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ORIGINAL ARTICLE

Analysis location of pressure fluctuation in hydraulic jump over roughened bed with negative step

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ABSTRACT

Hydraulic-jump stilling basins are used to dissipate the high energy contained in water. There are several different types of stilling basin which depending on the geometry of the channel boundaries. A negative step with abrupt drop is one these basins. Roughening of the basin bed also is an effective measure which decreases the characteristics of jump. In this study a stilling basin with a combination of bed roughness and negative step are studied experimentally and the pressure fluctuation through stilling basin was measured. From these data the location of maximum negative and positive pressure fluctuations coefficients were specified and compared with the previous studies which has been reported on classical jump and jump on smooth bed with negative step. The results show that maximum of C_p^- and C_p^+ in smooth bed will occur in near location toward step and C_p^+ is always decreasing more than C_p^- for transforming smooth bed to rough bed.

Key Words: *Stilling Basin, Hydraulic jump, negative step, Roughened Bed, hydrodynamic forces*

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INTRODUCTION

Hydraulic-jump stilling basins are used to dissipate the high energy contained in water passing down the spillway. The energy is removed in part by the generation of large-scale turbulence and the resultant conversion of turbulence to heat. Associated with this process is the generation of large, low-frequency pressure fluctuations. The use of a vertical downwards step to control and stabilize the position of hydraulic jump is well known now. The first research of about such stilling basins has been reported by Moore and Morgan [1]. They classified four types of jump which can occur within the basin as shown in Fig1.

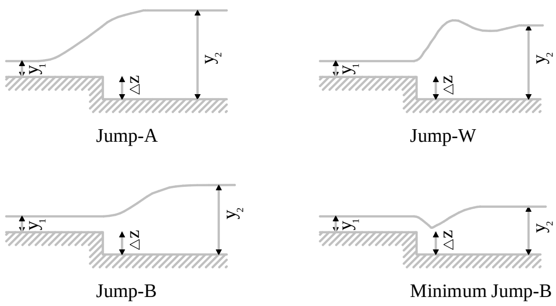


Fig1. Four types of hydraulic in case of stilling basin with negative step (Moore and Morgan 1958)

Moore and Morgan investigated the sequent depth and the flow velocity near the bed through the jump in negative step and showed that the ratio of flow bed velocity to the downstream velocity (v_b/v_2) along the jump, can vary when the incoming flow Froude number and type of jump change. This indicates that the bed fluctuation pressure through the basin can change. Sharp (1974) investigated the characteristics of hydraulic jump on a negative step with rounded drop and comparing it with abrupt drop [2]. He showed that the sequent depth is reduced in round edge drop; the reduction depends on the degree of roundness. For higher Froude number, however the roundness caused to increase the sequent depth. Hager and Kawagoshi (1990) continued the researching on hydraulic jump in negative step. They developed relation for predicting the sequent depth for jump on smooth bed with negative step [3].

For effect of roughness bed on the characteristics of the jump, Rajaratnam (1968) was the very first who showed that the length of the roller (L_r) and the length of the jump (L_j) over roughened bed would be reduced remarkable in compare to the classical jump [4]. Other studies by Gill [5], Hughes and Flack [6], Ead and Rajaratnam [7], Carollo and Ferro [8], Izadjoo and Shafai Bejestan [9] and Pagliara et all [10] proved that the roughness have remarkable effect on reducing the jump characteristics.

The significance role of hydraulic jump bed pressure fluctuations on stilling basin design was studied by many scientists. Vasiliev and Bukreyev (1967) published a paper on the full range of statistical parameters for one jump condition [11]. Toso and Bowers (1988) measured pressure fluctuation on a smooth bed of hydraulic jump and showed that the amount of positive and negative pressure fluctuations (C_p^+ and C_p^-) along the jump at any flow conditions(Froude number), at first shows increasing and then decreasing. These coefficients were introduced for study treatment of hydraulic forces in stilling basins [12]. In hydraulic classic jump Toso and Bowers realized that the location of the peak value of C'p, relative to the toe of the jump, has also varied significantly. Undeveloped flow tends to slightly increase the peak value of C'p for a given Froude number. These results are comparable to those realized by Lopardo and Henning [13] and Abdul Khader and Elango [14]. They also measured pressure fluctuation on classical jump. They showed that the developed inflow causes the peak value of C'p to decrease, an effect that may be due to turbulence breaking up faster in jumps with fully developed turbulent inflow [12]. Also they investigated and plotted the pressure fluctuations characteristics for type 2 and 3 of USBR stilling basins. They found a significant difference because of the presence of blocks in these basins. In their analysis, they introduced a non dimensional index (C'p) in the form of Eq. (1).

