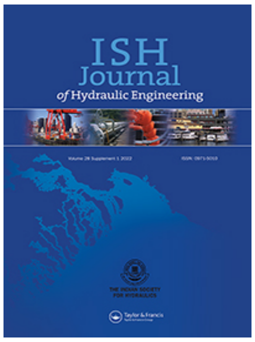

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Innovative hydraulic design of some canal and river structures for economy and efficiency

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ABSTRACT

Numerous hydraulic structures are to be provided in canals and rivers for storage, diversion and transport of water. Some innovative, economic and improved hydraulic design has been discussed. Transitions are to be provided in all canal structures wherever the canal is flumed to achieve economy. Most popular transition in the USA and Europe is Hinds transition. The author performed large numbers of experiments to introduce short curved transitions at entry and straight expansion at exit to attain higher efficiency and better performance. Energy dissipaters are usually provided with parallel side walls followed by transition structures to connect the stilling basin with normal channel section, resulting in huge cost of the structure. For low value of inflow Froude's number (F1), the author introduced a new type of energy dissipater with straight diverging side walls starting from toe of the structure so that it functions as both energy dissipater and flow diffuser. Flow metering structures are needed for flow measurement in both rivers and canals. Parshall flumes may be free or submerged. The author invented a new proportional-type flow meter, by simultaneously fluming and raising the bed so that the flow remains free for all discharges in a given range.

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Innovation; hydraulic design; flow transition; energy dissipation; flow metering

1. Introduction

Numerous cross-drainage and regulating structures, e.g. aqueducts, super passage, siphons, siphon aqueducts, level crossings, falls, regulators and flow meters, are to be provided in irrigation canals for conveying, distributing and management of canal water. There are also large numbers of structures, e.g. dams, barrages, bridges, culverts, intakes, flood control and river training works, which are built on rivers for meeting human needs. Design procedure for these structures has been outlined in several text books (USDI 1967, USDI 1974; Varshney et al. 1977; Leliavsky 1979; Novak et al. 1990; Mazumder 2008a, CBIP 1984) and manuals (CBIP 2008)). The author wishes to discuss about some innovative hydraulic design of only a few of them as mentioned above with a view to economise their cost and improve efficiency.

Transitions are to be provided in all canal structures wherever the canal is flumed to achieve economy. Two pairs of transitions are required at entry and exit of the flumed structure. Different shapes of transitions in common use are summarized in a book by Mazumder (2020a). Hinds (1928) is most popular in the USA and Europe. In deciding the length and shape of these classical transitions, certain hypotheses are made which are not verified experimentally. The author performed large numbers of experiments to introduce short curved transitions at entry and straight expansion at exit, providing appurtenances/adverse slope to floor in order to attain economy and higher efficiency.

Energy dissipaters are to be provided in dams and barrages in rivers and drop structures and regulators in canals. Different types of energy dissipaters based on inflow Froude's number are covered in literatures (Bradley and Peterka 1957; Hager 1992; Chow 1973). These are provided in basins with parallel side walls followed by transition structures to connect the stilling basin with normal channel section in case the channel is flumed. Blaisdell (1948) developed hydraulic design for Saint Anthony Falls (SAF) stilling basin for $5<F_1<10$. Bhowmik (1975) developed stilling basin for low inflow Froude no. F_1. Sharma (1966) Developed stilling basin spatial jump for energy dissipation. The author introduced a new type dissipater with straight diverging side walls so that it functions as both energy dissipater and flow diffuser (Mazumder 2020a; Mazumder and Naresh 1988) by providing suitable appurtenances and adverse slope to basin floor (Mazumder 2016).

Flow metering structures like weirs and flumes (Ackers et al. 1978) are commonly used for flow metering in open channels. Parshall (1950) developed a flume for flow measurement in both streams and canals. Parshall flume with level bed may be free or submerged depending upon tail water condition. It needs elaborate design curves for finding discharge coefficients for free and submerged flow conditions. Mazumder and Roy Indraneil (1999) invented a new proportional type flow meter by simultaneously fluming in plan and raising the bed so that the flow remains free for all discharges in a given range.

