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Impact of Chute Walls Convergence Angle on Flow Characteristics of Spillways using Numerical Modeling

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***Abstract*—**Concerns along with cost and valley geometry have led to interest in alternate spillway designs including convergent spillways. Hence, a study utilizing a three dimensional computational fluid dynamics (CFD) model was conducted using FLOW-3D to investigate the flow characteristics in these spillways with respect to different training wall convergence angles. It should be noted that in the CFD model, the similarity was achieved by the Froude number similarity law as well as boundary conditions and initial conditions were determined accordingly. Findings from this study showed that as the convergence angle of the training wall increased, the free surface profile as well as the velocity along the chute also increased. Also, through these investigations it was observed that an oblique hydraulic jump/shockwave along the training walls of the spillway has been occurred which caused turbulence in the flow and extra increase in flow depth near the walls. Also, through exploring the pressure values, it was relieved that due to the rise of the flow depth along the walls, the pressure increases near the chute walls accordingly. Furthermore, by calculating the cavitation number at different sections of the each numerical model it is realized that as the convergence angle of the model narrows, the cavitation index increases and consequently, the highest cavitation risk will be spotted for the least convergent model.

***Keywords*—** Convergent Spillway, Numerical Model, Flow Hydraulic Characteristics, Flow-3D.

I. Introduction

DAM construction has been one of the most important engineering activities throughout the world. Spillways are among the principle sections of a dam that are basically designed to pass big discharges in flood times. The constraints that have been imposed by site conditions such as geological formations and valley geometry usually dictate that spillways converge, yet engineers do not often advice or recommend convergent spillways because of the flow complexities that happen. The high costs of spillway construction as well as their plan service life completion make it necessary to do more and more investigation on this area. To date there has been no generalized guideline for convergent spillways. In this regard, a detailed knowledge of the flow behavior and the hydraulic characteristics through these spillways can be of a good assistance. Robinson et al. (1998) conducted a series of studies on a physical model of a steep stepped chute with convergence angles ranging from 0 to 32.5 [1]. Hanna and Pugh (1997) and Hunt (2008) and Woodbright (2006, 2008) investigated the hydraulic performance of stepped spillways with a convergence angle [2, 3, 4, 5]. Sabagh Yazdi et al. (2006) conducted numerical model studies on flow characteristics of Kamal-Saleh convergent chute using Nasir software [6]. Foroudi et al. (2014) utilized a 1:50 scale physical model study to conduct an investigation of cavitation index due to convergence angle [7]. Shayyan Seresht et al. (2014) conducted a research on cavitation index along Gavoshan Dam spillway using FLUENT numerical model and k-ϵ turbulence model [8]. This study is carried out to numerically model the flow over Kheirabad Dam Spillway using the CFD software FLOW-3D and investigate the flow characteristics in detail regarding various convergent angles.

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II. Case Study

Kheirabad Dam is an embankment dam with a clay core located on southeast of Khozestan province, Iran. The primary purpose of this dam is to prevent downstream floods, help meet energy demands, municipal water supply and irrigation. An ogee spillway is provided for Dam and joins to a chute of slope 12% with converging walls. In order to verify the applicability of the numerical model, its results are verified and validated using the laboratory data set available in this Dam’s report of prototype model. The prototype model tests were performed by Water Research Institute (Iran) based on a 1:50 scale Froude similitude model of the spillway. Accordingly, the velocity and flow depth values along the spillway crest and chute for various numerical model simulations were subjected to analysis and comparison with the results which were measured from the prototype model. The comparison points over the spillway are shown in Figure 1 and Table I [9].

TABLE I
MEASUREMENT POINTS OVER THE SPILLWAY

station	distance from the crest
A	0.4
B	1
C	2.7
D	3
E	6

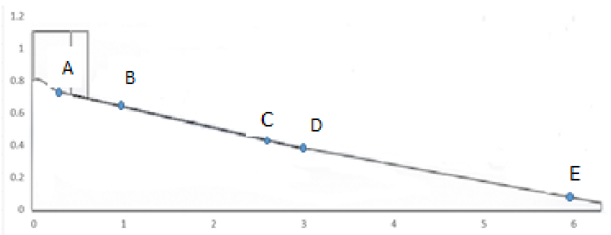


Fig.1 Measurement Points over the Spillway

III. THE NUMERICAL MODEL

The fundamental underlying equations in Flow-3D are Reynolds-averaged Navier Stokes (RANS) equations. The program uses a finite difference solution scheme and the Volume of Fluid (VOF) method which allows the model to include only the water portion of the flow neglect the motion of the surrounding air. Flow-3D also uses a fully structured computational grid by using a Fractional Area/Volume Obstacle Representation (FAVOR) method to define obstacles. The governing RANS and continuity equations for incompressible flow are:

$$\frac{\partial}{\partial x_i}(u_i A_i) = 0$$

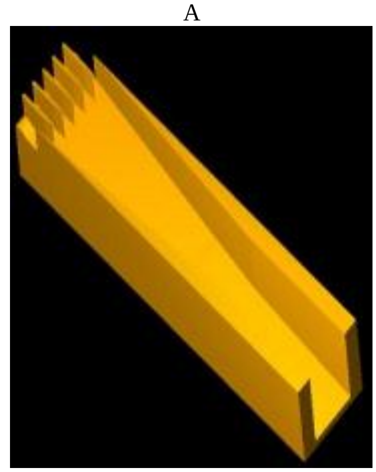
$$\frac{\partial u_i}{\partial t} + \frac{1}{V_F}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = \frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i + f_i$$

t is time; Ai is fractional areas open to flow in the subscript directions; ui represents the velocities in the xi directions; VF is volume fraction of fluid in each cell; ρ is density; whereas p is hydrostatic pressure; gi is gravitational force in the subscript directions and fi represents the Reynolds stresses[10].

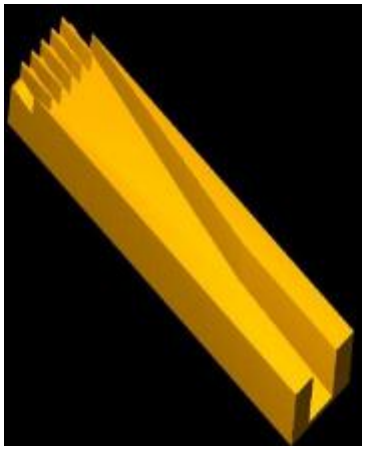
Yokhot showed in his studies on turbulence models that in comparison with k-ϵ model, the Renormalized Group Equations (RNG) model describe flows having strong shear regions and low intensity turbulence flows more accurately [11]. It should be noted that the RNG model is used as turbulence closure in this study. Three-dimensional solid geometry of Kheirabad Dam is drawn with no change using SolidWorks Modeling tool (Figure 1). In order to investigate the impacts of convergence angle on hydraulic flow characteristics of the spillway, three models with different convergence angles of 6, 8 and 12 are modeled and analyzed.

To obtain realistic results from the numerical model, a verity of mesh resolutions and boundary conditions were tested and analyzed for calibrating the model. In this regard the flow depth and velocity values of the appropriate model are compared with the ones of the prototype model along the measurement points presented in figure 1 (figure 3). It is noteworthy enough to mention that a symmetry condition is applied for the upstream boundary and a volume flow rate of 230 (l/s) is used. The bottom and side boundaries are assigned a wall boundary condition to represent the physical model environment. Furthermore, an outflow condition is used for downstream boundary and a symmetry condition is allocated to the top boundary which is considered as an inactive one. The flow region is subdivide into a mesh of rectangular cells. All of associated local average values of dependent variables are located in the centers of the cells except for velocities, which are located in cell faces. One should take into account that, mesh size is a weighty factor which affects the accuracy of results distinctively and at the same time has a direct connection with the duration of calculations. Regarding the seriousness of calculations at the spillway gates and also decreasing the computational processes, a multi resolution mesh grid was generated so that the accuracy of the results in the desired sections can be increased without dedicating considerably more computational resources and time than it takes normally. The mesh gird details are available in table II.

A



B



C

Fig 2 Physical Model Geometry of Kheirabad Dam Spillway, A) Convergence Angle of 12o, B) Convergence Angle of 8o, C) Convergence Angle of 6^0

The mesh generated model of the spillway is shown in figure 3.

