Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 3, No. 11, November, 2017

Three-Dimension Numerical Simulation of Scour Temporal Changes due to Flow in the Downstream of Combined Weirs and Gate Model

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Received 01 October 2017; Accepted 20 November 2017

Abstract

Most of weirs create a region with relatively static water in upstream, which can be the place of sediments and wastes deposition in water. Sediments accumulation in upstream changes flow conditions. In this case, combined weir and gate can be propounded as a useful solution. In the present paper, Flow3D was used to numerically simulate temporal changes of scour in combined free flow over weirs and below gates. Numerical modeling was run after fully preparing and the obtained data was analyzed under three-dimensional conditions. Comparing experimental and numerical results with data fitness revealed that determination coefficient (R^2) of the numerical model results to the experimental model results is 0.94. Also, it was found that the relative error of the numerical model results relative to the experimental results equals 7.36%. Further, it was found that at the start of computations in the numerical model, compared to the end of running the model, the turbulent energy dissipation was decreased to 38% and decreasing the turbulent energy dissipation led to the creation of scour hole balance in the numerical model.

Keywords: Numerical Model; Combined Model; Gate Weir; Scour; Bed Sediments; Flow3D.

1. Introduction

Scour refers to the erosion of bed and channel edge due to flow pass as well as the erosion of bed in hydraulic structures downstream as a result of highly intense flow or the erosion of bed due to topical turbulent flows. Heavy costs are spent to control and prevent scour in hydraulic structures downstream every year; therefore, it is necessary to predict it before constructing structure. The expansion of such a phenomenon can endanger the stability of the structure. Also, the accumulation of eroded materials influences the performance of the structure as a result of coastal digit change.

Gregory et al. (1963) reported that flow discharge is increased about 8% when 75% of weir height is filled by sediment [1]. Using the combined structure, the defects of using weir and gate separately can be removed. Hassen and Narayanan (1985) studied scour due to a 2D jet passing under the gate with apron and without apron. In their study, they investigated the effect of particles size, gate openness, inlet jet speed, and apron length on scour [2]. Chatterjee and Ghosh (1980) suggested some relations to compute the time necessary to arrive at balance mode, scour volume at time, maximum scour depth, and scour profile [3]. In an experimental study, Kells et al. (2001) investigated aggregation diameter in sour downstream of sluice gates. The obtained results indicated that high depth dependency and scour zone was as much as

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http://dx.doi.org/10.28991/cej-030941

the bed particles size. Such that, decreasing the particles size led to the increase of depth and scour zone. Moreover, they reported that the maximum scour depth place was transferred from flow upstream to downstream by increasing the flow discharge [4]. Negm et al. (2002) investigated a free- state combined flow for rectangular weir-gate with equal compression. The concluded that flow discharge coefficient had a direct relation with dimensionless parameters of total upstream head ratio to gate openness and the ratio of the head over the structure to weir and gate. Also, it was found that flow discharge coefficient had a reverse relation with the ratio of weir-gate distance to gate openness [5]. Dey and Sarkar (2006) carried out an experimental study on sediment beds scour in even and uneven states in downstream of aprons with different lengths. Their study revealed that decreasing the apron length leads to the increase of scour depth in balance state. Also, they found that increasing sediments' size and gate openness leads to the decrease of scour depth [6]. Safar and Kashefipour (2008) modeled hydraulic effects of flow and channel geometry on the floe intensity in weir-gate system. They concluded that the most effective parameter to determine the discharge passing the model using artificial neural network is upstream depth to gate openness ratio [7]. Sobeih et al. (2012) experimentally investigated downstream scour of weirs with body openness. In this study, hole's openness was created in the weir body and downstream scour was investigated with various flow conditions and hole's various diameters [8].

In Saneie (2005-2010) studies, it is intended to find the optimum distance between the shorter spur dike and the first spur dike in order to have minimum erosion in the first spur dike. From the hydraulics point of view, Lâ/L (the length of shorter spur dike to the length of first spur dike), X/L (the distance between first spur dike and shorter spur dike to the length of first spur dike) and H/Lâ (the depth of water at upstream to the length of shorter spur dike) has been studied and results has been presented in the form of equations [9, 10]. In the research Parsaie et al. (2017), discharge coefficient of weir-gate was predicated using adaptive neuro fuzzy inference systems (ANFIS). To compare the performance of ANFIS with other types of soft computing techniques, multilayer perceptron neural network (MLP) was prepared as well. Results of MLP and ANFIS showed that both models have high ability for modeling and predicting discharge coefficient; however, ANFIS is a bit more accurate. The sensitivity analysis of MLP and ANFIS showed that Froude number of flow at upstream of weir and ratio of gate opening height to the diameter of weir are the most effective parameters on discharge coefficient [11]. In this regard, the present study attempts to numerically simulate temporal changes of downstream scour in combined weir-gate model using Flow3D.

2. Methodology

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 [12]. The second method is fractional area-volume obstacle representation (FAVOR) which is used to simulate solid levels and volumes such as geometrical boundaries.

Movement of suspended sediments with fluid is due to local pressure's gradient changes. These suspended sediments may be created due to input flow containing suspended particles or due to bed erosion [13, 14]. Since bed erosions have been limited by neighboring particles and are not easily displaced, they can move only in case of changing into suspended load in shared level of bed and fluid. Suspended load can be changed into load when the velocity of depositing is higher than the velocity of bed erosion.

