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# Pressure fluctuation around chute blocks of SAF stilling basins

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## **Pressure Fluctuation around Chute Blocks of SAF Stilling Basins**

J. Farhoudi<sup>1\*</sup>, S. M. Sadat-Helbar<sup>1</sup>, and N. Aziz<sup>2</sup>

### **ABSTRACT**

Geometry of the chute blocks in stilling basins plays a significant role in size and type of these structures. One of the most influencing factors in the design of the blocks is the fluctuating pressure which may cause fatigue on the blocks. Despite investigations conducted by many researchers, there is not enough information about the pressure fluctuation around chute blocks in compacted stilling basins such as Saint Anthony Falls (SAF) basins. In this paper, the results of a naval experimental work and measurement of pressure fluctuations around chute blocks of SAF stilling basins are reported. The results show that the pressure fluctuations around the chute blocks cannot be overlooked in designing such structures. The variation of pressure fluctuation with Froude number of incoming supercritical flow at various faces of the chute block is reported, which shows an increasing trend of pressure fluctuation. It is also observed that the submergence of hydraulic jump will decreasingly affect the pressure fluctuations. The trend of variations will follow different patterns at the different faces of the block.

**Keywords:** Chute blocks, Pressure fluctuation, SAF stilling basin, Submergence ratio.

### **INTRODUCTION**

Hydraulic jump prevails at downstream of such hydraulic structures as spillways, sluice gates and spillways, whereby a supercritical flow of high kinetic energy occurs, which may endanger the stability of such structures. Precautions have to be taken in designing the stilling basins and their appurtenances encountered with these structures. In general, the mean velocities and hydrostatic pressures are considered in designing the stilling basins and such of their appurtenances as chute blocks, baffle blocks and end sills. It is quite evident that the presence of strong turbulent flow would not endorse the above mentioned procedure because of prevailing fluctuating characteristics. It is also known that the fluctuating pressures/forces would weaken

the structure through fatigue as the consequences of fluctuating pressures/forces. On the other hand, the measurement of fluctuating pressure/forces may not be too easy to conduct in the field. Therefore, it seems reasonable if the characteristics of pressure /force fluctuations at stilling basins and around their appurtenances be studied.

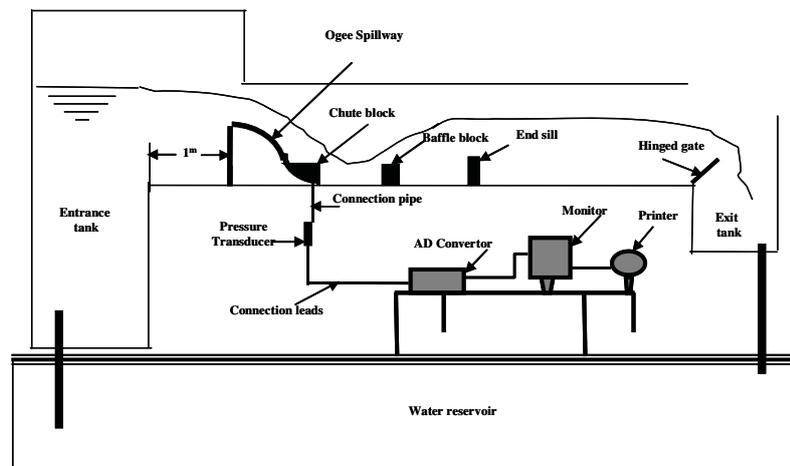
SAF stilling basin is one of the compacted structures which was designed and suggested by Blaisdell (1943, 1959) on the basis of mean flow characteristics and is frequently used in water conveyance systems with a wide range of Froude numbers extending from 1.7 to 17

Harleman (1955) was one of the pioneers who assessed the role of baffle blocks in functioning of stilling basins and their effects on flow characteristics. Basco and Adams (1971), studied the field of drag

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**Figure1.** Experimental layout (Not to scale).

