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RESEARCH PAPER

Experimental Study of Pressure Fluctuation in Stilling Basins

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Abstract Stilling basins dissipate energy to form hydraulic jumps and rotational flows. Hydraulic jump and rotational current phenomenon produce pressure fluctuation at the bottom of stilling basins. In the present study, pressure fluctuations and their locations have been studied in a physical model of Namrod Dam. Results showed that fluctuations in presence of jump in the basin are high and, therefore, the fluctuation factors are, respectively, high. In positive pressure coefficient (C_P^+), it is evident that when a jump is present, the turbulence and disturbance factors increase and, therefore, the pressure fluctuations go up, respectively. In negative pressure coefficients (C_P^-), as is expected from positive pressure coefficients, the maximum pressure fluctuations occurred at $Q/Q_{\max} = 0.47$ with regard to forming a complete hydraulic jump at this discharge. Regarding available empirical equations, the thickness of slab for different hydraulic conditions was calculated and compared in one-dimensional (1D) and two-dimensional (2D) conditions. By analyzing collected data, it was observed that, results of 1D were underestimated in comparison to 2D calculations. Concrete slab thickness could be observed that fluctuations have significant effect on thicknesses. However, such calculations can provide designers with general ideas on how to better understand the conditions.

Keywords Pressure fluctuation, Stilling basin, Hydraulic jump, Physical model, Namrod dam

Notation

B	Width of stilling basin
C	Center
$C_P{}'$	The dimensionless RMS of the pressure fluctuations
C_P^+	Positive pressure coefficient
C_P^-	Negative pressure coefficient
Fr_1	Froude Number
g	Acceleration of gravity
L	Left
L_j	Length of hydraulic jump for horizontal stilling basins
N	Total number of time intervals
P	Pressure at given time interval
$\bar{P}_-$	Mean pressure
$P_{\max}^+$	Maximum positive pressure
$P_{\max}^-$	Maximum negative pressure
Q	Discharge
$Q_{\max}$	Maximum discharge
R	Right
S	Slab thickness without reinforcement
S_1	One-dimensional slab thickness without reinforcement
V_1	Mean velocity of flow entering stilling basin
V_i	Inflow velocity
X	Distance from start of stilling basin along a longitudinal direction

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Y	Distance from start of stilling basin along a cross section
y_1	Primary depth
y_2	Secondary depth
y_2/y_1	Conjugate depths in hydraulic jump
$\Delta P^{+}_{\max}$	Maximum positive pressure deviation from the mean
$\Delta P^{-}_{\max}$	Maximum negative pressure deviation from the mean
Σ	Standard deviation or RMS
A	A function of the velocity
Ω	Dimensionless reduction factor in Eq. 9
γ_w	Specific weight of water
γ_c	Specific weight of concrete
$-$	Average value
$'$	Fluctuation

1 Introduction

Among energy dissipater structures, stilling basins have been shown to have good performance and could dissipate energy with minimum aspects [1]. Stilling basins dissipate energy to form hydraulic jumps and rotational flows. Hydraulic jump is a rapidly varied transition from supercritical to subcritical flow. This occurs due to generation of large-scale turbulence [2]. Some criteria which are used in the literature and also used in the present work to analyze the hydraulic jumps in the stilling basins are shown in Table 1.

