International Journal of
Science and Engineering Investigations vol. 7, issue 79, August 2018
ISSN: 2251-8843

Static Pressure Estimation on Converging USBR II Stilling Basin: Numerical Approach

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Abstract-Investigation on the static pressure is one of the most important subjects on hydraulic modelling of the stilling basins. In spite of lots of research on stilling basins, sufficient information has not been reported on converging stilling basins. In this study, the static pressures were considered experimentally and numerically in parallel and converging stilling basin with 5◦, 7.5◦, 10◦ and 12.5◦ convergence that has been done on the model of USBR II stilling basin of Nazloochay dam in water research institute-Iran. Then, the flow was simulated in stilling basin using RNG, K-Ɛ, ONE equation, and LES turbulent models for discharges of 300, 500 and 830 m3/s. The results indicate that the best stilling basin regarding static pressure is converging stilling basin. Increase in convergence angle causes the raise on static pressure, and improves the performance of the stilling basin Based on the pressure distribution in the bottom of stilling basin, it can be inferred that that the pressure does not follow hydrostatic pressure especially at the beginning of the stilling basin. The comparison of different turbulence models demonstrates that K-Ɛ and RNG models give excellent pressure estimation. Moreover, the results indicate the 30 meters difference between the minimum and maximum pressures in different discharges in the converging stilling basin.

Keywords- *Static Pressure, Converging Stilling Basin, Experimental Model, Turbulence Models*

I. INTRODUCTION

Stilling basin is a hydraulic structure which mostly locates after the chute and before downstream to dissipate energy via hydraulic jump. (Vischer and Hager 1998, Chanson 2015). Providing a hydraulic jump as well as controlling the jump location are considered as important parts of designing stilling basins which have been highlighted by different researchers There are different types of stilling basins and in all types the designing purpose is providing stable jump. Many experimental and numerical studies have been done regarding the hydraulic jump in the stilling basins (Rajaratnam, 1968; Hager, 1992; Jonsson et al., 2011; Lubin and Chanson, 2010).

Pressure fluctuations on the walls and bottom of the stilling basin can cause damages; therefore, studying pressure fluctuations and immediate treatment of flow are the most important issues in hydraulic Engineering. Hydrodynamic characteristics and pressure fluctuations of the hydraulic jump have been widely considered after the failure of stilling basin of Karnafuli Dam in Mexico and Bangladesh and Malpaso. Pressure fluctuations, in the mentioned structures, affected the concrete slabs, and caused the great damages in the weir and stilling basin of them (Bowers and Toso, 1987). Karki (1976) reported the mean pressure values on the end sill of the stilling basins, also, presented useful data about the effect of hydraulic jump’s location pressure distribution profile. Armenio et al., (2000) investigated the pressure fluctuations at the bottom of hydraulic jump using an inversed step. Gehlot and Tiwari (2014) reviewed several models of the stilling basin with rectangular and circular pipe outlet which have been done by other researchers.

Also vertical gate opening simulation performed by Hamedi (2016) beside NEXARD data that was used in the current numerical approach played an important part for convergence criteria.

Gamal et al., (2016) investigated the impact of different shapes of stilling basin with different heights of the end steps on characteristics of submerged hydraulic jump and energy dissipation at downstream of a sluice gate. Shearin-Feimster (2016) focused on the tail water effect on designing of several stilling basins in the United States. Chen et al., (2010) simulated flow as 3-Dimensional in stilling basins using VOF k-ε RNG and Mixture RNG k-ε models. They stated that the simulated water depth, velocity profile, and pressure distribution are in good agreement with the experimental data. Moreover, they claimed that the Mixture turbulence model is better than the VOF turbulence model for calculating the air entertainment. Guven et al., (2006) utilized a neural network to predict pressure fluctuations in a sloped stilling basin and developed a formula to calculate the average pressure fluctuations based on the features with the most impact on the hydraulic jump. Valero et al., (2016) studied the performance of USBR III stilling basin at downstream of the ogee and stepped spillways numerically. They employed unsteady RANS equations together with VOF method as well as k-ε RNG model to simulate free surface and turbulence flow respectively .

DFT study of adsorption also should a good approach for USBR II stilling basin.

Simulations in term of optimization and energy loss which was performed by Hamedi (2014, 2016), is used initially for calculation of static pressure in the current numerical approach.

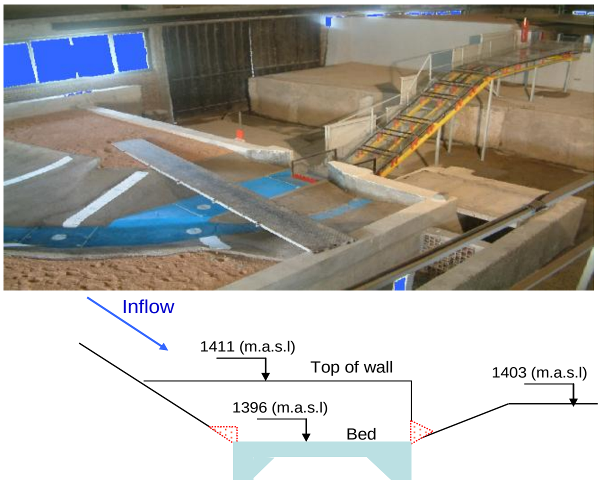
Some other studies also have been conducted on the pressure flactuations in the hydraulic jump stilling basin (Blaisdell, 1943; Harleman, 1955; Narayanan and Schizas, 1980; Armenio et al., 2000).