$$C'_p = \frac{\sigma_p / \gamma}{v_1^2 / 2g} \qquad (1)$$

In this equation $v_1^2/2g$ = kinetic energy head of the incoming flow and σ_p is the standard deviation of pressures which can be calculated from equation 2.

$$\sigma_P = \frac{1}{N^{0.5}} \left[\sum_{n=1}^{N} \left[p(x,y,n\Delta t) - \bar{P}(x,y) \right]^2 \right]^{0.5} \qquad (2)$$

In Eq 2: $\bar{P}(x,y)$ is the average pressure and $P(x,y,n\Delta t)$ is pressure at any time. N is the number of data which taken in series of the time and Δt is time period between the data recording.

Because P(t) is a random stationary process (e.g., Vasiliev and Bukreyev [11]), it is convenient to use the pressure fluctuation $p'(t) = p(t) - \bar{p}$ relative to the mean pressure value $\bar{p}$. The p'^+_{max} and p'^-_{max} are, respectively, the maximum and minimum measured pressure values. They are related to the C_p^+ and C_p^- coefficients (Toso and Bowers [12]; Fiorotto and Rinaldo [15]) by

$$\frac{\Delta p^+_{max}}{\gamma} = C_p^+ \frac{v_1^2}{2g} \quad \text{and} \quad \frac{\Delta p^-_{max}}{\gamma} = C_p^- \frac{v_1^2}{2g} \qquad (3\ a,b)$$

Fiorotto and Rinaldo (1992b) by compute these coefficients, focused on developing an equation for designing the thickness of the slab (s) [15]. For classical jump they recommended Eq.4

$$s = \Omega\left(\frac{L_1}{y}, \frac{L_1}{I_1}, \frac{L_2}{I_2}\right)\left(Cp^+ + Cp^-\right)\frac{v^2}{2g}\frac{\gamma}{\gamma_c - \gamma} \qquad (4)$$

Areminio et all (2000)'s studies was conducted to measure the pressure fluctuation on a smooth bed of negative step stilling basin [16]. In their research two types of step, rounded and abrupt, and two types of jump, W and B-Jump, were studied. They showed that in negative step the value of C'p, first will be increase and then when it reaches to the highest value, it start to decrease. Also by measuring C_p^+ and C_p^- they showed that the value of these coefficients for B-Jump is higher than the classic jump and therefore they concluded that the stilling basin with negative step requires a thicker slab than a classical smooth type of basin. Hassonizadeh and Shafai-Bajestan (2001) also reported pressure fluctuation on the bed of classical jump [17]. They found that both C_p^+ and C_p^- at any flow conditions along the jump, first will indicate increasing and after reaching the highest point will start to decrease. They showed that fluctuations in center line of jump, as same as the piezometer in left and right lines. Also they found that the highest values of fluctuations will happen at $X/Y_1<15$, that in which X is the distance from the beginning and Y_1 is the incoming flow depth [17].

MATERIALS AND METHODS

In this study, the tests were performed in a rectangular open channel about 80 cm wide, 70 cm deep and 15 m long. The side walls of the flume were made of Plexiglas. Water was pumped from a storage tank to the head tank of the flume by two centrifugal pumps. Cubed elements made of hard plastic (see Fig.2) was installed on the flume bed in such a way that the crests of the cubes were at the same level as the upstream bed. ($h_b=\Delta Z_0$). This roughness was installed in 17 rows. The supercritical flow was produced by a sluice gate. Water entered the flume under this sluice gate with a streamlined lip, thereby producing a uniform supercritical flow depth with a thickness of y_1. The height of step was 4.5 cm and a tailgate was used to control the tail water depth in the flume. In all experiments, the tailgate was adjusted so that the jumps were formed B-jump (see Fig. 1). The discharges were measured by an ultra sound flow meter installed in inlet pipe with DN=300mm. Values of y_1 and V_1 were selected to achieve a range of the Froude number, from 3.03 to 5.86. The Reynolds number $R_1=V_1y_1/\upsilon$ was in the range of 81416-143191. There were 37 copper connections for studying the pressure of the bed with 0.006 m diameter on the bed and through the center. The roughness arrayed 7-6-7 throughout bed and piezometers were installed in center of flume (see fig 3). Because of efficacy the fluctuations in first of jump, distance between the piezometers was lower in first (5 Cm). The pressure fluctuation is measured by pressure transducer DM5010S that designed and manufactured by Motorola Company. transducers worked in the limited +10 to -10 Kpa. Bendat and Piersol (1971) showed that the frequencies of much pressure fluctuations almost 30 Hz [18]. so the frequencies of sampling was chosen 40 Hz.

