).

STILLING BASIN WITH DIVERGING SIDE WALLS

The cost of a conventional stilling basin followed by a classical outlet transition in a canal drop, as indicated by dotted line (in plan) in Fig.4, is exorbitantly high. By using different types of appurtenances (like vanes, bed deflector, basin blocks etc) for preventing flow separation, Mazumder^{22,23,24} developed an innovative basin with rapidly diverging straight side walls having axial length equal to three times the offset i.e. $3(B-b)$ as shown in Fig.4. The basin functions both as energy dissipater and flow diffuser simultaneously. Without appurtenances, there will be violent separation of flow and highly non-uniform flow at the exit end of the basin.. With appurtenances, there is high efficiency and the flow becomes highly uniform at the exit. To reduce the additional cost of appurtenances, Mzumder^{25,26,27} developed another innovative method of boundary layer flow control by providing adversely sloping basin floor. Optimum value of inclination of basin floor (β_{opt}) corresponding to a given angle of divergence of the side wall (Φ), as indicated in Fig-5, can be expressed as

$$\begin{aligned}\beta_{opt} &= \tan^{-1} [(d_1^2 + d_2^2 + d_1 d_2) \tan \Phi / (b d_2 + B d_1 + 2b d_1 + 2B d_2)] \\ &= \tan^{-1} [2 (y_1/b) \tan \Phi (1 + \alpha + \alpha^2) / (2 + 2 \alpha r + \alpha + r)]\end{aligned}\quad (14)$$

where, $\alpha = d_2 / d_1$, $r = B / b$, d_1 and d_2 are the pre-jump and post- jump depths, b and B are the half widths of the basin at the entry and exit respectively. The conjugate depth ratio, α , in this non prismatic stilling basin with adverse bed slope such that the wall reaction is balanced by bed reaction can be expressed by the relation

$$F_1^2 = 1/2 [(1 - \alpha^2 r) / (1 - \alpha r)] \alpha r \quad (15)$$

In a prismatic channel of rectangular section when $r = 1$ (i.e. $b = B$), equation (15) reduces to the conjugate depth relation in a classical hydraulic jump given by

$$\alpha = d_2/d_1 = 1/2 [(8F_1^2 + 1)^{1/2} - 1] \quad (16)$$

Experimental values of β_{opt} for best performance of the basin with 3:1 flaring of side walls are given in Fig.5. Method of computing the theoretical and experimental values of β_{opt} has been explained through an illustrative example.