Regarding large-scale turbulence in hydraulic jumps, pressure fluctuation is on the floor and sidewalls of stilling basins which may cause serious damages due to lifting up the floor slabs, erosion of materials and cavitation [3]. Current spillway and stilling basin design procedures usually fail to include the effect of these pressures in the structural design of the basin and chute due to lack of design data on these pressures. Many experiments were performed to optimize the design of stilling basins. Elder [4] provided information on model–prototype relationships on stilling basins. Bowers and Toso [5] presented data on damage of Karnafuli Hydroelectric Project spillway, attributed to fluctuating pressures in the formed hydraulic jump. Vasiliev and Bukreyev [6] published a paper on the full range of statistical parameters for one jump condition. Schiebe [7] also described the stochastic characteristics of pressure fluctuations on the bed under a hydraulic jump. Resch and Leuthesser [8] established a technique to measure velocity fluctuations in the jump by means of hot film anemometry and indicated that inflow development is an important factor. Akbari et al. [9] investigated the turbulent pressure characteristics of the free and forced hydraulic jumps. Lopardo and Henning [10] presented pressures in the hydraulic jump too. Studies of turbulence characteristics in the hydraulic jump began in the late 1950s when instrumentation became available. Since fluctuating pressures are random in nature, much has been accomplished in defining the stochastic characteristics of the problem [3]. Fiorotto and Rinaldo presented hydrodynamic forces involved in the design of the lining of stilling basins [11]. Also they studied turbulent pressure fluctuations under hydraulic jumps [12]. Bellini and Fiorotto provided direct experimental evaluation of the up lift coefficient [13]. Hassonizadeh and Shafai-Bajestan investigated the dynamic forces on slab in stilling basins [14]. Guven et al. provided pressure fluctuations on artificial neural network models developed to simulate the mean pressure fluctuations beneath a hydraulic jump occurring on sloping stilling basins. The results of the neural network modeling were found to be higher than the regression models and confirmed the experimental results due to relatively small values of error [15]. Pei-Qing and Ai-Hua used both theoretical analysis and numerical simulation to study the mechanism of pressure fluctuation propagations within lining slab joints in stilling basins [16]. Farhoudi studied total pressure around chute blocks of Saint Anthony Falls (SAF) stilling basins [17]. Cerezer et al. presented pressure extreme in an energy dissipating structure using block maxima and expressed generalized extreme value (GEV) distribution gives generally an adequate representation of the frequencies of occurrence of maximum and minimum pressure heads for all discharges and at most measurement points [18]. Moreover, in the recent years, many numerical models were also developed to simulate the hydraulic phenomena [19–23]. Considering previous studies carried out to find pressure fluctuation distribution in stilling basins to form hydraulic jumps, lack of information on hydrodynamic loading on the bottom slabs is evident. The aim of the present study is to provide useful information on hydrodynamic loading due to pressure fluctuations along the stilling basins. Implications might include designing and maintenance of stilling basins downstream of large dams. To reach this goal, the hydraulic model of Namrod Dam was applied.

2 Materials and Methods

Experimental data were obtained from hydraulic model of Namrod Dam. Namrod Dam has been constructed on the Namrod River. The main purpose is to supply drinking water and regulating water demand for regional plains. The model of dam has been built by 1:40 scale [24]. The dam specifications are summarized in Table 2.

As mentioned in Table 2, the USBR (United State Bureau of Reclamation) stilling basin type 2 was designed for this project. To measure the pressures along the basin,

Table 1 Equations which were used in the present study

Eq.no.	Parameter description	Equation	Notations
1	Froude number (Fr_1)	$Fr_1 = \frac{V_1}{\sqrt{g y_1}}$	y_1 = primary depth (m) V_1 = mean velocity of flow entering stilling basin (m/s) g = the acceleration of gravity (m/s^2)
2	Conjugate depths in hydraulic jump (y_2/y_1)	$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right)$	y_2 = secondary depth (m)
3	Length of hydraulic jump for horizontal stilling basins [25] (L_j)	$1 < Fr_1 < 2.5 \rightarrow L_j = 3y_2 Fr_1^{0.5}$ $2.5 < Fr_1 < 4.5 \rightarrow L_j = 5(y_2 - y_1)$ $Fr_1 > 4.5 \rightarrow L_j = 6y_2$	
4	Mean pressure ($\bar{P}$)	$\overline{P} = \frac{\sum P}{N}$	P = pressure at given time interval (m) N = total number of time intervals
5	Standard deviation or RMS (σ)	$\sigma = \left(\frac{\sum (P - \overline{P})^2}{N}\right)^{\frac{1}{2}}$	
6	Positive pressure coefficient [3] (C_P^+)	$c_p^+ = \Delta P_{\max}^+ \Big/ \alpha \frac{V_i^2}{2g}$	$\Delta P_{\max}^- = P_{\max}^- - \bar{P}$ V_i = Inflow velocity (m/s) α = a function of the velocity profile and is usually assumed equal to 1.0
7	Negative pressure coefficient [3] (C_P^-)	$c_p^- = \Delta P_{\max}^- \Big/ \alpha \frac{V_i^2}{2g}$	$\Delta P_{\max}^- = P_{\max}^- - \bar{P}$
8	The dimensionless RMS of the pressure fluctuations [3] (C_P')	$C_p' = \mathrm{RMS} \Big/ \alpha \frac{V_i^2}{2g}$	
9	Slab thickness without reinforcement [11] (S)	$\frac{S}{\frac{V_i^2}{2g}} > \Omega (c_p^+ + c_p^-) \frac{\gamma_w}{\gamma_c - \gamma_w}$	Ω = dimensionless reduction factor (safe value of Ω, equal to 0.5) γ_w = specific weight of water (N/m^3) γ_c = specific weight of concrete (N/m^3)
10	One-dimensional slab thickness without reinforcement [11] (S_1)	$\frac{S_1}{\frac{V_i^2}{2g}} > 0.3$	

Table 2 Hydraulic specifications of Namrod Dam

Type of dam	Earthfill
Dam height from the River Bed	82 m
Spillway system	Ogee free over fall
Width of stilling basin	23 m
Length of stilling basin	33 m
Energy dissipating system	USBR stilling basin type 2
Probable maximum flood	1017.5 m^3/s

many piezometers were installed in the model. Piezometer positions which were used in the dynamic pressure measurements within the stilling basin are shown in Table 3 and Fig. 1a–c.