force in the hydraulic jump. Karki (1976) investigated the mean pressure on upstream face of an end sill in stilling basins and reported valuable information in relation to the influences of hydraulic jump position from the end sill on pressure distribution profiles. Narayanan and Schizas (1980), studied the influence of induced force by the hydraulic jump on the end sill in a USBR (US Bureau of Reclamation) Type II basin. Rouse *et al.* (1985), studied the turbulent characteristics of hydraulic jump using the transport equations which paved the way to assess the rate of energy dissipation through the phenomenon. Farhoudi and Narayanan (1991) studied experimentally the drag forces induced by hydraulic jump on baffle blocks in a stilling basin downstream of sluice gate. Firoto and Rinaldo (1992b), studied the features of hydraulic jump downstream of sluice gate, where the Froude number ranged between 5 and 9.5. Farhoudi and Volker (1995), assessed the pressure field around a cubic baffle block in stilling basin downstream of spillway and analyzed the effective mean pressure distribution. The function of induced dynamic force in stilling basins was experimentally measured and reported by Bellin and Firoto (1995).

Armenio *et al.* (2000) studied the induced pressure fluctuations by a negative step at bottom of hydraulic jump. Guven *et al.* (2006), utilized the neural network to predict

the pressure fluctuations in sloping stilling basins. Farhoudi (2008) conducted a research program to investigate the characteristics of mean pressure around chute blocks of SAF basins.

The present work would be devoted to investigate the pressure fluctuations around a selected chute block in SAF stilling basins downstream an ogee spillway which has been planned and conducted for the first time to investigate the contribution of pressure fluctuations to prevailed pressure field.

## MATERIALS AND METHODS

The experiments were conducted in a laboratory glass walled flume of 25 cm width, 30 cm height and 600 cm length. An ogee spillway of 40 cm height equipped with a SAF basin with 5 chute blocks (4 cm height, 3 cm width and 8 cm length), 4 baffle blocks and a solid end sill of 2 cm height were designed according to USBR and Blaisdell (1943; 1959) recommendations. The spillway was installed at a distance of 100 cm from the entrance tank of the flume shown in Figure 1. Assuming a symmetrical flow pattern in the flume, a chute block was selected at the centreline and 26 pressure holes then drilled on its different faces as depicted in Figure 2. A Druck type pressure

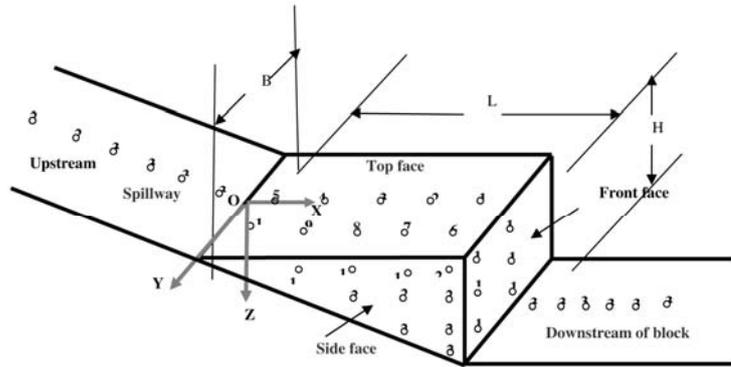


Figure 2. Position of pressure holes around the selected chute block.

transducer was used to detect the pressure fluctuations. All the pressure holes were connected to the pressure transducer by means of a transparent plastic hose and the measurements then taken by a speed of 100 readings per second. The information was then transmitted to an AD converter and analysed using View Deck software.

Preliminary examination showed that the acceptable time length for data acquisition would be in the order of 120 seconds and length of connection pipes between 50 and 120 cm. The rating curve of the spillway was achieved by measuring the flow height over the crest and discharge using a pre-calibrated rectangular sharp crested weir at the downstream of the flume. The flow discharge ranged from 17.93 to 104.2 lit sec<sup>-1</sup> (Froude number ranging from 5.5 to 12) where the submergence ratio varied from 0 to 100%, at intervals of 10%. A hinged gate was installed at the downstream end of the flume to control the flow depth throughout the reach for desired submergence ratios.

