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A New Roughened Bed Hydraulic Jump Stilling Basin

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Abstract: The main goal of this study is to introduce a new roughened bed hydraulic jump stilling basin. To reach such idea, first a new expression was developed for sequent depth and hydraulic jump length. Then, hydraulic jumps were conducted on a bed of prismatic roughness elements in a rectangular flume in order to investigate the jumps' effects on the characteristics of stilling basins. The roughed elements are glued on the bed of the flume downstream of ogee spillways in such a way that the incoming water jet is just above the element surface. Each rough element shape was tested under different Froude numbers, ranging 4.5 to 12. During each test, the water surface profile, the roller length and the jump length were measured and the longitudes and vertical flow velocity were also measured in some tests. Applying experimental results, the shear force coefficient was found. The results indicate that the presence of a rough element can increase the shear force and, consequently, reduce the jump length and sequent depth of flow. Comparison of the results with previous studies shows that using the new roughened bed, the length of the basin can be decrease as low as 40% of the regular basins.

Key words: Stilling basins, hydraulic jump, roughened bed, jump length, sequent depth

INTRODUCTION

Hydraulic jump stilling basins are type of irrigation structures which are constructed downstream of chutes, gates and spillways to dissipate excess kinetic energy. The dimensions of such structure depend on the jump length and the sequent depth of the jump. During the past decades attempt have been made to reduce the size of this structures by forcing the jump to occur using the blocks and end sills within the basin. Peterka (1978) classified the hydraulic jump into five categories based on the upstream Froude numbers. He conducted extensive experimental tests and introduce four types of hydraulic jump stilling basins. Type I, is a classical hydraulic jump type stilling basin (Fig. 1). The

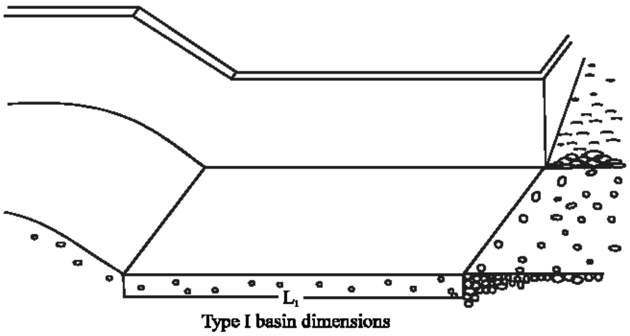

Fig. 1: USBR type I stilling basin

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basin cross section is rectangular of horizontal smooth bed. The length of such basin is equal to $6y_2$ and the required tailwater depth for best occurrence of the jump within the basin should be 1.1 y_2. Where y_2 is the subcritical flow depth. This type of basin is suitable for low Froude numbers. When the Froude number is greater than 4.5, the stilling basin of Type II or Type III is recommended. In Type II, Fig. 2, a series of chute blocks has been considered at the upstream of the basin to guaranty the start of the jump and to separated the incoming jet into several jets and at the end a continuous or dentate sills have been designed to force the jump to occur within the jump and not to move downstream of the basin. Length of Type II basin is less than the Type I and approximately is equal to 4.5 y_2 and the required tailwater depth is y_2. In Type III stilling basin, Fig. 3, baffle blocks also have

