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NUMERICAL SIMULATION OF EROSION PROCESSES ON CROSSBAR BLOCK RAMPS

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ABSTRACT

Crossbar block ramps are nature-like flow structures to conquer large river bottom steps with adequate flow velocities and flow depths for fish passage. Therefore, the channel will be divided into several basins, formed by crossbars of large stones. Within these basins, a bed material layer is placed to avoid erosion processes and hence to reduce the risk of structural failure. To guarantee stable block ramps, an adequate design is essential. Therefore, erosion processes within the basins must be analyzed to develop design formulas for practical engineers. In the main focus of interest is the material diameter, and density, to avoid relevant movement, which can decrease the stability of the structure. Nowadays, numerical simulation tools revolutionize the hydraulic engineering field and flow simulations in 1D and 2D are state-of-the-art. But sediment transport simulations are still imprecise and difficult to adopt. For 2D transport processes in plan view (depth averaged), numerical 2D simulation products can be used. Therefore, a detailed calibration with field data is necessary, to ensure correct results. For detailed sediment transport and erosion studies, e. g. in the near-field of hydraulic structures, 2D sectional models or 3D models are necessary. In this context the present paper deals with a numerical model of a crossbar block ramp. The code FLOW-3D is used to include a packed sediment fraction within the model. For various flow regimes the movement of base layer material between the crossbars is analyzed in detail. Numerical model results are compared with experimental model results from a scaled physical model. The aim of the study is to focus on the comparability between the experimental and numerical model relating scouring processes.

Keywords: Crossbar Block Ramp, Erosion, Scour, Experimental Model, Numerical VOF Simulation

1. INTRODUCTION

Block ramps are hydraulic structures, which can be used to reduce flow velocities and to increase flow depths for steep open channel flow systems. The main aim is to allow an adequate fish climb capability for various species. Crossbar block ramps are step-pool systems and part of the structured ramp family. With large boulders crossbars are formed as laterally installed structures. Usually, lower openings will be placed within these crossbars, representing the fish pass corridor. Formed basins are filled with a rough material layer to avoid erosion, to stabilize the structure and to create a pass corridor for tiny species. For a practical engineer it is essential to know about occurring scouring processes of the base material to design stable structures. Therefore, fundamental knowledge about loads on crossbar boulders as well as resistance forces is necessary (Oertel et al., 2011). Scouring and erosion of bed material may lead to an insufficient embedment depth of the boulders and thus, to a failure of the structure. In this context, Oertel and Bung (2015) analyze the stability of bed material in crossbar block ramp basins and developed formulas for critical flow conditions.

In the past, many investigation programs were carried out to focus on the hydraulic and the stability of block ramps. Whittaker and Jäggi (1984) present first design formulas due to stability of block ramps. Carlin (2002) focuses at the initial motion of boulders in bedrock channels. Pagliara (2007) analyses failure mechanism on base and reinforced block ramps by determining transport processes of arranged stones and bed material. Korecky and Hengel (2008) focus on the design and stability of unstructured block ramps. The literature provides a lot more experimental studies on block ramp flow with included stability considerations. More details can be found in Oertel (2012).