**Dimensional Analysis**

The pressure fluctuations would be affected by the following parameters:

**Flow Characteristics**

$p'$ = Pressure fluctuation,

- $d_f$ = Supercritical flow depth entering the stilling basin,
- $T_w$ = Tailwater depth,
- $v_f$ = Mean flow velocity of incoming flow to the stilling basin,
- $\rho$ = Mass density of flow (water),
- $\mu$ = Flow viscosity,
- $g$ = Gravitational acceleration, and

**Structural Geometry**

- $L_B$ = The length of stilling basin,
- $H, B$  and  $L$ = Height, width and length of the chute block, respectively,
- $\beta$ = The coverage ratio of chute blocks,
- $x, y, z$  = Cartesian coordinates of each hole from origin O as in Figure 2,

Therefore, the pressure fluctuation could be defined as:

$$F(p', d_f, v_f, T_w, \rho, \mu, g, L_B, \beta, H, B, L, x, y, z) = 0 \quad (1-1)$$

Taking recourse from Buckingham's theorem, the following non-dimensional parameters would be concluded to define the pressure fluctuations around the experimental chute block:

$$C'_p = \varphi(Fr_f, Re, L_B/d_f, S_d, \beta, H/d_f, B/d_f, L/d_f, x/d_f, y/d_f, z/d_f) \quad (1-2)$$

where:

$C'_p$ = Coefficient of pressure fluctuation=

$$\frac{\sqrt{(\overline{p'^2})}}{\frac{1}{2}\rho v^2} = \frac{RMS}{\frac{1}{2}\rho v^2}$$



$Fr_1$ = Froude number of incoming flow at the toe of spillway,

$Re$ = Flow Reynolds number,

RMS= Root Mean Square

$$S_d = \text{Submergence ratio} = \frac{T_w}{d_2} - 1$$

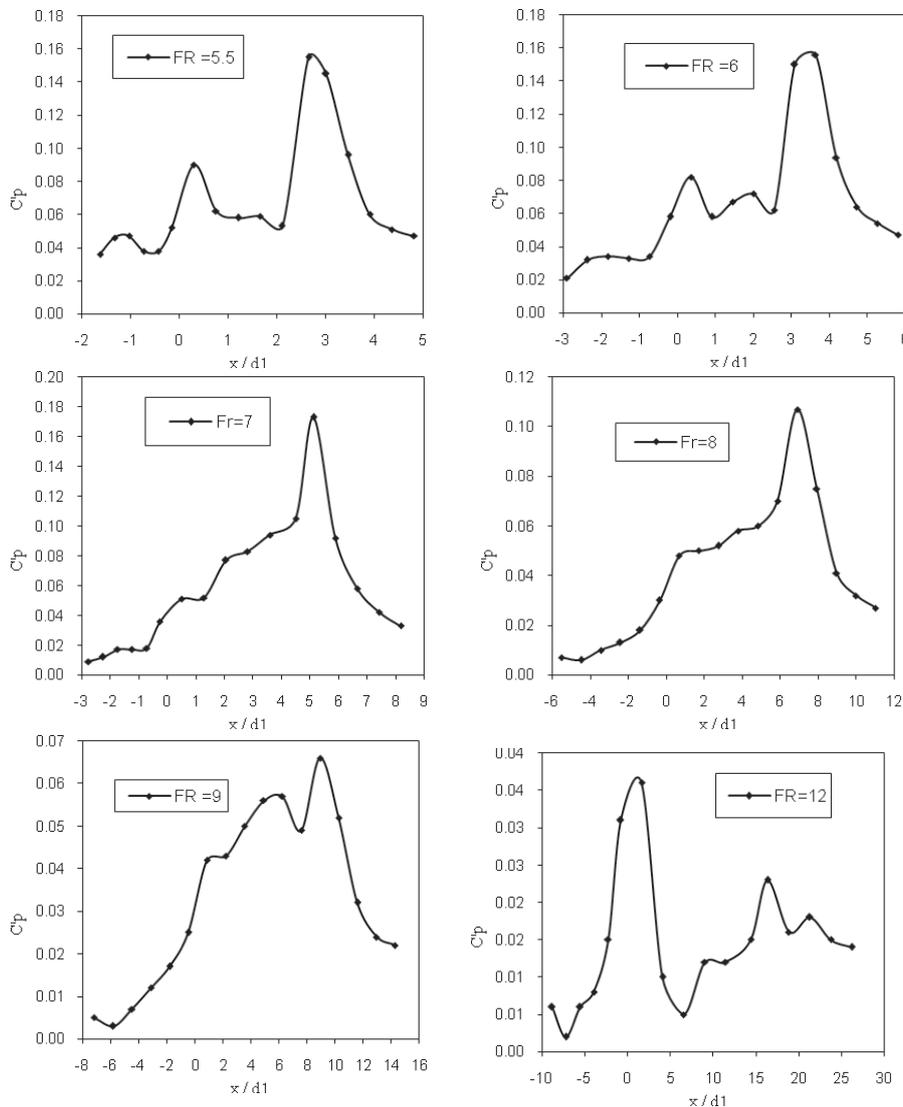
Since throughout the experiments,  $Re$  exceeded  $10^4$  and the values of  $\beta$ ,  $H$ ,  $B$ ,  $L$  and  $L_B$  were fixed, the Equation (1-1) can be simplified as;

