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Numerical Modeling of Flow Field in Morning Glory Spillways and Determining Rating Curve at Different Flow Rates

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Abstract

Morning glory spillways with drop inlets are normally employed in dams built on narrow valleys or placed on steep slopes. In Iran, morning glory spillways have been commonly used in large Dam projects such as Sefidrood dam, Alborz dam, and Haraz dam. Physical models should be built to accurately determine hydraulic parameters of the flow and flow field in spillways. Establishment of a physical model involves extravagant costs and conditions that cannot be justified in some cases. Therefore, suitable numerical models can be proposed for such circumstances. Using FLOW3D numerical models, 3-dimensional numerical modelling of the flow was calibrated and validated by experimental information associated with morning glory spillway of Alborz dam and accuracy of numerical modelling was determined by relative error of numerical model. So it was attempted to determine flow pattern and control conditions of morning glory spillways in different modes using boundary conditions, inlet conditions and grid spacing of flow field and project rating curve of morning glory spillways. According to the results of numerical model, relative error of numerical modelling equals 6.4% for calculating discharge rate of the spillways. Numerical modelling error is 7.6% for determining depth parameter of the flow in spillway crest in comparison with experimental results.

Keywords: Morning Glory Spillway; Rating Curve; Numerical Model; Alborz Dam; FLOW3D.

1. Introduction

Morning glory spillway is a roofed conduit that quickly transfers the flow from an upper level to a lower level. This type of spillway is similar to siphon spillway but it performs different from siphon type. These spillways are not only used for dams, but also to control erosion of structures and highway culverts. Using this type of spillway is cost-effective in dams having steep abutments over narrow valleys or a diversion tunnel to transfer water flow to downstream of the dam. Moreover, morning glory spillways transfer the flow from upstream to downstream level (from catchment basin to tunnel drainage system in mountainous regions) in storm water drainage systems or water conveyance system. In such cases, morning glory spillways are employed with certain types of basins called “vortex basins” which give the flow an angular velocity leading to a circulating flow in glory hole. A variety of researches such as experimental studies, numerical modeling and simulations, analytic studies, etc. have been conducted on morning glory spillways. Here, it is attempted to present a set of the most important and recent studies in this field.

Ervine and Ahmed (1982) studied on flow aeration characteristics in a vertical nappe shaft [1]. In 2006, Zhao conducted experimental studies on hydraulic parameters of flow in morning glory spillways under nappe flow conditions [2]. Nohani and Mousavi (2009) investigated impact of number and thickness of vortex breaker blades on strength of spiral vortices and efficiency of the spillway discharge system by making a physical model of morning glory spillway and conducting experiments. The results showed that discharge coefficient of morning glory spillway enhanced up by 20% via increasing number of blades and 9% via increasing both number and thickness of blades [3]. In a study, Nohani and Naqshineh (2013) explored into effect of number, thickness and angle of vortex breaker blades

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on discharge coefficient of morning glory spillway by making a physical model and conducting experiments; so it was found that locating blades at angles 30 and 60 degrees had a greater impact on increasing flow rate than 90 degrees and also, enhancing thickness of blades reduced flow rate and discharge coefficient [4].

In 2014, Nohani's study was aimed to determine discharge coefficient of morning glory spillways under geometrical conditions of spillway crest using a physical experimental model. The study was carried out on morning glory spillways at different diameters with/without vortex breakers in spillway crest. It should be noted that type of crest edge was also assessed in this study. So, two kinds of crest edges, including sharp edged and flat edged crests, were examined in this study [5].

In 2014, Nohani and Jamali Imam Gheisi carried out an experimental study about effect of vortex breaker length on discharge coefficient in morning glory spillway [6]. In 2010, Nohani et al conducted an experimental investigation into effect of angle of anti-vortex plates on discharge coefficient in glory hole spillway [7].

In 2015, Xianqi examined flow characteristics in morning glory spillway of large dams. 5 different geometric and hydraulic plans were applied using a physical model and equation of discharge coefficient was determined for each morning glory spillway [8].

In 2010, Nohani and Heidarnejad conducted an experimental investigation into effect of angle of anti-vortex plates on discharge coefficient in glory hole spillway. The results demonstrated that discharge coefficient enhances by decreasing angle of anti-vortex plates; so that maximum discharge coefficient was obtained when five anti-vortex plates were installed at 60 degrees [9]. Nohani et al (2016) numerically evaluated impact of anti-vortex plates on inflow pattern in morning glory spillways via FLOW3D software. The results indicated that in a vortex breaker structure with dimensions of 5 × 8 × 10, presence of vortex breaker significantly increases water flow in fixed water heights compared to control situation and discharge rate enhances by increasing number of vortex breakers [10].

