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Conference Paper

Simulation of local scour development downstream of broad-crested weir with inclined apron

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Abstract

Broad crested weirs are hydraulic structures used to control the flow depth and discharge of channels. Structures constructed in rivers and channels are exposed to scour around their foundations as they cause turbulences in uniform flow and sediment transport as a result of increase in flow velocities at downstream. If the scour depth becomes substantial the stability of the foundations endangered with a resultant hazard to the structural failure. In this study the flow field variation and the equivalent depth of scour was simulated by means of three-dimensional numerical analysis using a sediment scour model of FLOW-3D program. The sediment scour model in FLOW-3D is able to simulate the scour hole development process, in this study four models of inclined apron of broad crested weirs [A, B, C, D] with different downstream reverse angles (0˚, 4.5˚, 8.7˚ ,13˚) respectively are tested under the same flow intensity and the same duration, based on experimental study from the literature that has been held for a duration of 6 hours to see if the same behavior will be concluded for scour reduction. Downstream of the first models act as ordinary weir while the other models act as an obstacle toward the flow, the water flows above the sloped downstream bed and dissipates some of its energy. There was a good agreement between experimental and FLOW-3D results. The results showed, that model C reduces local scour hole volume, the maximum scour depth in addition shift the scour holes away from the structure as compared to the other models. The idea is decreasing downstream height of broad crested weir while providing an obstacle in shape of sloped downstream bed toward the flowing water. This reduction gave the weir a new performance by making it as an energy dissipater. The present technique similarly reduces construction costs also improves the hydraulic performance of single step broad crested weirs.

Keywords: Sediment scour, scour reduction, erosion, FLOW-3D, broad crested weir.

1. Introduction

Weirs are defined as an obstacle in an open channel system which water flow over it and based on the geometry of the weir and head on the weir crest, it is used as an indirect technique for the flow rate measuring (King and Braver, 1963). One of the most common types of weirs are the broad-crested weir, the main issues related to such structures are scouring at the downstream of weir structures which are the leading causes of their failure. Numerous different methods were tested and applied to study and minimize the local scour. Ozmen-Cagatay and Kocaman (2011), for simulating a dam-break used FLOW-3D software where the applied turbulence model presented good agreement to experimental outcomes. Amin (2015) used physical model to evaluate and compute the influence of hydraulic structural measure (double lines water jets) on minimalizing the dimensions of scour-hole downstream of a Faiyum model of weir. His experimental outcomes confirmed the suitability and the usefulness of the proposed measure (floor water jets) in improving the flow hydraulic conditions and the local scour dimensions downstream Faiyum type weir. Helal (2013), studied the effect of installing a single line water jets to the floor of the hydraulic structures on reducing the scour hole sizes and determined that the system of floor water jets is effective in reducing the cost of energy dissipating stilling basin. Abdelhaleem (2013) experimentally studied the influence of semi-circular shapes of baffle block on local scouring downstream of a Faiyum kind weir. He reported that; the existence of baffle blocks, both upstream and downstream slopes of the scour hole formation increase but the downstream slope is steeper than the upstream, that specifies the important impact of baffle blocks on the scour hole dimensions. Dargahi (2003) conducted a laboratory investigation to study the scour profiles and the scour geometry likeness. No experimental indication was determined in support of the similarity assumption for time-based progress of the scouring development. For the geometry of scour hole prediction, he introduced power-law form equations, primarily in terms of affecting variables such as, depth of flow over the spillway crest and sediment particle size.

In this study, validation of FLOW-3D program is conducted in terms of the program capabilities for predicting scour developments downstream of broad crested weir. The validation is based on the simulation of the experimental study made by Abdulnaser et al (2015). The maximum scouring depths and volume of scour downstream weirs crest are compared with available experimental data. Additionally, the conclusion of the best model for scour reduction are investigated.

1 2. Model Setup

In this study FLOW-3D is used to simulate a numerical model based on an experimental study of (Abulnaser et al, 2015). FLOW-3D is a commercial package developed by Flow Science Inc. (Flow Science Inc., 2009) at Los Alamos Scientific Lab. The software practices some superior features for numerical solution of the Navier-Stokes equations for free surface flows (VOF-method) and meshing of complex geometries (FAVOR method). The sediment scour model in FLOW-3D treats sediment by way of two concentration fields (Brethour, 2003): the suspended sediment and the packed sediment. The suspended sediment advects and drifts with the fluid because of the effect of the local pressure gradient. Suspended sediment initiates from inflow boundaries or from erosion of packed sediment. The packed sediment does not advect, and characterizes sediment that is bound by adjacent sediment particles.