3. Numerical Modeling and Results

To numerically simulating the temporal changes of downstream scour in scour of combined weir-gate model using Flow3D, various parts of simulation in Flow3D model should be applied. To this end, boundary conditions and girding of numerical model were applied for the constructed geometrical model. Numerical modelling was run after fully preparing and the obtained data was analysed under three-dimensional conditions. Changing the dimensions of gridding in the numerical model, the most optimal ad appropriate dimensions for gridding cells (1cm length, 1 cm width and 1cm depth) were considered. Various conditions of computational cells dimensions have been shown in Figure 1. Notably, 398370 computational cells have been considered for simulation. It should be also noted that a flume with the length of 5.75 m, the width of 22.5 cm and the depth of 35 cm was simulated.

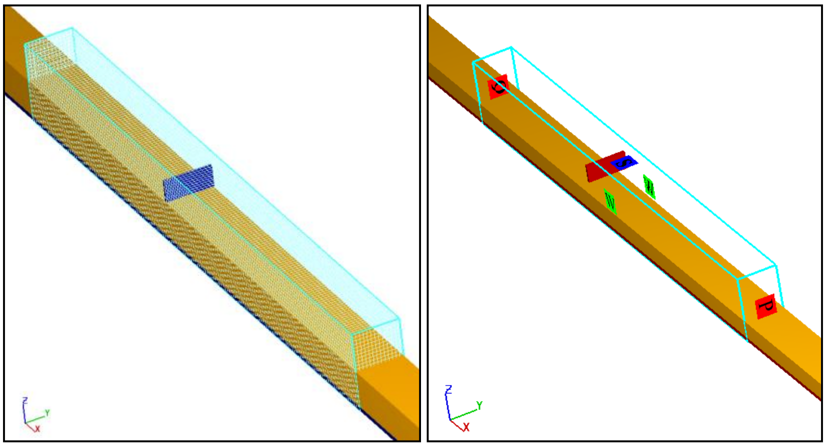


Figure 1. Computational cells and boundary conditions over flume gridding block, weir-gate and erodible bed in Flow3D

Table 1. Comparing and selecting turbulent model for flow field simulation in weir-gate combined models

	Experimental			**Numerical Model: K-ε**			**Numerical Model: RNG**		
	H (cm) Exp	Q (m^3/s) Exp	Ds (cm) Exp	H(cm) Flow3D	Q (m^3/s) Flow3D	Ds (cm) Flow3D	H(cm) Flow3D	Q (m^3/s) Flow3D	Ds (cm) Flow3D
Data	14.1	5	6.99	12.8	4.8	7.81	13.24	4.95	7.47
Error %				9.22	4.00	11.73	6.10	1.00	6.87
				Ave Error: 8.31			**Ave Error: 7.64**		

As observed in Table 1, the maximum mean error of various parameters for K-ε turbulent model and RNG turbulent model are 8.31% and 7.645, respectively. The maximum mean error of various parameters for K-ε turbulent model is higher than RNG one. Other parameters required for the numerical model have been also selected according to actual conditions. As instance, water as a non-viscous and incompressible fluid, air entry with the density of 1.2 kg/m3 and its shear cut of 0.073 were considered. One of the most important parameters that should be observed in the numerical model is to create stable flow conditions in the flume. Therefore, flow stabilization conditions were evaluated using the numerical model outputs. Figure 2 shows input and out discharge values for the numerical model.

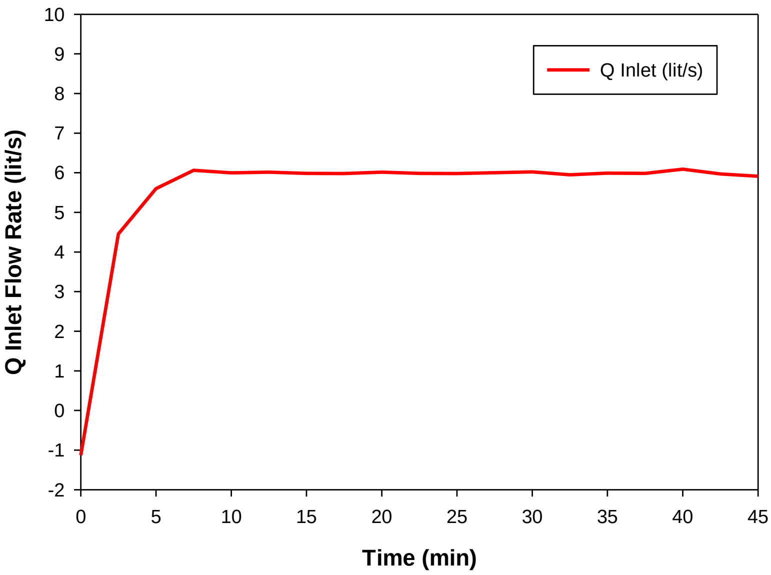


Figure 2. The diagram of output discharge changes

As shown in Figure 2, entering the flow with the discharge of 6 L/s and running the program, output discharge values approach to 6 L/s. Also, the stable flow in the flume is formed from the weir and the gate. Table 2 shows the geometrical and hydraulic characteristics of the modeling in Flow3D.

