Numerical Investigation of Passed Flow Different Parameters over a Standard Ogee Spillway to Satisfy Flow Profile in CFD Method

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Paper Reference Number: 0103-680
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Abstract

One of the most important structures built at the same time of the construction of a dam is called spillway used to discharge surplus water exceeding the capacity of dam. Ogee spillway is one of the most efficient and famed ones, which is therefore liable to study. In this research, the impacts of different types of meshing on the proper calculation of flow parameters have been studied using numerical evaluation and Finite volume method. In case of using proper meshing, the results obtained from numerical method show considerably lower relative error in comparison with laboratory results. It seems that in case the meshing with 0.0065 m is used, around 66.7 percent of time and a considerable amount of price is saved. The percentage of relative error of the flow discharge over ogee spillway is 9.6871, which indicates that this method is highly precise. Whereas the decision criterion (P-value) of SPSS software is about 0.00002, and is very lower than 0.05, therefore it is proved that the numerical study is of high precision. The obtained numerical results have been compared with the results obtained from numerical, laboratory methods, and USBR and USACE diagrams and it was proved that they match appropriately. Therefore, the use of numerical model is strongly recommended.

Key words: Ogee Spillway, Finite volume method, Convergence Condition, Sensitivity Analysis, Meshing Dimension

1. Introduction

One of the important structures, which is required to be built at the same time of constructing dam and enables the discharge of floodwater exceeding the capacity of dam, is called spillway. Another application of spillways is to control the height and volume of the water of the lake behind dam. In this state, the form and dimensions of spillway is a function of geographical and hydrological situation of the region. One of the most famous

with highest application is ogee spillway. Due to its proper hydraulic properties, ogee spillway has been studies frequently. In the following, the studies and researches conducted on ogee spillway and its form and properties, have been described:
In 1965, Cassidy used numerical model in a 2D space to determine the pressure on the crest of ogee spillway based on potential flow [1]. In 1998, Olsen and Kjellesvig used Reynolds equations and standard k - ε equation in finite volume method to analyze the flow over ogee spillway in 3D and 2D spaces [2]. In 1999, Burgisser and Rutschmann used finite element method to analyze the vertical component of flow over the crest of spillway in 2D space supposing that there is incompressible and turbulent flow [3]. Tufi and Wilson used in 2001 the finite difference method to analyze vertical flow over ogee spillway crest in a 2D space assuming that there is a potential flow and Neumann condition is imposed on the boundaries of flow field [4]. Bruce et al. conducted in 2001 a comprehensive study to compare the parameters of flow over standard crested ogee spillways using a physical model, numerical model and existing studies [5]. Latif Bouhadji conducted in 2002 a numerical study on turbulent flow over spillways in a 3D space [6]. In 2003, Chen et al. modeled turbulent flow over stepped spillway using finite volume method [7]. In 2003, Ho et al. studied the maximum impacts of contingent floodwater over spillways [8]. In 2004, Jean and Mazen modeled flow over ogee spillway numerically [9]. In 2005, Dae Geun Kim and Jae Hyun Park used the commercial numerical model of computational fluid dynamics of Flow 3D software to study the properties of flow including flow rate, water surface profile, pressure imposed on the crest of ogee spillway, pressure vertical distribution and speed based on the scale of model, the impact of surface roughness and details [10]. In 2006, Bhajantri et al. studied the hydraulic model of flow over ogee spillway numerically considering downstream and the information obtained from two physical models have been compared with the results obtained from numerical study of two crested ogee spillways [12]. In 2009, Vosoughifar and Daneshkhah used numerical methods such as finite difference and finite volume to evaluate numerically the impacts and function of the surge tank of hydraulic hammer on the cover of water tunnels transferring water to concrete dam turbines [13]. In 2009, Angela Ferrari simulated numerically the flow with free surface over a spillway with sharp crest [14]. In this research, investigation of the sensitivity analysis of meshing dimension is compared to calculate properly the profile of flow over ogee spillway using finite volume method.

