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Research Article

EFFECT OF SHALLOW DEPTH OF PLUNGE POOL ON DYNAMIC PRESSURE DUE TO IMPACT OF WATER JET, USING FLOW 3D NUMERICAL MODELING (CASE STUDY: BALAROOD DAM)

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ABSTRACT

In investigating goblet-shaped projectiles in dams, forces that their exiting jet flow exerts in the impact site with the downstream bed, because scouring or failure of bottom concrete slab, This phenomenon compared to other structures, requires more investigations and studies. Determining dynamic pressure properties in the impact site in various conditions, allows us that in case of occurrence of such conditions in the performing structures, determine the probability of occurrence of scouring and its accurate level, and also we can accurately determine the probability of creation of crack in the downstream bottom slab, or the phase related to separation of particles from the bed, which are of high importance in designing plunge pool. In this study (Balarood dam), by providing conditions of measuring dynamic pressures on the bottom due to impact of the exiting jet from the goblet-shaped projectile, we have attempted to extract some data in various conditions of impact in terms of exit jet discharge and the shallow depth. The obtained results indicate that the downstream plunge pool, would be effective time goblet-shaped projectiles in which the ratio of pool's water depth to thickness of the colliding jet (Y/Bj) is bigger than 3.

***Keywords:** Goblet-Shaped Projectiles, Shallow Depth, Dynamic Pressures, Plunge Pool*

INTRODUCTION

Water structures by causing changes in water uniform flow regime, cause energy imbalance between upstream and downstream of structures. In some cases, in order to retrieve this balance in the system, a portion of energy needs to be dissipated. Various issues considered in the energy dissipaters program, have caused that an economic, certain, and compatible design with the existing conditions would be regarded. One of the usual and effective methods for dissipating extra energy in dams with high heights is to use free falling jets and impact of them with pools located at the tow of the dam.Energy waste extent is not noticeable in the eruptive flow and free projective jet, and according to Horony it is about 12%, and the main portion of water jet energy dissipates in impactwith the water surface of the pool, penetrating into it and dispersing in it (Annandale, 1995).

In downstream of cascade-eruptive flows such as sky jump overflows, goblet-shaped projectiles, and free falling jets, it is necessary to use plunge pool for dissipating the extra energy of flows. Design principle of the plunge pool is based on free fall of jet flow into it. The most important factor in designing such plunge pools is fluctuation of dynamic pressure on the floor and walls of the pool and forces due to impact of water jet. Also in natural plunge pools, on the river bed, the important factor is erosion (Safarkhani, 2007).

Applying goblet-shaped projectiles in dams, because of forces caused by their exiting flow which exert in the contact point to the bed level of the downstream and causes scouring, compared to other structures, need more investigations and studies. This type of structure can be used in places that the bed level has enough resistance. Often in the downstream of this structure, in order to prevent from direct impact of the exiting jet with river bed, plunge pools are applied. Application of plunge pools basically depends on the quality of regions that flow jet impacts on.

Generally, there are two types of plunge pool structures based on the geometry of exiting jet from the dam overflow. A. Circular jets (e.g. Moro Point in the United States), B. rectangular jets (e.g. Lium in Spain and Cristal dam in the United States). Entrance of jet into the pool, causes dissipation of a noticeable part of water jet energy due to factors such as powdering of water flow in the air, air friction, air collection of jet in the atmosphere, impact on the pool water level and penetration into it, entrance of the air included by the jet into the water volume and finally colliding with the bed level and creation of turbulence in dispersion of the pool and fluctuations of water surface. These actions are accompanied with intense turbulence of water and intense fluctuation of pressure. Increase of water depth in plunge pools decreases the effect of hydrodynamic jet on the bottom and walls and consequently obviates the necessity of stabilization. However, requiring deeper pool usually requires large investment (Bollaert, 2002).