Table 2. The geometrical and hydraulic characteristics of the flow conditions in Flow3D

Run Number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Opening Gate W (cm)	0.7	0.7	0.7	1.7	1.7	2.7	2.7
Flow Rate Q (Lit/s)	3.1	4	2.7	5	3	5	6
Tailwater T_w (cm)	10.8	12	9.3	12.3	9.5	10.5	10.8
Head Y (cm)	12.7	13.4	12.7	14.1	12.6	14	14.3

After applying each of the geometrical and hydraulic conditions in the numerical model, 3D simulation of the flow field in the flume and the combined weir-gate model was performed. Figure 3 shows the flow pass and the model output.

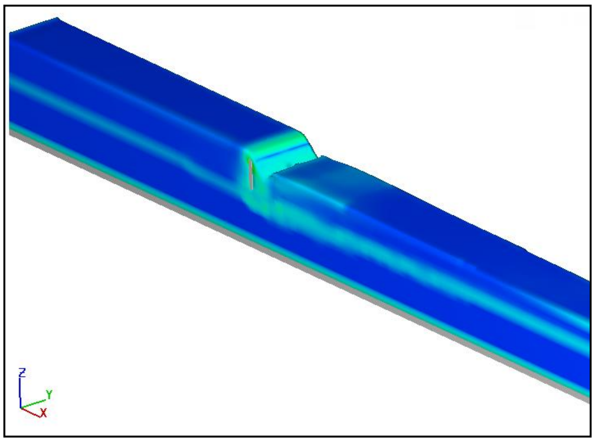
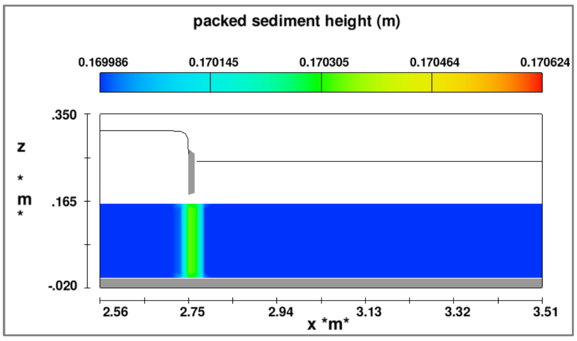
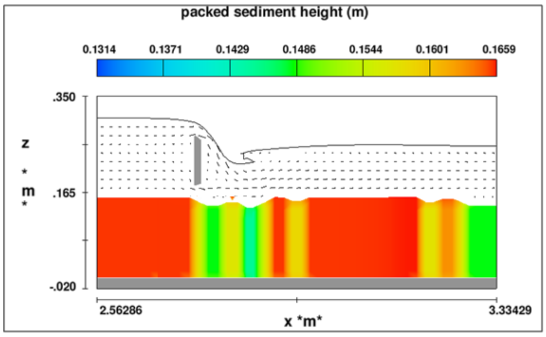


Figure 3. The three-dimensional numerical modelling of the flow in the combined weir-gate model

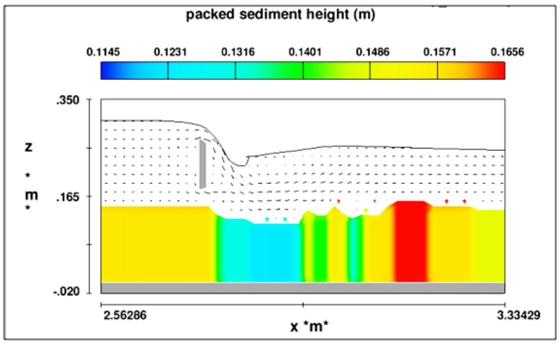
After passing from the weir and the fate, the flow in the flume goes to the downstream and then exists at the end of the flume. Due to passing the flow over the weir and below the gate, downstream scour is created that varies during various times. The way of changing and forming downstream scour of the combined weir-gate model by Flow3D has been shown in Figure 4. As observed, the flume is made of erodible materials before passing the flow from the combined weir-gate. Also, after running the program, scour is started in the numerical model. In the following, for various time intervals, the way of downstream scour has been shown in the numerical model.