2. Necessity of improved hydraulic design

Most important components of design of hydraulic structures are structural safety and proper foundation to avoid failure. Hydraulic design is as important as structural and foundation design since any inadequacy in hydraulic design often causes poor performance and excessive costs. A design engineer often neglects proper hydrologic and hydraulic design of the structures due to inadequacy of information and knowledge in the subject. Author is aware of excessive

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scour/erosion that occurred downstream of bridges and barrages (Mazumder 2020b; Lofty et al., 2020b) due to inadequacy of hydraulic design. Some of the bridges and cross-drainage works on rivers/canals in plains cause excessive afflux resulting in submergence of land, destruction of properties and breaching of flood embankments (Mazumder 2008b), resulting in unimaginable human miseries, excessive cost of repair and costly river protective measures. There is a common tendency to incur huge cost in repair and maintenance, and very little effort is made to investigate the cause of poor performance so as to improve upon the existing design practice. The author wishes to discuss about the shortcomings of some of the existing hydraulic design practice and introduce improved hydraulic design of a few of such hydraulic structures as mentioned above.

3. Flow transition structures

Whenever a canal is constricted for economic reasons, a pair of transitions is to be provided both upstream and downstream of the structures, e.g. cross-drainage works, flumes, regulators, drops etc. Figure 1 illustrates a typical flumed hydraulic structure (e.g. a canal drop/regulator) with a pair of curved inlet transition and straight expanding transition at the exit connecting the flumed structure with original canal section. Purpose of inlet transition is to smoothly contract the flow so that energy loss is minimum at entry. Outlet transition is to be provided for flow diffusion so that the flow is normal and scour free after the outlet.

(Note: Y_1 and Y_2 are flow depths, E_{f1} and E_{f2} are specific energies, V_1 and V_2 are mean flow velocities, H_{Li} and H_{Lo} are energy losses at entry and exit, respectively, H_{Lj} is head loss in hydraulic jump, Y_c is critical depth at control section, Δ is height of crest above bed, B is mean bed width of channel and b is width of flumed section)

In case flow is sub-critical throughout, as in an aqueduct, both the inlet and outlet transitions are to be hydraulically designed to minimise energy loss both at inlet and at outlet so that afflux is minimum. Numerous shapes of inlet and outlet transitions of varying lengths and complicated shapes have been adopted in the past (Mazumder 2020a). Hinds (1928) is most popular in the USA and Europe for the design of transitions in sub-critical flow. These designs are, however, based on certain hypothesis which is never verified. The author (Mazumder 2020a) performed a large number of experiments with varying shapes of contracting and expanding transitions in sub-critical flow in order to find optimum axial lengths for minimum head loss. Figure 2 shows that minimum head loss occurs for Jaeger (1956)-type contracting transition at an axial length governed by average side splay 3.3:1. For an eddy-shaped expanding transition (Mazumder 1966), the corresponding value was found to