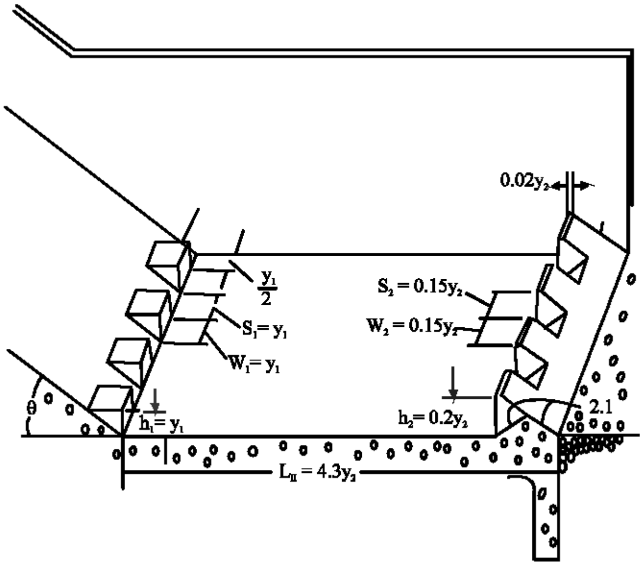

Fig. 2: USBR type II stilling basin

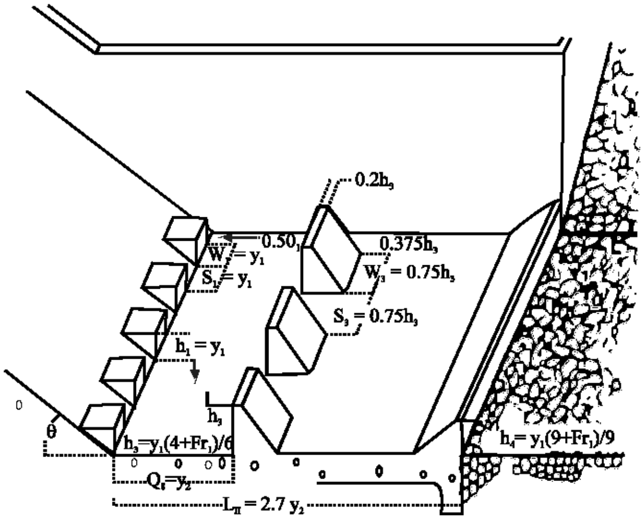

Fig. 3: USBR type III stilling basin

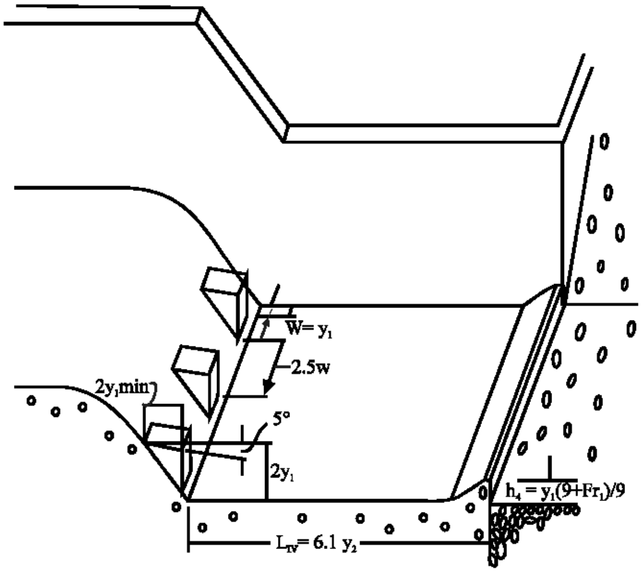

Fig. 4: USBR type IV stilling basin

been added for dispreading the incoming jet and mixing the jets into the water body of the basin. This will create more turbulence and dissipate more kinetic energy results a shorter basin up to 60% compare to the Type I. Since, baffle block within the basin can protrude into the flow which may cause cavitations problems and damaged the basin, Type III must not considered for the places where the incoming flow jet velocity is more than 16 m sec^{-1}. The Type IV stilling basin (Fig. 4) developed by Peterka (1978), for the incoming Froude number ranged 2.5 to 4.5. In type IV, the chute blocks and continues end sill have been considered. The length and sequent depth of this basin are the same as Type I stilling basin. Similar to Type III, chute blocks, baffle blocks and end sill have been considered in SAF basin. The length and the required tailwater depth of flow in SAF basin is less than Type II basin. Figure 5 shows the SAF basin. In earlier study, it is also developed a stilling basin for low Froude number(less than 4.5) using chute blocks, wedged-shaped baffle pier and end sill (Fig. 6). This basin has the same length as SAF basin. But the required tailwater depth is smaller than SAF basin. In an attempt to develop economic stilling basin structures, Hughes and Flack (1984) also carried out experimental tests on hydraulic jumps over a bed of block elements and found that, the boundary layers would develop faster and the jump dimensions would decrease considerably. Mohamad Ali (1991) performed a series of experiments on a rough bed using cubed block elements and found that the hydraulic jump length is reduced ranges from 27.4 to about 67.4% for F_1 ranging from 4 to 10. Alhamid (1994) conducted experiments on a horizontal rectangular channel bed using rough wooden blocks over a fixed length with different densities. Ead *et al.* (2000) performed tests on turbulent open channel flow in a circular corrugated culvert and found that the intense mixing induced by the rough bed produced significant Reynolds shear stresses and significant reduction in the velocity field above the corrugation. Ead and Rajaratnam (2002) performed an experimental study on hydraulic jump over a round corrugated bed. Their results indicated that the integrated bed's shear stress on the corrugated bed was about ten times that on smooth beds. Carolo *et al.* (2007) proposed an expression for the integrated bed's shear stress force of a jump over a rough bed. They applied the experimental data of Hughes and Flack (1984) for block roughness height ranging from 0.32-1.04 cm and developed relationship for shear force coefficient as function of h_R/y_1 where h_R is the height of rough element.