The conducted studies in the field of erosion level can be summarized into four general models including empirical models, empirical-analytical models, model of final dynamic pressures calculations in the pool's bed level, and the model of calculation of dynamic pressures difference in the pool's bed level. In the model related to calculation of final dynamic pressures, by calculating variable such as maximum positive and negative measure of scouring, mean root square of pressure squares, average of depth pressure, and spectrum value, the ability to distribute fluctuating dynamic pressures will be evaluated. By help of these variables, the maximum load under the block or slab and the minimum loads on them are determined, and consequently the maximum uplift force will be obtainable. This method has been mainly based on comprehensive studies conducted by Ervine *et al.*, (1997).

Accordingly, a design criterion is proposed for slab thickness as equation 1 in which slab thickness (m) is obtained as a function of positive and negative pressures in the slab surface and reduction factor (Ω). Belin and Fioroto proposed reduction factor to be between 0.1 and 0.25, which depends on shape of slab and primary Freud number (F0) of the hydraulic jump (Bollaert and Schleiss, 2003).

$$S = \Omega \cdot (C_P^{+} + C_P^{-}) \cdot \frac{V_j^2}{2g} \cdot \frac{7}{\gamma_S - \gamma} \qquad (1)$$

Where,

C_P^{+}andC_P^{-} are negative and positive factors of dynamic pressure fluctuation, regarding how to calculate them, comprehensive explanations are provided. γ andγ_S are specific weight of water and slab, respectively, and $\frac{V_j^2}{2g}$ is the kinematic energy of jet entering the pool.

Bollaert and Schleiss (2003), by conducting tests on the modeled cracks in 3D cubes, by applying almost real dimensions, investigated transitional pressures in walls and impacts of dynamic pressure fluctuations in these pressures and proposed empirical-analytical relations for maximum dynamic loads on bed level of the plunge pool (Castillo, 2006).

MATERIALS AND METHODS

A. Root Mean Square of Pressure Fluctuations

Dynamic pressure fluctuations are indicated using C'_p coefficient. This coefficient is obtained by dividing root mean square value of pressure fluctuations (H´) on head of kinematic energy $\frac{V_j^2}{2g}$. Equation 2 is proposed by Ervine *et al.*,

$$C'_p = \frac{H'}{\frac{V_j^2}{2g}} \qquad (2)$$

B. Length of Jet Core

Core length depends on jet distribution internal angle (α_{in}), which was measured to be about 4 to 5 degrees for plunged jets and about 8 degrees for very turbulent falling jets.

Core length is in fact determined based on length of stabilization region of the flow in impact of water jet. In impact of water jet, first, in a length of the pool, stabilization process occurs and then the stabilized flow collides with the bed level of the pool. Stabilization region of the flow is a place where the shear stresses created beside the jet, decrease the speed in the walls. By end of stabilization region, the jet would be stable and in this region, no more sign of jet core would be observed. Hence, dynamic pressure which applies on border of water and bed level, might be created by collision of the jet with the "core" $\left(\frac{y}{D_j \text{ or } B_j} < 4 - 6\right)$, according to figure 1, for shallow depth pools, or by impact of shearing layer with intense turbulence as a developed jet $(\frac{y}{D_j \text{ or } B_j} > 4-6)$, for deep pools. Y is water depth, and Dj and Bj are jet diameter and thickness in the collision site, respectively (Ervine *et al.*, 1997).