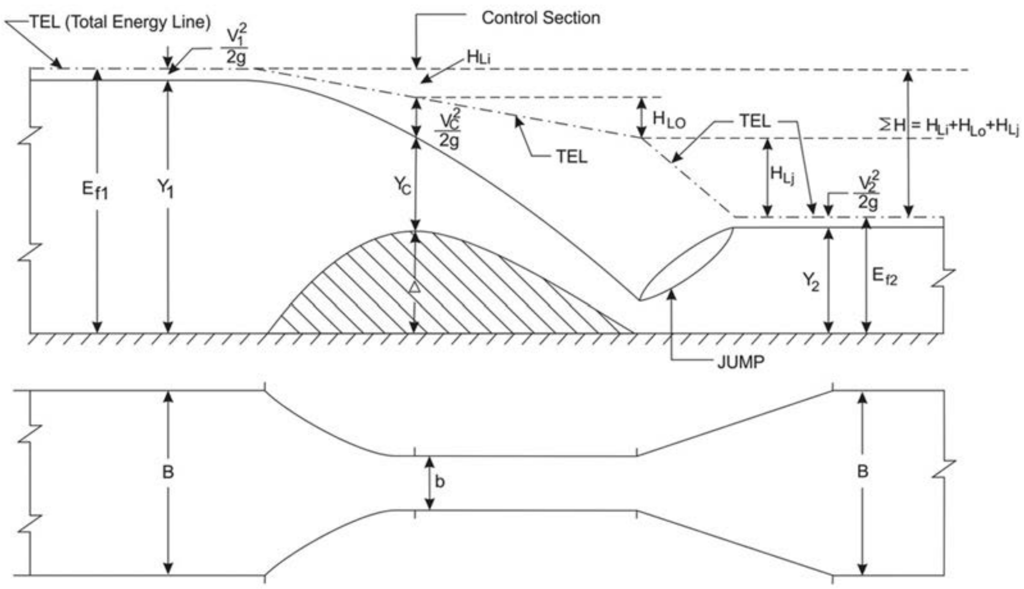


Figure 1. Showing curved inlet and straight outlet transition.

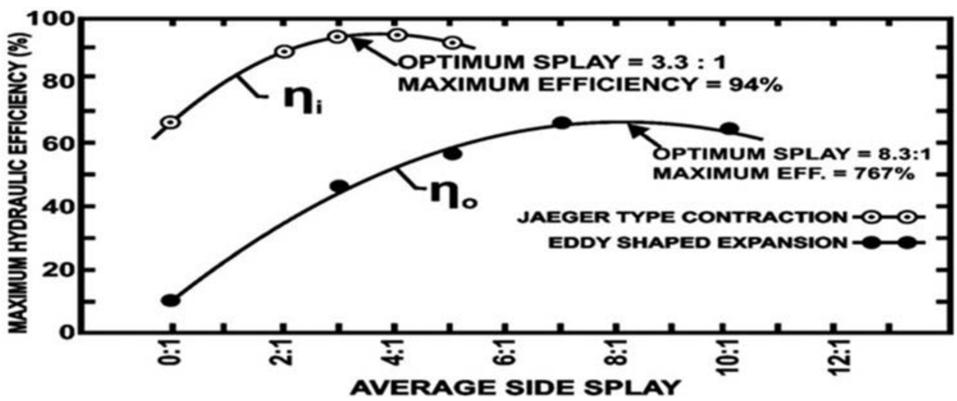


Figure 2. Comparison of hydraulic efficiencies between Jaeger-type contracting transition and eddy-shaped expansion.

be 8.3:1 (Figure 2). Flow characterstics in closed conduit expansion was exhaustively studied by Chaturvedi (1963).

From the above results, it is apparent that for contracting transitions, it suffices to provide a curved transition of Jaeger type with 3:1 average side-splay. It may be made still shorter (2:1) with marginal fall in hydraulic efficiency. It is also concluded that curved expansion of optimum length with complicated shapes is not only costly but inefficient too. Flow always separates from the boundary of such curved expansion resulting in head loss and non-uniform distribution of velocity at exit causing scour in tail channel.

Sub-critical expansion flow with positive pressure gradient in the direction of flow is responsible for boundary layer separation. Hence, the problem of flow expansion/diffusion in sub-critical flow should be tackled by adopting techniques of boundary layer flow control. Straight expansion with short length (3:1 side splay) performed more efficiently by using triangular vanes (Mazumder and Rao 1971) and other boundary layer control devices (Mazumder and Sharma 1983) and found to be hydraulically more efficient compared to Hinds and other conventional designs of complicated shapes and long lengths.

4. Energy dissipation structures

In hydraulic structures like dams/barrages on rivers and falls/regulators in canals, it is compulsory to provide energy dissipating structures to prevent scour/erosion downstream. Bradley and Peterka (1957), Hager (1992) developed different types of stilling basins for energy dissipation. Depending upon the pre-jump Froude's number of flow (F_1), several types of stilling basins were developed by USBR (1968). Stilling basin – an integral part of dams and barrages and other hydraulic structures – is provided to dissipate the differential energy (ΔE), i.e. the difference of energy levels between the entry of a basin and tail channel downstream of the basin. As shown in Figure 3, upper total energy line (TEL) refers to the basin with level floor ($\beta = 0°$) and the lower one (desired) gives TEL for the basin with adversely sloping floor ($\beta = \beta_{opt}$). With level floor, flow separated at the entry to expansion and the jump front was skewed. With sloping floor, there was no flow separation, jump front was normal to flow and the flow diffused completely within the basin. Photo-1(Photo,b) depicts the flow condition in the expansion with level and adversely sloping floor of the basin.