At the first time, Jumping in converged stilling basins was investigated by Ippen (1951). Chanson and Montes (1995) were studied experiments on a hydraulic jump in converged sections at rectangular channels. Their research has shown that the classical theory of hydraulic jump convergent points during a hydraulic jump is more consistent with supercritical flows. Pirestani et al., (2012) investigated the impact of convergence walls on energy dissipation in the stilling basin experimentally. In addition, Babaali et al., (2015) simulated hydraulic jump in stilling basin with convergence walls using flow-3D .

As it is clear from the literature review, just little number of researchers has paid attention to the converged stilling basins. In this study, the USBR II stilling basin of Nazloochay dam model in water research institute in Iran was modified to estimate pressure fluctuations. Then, stilling basin was numerically simulated in six scenarios using computational fluid dynamics in discharges of 300, 500 and 830 m3/s. Finally, the most appropriate scenario of stilling basin was chosen.

II. METHODOLOGY PHYSICAL MODEL

In this study, static pressure has been investigated in stilling basin model of Nazloochay dam in water research institute-Iran. Nazloochay reservoir dam was built with a height of 100 meters on Nazloochay River in north-western-Iran. The hydraulic model of flooding discharge system was made on the based on similarity of Froude number with 1:40 scale. The bottom of the basin, walls of weir and stilling basin was made by Plexiglas. Flooding discharge system of dam includes input channel, ogee free overflow, chute and USBR II stilling basin (Figure1).



description	chute	Stilling Basin	riprap	River bed
Length(m)	104.11	43.0	21.0	……..

Figure 1. Hydraulic model of Nazloochay dam

Stilling basin of Nazloochay dam has been designed for flooding 500 m^3/s with a 1000-year return period. For measuring hydraulic parameters in the stilling basin, six sections have been selected and reported in Table 1 and Figure 2. A total 21 piezometers were installed in three rows at the bottom of the stilling basin, also, on the side walls 28 piezometers in two rows were installed to measure the pressures (Figure 3).

TABLE I. MEASURED SECTIONS IN THE STILLING BASIN

The measured sections	N	O	P	Q
The distance from the measured sections to weir sill (m)	270	285	300	315

Figure 2. Sections of measuring hydraulic parameters

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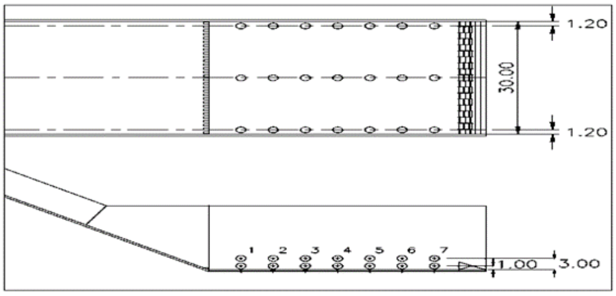

Figure 3. . Position of piezometers

III. NUMERICAL MODEL

The mathematical models must be able to represent the unsteady and arbitrary shape of the free surface, the curved rigid boundary, and the turbulence dynamics to successfully simulate the flow in stilling basins (Wu and zheng 2010; Wang and et al., 2009).

Numerous mathematical models are available to simulate the flow turbulence based on the Reynolds-Averaged Navier-Stokes equations (RANS) with eddy-viscosity models for high-velocity and widely engineering usages (Davidson 2015, Felder and chanson 2013). The mathematical model which has been used in this study solves RANS equations by using Volume-of-Fluid (VOF) method to simulate the behavior of flow free surface. Moreover, the Fractional Area / Volume Obstacle Representation (FAVOR) method has been used for rigid obstacles and volumes .The basic equations of continuity and momentum (Navier–Stokes equations) are defined as follows:

The continuity equation is given for fluid flow at three-dimensional Cartesian coordinates as Equation 1:

$$V_F \frac{\partial P}{\partial t} + \frac{\partial (uAx)}{\partial x} + \frac{\partial (vAy)}{\partial y} + \frac{\partial (wAz)}{\partial z} = \frac{R_{SOR}}{\rho}$$

Where V_f is the volume fraction of the fluid, P is the fluid pressure, ρ is the fluid density, (u, v, w) are velocity components in the (x, y, z) directions, A_x, A_y, A_z are cross-sectional areas of the flow, R_{SOR} is the term of mass source.