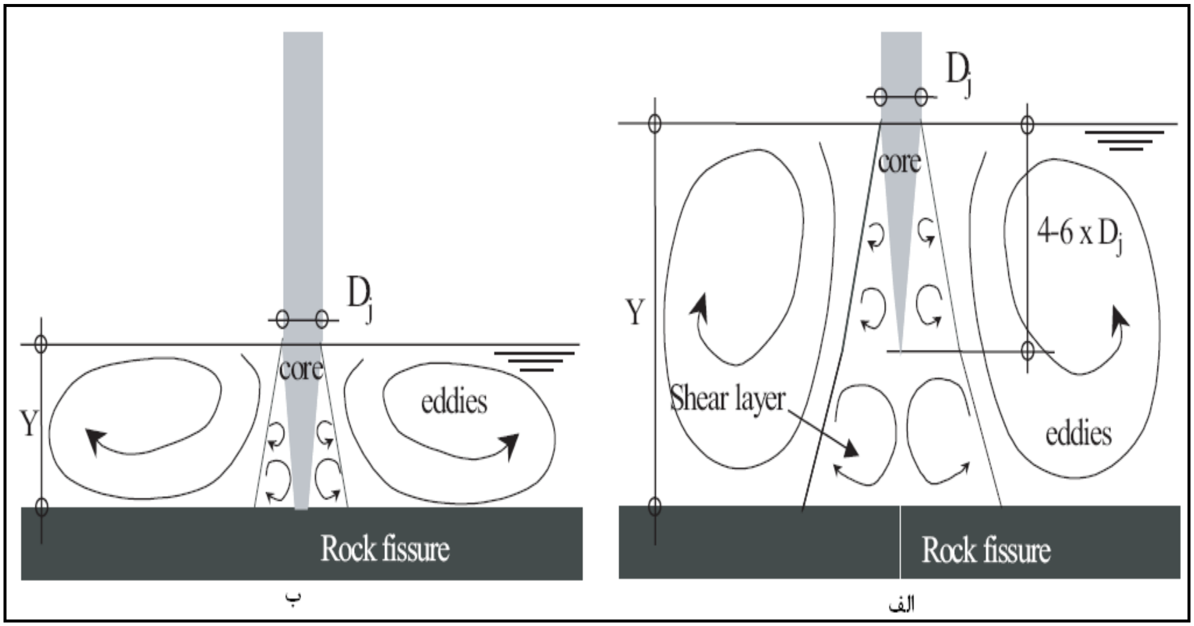

Figure 1: Plunge pool; A. Jet with core $\left(\frac{y}{D_j \text{ or } B_j} < 4-6\right)$, B. Developed jet $(\frac{y}{D_j \text{ or } B_j} > 4-6)$

C. Dynamic Pressures Mean

Mean of dynamic pressures is calculated based on results obtained from studies of Ervine *et al.*, (1997) by dimensionless factor of Cp. This factor is obtained by dividing dynamic pressure head mean value measured in the bed contact point $(H_m - y)$ (m) by kinematic energy of entering head $\frac{V_j^2}{2g}$ (m), in the form of equation 3 (Bollaert and Schleiss, 2003).

$$C_p = \frac{H_m - y}{\frac{V_j^2}{2g}} \qquad (3)$$

D. Maximum and Minimum Pressure Fluctuations

Pressure limit values are often calculated for short-term courses. Toso and Bowers (1988) calculated pressures under the hydraulic jump place and obtained limit pressure values within 24 hours and observed that these limit values are equal to limit values obtained in the 10-minute test. The reason of this phenomenon can be attributed to alternation in turbulence fluctuation of the flow. Pressure limit values were investigated by Bollaert and Schleiss (2003) and the modified equations of the dynamic pressure limit values are proposed in the form of following equations.

$$C_{pa^+} = \frac{H_{max} - H_m}{\varphi \cdot \frac{U_j^2}{2g}} \qquad (5)$$

$$C_{pa^-} = \frac{H_m - H_{min}}{\varphi \cdot \frac{U_j^2}{2g}} \qquad (6)$$

Where,

H_{max} and H_{min} represent maximum and minimum dynamic pressure head (m). Changes of these factors are indicated in figure 2 in terms of changes of water depth to jet diameter $(\frac{Y}{D_j})$. In these figures, results of works of Ervine and his team are proposed for comparison (Bollaert and Schleiss, 2003).