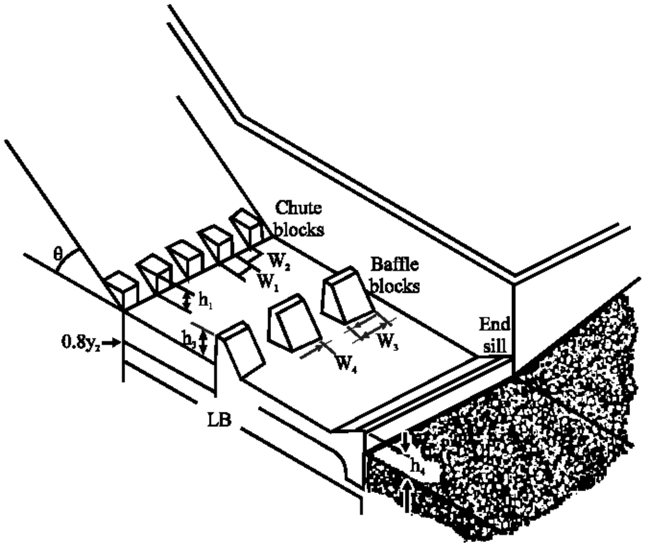

Fig. 5: SAF stilling basin

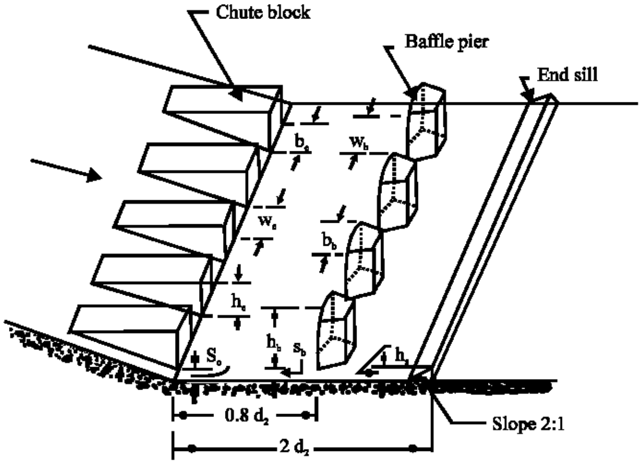

Fig. 6: Pillari's stilling basin

Izadjoo and Shafai-Bejestan (2007) conducted hydraulic jump tests on a bed of trapezoidal-shaped corrugated roughness. Their results indicated that the integrated shear force in rough bed is ten times that in smooth bed. Recently Carolo *et al.* (2007) performed extensive tests on jump over a natural roughened bed. Different natural gravels and cobbles of median size ranging from 0.46 to 3.2 cm under different Froude numbers ranging from 4-12 were tested. Their results proved that in roughened bed the hydraulic jump and the sequent depth ratio is less than in smooth bed and the reduction depends on both relative roughness ratio (h_R/y_1) and Froude number. A new solution of sequent depth ratio of hydraulic jump on smooth and rough bed have been presented by Carolo *et al.* (2009) by introducing a coefficient of shear force in the momentum equation.

Earlier studies have shown that the length and the sequent depth of a jump over rough boundaries are significantly shorter than those of the classical jump. However, the main concern with a jump on a roughened bed is that the rough element can cause separation of flow and might be subject to cavitations, which can damage the stilling basin slab. However, the study of Ead *et al*. (2000), Ead and Rajaratnam (2002) and Izadjoo and Shafai-Bejestan (2007) indicated that, if the rough element is placed on the bed as the jump occurs above the rough element-in other words, if the crest of the rough element is just below the lower level of the incoming jet-the elements would not protrude into the flow and will not cause any cavitations. Therefore, it is the purpose of this study to investigate the effects of different shapes of artificially rough elements on the sequent depth of hydraulic jumps.

MATERIAL AND METHODS

Dimensional Analysis

The sequent depth (y_{2R}) and length of jump (L_{jR}) over roughened bed depends on the upstream flow conditions such as flow depth (y_1) and flow velocity (v_1), the fluid characteristics such fluid density (ρ) and fluid viscosity (μ) and the acceleration of gravity (g) which one may write in the follwing form:

$$y_{2R} \quad \text{or} \quad L_{jR} = f(y_1, v_1, g, \rho, \mu) \tag{1}$$

Selecting y_1, g and ρ as three repeated variables, the following dimensionless equation can be developed using the Buckingham's II theorem:

$$\frac{y_{2R}}{y_1} \quad \text{or} \quad \frac{L_{jR}}{y_{2R}} = f(F_1, R_e) \tag{2}$$

where, F_1 and R_e are the Froude number and Reynolds number at the upstream section of the jump, respectively. In this study the Reynolds number during the experimental tests was greater than 13000, therefore the effect of Reynolds number can be assumed to be negligible. Therefore, the final expressions for the sequent depth and the length of the basin can be written as:

$$\frac{y_{2R}}{y_1} \quad \text{or} \quad \frac{L_{jR}}{y_{2R}} = f(F_1) \tag{3}$$

Equation 2 is a general expression for the sequent depth and hydraulic jump length for stilling basin over roughened bed. To determine the coefficients of this relation, experimental tests were conducted which are discussed later.

Experimental Program

To reach the purpose of this study, experimental were carried out using a rectangular laboratory canal at the hydraulic laboratory of Shahid Chamran University (Ahwaz, Iran), during Summer and Fall 2008. The flume was 7.5 m long, 0.35 wide and 0.50 m deep, with plexi-glass sides. An ogee spillway was installed at the upstream end of the flume to produce the hydraulic jump. Figure 7a and b shows a plan view and cross section of the experimental facilities. The roughness elements were glued on the bed of flume downstream of spillway in such a way that the crest of elements was at the same level as the downstream end of spillway. This means that the elements are not act as blocks and are not directly subject to the incoming jet. The rough elements acts as depressions in the bed to create more turbulent eddies which will increase bed shear stress. Lozenge rough element shape tested under different Froude number ranged 4.5-12. Figure 8 shows shape and size of roughness has been studied.