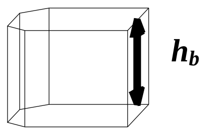


Fig2. 3D shape of Cubed elements

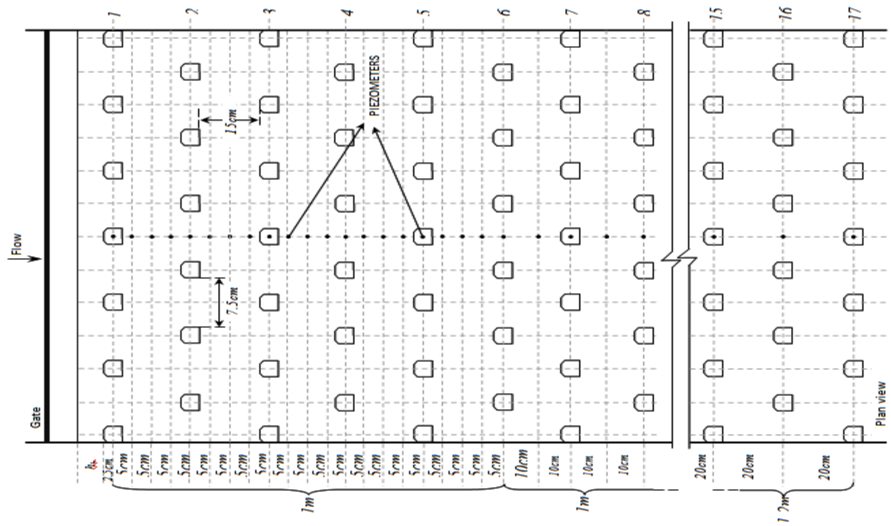


Fig3. Arrangement of roughness and piezometers in bed

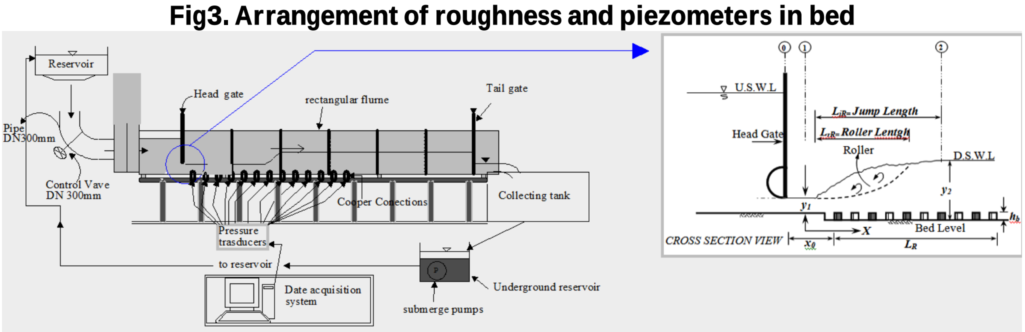
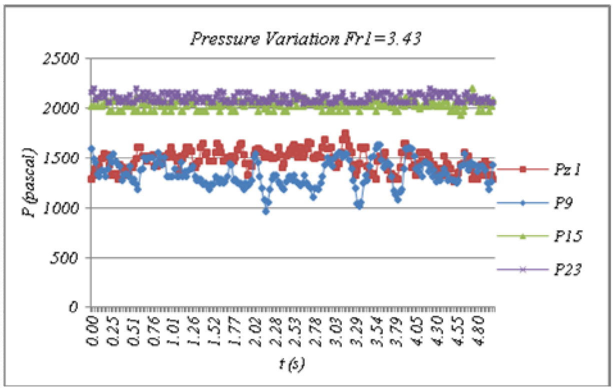