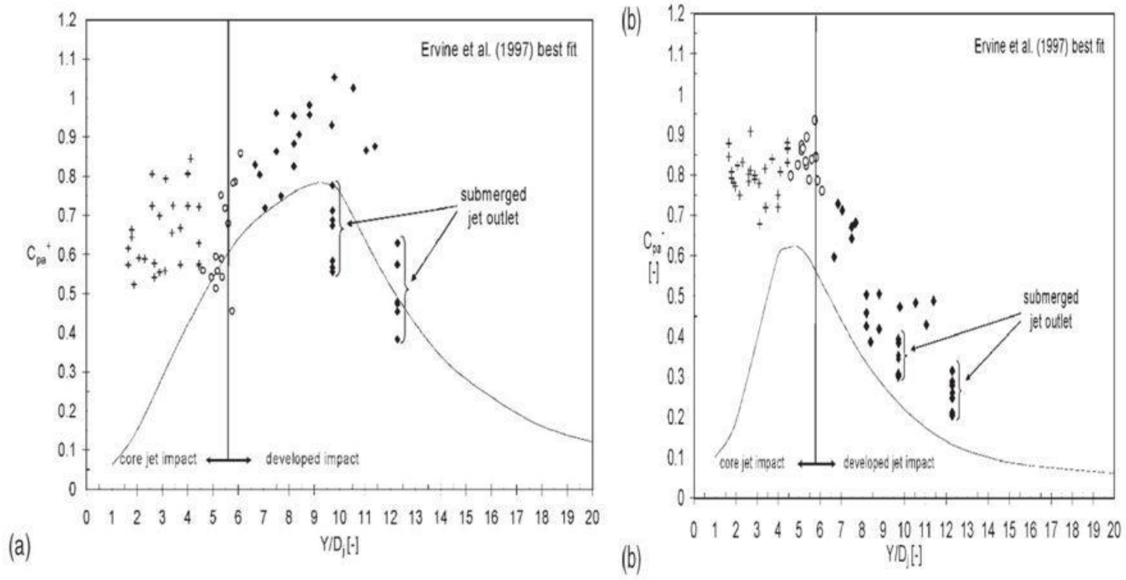

Figure 2: Changes of pressure limit values; a:C_{pa^+}, and b:C_{pa^-}

E. Jet Break Up Length

For jets dropping from high heights, surface disturbances of turbulence may be such big that penetrates into jet core and as a result of that, divide it into separated drops (region C, figure 8-2). This phenomenon is defined under variable of jet break up length (L_b). In other words, after this length, the jet develops completely and the core does not exist and in fact is changed into a series of drops and balls of water. For each drop or ball of water, drop speed is solely decreased due to air resistance and finally it drops with limit speed which depends on the weight of each drop or ball of water. Consequently, such action causes limitation of erosion capacity of completely developed jet (Castillo, 2006).

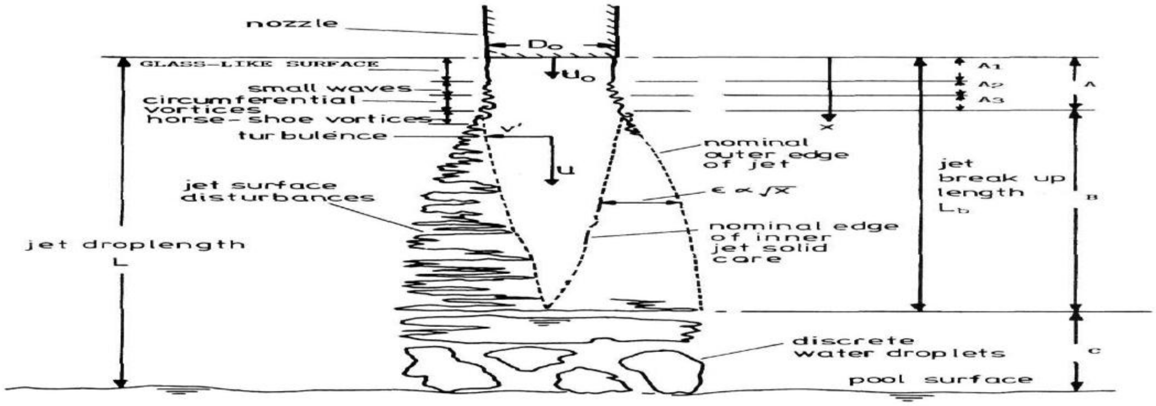

Figure 3: Properties of jet in drop state, and its break up manner

F. Laboratorial Equipment

For designing plunge pool in downstream of the goblet-shaped projectile, a plexiglass square sheet with dimensions of 0.5×0.5 (m) was used. 37 holes with 2 millimeters diameter are considered for connection of piezometer tubes to measure dynamic pressures in the collision place of jet with the plate inside it. In figure 4, the mentioned sheet and array of holes are indicated. The said sheet was installed on a metal system which is able to displace the sheet in vertical axis (to create water depth in the collision site of jet) and also rotation around horizontal axis (to create impact angle of 90 degrees with the sheet). Finally, the fuzzy system inside the jet drop storage which is located under the edge of goblet-shaped projectile is transferred. In figure 4, the general view of metal system is indicated.