A centrifugal pump supplied water from a canal to the reservoir of the model. A sharp crested rectangular weir was installed downstream of the model for discharge (Q) measuring. A precise limnimeter was used to measure the water surface elevation. Pressure fluctuations were recorded using pressure transducers with 100 sampling rate per second. For each piezometer, 30-s data were recorded. Experiments were performed in three discharges. In each set of tests, pressures were recorded in right, center and left of basin in the floor. Moreover, five piezometers were installed in each side to measure fluctuations along the basin.

Table 3 Piezometers coordinate within the stilling basin

Station	*L*		*C*		*R*	
	X/*b*	*Y*/*b*	*X*/*b*	*Y*/*b*	*X*/*b*	*Y*/*b*
1	0.05	0.95	0.05	0.50	0.05	0.05
2	0.40	0.95	0.40	0.50	0.40	0.05
3	0.75	0.95	0.75	0.50	0.75	0.05
4	1.10	0.95	1.10	0.50	1.10	0.05

3 Experimental Result

It was seen that in three tested discharges, hydraulic jump moved, respectively. In first discharge $Q/Q_{\max} = 0.47$, ($Q_{\max}$, maximum discharge), the jump formed from

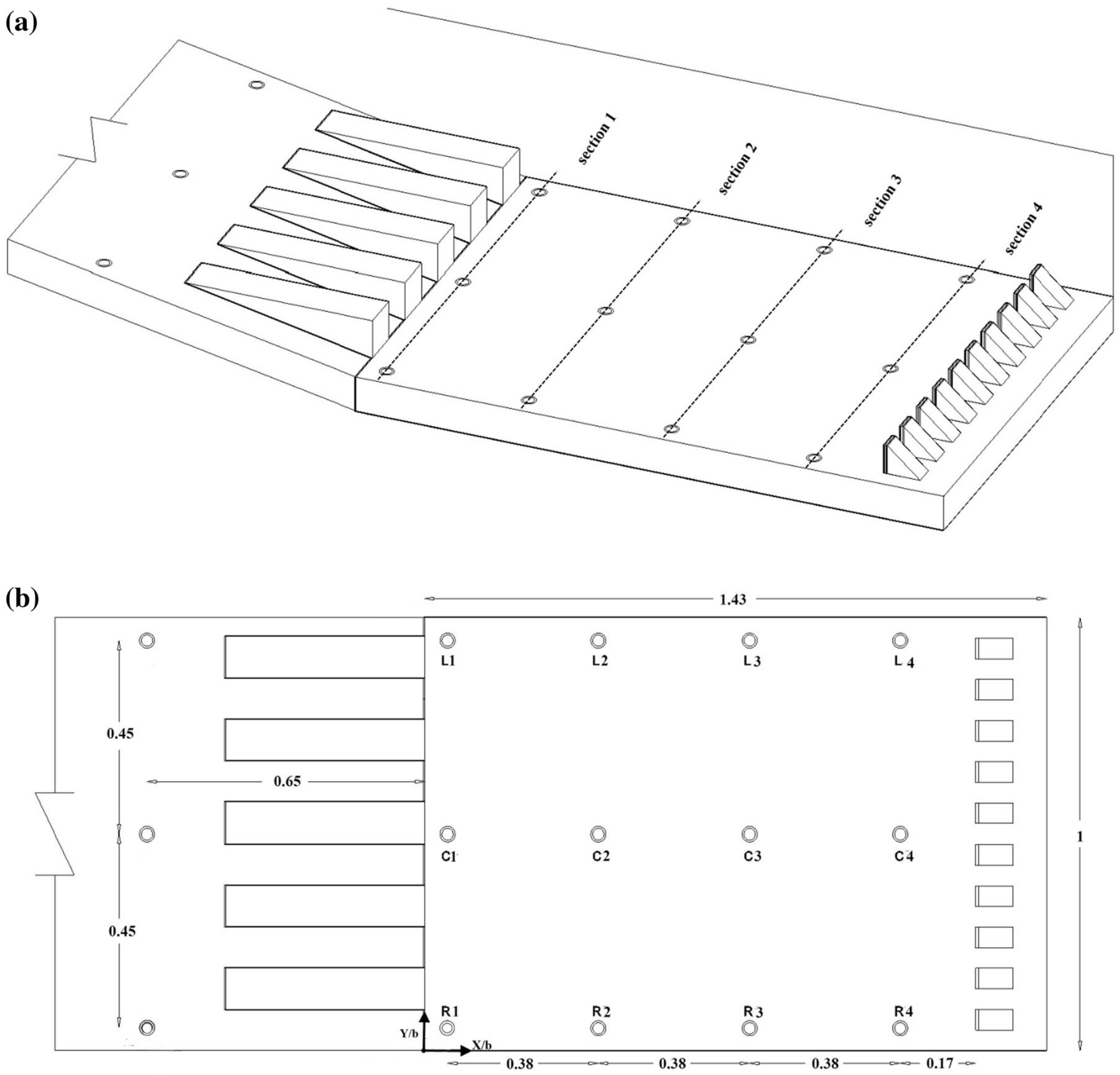

Fig. 1 **a** Piezometer positions used in the dynamic pressure within the stilling basin. **b** Stilling basin plan

section 1 (Figs. 1a, 2a). In discharge equal to $Q/Q_{\max} = 0.69$, the jump formed from a section between section 1 and 2 (Figs. 1a, 2b). This means the beginning point of jump moved about $X/b = 0.18$, (X distance from start of stilling basin a long a longitudinal direction, b width of stilling basin). Final tested discharge which was at maximum state ($Q/Q_{\max} = 1$) moved about $X/b = 0.52$ in comparison to previous condition and formed jump from section 3 (Figs. 1a, 2c).