2. Materials and Methods

In this study on details of morning glory spillways and aeration characteristics and geometry, it was chosen to make a physical model for 3D simulation of flow field. Geometric features of morning glory spillway are illustrated in following figures, which is physical model of Alborz dam in Tehran Water Research Institute. Alborz reservoir dam is constructed on Babol River in 45 km southeast of Babol and "269 km northeast of Tehran". The dam is made of gravel with a clay core and the spillway is located on the left of its abutment and the experimental model is created on a 1:42 scale. Geometry of morning glory spillway used in this study is shown in the following figure [13]. To create a hydraulic model of morning glory spillway and its elements in FLOW3D, whole solid body of the spillway was made as a three-dimensional model by geometric simulating software (SolidWorks 2011).

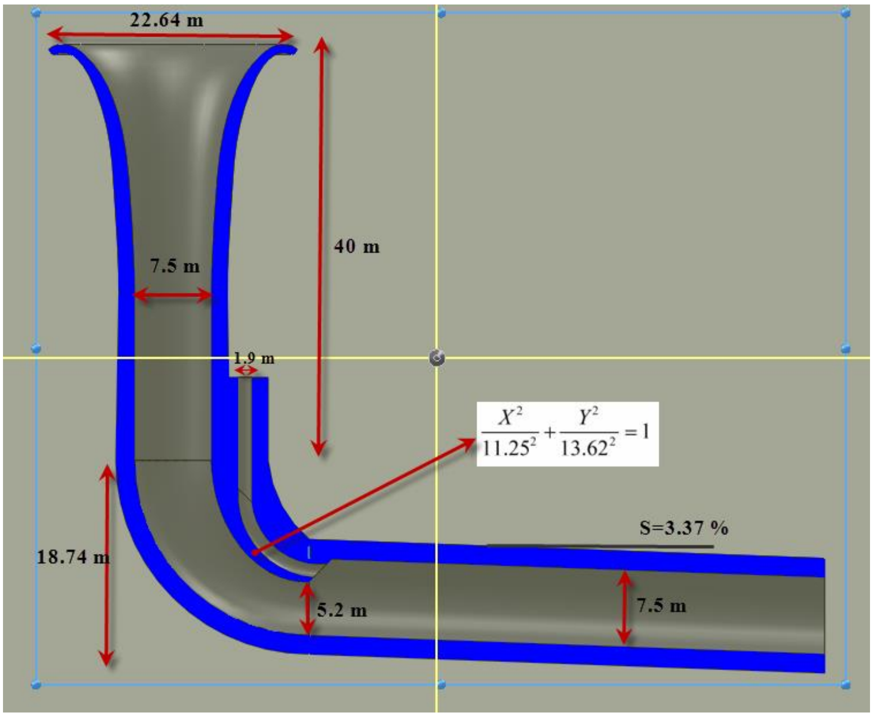

Figure 1. Geometrical features of morning glory spillway in Alborz dam

3. FLOW3D and Governing Equations of Fluid Dynamics

FLOW3D is an appropriate model for complex fluids problems. This numerical model is widely used, particularly for unsteady 3-dimensional flows with free level and complex geometry. In this model, finite volume method is used in regular rectangular grid generation. Due to using finite volume method in a regular grid, the form of the employed discrete equations is similar to discrete equations in finite difference method. Accordingly, FLOW3D enjoys first and second-order reliability methods which are explained in the following. Also, this software uses five turbulence models such as k-ε and RNG. In FLOW3D, two methods have been simultaneously used for geometrical simulation. The first method is volume of fluid (VOF) which is used to show the behavior of fluid at free level. The second method is fractional area-volume obstacle representation (FAVOR) which is used to simulate solid levels and volumes such as geometrical boundaries.

Equations governing fluid flow are obtained from the law of conservation of mass and the law of conservation of momentum. These equations are in the form of partial differential equations. In general, to obtain flow equations, three steps should be considered: selecting accurate base laws, applying laws by an appropriate model and adopting mathematical equations showing the above physical laws. The main equations to simulate 3-dimensional flow are three differential equations including continuity relations and movement size in x, y and z directions.

A flow continuity equation is obtained from the law of conservation of mass and writing balance equation for a fluid element. General continuity equation is presented as Equation 1.

$$V_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + \frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) = 0 \tag{1}$$

Where V_f indicates the fraction of open volume to flow; ρ indicates fluid density; (u,v,w) indicate velocity components in the directions of (x,y,z); Ax indicates the fraction of open level in x direction; A_y and A_z indicate the fraction of open level in y and z directions.

Fluid movement equations with velocity components of (u,v,w) in three different directions, i.e. Navier-Stokes equations are presented as following:

$$\begin{cases} \frac{\partial u}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x \\ \frac{\partial v}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial y} + G_y + f_y \\ \frac{\partial w}{\partial t} + \frac{1}{V_F}\left(uA_x \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z \end{cases} \tag{2}$$

In these equations, (G_x, G_y, G_z) indicates mass acceleration and (f_x, f_y, f_z) indicate viscosity accelerations.

