National Symposium on Recent Trends in Design of Hydraulic Structures
Dept. of Civil Engg., UOR, Roorkee
March 18-19, 1994

STILLING BASIN WITH RAPIDLY DIVERGING SIDE WALLS FOR FLUMED HYDRAULIC STRUCTURES

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ABSTRACT

In a conventional stilling basin, the side walls are parallel to flow axis resulting in only one roller in the vertical plane. In the proposed basin with rapidly diverging side walls, two additional side rollers are formed in the horizontal plane in between the incoming high velocity jet and the side walls resulting in more dissipation of energy. Theoretically, the conjugate depth decreases and energy loss increases with increase in angle of divergence of the side walls. However, when the angle of divergence exceeds a limiting value of 4 to 5 degree, the jump front becomes skew resulting in jet flow on one side and back flow on the other, if the basin floor is kept level. There is hardly any energy dissipation and deep erosion occurs in the tail channel. Present study aims at developing suitable devices to stabilise and confine the side rollers within the basin so that the flow downstream becomes uniform and smooth without any separation and erosion in tail channel. Two devices developed to improve the basin performance have been discussed in the paper. The basin is highly efficient and economic since the dissipating and the transition structures are combined unlike a conventional basin where a long transition follows the dissipating unit.

INTRODUCTION

Numerous canal structures eg. structures eg. drops, regulators, flow meters etc. require energy dissipating arrangement to avoid scouring downstream. Uncontrolled erosion and deposition not only threaten the safety of the structure, it causes problems of maintenance with recurring annual cost. Proper design of energy dissipator is, therefore, extremely important. As shown in fig. 1, such structures are invariably flumed to reduce the cost. Extent of fluming is, however, governed by the incoming Froude's number of flow in the normal channel section (Mazumder, 1979). Transition structures connecting the flumed section with the normal section are provided upstream and downstream. Both the contracting and expanding transitions are conventionally designed by popular methods eg. Hinds (1928), Chaturvedi (1963), Vittal & Chiranjibi (1983) etc. Optimum axial lengths of such transitions were found by Mazumder (1967; 1978) experimentally. Conventionally, the expanding transition is provided after the energy dissipator as shown by dotted line (1-2-3) in fig. 1. The side walls of the conventional stilling basin are kept parallel to flow axis upto the jump end. In such a basin, hydraulic jump occurs in a prismatic channel of rectangular cross-section and the jump characteristics are well defined (Hager 1992). Flow in the expansion is sub-critical althrough the transition. Because of

high turbulence level prevailing after jump, it may be possible to curtail the length of transition (Kline 1959). Further curtailment of length is possible by use of appurtenances (Mazumder 1971). In a hydraulic jump, turbulence level is highest near jump front (Rouse 1959). It is possible to adopt a basin with straight side walls diverging from jump front i.e. the toe of the spillway/glacis as shown in fig. 1 (Line 1-4). Such a basin will be more economic compared to the conventional one, since the transition and dissipating structures are combined. Several problems encountered in a basin with rapidly diverging side-walls were overcome through experimental research study (DST 1989). Results obtained (Mazumder 1987) are discussed in the following paragraphs.

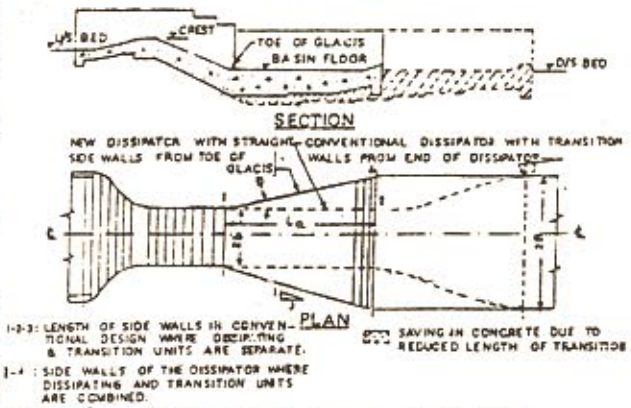


FIG. 1 CONVENTIONAL TYPE AND NEW DISSIPATOR WITH DIVERGING WALLS.