Results could be divided into four different parts and analyzed accordingly. In Part 3.1., by calculating the positive pressure coefficients (C_P^+) for each discharge ($Q/Q_{\max}$) and along the stilling basin (X/b), results are presented in Figs. 3 and 4. Almost the same, in Part 3.2., the negative pressure coefficients (C_P^-) were calculated and are plotted in Figs. 5 and 6. To see the pressure fluctuations within the width of stilling basins, the dimensionless pressure fluctuations ($C_P{}'$) are presented for all test sets in Part 3.3. and Fig. 7. Finally, using the collected data in the bottom of stilling basin and employing proposed equation of Fiorotto and Rinaldo for calculating the concrete slab thickness, this factor was calculated for this project at Part 3.4. (Figure 8). The calculated slab thicknesses are presented by assuming the slab in one and two dimensions in this part too and results were compared together.

3.1 Positive Pressure Coefficients (C_P^+)

Using the measured pressures at all points, positive pressure coefficients were calculated regarding to Eq. 6 and are

Fig. 2 Formation of hydraulic jump at different discharges [24, 26]

shown in Table 1. Results have been plotted and presented in three discharges and three sides (Right, Left and Center) in Figs. 3 and 4.

In general, Figs. 3 and 4 show that the maximum positive pressures have occurred at $Q/Q_{\max} = 0.47$. This could have resulted from complete hydraulic jump at this discharge. It is evident that when a jump is present, the turbulence and disturbance factors increase and, therefore, the pressure fluctuations go up, respectively. In other plots of jump length calculated from Eq. 3, the peak of fluctuations is moved.