4. Numerical Modeling of the Flow in Morning Glory Spillways

In all simulations performed in this study, three-dimensional flow field is solved by RNG turbulence model. That is because of features and benefits of this turbulence model compared to the other such as k-ε model. Due to additional term of ε, this model is improved to analyze rapidly strained flows and nappe flows with intensive geometric variations; and it has also great capabilities in simulating passing flows [11]. According to a comparison of turbulence models accomplished by Rostami using FLOW3D in 2007, RNG turbulence model provided more accurate results about spillways than the other; so that he applied RNG turbulence model in his studies [12]. The simulation is related to morning glory spillway of Alborz dam which is created in hydraulic models experimental of Tehran Water Research Institute. In this study, a non-viscous incompressible fluid and air density of 1.2 kg/m^3 and shear stress coefficient of 0.073 were considered. In numerical modeling, boundary conditions should be introduced to the numerical model based on existing experimental conditions. All boundary conditions were applied as shown below.

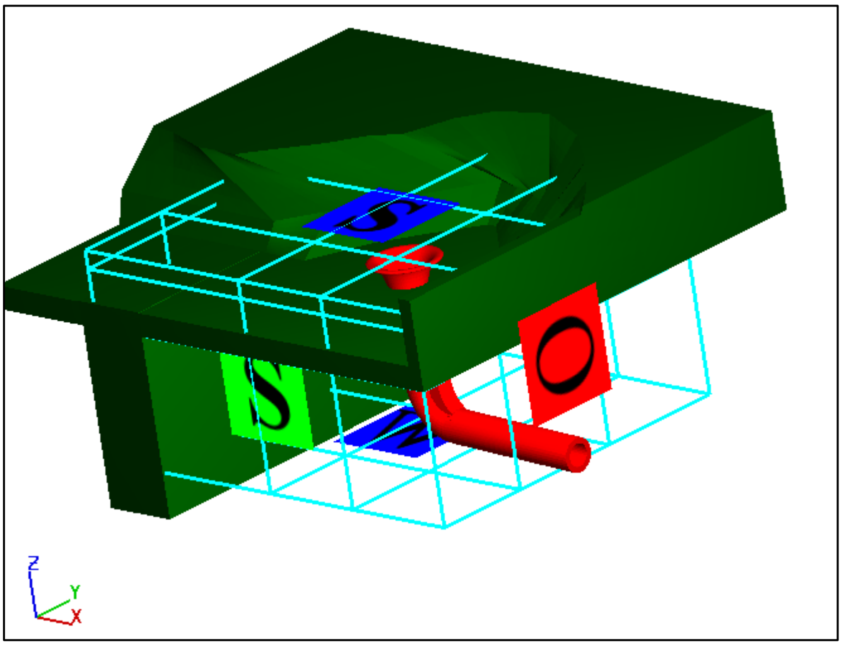

Figure 2. Applied boundary conditions in simulation of the flow on morning glory spillway in Alborz dam

At first step, the numerical model must be calibrated. It means that impact of external factors ought to be minimized and model's circumstances should be the most similar to real or experimental situation. Calibration and validation of results of numerical model is addressed here in regard to boundary conditions and other hydraulic parameters. It is necessary to achieve stable conditions in order to extract accurate data of a numerical or experimental model. After reviewing several models, the right time to extract results of the numerical model was considered 100 seconds. Following figure illustrates how the flow passed through glory hole spillway in various times. After 100 seconds, the flow becomes stable on morning glory spillway. In these figures, it must be noted that water depth on spillway crest is 3.5 m with flow rate of 950 m^3/sec, according to the experimental data.

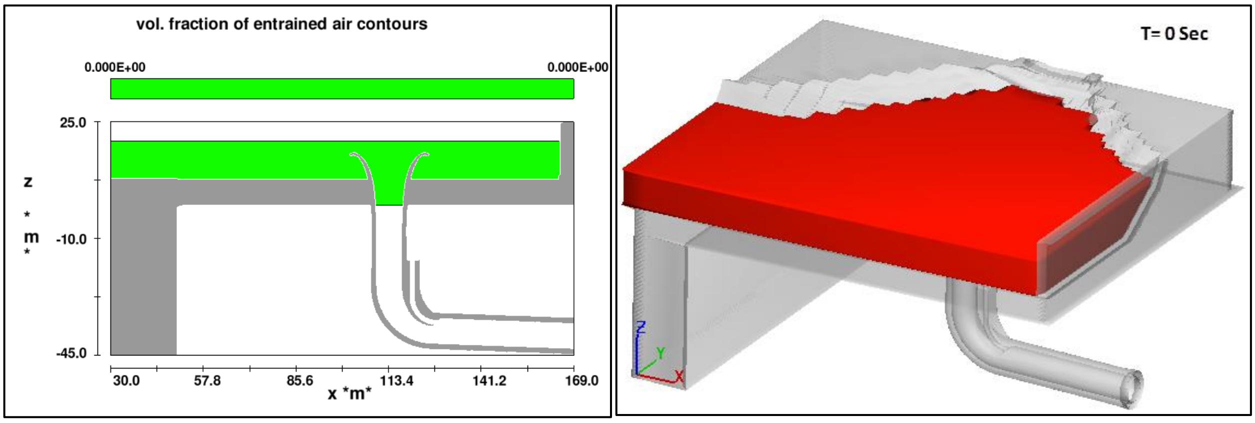

Figure 3. Hydraulic conditions of morning glory spillway before calculations in the numerical model (T=0 sec)

