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Hydraulic jump control using stilling basin with Adverse slope and positive step

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The paper deals with hydraulic jump characteristics in a stilling basin (called basin hereafter) provided with an adverse slope and a positive step at the end of the basin. Different characteristics of hydraulic jump, studied both analytically and experimentally, include (i) conjugate depth relation \((D_2/D_1)\) (ii) lengths of roller \((L_r)\) (iii) jump length \((L_j)\) and (iv) relative loss of energy \((\Delta E/E_1)\) in the jump within the basin. Studies were made for four different slopes \((0; 0.01; 0.03\) and 0.05\) combined with three positive steps of heights \((0; 3\) cm and 5 \(cm)\). In total, 144 experiments were performed with inflow Froude’s no. \((F_1)\) varying from 4 to 10. It is concluded that the sequent depth ratio, jump length and roller length reduce with increase in slope and height of positive step by 20\%, 39.3\% and 32.6\%, respectively, as compared to those in a classical jump on level floor. Relative energy loss increased with rise in slope and step height by 13\% more than that in a classical jump. Fig. 7(a) and 7(b) illustrate the variation of the above jump characteristics with slope and step height, compared to ones in classical jump. Fig. 8(a) and 8(b) indicate the variation of relative energy loss \((\Delta E/E_1)\) and jump efficiency \((\eta)\) respectively with pre-jump Froude’s number \((F_1)\) for different slopes and step heights. Values of \(\Delta E/E_1\) and \(\eta\) are compared with those in a classical jump on level floor. Authors are, however, silent about how to decide the slope and step height combined together for best performance of stilling basin operated under different \(F_1\)-values corresponding to different flows. Too high step may cause flow choking and jump submergence and too low step may result in re-rolled jump. In case tail water depth is less than sequent depth, Ranga Raju (1993) plotted relation between \(F_1\) and \(D_2/D_1\) for different values of positive step height such that the hydraulic jump ends at the step in a stilling basin of length \(5(D_2+\Delta Z)\) where \(\Delta Z\) is the height of positive step. Earlier a similar paper on ‘Characteristics of hydraulic jump on rough bed with adverse slope’ (Parsamehr et al. 2017) was published in ISH J. of Hyd. Engg. and discussed by Mazumder (2017). Discusser (Mazumder and Naresh 1988) performed a series of experiments to find hydraulic jump characteristics with both horizontal floor, as well as floor with adverse slope. Variation of conjugate depth, length of jump, roller length and relative energy loss were plotted against pre-jump Froude’s no. of flow \((F_1)\) for different slopes. Results obtained were almost similar to the ones found by the authors of the paper. Use of chute blocks, baffle blocks and end sill has been prescribed by Bradley and Peterka (1957) for reducing length and conjugate depth and for improving the efficiency of USBR type stilling basins (1968). SAF basin was developed in St. Anthony Falls Hydraulics Laboratory in USA. 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 \((\Delta E)\), i.e. the difference of energy levels between the entry of a basin and tail channel downstream of the basin as shown in Figure 1. It is presumed that the differential energy \((\Delta E)\) is completely dissipated within the basin due to hydraulic jump formation within the basin. Basin length usually varies from 4 to 6 times the conjugate depth \((D_2)\) depending upon inflow pre-jump Froude’s number \((F_1)\). 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 less than 4.5. Since authors have studied jump characteristics and energy loss for \(4 < F_1 < 10\), the results may not be applicable in such situations. For example, inflow \(F_1\) – values at design flood discharge in Farakka and Kosi barrages in India are \(F_1 = 2.8\) and \(F_1 = 3.4\), respectively. In these low height dams/barrages, drops, regulators, etc., the jump is not perfect as the basin efficiency is poor and hence considerable amount of residual kinetic energy leaves the basin as shown in Figure 1.

From Figs.7 and 8 in the paper, it is observed that both \(\Delta E/E_1\) and \(\eta\)-values decrease with reduction in \(F_1\)-values. Efficiency of a stilling basin (as energy dissipater) is different from hydraulic jump efficiency. Referring to Figure 1, if the actual energy dissipated within the basin is \(\Delta E\) and the differential energy required to be dissipated is \((\Delta E)\), the residual kinetic energy of flow leaving the basin is \((\Delta E-\Delta E')\). As the tail water depth \(D_2\) after the basin remains the same, the only way the residual energy can be contained by the flow with same depth \((D_2)\) and same mean velocity of flow \((V_2)\) is through non-uniformity of velocity distribution as indicated in Figure 2(a) and 2(b).

Coriolis’ coefficient \((\alpha)\) is an index by which non-uniformity of velocity can be expressed as

\[
\alpha=\left[1/(AV^3)\right]\int_0^1 u^2\,dA
\]

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 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 \(\alpha\) (Figure 2). At the exit of the basin, the value of \(\alpha \quad(\alpha_2)\) 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

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

where $V_2$ is the mean velocity of flow and $\alpha_2$ is the Coriolis' coefficient at the basin end which can be expressed as

$$\alpha_2 = \left| \frac{1}{(A_2V_2^2)} \right| \int u^2 \, dA$$  \hfill (3)

where $A_2$ and $V_2$ are the sectional area and mean velocity of flow at the basin end, respectively.