2. Research Methodology

In this research, Finite volume method has been used to study the numerical performance of flow over ogee spillway. This software is able to determine the free surface of flow by applying VOF model (volume of fluid model) and assuming the effect of turbulence. VOF model was introduced by Nichols and Hirt to determine the common surface of air-water two-phase flow model in many hydraulic problems [20]. In this research, 90% of the volume of cell is water and the remaining part is air. Before using this software, auxiliary software like GAMBIT was used to plot the geometry of this model. Thereafter, the output file of GAMBIT is inserted through the read case of FLUENT. This software is based on finite volume method, which is a very strong method for solving computational fluid dynamics. The equations governing flow in this software include continuity equation (law of mass conservation), and Navier-Stokes equation (momentum conservation law). In this research, Reynolds-Average method was used to solve Navier-Stokes equation in such a way that turbulent flow is inserted into the equations indirectly. Thus, continuity equations and momentum are determined.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + g_{x_i} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \overline{u}_i}{\partial x_j} - \overline{u_i' u_j'} \right) \tag{2}$$

Eq. 2 is known as Reynolds Averaged Navier Stokes Equation. This equation is just like Navier-Stokes equation, and the only additional term of these equations is the parameter of ($-\rho.\overline{u_i' u_j'}$), which is called Reynolds stress and it applied to the fluid and causes the impact of turbulent vortex to be applied to the fluid [15].

2.1 Statistical Analysis Method with SPSS

The Statistical analysis method (p-value) with SPSS software has been used to compare the parameters of flow over ogee spillway. Statistical analysis method is used to confirm null hypothesis (meaningful difference) or reject null hypothesis (considerable difference). The correctness of null hypothesis (H_0) has been always emphasized, unless something contrary is proved. Significance level (α) is the error level designated by the researcher as a criteria to reject null hypothesis (H_0) (usually 5%). P – Value, which is called decision criterion, is level of error for rejecting null hypothesis and it is shown in form of *Sig (2-tailed)*. If the P-value is lesser that Alpha, null hypothesis can be rejected more easily. In this research, the lesser amount of this value proves the reality of numerical solution [17].

2.2 Two Dimensional Discretization of Equation

For the convergence of numerical modeling, it was required to control the equations and their related relations in order to define temporal steps for the software. For this purpose, the temporal steps shall be applied based on the meshing measure to achieve sustainability. The discrete differential equation of nonpermanent fluid flow is as follows:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) + S \tag{3}$$

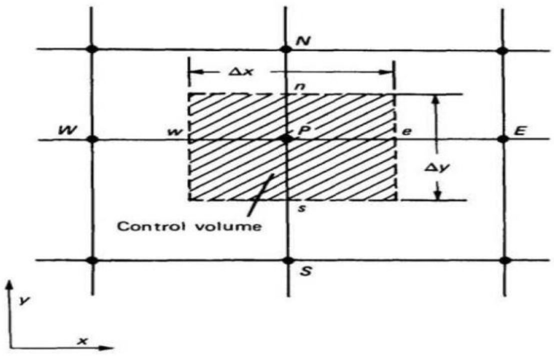

Fig 1: Control Volume for 2D Coordinate.

$$a_P T_P = a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_T T_T + a_B T_B + b \tag{4}$$

There are different iteration methods for solving algebraic equations, among which the Gauss-Seidel Point – by – Point Method was used. In this method, the variable values of each node have been calculated based on specified instruction. Discrete equation is as follows:

$$a_T T_P = \Sigma a_{nb} T_{nb} + b \tag{5}$$

Where, nb indicates neighbor node, and T_p is calculated using the following formula.

$$T_P = \frac{\sum a_{nb} T_{nb}{*} + b}{a_P} \tag{6}$$

In the abovementioned equation, T_{nb}* indicates the value of neighbor node in the memory of the computer. For the neighbors considered previously during the current iteration, the value of T_{nb}* is related to the previous iteration. Anyhow, T_{nb}* is the last accessible value for the temperature of neighbor node. After all nodes are taken into consideration, one iteration is completed using the method of Gauss–Seidel Point-by-Point. The said method is not always convergent. Indeed, whenever Scarborough criterion (1985) is true, the convergence of Gauss-Seidel method is guaranteed. This is as follows:

$$\frac{\sum |a_{nb}|}{|a_p|} \begin{cases} \leq 1 & \text{for all equations} \\ < 1 & \text{Atleast for one equation} \end{cases} \tag{7}$$

In case the interval times are chosen properly, the above mentioned convergence relation will be acceptable[18]. The time interval used in this research is equal to 0.01 second, which covers the convergence condition of Gauss – Seidel very well.