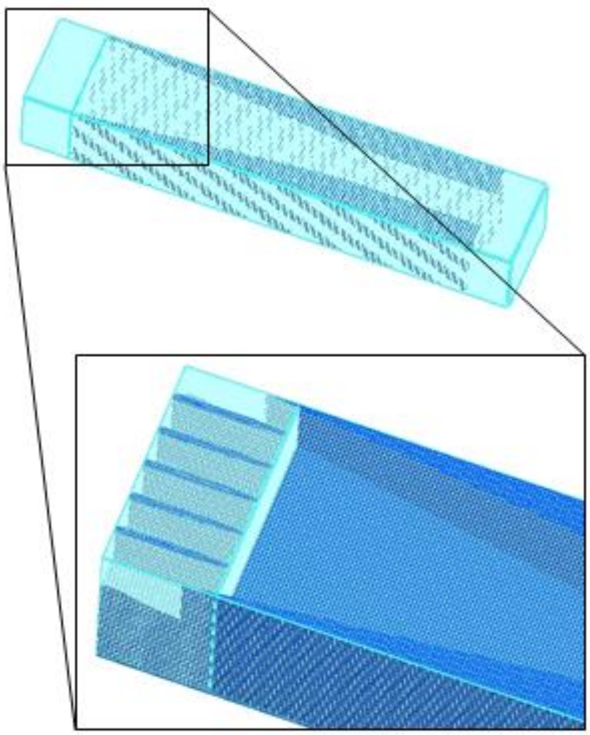


Fig.3 Multi Resolution Mesh of the Model

TABLE II
SUMMARY OF THE MODEL GRID GENERATION

Block	Total Number of Cells in x Direction	Total Number of Cells in y Direction	Total Number of Cells in z Direction	Total Number of Real Cells	Average Cell Size in x Direction
Block 1	110	60	55	363000	0.006
Block 2	280	60	55	924000	0.02

The velocity and flow depth of the calibrated model are compared with the experimental results of the physical model in figure 4.

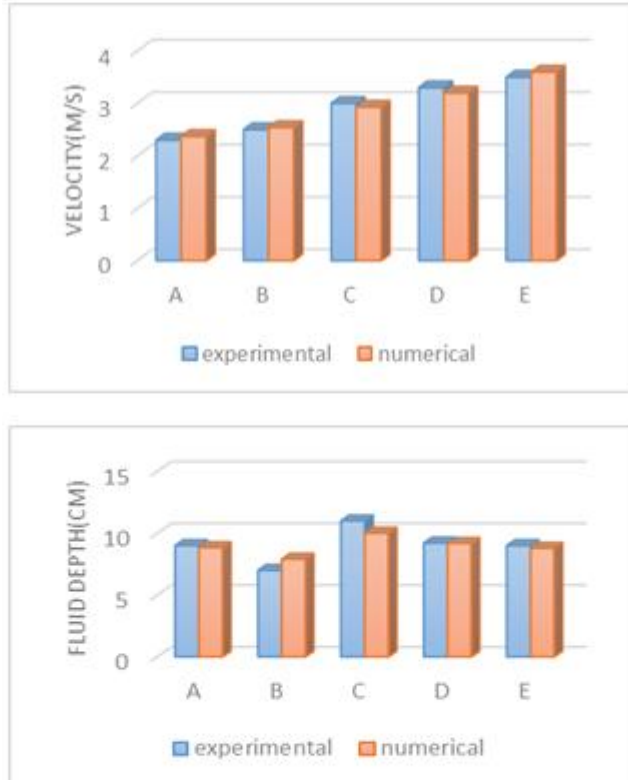


Fig.4 Physical model to Numerical Model Comparisons

IV. RESULTS AND DISCUSSION

In order to investigate the flow behavior through spillways with respect to convergence of the walls, convergence angles of 6o, 80 and 120 were applied to Kheirabad Dam's numerical model. The investigation includes examining the flow pattern and its characteristics due to changing the convergence angle of the walls. The free surface elevation is presented in figure 5 and as it shows, an increase in convergence angle leads to an increase in free surface elevation of the flow.