2. EXPERIMENTAL AND NUMERICAL MODEL

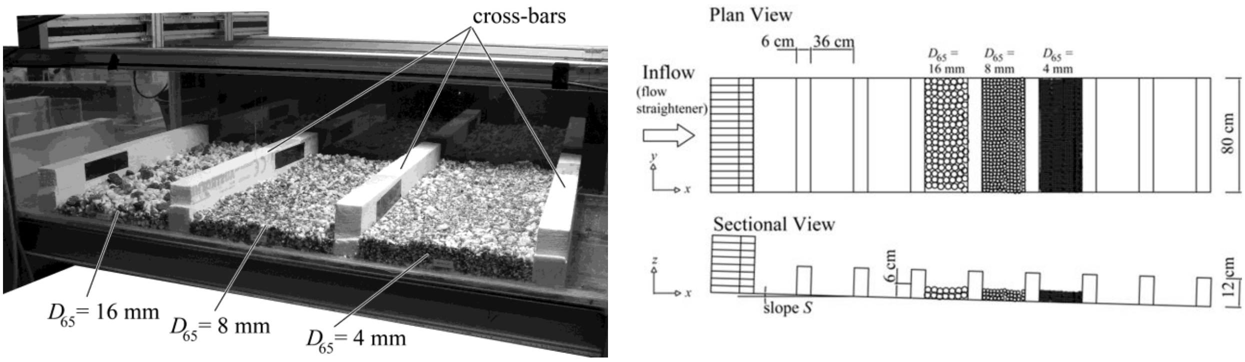
2.1 General

Experimental model data was produced at the University of Wuppertal's Hydraulic Engineering Section (Oertel, 2012). The model was built up to analyze bed material stability on crossbar block ramps. Thereby varying slopes, discharges and bed material diameters were investigated. Referring to the physical model a numerical simulation is used to reproduce the results. The simulation of sediment transport and scouring can be calculated with the CFD software FLOW-3D. In this context, the sediment scour model provides the opportunity to analyze sediment-drives caused by fluid flow and complex flow patterns.

2.2 Experimental model

The model was arranged in a tilting flume with a total length of 9.0 m, a width of 0.8 m and a height of 0.5 m. The investigated slopes were S = 1:50, S = 1:30, S = 1:20. N_{CB} = 10 crossbars with a height of 12 cm (6 cm above bed surface) and a longitudinal width of D_{CB} = 6 cm were arranged on a total length of L = 4.2 m. Accordingly the space between two cross-bars was $6h_s$ = 36 cm. Within the study, three different bed materials were selected and have been tested at same model runs (Fig. 1), because effects of the bed material on the water surface and energy dissipation are negligible (see Oertel and Schlenkhoff, 2011). The characteristics of the chosen materials are shown in Table 1. Furthermore, Figure 2 shows the respective grading curves. Discharges varied between Q = 5 l/s and 100 l/s in the physical model and were measured with an electromagnetic flow meter (manufacturer: Krohne, type: OPTIFLUX, velocity accuracy: +/–0.1 l/s). Details can be found in Oertel and Bung (2015).

A measurement campaign was done to identify scour development in the three basins after various time steps of 0, 5, 10, 15, 20, 30 min. Therefore, the model was assembled with three initial material beds (Figure 1). After the defined time steps the water supply was slowly switched off to keep the shape of the developed scour. Subsequently the scour surface was measured with ultrasonic sensors (USS) at three longitudinal sections (manufacturer: General Acoustics, type: USS635, accuracy: +/–0.2 mm, frequency: 75 Hz, sample rate: 5 sec).



(a) (b)

Figure 1. Physical model, (a) example photograph, (b) schematic plot (Oertel 2012, Oertel and Bung 2015)

Table 1. Bed material characteristics

MATERIAL	D_{65} [mm]	$D_{65}h_B^{-1}$ [–]	ρ_p [kgm^{-3}]	φ[°]
No. 1	4.0	0.067	2678.7	26.96
No. 2	8.0	0.133	2431.0	27.68
No. 3	16.0	0.267	2737.4	25.40

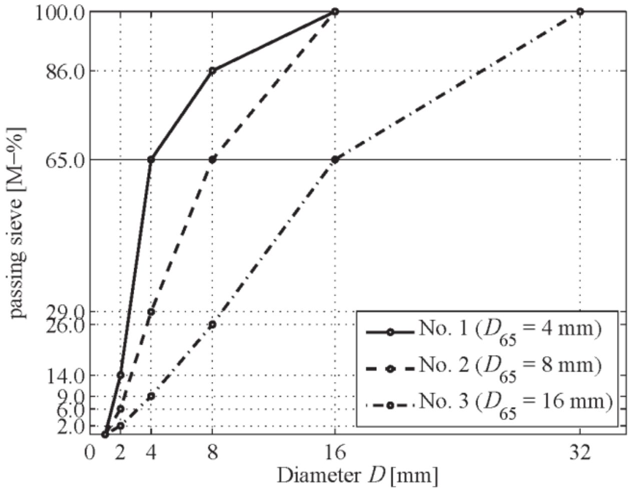


Figure 2. Grading curves of bed materials (Oertel, 2012)

