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Full Length Research Paper

Hydraulic jump in stilling basin with vertical end sill

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Stilling basins with dentiated or continuous sills are frequently used as energy dissipaters downstream of hydraulic structures. In this study, experiments are conducted to evaluate effects of a single vertical continuous sill and its position on control of depth and length of a forced jump in stilling basin without considering tailwater depth which is variable and totally controlled by downstream river conditions. A sill with five different heights was placed at three different longitudinal distances along a scaled model of a stilling basin. The hydraulic characteristics of the jump were measured and compared with the classical hydraulic jump under variable discharges. Results of experiments confirmed significant effect of the sill on dissipation of energy. A new relationship was developed between sill height and position, sequent depth ratio, and length of stilling basin. The advantage of the proposed relationship in practice is its capability to design stilling basin where tailwater depth is unpredictable

Key words: Hydraulic jump, baffle block, sequent depth.

INTRODUCTION

Kinetic energy of water over the spillway must be dissipated in order to prevent severe scouring of downstream riverbed and failure of downstream structures. The shut block and sills with different configurations are used in the stilling basin to disturb water and dissipate large amount water energy through formation of a hydraulic jump. To ensure proper performance and energy dissipation, the basin should be designed to reduce the sequent depth of the hydraulic jump and keep it less than the tailwater depth. Otherwise jump will weep out of the basin and downstream scouring will be unavoidable. To reduce the sequent depth particularly where the tailwater depth is too small (normally where downstream of the structure is steep), a continuous sill can control and stabilize the jump, thus reducing the basin length. Sill height, position and configuration (where more than one sill is used) have considerable impact on the jump and dissipation of water energy.

Hager (1992) classified the jump over a vertical sill into A-jump, B-jump, minimum B-jump, C-jump and D-jump. The A-jump is classical hydraulic jump which is characterized by the maximum sequent depth ratio (where sill is far away to affect the jump). By decreasing the tailwater depth, toe of jump moves toward the sill and a B-jump occurs in which the flow is considerably modified by sill and the streamline pattern becomes curved over sill. Also the height of bottom rollers grows and a surface boil appears at the rear sill side, yet without significantly changing the free surface profile. As the tailwater depth decreases more, the distance between the toe of the jump and upstream sill face is further reduced and the curved flow pattern over the sill is amplified. Morever, the surface current starts to plunge behind the sill, yet without reaching the channel bottom. A further characteristics of such flow, referred to as minimum B-jump, is the formation of a second roller at the downstream sill zone and a C-jump is characterized by having the maximum difference between the depth of flow over the sill and the tailwater depth. D-jump initiates when flow is disturbed more and roller waves can reach the bed and scouring becomes expectable. When tailwater depth is low, D-jump may appear sooner than normal conditions allow.

Ohtsu et al. (2001) presented the upper limit of the inflow Froude number for undular-jump formations in smooth rectangular channels. It has been found that the formation of undular jumps depends not only on the inflow Froude number but on the boundary-layer develop-

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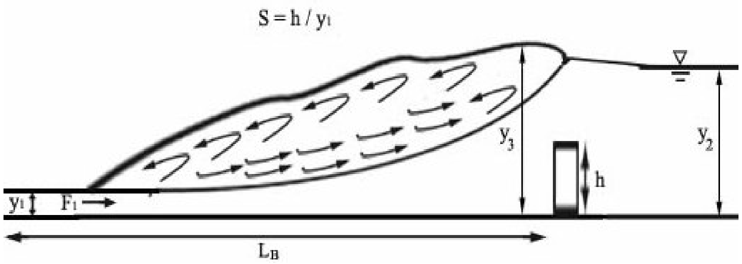


Figure 1. Forced hydraulic jump in stilling basin with a continuous sill.

ment at the toe of the jump under conditions in which the effects of the aspect ratio and the Reynolds number on the flow condition are negligible. Furthermore, Debabeche and Achour (2007) studied the effect of a continuous sill on hydraulic jump in a triangle channel.

Deng et al. (2007) represented the prototype measurements of pressure fluctuations for hydraulic jump while a study deals with statistical analysis of pressure fluctuations at the bottom of spatial hydraulic jumps with abrupt lateral expansions was conducted by Yan et al., (2006). The effects of the channel expansion ratio and inflow condition on the power spectral and dominant frequency were examined. Pressure data were recorded for different Froude numbers ranging from 3.52 - 6.86 and channel expansion ratios ranging from 1.5 - 3.0.