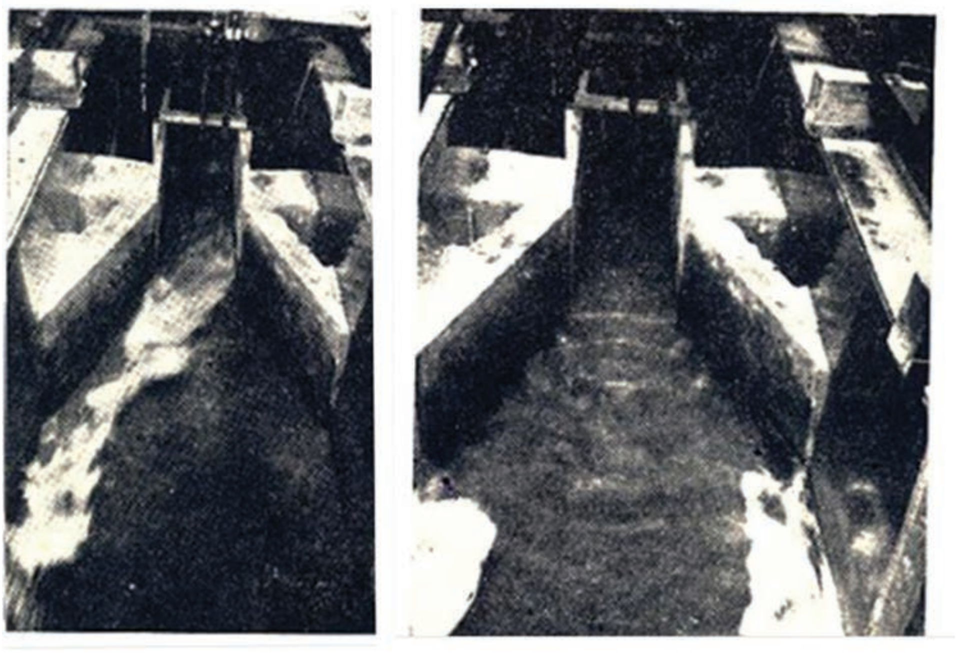
It is usually presumed that the differential energy (ΔE) as shown in Figure 3 is completely dissipated within the basin due to hydraulic jump formation within the basin. Basin length usually varies from four to six times the conjugate depth (d_2) depending upon inflow pre-jump Froude's number of flow (F_1). It is well established that the jump is steady and perfect only when F_1 is greater than 4.5 as in high dams. In many of the low-height hydraulic structures (e.g. barrages, canal drops, regulators, etc.), F_1 is found to be much less than 4.5. For instance, inflow F_1 value at design flood discharge in Farakka barrage (Mazumder, 2015) in India is 2.8. The hydraulic jump in such a situation is not perfect, resulting in poor performance of the basin.

Efficiency of a stilling basin (as energy dissipater) is different from hydraulic jump efficiency. Referring to Figure 3, if the actual energy dissipated within the basin is $\Delta E'$ and the differential energy required to be dissipated is (ΔE), the residual kinetic energy of flow leaving the basin is (Δ E-Δ E′). This residual energy is manifested in terms of non-uniformity of velocity distribution and also wave formation as indicated in Figures 4(a,b) and Photographs-1(a,b). However, considering the overall energy content of the flow, the tail water depth in the exit region can be assumed to be the same as D2, with the mean velocity V2 also remaining the same.

Coriolis' coefficient (α) which is an index for non-uniformity of velocity can be expressed as follows:

$$\alpha = 1/AV^3 \; u^3 \mathrm{d}A \tag{1}$$

where u is the local velocity normal to an elementary area dA, A is the sectional area of flow and V is the mean velocity



(a) (b)

Photo-1 Flow conditions in basin with straight diverging (3:1) side walls: (a) hydraulic jump with level floor and (b) with adversely sloping floor (note: white patches are aluminium powder).