The following equations which was derived by Zeidi and Mahdi (2015) with its detail played an important role to find the following equations. In the mentioned study, an Eulerian/Lagrangian approach was used by utilization of RANS equations and those derivations played an important role for calculating equation 3 and 4.

The three-dimensional momentum equations are given in the Equation 2.

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\{uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}\} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_x + f_x$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}\{uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z}\} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + G_y + f_y$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}\{uA_x \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z}\} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + G_z + f_z$$

where G_x, G_y, G_z are the accelerations created by body fluids, f_x, f_y, f_z are viscosity accelerations in three dimensions, and V_F is related to the volume of fluid, defined by Equation 3:

$$\frac{\partial F}{\partial t} + \frac{1}{V_F}\{\frac{\partial}{\partial x}(FA_x u) + \frac{\partial}{\partial y}(FA_y v) + \frac{\partial}{\partial z}(FA_z w)\} = 0$$

Prandtl Mixing-Length Model, One equation Turbulent Energy Model, Re-Normalization Group methods (RNG), K-epsilon and Large Eddy Simulation (LES) were used in this study to simulate pressure in stilling basin.

IV. VERIFICATION, MESHING AND BOUNDARY CONDITIONS

In this study, the end structures and walls of USBR II stilling basin of Nazloochay dam in water research institute – Iran have been modified to investigate the pressure in stilling basin. Then the flow has been simulated in stilling basin using numerical model. In addition, USBR II stilling basin has been used to verify the numerical model. (Figure 4).

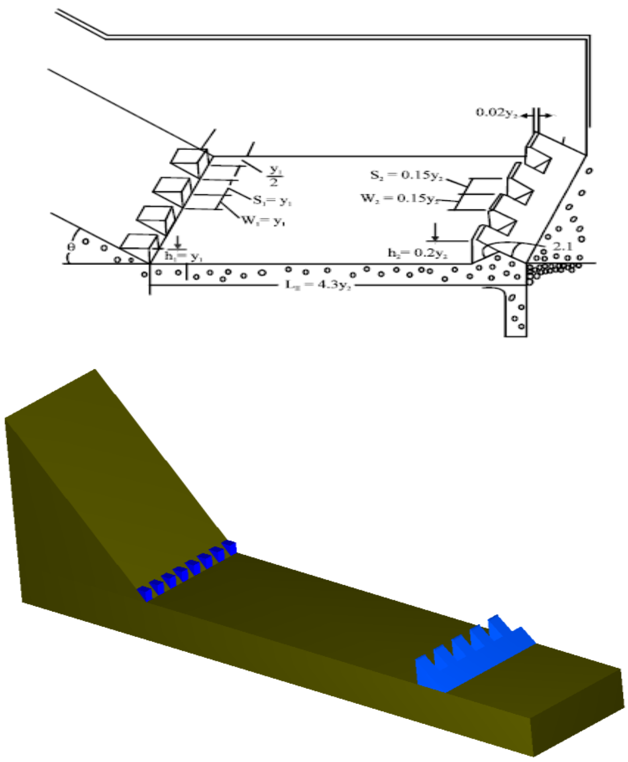

Figure 4. USBR II stilling basin

The number of meshes were investigated in (x, y, z) directions by using maximum aspect ratios and maximum adjacent cell size ratio parameters to make the solution more accurate and improve the quality of the grid. The number of them should be less than 3 and 1.3 respectively. Table 2 presents the characteristics of the numerical and experimental model of USBR II stilling basin. In figure 5, a computational grid of USBR II stilling basin model are presented.

TABLE II. MODEL CHARACTERISTICS OF USBR II STILLING BASIN

	Basin length (m)	Basin weight (m)	Mesh Dimension	Initial depth (m)	Conjugate depth (m)	Initial velocity (m/s)	Q (m^2/s)
Experimental Model	70.20	20		1.33	16.38	32.46	43.2
Numerical model			0.5*0.5*0.3	1.32	15.92	32.36	43.2

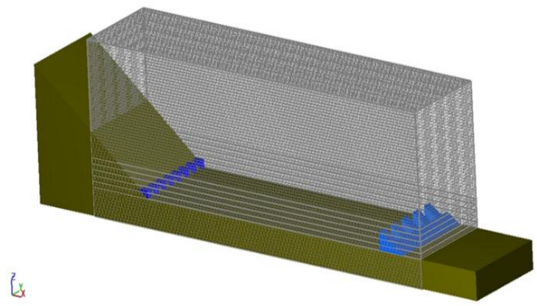

Figure 5. Computational grid of USBR II stilling basin model

The boundary conditions which have been used in this study are listed below:

- Upstream boundary condition (x_{min}): Specified velocity
- Downstream boundary condition (x_{max}): Specified pressure
- Side walls (y_{min}, y_{max}): Symmetry
- Lower (z_{min}): Specified pressure
- Upper (z_{max}): Symmetry

In figure 6, the values of flow depth obtained by numerical model have been presented to compare with experimental results in USBR II stilling basin.