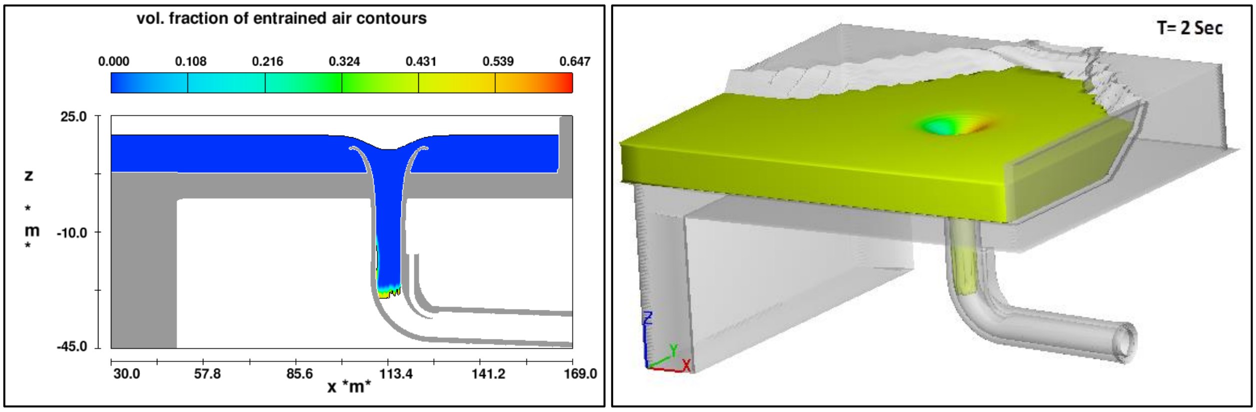

Figure 4. Flow formation in vertical shaft of glory morning spillway in the numerical model (T=2 sec)

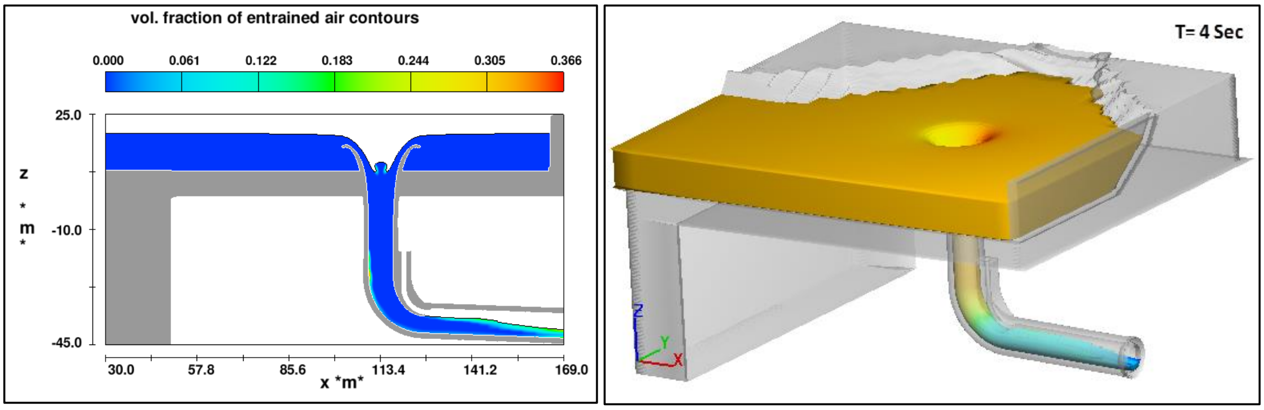

Figure 5. Flow formation in horizontal shaft of glory morning spillway in the numerical model (T=4 sec)

