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The Effect of Six-Legged Concrete Elements on Hydraulic Jump Characteristics

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ABSTRACT

In the present study, the six legged concrete (SLC) elements are placed at the bed of a flume downstream of a chute in different layouts, densities and number of longitudinal rows of SLC elements. Each test was run for different flow conditions (Froude numbers ranged 5.3 to 8.1). During each test, the water surface profile, the roller length and the jump length measured. Applying the experimental results, the sequent depth ratio and the dimensionless jump length calculated and compared to obtain the best layouts, the best densities and the minimum number of longitudinal rows of SLC elements. The results indicated that generally, the SLC elements can increase the shear force and consequently, reduce the jump length and the sequent depth of the jump. For the best layout, a linear type obtained when the SLC elements placed with 26% density. For the case of 100% density, the minimum longitudinal rows of SLC elements obtained to be equal to 21, or a basin 32% shorter than the smooth bed basin.

1. Introduction

Hydraulic jump stilling basins are common types of hydraulic structures, which are built in places where the inflow velocity is high enough. These basins usually dissipate excess inflow kinetic energy by creating high turbulence due to developing a hydraulic jump. The rate of energy dissipation due to a hydraulic jump is a function of the inflow Froude number. For Froude number ranged from 4.5 to 9, which usually a stilling basin is required, 45% to 70% of the inflow energy is dissipated (Peterka, 1958, Hager, 1992). Dimensions of these basins depend on the jump characteristics mainly jump length and the sequent depth ratio. Development of an efficient and economic basin with shorter length has attracted many researchers during

past decades. Peterka (1958) summarized the extensive experimental tests conducted at USBR and introduced four different types of hydraulic jump stilling basins. The number of the hydraulic jump basins to be constructed in any of the irrigation and drainage projects is high and they are too expensive, especially in developing countries. Therefore, effort to introduce an efficient and economic basin has attracted many researchers in the past decades. The main purpose has been a shorter basin length that requires a lower sequent depth and has no thread of cavitation damages. Among these investigators are Hughes and Flack (1984) who carried out experimental tests on the hydraulic jumps over a bed of block elements. El-Azizi (1985) studied the effect

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of different intensities of bed roughness on submerged hydraulic jump. Mohammad Ali (1991) performed a series of experiments on a rough bed using cubed block elements and found that the hydraulic jump length reduced from 27.4% to about 67.4%. Negm et al. (1993) studied the hexagonal and cylindrical types of roughness in different intensities and found that 13% and 16% roughness intensities provide the minimum jump length. Alhamid (1994) condu-cted experiments on a rough bed using cubic blocksa nd Ead and Rajaratnam (2002) studied hydraulic jumps over a round shape corrugated bed and found the jump length can decrease as much as 50%. 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 the smooth bed. Carollo et al. (2007) measured the hydraulic jump characteristics on a bed roughened by closely packed crushed gravel particles cemented to the bottom. Pagliara et al. (2008) studied the parameters that affect the sequent depth and the length of the hydraulic jump over the homogenous and non-homogenous rough bed channels downstream of block ramps. Shafai Bejestan and Neisi (2009) studied the effect of lozenge roughness shape on the hydraulic jump. They found that this shape reduces the tailwater depth and the hydraulic jump length by 24% and 40%, respectively compared with the smooth bed. Ezizah et al. (2012) carried out experimental tests using U-shaped rough elements and founded better results than cubic elements. Tokyay and Simsek (2011) performed tests to determine the effects of corrugations and prismatic roughness elements and found that these elements significantly reduced the jump length and jump sequent depth Abdelhaleem et al. (2012) applied three different shapes of corrugated beds and

found that the triangular shape of the corrugation has highly decreased the required tail water depth. The effect of corrugate beds on characteristics of submerged jump have been extensively investigated by Ali Ahmed et al. (2014). Abbaspour et al. (2009), Ezizah et al. (2012) and Zhilin and Ashraf (2012) also are among the researchers who studied the effect of sinusoidal corrugate, different shape of corrugates and prismatic elements on jump characteristics, respectively.