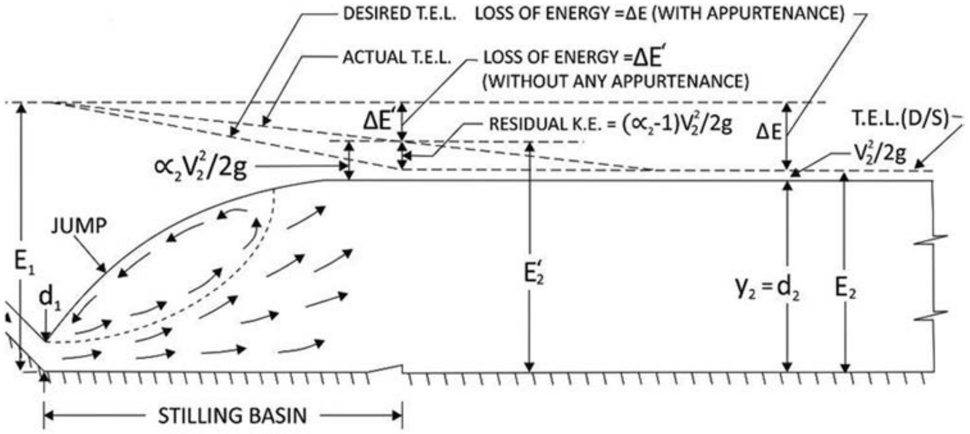


Figure 3. Hydraulic jump, total energy line (TEL) and residual kinetic energy (ΔE-ΔE/).