In order to measure dynamic pressure, pressure transducers were used. To measure dynamic pressures, transducer sensor is linked to the piezometer, and these sensors, through connecting wires, are linked to converter device and then to the computer system and data process software. Total number of tests applied in this research is 20, in which measurement was conducted for five discharges including 0.32, 0.39, 0.18, 0.25, 0.11, litre per second, and four shallow depths each with a 15 cm increase, to create the collision state of jet with the core and developed state.

Figure 4: Jet collision sheet installed on metal system inside the jet drop storage

RESULTS AND DISCUSSION

As mentioned before, main objectives of this research are to investigate dynamic pressures fluctuations resulted from collision of jets caused by goblet-shaped projectiles in Balarood dam. Also in this research, various parameters and components of jet flow in the air and inside plunge pool were investigated and analyzed. To achieve the mentioned objectives, a numerical model proportionate to the research object was simulated. Various tests were conducted and the results were obtained. In this part, all obtained simulation results are provided. Results obtained in this season are divided into different divisions.

1. Investigating Effect of Jet Break up Length on Mean Factor of Dynamic Pressure

Two factors of jet break up length and (L_b) and air entrance along with jet β_i into the pool are of those factors that cause reduction of mean factor of dynamic pressure (C_p), and fluctuation factor of dynamic pressure (C'_p). In figure 5, diagram related to mean factor of dynamic pressure (C_p) is proposed against ratio of break up length to drop length of jet (L/L_b). As it can be observed in figure 5, by increase of ratio of (L/L_b), values of C_p factor will have a decreasing trend.

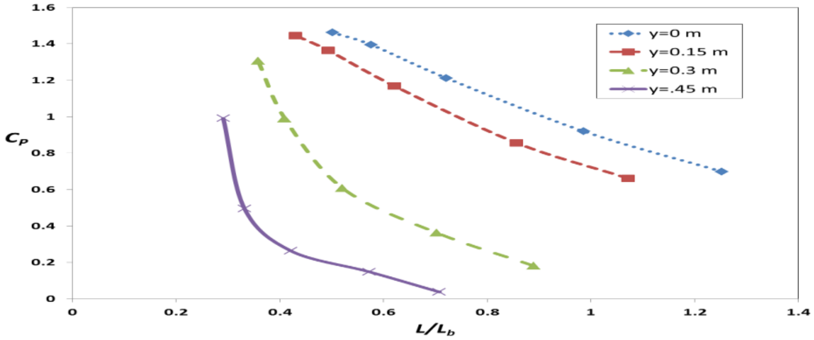

Figure 5: C_p factor changes in terms of change of ratio of (L/L_b)

This descending pattern has almost a linear trend in two cases of without water depth and low water depth, but by increase of water depth, this descending trend takes the form of exponential. When water depth doesn't exist or it is low, breaks up length and air inclusion of jet flow while dropping, and is the only factors that are effective in increase of energy dissipation level of jet. Air collecting behavior of jet flow and increase of ratio of (L/L_b) will result in decrease of C_p factor, but by increase of plunge pool depth, the decreasing trend becomes more affected by turbulent and rotating currents and takes a form of exponential. According to results obtained for all tests, it was determined that there is a significant relationship between dynamic pressure mean factor and parameters related to test. Among all these models, finally, the following relation was extracted as a significant relationship.

$$C_P = 1.76\left(\frac{y}{B_j}\right)^{-1.13} + 0.012\left(\frac{L}{L_b}\right)^{-3.42} \qquad (7)$$

Regression coefficient (R2) among the aforesaid dimensionless parameters was obtained in acceptable level and equal to 0.87 which indicates a strong correlation between the parameters.