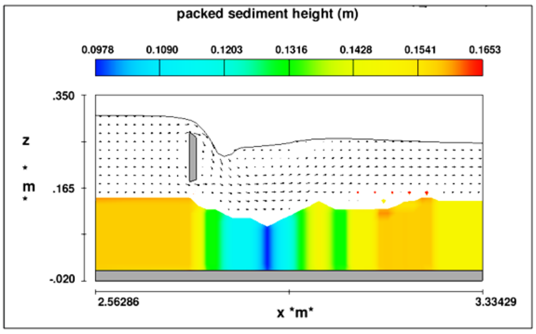
$(t = 0)$



$(t = 1\ min)$



$(t = 2\ min)$



$(t = 3\ min)$

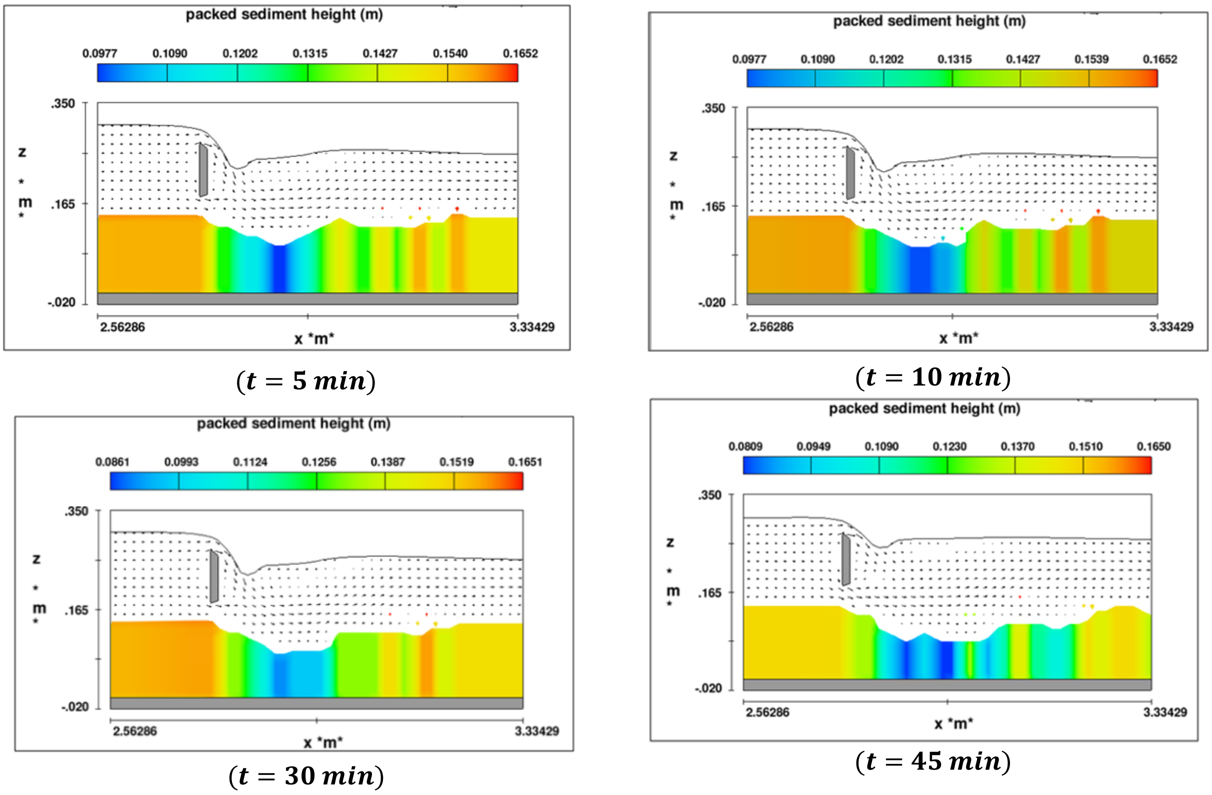


Figure 4. The lateral section of the weir-gate numerical model at time

To investigate the numerical modeling results and comparing them with the experimental results, for each of the following, the maximum scour depth values were extracted from the numerical model during 12 temporal steps. Then, the extracted values were compared to the experimental results. Figure 5 is based on the primary simulation conditions of the maximum scour depth at different times.

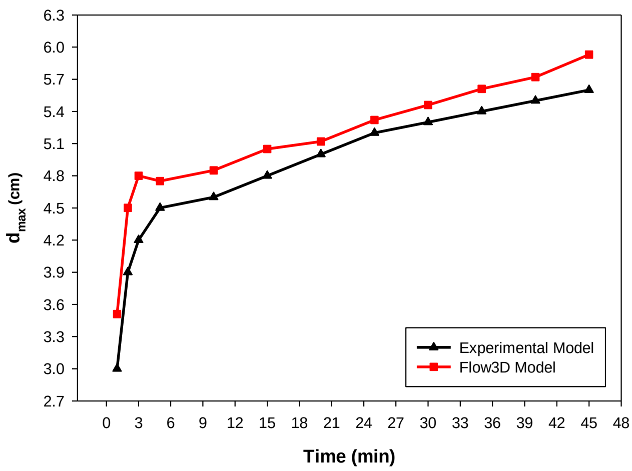


Figure 5. Comparing the experimental and numerical modelling results for conditions

To compute the relative error of the numerical model data and the experimental model, the following equation is used:

$$Error\ \% = 100 * \frac{X_{Num} - X_{Exp}}{X_{Exp}} \tag{1}$$

Where X_{Exp} indicates experimental values and X_{Num} indicates the simulated values. According to the above equation, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (17% in the first 60s). The error mean of the numerical data during the modeling is 7.1%.