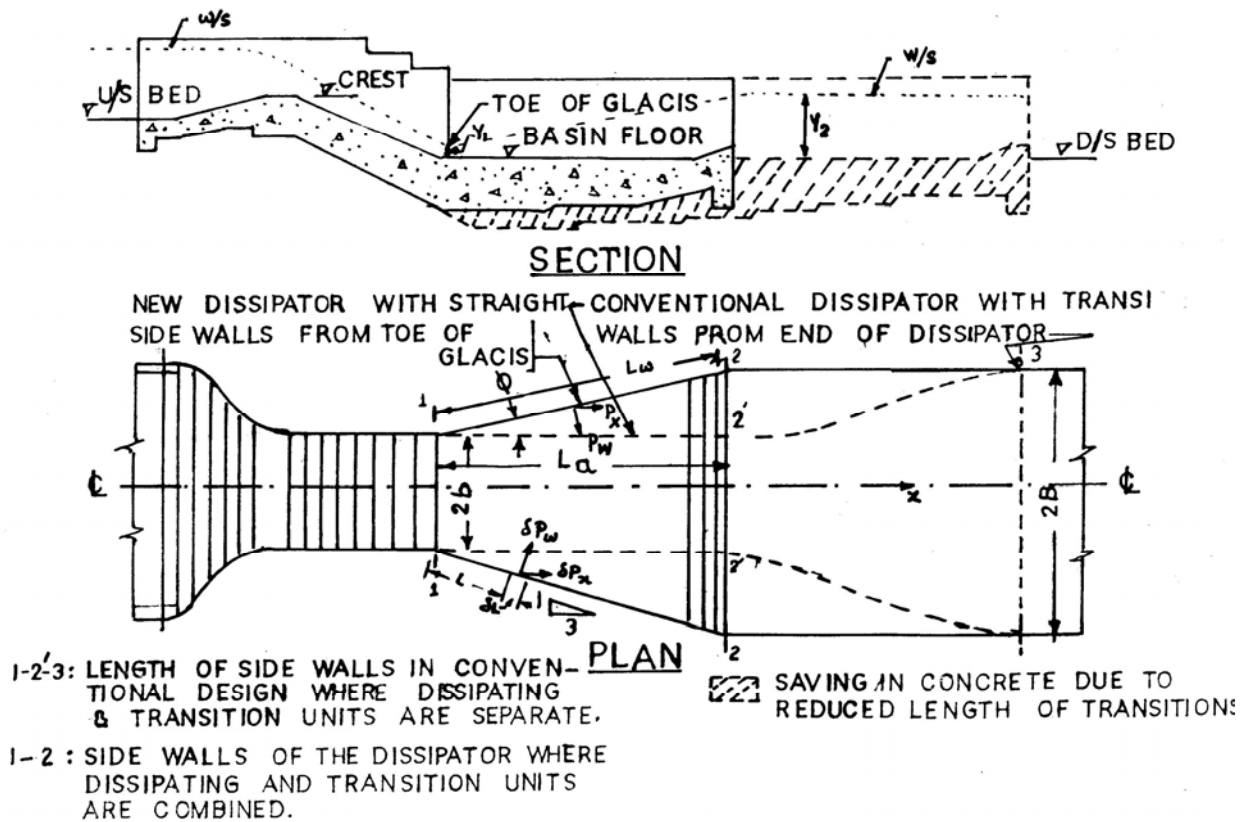


Fig.4 Plan & Sectional View of a Canal Drop Showing Economic and Innovative Design (in Full Line) as Compared to the Conventional Design (in Dotted line)

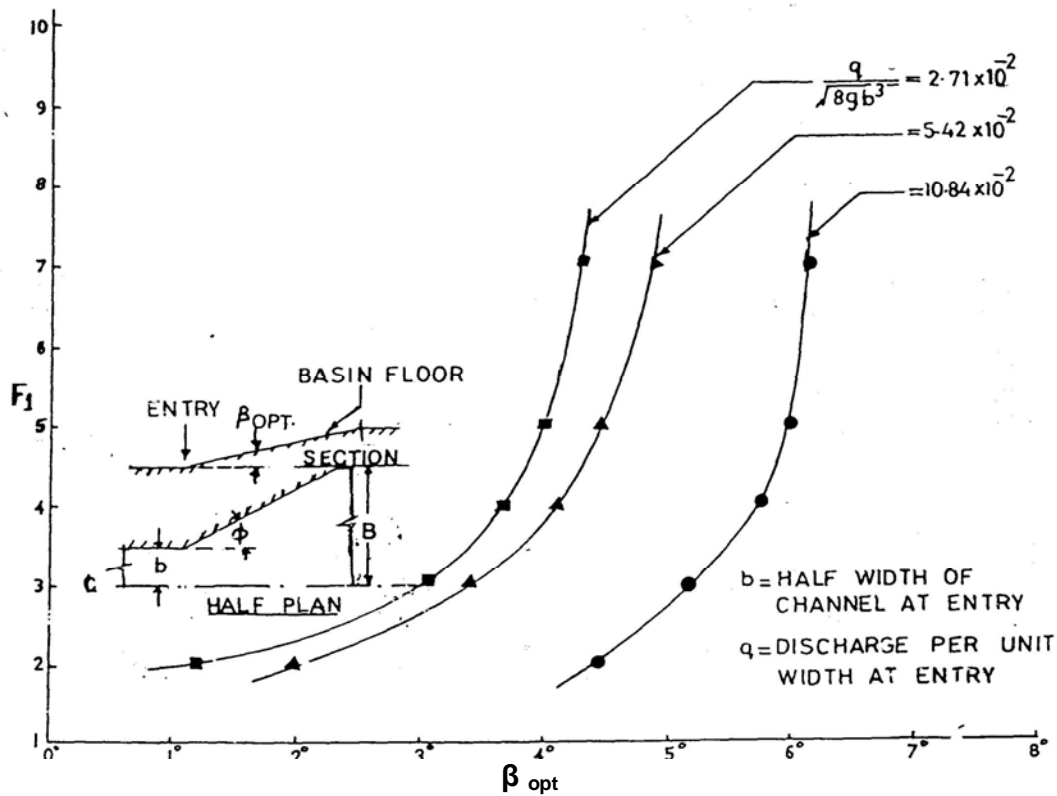


Fig.5 Optimum Inclination of Basin Floor (β_{opt}) for Different Values of Pre-jump Froude's No. F_1