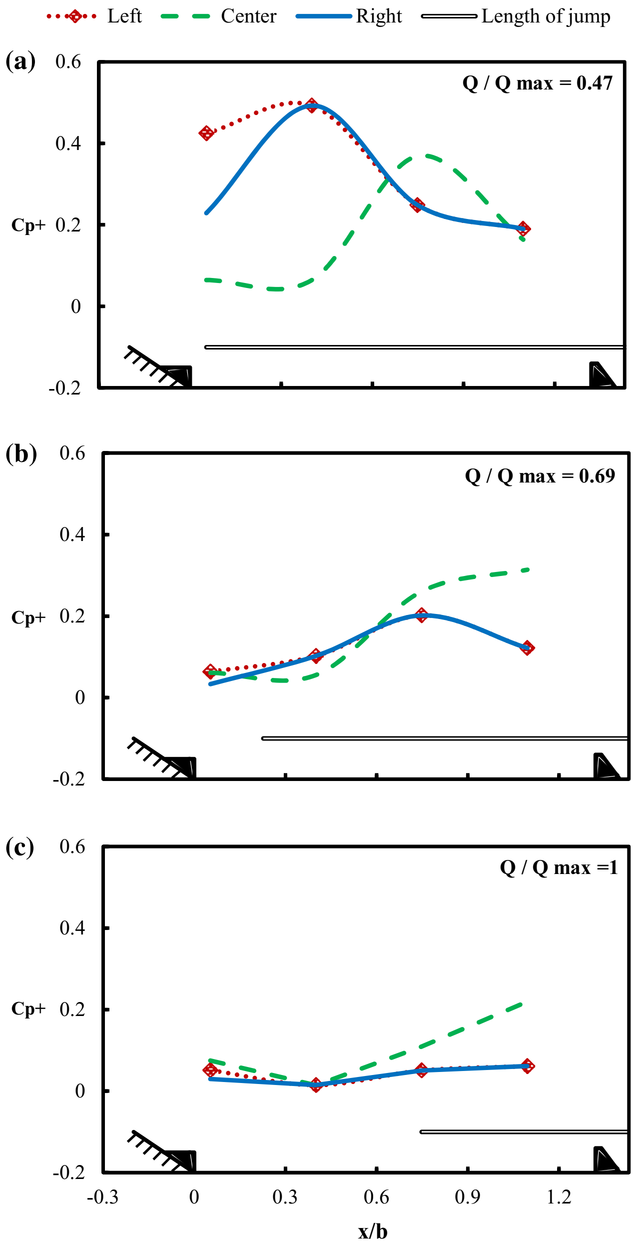

Fig. 3 Calculated positive pressure coefficients (C_P^+) for different discharges

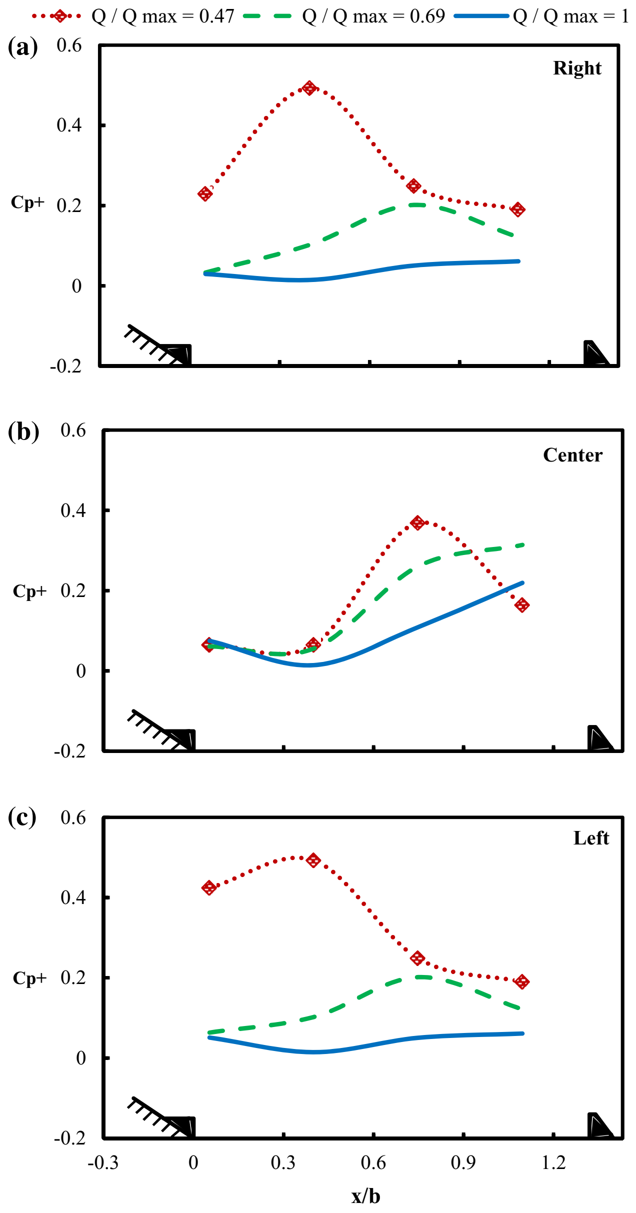

Fig. 4 Calculated positive pressure coefficients (C_P^+) for different sides

3.2 Negative Pressure Coefficients (C_P^-)

In Figs. 5 and 6, calculated negative pressure coefficients from Eq. 7 are presented in three discharges and three sides of measurement. These calculations will help the engineers and designers to have a better estimation about what is happening in the stilling basins due to hydraulic jumps.

As expected from positive pressure coefficients, in Figs. 5 and 6 also, the maximum pressure fluctuations occurred at $Q/Q_{\max} = 0.47$ with regards to forming a complete hydraulic jump at this discharge.