2.3 Numerical model

With the scour model being included in FLOW-3D sediment transport processes can be simulated. In the present investigation, the main focus is on the definition of the sediment which is, among other factors including particle size, density and angle of repose as well as the composition of packed sediment, depending on highly complex parameters. Furthermore, FLOW-3D permits to configure four additional parameters. Those include the drag coefficient as well as the critical shields number, the bed load coefficient and the entrainment coefficient. A parametric study investigates their influence on the sediment-drive during the flow process. This is necessary to reproduce sediment deposits and transports, based on the results of the physical model. The investigation program includes the slope of S = 1:30 and the discharges of Q_m = 40, 60, 80 and 100 l\s. In addition only the bed materials No. 1 and 2 (D_{65} = 4.0 and 8.0 mm) were chosen. It must be noticed, that newer releases of FLOW-3D changed due to the scouring model and hence, parameters can vary slightly.

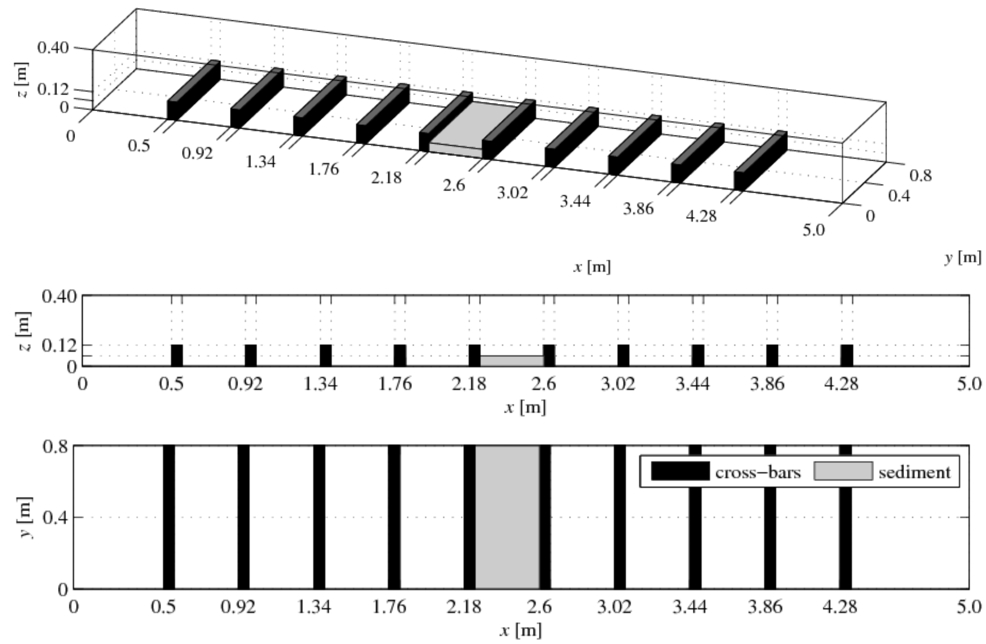


Figure 3. Sketches of the numerical model, top: 3D view, middle: sectional view, bottom: plan view (Balmes, 2012), flow direction left to right

2.3.1 Model geometry

The geometry of the numerical model (Fig. 3) equates the experimental model within the tilting flume with the same arrangement of crossbars. Only the length was reduced to decrease calculation times; L = 5.0 m instead of 9.0 m. The missing section is located downstream the last crossbar and hence will not affect the sediment transport processes. To reduce the influence of the inflow and outflow conditions the packed sediment is placed in the fifth basin with a bed surface of h_s = 6 cm.