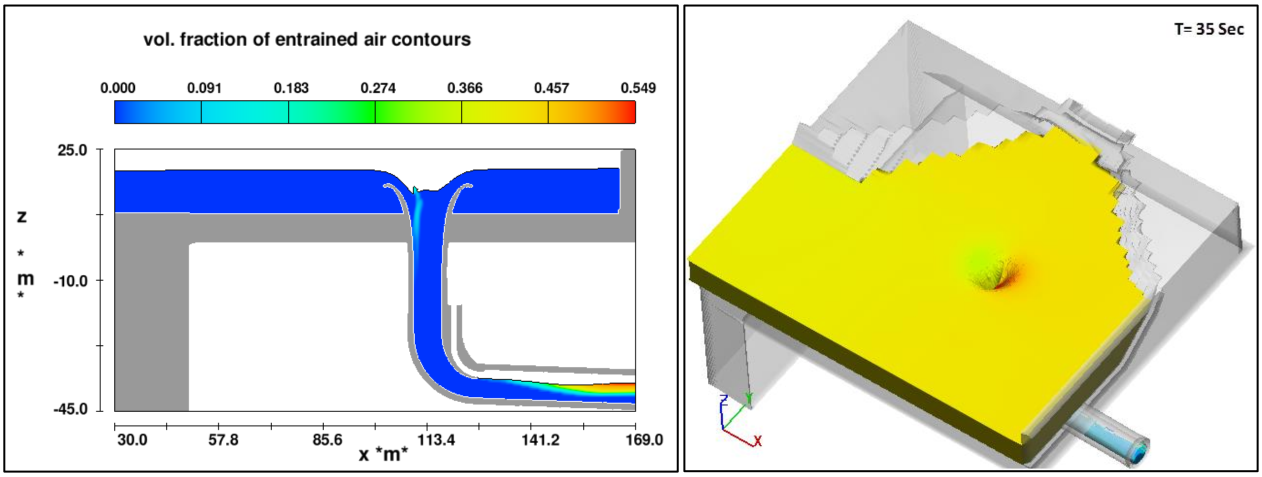

Figure 6. Discharging dam reservoir and providing stable conditions in morning glory spillway in the numerical model (T=35 sec)

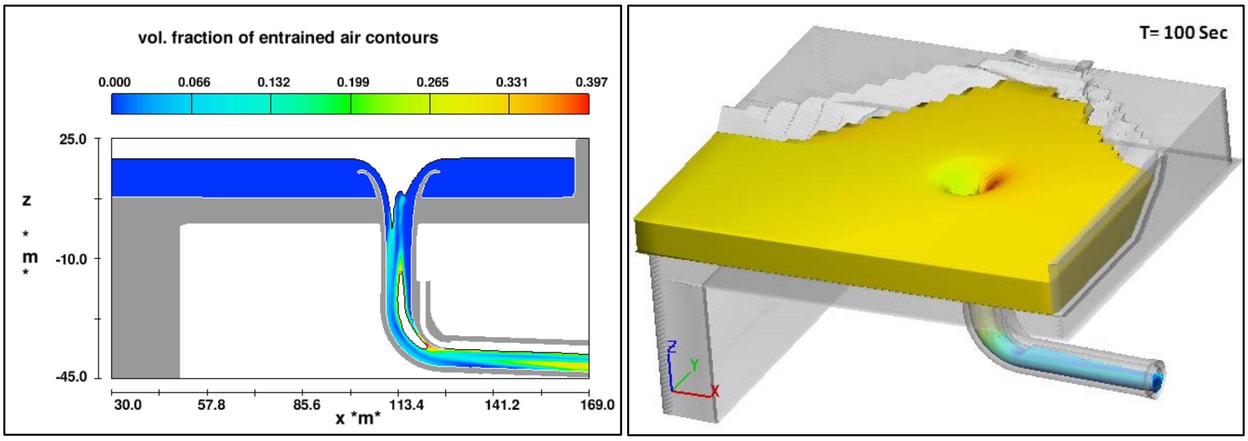

Figure 7. Stability of flow passing through morning glory spillway in the numerical model (T=100 sec)

As shown above, at the beginning of numerical model calculations (T = 0.0 Sec), corresponding fluid height for given data was introduced to the model (in the picture above, fluid height is 5.3 m on spillway crest). The flow started passing through vertical tunnel of spillway according to the figure as the software began calculations (T = 1 sec). At the time (T = 2 sec), the flow traveled through spillway vertical shaft and reached to the model's elbow. As shown in the figure, at the time (T = 35 sec) inconstant effect of the flow was evident and also, there was no stable flow in vertical and horizontal tunnel of spillway. Since the time (T = 75 sec) the flow almost appeared constant and more focus on fluid fraction differences at following times demonstrated that the flow became constant since the time (T = 100 sec). The figures above illustrate spillway cross-section at the time (T = 100 sec) which represent flow formation in morning glory spillway. It should be declared that the numerical model notified flow constancy at the time (T = 97 sec).

To ensure stability and balance of flow field on morning glory spillways, chart of discharge rate variations vs time at the outlet of model is represented that illustrates flow stability and constancy after 100 seconds and verifies stability of the simulation.