HYDRAULIC JUMP CHARACTERISTICS IN A BASIN WITH DIVERGING SIDE WALLS

Spatial jump characteristics in abrupt and gradual expansions have been studied by several authors, viz. Unny (1960), Rajaratnam (1965), Bremen (1990). Conjugate depth and energy loss in a gradually expanding basin, obtained by Rajaratnam, are shown in figs. 2(a) & 2(b). It may be seen that the conjugate depth reduces and energy loss increases with increasing angle of divergence (ϕ) of the side-wall compared to those in a jump in prismatic basin with parallel side walls ($\phi = 0^{\circ}$). However, several drawbacks, as observed in experiments are: (i) upto a certain angle of divergence ($\phi = 5^{\circ}$), jump front is normal to flow axis and the downsteam flow is uniform. As the angle of divergence exceeds the above limit, the flow becomes asymmetric with oblique jump front. There is jet flow on one side and return flow on the other side as shown in fig. 3. (ii) Weak mixing of the jet with the surrounding fluid resulting in highly non-uniform flow at the basin end (fig. 3). (iii) Extremely poor energy dissipation within the basin accompanied with surface waves and deep erosion of tail channel. (iv) The jet flow is unstable and it is found to periodically swing from one side to the other, thereby exposing the entire tail channel to jet action and scouring.

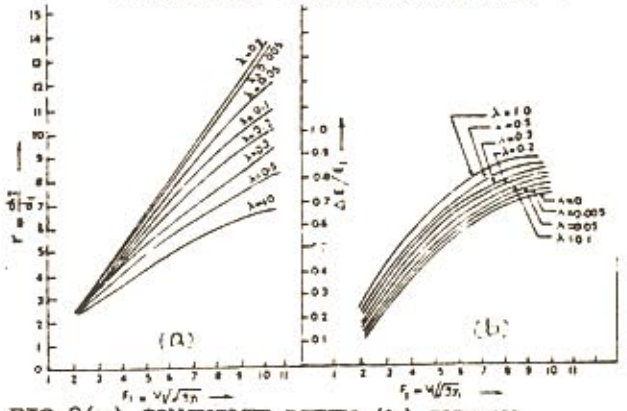


FIG.2(a) CONJUGATE DEPTH (b) ENERGY LOSS

PARAMETERS GOVERNING BASIN PERFORMANCE

The different draw backs of spatial jump in a basin with rapidly diverging side-walls as pointed above, were overcome by systematic study of the effect of certain appurtenances (Mazumder 1988) on the basin performance. The different parameters used are:

Efficiency of Basin (η)

Basin efficiency is defined as the ratio of energy actually dissipated within the basin ($\Delta E'$) to the required loss of energy (ΔE) as shown in fig. 3 i.e.

$$\eta = \Delta E'/\Delta E \qquad (1)$$

Higher the value of $\Delta E'$, less will be the residual kinetic energy of flow leaving the basin ($\Delta E - \Delta E'$) and hence more efficient will be the basin.

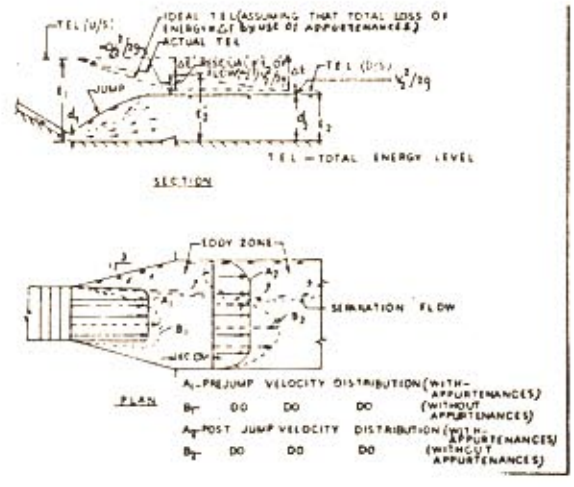


FIG.3 ENERGY LOSS AND VELOCITY DISTRIBUTION IN DISSIPATOR WITH AND WITHOUT USE OF APPURTEANCES

Kinetic Energy Correction Factor at Basin Exit (α_2)