In the present study, the precast concrete six legged concrete (SLC) element on the floor of a basin was studied. Each SLC element consisted of two concrete T-shaped pieces join-ed perpendicularly in the middle; forming six legs (Fig. 1).
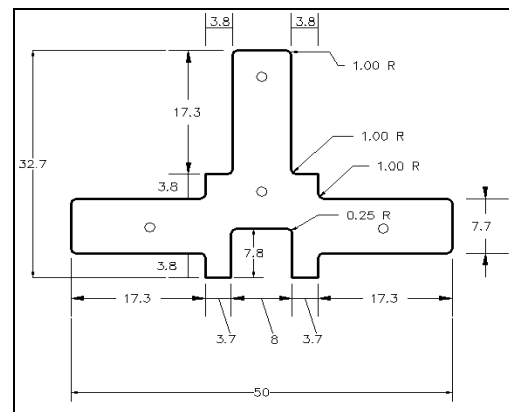
a) One piece of T shape(measures in mm)

b) precast SLC elements

Fig. 1. SLC elements used in this study

These elements have been used in many irrigation, river and coastal engineering applications (Anonymous, 2016). The primary mechanism of SLC elements for the hydraulic jump basin is to increase the bed roughness as well as to disperse the incoming compact flow jet; dissipates more kinetic energy within the basin of lower tailwater depth and shorten the length. The SLC elements can be assembled and placed in different types of layouts and densities along the protected channel bed so that each element is either anchored with the basin floor or interconnected to each other and placed on the top of the alluvial channel bed. Since the application of SLC elements on the hydraulic jump basins has not been studied, it is therefore the main purpose of this study to experimentally investigate the effect of different types of layouts, densities and the number of longitudinal rows of SLC elements on the hydraulic jump sequent depth and length.

2. Experimental setup

To reach the purpose of this study, extensive experimental tests were carried out using a rectangular laboratory flume at the hydraulic laboratory of Shahid Chamran University of Ahvaz, Iran. The flume was 7.5 m long, 0.30 m wide and 0.40 m deep with plexi-glass sides. The hydraulic jump was developed downstream of a chute. Figure 2 shows a plan view and cross section of the experimental facilities.

Small scale model (1/12 of the original size, Anonymous, 2016) of concreted six-leg elements (Fig. 1) used in the experiment. The precast SLC elements were glued on the bed of the flume downstream of the spillway in such a way that the crest of the elements was at the same level as the downstream end of the spillway. This means that the elements did not act as blocks and were not directly impacted by the incoming jet. The SLC elements acted as depressions in the bed to create more turbulent eddies, which will increase bed shear forces.
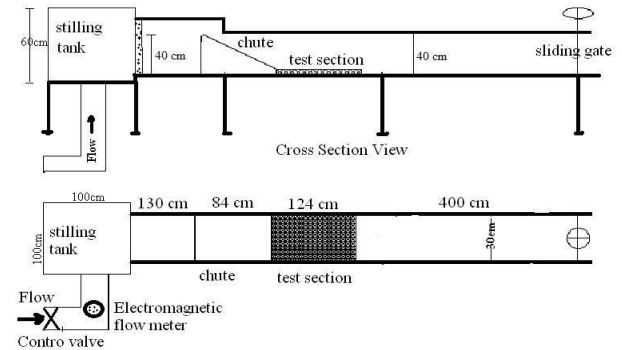

Fig. 2. Experimental facilities

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 with a ±0.01 lit/sec accuracy. At the upstream of the flow, a stilling tank was installed, which could dissipate the kinetic energy of the incoming flow. A tailgate was used to control the tailwater depth in the flume. In all the tests, the tailgate was adjusted so that the jumps were performed in the downstream end of the chute or the start of the basin.

The experimental procedure started by turning on the pump to let water enter the flume by opening the entrance valve very gradually. When achieving the desired discharge, the tailgate gradually closed till the tailwater reached the desired depth. This situation was kept constant for enough time to take the required data. During each test, the water surface profile along the jump, the roller length, and the jump length were measured by a point gage with an accuracy of ±0.1 mm. The data was rechecked by taking high resolution digital photos and processing them by the Engauge Digitizer 4.1 software. Hydraulic length is defined as 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.