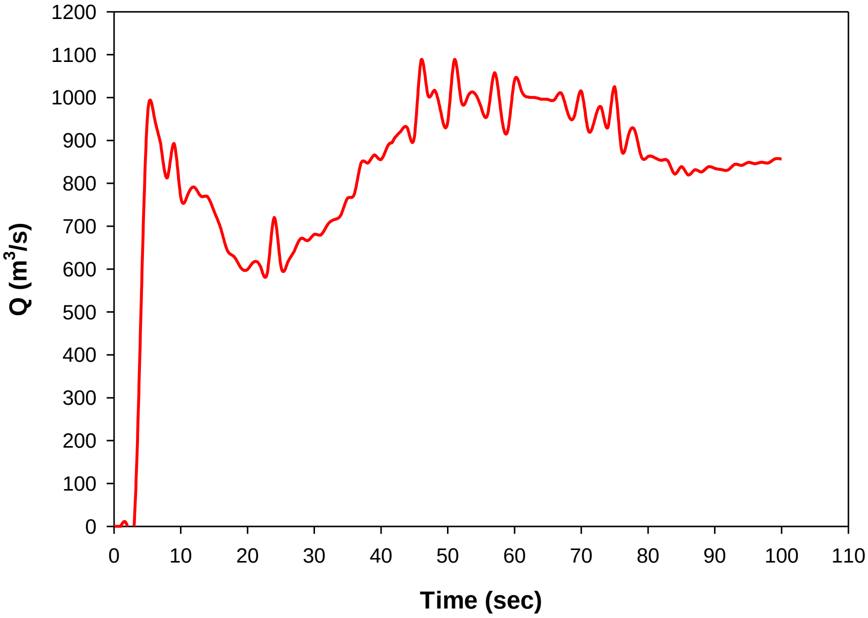

Figure 8. Discharge rate variations vs time at the outlet

The chart indicates that the numerical model initially introduced greater flow rates for passing through vertical and horizontal shaft of spillway; and the reservoir and morning glory spillway achieved a balance in 80 seconds after introducing flow rates into the numerical model by inlet boundary condition. Consequently, flow stability occured after 80 seconds at inlet condition and outlet boundary condition must be evaluated to finish numerical model calculations. According to the chart and results, it could be concluded that the numerical model was calibrated and validated in regard to timing of flow stability in morning glory spillway.

Calibration and validation of the numerical model were carrid out in regard to the most important hydraulic parameters for 4 discharge rates in morning glory spillway of Alborz dam. Therefore, parameters including average water depth on spillway crest, discharge rate of spillway, average flow velocity on spillway crest and average pressure on spillway crest were extracted from the numerical model and evaluated and compared with experimental results and relative error of numerical model was then determined. Note that relative error was obtained using:

$$Error\ \% = 100 \times \frac{X_{Exp} - X_{Num}}{X_{Exp}} \tag{3}$$

Where X_{Exp} refers to exact value of parameters (experimental values) and X_{Num} refers to simulated values of parameters.

Table 1. Comparison between error of numerical modelling of flow hydraulic parameters and experimental results

Run No.	Discharge (m³/s)			Head (m)			Velocity (m/s)			Pressure (pa)		
	Exp	Num	Error%	Exp	Num	Error%	Exp	Num	Error%	Exp	Num	Error%
1	180	192	6.7	1.25	1.15	8.0	2.35	2.17	7.7	5494	4981	9.3
2	450	483	7.3	2.15	2.05	4.7	3.9	3.51	10.0	4316	3992	7.5
3	950	1005	5.8	3.5	3.18	9.1	5.23	5.01	4.2	1024	923	9.9
4	1050	1112	5.9	4.75	4.51	5.1	5.34	5.01	6.2	985	914	7.2
Ave Error %	6.4			6.7			7.0			8.4		

As shown in the table above, error percentage of numerical modeling under boundary conditions, grid spacing and inlet conditions was acceptable. According to results of numerical modeling, relative error of the numerical model in determining discharge rate of spillway was 6.4%. Relative error of the numerical model in calculating parameter of flow depth on spillway crest was 6.7%, compared to experimental results. Error of the numerical model in determinig average flow velocity in spillway crest equaled 7%, as well. Relative error for hydrostatic pressure of the flow on spillway crest was 8.4%. Given various factors affecting hydraulic parameters, error of the numerical modeling was totally acceptable compared to experimental results and this numerical model could be considered as a calibrated and validated model for this study. Flow rate variations based on flow depth compared to spillway crest or so-called "rating curve" of the flow was presented using results of the numerical modeling.