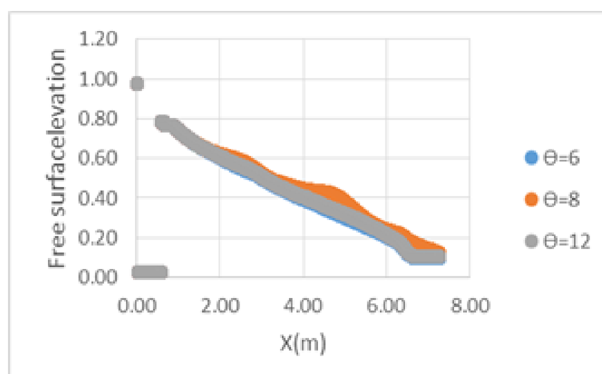


Fig. 5 Free Surface Elevation along the Chute for Multiple Convergences

Convergence leads to formation of an oblique shockwave along the training walls of the spillway and makes the flow run-up along the wall increase [12]. Figures 6 and 7 show the flow depth along the walls for several converging angles. Findings from these figures indicate that as convergence angle of the wall increased the flow depth along the wall also increased. It is noticed that the intensity of the increase is greater downstream of the spillway where the contraction end width becomes narrow. In the aforementioned figures, ϴ is convergence angle, yw is water depth across the walls, yc is critical depth and x represents distance from the crest.

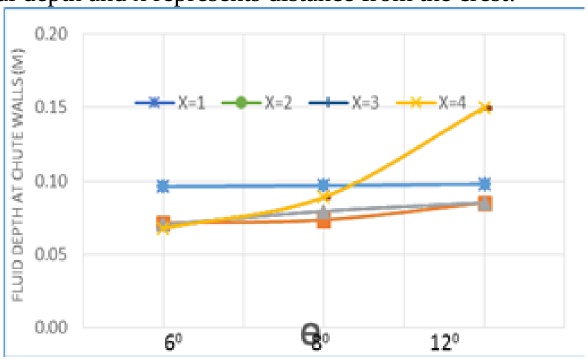


Fig.6 Flow Depth along the Walls vs. Convergence Angles

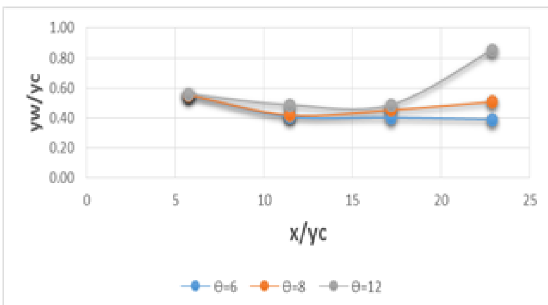
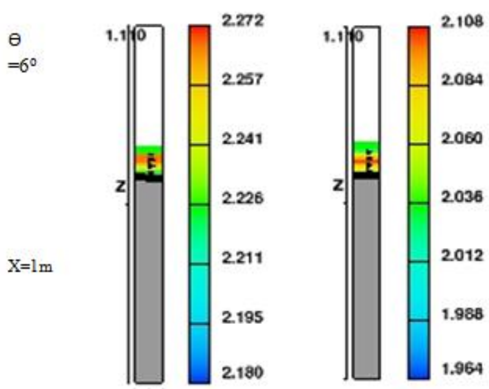
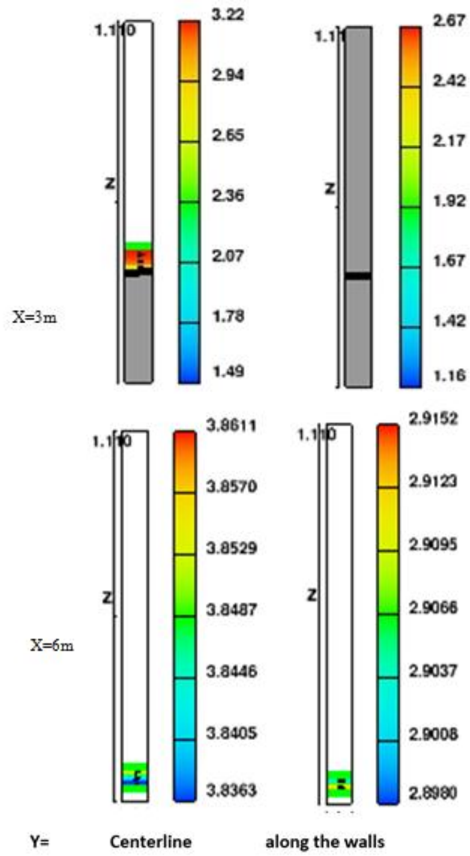
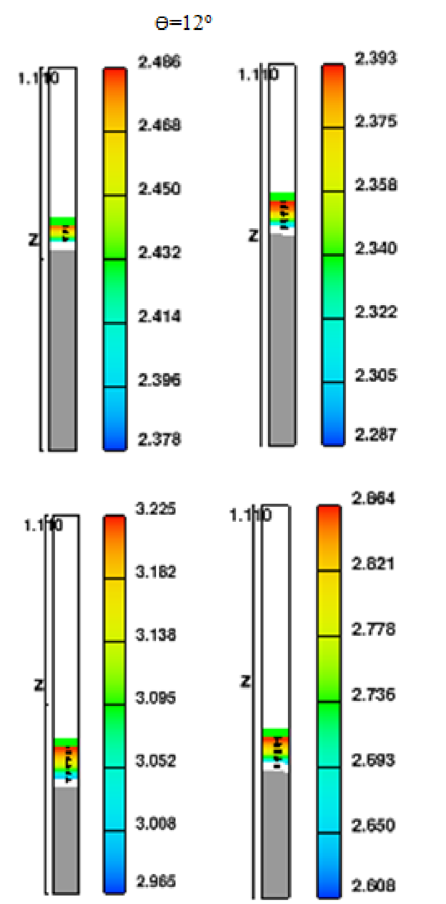