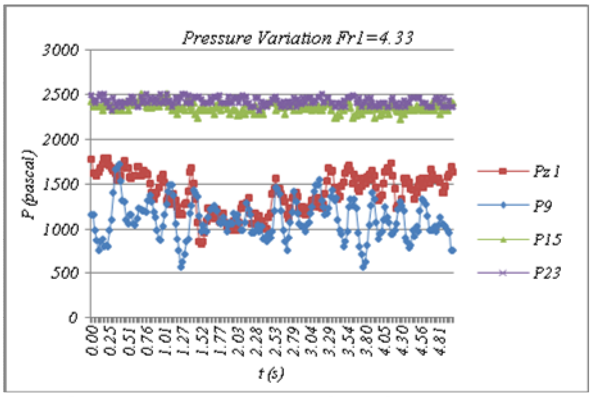
Fig4. Schematic of the experimental setup

RESULTS AND DISCUSSION

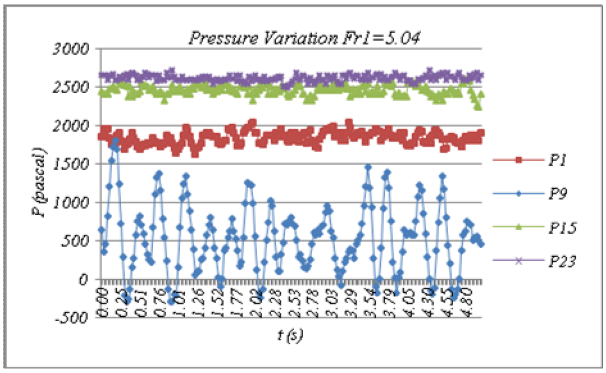
When the data collection was complete, the data sets were retrieved from disk storage and analyzed. In figure 5 variations of pressure ratio versus time for different flow conditions, Froude number ranged from 3.43 to 5.85 has been plotted. It can be seen that the measured pressure by Piezometer #9 is remarkable lower than measured pressure at other locations and it is true for all flow conditions. The difference even increases with increasing the Froude number; for Froude number equal 5.04 and 5.85 the pressure is negative and about -500 pascals. X/Y_1 for piezometer #9 is equal to 10.44. X is distance from first of jump and Y_1 is primary depth. The reason of accomplish this phenomena in location piezometer #9, is affect inlet flow jet to row #3 (see fig 3) and swerve from bed. Fig 6 shows what was happened in experiments.



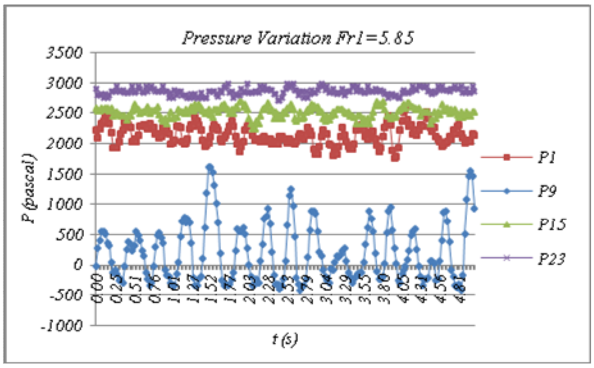
a . Pressure fluctuations in Fr_1=3.43



b . Pressure fluctuations in Fr_1=4.33



c . Pressure fluctuations in Fr_1=5.04



d . Pressure fluctuations in Fr_1=5.85

Fig5. Time dependent pressure fluctuations measurement for negative step of roughened bed at different flow conditions