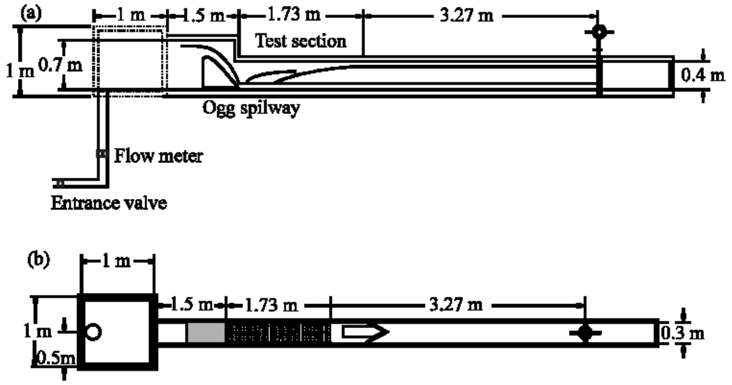

Fig. 7: Experimental flume (a) section view and (b) plan view

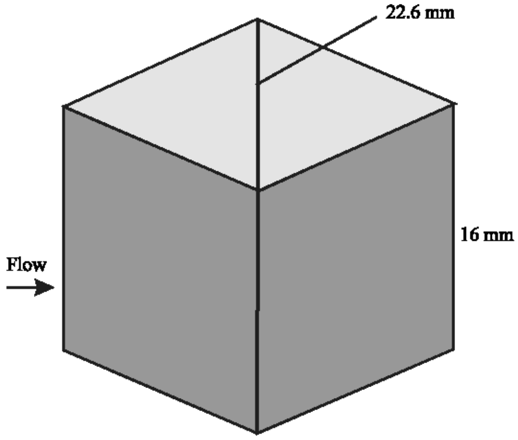

Fig. 8: Lozenge roughness shape tested in this study

The arrangement of rough elements is shown in Fig. 9. Water was supplied by a centrifugal pump from the main hydraulic laboratory reservoir. An electronic flow meter was installed at the pipe after the pump which can measure the flow discharge by 0.01 L sec^{-1} accuracy. At the upstream of the flow a stilling tank was installed which can dissipate the kinetic energy of the incoming flow. A tailgate was used to control the tail water depth in the flume. In all test, the tailgate was adjusted so the jumps were performed at the start of rough element or at the down stream end of the spillway.

The experimental procedure was started by turning on the pump. The water was let to enter the flume by opening the entrance valve very gradually. When the desired discharge was achieved, the tailgate was gradually close till the tail water reached to the desired depth. This situation was kept constant for enough time to take the required data. Usually the water surface profile along the jump, the roller length and the jump length were measured in all tests. Hydraulic length is a horizontal distance from the beginning of the jump to the section beyond which the water surface is horizontal. The roller length is a horizontal distance from the beginning of the jump to the roller end which can be determined by dye plumes or with a float to recognize the stagnation point. Velocity profiles were measured at several vertical sections inside the jump and in the vertical center plane of the flume above the crest of roughness. The Reynolds number in this experimental study ranged 13800-218000.