$$C'_p = \varphi(Fr_1, S_d, x/d_1, y/d_1, z/d_1) \quad (2)$$

### Data Analysis

#### Pressure fluctuation throughout the upstream to downstream of chute blocks

Observations of pressure fluctuation from upstream to downstream of chute block for different  $Fr_1$  and  $S_d = 0$  are depicted in Figure 3. It was revealed that the pressure fluctuation, on the face of spillway, remained almost independent from incoming flow conditions. It rapidly increased as the flow impinged on the chute block,



**Figure 3.** Variation of  $C'_p$  with  $Fr_1$  for  $S_d = 0$ , at the flow direction throughout upstream to downstream of chute blocks.

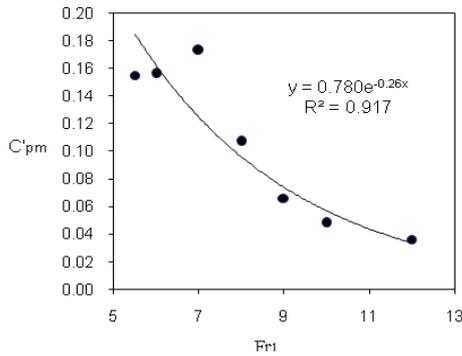


Figure 4. Variation of  $C'_{pm}$  with  $Fr_1$  on the top face of chute block.

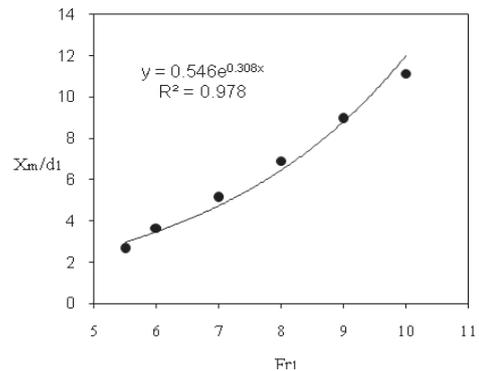


Figure 5. Variation of  $x_m/d_1$  with  $Fr_1$  on the top face of chute block.

demonstrating two successive peak values with the higher one at the top face, adjacent to the downstream edge of the chute block. However, as the incoming flow tended to become more supercritical the smaller peak fluctuation decayed leaving the profile with one maximum  $C'_p$  value which occurred over the top face of the block.