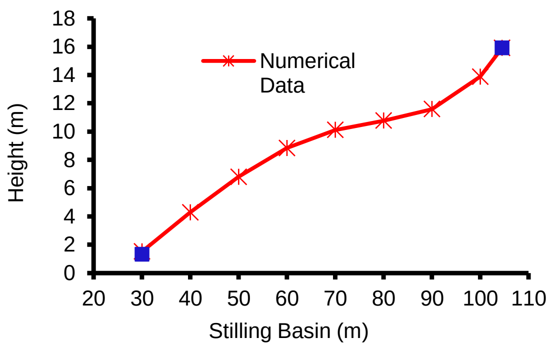

Figure 6. Flow depth versus the length of stilling basin

According to Figure 6, the flow depth in the inlet and outlet of the USBR II stilling basin physical model are respectively 1.32 and 15.92 meters, while the difference of flow depth between numerical and experimental model is almost zero in inlet and about 0.46 meters in outlet (less than 3%) which show a high accuracy of the numerical model.

V. RESULTS AND DISCUSSION

In this study, the structure of USBR II stilling basin of Nazloochay dam model was modified and the pressure was investigated in three scenarios which are listed below:

1. The Stilling basin with parallel walls and end adverse slope

2. The Stilling basin with parallel walls and end adverse steps

3. The Stilling basin with converged walls and end adverse steps

In all mentioned scenarios, the entering flow to the stilling basin is a supercritical flow with high-range Froude number. Then, the hydraulic jump happens inside the basin to dissipate the energy. Finally, the subcritical flow can be seen after the basin.

A. Stilling Basin with Parallel Walls and End Adverse Slope

In this scenario, stilling basin was modeled by applying adverse slope (1:3; V: H) at the end the stilling basin of Nazloochay dam (Figure 7).

Figure 7. USBR II stilling basin with parallel walls and end adverse slope

B. Stilling Basin with Parallel Walls and End Adverse Steps

In this scenario the dentate were eliminated and adverse steps were added instead of them to the end of the stilling basin (figure 8). The values of pressure in the stilling basin with parallel walls and end adverse steps are presented in figure 9.

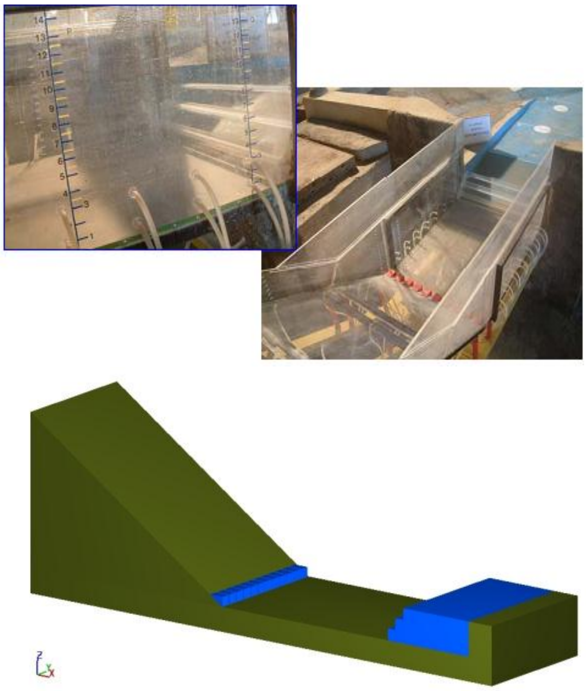

Figure 8. USBR II stilling basin with parallel walls and end adverse steps

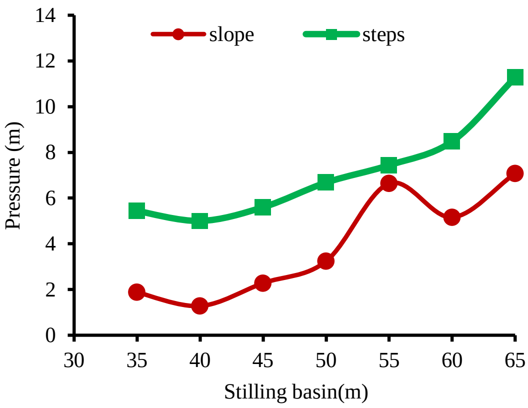

Figure 9. Pressure changes in the stilling basin with parallel walls and end adverse steps

As it can be seen in Figure 9, the static pressures increased at the end of the stilling basin when the end structure of the basin was modified.

The results indicate that the stilling basin with parallel walls and end adverse steps performs better than end adverse slope. Although modifications which have been done to the structure lead to stable hydraulic jump in the basin, still serious problems can be seen on the performance of basin in large discharges. Therefore, stilling basin with converged walls was used to improve the performance of the basin.

Figure 10 shows the pressure around inlet and outlet obstacles at stilling basin in discharge 500 m^3/s. In this figure, it can be seen that the pressure in front of obstacles is increased because the flow is encountered to obstacles.