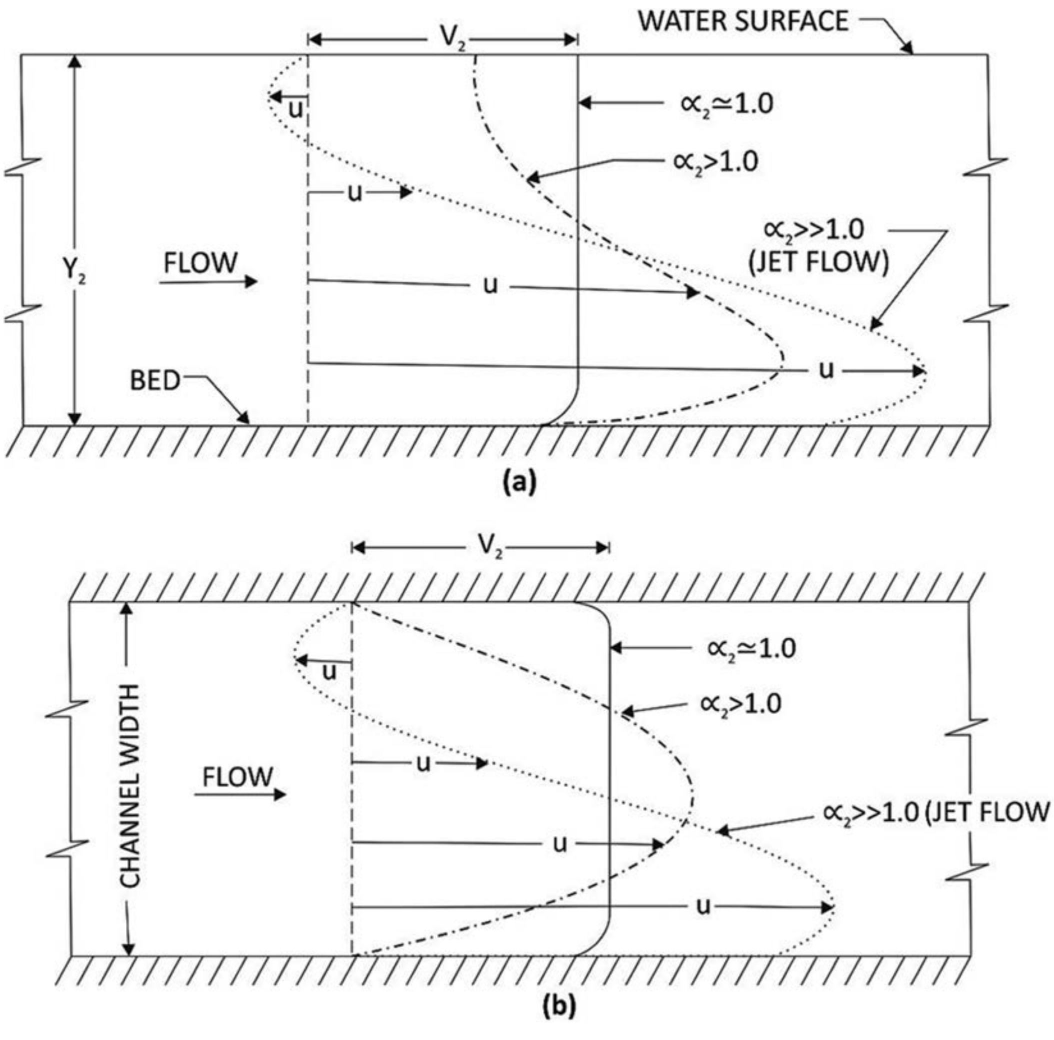


Figure 4. Showing distortion of flow velocity in a channel D/S of basin due to residual kinetic energy. (a) Along depth and (b) along width.

through the sectional area A. It may be noted that when $u = V$, i.e. for uniform distribution of velocity, $\alpha = 1$. Greater the non-uniformity, higher is the value of α_2 (Figure 4). At the exit of the basin, the value of α ($=\alpha_2$) will be greater than unity whenever there is residual energy in the flow leaving the basin. Since the flow depth after the basin is constant, the residual kinetic energy of flow can be expressed as

$$\Delta E - \Delta E' = = (\alpha_2 - 1)\mathrm{V_2}^2/2\mathrm{g} \quad (2)$$

where V_2 is the mean velocity of flow and α_2 is the Coriolis co-efficient at the end of basin, respectively. Defining efficiency (η) of a basin as energy dissipater

$$\eta = \Delta E'/\Delta E = 1 - [(\alpha_2 - 1)\mathrm{V_2}^2/2\mathrm{g}]/\Delta E \quad (3)$$

Equation 3 shows that $\eta = 1$ (i.e. basin efficiency is 100%) when $\alpha_2 = 1$. Higher the α_2-value, more is the residual kinetic energy, lower is the basin efficiency and greater will be the non-uniformity of flow and scour downstream, especially