3.3 Dimensionless Pressure Fluctuations ($C_P{}'$)

By calculating the dimensionless pressure fluctuations (Eq. 8) in each section (Fig. 1a) and each point in a section (Fig. 1c), Fig. 7 has been plotted.

As can be seen from Fig. 7, Fig. 7a shows great fluctuations from section 1 to the next. This clearly shows the effect of forming a complete jump in the basin. Hydraulic jump formation is parallel with the fluctuation occurring in the flow and will cause more turbulence and disturbance in the basin. A better performance is expected when the

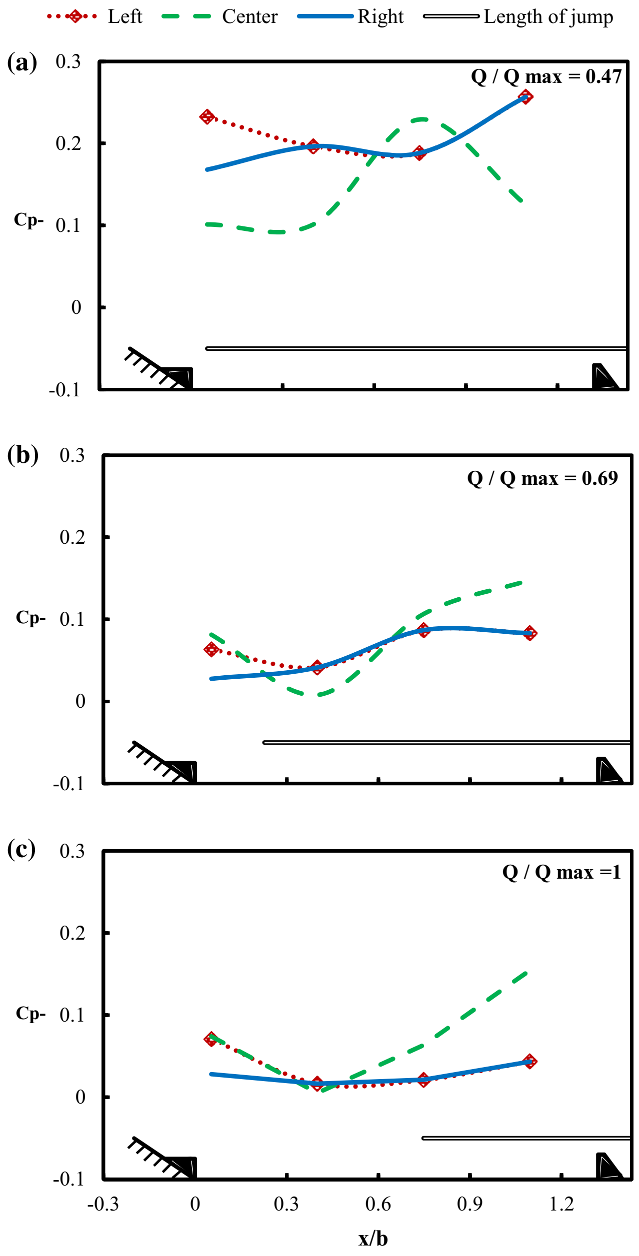

Fig. 5 Calculated positive pressure coefficients ($\overline{C_P}$) for different discharges