2.3.2 Physics

There are three important preferences relating to the defined physics in FLOW-3D. (1) The specification of gravity is used to generate the slope of S = 1:30. Hence, the gravity components are: g_x = 0.3268, g_y = 0 and g_z = -9.8046 (in ms^{-2}). (2) For the viscosity and turbulence options the viscous flow is activated and turbulences were calculated with the RNG-model. (3) The most consequential preference is the activation of the sediment scour model and the definition of the sediments. Both chosen bed materials are composed of four sediments with diameters of 2, 4, 8 and 16 mm. Differences between D_{65} = 4 mm and D_{65} = 8 mm are only the diversities in density and angle of repose (Tab. 1). A performed parametric study has shown that the default settings for the drag coefficient, the critical shields number and the bed load coefficient are worthy for the intended use. The entrainment coefficient is set to zero (deactivated) because test simulations have shown that an activation leads to a segregation of the sediments which does not correspond to the physical model results. Table 2 shows the elected values for each parameter. The missing specification for θ_c means, FLOW-3D will calculate the number form the Shields curve using the Soulsby-Whitehouse equation (Brethour and Burnham 2010).

Table 2. Parameter settings

CRITICAL SHIELDS NUMBER θ_c	DRAG COEFFICIENT C_D	BED LOAD COEFFICIENT Φ	ENTRAINMENT COEFFICIENT α
-	0.5	8	0

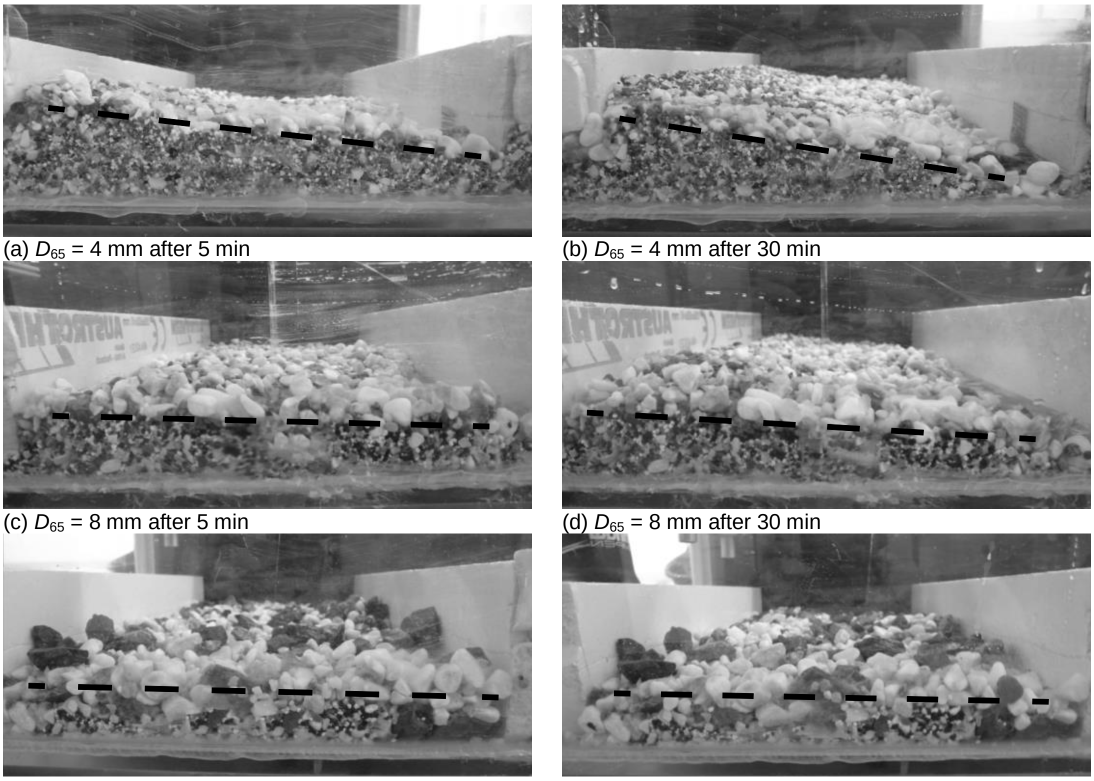
2.3.3 Boundary conditions and mesh grid

The hydraulic boundary conditions refer to the physical model data. Hence, the inflow elevations are determined by the water levels which were measured for each discharge in the laboratory. To generate a flow rate the velocity is defined according to the specified water level. The boundary condition at the downstream end of the ramp is described by an outflow. The mesh grid has a resolution of d_x *and* d_z = 1.0 cm. To perform a two dimensional calculation the width of the model is defined by one cell with d_y = 0.8 m. Hence, boundary conditions for the lateral limits must set to symmetry.