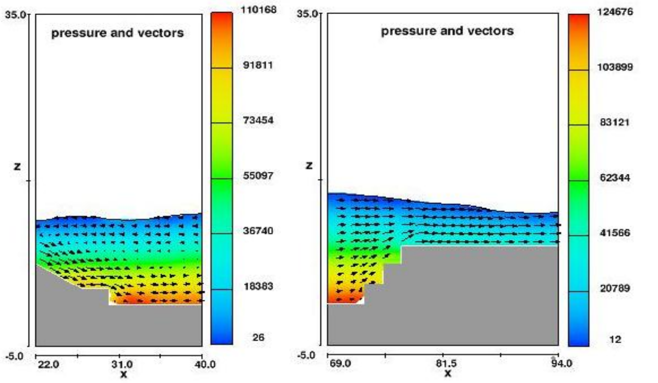

Figure 10. Pressure around obstacles, Q= 500 m^3/s

C. The Stilling Basin with Converged Walls and End Adverse Steps

In this scenario, converged walls have been symmetrically installed in the stilling basin with 5°, 7.5°, and 10° and 12.5° convergence (Figure 11). In figure 12, pressure distribution is shown at different altitudinal levels in converging stilling basin with 10° convergence.

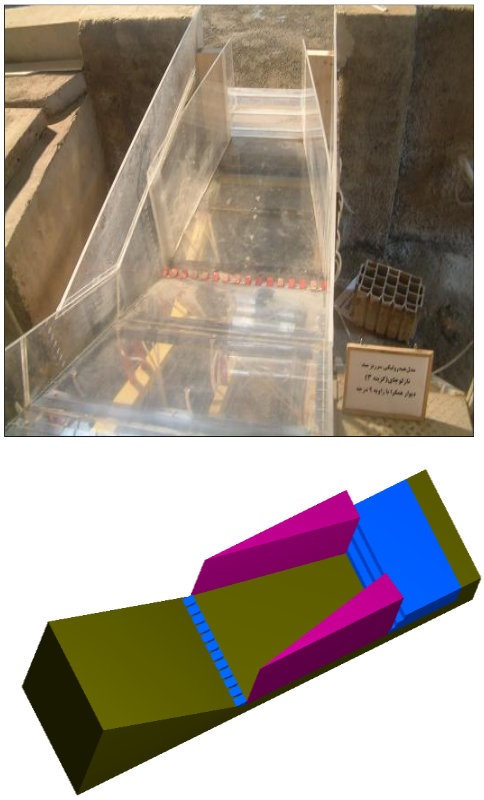

Figure 11. USBR II stilling basin with converged walls and end adverse steps

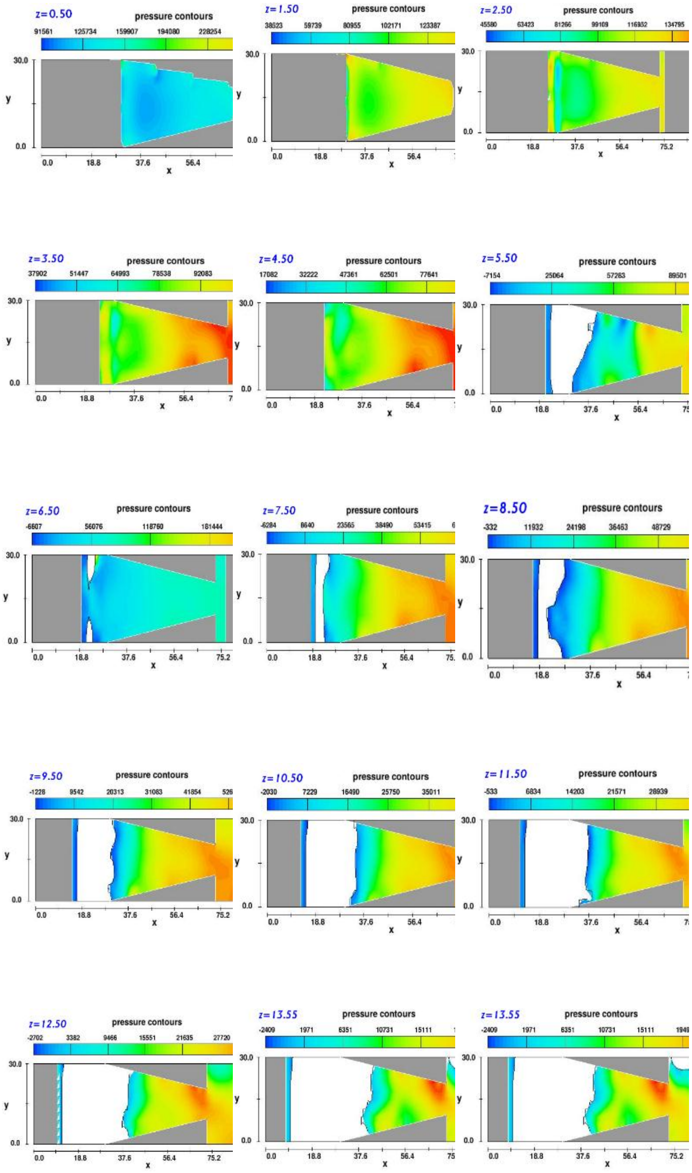

Figure 12. Pressure distribution at different height levels with 10°convergence in stilling basin