2. Dynamic Pressures Mean Factor of Bed Level

Measured value of C_p factor in jet collision site is indicated in figure 5 for jets with the core and developed state.

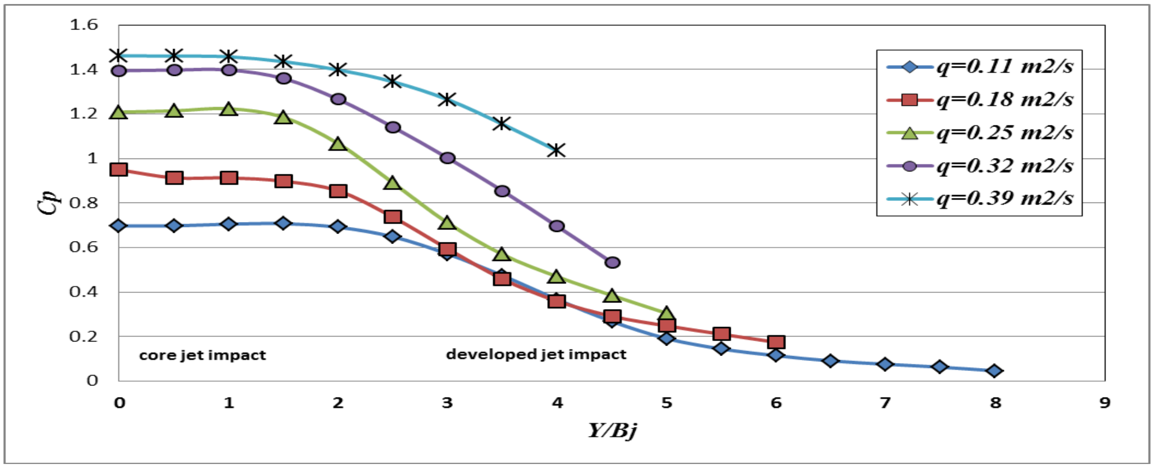

Figure 6: C_p factor against Y/Bj in collision place of jet central axis

Distance between two collision sites related to jet with core and developed jet is determined with portion of Y/Bj<2~3. Therefore, plunge pools in downstream of goblet-shaped projectiles are effective when we have Y/Bj>2~3. The obtained ratio of Y/Bj for determining the effective plunge pool in the present research, is less than the value calculated by other researchers for vertical jets. The reason of this reduction can be investigated in the figure of jet trajectory curve. When all hydraulic conditions are constant, jets resulted from goblet-shaped projectiles pass a more distance in the air, and therefore, two stages of flow energy dissipation which occur in the air (air collecting and powdering of flow), in this type of jet is more than vertical jets and this causes decrease of jet kinematic energy and finally reduction of dynamic pressures which applies in the border of water and bed level.

3. Root Mean Square (RMS) of Bed Level Pressure Fluctuation

Of characteristics of turbulent flow is that each quantity is expressed in a form of sum of time mean and a fluctuation component, and root mean square of fluctuations value, is an index for turbulence intensity. Pressure fluctuations of RMS factor of C'p fluctuations, have become quantified and comparable (figure 7).

As it can be observed, trend of changes of factor based on changes of water depth in pool (Y/Bj), is not absolutely ascending or descending and it reaches maximum point in a specific depth which indicates that in requires a specific depth to create vortexes and high turbulent currents containing short frequencies and high energy. Meaning that maximum pressure fluctuations of bed level does not occur in direct collision (water cushion), but it occurs when there is a thin layer of water cushion. In fact this thin layer, provides the opportunity for development of turbulent flows.