3. RESULTS AND DISCUSSION

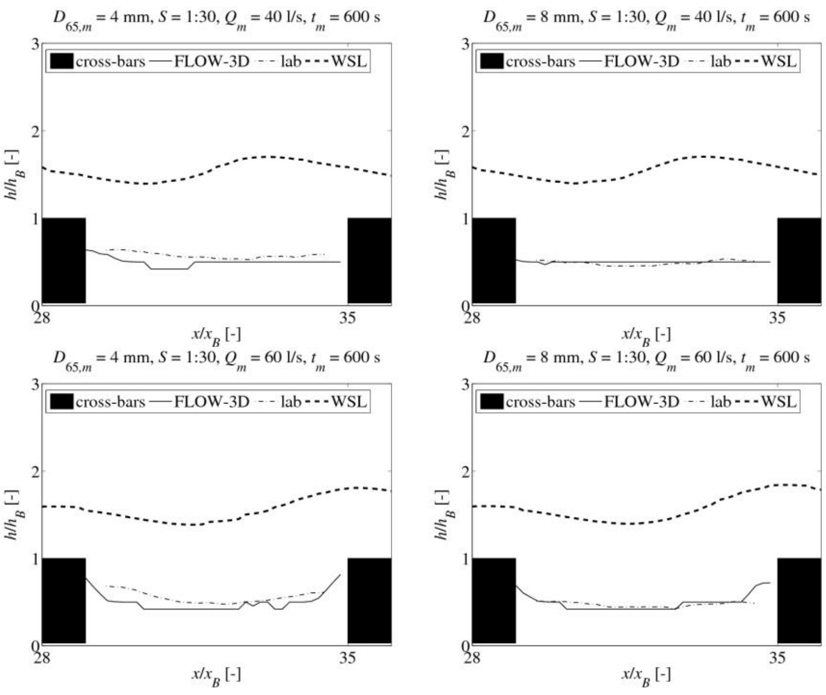
Figure 4 gives example results (experimental model) for the scour development for configuration S = 1:30 and Q = 100 l/s. Those represent the main phenomenon which has been pointed out for most cases (Oertel and Schlenkhoff, 2012). It can be shown that the bed material will be transported upstream and the main erosion takes place at the downstream basin end. For smaller particle sizes more movement can be observed (Fig. 4 b) while larger particles are more stable (Fig. 4 f). Also a progress of the sediment development can be determined. Erosion processes increasing with time, hence erosion is larger after 30 min than after 5 min, obviously. The surrounding material of the boulders will be eroded with proceeding scouring. Hence, the stability of the crossbars will be decreased because of the dependence on missing bed layer material.

In Figure 5 results of the experimental and numerical models are compared. The left column shows the sediment development for D_{65} = 4 mm and the right column for D_{65} = 8 mm after 10 min and the discharges Q = 40, 60, 80 and 100 l/s. It can be observed that only results for the lowest discharge are fitting well. The finer bed material will be transported upstream, both in the experimental and the numerical model. The coarser material shows almost no development related to the initial state. For all other discharges, the numerical model presents sediment deposits at both basin ends close to the crossbars. Thus, scour forms in the center of the basin. In consequence of the increasing discharges and the elected bed materials, differences between the results are negligible. Therefore, it can be stated that when sediment transport occurs, there is always a nearly identic formation within the numerical model. This does not represent the results of the measurement campaigns performed in the laboratory.