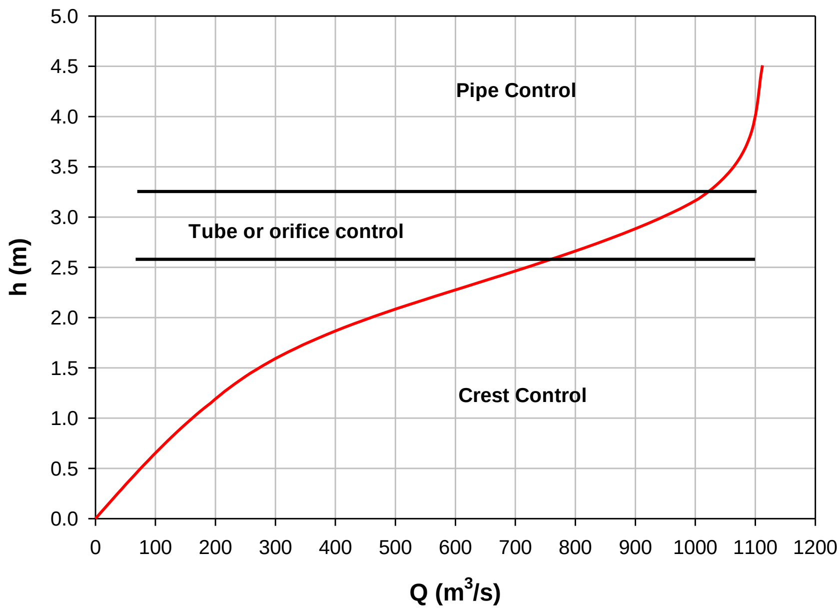

Figure 9. Flow rate variations of glory hole spillway based on flow depth (rating curve)

As shown in the figure above, flow rate of glory hole spillways has three modes based on fluid depth:

- First mode: crest control
- Second mode: tube or orifice control
- Third mode: pipe control

Each mode of flow properties was illustrated on the picture above. Following table provided flow rate characteristics for each control mode.

Table 2. Discharge hydrograph classification of morning glory spillway in Alborz dam using results of the numerical model

Series	Description	Head (m)	Considerations
1	The minimum discharge up to 400 m^3/s	0-2.01	Crest Control
2	From 400 to 600 m^3/s	2.01-2.60	Crest Control
3	From 600 to 800 m^3/s	2.60-3.15	In the range of 800 m^3/s flow control Mode change
4	From 800 to 1050 m^3/s	3.15-3.90	Tube or Orifice Control
5	From 1050 to 1112 m^3/s	3.90-6.00	pipe control

The spillway was in a complete choking situation when vertical shaft filled up to the end of elbow with flow rate of 1050 m^3/sec . Each control mode of the flow on morning glory spillway within the numerical model was represented in figures.

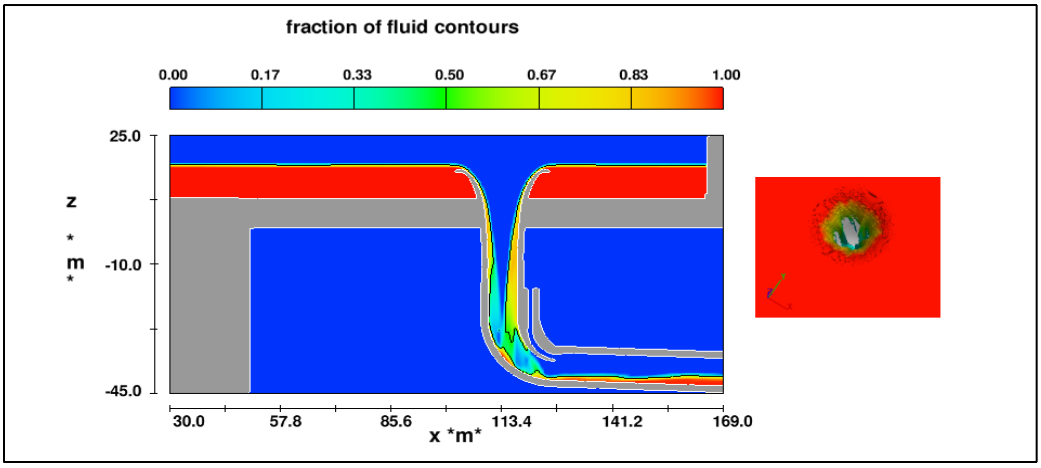

Figure 10. Flow profile of morning glory spillway under flow control of spillway crest for discharge rate of 180 m^3/sec

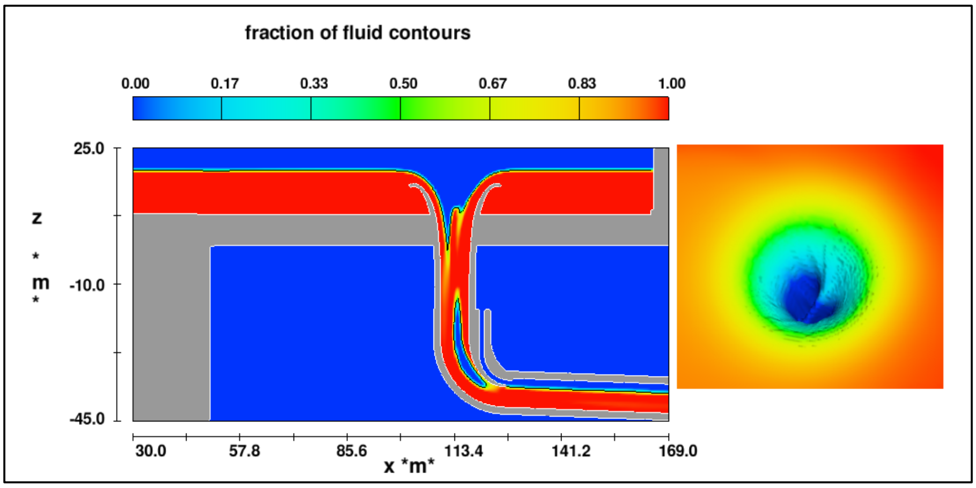

Figure 11. Flow profile of morning glory spillway under flow control of spillway crest for discharge rate of 800 m^3/sec