ILLUSTRATIVE EXAMPLE

Design a drop for a canal with data given below:

- (i) Full supply Discharge in the canal, $Q_{max} = 99.1$ cumec
- (ii) Full supply depth, $Y_{1max} = 3.629$ m
- (iii) Mean Flow width of canal at FSL = 29.87m
- (iv) Longitudinal slope of bed = 1 in 8,000
- (v) Manning's roughness coefficient, $N = 0.025$
- (vi) Height of drop = 3m
- (vii) Minimum flow in the canal $Q_{min} = 21.5$ cumec
- (viii) Corresponding minimum depth of flow = $Y_{1min} = 1.38$ m

Computation of Flume width at throat (B_o) and Crest height (Δ)

(a) From Proportionate Flow/ Flow Regime Consideration

$$V_{1max} = 0.914 \text{ m/s}, E_{1max} = Y_{1max} + (V_{1max})^2/2g = 3.672 \text{ m}, F_1 = V_{1max}/(g Y_{1max})^{1/2} = 0.153$$

$$V_{1\min} = 0.522 \text{ m/s}, E_{1\min} = Y_{1\min} + (V_{1\min})^2 / 2g = 1.394 \text{ m}$$

$$B_0 = [0.7 (Q_{\max}^{2/3} - Q_{\min}^{2/3}) / (E_{1\max} - E_{1\min})]^{3/2} = 8.64 \text{ m}, Y_0 = Y_c = 2.374 \text{ m and } F_0 = 1.0$$

(b) Economic / Hydraulic Consideration

Since the flow at critical stage is wavy in the flumed section and from Fig.1, it is noticed that for an approaching flow Froude's number, $F_1 = 0.153$, there is hardly any economy in fluming beyond

$F_0 = 0.6$, adopt $F_0 = 0.6$ for determining economic fluming ratio given by equation (1) i.e.

$$B_0/B_1 = (F_1/F_0) [(2+F_0^2) / (2+F_1^2)]^{3/2} = 0.322 \text{ and hence } B_0 = 8.9\text{m};$$

Adopted bed width at flumed section, $B_0 = 10\text{m}$

$$\text{Corresponding value of crest height, } \Delta = E_{1\max} - 3/2 [(Q_{\max}^2 / B_0^2) / g]^{1/3} = 0.44\text{m}$$

Assuming no loss in head in inlet transition i.e. $C_i = 0$ or $h_{L_i} = 0$, $E_0 = E_1$

$$\text{or, } E_0 = Y_0 + V_0^2/2g = 3.672 \text{ and } q_0 = Q/B_0 = 9.9 = V_0 Y_0$$

$$\text{Solving by trial, } Y_0 = 3.176 \text{ m and } V_0 = 3.118 \text{ m/s; } F_0 = V_0 / (gY_0)^{1/2} = 0.558$$

$$\text{Check: } B_0/B_1 = (0.153/0.558) [(2+0.558^2) / (2 + 0.153^2)]^{3/2} = 0.335 \text{ and } B_0 = 0.335 * 29.87 = 10\text{m}$$

Design of Inlet Transition

With 2 : 1 average side splay, axial length of inlet transition, $L_c = 1/2 (B_1 - B_0) * 2 = 19.87$ say 20m

Adopt Jaeger type transition given by Equations (7) to (11) as follows:

$$a = 0.5 (V_0 - V_1) = 0.5 (3.118 - 0.914) = 1.102, \Phi = \pi x / L_c = \pi x / 20$$

$$V_x = V_1 + a (1 - \text{Cos}\Phi) = 0.91 + 1.102(1 - \text{Cos}\Phi)$$

$$Y_x = Y_1 - a/g [(a+V_1) (1 - \text{Cos}\Phi) - 1/2 a \text{Sin}^2 \Phi] = 3.629 - [0.227(1 - \text{Cos}\Phi) - 0.062 \text{Sin}^2 \Phi]$$