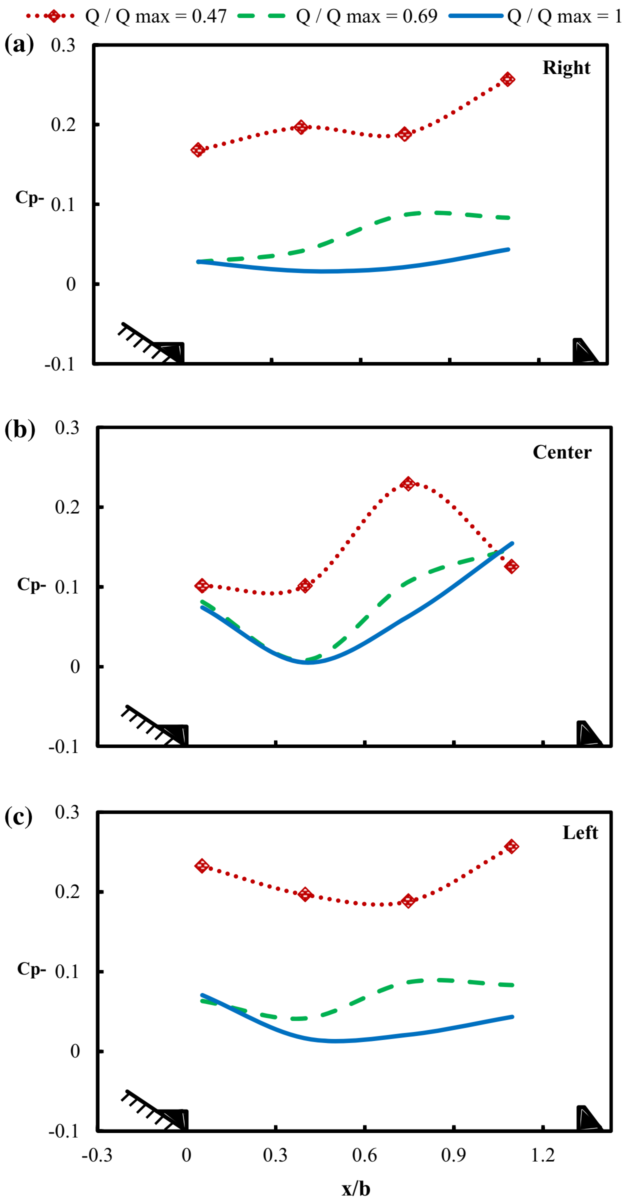

Fig. 6 Calculated positive pressure coefficients ($\overline{C_P}$) for different sides

fluctuations damp in the basin and a relaxed flow goes out from the basin (Table 4).

3.4 Concrete Slab Thickness

In this part, by calculating the concrete slab thickness (Eq. 9) at the bottom of basin, Fig. 8 is presented.

Figure 8 shows that one could see the effect of pressure fluctuations on thickness of designed concrete slab (without reinforcement) at different discharges and sides. Figure 8 shows that unlike the pressure fluctuations, Fig. 8a more than Fig. 8b, c, (Figs. 3, 4, 5, 6 and 7) the thickness of slab in Fig. 8b is generally greater. This happened as a result of inlet velocity which in turn has an effect on calculations and this effect caused a thicker slab in this position. In other calculations regarding Eqs. 10 and 9, an overall thickness and maximum, minimum and average thickness in center could be achieved for each discharge (Table 5).

In this table it could be observed that fluctuations have significant effect on thicknesses. However, such calculations can provide designers with general ideas on how to better understand the conditions.

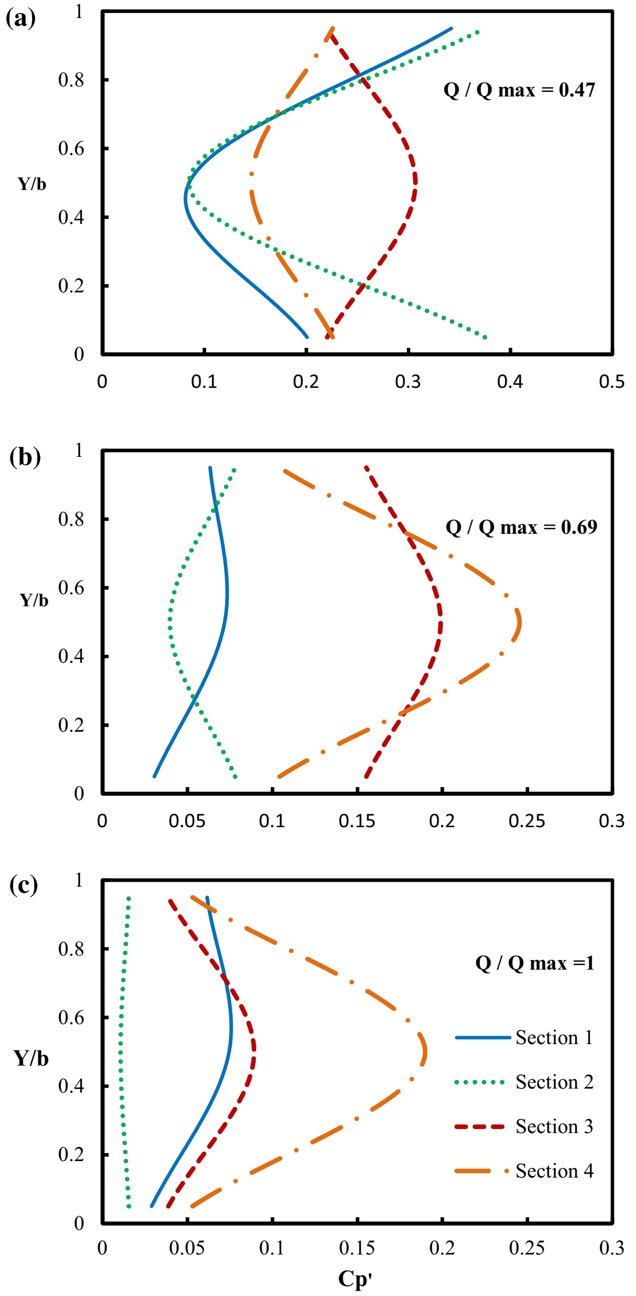

Fig. 7 Calculated dimensionless pressure fluctuations ($C_P^{'}$) for different discharges and sections