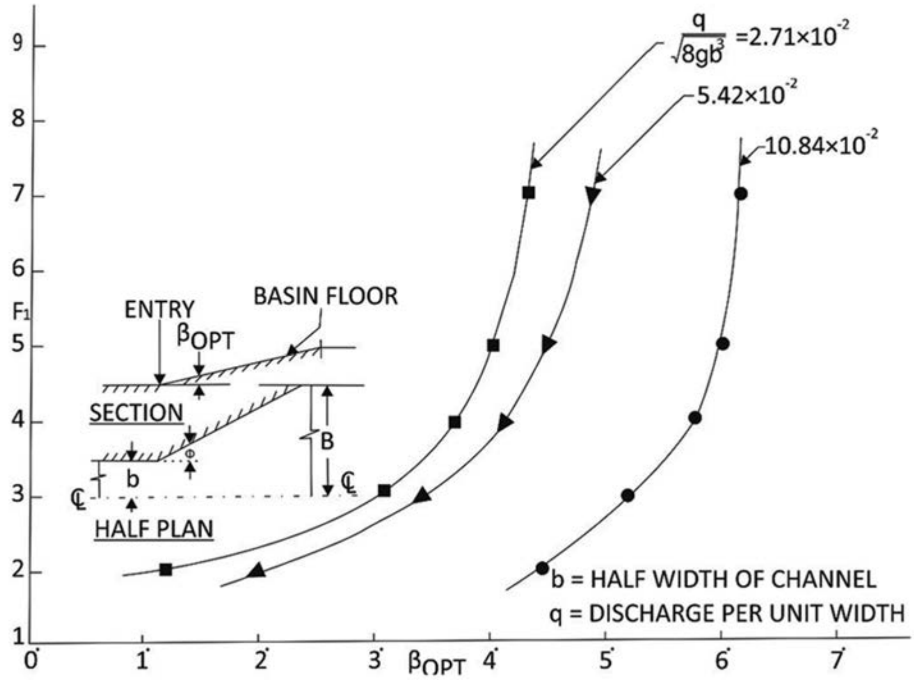


Figure 5. Showing optimum adverse slope of basin floor (βopt) for different prejump Froude no. Fr1 (=F1) and discharge intensity (q = Q/2b).

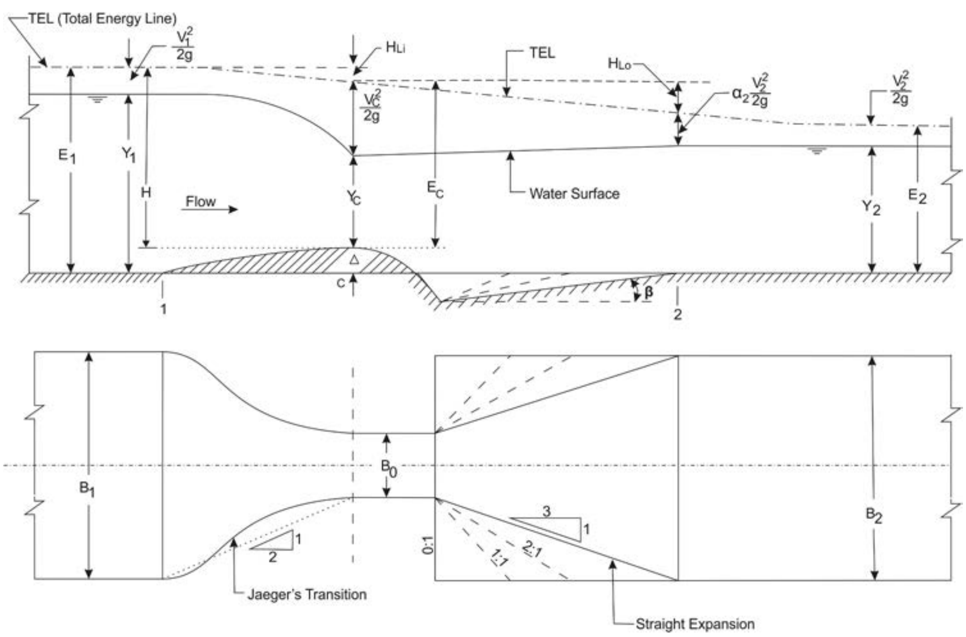


Figure 6. A proportional-type flow meter with negligible afflux and free flow.

where the bed and bank consist of fine materials like silt and sand.

Mazumder (2012, 1994) and Mazumder and Sharma (1983) developed an innovative method for improving basin performance by providing adverse slope (β) to the floor of basin with straight diverging sidewalls. β -Value was derived (Equation 4) such that the axial components of sidewall reactions acting in the flow direction are neutralised by the axial component of bed reaction acting against the flow direction.

$$\beta = tan^{-1}[(d_1^2 + d_2^2 + d_1 d_2) tan\phi/(bd2 + Bd1 + 2Bd2 + 2bd1)] \quad (4)$$

where b and B are half widths of basin; d_1 and d_2 are pre-jump and post-jump depths at the entry and exit of the basin, respectively; and ϕ is the angle of divergence of the side walls as shown in Figure 5. Large numbers of experiments were conducted and the performance of the basin was measured with and without basin floor slope (β). Optimum values of slope (βopt.) for best performance of the basin are given in Figure 5. With level floor ($\beta = 0°$), the performance of the basin measured in terms of η and α_2 was extremely poor. With adverse slope ($\beta = \beta$opt), performance improved remarkably and the computed values of η and α_2 were found to be almost equal to unity, indicating that there was hardly any residual kinetic energy of flow leaving the basin (Mazumder 2020b).