(a) D_{65} = 4 mm after 5 min
(b) D_{65} = 4 mm after 30 min
(c) D_{65} = 8 mm after 5 min
(d) D_{65} = 8 mm after 30 min
(e) D_{65} = 16 mm after 5 min
(f) D_{65} = 16 mm after 30 min

Figure 4. Example photographs for surface development of basin materials, S = 1:30 and Q = 100 l/s (Oertel, 2012), flow direction left to right



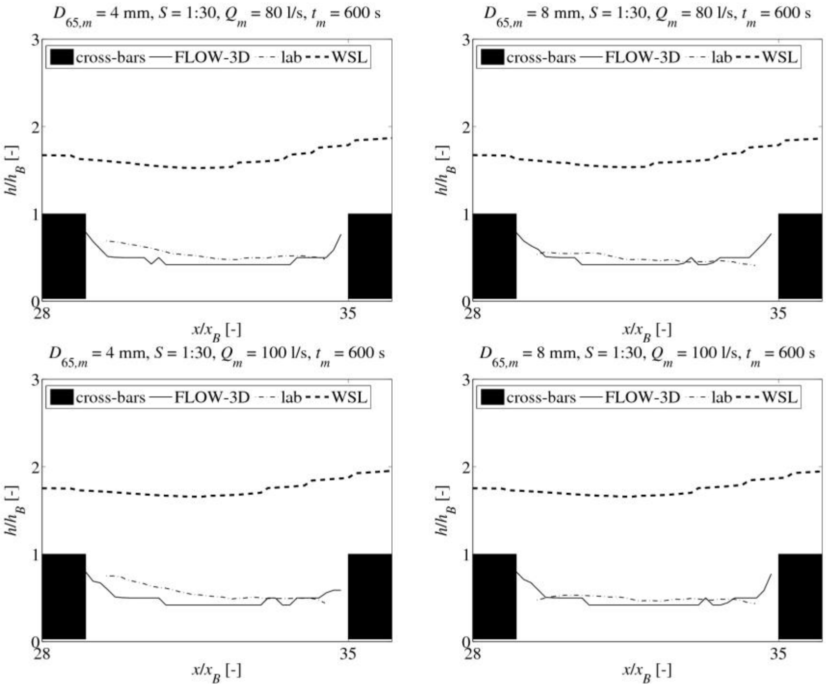
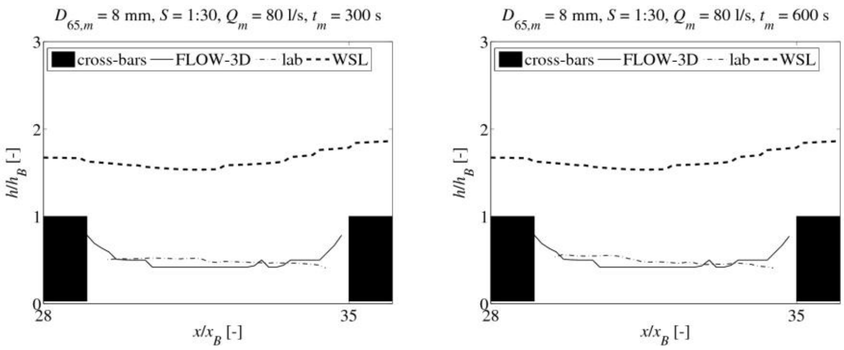


Figure 5. Comparison of experimental and numerical results for S = 1:30, Q = 40 to 100 l/s, t = 10 min; D_{65} = 4 mm left column and D_{65} = 8 mm right column (Balmes, 2012), flow direction left to right

3.1 Time-dependence

Given that the laboratory tests have shown that the sediment transport progresses steadily from 5 to 30 min, Figure 6 represents an example of time depending scouring. The configuration is defined by D_{65} = 8 mm and Q = 80 l/s. While a development of the sediment transport (upstream) can be observed within the experimental model, the sediment formation in the numerical model after 10 min equals those after 5 min. More important in addition to the stagnation of the transport is that the deposits after 5 min are much bigger in comparison to the formation in the physical model. Again, discrepancies between the experimental and numerical results can be stated out.