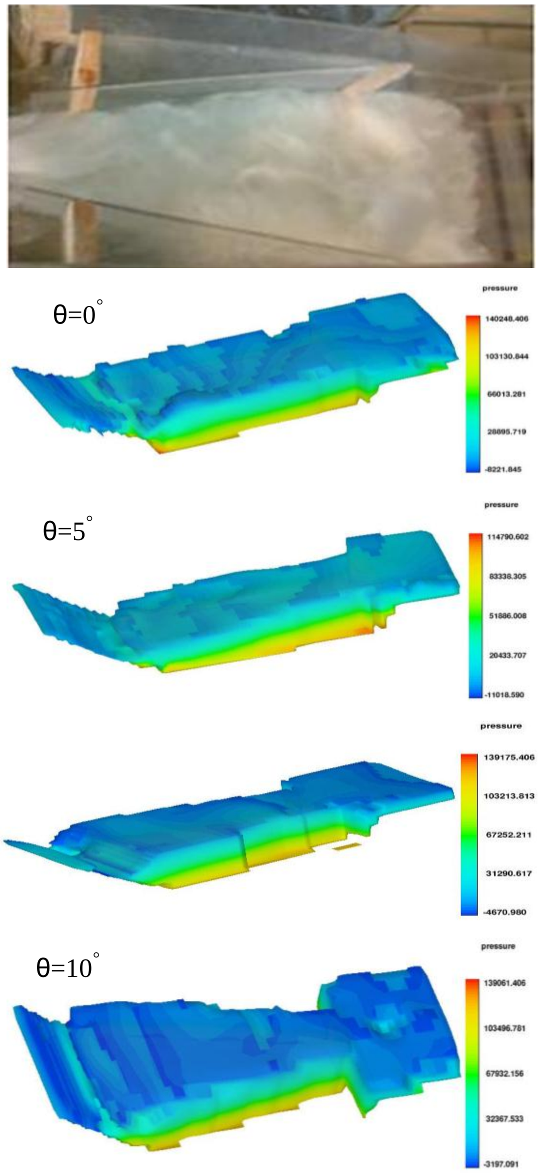

Figure 13. Pressure in stilling basin with converged wall (from top to bottom θ is 0, 5, 7.5 and 10 degree)

Comparison of the pressure at different altitudinal levels shows that because the flow encounters the obstacle, the maximum pressure happens in the middle of the basin (Figure 12).

D. The Impact of the Angle of the Convergence Walls on the Pressure

The pressure has been simulated in the stilling basin with converged wall (Figure 13).

In figure 14, pressure fluctuations have been presented in different convergence angles of stilling basin.

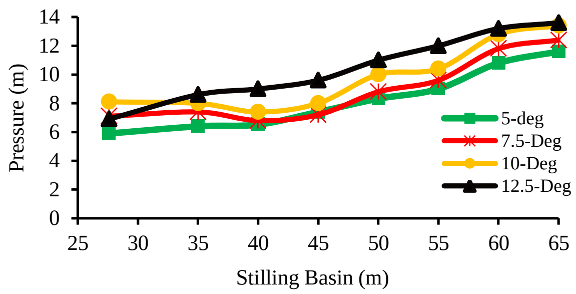

Figure 14. Values of experimental pressure in the stilling basin with converged wall, Q = 830 m3/s

The results indicate that raise in convergence angle leads to increase the value of pressure (Figure 14). With converging stilling basin walls, the length of hydraulic jump reduces in the outlet of stilling basin.

E. The Effect of Different Turbulence Models on Pressure

In Figure 15, numerical simulation of flow in stilling basin with converged wall has been shown for different turbulence models with 12.5^0 convergence and discharge 300m^3/s.

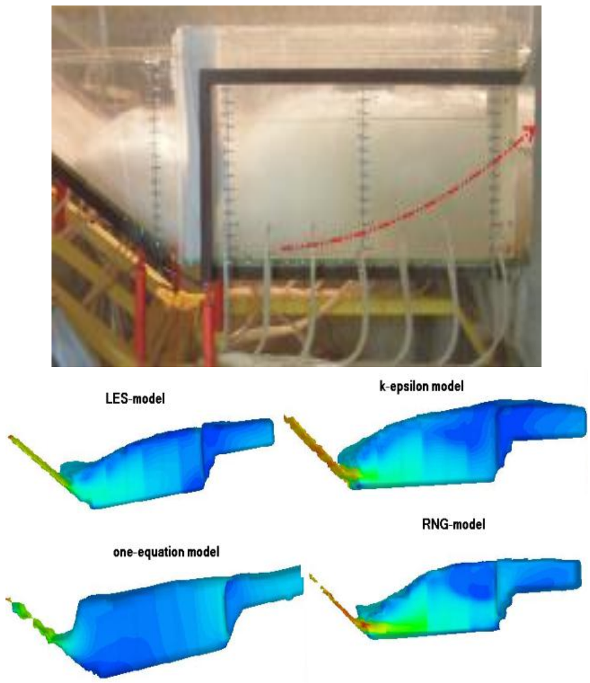

Figure 15. Numerical simulation of the stilling basin with converged wall, 12.5^0 convergence, Q=300m^3/s

In Table 3, experimental and numerical values of pressure are presented in stilling basin with converged wall with 12.5^0 convergences and discharge 300 m^3/s.