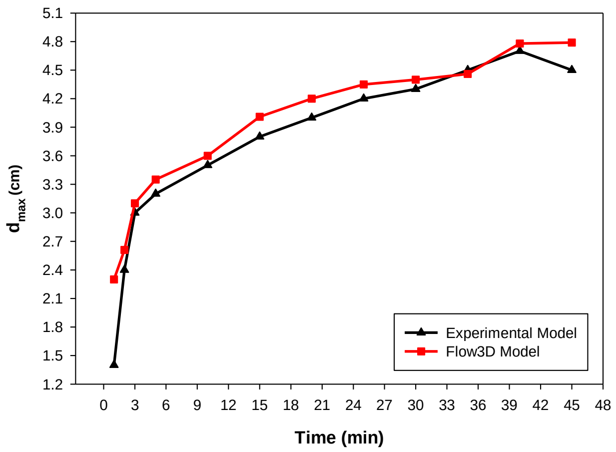


Figure 6. Comparing the experimental and numerical modelling results for conditions

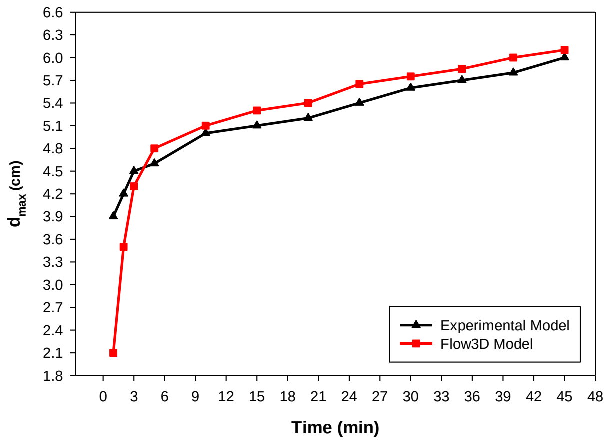


Figure 7. Comparing the experimental and numerical modelling results for conditions

As shown in the figure, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (64% in the first 60s). The error mean of the numerical data during the modelling is 14.3%. As shown in the Figure 7, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (64% in the first 60s). The error mean of the numerical data during the modelling is 8.03%.

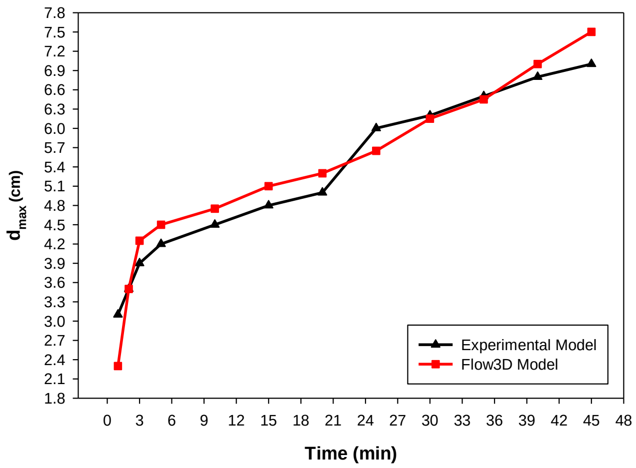


Figure 8. Comparing the experimental and numerical modelling results for conditions

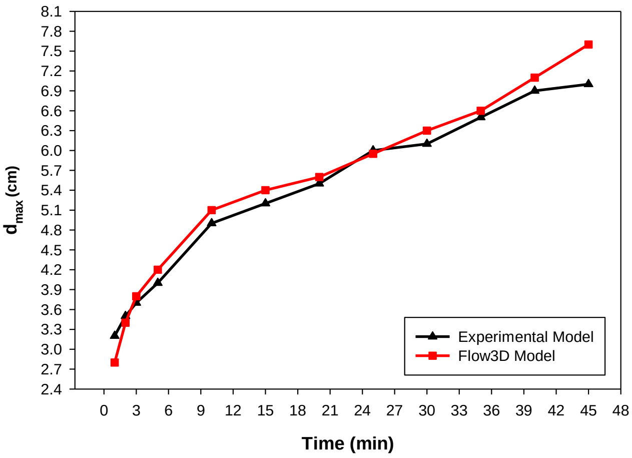


Figure 9. Comparing the experimental and numerical modelling results for conditions

According to the figure, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (25.8% in the first 60s). The error mean of the numerical data during the modeling is 6.4%. According to the Figure 9, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (12.5% in the first 60s). The error mean of the numerical data during the modeling is 4.16%.

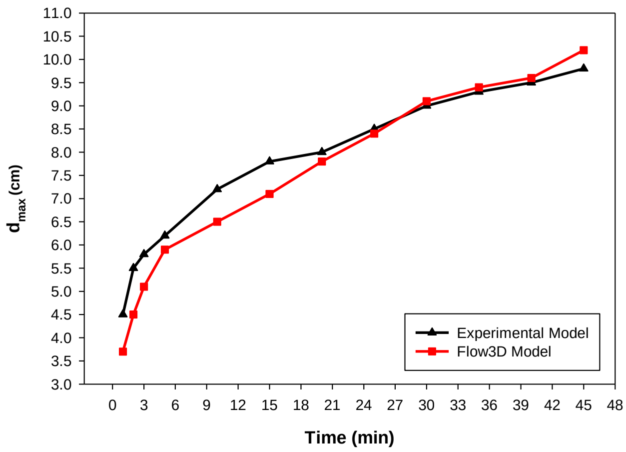


Figure 10. Comparing the experimental and numerical modelling results for conditions