A numerical simulation of minimum B-jumps in horizontal rectangular channels having an abrupt drop is given by Tokyay et al. (2008). Before that, A-type jump at a positive step was simulated numerically by Altan-Sakarya and Tokyay (2000).

Review of literature reveals that previous studies on forced hydraulic jump by large rely on tailwater depth downstream of the stilling basin. For the same flow and jump conditions, tailwater depth can be different as it is highly controlled by slope and cross section of river downstream of the basin. The purpose of this study is to propose design criteria for estimation of the stilling basin length without consideration of tailwater. This is done by creating and testing forced hydraulic jumps using a single continuous sill with variable height and position in a scaled model of a stilling basin.

MATERIALS AND METHOD

Theory

Consider a stilling basin at the end of a chute in which a rectangular continuous sill located a distance of L_B from the entrance is used to develop a forced hydraulic jump (Figure 1). The effective hydraulic parameters are shown in the figure. y_3 and x_s coordinates the point for maximum depth of flow over the sill and distance from the beginning of the basin.

The following functional relationship among significant parameters is used to characterize the forced hydraulic jump due to the presence of a continuous sill in a rectangular stilling basin.

$$f(h, y_1, y_2, y_3, v_1, x_s, L_B, L_j, i, g, \rho, \mu) = 0 \quad (1)$$

Where; h is the height of sill, y_1 and v_1 are depth and average velocity of the supercritical stream at distance x_s upstream of the sill, y_2 is the sequent depth of jump (or in fact flow depth immediately after sill for a forced jump), y_3 is maximum flow depth upstream of the sill. L_B is the length of the stilling basin or distance from the beginning of the stilling basin to the upstream face of the sill, L_j is the length of the hydraulic jump, i is channel slope, g is gravity, ρ and μ are water density and viscosity respectively. Assuming a horizontal stilling basin ($i = 0$) and fully turbulent flow independent of Reynolds number, the dimensionless parameters are summarized as:

$$f\left(\frac{h}{y_1}, \frac{y_2}{y_1}, \frac{y_3}{y_1}, \frac{x_s}{L_j}, \frac{L_B}{y_1}, F_1\right) = 0 \quad (2)$$

According to Belanger Equation, the sequent depth ratio for a classical hydraulic jump is given by,

$$Y^* = \frac{y_2^*}{y_1} = \frac{1}{2}\left[\left(1 + 8F_1^2\right)^{\frac{1}{2}} - 1\right] \quad (3)$$

Where; y_2^* is the sequent depth of classical hydraulic jump. For $F_1 \geq 2.5$, the sequent depth ratio can be approximated as follows,

$$Y^* = \sqrt{2}F_1 - \frac{1}{2} \quad (4)$$

Based on experimental observations of Hager (1992), the following relation was found when a continuous sill is located in front of the hydraulic jump.

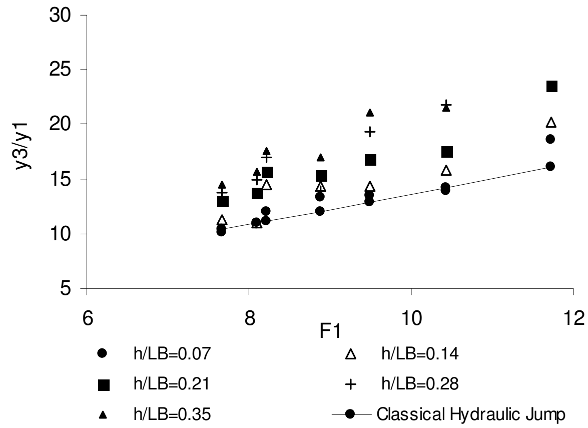
$$Y = \frac{y_2}{y_1} = Y^* - Y_s \quad (5)$$

Where the sill effect compared to a classical jump (Y_s) is expressed by the following relationship.