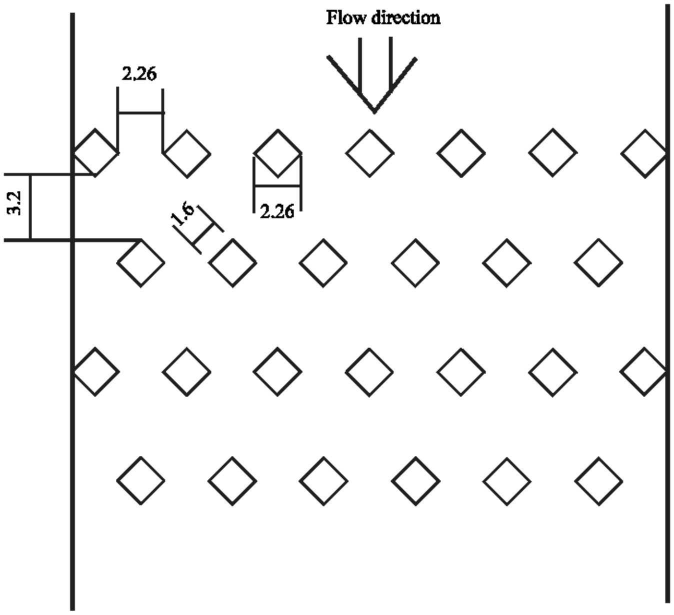

Fig. 9: Arrangement of roughness elements in this study

RESULTS

The required tailwater depth and the hydraulic jump length are the two main variables which must be determined for design of hydraulic jump stilling basin. Using the experimental data, relations for computing these two variables for the new stilling basin are developed which are presented below:

Sequent Depth Ratio

Figure 10 shows variation of sequent depth ratio versus Froude number. The best fitted expression which can be developed by regress ional analysis is as follow:

$$\frac{y_{2R}}{y_1} = 0.8676\,F_1 + 0.9717 \quad R^2 = 0.981 \tag{4}$$

On this figure variation of sequent depth ratio for classical jump, or Blanger's equation, also have been plotted. Using the above equation, the required tailwater depth for proper occurrence of jump in the new stilling basin can be determined.

Jump Length

Figure 11 shows variation of the ratio of hydraulic jump length to sequent depth versus Froude number. The best fitted equation from the experimental results is:

$$\frac{L_{JR}}{y_2} = 6.281\,e^{-0.0735F_1} \quad R^2 = 0.966 \tag{5}$$

On this figure variation of the ratio of hydraulic jump length to sequent depth for the type I stilling basin, also have been plotted.

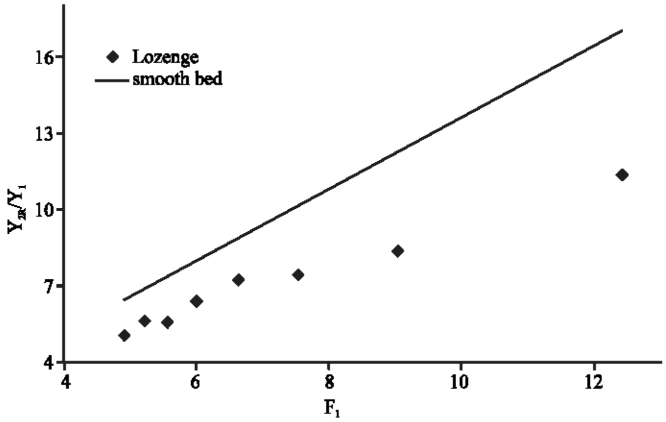

Fig. 10: Sequent depth ratio versus Froude number

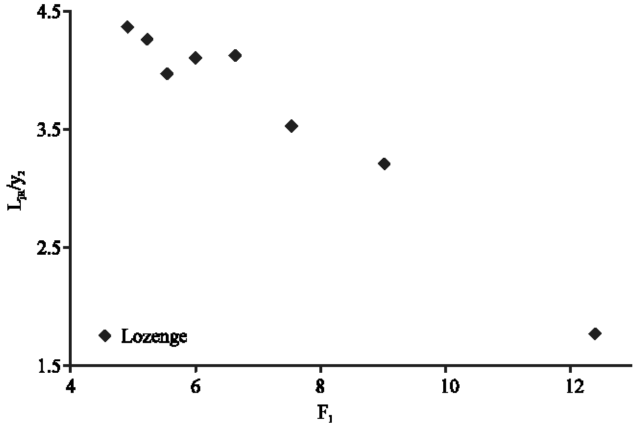

Fig. 11: Stilling basin length versus Froude nember

DISCUSSION

The main goal of this study was to introduce a new stilling basin using rough elements on the bed. The dimensions of the new basin found to be smaller than the existing basins. More discussion on the new founding is presented below.