It may be proved that in a channel with non-uniform flow distribution, the kinetic energy correction factor, α_2, is given by the relation

$$\alpha_2 = 1/A_2 V_2^3 \int u^3 dA \qquad (2)$$

where u is the local velocity through an elementary area dA. A_2 is the area of flow section and V_2 is the mean velocity of flow at the basin exit. Higher is the non-uniformity of flow, greater will be α_2 and more will be the residual kinetic energy flow given by

$$\Delta E - \Delta E' = (\alpha_2 - 1) \cdot V_2^2 / 2g \qquad (3)$$

As $\alpha_2 \to 1.00$, $\eta \to 100\%$. Objective should be to obtain as low α_2 and as high value of η as possible.

Scour Downsteam of Basin

Basic performance is best reflected through local scour pattern downstream of the basin. An inefficient basin will bring about more scour. Objective should be to eliminate or minimise the scour downstream of the basin.

USE OF BED DEFLECTOR TO IMPROVE BASIN PERFORMANCE

Bed deflector as shown in fig. 4, was found to be the best. Results obtained with bed deflector and other appurtences are given in reference (Mazumder 1988). Optimum geometry of the bed deflector and other details are also given there. All the experiments were performed in the hydraulics laboratory of Delhi College of Engineering in 120 cm wide masonary flume. The test basin was constructed below a straight glacis (3H:1V) type fall with a maximum flow 30 L/S, with tail water depth computed from Rajaratnam's equation. Without deflector, the basin performance was extremely poor (η = 92.1%, α_2 = 5.55). Performance improved remarkably with use of bed deflector of optimum size (η = 99.6%, α_2 = 1.22). The basin performance was excellent both at half and quarter supply.

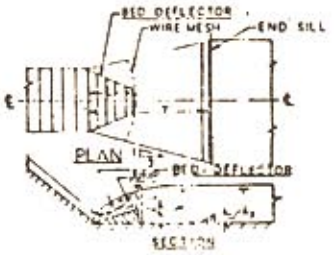


FIG. 4 DISSIPATOR WITH BED DEFLECTOR

USE OF ADVERSE SLOPE TO BASIN FLOOR

Another ingenious device for improving the basin performance was developed by the author (Mazumder 1987) by providing adverse slope (β) to the basin floor as shown in fig. 5. The optimum angle of inclination (β opt) was computed theoretically by equating the axial component of bed reaction (F_x) acting against the flow with the axial components of side wall reactions ($2P_x$) acting in the direction of flow (Fig. 5). Assuming linear variation of jump profile and hydrostatic pressure distribution before and after the jump, it may be provedthat

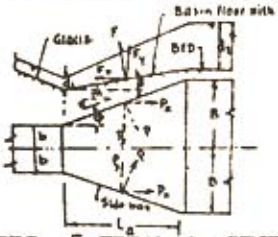


FIG. 5 PLAN & SECTION OF BASIN WITH DIVERGING SIDE WALLS

$$F_x = \frac{1}{3} \gamma_w L_a \tan\beta \,(b d_2 + B d_1 + 2B d_2 + 2b d_1) \qquad (4)$$

$$2P_x = \frac{1}{3} \gamma_w L_a \tan\phi \,(d_1^2 + d_2^2 + d_1 d_2) \qquad (5)$$