Four series of tests were performed in this study. The first series (or base line tests) were carried out on a smooth bed. Total of five tests under five different flow conditions (F_{r1} ranged from 5.3 to 8.1) were conducted. The second series, which consisted of 30 tests, were conducted to study the effect of SLC layout. Six different layouts were tested by applying five different flow conditions (F_{r1} ranged from 5.3 to 8.1) for each layout, as shown in Fig. 3. Total of 20 tests were also performed for the third series of the tests to study the effect of the SLC elements' density on the jump characteristics. Four different densities (100%, 63%, 36% and 27%) were tested each under five different flow conditions, as shown in Fig. 4.
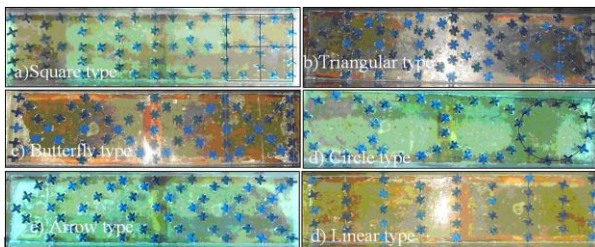

Fig. 3. Different tested layouts

a) 26% density
b) 36% density
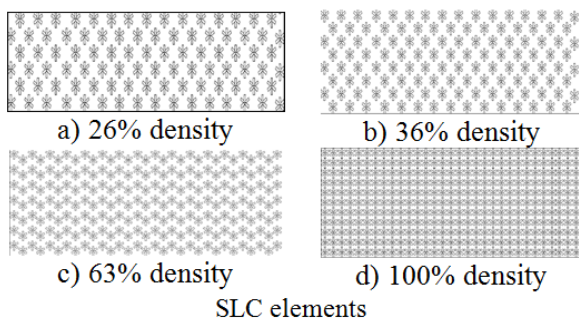c) 63% density
d) 100% density
SLC elements

Fig. 4. Different tested densities

Density was defined as the number of elements on each row. For a 100% density, the total number of elements was 11 elements in each row. The longitudinal distance in which the bed was covered with SLC elements in 2nd and 3rd series of the tests was equal to 1.24 m (or 31 longitudinal rows of SLC elements, when placed with 100% density). This length obtained as the longest basin length for smooth bed (equal to *6Y₂*). In the fourth series of the tests, a total number of 14 experiments were performed to study the effect of length of bed covered with the elements. The SLC elements placed with 100% density and 7 different longitudinal rows (24, 16, 10, 8, 7, 5 and 3 SLC elements row). Each case run for two different Froude numbers.

3. Results

3.1 Effect of SLC layout on the sequent depth ratio

Figure 5 shows variation of the sequent depth ratio versus Froude number for six different SLC layouts. In addition, variations of the sequent depth ratio for classical jump, calculated using Blanger's equation, is also plotted.
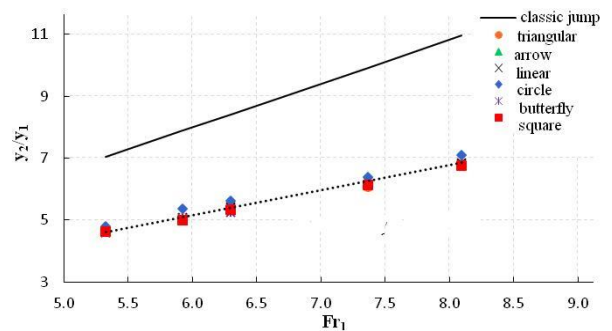

Fig. 5. y_2/y_1 versus F_r for different layouts of the SLC elements

As can be seen, the ratio of y_2/y_1 for the SLC layouts was less than the ratio of y_2/y_1 for the classical jump. The percent of reduction of y_2/y_1 ratio for each test can be calculated from the following equation:

$$D_* = \frac{y_2 - y_{2R}}{y_2} \times 100 \qquad (1)$$

where y_2 and y_{2R} are the subcritical depths of the flow for the smooth and rough beds, respectively. These values are presented in Table 1. The average values of D_* were also computed for any type of SLC layout and found to be in the range of 33%-39% with an average of 36% for all the SLC layouts. This means that for a hydraulic jump over the SLC element, regardless of the type of their layout, the required tailwater depth is as low as $0.64y_2$. Previous studies have shown that the required tailwater depth for stilling basin type II is $0.83y_2$ (Peterka, 1958), for lozenge shape rough elements is $0.74y_2$ (Shafai Bejestan and Neisi, 2009), for corrugated stilling basin bed is $0.75y_2$ (Ead and Rajaratnam, 2002) and $0.8y_2$ (Izadjoo and Shafai Bejestan, 1994). The aforementioned results revealed that the hydraulic jump sequent depth for the basin covered with SLC elements is much less than other types of rough elements. The possible explanation is that the SLC elements are permeable elements and are attached to the bed by their legs, which allows jet dispersion. A portion of the incoming jet penetrates the underneath of the elements and spouts upward from the pores between the elements creating more turbulence so that more kinetic energy is dissipated. The percent reduction of the energy dissipated by the jump over the SLC elements (G) is calculated as follows:

$$G = \frac{E_L - E_{L2}}{E_L} \times 100 \qquad (2)$$

where E_L and E_{L2} are the energy loss over the smooth bed and the SLC element,

respectively. The calculated G was in the range of 16% to 26% for different Froude numbers and did not vary as the SLC layouts changed.