Figure 1 shows the experimental flume setup for an inclined apron of broad crested weirs. Water enters the flume with a discharge of 25 l/s. The water flows over a solid bed, 38.4 cm in length, before contacting a packed bed of sand 200 cm in length and 19.2 cm in depth. The median diameter of the sand grains is 1.8 mm. The channel is 80 cm in width, the scour profiles were measured down the centerline of the flume.

FLOW-3D mesh generator to handle the complex geometries uses the FAVORTM technique in an orthogonal mesh defined in Cartesian or cylindrical coordinates. Only the orthogonal mesh is permitted to simplify the development of meshing domain in FLOW-3D. The obstacles and baffles are embedded in the orthogonal mesh, which tolerates separate characterization of the mesh and geometry. Figure 2 shows the 3D computational domain that is 300 cm long starting the slit and 50 cm high including 19.2 cm of packed bed. There are 23634 mesh cells in total. In the simulation, the density of sand is 2.65 g/cm3.The weir downstream adverse slope arrangement in FLOW-3D was achieved by inserting a STL file format. In STL files formats solid object surfaces are approached by triangle systems. To convert the solid model into STL format AutoCAD program was used. One uniform mesh block was used for the domain discretization. A grid sensitivity analysis with respect to the computational time was performed. The grid was refined till the computational time increased unreasonably.

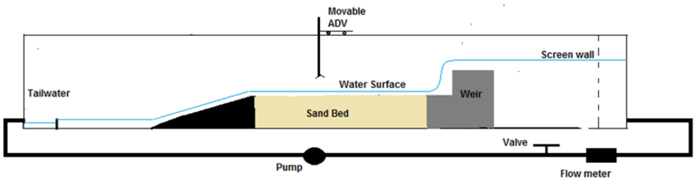


Figure 1. Schematic layout of the flume (Abdulnaser et al, 2015).

Boundary conditions for y minimum direction was considered to be "symmetry", which indicates that identical flows happen on the other side of the boundary and hence there is no drag on this boundary. In the x direction, the boundary condition was "specified stagnation pressure". With this algorithm, FLOW-3D is able to model various flow heights beginning at a stagnation pressure state. A continual volume flow rate was used as inflow boundary condition. Figure 2 represents boundary conditions on the x-y-z planes. In the simulation with single fluid, the critical Shields parameter was 0.05, both the entrainment and bed load transport coefficient values were 0.0018 and 8.0, respectively, the angle of repose was 45° and the critical packing fraction was 0.64. The turbulence was predicted using Renormalized group (RNG) model.

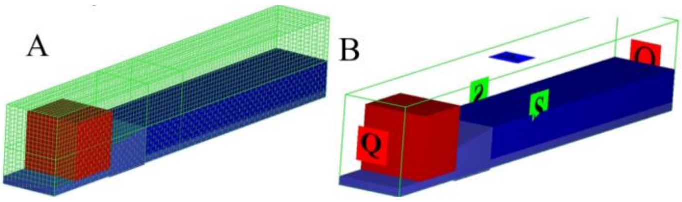


Figure 2. A- Computational domain and mesh setup to simulate scour in the flume, B- Configurations of boundary conditions.

3. Results and Discussion

3.1 Investigating effect of inverted slope on water surface profile and velocity downstream of weirs crest

In different models of weirs' crest, the changes of water surface profile of numerical results are investigated and compared with experimental data (Figure 3 and 4). Based on the results extracted from the diagram of water surface profile on weirs' crest, it can be predicted that there is a clear influence of the change in downstream slope on the water surface profile which results in the change of the hydraulic parameters of the system. In addition, leads to change in the rate of the scouring. Figures 3 and 4 shows the experimental and numerical results and from these plots it can be understood that there is a good agreement among the Flow-3D and experimental results. As its seen the water surface at model A is smooth and effect on larger distance at downstream of the weir but the water surface at model B and D are more turbulent because the effect of inverted slope on water falling at downstream of the weir, hence the horseshoe vortex is very strong for models B and D, but then again the effect of horseshoe vortex is reduced for model C as a result of large energy dissipation and effect of the downstream slope of the weir lead to decrease the energy of water. It is Obvious from Figure 4 that the maximum velocity was found on the sloped bed and then decreased immediately after the weir structure due to the energy dissipation on the sloped bed, as model C downstream slope caused energy dissipation more than other models which resulted in the high scour reduction.