2.3 Case Study

2.3.1 Data and Material

The physical model of the case study of ogee spillway is made of Plexiglas prepared at Utah Water Research Laboratory (UWRL) based on standard mold. The dimensions of this model are as follows, Fig. 2 [5]:

Design head (H_d) = 0.301 m
Width = 1.83 m
Height of spillway crest (P) = 0.8127 cm

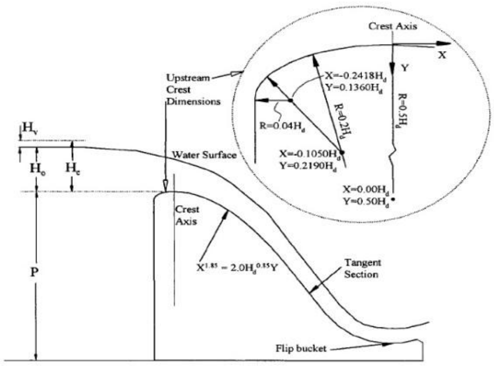

Fig 2: The Dimensions of Ogee Spillway and Flow Parameters.

2.3.2. Boundary Conditions

In general, one of the most important phases of the numerical analysis of flow field is to determine proper boundary conditions, which are matched appropriately with the physical conditions of the problem. For numerical modeling of ogee spillway, the boundary conditions of the Fig. 3 have been provided.

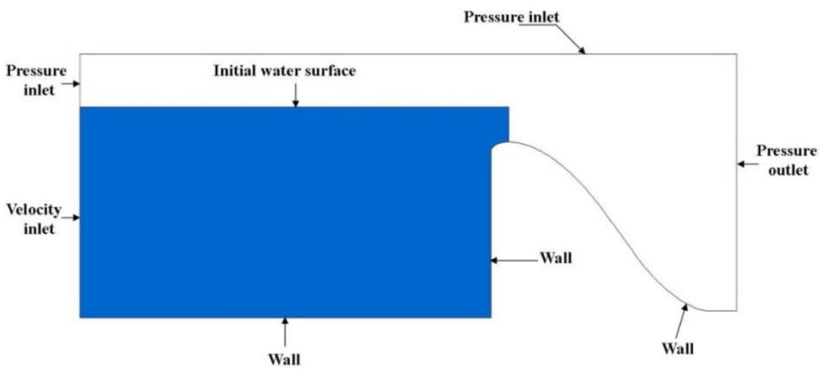

Fig 3: The Boundary Conditions of the Ogee Spillway of Simulated Numerical Model.

2.3.3. Analysis Method

Based on the curvature of ogee spillway and the proper direction of meshing of these surfaces, pave meshing has been used. For having access to this type of meshing, two types of tri-pave meshing and quad-pave meshing have been studied under similar conditions. According to the Fig. 4, it is observed that the model using tri-pave meshing is not able to model the profile of the flow over ogee spillway.

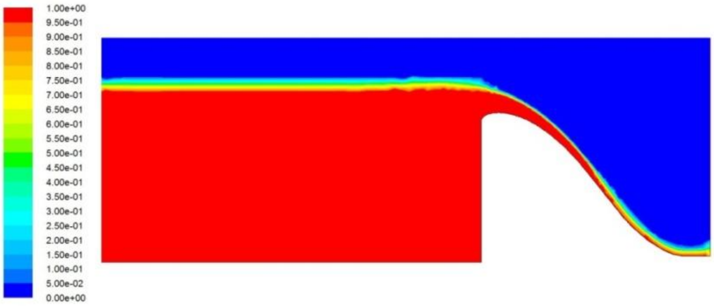

Fig 4: Flow Profile in Tri-Pave Meshing.

According to the Fig. 5, it can be concluded that quad-pave meshing is the appropriate type of meshing.

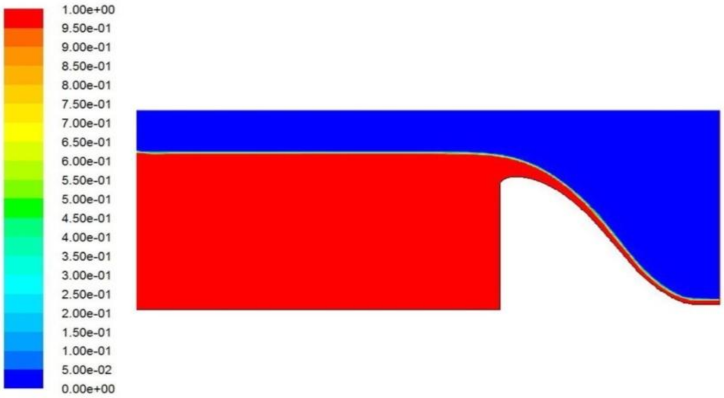

Fig 5: Flow Profile in Quad-Pave Meshing.