X (m)	=	0	5	10	15	20
Φ_x (degree)	=	0	45	90	135	180
V_x (m/s)	=	0.914	1.234	2.016	2.795	3.118
Y_x (m)	=	3.629	3.499	3.404	3.272	3.176
B_x (m)	=	29.87	22.90	14.19	10.83	10
F_x	=	0.153	0.211	0.346	0.493	0.558

Jaeger Type Inlet transition curve is obtained by plotting widths B_x at different X -values as shown in Fig.2.

Design of Crest Profile

Assuming that there is no regulator over crest, the co-ordinates of the curved d/s glacis are found from Creager's formula (Eq.5), with $H_0 = E_1 - \Delta = 3.232$

$$Y/H_0 = K (X/H_0)^n$$

K and n values are found to be 0.56 and 1.75 for approach velocity head ($h_a = V_1^2/2g$) of 0.043 m and design head above crest ($H_0 =$ of 3.232m (3.672- 0.44) respectively from USBR⁶.

X(m)	=0.25	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	4.663
X/H ₀	= 0.078	0.155	0.309	0.464	0.619	0.774	0.928	1.083	1.237	1.392	1.442
Y/H ₀	= 0.006	0.021	0.073	0.146	0.242	0.357	0.491	0.643	0.812	0.999	1.064
Y(m)	=0.019	0.068	0.236	0.472	0.782	1.153	1.567	2.078	2.624	3.220	3.440

The X,Y co-ordinates are plotted with crest as origin to obtain the d/s glacis profile as shown in Fig.2.

DESIGN OF STILLING BASIN WITH DIVERGING SIDE WALLS

Assuming no head loss up to toe of the d/s glacis, specific energy of flow at toe (E_t) is given by

$$E_{t1} = E_{1max} + \text{height of drop} = 3.672 + 3 = 6.672 = d_1 + U_t^2/2g$$

$$q = Q/B_0 = 9.9 = d_1 * U_t$$

where d_1 and U_1 are the pre-jump depth and velocity of flow at toe of d/s glacis respectively. Solving the above two expressions by trial

$$d_1 = 0.84 \text{ m and } U_1 = 10.72 \text{ and } F_{t1} = 3.73$$

$$\text{Axial Length of the Basin: } L_b = 3 (B_1 - B_0)/2 = 29.8 \text{ m say } 30 \text{ m}$$

Conjugate depth ratio for the non-prismatic basin is given by equation (15)

$$F_1^2 = 1/2 [(1 - \alpha^2 r) / (1 - \alpha r)] \alpha r$$

Putting $F_1 = F_{t1} = 3.73$, $r = B/b$ (Fig.5) = 2.987, the above equation reduces to

$$\alpha^3 - 9.95 \alpha + 3.219 = 0$$

Solving by trial, $\alpha = 3$ and $d_2 = 3d_1 = 3(0.84) = 2.52\text{m}$ and submergence $= 3.629/2.52 = 1.44$ i.e.the basin will operate under 44% submergence at maximum flow which is permitted as per test results.

Theoretical value of basin floor inclination, β_{opt} is given by equation 14

$$\beta_{\text{opt}} = \tan^{-1} [2 y_1/b \tan\Phi (1+\alpha + \alpha^2) / (2 + 2 \alpha r + \alpha + r)]$$

With $y_1 = d_1 = 0.84\text{m}$, $b = 5\text{m}$, $\tan\Phi = 1/3$ and $r = 2.987$, $\beta_{\text{opt}} = 3.36^\circ$

Experimental value of β_{opt} can be found from Fig.5 as follows:

$$q / (8gb^3)^{1/2} = 9 / (8*9.8*5^3)^{1/2} = 0.091 = 9.1 * 10^{-2}$$

corresponding to above value of $q / (8gb^3)^{1/2}$ and $F_1 = 3.73$. $\beta_{\text{opt}} = 4.5^\circ$ (from Fig.6)

Provide basin Floor slope of $\beta_{\text{opt}} = 4.5^\circ$ for best performance.

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