The magnitude and position of the maximum pressure fluctuation ( $C'_{pm}$ ) on the top face changed with Froude number of incoming flow. Close assessment of the observations indicated that the maximum pressure fluctuation would follow a decaying exponential relationship with Froude number of incoming flow as expressed by equation (3) and shown in Figure 4.

$$C'_{pm} = 0.78EXP(-0.262Fr_1) \quad (3)$$

The position of maximum pressure fluctuation ( $x_m$ ) over the block would fall in a rising exponential relationship with Froude number of incoming flow as shown in Equation (5) and in Figure 5.

$$\frac{X_m}{d_1} = 0.5467EXP(0.309Fr_1) \quad (4)$$

As can be seen in Figures 4 and 5, that equations 3 and 4 fit the observations with a high level of confidence with  $R^2$  higher than 0.9175.

Variation of  $C'_p$  with submergence ratio ( $S_d$ ) for  $Fr_1 = 8$  is sketched in Figure 6. The diagram verifies the trend of pressure fluctuations, depicted in Figure 3, and shows decreasing  $C'_p$  values with increasing  $S_d$ . In other words, high submergence ratio would relieve the SAF basins from high pressure

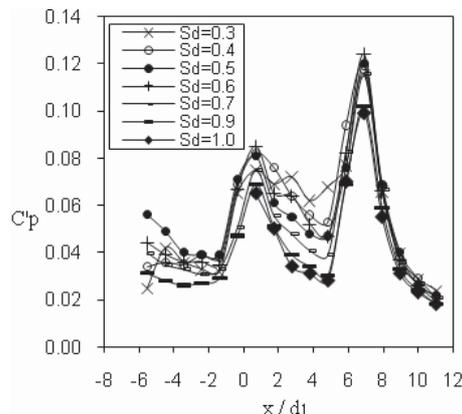


Figure 6. Variation of  $C'_p$  with  $S_d$  for  $Fr_1 = 8$ , at the flow direction throughout upstream to downstream of chute block.

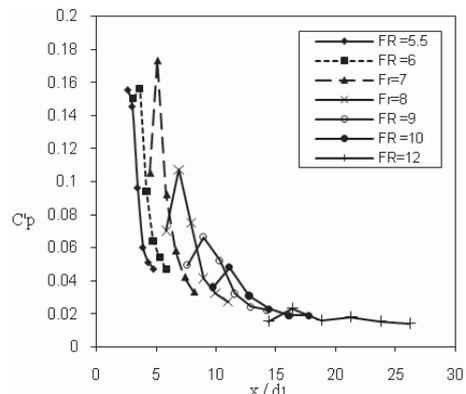
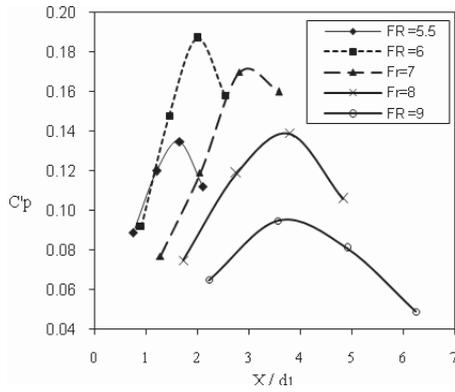
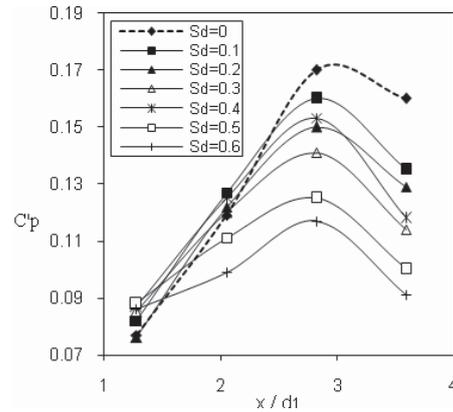


Figure 7. Variation of  $C'_p$  with  $Fr_1$  for free hydraulic jump ( $S_d = 0$ ) between chute and baffle blocks.



**Figure 8.** Variation of  $C'_p$  with  $Fr_1$  at XZ-plane and elevation of  $Z= H/8$  from the top face in X-direction for free hydraulic jump ( $S_d= 0$ ).