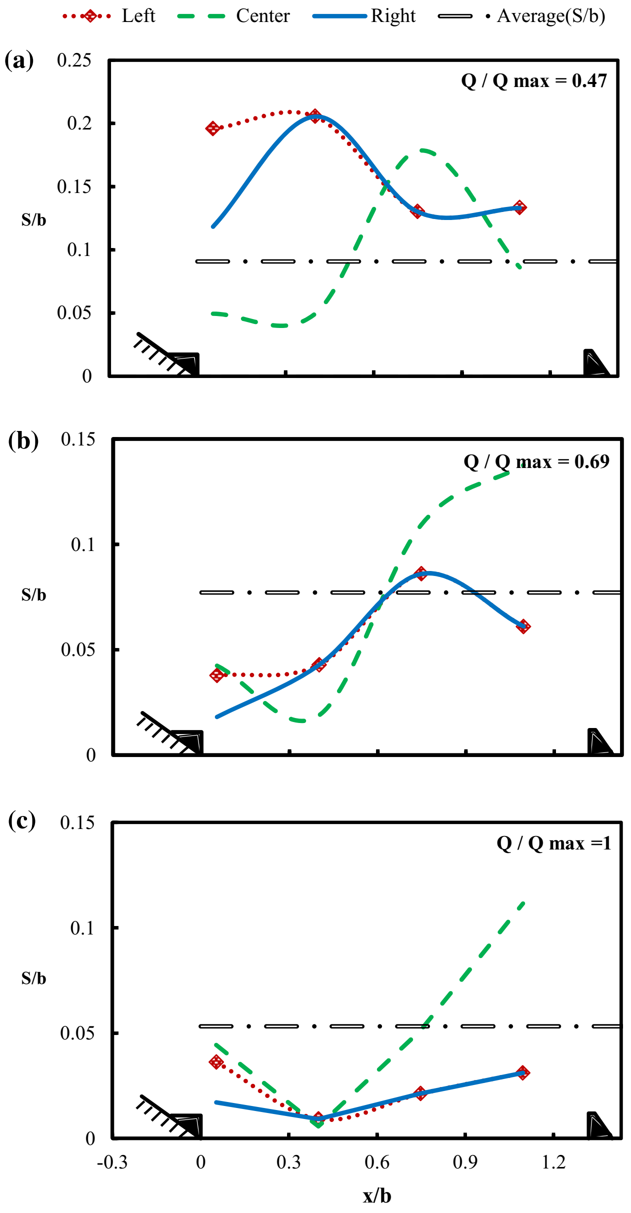

Fig. 8 Calculated thickness of *bottom* slab (Eq. 9) along the basin at different discharges and sides

Table 4 Beginning point of jump in different tests

$Q/Q_{\max}$	Beginning point of jump	X/b	Figures
0.47	Section 1	0.05	1a, 2a
0.69	Between Section 1 and 2	0.23	1a, 2b
1	Section 3	0.75	1a, 2c

Table 5 Calculations of bottom slab thickness

$Q/Q_{\max}$	$S_{\min}/b$	$S_{\max}/b$	S_{average}/b	S_1/b
0.47	0.049	0.178	0.091	0.299
0.69	0.018	0.137	0.077	0.491
1.00	0.006	0.112	0.053	0.542

4 Conclusions

In the present experimental study, by measuring dynamic pressures at bottom of a stilling basin, fluctuations were analyzed in different hydraulic conditions. Results showed that when jump was formed completely in the basin, factors of fluctuations were high. Formation of jump in different tests caused a non-uniform distribution pressure at the bottom of the basin. In positive pressure coefficient (C_P^+), it is evident that when a jump is present, the turbulence and disturbance factors increase and, therefore, the pressure fluctuations go up, respectively. In negative pressure coefficients (C_P^-), as is expected from positive pressure coefficients, the maximum pressure fluctuations occurred at $Q/Q_{max} = 0.47$ with regard to forming a complete hydraulic jump at this discharge. Therefore, by plotting the factors of fluctuations within the X and Y directions of the slab, useful plots in point view of engineering design were also generated. Concrete slab thickness shows that fluctuations have significant effect on thicknesses. Moreover, the thickness of slab for both one and two dimensions were calculated and compared. However, such calculations can provide designers with general ideas on how to better understand the conditions.

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