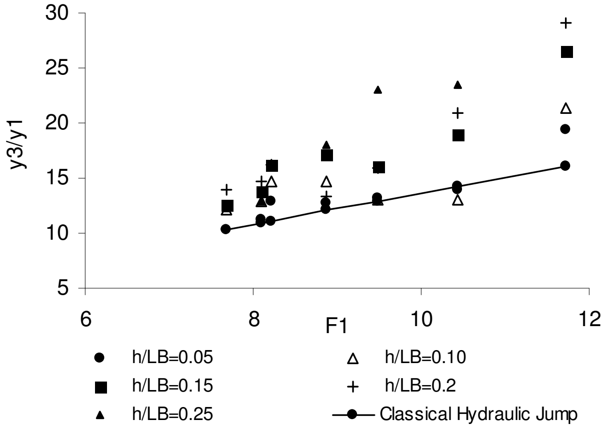
$$Y_s = \alpha S^{\beta} \quad (6)$$

The coefficients (α, β) depend on the type of hydraulic jump.

(a) LB=93.3 mm



(b) B=133 mm



(c) LB=167 mm

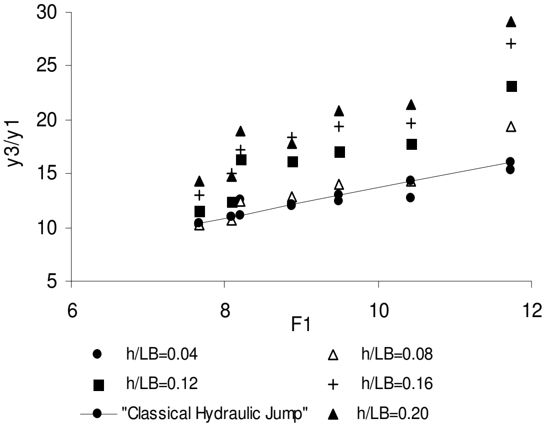


Figure 2. Variation of maximum depth ratio with sill height ratio.

According to Equation 6, the maximum amount of Y_s can be obtained by increasing the height of the sill. If the height of the sill (*h*) becomes larger than a limit value S_L, the sill flow is changed into weir flow. The following relationship is suggested for the limited value of S_L (Hager (1992).

$$S_L = \frac{1}{6} F_1^{1.645} \tag{7}$$

For a given F_1, the relative height of sill must be smaller than S_L. This condition must be satisfied for the proposed design criteria of this study.

Experiments

Experiments were conducted on a 1/30 scale model of Galabar dam spillway in the Research Institute of the Ministry of Power of Iran. This was done to develop the design criteria for estimation of stilling basin length for the forced jump as result of a continuous sill at the end of a horizontal basin. A single sill with five heights of 6.7, 13.3, 20.0, 26.7, and 33.3 cm was tested at 3 distances of 93.3, 133, and 167 cm from beginning of the basin. Test were conducted with many discharges around the designed discharges based on 1000 and 10000 return years and PMF (Probable Maximum Flood) which were previously estimated to be 221.7, 335.8, and 592.9 m^3 sec^{-1} respectively.

RESULTS AND DISCUSSIONS

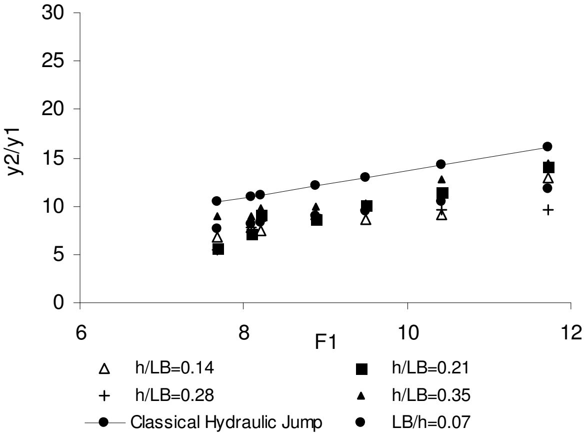
The main purpose of this study was the development of design criteria for estimating the stilling basin length where a continuous sill is located at the downstream end of the basin. Since tailwater depth is variable and completely dependent on downstream conditions, the advantage of the present work is elimination of the tailwater depth from the analysis.

Figure 2 (a) illustrates the variation of the maximum depth ratio y_3/y_1 with Froude number for the forced hydraulic jump due to a continuous sill at L_B = 93.3 cm with five heights. Similar is repeated in Figures 2b and 2c for L_B = 133 and 167 cm. For similar inflow, the result of maximum depth ratios y_3/y_1 for forced hydraulic jump in this study is significantly higher than those for free hydraulic jump calculated from Belanger equation (Equation 3). In addition, Figures 3(a) - 3(c) demonstrate the variation of the sequent depth ratio y_2/y_1 with Froude number for the forced hydraulic jump due to a continuous sill for fifteen ratios of h/L_B. An inverse result was obtained when they were compared with the sequent depth ratios of free hydraulic jumps from Equation 3 for the same flow condition. This shows significant effect of the sill on the reduction of flow depth after it.