3.2. Effect of the SLC layout on the jump length

The measured dimensionless jump lengths (Lj/y_2) for all the tests were calculated for all types of the SLC layouts. The results showed that usually the jump lengths over the SLC elements were lower than the jump over the smooth bed and the type of the SLC element layout has no effect on the jump length. It was found that the average value for the $Lj/y2$ was equal to 4.47 for all tested layouts. The results showed an average reduction of 26% in the jump length compared to the jump length over the smooth bed. The average jump length reduction by Mohammad Ali (1991) was reported to be in the order of 38.8%.

3.3. Effect of the SLC density on the sequent depth and jump length

The aforementioned results on different types of the SLC layout showed that it has no significant effect on the jump characteristics, therefore the linear layout, which is a simple layout for the construction, was selected to test under different densities. In these tests, the SLC elements were placed in consecutive lines whle in the linear layout discussed earlier, the SLC elements were placed in every other line. Density here was defined as the number of elements per row. Five different densities, as discussed previously, were tested each under five different Froude numbers. Figures 6 and 7 show the dimensionless sequent depth and jump length versus Froude number for different Froude numbers, respectively. The values of y_2/y_1 and Lj/y_2 for the smooth bed computed using

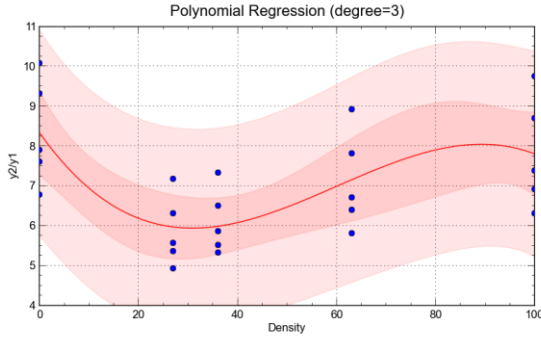Blanger equation are also shown in this figure as zero densities.

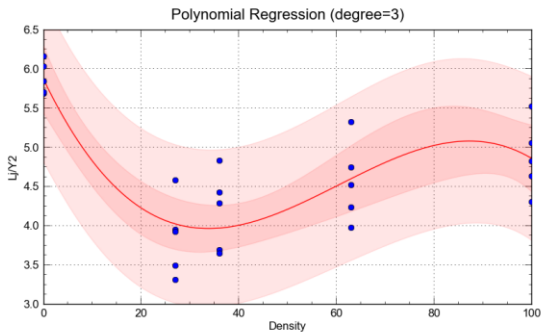Fig. 6. y_2/y_1 versus F_r for different densities

Fig. 7. Lj/y_2 versus F_r for different densities

An average third order polynomial fitted to the experimental data showed that as densities decrease from 100%, the sequent depth ratio and the jump length decreased and reached to a minimum value at about 26% densities. The study of Negm et al. (1993) on the jump over the hexagonal and cylindrical types of roughness showed that 13% and 16% roughness densities provide the minimum jump length. The difference between our results and the aforementioned study is because of the different size and shape of the elements used in these studies. For the density of 26%, the ratio of y_2/y_1 varies from 5 (Fr=5.3) to 7.2 (Fr=8.1), showing reduction of 24% (Fr=5.3) to 31% (Fr=8.1) with an average of 27% compared to the jump over the smooth bed. This was lower than what obtained from the tests with linear layouts, which were in the order of 36%. The jump

length also is reduced where the densities decreased. To see the amount of reduction in the jump length due to different SLC densities, the percent reduction was computed from the following equation:

$$L_* = \frac{L_j - L_{jR}}{L_j} \times 100 \qquad (3)$$

where L_j and L_{jR} are the jump length for the smooth stilling basin and the SLC stilling basin. By a close look at Fig. 7, it is clear that for the minimum densities of 26%, the ratio of Lj/y_2 decreased from 4.6 (for Fr=8.1) to 3.6 (for Fr=5.3). Comparison of these results with the same values for the smooth bed (zero densities) showed that the ratio of Lj/y_2 reduced from 27% (Fr=8.1) to 42% (Fr=5.3) with an average reduction of 35%. This was higher than what was obtained from tests with linear layouts, which were obtained to be in the order of 26%. In the later tests, the SLC elements were installed in successive rows, while the SLC elements were placed with an empty row between them in the former tests (linear layout). These results revealed that the rough elements should be placed with some longitude distance between each row to get better performance for the sequent depth, while for the best performance of the jump length it was better for the SLC elements to be placed in successive rows.