Equating Eq.(4) and Eq.(5), the value of βopt is given by

$$\beta_{opt} = \tan^{-1}[(d_1^2 + d_2^2 + d_1 d_2)\tan\phi / (b d_2 + B d_1 + 2B d_2 + 2b d_1)] \qquad (6)$$

$$= \tan^{-1}[2d_1/b \,\tan\phi\,(1 + \alpha + \alpha^2)/(2 + 2\alpha r + \alpha + r)] \qquad (7)$$

where $\alpha = d_2/d_1$, $r = B/b$. Values of βopt determined from equation 6 were found to be $1^\circ 45'$, $2^\circ 37'$ and $5^\circ 14'$ corresponding to tan ϕ equal to 0.33, 0.50 and 1.0 respectively, for the given flow conditions, namely, 2b = 53.3 cm, 2B = 120 cm, d_1 = 2.35 cm, d_2 = 12.57 cm, Q = 30 LPS. F_1 = 5.15 and tan ϕ = 0.33. Experiments were performed with different inclinations(β) of basin floor and different F_1 values. β opt values were determined from graphical plot of α_2 against β. Minimum β-value at which the downstream flow was normal (α_2 ranging between 1.10 to 1.20) was taken as β opt. Values of β opt, determined experimentally, differed from the theoretical values due to simplified assumptions made in the derivation of equations (4), (5) and (6). β opt values were also

found to vary slightly with inflow conditions defined by angle of obliquity (δ) as shown in fig. 6(a), (b) & (c). Fig. 7 gives the variation βopt with for Q = 30 LPS & F_1 = 5.15.

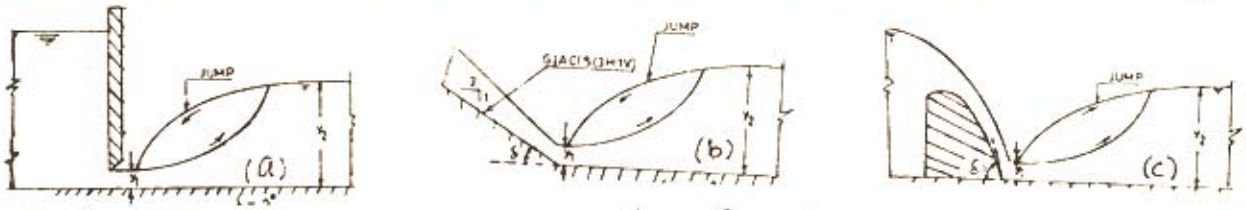


FIG. 6(a) SLUICE TYPE OUTLET (δ = 0°) (b) STRAIGHT GLACIS (3H:1V) (δ= 18.4°) (c) OGEE TYPE GLACIS (δ= 37.5°)

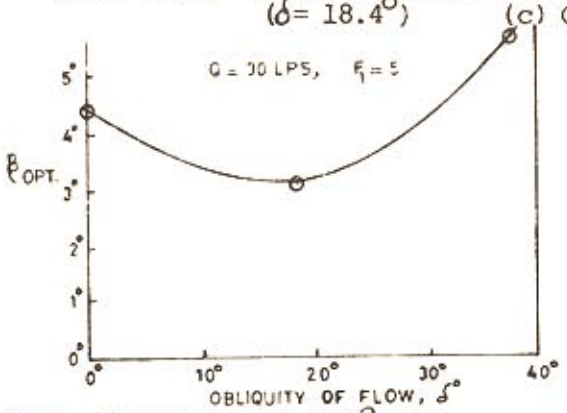


FIG. 7 VARIATION OF β OPT WITH δ.