**Figure 9.** Variation of  $C'_p$  with  $S_d$  at XZ-plane and elevation of  $Z= H/8$  from the top face in X-direction for  $Fr_1= 7$ .

fluctuations. Figure 6 clearly demonstrates that the increase in submergence ratios resonates the presence of successive peak values in pressure fluctuations at the reach. A closer look at the depicted curves in Figure 6 reveals that the variation of the maximum pressure fluctuation ( $C'_{pm}$ ) with  $S_d$  is falling in a polynomial relationship as:

$$C'_{pm} = A_1(S_d^2) + B_1(S_d) + C_1 = \varphi(S_d) \quad (5)$$

where  $A_1$ ,  $B_1$  and  $C_1$  are functions of  $Fr_1$  as:

$$A_1 = 0.91Fr_1^2 - 1.62Fr_1 + 6.92, \quad (5-1)$$

$$B_1 = -0.056Fr_1^2 + 1.02Fr_1 - 4.51, \quad (5-2)$$

$$C_1 = 0.0112Fr_1^2 - 0.23Fr_1 + 1.23 \quad (5-3)$$

The level of fitness and RMSE values of Equations (5-1), (5-2) and (5-3) are shown in Table 1.

Application of Equations 3, 4 and 5, enables one to determine the peak pressure fluctuation and its location of occurrence at the top face of chute blocks in SAF stilling basins under different flow conditions and

**Table 1.** Functional parameters of Equation (5).

Equation	R <sup>2</sup>	RMSE
$A_1 = 0.91Fr_1^2 - 1.62Fr_1 + 6.92$	0.794	0.063
$B_1 = -0.056Fr_1^2 + 1.02Fr_1 - 4.51$	0.994	0.009
$C_1 = 0.0112Fr_1^2 - 0.23Fr_1 + 1.23$	0.999	0.001

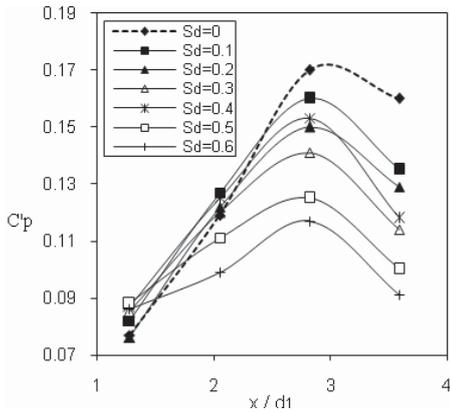
submergence ratios.

Variation of  $C'_p$  with  $Fr_1$ , between chute blocks and baffle blocks, is shown in Figure 7 for free hydraulic jump ( $S_d= 0$ ). Assessment of Figure 7 reveals that the variation of  $C'_p$  with  $Fr_1$  follows an oscillating trend with a peak occurring between chute and baffle blocks adjacent to downstream edge of chute blocks (pressure hole No. 35 in Figure 2) and decaying as flow passes towards baffle block. Observations showed that the magnitude of maximum  $C'_p$  in this reach is a function of  $Fr_1$  and of  $S_d$ .

### Pressure fluctuation on the side face of chute blocks at flow direction (XZ plane)

Variation of  $C'_p$  on side face of chute block (XZ plane) was assessed at both X and Z directions. The results are as follows:

1) At an elevation of  $Z= H/8$  from the top face,  $C'_p$  was measured under different  $Fr_1$ s and values of increasing  $S_d$  with observations being shown in Figures 8 and 9, respectively. As can be seen from Figure 8, the variation of  $C'_p$  with  $Fr_1$ s increased in the X-direction passes its maximum at  $4 > x/d_1 > 1.5$  and decayed towards downstream edge of the block.  $C'_p$  tends to decrease as  $Fr_1$  increases.

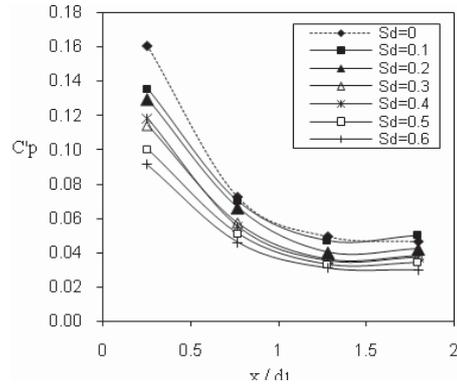


**Figure 10.** Variation of  $C'_p$  with  $Fr_1$  at XZ-plane and in Z-direction at  $x= 15/16 L$  for free hydraulic jump ( $S_d= 0$ ).