## 3.4. Effect of the length of bed covered with the SLC elements

As it discussed earlier, tests also were performed to study the effect of the number of SLC element longitudinal rows on the jump characteristics. Eight different number of rows (31, 24, 16, 10, 8, 7, 5 and 3 rows) were tested under two different flow conditions. The SLC elements were placed with 100% densities. Figures 8a and 8b display the variations of the sequent depth ratio and

dimensionless jump length versus number of SLC elements longitudinal rows for two different Froude numbers, respectively.

Both figures show concave curves. The curves show a decreasing trend as long as the number of rows decreases from 31 to 21. Then, a rising trend was observed in all curves. Therefore, the best performance can be obtained when the longitudinal number of SLC element rows is selected to be 21 or a basin of 0.84 m long, which indicates that the new basin length is 32% less than a smooth bed basin. This result is in agreement with the results of the third series of data.
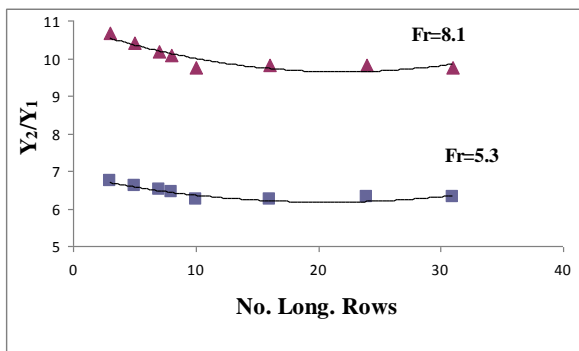
a) Sequent depth ratio
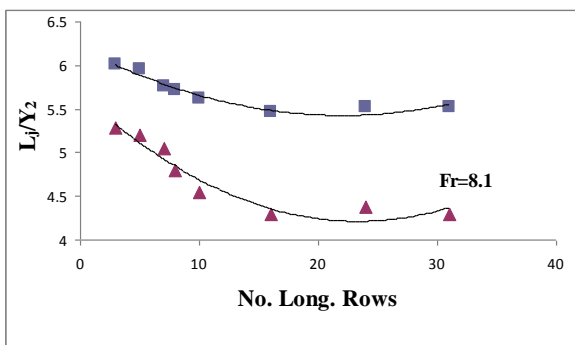
b) Jump length dimensionless

Fig. 8. y_2/y_1 and L_j/y_2 versus number of SLC elements longitudinal rows

4. Conclusions

In the present study, application of the six legged concrete elements on the hydraulic jump sequent depth and the jump length was experimentally investigated for the first time. Total of 50 tests were performed to investigate the best types of layouts, densities and number of longitudinal SLC element rows on the hydraulic jump sequent depth and jump length. The Froude number in the present study ranged from 5.3 to 8.1. The main conclusions from this study are:

The sequent depth ratio and the jump length decreased when the bed covered with SLC elements.

It was found that the type of layouts has no significant effect on the jump performance.

In tests with different layouts, the sequent depth and the jump length decreased by an average of 36% and 26%, respectively.

In tests with different densities, the sequent depth and the jump length decreased by an average of 24% and 35%, respectively.

It was found that if the SLC elements are placed in sequential rows, the reduction of the jump length is higher than when they are placed in alternate rows.

The minimum number of SLC longitude rows to be placed on the basin floor under 100% densities was found to be 21 rows, which makes the basin 32% shorter than the basin with a smooth floor.

One of the key advantages of using SLC elements is that when they are quite interlocked to each other (100% densities), they can act as the basin apron, too. Therefore, the SLC elements can be directly placed on the top of the alluvial beds. In this case, some bed scouring is expected beneath the SLC elements or in downstream of the

basin, which needs further study before field application.

Acknowledgement

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