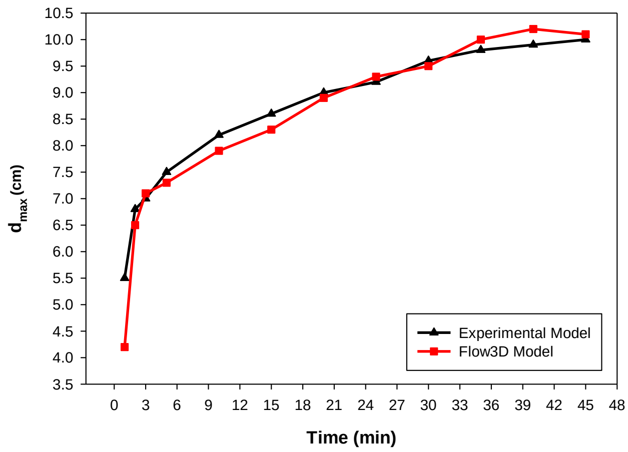


Figure 11. Comparing the experimental and numerical modelling results for conditions

As shown, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (17.7% in the first 60s). The error mean of the numerical data during the modeling is 6.8%. As shown in the Figure 11, the relative maximum error of the numerical model data with the experimental model occurs at the first 1 minute of the simulation (23.63% in the first 60s). The error mean of the numerical data during the modeling is 4.8%.

The relative error mean of all the above shown models reveals that the relative error mean of the numerical simulation equals 7.37% which is an acceptable value for the present numerical model. Notably, in all the simulations, the maximum error of the model has occurred at the first 60 seconds. It is due to the difference in regulating the exact value of passing flow at the moment of starting the experiments. In the experimental models, the exact regulation of the system's output discharge is not performed with a high velocity. In other words, at the onset of the experiment, the discharge value does not equal the other data acquisition times; however, in the numerical model, the output discharge values are exactly applied to the model from the beginning of simulation. Further, other factors include bed materials compression, geometrical shape of aggregates, cohesive conditions of materials, measurement tools accuracy in laboratory, etc. To determine the optimal follow passing over the weir to the flow passing through the gate, for various geometrical and hydraulic conditions of the simulations, the diagram of the maximum scour depth for 7 models were compared (Figure 12).

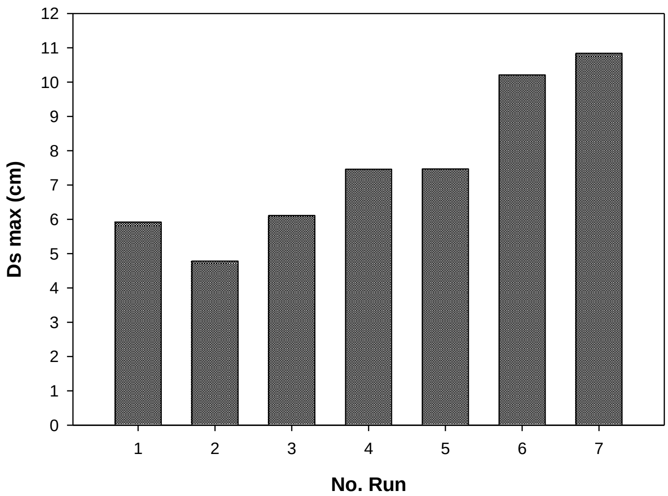


Figure 12. The diagram of the maximum scour depth changes for various hydraulic and geometrical conditions of the flow

Comparing the maximum scour values in the numerical models reveals that the conditions of the model No. 2 has the lowest scour depth; so, it is the best and most optimal model. According to the comparison, the best gate openness to the depth of water flow is over weir crown ratio (y/h=0.35) which has the lowest scour depth in the performed models.

Comparing the diagrams in various simulation conditions shows that the maximum difference between the numerical model results and the experimental results has occurred at the first 60 seconds of running the program. For other simulation times, the difference has been slight and acceptable. Investigating various diagrams of downstream scour simulation in the combined weir-gate model indicates that, on average, 45% of the maximum scour depth and 75% of scour in the numerical model has occurred at the first 3 minutes and the first 10 minutes, respectively. In each of the above shown figures, it is observed that in the 7 simulation conditions, the numerical results are close to the experimental results with a relatively high accuracy. To investigate the numerical and experimental results, for the maximum scour depth, various time periods of each of the data have been fitted in Sigma Plot Software. Also, the determination coefficient of the data that shows the relative error of the data has been computed. Figure 13 shows the maximum scour depth in the combined weir-gate model at different times, compared to the experimental results.

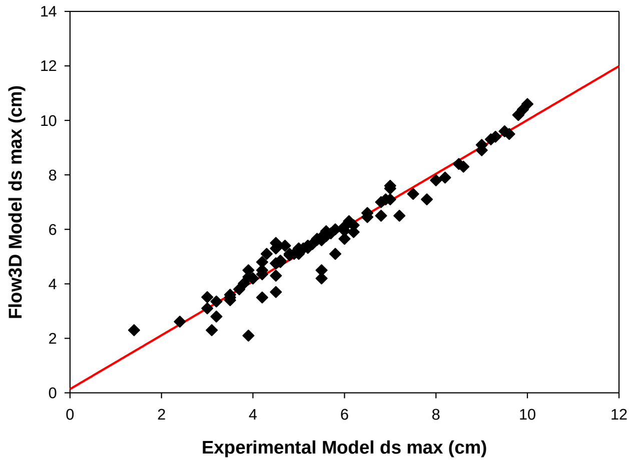


Figure 13. The diagram of the maximum scour depth in the numerical model compared to the experimental model

In this fitness, the determination coefficient (R^2) of the numerical results, compared to the experimental results, is 0.94% and the relative error of the numerical results, compared to the experimental results, is 7.36%. Notably, the determination coefficient of 1 indicates the total accordance of the numerical results and the experimental results. In this study, the determination coefficient has acceptable results with the error mean of 7.36%.