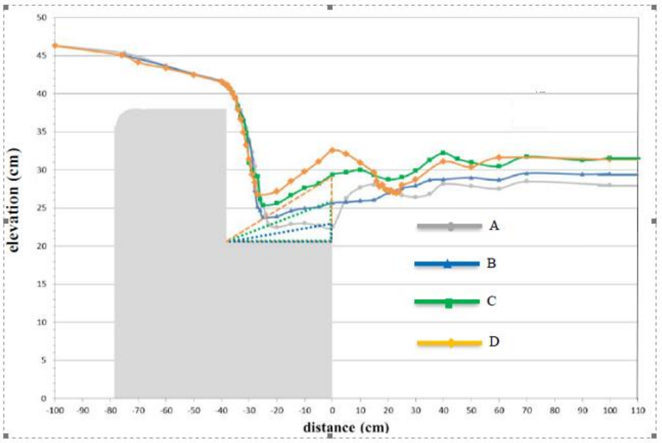


Figure 3. Experimental longitudinal water surface for each model Q = 25 **l/s**

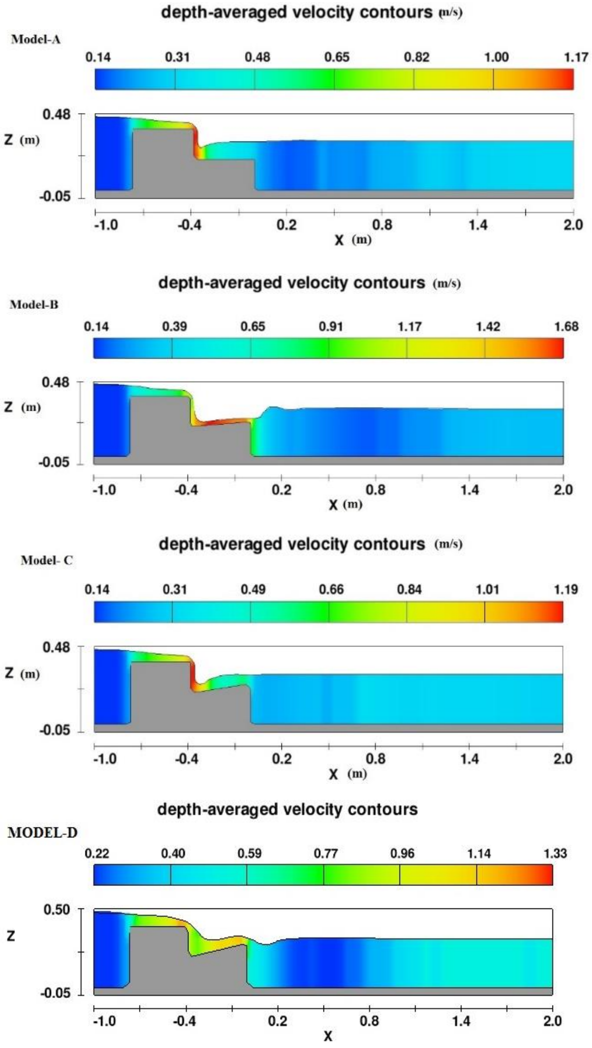


Figure 4. Comparison of longitudinal water surface profile and depth average velocity at the central axis on the weirs' crest in various models Q = 25 l/s

3.2 Investigating effect of inverted slope on scouring downstream of weirs crest

Figures 5 and 6 present the measured and the calculated scour profiles for all models, respectively. It is found the calculated shape and elevation of the sand bed compare well to those measured in the experiment. As measured, a scour hole is generated just behind the weir due to entrainment and bedload transport. Figure 6 shows the maximum scour hole depth from numerical results. Good agreement is observed between the measurement and the calculation. The maximum scour hole depth is only slightly underestimated.