Comparison of experimental and numerical values of pressure indicates that values of pressure for RNG and K-Ɛ turbulence models have the most agreement with the experimental results rather than other models (Table 3). In figure 16, the pressure values have been presented in converging stilling basin for different turbulence models in discharge 300 m^3/s and 12.5-degree convergence.

According to the figure 16, it can be stated that K-Ɛ and RNG turbulence models present values close to experimental data. Also, ONE-Equation turbulence model is less reliable than other models because of the nature of hydraulic jump and forming mathematical model. In figures 17 (a) and (b), static pressure has been calculated for different convergence angles in discharge 830 m3/s and RNG and K- Ɛ turbulence models. As it can be seen from figures 17 (a) and (b), the pressure increases in the stilling basin with increasing convergence angle.

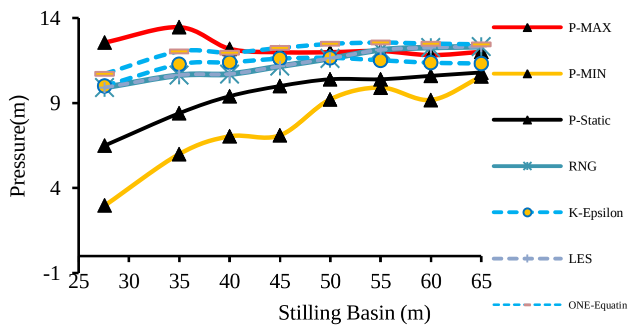

Figure 16. Computational pressure in stilling basin with 12.5° convergence, Q=300 m^3/s

TABLE III. EXPERIMENTAL AND NUMERICAL RESULTS OF THE PRESSURES IN THE STILLING BASIN WITH12.5^0 CONVERGENCE AND Q=300 M^3/S

[3] Q=300m^3/s [4] d=12.5º	[2] Experimental values			[1] Numerical values			
[12] X(m)	**[11] Max**	**[10] Min**	**[9] Static**	**[8] RNG**	**[7] K-Ɛ**	**[6] LES**	[5] ONE
[20] 27.6	[19] 12.56	[18] 2.97	[17] 6.5	[16] 9.91	[15] 10.01	[14] 9.91	**[13]** 10.72
[28] 35	[27] 13.46	[26] 6	[25] 8.4	[24] 10.63	[23] 11.28	[22] 10.63	**[21]** 12.03
[36] 40	[35] 12.19	[34] 7.04	[33] 9.4	[32] 10.7	[31] 11.39	[30] 10.70	**[29]** 11.96
[44] 45	[43] 11.99	[42] 7.10	[41] 10	[40] 11.16	[39] 11.61	[38] 11.16	**[37]** 12.23
[52] 50	[51] 11.99	[50] 9.22	[49] 10.40	[48] 11.62	[47] 11.66	[46] 11.63	**[45]** 12.47
[60] 55	[59] 12.06	[58] 9.91	[57] 10.40	[56] 12.12	[55] 11.51	[54] 12.12	**[53]** 12.55
[68] 60	[67] 11.82	[66] 9.18	[65] 10.6	[64] 12.26	[63] 11.37	[62] 12.26	**[61]** 12.49
[76] 65	[75] 12.01	[74] 10.56	[73] 10.8	[72] 12.31	[71] 11.32	[70] 12.31	**[69]** 12.45