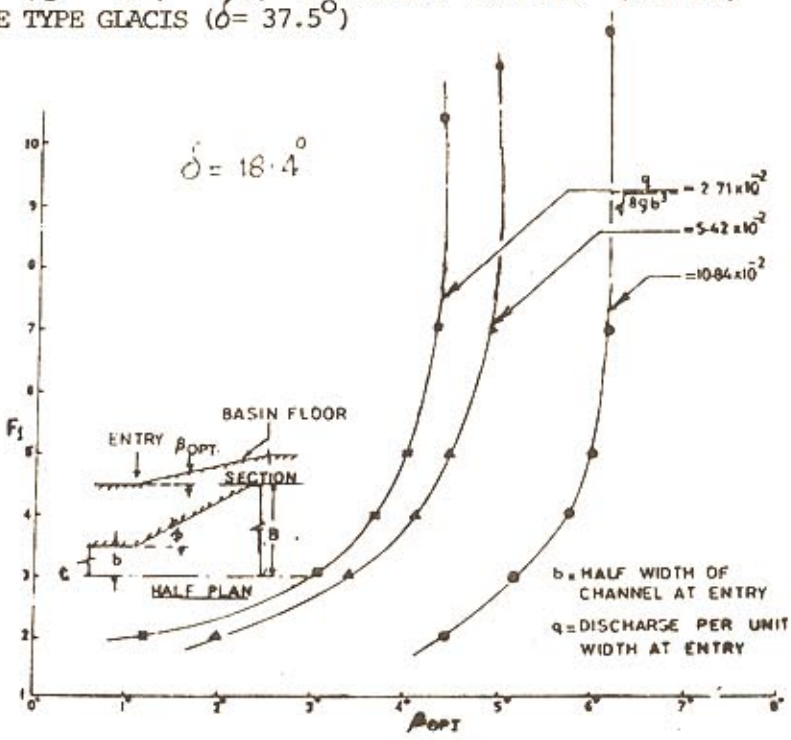


FIG. 8 OPTIMUM SLOPE OF BASIN FLOOR

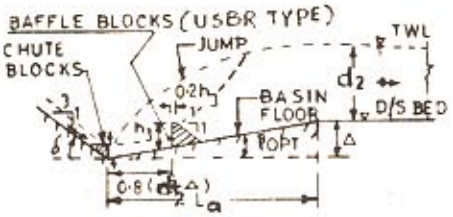


FIG. 9 SHOWING LOCATION OF BAFFLE BLOCKS & βOPT.

Fig. 8 shows the experimental βopt values for different F_1 and Q values for a given δ equal to 18.4°(fig. 6.b). It may be seen that for a given value of Q, βopt increases with F_1 upto a certain limiting value of F_1 and thereafter it remains independent of F_1. For a given F_1, βopt increases with discharge intensity as shown in fig. 8. Table-1 indicates the performance of the basin for different conditions of flow over ogee type entry (δ= 37.5°) as shown in fig.6(c).

T A B L E - 1

PERFORMANCE OF STILLING BASIN WITH DIVERGING(3:1) SIDE WALL

β	Q(LPS)	F_1	d_2(cm)	α_2	%η=$\Delta E'/\Delta E$	REMARKS
2.5°	15	18.8	3.25	72·0	68.8	Withhout Baffle Block
2.5°	30	13.6	4.91	78·0	41.5	Without Baffle Block
2.5°	50	10.7	9.10	86·0	30.8	Without Baffle Block
4.0°	15	18.8	5.0	2.6	99.8	Without Baffle Block
4.0°	30	13.6	6.5	3.7	98.8	Without Baffle Block
4.0°	50	10.7	7.3	17.6	84.3	Without Baffle Block
5.0°	15	18.8	3.6	1.3	97.9	Without Baffle Block
5.0°	30	13.6	5.6	3.3	93.8	Without Baffle Block
5.0°	50	10.7	6.1	9.2	89.0	Without Baffle Block
5.0°	15	18.8	4.6	1.2	99.9	With one row of Baffle Block
5.0°	30	13.6	6.5	1.3	99.9	Do
6.0°	15	18.8	4.0	1.2	99.9	Without Baffle Block