In the following Figs. 6~9 the meshing in different points of ogee spillway has been shown.

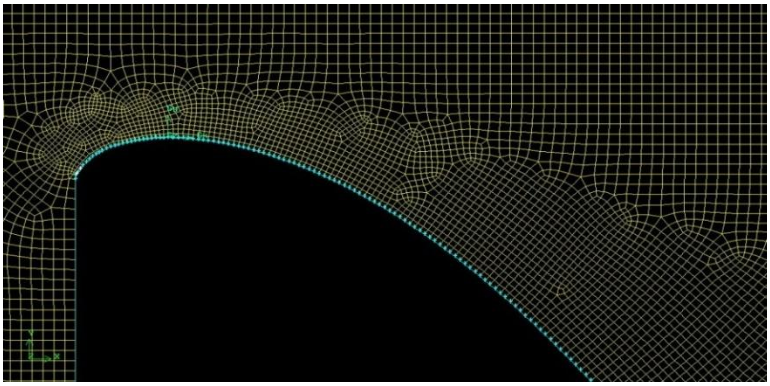
Fig 6: Meshing and the distribution throughout the model of ogee spillway.

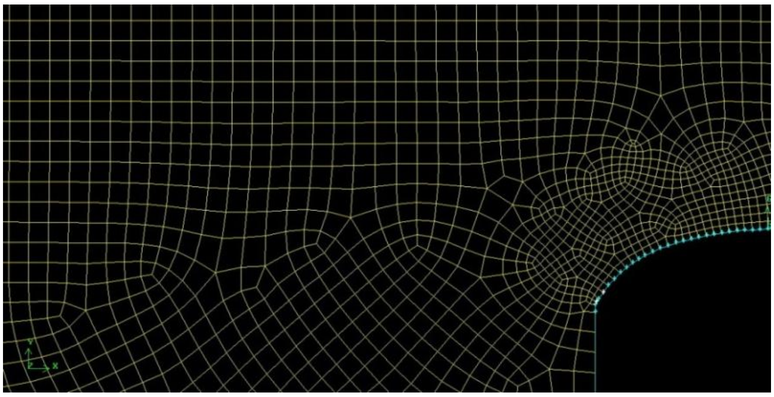

Fig 7: Meshing at the beginning of ogee spillway.

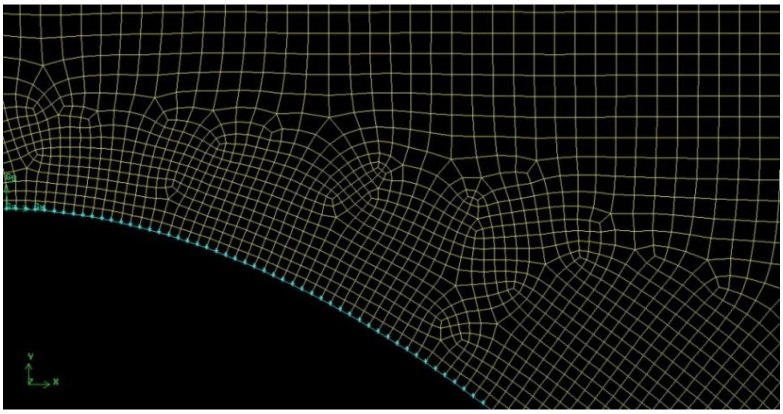

Fig 8: Meshing in the middle of ogee spillway.

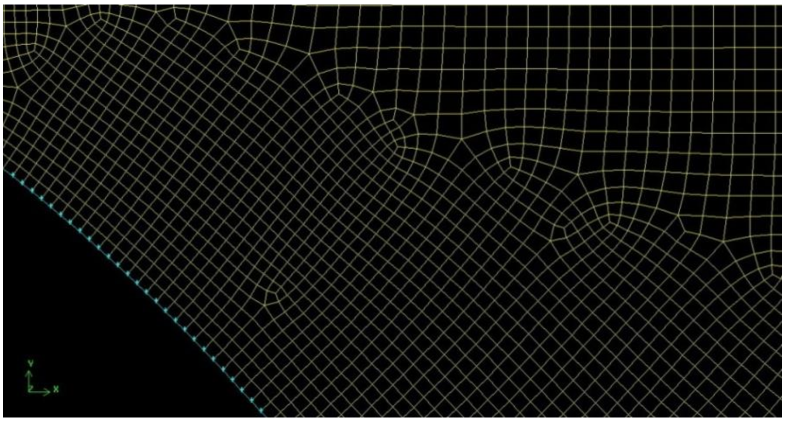

Fig 9: Meshing at the end of ogee spillway.