Figure 14 shows the values of velocity over the weir and below the gate with velocity vectors. Here, it has been tried to extract velocity flow changes with velocity vectors for various times of downstream scour in the combined weir-gate model by Flow3D. According to the following figure, velocity values at the moment of beginning computations and before scour have been extracted from the numerical model.

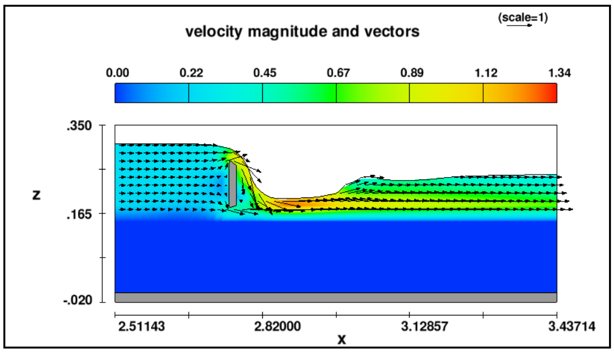


Figure 14. The velocity vectors at the moment of beginning numerical model running

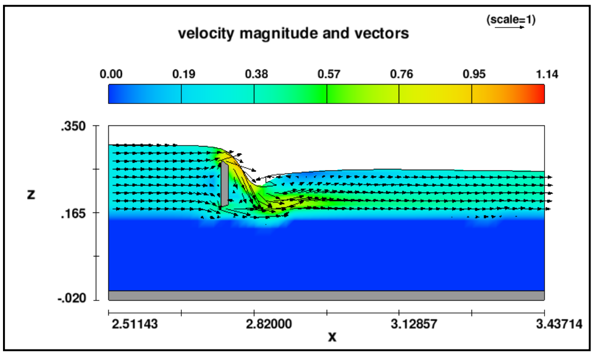
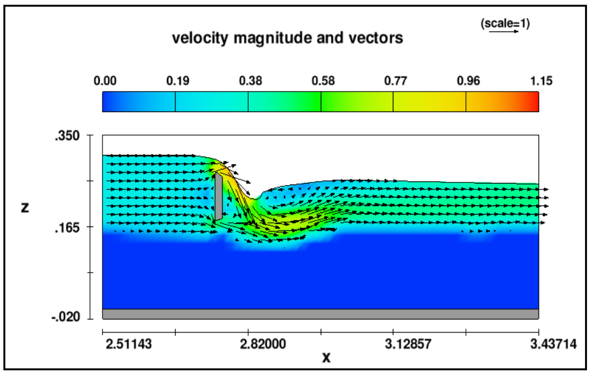


Figure 15. The velocity values with velocity vectors at the moment of beginning the numerical model run

As shown Figure 14, after running the numerical model, all boundary conditions and primary conditions introduced to the numerical model are applied to the solution field. The figure indicates that the maximum velocity values at the initial times (t<1min) of flow passing in the weir and the gate are formed at downstream place. In this case, for the maximum discharge in the combined weir-gate model, the maximum flow velocity in downstream is 1.34 m/s. Figure 15 shows flow velocity values and velocity vectors for time (t=1min).

As shown in Figure 15, passing time, a topical downstream scour is formed in the combined weir-gate mode. It is located at the downstream maximum velocity section. Passing much time (t=2min), a downstream partial swirling flow is formed at the numerical model. This swirling flow causes to increase the depth of downstream scour hole and to decrease the maximum velocity in downstream.



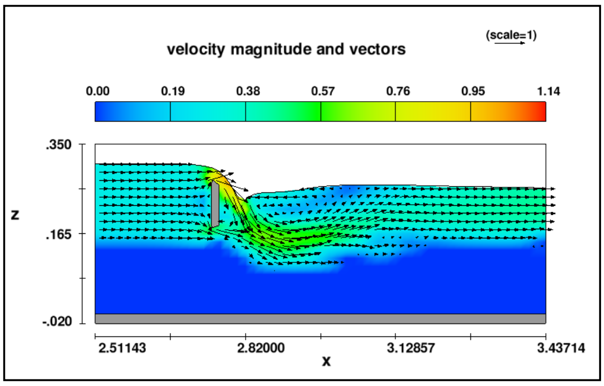
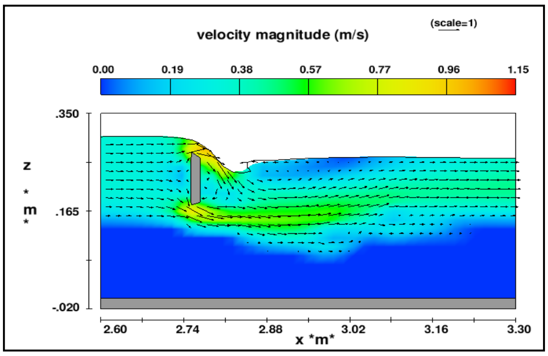