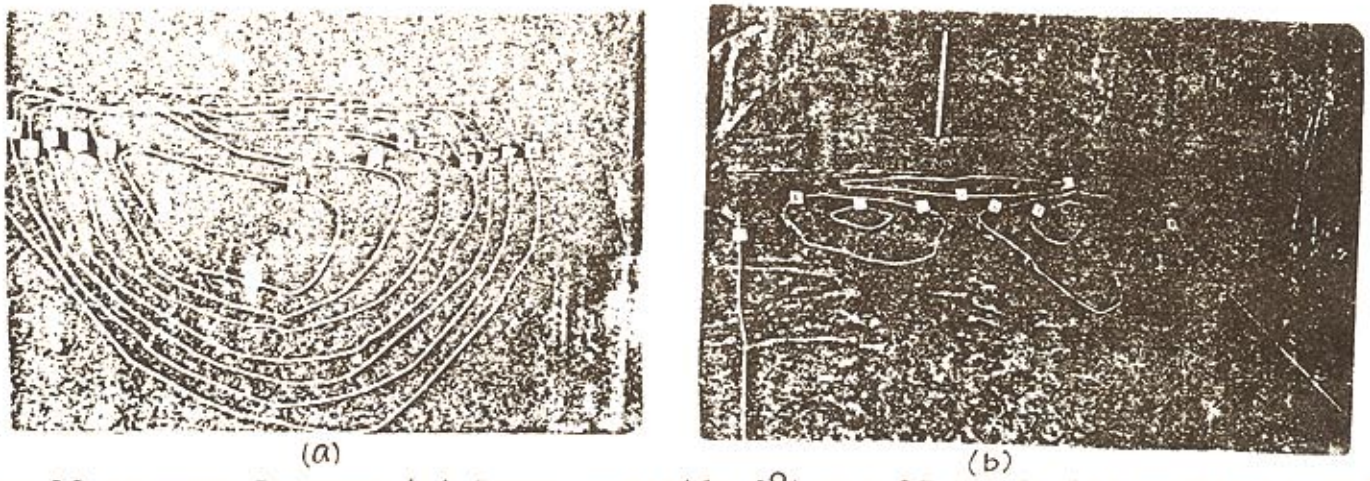
TABLE - 1 (Contd.)

β	Q(LPS)	F_1	d_2(cm)	α_2	$\eta = \Delta E'/\Delta E$	REMARKS
6.0°	30	13.6	4.9	2.0	99.2	Without Baffle Block
6.0°	50	10.7	6.5	2.1	98.7	Do
6.0°	50	10.7	6.5	1.6	97.3	With one row of Baffle Block

A row of baffle block, as illustrated in Fig.9, further improved the basin performance. Typical scour pattern are shown in fig. 10(a) and 10(b). Performance of the basin designed for a higher flow (with higher Q-value) improved further at half and quarter supply condition as apparent from table 1.

EFFECT OF TAIL WATER VARIATION ON BASIN PERFORMANCE

When $\beta = \beta_{opt}$, the forces Fx balance 2Px. Applying momentum and continuity



(a) (b)

FIG 10 EROSION PATTERN (a) LEVEL BASIN($\beta = 0^\circ$) Q = 15.0 L/s (b) SLOPING BASIN ($\beta = 3^\circ$) Q = 30 L/s , $\delta = 18.4^\circ$.

principles under such balanced condition, it may be proved that the conjungate depth relation is given by

$$F_1^2 = \frac{1}{2}\left(\frac{1-\alpha^2 r}{1-\alpha r}\right)\cdot \alpha r \qquad (8)$$

With r = 1, classical conjugate depth relation for prismatic channel of rectangular section may be obtained from Eq.(8). For r>1, conjugate depth d_2 will be lower than that in a prismatic basin. Higher is the value of r, lower will be d_2 required. Performance of the non-prismatic basin was obtained with d_2 given by eq.(8) as well as depths lower and higher than d_2. The basin performance was found to be excellent even with 50% reduction in d_2 obtained from eq.(8). However, when tail water depth exceeded the conjugate depth by 20 to 25%, the flow downstream was found to be asymmetric.