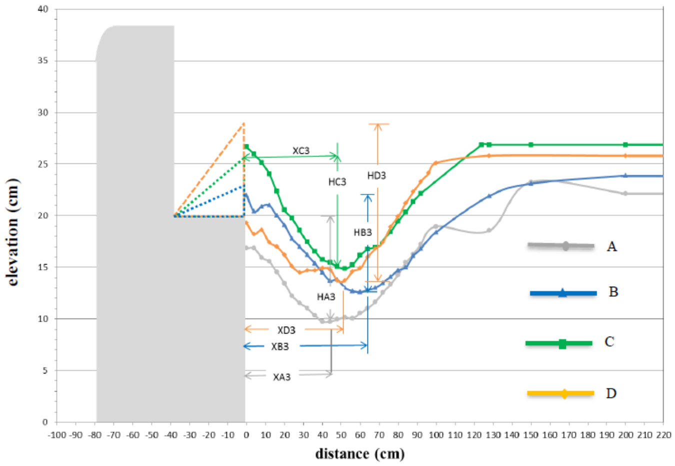
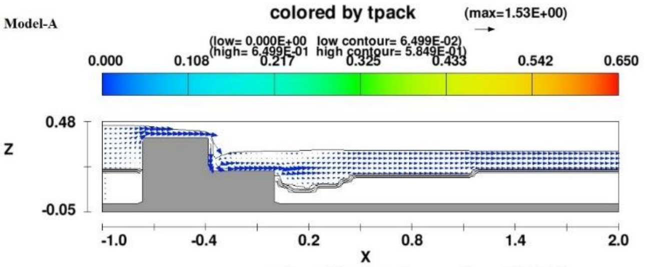
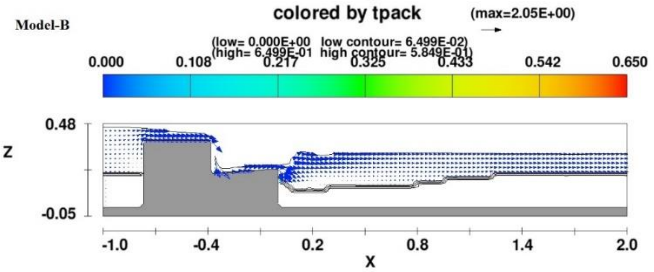
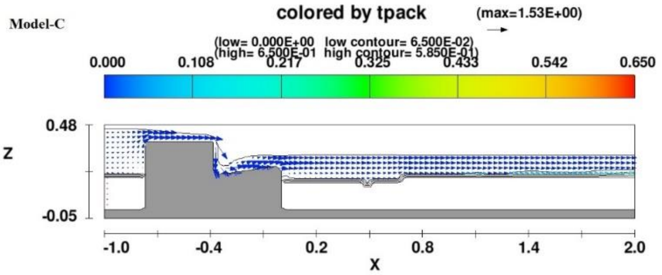


Figure 5. Experimental result of longitudinal scour holes and distances from the weir for each model Q = 25 l/s.







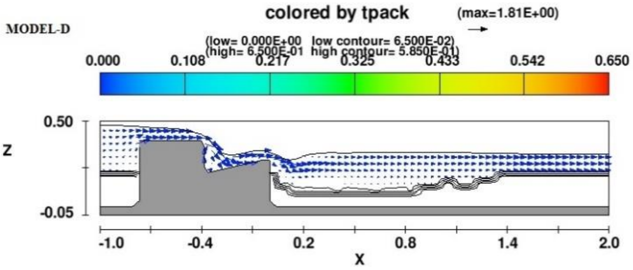


Figure 6. Calculated results of longitudinal scour holes and distances from the weir for each model and discharge (25 l/s), tpack (total packed sediment solid fraction).

As shown in Figures the maximum scour depth was initiated after the weir model D for the reason that the drop of water adjacent from the toe of the weir. This case increases the danger of failure of the weir. While model C reduces depth of scour and creating least scour in the downstream of the weir and pushes the drop of water away from the weir.

From Table 1 it is obvious that the model C reduces the scour depth and the volume of local scour as compared to the other models. This is because the slope of downstream of the weir resulted in the formation of weak horse shoe vortex. Results comparison for the same discharge of 25 l/s showed that in the experimental results model C reduced scour depth and scour hole volume about 24.2% and 44.8% respectively as compared to the models D. While from numerical results comparison showed that scour depth and scour hole volume was reduced about 37.5% and 50.1% respectively.