Figure 16. Flow velocity magnitudes with velocity vectors at the moment of starting the model run (t=3 min)

Figure 17. Flow velocity magnitudes with velocity vectors at the moment of starting the model run (t=5 min)

Passing time (t=3min), in the numerical model, the downstream swirling vortex becomes greater in the combined model; also, total profile and scour area in the numerical model is formed at this time. Passing time (t=5min), scour depth the length of swirling vortex are increased. Continuing the numerical model run shows that at the times much than 5 minutes (t>5min), scour depth is increased and downstream swirling flow is increased. Decreasing velocity magnitudes in downstream continues till scour depth becomes constant for passing time. In this case, downstream scour profile in the combined model has reached the balance state. Figures 18 and 19 show the final scour profile for 45 minutes (t=45 min).



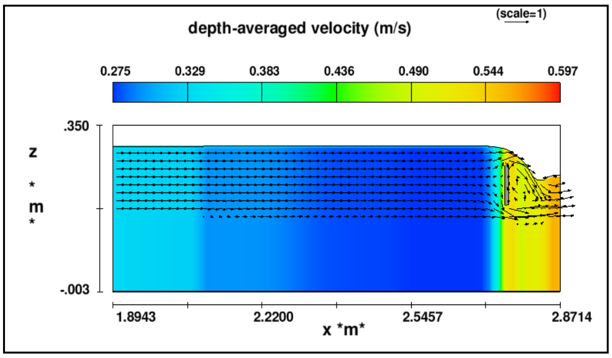
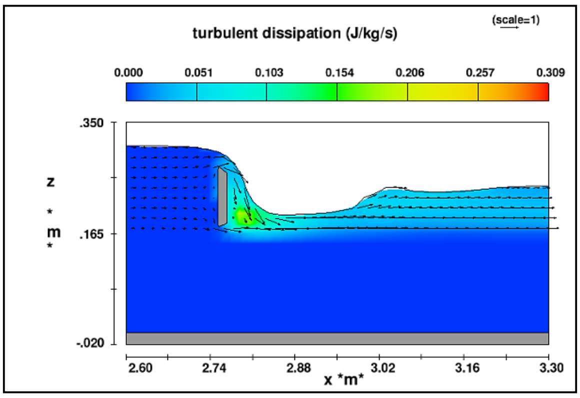


Figure 18. Flow velocity magnitudes with velocity vectors at the moment of starting the model run (t=45min)

Figure 19. Flow velocity with velocity vectors in the weir-gate upstream

The level of turbulent energy dissipation at the combined weir-gate downstream was also investigated at the time of starting to run Flow3D and at the end of running it. Figures 20 and 21 show the results.



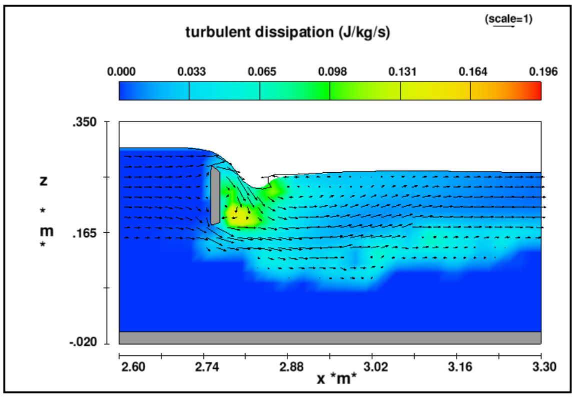


Figure 20. Flow turbulent energy dissipation changes in the combined weir-gate model downstream (t=0)

Figure 21. Flow turbulent energy dissipation changes in the combined weir-gate model downstream (t=45)

As shown in Figures 20 and 21, at the start of computations in the numerical model, compared to the end of running, turbulent energy dissipation has decreased to 38%. Decreasing turbulent energy dissipation leads to the scour hole balance in the numerical model.

4. Conclusion

Combined behavior of the flow falling from the weir with the output jet below the gate creates different conditions in the downstream of such structures and causes scour changes in the downstream of these structures. Scour is a phenomenon caused as a result of water and soil interaction in the vicinity of hydraulic structures. Predicting scour in the bed is a considerable issue in hydraulic. Every year, heavy costs are spent to control and prevent scour in the downstream of hydraulic structures; therefore, predicting scour before constructing a structure is necessary for every design. The expansion of such a phenomenon can endanger the stability of the structure. In this regard, this study attempted to numerically simulate temporal changes of scour in the downstream of the combined weir-gate model by Flow3D. For numerical modeling, the temporal changes of scour in the downstream of the combined weir-gate model by Flow3D, various sections of simulation were presented. Also, boundary conditions and the numerical model gridding were constructed for the geometry model. Numerical modeling was run after fully preparing and the obtained data was analyzed under three-dimensional conditions. Comparing experimental and numerical results with data fitness revealed that determination coefficient (R^2) of the numerical model results to the experimental model results is 0.94. Also, it was found that the relative error of the numerical model results relative to the experimental results equals 7.36%. Further, it was found that at the start of computations in the numerical model, compared to the end of running the model, the turbulent energy dissipation was decreased to 38% and decreasing the turbulent energy dissipation led to the creation of scour hole balance in the numerical model.

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