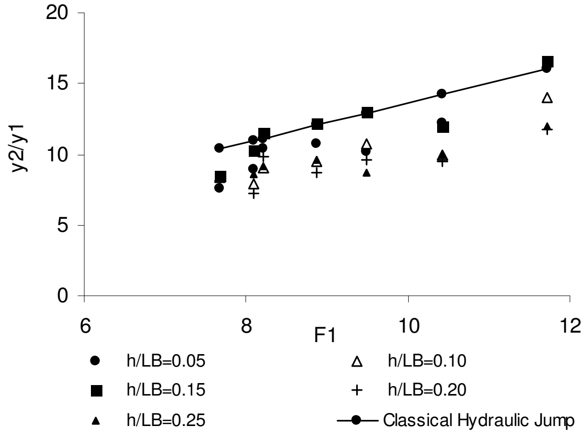
All figures prove an increase in the maximum depth and a decrease in the sequent depth if the sill height is increased for a particular L_B. Although smaller sill positions showed to have more effect on increasing of y_3 and reducing of y_2, more experiments are required to find the most effective sill distance. However, sill positions larger than 167 cm did not show a significant effect on y_2 and y_3.

The experiments revealed that both y_2 and y_3 respon-

(a) LB=93.3 mm



(b) LB=133 mm



(c) LB=167 mm

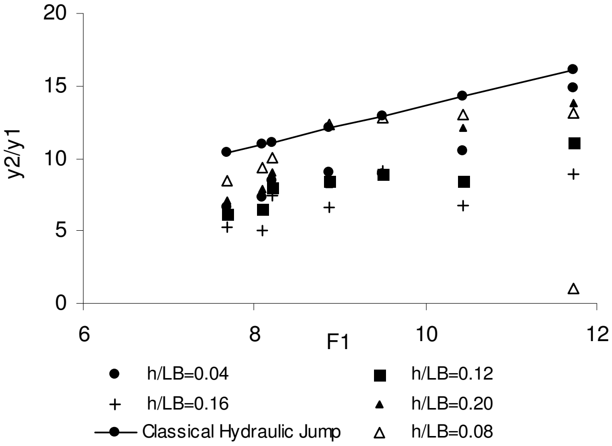


Figure 3. Variation of sequent depth ratio with sill height ratio.

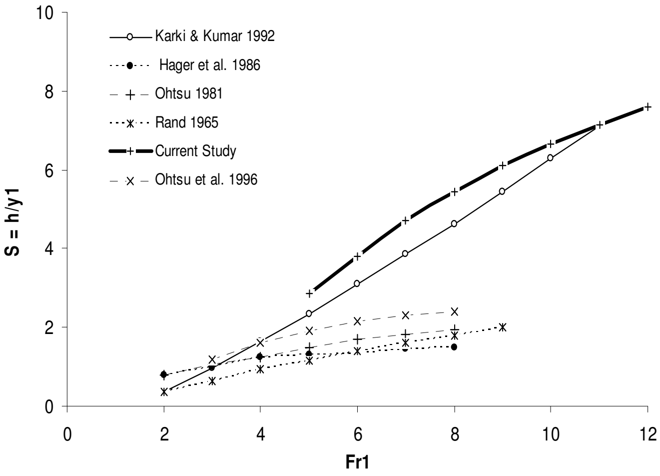


Figure 4. Comparison of the results with previous studies (from Ohtsu et al., 1996)

ded to ratio of h/L_B much better than h or L_B alone, and for ratios of h/L_B less than 0.015 no significant effect was observed on both y_2 and y_3.

Results of this study for a relation between Froude number (F_1) and sill height ratio (h/y_1) are compared with previous studies (from Ohtsu et al., 1996) in Figure 4. Previous studies by large have been concentrated on conditions to initiate an incipient jump by regular end sills. For this reason, while results are concurred with previous studies for lower Froude numbers and about incipient condition, they are in line with Karki's results deviate from other studies at higher Froude numbers. Main reason for deviation is the tallness of the sill and control of flows with higher Froude number in shorter distance. However, effects due to difference in scale and boundary flow condition might be ground for divergence of the results in Figure 4.