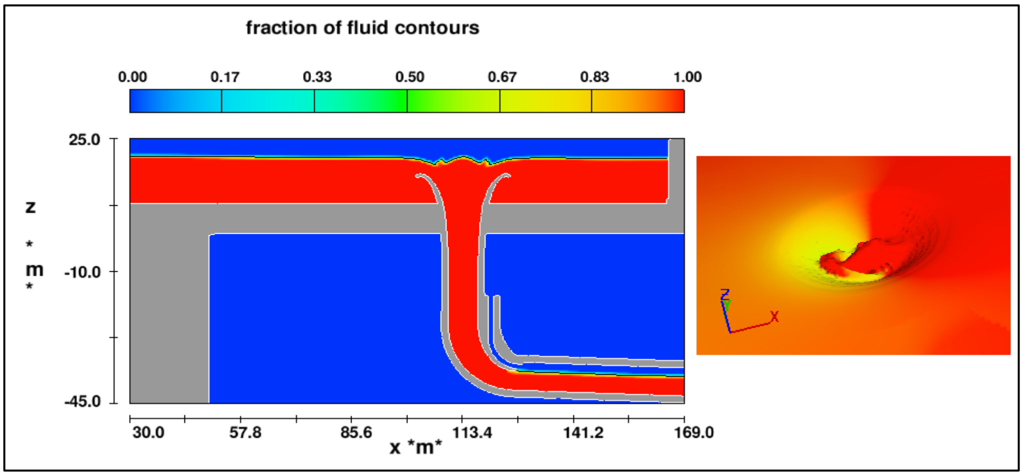

Figure 11. Flow profile of morning glory spillway under flow control of spillway crest for discharge rate of 1050 m^3/sec

An analysis on previous charts indicated that in case of considering morning glory spillway crest as control section, the flow would skim over ogee crest profile toward bottom of ogee slope and then freely fall down the elbow's end. Skimming water flow on the crest got thicker as flow rate increased in the numerical model and finally, it would turn into a vertical jet. Intersection (crotch) of skimming water flow and vertical jet resulted from vortex flow in the spillway throat was shown below.

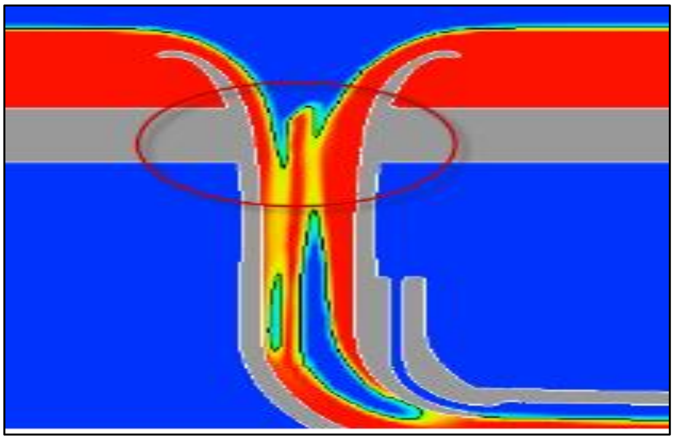

Figure 13. Intersection (crotch) of skimming water flow and vertical jet resulted from vortex flow in the spillway throat

Crotch point and the convexity raised as water flow height on spillway increased. For extremely great heights, intersection and bulge point may almost submerge and just a small bulge and vortex stay on water surface. Subsequently, submergence began on spillway and its crest then submerged completely. In this case, flow control could be performed by a compact jet formed at the crest inlet.

5. Conclusion

In this study, it was attempted to determine flow pattern and control conditions of morning glory spillways in different modes using boundary conditions, inlet conditions and grid spacing of flow field. After reviewing several models, the right time to extract results of the numerical model was considered 100 seconds. At this time, a stable flow was created in the numerical model and it notified flow constancy at the time (T = 97 sec). According to results of numerical modelling, relative error of the numerical model in determining discharge rate of spillway was 6.4%. Relative error of the numerical model in calculating parameter of flow depth on spillway crest was 6.7%, compared to experimental results. Error of the numerical model in determining average flow velocity in spillway crest equalled 7%. Relative error for hydrostatic pressure of the flow on spillway crest was 8.4%. The results of spillway rating curve of the numerical model demonstrated that flow control was performed in the spillway crest at flow rates up to 600 m^3/sec. Flow control conditions changed at flow rates of 600-800 m^3/sec; so that flow control varied from vertical shaft to the elbows end at flow rates of 800-1050 m^3/sec. Flow control would be in the tunnel at flow rates of 1050-1112 m^3/sec.

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