Table 1. Local scour dimensions for each model

Model	**θ°**	**Q (l/s)**	**Volume of scour (cm^3)**		**Max. depth of scour H (cm)**		**Distance from weir X (cm)**	
			Exp.	**Num.**	**Exp.**	**Num.**	**Exp.**	**Num.**
A	0	25	48583	47800	12.4	11.8	68	40
B	4.5	25	52680	42500	12.4	10.1	48	36
C	8.7	25	43784	33200	12.2	8.5	76	69
D	13	25	79316	66600	16.1	13.6	48	44

3.3 Investigating effect of inverted slope on flow pressure distribution downstream of weirs crest

In various models of weirs' crest, the outcome of flow pressure distribution changes on broad-crested weirs is studied. In Figure 7, flow pressure values simulated for central axis of channel in longitudinal direction and has been presented. It is useful to determine the way of pressure distribution to consciously apply energy equations and motion size in weirs. If in case of designing, pressure imposed on weir is more than atmosphere pressure, discharge is decreased and vice versa; also, it simultaneously causes to the creation of cavitation phenomenon. Therefore, it is highly important to investigate pressure distribution on weirs' crest. Accordingly, in the following, precise process of pressure distribution and changes under the impact of weir’s downstream slope are investigated. And the outcomes show that the higher the pressure occurred at the location of maximum socur of the models and model C reduced pressure at the downstream in a great manner and caused a high reduction in socur hole formation. Which indicates that Increasing inverse downstream slope with a spcific degree leads to the decrease of pressure value, which shows the energy dessipasion caused by ineverted downstream slope as it can been seen clearly from model C.

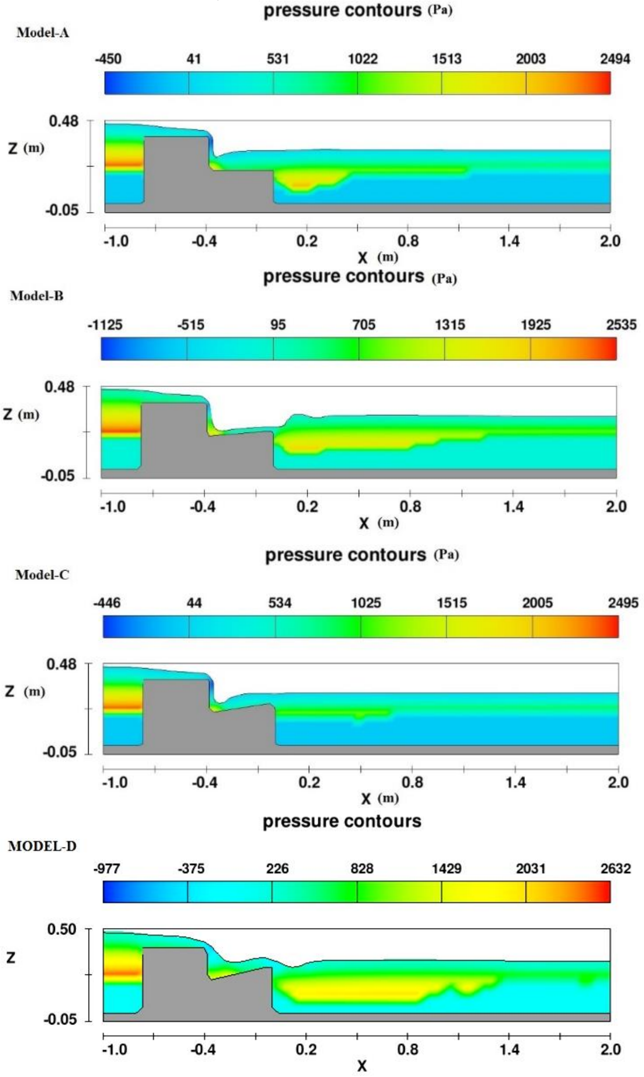


Figure 1. Flow pressure distribution changes on weirs’ crest for different models.

4. Conclusions and recommendations

The present work was an effort to examine hydraulic characteristics and parameters that reduces scour due to the change of the downstream apron inclination of broad crested weir and checking numerical capabilities using computational fluid dynamics method. In this regard, FLOW-3D model was studied by changing gridding as well as changing different parameters of the model. For the result validation, FLOW-3D study was based on laboratory experiment models from literature experiments studied the application of a new shape of downstream apron of broad crested weirs. Changing the slope of downstream apron is not only effective for reducing local scour but it is also much more economic when it is related to traditional broad crested weir. The current study demonstrates that there is no need to countermeasure the scour depth by lining with rubbles and riprap to protect from failure since the distance of scour from weir was significant to avoid that, the new idea is only to change the inclination of downstream apron of the weir.

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