DESIGN CRITERIA FOR SILL-CONTROLLED STILLING BASIN

The results in this study in concurrence with previous studies proved considerable effect of sill height and position in reduction of the sequent depth and length of the stilling basin. Thus, proper designs of the sill height and its location have significant contribution to cost effectiveness of a stilling basin.

Based on the experiment results, a relationship between the most effective dimensionless parameters in Equation 1 is constructed to help design of a sill-controlled stilling basin. Figure 5 shows the relationship between inflow Froude number, ratios of L_B/y_1 and h/y_1 as main parameters to express inflow condition, stilling basin and sill geometry respectively.

Figure 5 enables the design of an end sill-controlled stilling basins (estimation of L_B and h), once the inflow conditions y_1 and F_1 are known. Diagrams are constructed so that by selecting a basin length of L_B, the

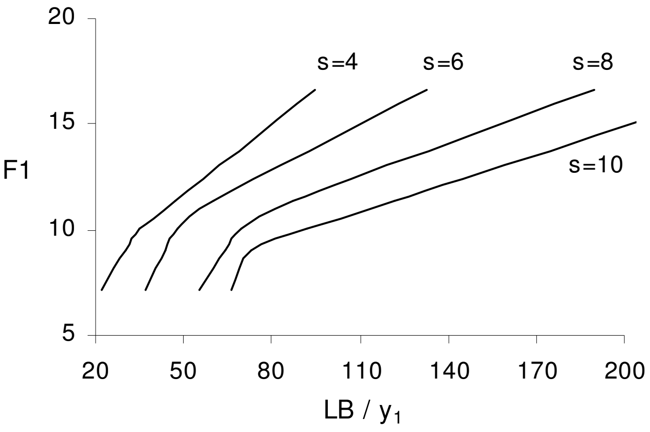


Figure 5. Design diagram for jumps in sill-controlled stilling basin (s = h/y_1).

required sill height (*h*) can be predicted. The predicted sill height (*h*) should be checked to be less than the Froude number based parameter S_L calculated from Equation 7. This may require several estimations of L_B. Based on the extensive testing and observations in this study, it is recommended to select initial stilling basin length L_B based on the following relationship.

$$3(y_2-y_1)\le L_B \le 5(y_2-y_1) \tag{8}$$

For L_B smaller than $3(y_2-y_1)$, the jump plunged downstream of the sill and scouring may be unavoidable, while for larger values than $5(y_2-y_1)$ the effect of the sill was not significant. Figure 5 and the proposed design criteria are based on inflow Froude numbers ranging from 4 to around 12 and s = h /y_1 from 2 to 8.

CONCLUSION

Experiments were conducted on a 1/30 scale model of a dam spillway and stilling basin to propose a design criteria for forced hydraulic jump as a result of single continuous sill at the end of stilling basin. The objective was to estimate the efficient sill height and distance to reduce jump and basin length, thus cost.

Design criteria is basically developed for B-jump with inflow Froude numbers F_1 = 4-12 and h/y_1 = 2 - 8. However, an over design of sill height to about 20% and 30% will facilitate it for C-jump and D-jump respectively. Comparison of forced jump results of this study with free jump relationships confirm up to 30% reduction in length of stilling basin where sill is there to control the jump. The advantage of the proposed method is its simplicity in practice and its capability to estimate sill height and basin length for most flow type without considering tailwater depth which is controlled by slope and river conditions downstream of the basin.

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Notations: F_1 ; approaching Froude number, g ; acceleration due to gravity, h ; height of sill, i ; channel slope, L_B ; length of stilling basin, L_j ; length of hydraulic jump, L_r^* ; length of roller for classical hydraulic jump, μ ; water viscosity, ρ ; water density, s ; relative sill height, v_1 ; average velocity of supercritical flow, x_s ; distance from toe of the jump to upstream sill face, y_1 ; depth of supercritical flow, y_2 ; sequent depth of forced hydraulic jump, y_2^* ; sequent depth of classical hydraulic jump, y_3 ; maximum depth of flow over the sill, y_t ; tailwater depth, Y ; sequent depth ratio for forced hydraulic jump, Y^* ; sequent depth ratio for classical hydraulic jump, Y_3 ; maximum depth ratio for forced hydraulic jump, Y_s ; depth effect of sill.

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