The effect of submergence ratio on  $C'_p$  is demonstrated in Figure 9. As it was stated previously, the increase in  $S_d$  values would inversely affect the pressure fluctuation at XZ plane in the X direction.

Variation of  $C'_p$  at XZ plane in Z directions at  $x= 15/16L$  under different  $Fr_1$  and  $S_d$  values was observed and the results shown in Figures 10 and 11 respectively.

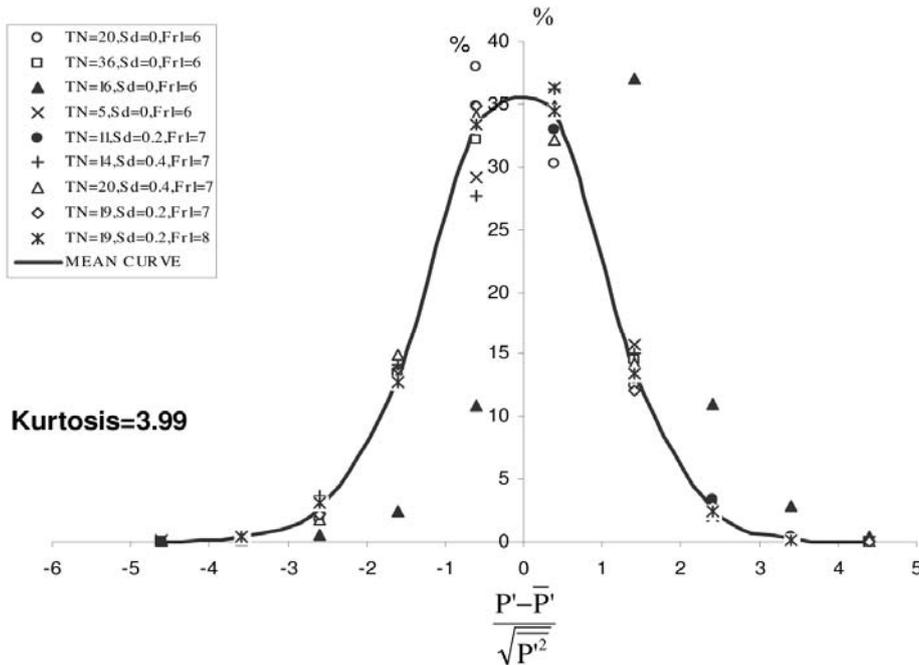
Figure 10 shows an increasing trend of  $C'_p$  with  $Fr_1$  at XZ- plane, tending towards zero



**Figure 11.** Variation of  $C'_p$  with  $S_d$  at XZ-plane and in Z-direction at  $x= 15/16 L$  for  $Fr_1= 7$ .

pressure fluctuation in Z- direction and becoming independent from  $Fr_1$  values. It is also shown in Figure 11 that the submergence ratios would inversely affect the pressure fluctuation at XZ plane in Z direction. The observations showed that the pressure fluctuations at the downstream edge of chute blocks tend to be zero either X-wise or Z-wise reflecting the possibility of flow separation at the entire edge of the chute block, which might end up with cavitation.

Figure 12 shows typical experimental



**Figure 12.** Probability density distributions of pressure fluctuations.



probability density of the pressure fluctuations for various Froude numbers and submergence ratios at different pressure holes. Analysis of the results gathered in the present research shows that the peak instantaneous pressure fluctuations could be as large as  $\pm 4.5$  times the *RMS* value, as depicted in Figure 12.

## CONCLUSIONS

The pressure fluctuations around chute blocks of SAF stilling basins were, for the first time, observed under various flow conditions and under various submergence ratios which led to the following conclusions:

The pressure fluctuation at flow direction and on the top face of chute blocks reaches its maximum at the toe of spillway, where it joints to chute blocks and decreases thereafter towards downstream reach.