Defining efficiency of a basin as energy dissipator

$$\eta = \Delta E' / \Delta E$$  \hfill (4)

or,

$$1 - \eta = 1 - (\Delta E' / \Delta E) = (\Delta E - \Delta E') / \Delta E = [(\alpha_2 - 1)V_2^2/2g] / \Delta E$$  \hfill (5)

or,

$$\eta = 1 - [(\alpha_2 - 1)V_2^2/2g] / \Delta E$$  \hfill (6)

Equation (6) shows that $\eta = 1$ (i.e. basin efficiency is 100%) when $\alpha_2 = 1$. Higher the $\alpha_2$ 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 where the bed and bank consist of fine materials like silt and sand.

Figure 3 is a plot of $\eta$ against $\alpha_2$ for different discharges ($Q$) obtained by the discusser experimentally (Mazumder and Naresh 1988). It may be seen that when the residual energy is 1%, i.e. $\eta = 99\%$, $\alpha_2$ values are about 3, 4 and 7 for $Q$-values of 31, 15.5 and 7.75 LPS, respectively. With 2% residual energy (i.e. $\eta = 98\%$), respective values of $\alpha_2$ are about 4, 6 and 12 which indicate very high degree of non-uniformity of flow (Figure 2) leaving the basin and causing scour downstream. It may be noted that in sub-critical flow, kinetic energy of flow is very low compared to flow depth and hence even a small amount of residual kinetic energy of flow causes a high degree of non-uniformity of flow responsible for scour and erosion downstream.

Discussors (Mazumder 1994; Mazumder and Sharma 1983) developed an innovative method of improving basin performance by providing reverse slope ($\beta$) to the floor of basin with straight diverging sidewalls. $\beta$ Value was derived (Equation 7) 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.

$$\beta = \tan^{-1} [(d_1^2 + d_2^2 + d_1d_2)\tan\phi / (bd_2 + Bd_1 + 2Bd_2 + 2bd_1)]$$  \hfill (7)

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; $\phi$ is the angle of divergence of the side walls as

Figure 4. Showing optimum adverse slope of basin floor ($\beta_{opt}$) for different prejump froude no. $F_r_i (= F_i)$ and discharge intensity ($q = Q/2b$).
shown in Figure 4. Experiments were conducted and the performance of the basin was measured with and without basin floor slope ($\beta$). Optimum values of slope ($\beta_{\text{opt}}$) for best performance of the basin are given in Figure 4. With level floor ($\beta = 0^\circ$), the performance of the basin measured in terms of $\eta$ and $\alpha_2$ was extremely poor. With adverse slope ($\beta = \beta_{\text{opt}}$), performance improved remarkably and the computed values of $\eta$ and $\alpha_2$ were found to be almost equal to unity indicating that there was hardly any residual kinetic energy of flow leaving the basin (Mazumder, 2020).

Scour downstream of a stilling basin in weirs and barriages is primarily due to the inefficient stilling basin performance which in turn is dependent on the nature of hydraulic jump formed within the basin and the energy dissipation that actually occurs within the basin. A part of the pre-jump energy ($E_1$ in Figure 1) is converted to pressure energy as the depth increases from $d_1$ to $d_2$ as shown in Figure 1. The remaining energy (mostly kinetic energy, since $d_1$ is very small compared to $V_f^2/2g$), transferred to turbulent flow field, can not be recovered and is commonly known as head loss in jump. Chaturvedi (1963) measured turbulent quantities in a conical diffuser and found the head losses in terms of the turbulence parameters ($u'$, $v'$ and $w'$). Production of turbulence in hydraulic jump is dependent upon the nature of impact (Hinze 1959) between the incoming super-critical flow and outgoing sub-critical flow. When $F_1 < 4.5$, strength of impact is poor resulting in low turbulence production giving rise to residual kinetic energy of flow leaving the basin.

Basin efficiency as an energy dissipater is also governed by the skewness of jump front. Model study (Lofty et al. 2020) was carried out to investigate scour downstream of several barriages on river Nyle in Egypt due to asymmetric operation of gates. Non-dimensional scour depths, $d_j/a_g$ (where $d_j$ is scour depth and $a_g$ is gate opening) were measured in 80 experiments performed with different gate operation schedule – both symmetric and asymmetric – to investigate the effect of several parameters, e.g. pre-jump Froude’s number ($F_{11}$), jump submergence ($S_j$), variation of head ($h$) and expansion ratio ($e$) on the scour downstream of the barrage gates. While the effect of other parameters on jump performance is established (Rajaratnam 1965; USBR 1968; Peterka, 1958; Chow 1973; Hager 1992), the effect of expansion ratio ($e$) on jump performance and scour due to asymmetric operation of gates was investigated first time by Ahmed. Expressing $e$ as the ratio of gate width in operation to the total width of the channel, authors found that the scour depth increased significantly due to partial and asymmetric operation of gates. Scour depth $d_j/a_g = 0.24$ with $e = 1.21$ when all the five gates were opened. Scour depth $d_j/a_g = 2.76$ with $e = 6.12$ when only one side gate was open showing an unprecedented increase in scour by 1050%.

**Disclosure statement**

No potential conflict of interest was reported by the author.

**References**