CONCLUSIONS

(i) Conventional stilling basin in a flumed hydraulic structure require long expensive transition. Cost of such structures can be considerably reduced by adopting the new basin where the dissipating and the transition structures are combined in the same unit.
(ii) Theory of hydraulic jump in a basin with expanding side walls indicate that conjugate depth is lower and energy loss is higher than those found in a conventional basin. However, it is found from experiments that there are several problems in widely diverging basin with level floor. Flow is highly non-uniform and deep erosion occur in the tail channel.
(iii) Performance of the basin could be remarkably improved by use of bed deflector of appropriate size & shape and also by adopting adverse slope (β_{opt}) to floor.
(iv) β_{opt} value determined experimentally was somewhat different from that

found from theory due to simplified assumptions made in derivation.
(vi) βopt value increases with F_1 initially and it remains constant after a limiting value of F_1. For a given value of F_1, βopt increases with discharge intensity (q).
(vii) βopt is also found to be slightly different for different approach flow conditions given by angle of obliquity, δ, between incoming and outgoing flow.
(viii) Basin designed for higher design flow (Qmax) was equally efficient at half and quarter supply.
(ix) Basin performance remained unaffected even with 50% reduction in conjugate depth flow which is lower than that in a conventional basin.
(x) Basin performance deteriorated when the basin was submerged more than 25%.

ACKNOWLEDGEMENT

Author is grateful to the Department of Science and Technology, Govt. of India, for the financial assistance rendered for the Research Scheme. Author also expresses his gratitude to Delhi College of Engineering authorities for permission to use the hydraulics laboratory and other facilities.

REFERENCES

Bremen, R. 1990. Expanding Stilling Basin, Thesis 850, Swiss Federal Institute of Technology, EPFL, Lausanne, Switzerland.

Chaturvedi, R.S. 1963. Expansive Sub-critical Flow in Open Channel Transition, J. of Instn. of Engrs. (I), Vol. 43, No. 9, Pt. CI5, May, P.447.

Deptt. of Science & Technology, 1989. Development of Appurtenances for Economic and Efficient Design of Hydraulic Structures, Project Report No. HCS/DST/1126/81, July.

Hager, W.H., 1992. Energy Dissipators and Hydraulic Jump, Water Sciences & Technology Library, Kluwar Academic Publishers.

Hinds, J. 1928. The Hydraulic Design of Flume and Syphon Transitions. Trans. ASCE, Vol.92, PP. 423-59.

Kline, S.J., Abott, D.E., and Fox, R.W., 1959. Optimum Design of Straight Walled Diffusers, J. of Basic Engg., Trans. ASME, Sept. P.321.

Mazumder, S.K., 1967. Optimum Length of Transition in Open-Channel Expansive Sub-critical Flow, J. of Instn. of Engrs.(I), Vol. 40, No. 3, Pt. CI-2, Nov.

Mazumder, S.K., 1971. Use of Short Triangular vanes for Efficient Design of Wide-angle Open Channel Expansion, J. of Instn. of Engrs.(I), Vol. 51, No. 9, Pt. CI-5, May.

Mazumder, S.K., 1978. Optimum Length of Contracting Transition in Open-Channel Sub-Critical Flow, J. of Instn. of Engrs(I), Vol. 58, Pt. CI-5, March.

Mazumder, S.K., 1979. Economic and Efficient Design of Transition in Open Channel Sub-Critical Flow, Proc., National Seminar on Hydraulics and Water Resources Engg. Practice in India, College of Engg. Guindy, Madras, Vol.III, Section-IV, Jan.

Mazumder, S.K. and Gupta, B.K., 1987. Stilling Basin withh Diverging Side-Walls, Proc. of C.B.I. & P, Model Testing in Hydraulic Research at CW & PRS, Pune, 24-26 Sept.

Mazumder, S.K. 1988, Use of Appurtenances for Efficient Design of Jump type Dissipators having Diverging Side-Walls for flumed Canal Falls, J. of Instn. of Engrs(I), Vol. 68, Pt. CI6, May.

Rouse, H., Siao, T.T. & Nagaratnam, S.1959. Turbulence Characteristics of the Hydraulic Jump, Trans. ASCE, 124, P. 926-966.

Unny, T.E., 1960. Spatial Hydraulic Jump, Doctoral Thesis submitted to Tech. Univ., Dresden, Nov.

Vittal, N. and Chiranjivi, V.V. 1983, Open-Channel Transition : Rational Method of Design, J. of Hyd. Engg., ASCE, 109(1), P.99-115.