The value of peak pressure fluctuation on the top face of the chute blocks is negatively related to Froude number of incoming flow with a decaying exponential relationship. The position of occurrence follows a rising exponential relationship with Froude number of incoming flow. It was also observed that the peak pressure fluctuation on the top face of the chute blocks is a polynomial function of second order with its parameters a function of  $Fr_1$ .

The pressure fluctuation at flow direction on the side face has a similar trend to the top face with a different relationship. The fluctuation in vertical direction increases from top to the bottom of the blocks decreasing with submergence ratio so that it tends towards zero under free hydraulic jump. This may result in flow separation at the downstream edge of the chute blocks which could cause cavitation.

Statistical analysis showed that the peak instantaneous pressure fluctuations could be as large as  $\pm 4.5$  times the *RMS* value.

Submerged flow operation in SAF basins is recommended as indicated by the results. However, if the operation under free

hydraulic jump is to be the frequent condition of operation, it is recommended that the downstream face of the chute blocks be rounded.

Further investigations are suggested to study the pressure fluctuations around baffle blocks and end sill of SAF basin where these appurtenances may be subjected to probable cavitation.

## Nomenclature

- $A_1, B_1$  and  $C_1$  Function of  $Fr_1$
- $B, H$  and  $L$  Width, height and length of experimental chute block respectively
- $C'_p$  Coefficient of pressure fluctuation
- $C'_{pm}$  Maximum coefficient of pressure fluctuation
- $Fr_1$  Froude number of incoming flow to the stilling basin
- $L_B$  Length of stilling basin
- $Re$  Reynolds number
- RMS* Root Mean Square of Pressure Fluctuation
- $S_d$  Submergence ratio
- $T_w$  Tailwater depth
- $x, y, z$  Cartesian coordinates of each hole from origin O in Fig.2
- $x_m$  Longitudinal coordinates of the pressure hole where maximum pressure fluctuation occurs
- $d_1$  and  $d_2$  Super-critical depth and sub-critical flow depth respectively
- $g$  Gravitational acceleration
- $p'$  Measured pressure fluctuation
- $\overline{p'}$  Mean pressure fluctuation
- $v$  Mean flow velocity
- $v_1$  Mean flow velocity of incoming flow to the stilling basin
- $\varphi$  Function of
- $\rho$  Mass density of water
- $\mu$  Dynamic viscosity of water
- $\nu$  Kinematic viscosity

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## نوسانات فشار در اطراف بلوک های پای تنداب حوضچه آرامش ساف (SAF)

ج. فرهودی، س. م. سادات هلبار و ن. عزیز

### چکیده

ابعاد بلوک های پای تنداب در حوضچه های آرامش نقش مهمی در نوع و اندازه این گونه سازه ها ایفا می کند. یکی از شاخص های مهم در طراحی این بلوک ها نوسانات فشار است که می تواند سبب بروز پدیده خستگی در بلوک ها شود. علی رغم تحقیقات صورت گرفته توسط بسیاری از محققین، اطلاعات کافی در خصوص نوسانات فشار در اطراف بلوک های پای تنداب در حوضچه های آرامش فشرده از قبیل حوضچه های SAF وجود ندارد. در این مقاله، نتایج تحقیقات آزمایشگاهی جدیدی در رابطه با نوسانات فشار در اطراف بلوک های پای تنداب حوضچه های SAF ارایه شده است. نتایج نشان می دهد که در طراحی بلوک های پای تنداب اینگونه سازه ها نمی توان نوسانات فشار را نادیده گرفت. مشاهدات بیانگر آنست که روند تغییرات نوسانات فشار با عدد فرود فوق بحرانی جریان بالادست جهش در وجوه



مختلف بلوک پای تنداب، افزایشی است. همچنین مشاهده شد که درجه استعراق جهش آبی اثرکاهشی در نوسانات فشار داشته و روند تغییرات آن، در وجوه مختلف بلوک، از الگوهای متفاوتی پیروی می کند.