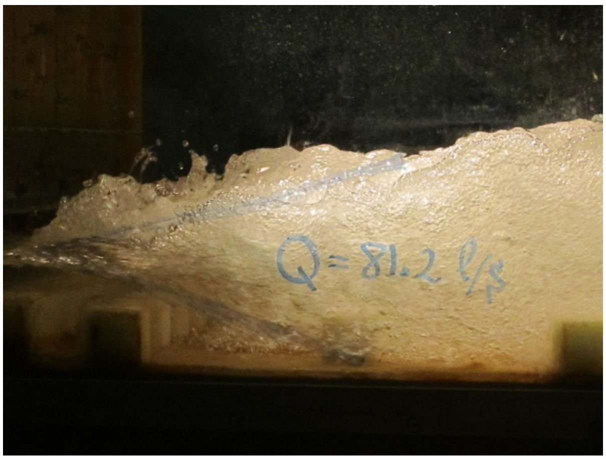
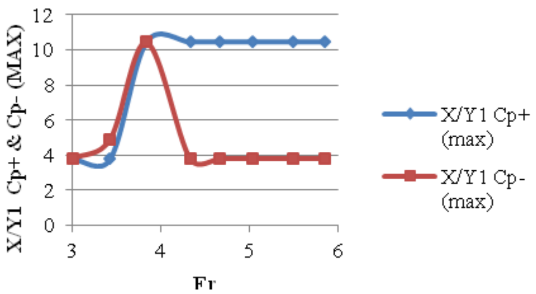
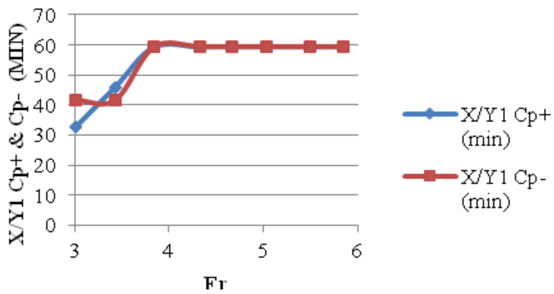


Fig6. Affect inlet flow jet to row #3 and swerve from bed

For investigate the hydrodynamic forces survey the negative and positive fluctuations (C_p^+ and C_p^-). In experiment observed that variance of negative and positive fluctuations at the beginning of the jump is hard, but as it goes further from the beginning and increasing the depth of water, the intensity will be decreased. Particularly of the places $C_p^-{}_{max}$, $C_p^+{}_{max}$, $C_p^-{}_{min}$ and $C_p^+{}_{min}$ through of the jump has been done to draw X/Y_1 in versus Froude number. These cases have been shown in figure 7. These differences are because of increasing flow depth and reducing fluctuations effect.



The location of $C_p^-{}_{max}$ and $C_p^+{}_{max}$



The location of $Cp^-{}_{min}$ and $Cp^+{}_{min}$

Fig7. The location of creation C_p^+ and C_p^- (max and min) with variation of Fr

With attend to figure 7 we can see that $Cp^-{}_{max}$ and $Cp^+{}_{max}$ at first in Fr≤4 at the same location happens. Then these locations are parted. $Cp^+{}_{max}$ in X/Y_1=10.44 and $Cp^-{}_{max}$ in X/Y_1=3.78 will be stabled. Also $Cp^-{}_{min}$ and $Cp^+{}_{min}$ would be the same variance but both of these location for Fr>4 is equal and in X/Y_1=59.33 stabled. Table 1 has been showed the variations of Cp^- and Cp^+ in rough and smooth bed in comparing with data form Armenio and Toscano's (2000) experiments for abrupt drop with smooth bed [16].

Table1. The comparing Cp^- and Cp^+ in rough and smooth bed with negative step

Jump Type	*Author*	*Fr_1*	*x/y_1*	*Cp^-*	*Cp^+*	*Cp^- decrease%*	*Cp^+ decrease%*
		6	*4.92*	*0.702*	*0.891*	*-*	*-*
Abrupt Drop 1	*Armenio&Toscano*	*6*	*6.15*	*0.765*	*0.808*	*-*	*-*
		6	*7.38*	*0.751*	*1.02*	*-*	*-*
		5.85	*4.9*	*0.018*	*0.018*	*97.37*	*98.00*
		5.85	*6.15*	*0.022*	*0.020*	*97.16*	*97.57*
Abrupt Drop 1 with Roughness	*This study*	*5.85*	*7.38*	*0.043*	*0.039*	*94.29*	*96.20*
		5.85	*8.22*	*0.076*	*0.0697*	*-*	*-*
		5.85	*10.44*	*0.083*	*0.0704*	*-*	*-*
		5.85	*13.78*	*0.056*	*0.045*	*-*	*-*

The analysis of the table suggests that:

1- $Cp^-{}_{max}$ and $Cp^+{}_{max}$ in smooth bed will occur in near location toward step.
2- Cp^+ is always decreasing more than Cp^- for transforming smooth bed to rough bed.
3- In every distance from the beginning of the jump, Cp^- and Cp^+ in rough bed is less than smooth bed and this decrease was more than 90%.