Fig.7 Non-Dimensional Plot of Flow Depth along the Walls vs. Critical Depth for Multiple Convergence Angles

For all three tested convergence angles, flow velocity distributions throughout water depths along three sections of the spillway is presented (figure 8).







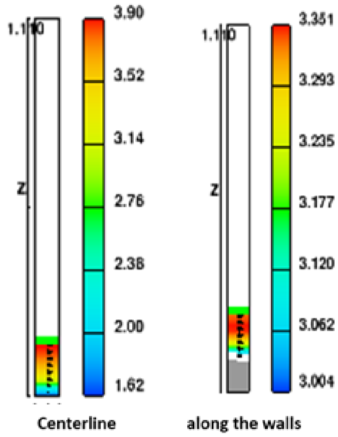


Fig. 8 Velocity depth profile for Three Longitudinal and two transverse sections for the three convergence angles

It is noted that as the flow depth decreases, the flow velocity increases and for higher convergence angles, the increase becomes even more rapid. It is perceived that throughout the spillway the velocities generally increase as the walls converge (figure 9). Due to the gradual increase of the velocity on the spillway and the constant decrease of the width, the velocity value grows much more rapidly in downstream parts of the spillway than the upstream section.

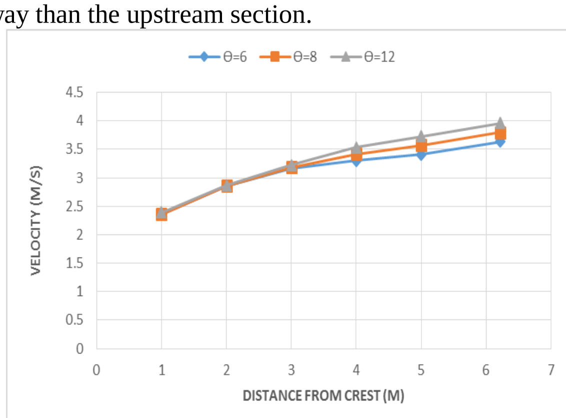


Fig.9 Flow Velocity along the Spillway for Various Convergence Angles

One of the principal factors that plays a critical role in spillway designs, is cavitation which is one of the most common and devastating causes of failure for the spillways. The potential of cavitation happening is evaluated by the cavitation dimensionless index, σ which can be calculated by the following equation:

$$\sigma = \frac{P - Pv}{\rho \frac{v^2}{2}}$$

Where P and V are the pressure and average velocity of the fluid respectively; whereas Pv is the water vapor pressure and at temperature of 20o is equal to 2330 Pa. Also, it is assumed the density of water ρ is 1000 kg/m3 and Patm is 83657.40 Pa. Figure 10 demonstrates that the convergence angle of ϴ=6 has the most critical scenario in terms of cavitation. According to the outcomes, there is almost an agreement between the increase of the convergence angle and cavitation index. Moreover, the gradient of the increase becomes more intense in downstream parts.