3. Results and Analysis

To determine the measure of meshing in proper calculating flow parameters at step time of 0.01 second over ogee spillway, the results obtained from simulation of the parameters of numerical method have been compared with the measures of laboratory samples, and considering the value of relative error, the most appropriate choice have been expressed for such a measure. Based on the Eq. 8, relative error is equal to the modulus of the difference between the value of numerical method and laboratory value divided by the value of numerical method.

$$Percentage\ of\ relative\, error = \frac{numerical\ method - labratoty\, value}{numerical\ method} * 100 \qquad (8)$$

The Table. 1 shows the numerical results obtained from discharge parameter and laboratory value for the measures of different meshing.

Meshing size(m)	Q(m^3/s)	Percentage of relative error	Time(s)
0.01	0.101802064	26.6851	7.5
0.0095	0.103838894	24.2001	20
0.009	0.105709704	22.002	25
0.0085	0.106931413	20.6082	40
0.008	0.107593141	19.8664	50
0.0075	0.110628012	16.5781	55
0.007	0.11729641	9.9505	60
0.0065	0.117578074	9.6871	70
0.006	0.11763121	9.6376	110

Table 1. Meshing Sensitivity Analysis.

4. Conclusions

Based on the appropriate convergence within time interval of 0.01 second, it can be claimed that the convergence condition of Gauss-Seidel method is a proper choice for the convergence of the equation of flow over ogee spillways.

The percentage of relative error between meshing with measures of 0.006 to 0.007 has been minimized to its lowest amount. Whereas the time required for convergence in the meshing with the measure of 0.0065 and 0.006 has increased approximately by 16.667 and 83.333 percent respectively in comparison with the meshing with the measure of 0.007, and considering the reduction of percentage of relative error about 0.2634 and 0.0496 respectively, and as the time required for convergence in the meshing with the measure of 0.006 has been increased by about fivefold that of meshing with the measure of 0.007, it can be proved that the meshing with the measure of 0.0065 leads to lower error and is more economic. Therefore, it seems that this measure of meshing shall be used for the proper calculation of the parameters of flow over ogee spillway. Since the production of physical models is of high expense, and the problems due to the effects of scale can be seen in the results, therefore numerical models are recommended.

It seems that tri-pave meshing is not a proper choice for numerical models of the flow over ogee spillways and therefore quad-pave meshing is preferred.

In case of using proper meshing, the results obtained from numerical method show considerably lower relative error in comparison with laboratory results.

It seems that in case the meshing with 0.0065 m is used, around 66.7 percent of time and a considerable amount of price is saved. The percentage of relative error of the flow discharge over ogee spillway is 9.6871, which indicates that this method is highly precise.

Whereas the decision criterion (P-value) of SPSS software is about 0.00002, and is very lower than 0.05, therefore it is proved that the numerical study is of high precision.

The discharge rate obtained from the numerical solution of the Finite volume method has been equal to 0.1175781 m^3/s , while the discharge rate obtained by Bruce et al. using Flow 3D software is equal to 0.125208 m^3/s [5]. The USBR graphs show the discharge equal to 0.119944 m^3/s and USACE graphs show the discharge rate equal to 0.1222 m^3/s.

By considering the results of the abovementioned methods, it can be observed that the results of this research are very similar to the results of USBR graphs, and are of high precision [19]. Decision criterion (P-value) obtained from numerical study is about 0.000025, which is in comparison with the results of the study of Bruce et al. conducted using Flow 3D software, of high exactness [5]. The decision criterion (P-value) obtained from numerical method of Finite volume method with USBR graphs is approximately equal to 0.001037 and with USACE graphs is equal to 0.000138, which are lower than 0.05, and it proves the high accuracy of the numerical method used in this research [19]. Based on the abovementioned facts, and this research to analyze the sensitivity of meshing, it can be claimed that quad-pave meshing with the measure of 0.0065 m is of high accuracy.

Acknowledgements

The support by Savage, Bruce Ph.D from Idaho State University is greatly appreciated.

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