For more explain in fig 8 Cp^- and Cp^+ in classic jump (Toso and Bowers [12]) and abrupt drop with rough bed plot. We can see that maximum Cp^- and Cp^+ in classic jump is more distance from toe and happened in X/Y_1=17 and 8.5 respectively. Also we can found that maximum Cp^- and Cp^+ in abrupt drop with rough bed are closer than classic jump to the first of jump.

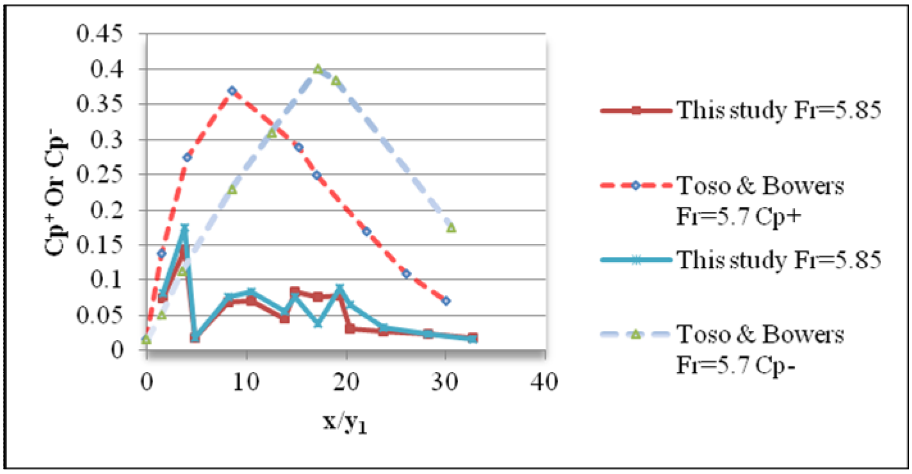


Fig8. Comparing Cp- and Cp+ in classic jump and abrupt drop with rough bed

With analysis of the fig8 we can find:

1- Maximum Cp- and Cp+ in abrupt drop with rough bed is closer than classic jump to the first of jump and both happened in X/Y_1=3.78.
2- Maximum Cp- and Cp+ in classic jump is more distance from toe and happened in X/Y_1=17 and 8.5 respectively.
3- The amount of Cp- and Cp+ in abrupt drop with rough bed is steady in $X/Y_1 \geq 28$.
4- The amount of Cp- and Cp+ in abrupt drop with rough bed is less than classic jump. Maximum Cp- and Cp+ in abrupt drop with rough bed is 0.17 and 0.14 respectively and in classic jump is 0.40 and 0.37 respectively.
5- Maximum Cp- is bigger than Cp+ in both type of jump.

For comparison of pressure fluctuation (C'p) of this study with other type of basins, data of Toso and Bowers (1988) for smooth bed in horizontal basin [12] and Armenio and Toscano (2000) for smooth bed with negative step [16] were plotted on Fig. (9). The C'p value for smooth bed with negative step shows an increase at first and after reached to about 0.128 it started to decrease. The maximum C'p value at this type of basin occurs at location of $8Y_1$ from the beginning of the basin compare to $10.44Y_1$ at roughened bed negative step.

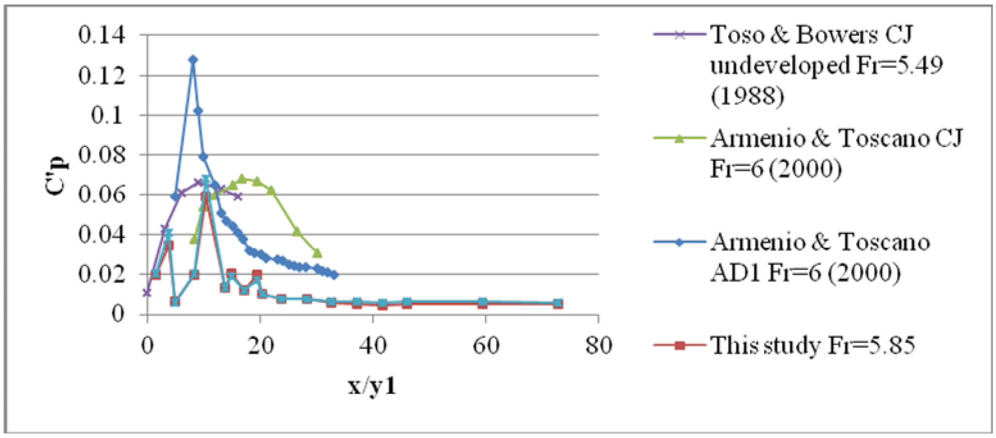


Fig9. Comparing C'p in this study with the same done

In consideration of the fig9 we can find:

1- Maximum C'p value in negative step with smooth bed is bigger than the other type (C'p =0.128) and it's happened nearly to the toe at X/Y_1=8.
2- Maximum C'p value in negative step with rough bed and classic jump is almost equal (C'p ≈0.06), but in negative step with rough bed is smaller and nearly to the toe at X/Y_1=10.44.
3- In negative step with rough bed fluctuations is dissipate in lower distance from first of jump.

4- The above results show that the roughness elements on the bed of basin can reduce the C'p value in which can reduce the possibility of basin bed cavitations.

As it can see, the C'p value along the roughened bed with negative step basin varies sinusoidal form especially at the first of the basin. One explanation for such occurrences is the development of vertical vortices between the roughness rows which is form similar to tornado as seen in Fig. (10). these vortices can reduce the kinetic energy of flow and reduce the pressure fluctuation or the C'p value.

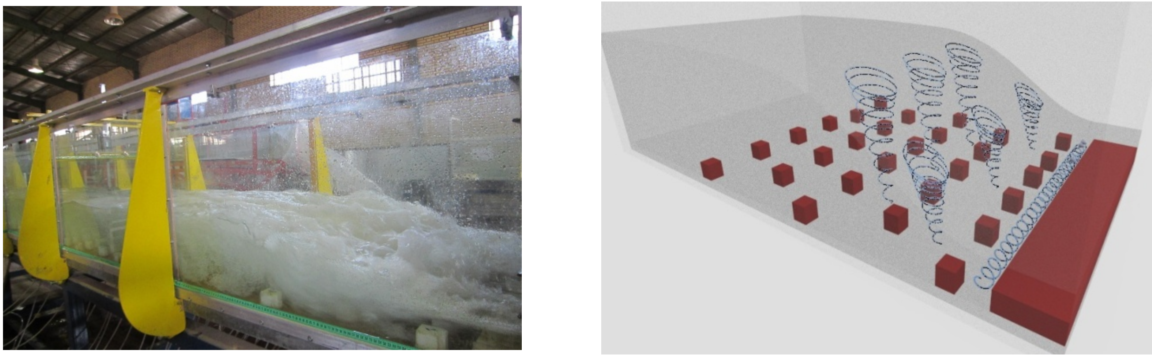


Fig10. The conditions of horizontal and vertical vortexes in flume

CONCLUSIONS

In this paper the pressure fluctuations beneath a hydraulic jump that develops over a negative step with rough bed have been investigated. The effect of roughness on hydraulic jump with negative step is obvious and these influences are decreasing energy in jump and hydrodynamic forces on bed. In the whole expressed maters in pre-section it can be counted as below:

1- The most critical region of jump in case of cavitations for negative step with rough bed is in $X/Y_1 \approx 10.44$.
2- Increasing of Froude number makes amount of pressure coefficients (C'p, C^+_P and C^-_P) grater.
3- C'p in negative step with rough bed is less than smooth bed. This phenomena is because of vertical vortex in behind of roughness.
4- Maximum C'p value in negative step with rough bed and classic jump is almost equal (C'p ≈ 0.06), but in negative step with rough bed is smaller and nearly to the toe at X/Y_1=10.44.
5- The pressure fluctuations with increasing X from step in rough bed, at first increase and when it reaches the highest point, comes down. These changes because of increasing depth of water and therefore decreasing effect of secondary flow happen.
6- Maximum Cp^- and Cp^+ in abrupt drop with rough bed is closer than classic jump to the first of jump and both happened in X/Y_1=3.78.
7- The location of Cp^-_{max} and Cp^+_{max} in negative step with rough bed, for Fr≤4 in the same location and after that, for Fr>4 these locations be parted. Cp^+_{max} in X/Y_1=10.44 and Cp^-_{max} in X/Y_1=3.78 will be stabled.

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