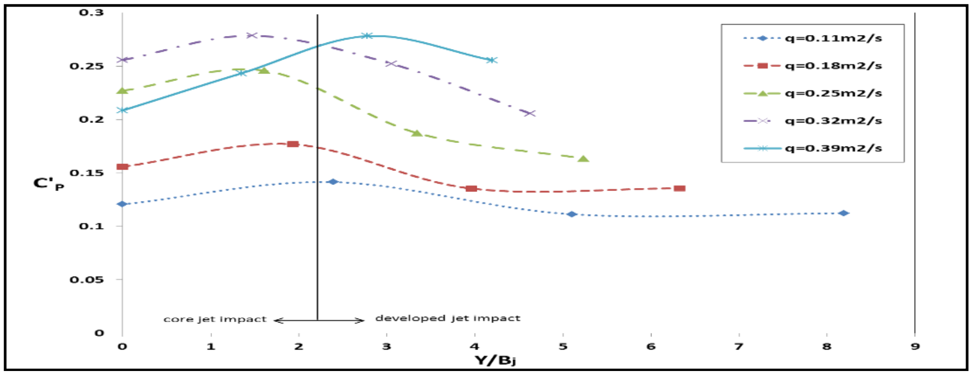

Figure 7: Changes of pressure fluctuation factor, based on changes of depth of water cushion to jet diameter (Y/Bj)

4. Investigating Effect of Jet Break up Length on Factor of Dynamic Pressure Fluctuations

Regarding jets dropping from high heights, surface disturbances of turbulence may such wide that penetrate in the core and as a result of that it divides into separated drops of water. Separation of the falling jet causes reduction of pressure fluctuation and consequently decreases. In figure 8, results obtained fromthe effect of jet break up length to pressure fluctuations factor are indicated beside results obtained by other researchers.

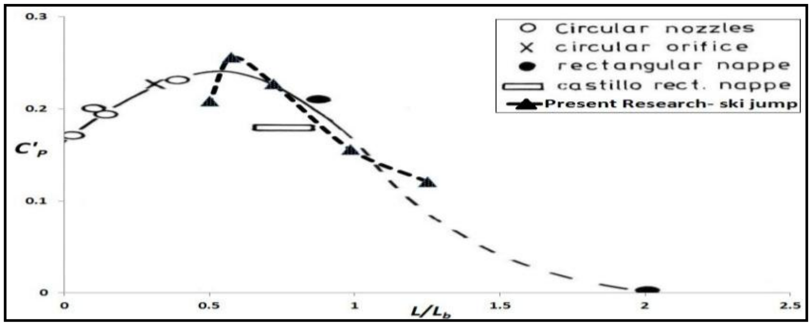

Figure 8: Changes of factor based on change of L/L$_b$ ratio

5. Maximum and Minimum Values for Dynamic Pressure Fluctuations

In figures 8 and 9, respectively, changes of positive and negative factors of pressure fluctuation, based on changes of depth of water cushion (Y/Bj), were separately drawn for test discharges and compared with diagrams provided by other researchers.

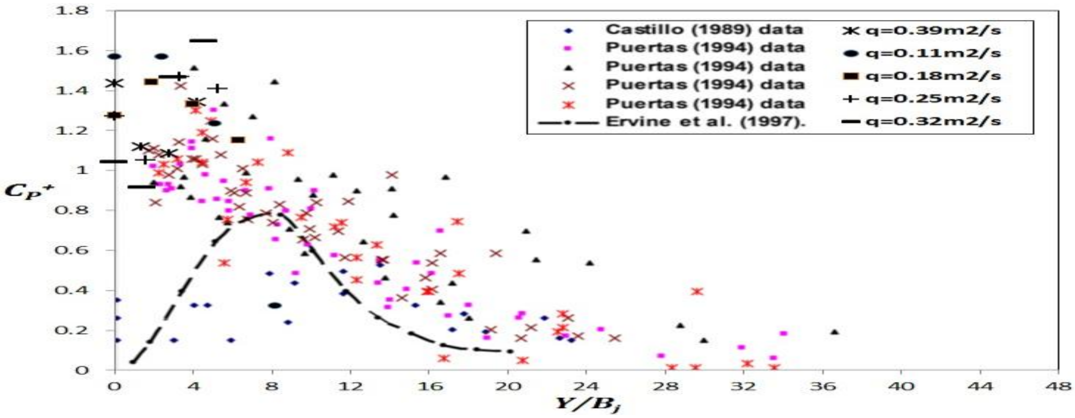

Figure 8: Factor of positive limit value against (Y/Bj)