5. Flow metering structures

A flow meter where there is negligible afflux and continues to act under free flow condition irrespective of magnitude of incoming discharge was invented by the author (Mazumder 2020c) by simultaneous fluming in both horizontal and vertical plains as shown in Figure 6. It acts always under free flow condition irrespective of magnitude of incoming flow in the design flow range Q_{max} and Q_{min}. It is scientific and superior to Parshall (1950). Equation 5 and 6 give the width (B_0) and corresponding rise (Δ) at control section.

$$Bo = \left[0.7\left({Q_{max}}^{2/3} - {Q_{min}}^{2/3}\right)/(E_{1max} - E_{1min})\right]^{3/2} \quad (5)$$

$$\Delta = E_{1max} - 3/2[(Q_{max}/B_0)2/g]^{1/3} \quad (6)$$

Jaeger-type inlet transition was provided to minimize head loss at entry (C_i) to ensure smooth flow at the control section. Outlet loss coefficient (Co) could be significantly reduced by preventing flow separation with adverse bed slope (β) corresponding to the rate of flaring of side walls as illustrated in Figure 1. β-values were found from Equation 7 developed by Mazumder (1994).

$$\beta = \tan - 1[(y_c/B_0)\{(\delta 2 + \delta + 1)/(2 + \delta + \lambda + 2\lambda\delta)\}\tan\theta \quad (7)$$

where $\delta = y_c/y_2$, $\lambda = B_1/B_0$ and θ = angle of divergence of side walls downstream. Values of C_d and hydraulic efficiencies of inlet, $\eta_i = 1/(1+C_i)$, and outlet, $\eta o = (1-C_o)$, transitions were high, and Corriolis coefficients (α_2) at the exit were low. Performance of the flow meter were measured in 24 experiments (Mazumder and Roy Indraneil 1999). With level floor ($\beta = 0°$), basin performance was very poor. With adverse slope to floor ($\beta = \beta_{opt}$), the performance of the basin was extremely good.

6. Conclusions

Conventional hydraulic design of canal and river structures is not only costly, but their hydraulic performance is also not satisfactory. The author developed some innovative hydraulic designs with a view to economise cost and achieve higher efficiency. Hinds method of hydraulic design of flow transition, popularly used in Europe and the USA, is based on certain hypothesis which is never verified. It is not only costly due to long length, but its performance also is not satisfactory. From large numbers of experiments carried out by the author, it was concluded that Jaeger-type inlet transition with short axial length performs far better. Classical methods of hydraulic design of expanding transition are not only costly, but their performance too is unsatisfactory since flow separates and scour occurs in tail channel due to non-uniformity of velocity distribution. Short straight expansion with appurtenances/adverse floor slope is cheaper and perform far better. The author performed large numbers of experiments to develop suitable appurtenances to ensure separation free uniform flow at exit of the expansion.

Existing hydraulic design of energy dissipaters at low inflow Froude's number (F_1) is not efficient as the jump is not perfect at low F_1-values as in barrages on rivers and drop structures in canals. Considerable amount of residual kinetic energy leaves the basin efficiency of which was defined in terms of Corrioli's coefficient, α_2. With level floor in a classical basin, kinetic energy coefficienr (α_2) was found to be very high, resulting in scour in tail channel. From large numbers of experiments, it was found that the performance of a basin provided with adverse bed slope (β_{opt}) is excellent. Unlike a classical type basin where the basin is provided with parallel side walls up to the end of jump, side walls are diverged from the toe of the structure in the new basin, thereby not only reducing its cost but of better performance.

Flow meters like weirs and venturis are needed to measure flow in open channels for management of water. Pasrhall-type venturi flow meters with level bed are popular in India and abroad. However, it needs elaborate design curves for finding flow under free and submerged condition. The author developed a new proportional flow meter with negligible afflux running under free flow condition within a given flow range. It has high modular limit, and the coefficient of discharge remains almost constant in free flow condition within a given range of discharge.

Disclosure statement

No potential conflict of interest was reported by the author.

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