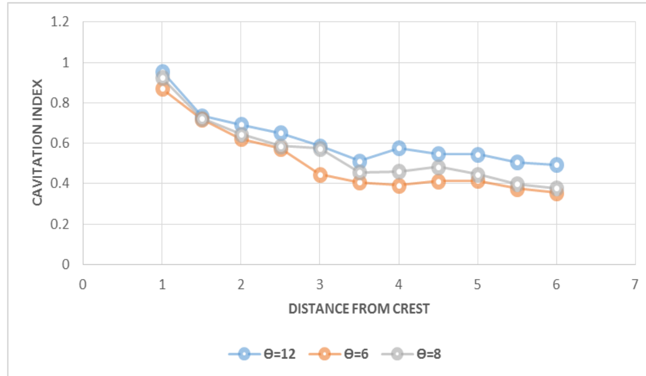
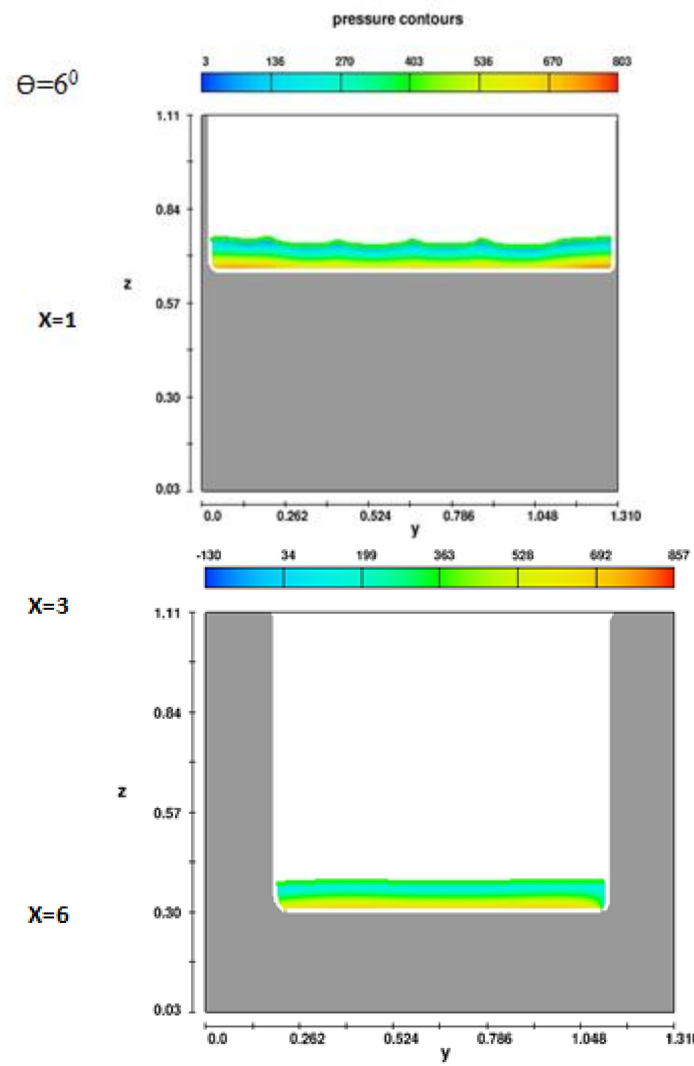
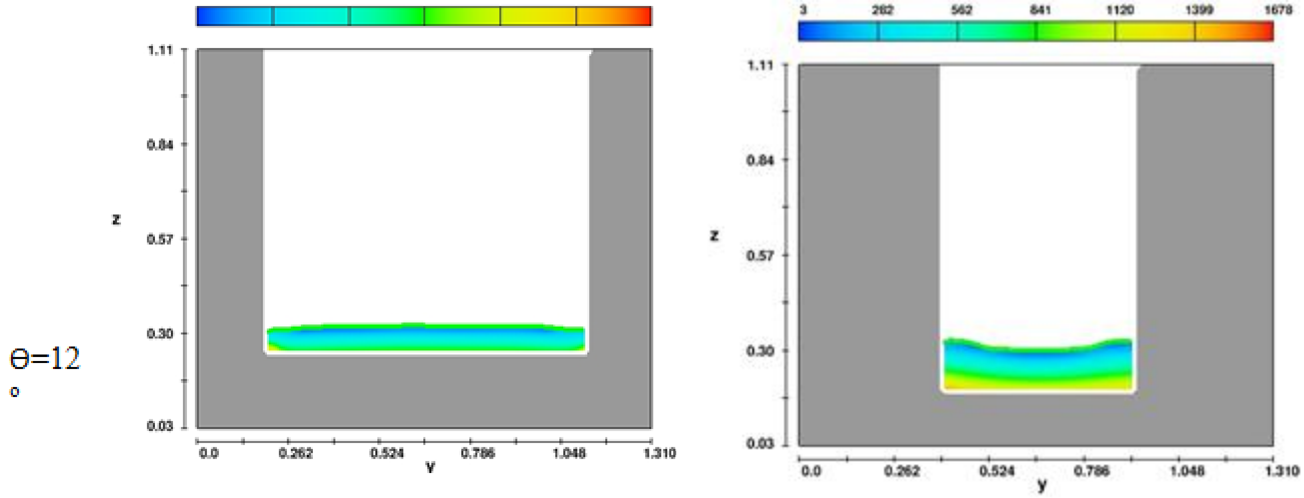