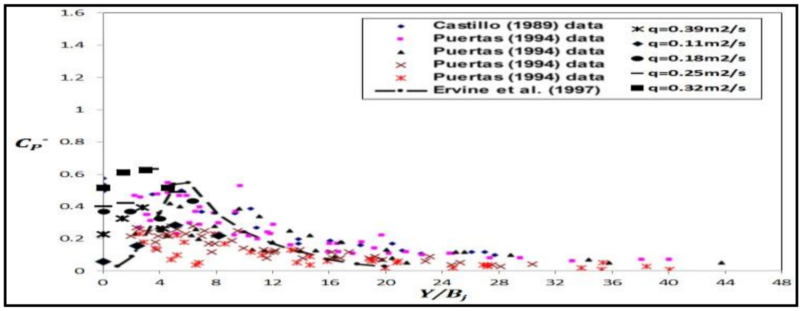

Figure 9: Factor of positive limit value against (Y/Bj)

Conclusion

1. In the cases without water depth and with low water depth, by increase of L/L_b ratio, values of C_p factor would have a descending trend. This decreasing pattern has almost a linear trend, but by increase of water depth, takes an exponential figure.

2. Comparing diagrams obtained in this research with diagrams proposed with other researchers for limit factors of C_p^+ and C_p^- against Y/Bj, it is indicated that Y/Bj is small in this research and the main reason of that is low value of speed and water cushion thickness used in this test.

3. Maximum pressure fluctuations of bed level does not occur in direct collision (without water cushion), but it occurs when there is a thin layer of water cushion. In fact this thin layer provides an opportunity for development of turbulent flows.

4. Regarding goblet-shaped projectiles, the maximum value of factor of C_p^+ by considering $\frac{Y}{B_j} \approx 5$ is equal to 1.6, and the maximum value of factor of C_p^- by considering $\frac{Y}{B_j} \approx 4$ is equal to 0.6.

5. In plunge pools located in downstream of goblet-shaped projectiles, the distance between two collision places of jet with core and the developed jet, is determined by $\frac{y}{B_j} = 2\sim 3$. Therefore, these pools are effective when $\frac{y}{B_j} > 2\sim 3$.

Suggestions

1. It is suggested that tests would be applied for different ranges of discharge and plunging height.

2. It is suggested to conduct simulations with a variety of collision angles and also variety of jet exiting source shapes.

REFERENCES

Annandale GW (1995). Erodibility. *Journal of Hydraulic Research*, IAHR **33**(4).

Bollaert E (2002). Transient water pressures in joints and formation of rock scour due to high- velocity Jet impact. Communication 13 Laboratory of Hydraulic Constructions, EPFL, Lausanne Switzerland.

Bollaert E and Schleiss A (2003). Scour of rock due to the impact of plunging high velocity jets: Part I, *Hydraulic Research, IAHR* **41**(5) 451-464.

Bollaert E and Schleiss A (2003). Scour of rock due to the impact of plunging high velocity jets: Part II, *Hydraulic Research, IAHR* **41**(5) 465-480.

Castillo ELG (2006). Aerated Jets and Pressure Fluctuation in Plunge Pools. *7th International Conference on Hydroscience and Engineering (ICHE-2006), Philadelphia, USA.*

Ervine DA, Falvey HT and Withers W (1997). Pressure fluctuation on plunge pool floors. *Journal of Hydraulic Research, IAHR* **35**(2).

Safarkhani S (2007). Investigating hydrodynamic pressure fluctuations of bed and walls of plunge pool, under effect of jet geometry. Dissertation of MSc, Faculty of Civil Engineering, University of Sharif.

Zarnani P (2005). Investigating hydrodynamic pressure fluctuations of rectangular and circular jets in plunge pools. Dissertation of MSc, Faculty of Civil Engineering, University of Sharif.