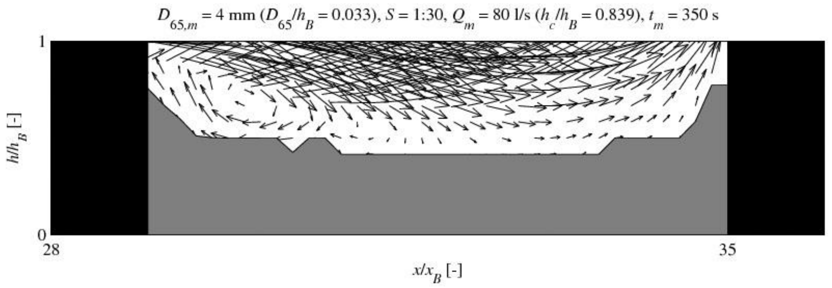
(a) after 5 min

(b) after 10 min

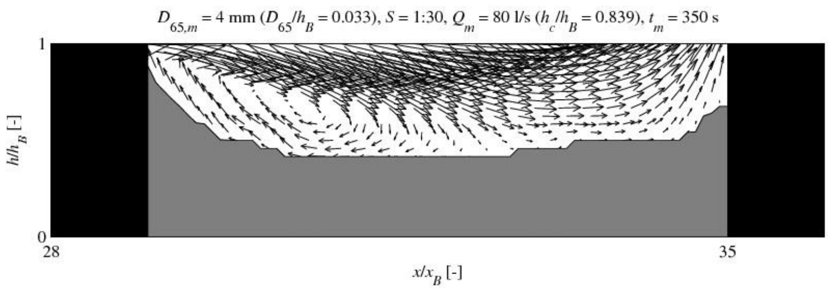
Figure 6. Scour development for S = 1:30, Q = 80 l/s and D_{65} = 8 mm (Balmes, 2012), flow direction left to right

3.2 Mesh grid resolution

Figure 7 shows results for the influence of the chosen mesh grid resolution. Due to long computation times d_x and d_z were set to 1.0 cm. To analyze possible changes for the scour development as a consequence of smaller cell sizes a simulation with $d_x = d_z$ = 0.5 cm was carried out. Therefore the discharge Q = 80 l/s and bed material D_{65} = 4 mm were chosen, exemplary. In addition to the bed material also the velocity vectors are shown to display differences related to the calculated hydraulic. It can be shown that on the one hand the scour formation of the sediments is more precisely and on the other hand there is a different sediment distribution between the two simulation results. The deposit upstream will be increased and the deposit at the downstream end of the basin will be decreased. Hence, a major part of the bed material will be transported upstream. This would correspond rather to the results of the experimental model. Furthermore, it can be observed that the vortex, which has the most influence on the sediment transport upstream, is larger for the simulation with a cell size of 0.5 cm. The current downstream is lower as well as the deposition of particles. Hence, results show a significant influence related to the chosen mesh grid resolution.



(a) $d_x = d_z$ = 1.0 cm



(b) $d_x = d_z$ = 0.5 cm

Figure 7. Influence of the chosen mesh grid resolution (Balmes, 2012), flow direction left to right

4. SUMMARY AND CONCLUSION

With the scour model within FLOW-3D sediment development can be calculated but the reproduction of experimental model results is less precisely due to several parameters. While the experimental model has shown that the bed materials will be transported upstream, the performed numerical simulations have shown that there are major differences compared to laboratory results. Either there is no sediment development or scouring in the center of the basin. In the second case there are deposits at both basin ends. Furthermore changes of sediment transport as a consequence of varies discharges were marginal and the movement of the bed material stops after 5 min. In contrast the observations of the experimental model have shown a continuously change of the sediment layer between 5 to 30 min.

As an outlook for further investigations the current FLOW-3D version 11.0.3 provides an update of the sediment scour model. Therefore it is important to analyze the improvements and how they affect the results. A comprehensive parameter study is necessary to calibrate the numerical model with experimental model results. Especially the configuration of the critical shields number is of main interest. FLOW-3D offers the calculation of bed slope effects. That means the critical shields parameter can be modified because of the idea that packed sediment is less stable on sloping interfaces and thus it is more easily entrained by the current. Concerning the sediment definition the composition of the packed bed materials could be divided into more than four particle sizes. Moreover in relation to small particles, the influence of the chosen mesh grid should be checked up.

Generally, scouring can be modeled via numerical CFD simulation, but it must be noted, that a detailed calibration of the numerical model with field or laboratory data is essential to guarantee useful and exact results.

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