Sequent Depth Ratio

As it can be seen from Fig. 10, the experimental data are located under the classical jump equation which means that the sequent depth ratio in new stilling basin is always smaller than in classical jump. The amount of reduction depends on the Froude number. To see to what extent such reduction can occur, the magnitude of reduction was computed from the following equation:

$$D_* = \frac{y_2 - y_{2R}}{y_2} \tag{6}$$

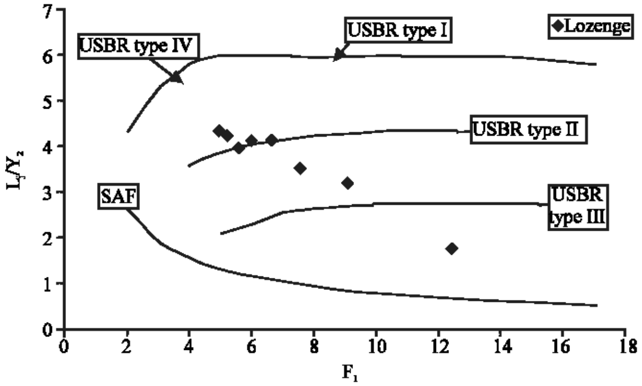

Fig. 12: Length of new stilling basin compare to USBR and SAF stilling basins

where, y_2 and y_{2R} are the subcritical depth of flow for smooth and rough beds, respectively. The average values of D_* was computed and found to be in the order of 0.24. This means that the required tailwater depth for proper hydraulic jump in new stilling basin is as low as $0.76y_{2R}$. Comparison of the results of this study with previous studies shows that: the required tailwater depth for stilling basin type II is $0.83y_2$ (Peterka, 1978) which means that the lozenge shape rough elements which introduced in this study can create more shear force than the blocks on the Type II USBR stilling basin. The D_* -value of 0.24 found in this study is close to the D_* -values obtained by Ead and Rajaratnam (2002) and Izadjoo and Shafai-Bejestan (2007) for corrugated bed. D_*-values found by these researchers were in the order of 0.25 and 0.20, respectively. However the main significant of using rough elements which introduce in this study is that they are not subject to the inflow water jets and therefore the cavitations will not occur.

Hydraulic Jump Length

As it can be seen from Fig. 11, the experimental data are located under the classical jump equation which means that the jump length for jump of new stilling basin is always smaller than in stilling basin type I. The amount of reduction depends on the Froude number. To see to what extent such reduction can occur, the magnitude of reduction was computed from the following equation:

$$L_* = \frac{L_j - L_{jR}}{L_j} \times 100 \tag{7}$$

where, L_j and L_{jR} are the jump length for stilling basin Type I and the new stilling basin, respectively. The average values of L_* was computed and found to be in the order of 40.91%. This means that for hydraulic jump over lozenge shape rough element the hydraulic jump is reduced approximately 41%. To compare the length of the new stilling basin introduced in this study with the length of four types of existing basins such as USBR (Peterka, 1978) and stilling basins, Fig. 12 was plotted. As it can be found from this figure, the new stilling basin length is close to the USBR type II when the Froude number is between 4.5-7. For Froude number more than 7 the stilling basin length will be shorter and will be approximately equal to the length of USBR type III. The main difference of this new basins with the existing basins is that, the cavitations is now longer problem in the new stilling basin, since the rough elements are not subject to the incoming flowing jet.

CONCLUSION

In the present study attempt was made to develop a new hydraulic jump type stilling basin. The basin floor covers with cubic rough element. The experimental tests have proven that the required tailwater depth and the hydraulic jump length of new roughened bed stilling are shorter than other types of basins. The reduction of required tailwater depth is about 26% and the hydraulic jump length is reduced about 41% . The rough element does not protrude into the flow and therefore they will not cause any cavitations. It is suggested that more tests on large scale model should be conducted before any field application.

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