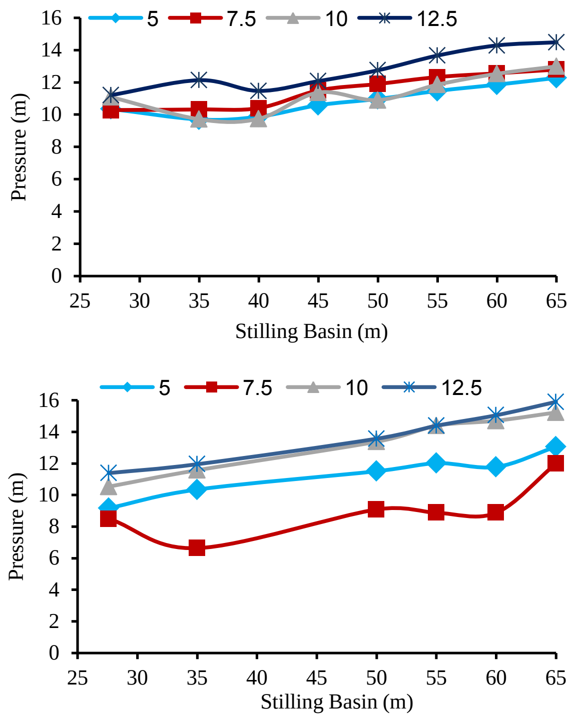

Figure 17. Static pressure in converging stilling basin, Q=830 m^3/s

F. *The impact of discharge on the pressure in the converging stilling basin*

In this section, pressure changes have been investigated for discharges of 300, 500 and 830 m^3/s by using different turbulence models .In figures 18 (a, b and c), pressure values have been illustrated in converging stilling basin for different discharges and turbulence models.

Comparing the pressure values in figures 18 (a, b and c) shows that raise the discharge in the inlet of the stilling basin lead to raise in pressure. Also, in some places, the pressure is negative, and maximum and minimum pressures difference is more than 30 meters.

VI. CONCLUSION

Stilling basin is one of energy dissipaters which has been used at downstream of the hydraulic structures such as gates, weirs, and chutes. In these hydraulic structures, flow is accompanied with high energy rate as well as high turbulence and pressure fluctuations. In this study, the model of the USBR II stilling basin of Nazloochay dam in water research institute-Iran were modified and static pressures have been investigated by using different turbulence models in discharges of 300, 500 and 830 m3/s. In this research, at first, adverse slope added to the end of the USBR II stilling basin then it removed and changed to adverse steps. Finally, walls of the basin were converged. Either of experimental and numerical values of pressure show that convergence of walls leads to increase pressure in stilling basin. The results of numerical simulations and experimental data carried out for static pressure show that the most appropriate stilling basin is stilling basin with converging walls and end steps. Moreover, the results indicate that raise in discharge leads to increase the pressure in the inlet of converging stilling basin, and using converging walls eliminates negative pressure in some sections. Furthermore, the pressures calculated numerically by using RNG and κ-$\mathcal{E}$ turbulence models give values between static and maximum pressure while ONE- Equation and LES turbulence models give values close to static and minimum pressure.

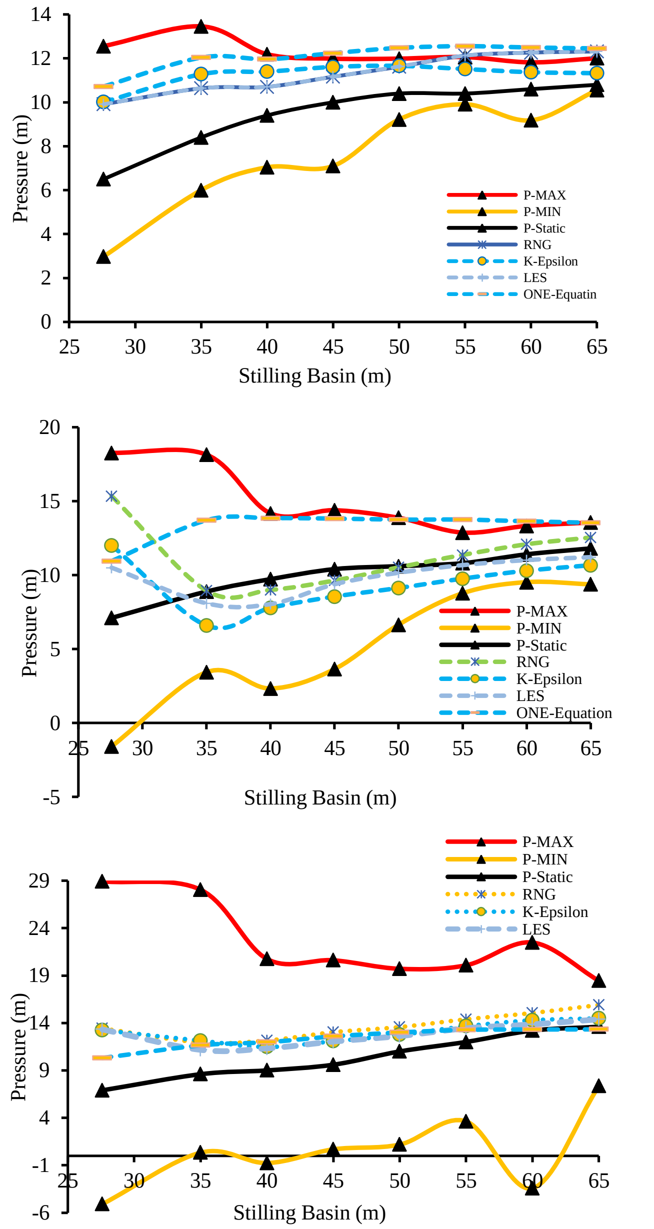

Figure 18. Pressure changes in the stilling basin with 12.5° convergence

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