Fig.10 Cavitation Indexes along the Spillway for Various Convergences

Water pressure distributions across the spillway are shown in figure 11 for the three cross sections which are at the beginning, the middle and the end of the spillway. It can be inferred that because of the rise of the flow height along the chute walls (figures 6 and 7), the water pressure near the walls rises too. Also, the pressure values appear to approach a higher gradient for downstream as well as larger convergence angle.





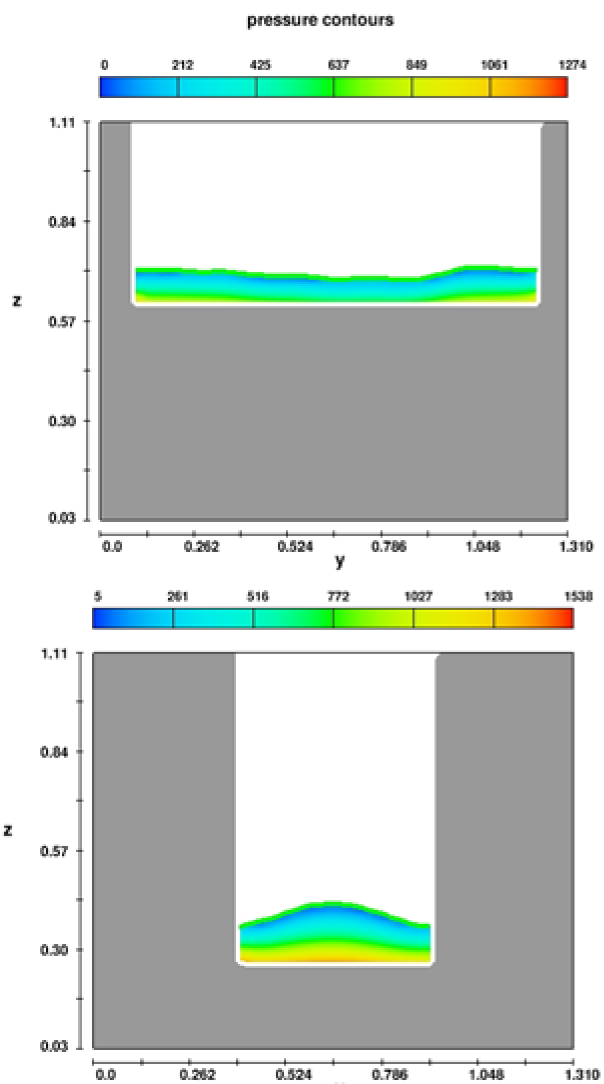


Fig. 11 Pressure gradient across the spillway in three longitudinal sections

V. Conclusion

Concerns with savings in rock excavation and limitations of valley geometry have highlighted the necessity of convergent spillways which offer major advantages in both cost and design. In the present study, the hydraulic characteristics of flow over Kheirabad spillway such as velocity, depth, cavitation index, pressure and their distribution pattern are investigated comprehensively with respect to convergence angle of the spillway walls. In this regard, the flow over the spillway is modeled numerically in three dimensions and the initial and boundary conditions were specified by the Froude similarity law.

Results show that water surface profile for all of the convergence angle scenarios increases considerably along the chute and it becomes even greater at higher angles. Besides, the spillway contractions lead to development of a standing shock wave at converging walls which results in a greater run-up height across the walls. As the walls converge more and more, a rapid increase in velocity occurs especially downstream of the spillway. Its major explanation lies in Spillway's width constriction due to convergence and subsequently the increase of the flow depth. Moreover, due to the increase of flow depth along the walls, the pressure values become greater and this behavior gets much more distinguishable as flow gets closer to the downstream end and the convergence angle increases. Additionally, the simulation results reveal that the most critical cavitation index takes place while the convergence angle is the least. Also, as the convergence angle becomes larger, the cavitation index generally increases, particularly downstream of the spillway.

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