

SCOURING AT THE INTERFACE BETWEEN FIXED AND MOBILE BED IN STEEP SLOPED CHANNELS

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ABSTRACT

The intense scouring occurring at the interface between fixed and mobile bed can have a strong impact on the stability of structures and on the global morphological changes in rivers. Often, this transition is studied in flat or mild-slope channels. However, in order to better understand this phenomenon, it is important also to understand what can happen in steeper channels. The research presented here focuses on an experimental study of scouring at the interface between fixed-mobile beds in a steep channel with a 5% bed slope. The experiments are conducted in an 8m long flume featuring a 2m long fixed bed followed by a mobile bed portion. Results are captured using two types of cameras: a classical camera capturing 12 pictures per second and a high-speed camera capturing 500 pictures per second. The first one is used to capture the bed- and water-level evolution during the scouring process. The second one allowed the study of the movement of the individual sand particles. The flow is controlled by a fixed discharge upstream and a 0.30m high weir downstream. The experiments are run using four different constant discharges. All tests are repeated 3 to 5 times and showed good repeatability. The results highlighted four different stages in the scouring process as well as the links between the velocity field and the evolution of the bed morphology. The experimental results are then compared to numerical simulations using a one-dimensional finite-volume model.

Keywords: Erosion processes; flow-structure interactions; flow visualization and imaging; laboratory experiments; Particle Tracking Velocimetry (PTV).

1 INTRODUCTION

Local scouring due the interaction between flow and hydraulic structures is an important phenomenon to take into account when studying the stability of hydraulic structures built along rivers. Majority of researches focus on the study of the local scour around bridge abutments and piers (Melville et al. 2008; Richardson and Richardson 2008). However, the scouring occurring after the transition between a fixed and mobile bed can have a tremendous impact on the stability of the downstream structures.

During the Sinlaku Typhoon in 2008 in central Taiwan, the Houfeng Bridge, located on the Da-Chia River, collapsed due to an important scouring amplified by a transition between fixed and mobile bed (Hong et al. 2012). During this event, a pipeline, located 20 m upstream of the bridge and originally buried in the bed, became visible. The non-erodible protection around the pipe created a transition between this fixed bed and the mobile riverbed that generated a deep scour hole downstream. This scour hole weakened the foundations of the bridge pillars, leading to their destruction. These transitions between fixed and mobile bed are not only occurring around structures. Along the course of a river, portion of non-erodible bedrock in sand beds create a similar problem.

To simulate these transitions in rivers, the shallow-water equations complemented by the Exner equation for the bed evolution are used, often with a non-equilibrium sediment transport model (Daubert and Lebreton, 1967; Bell and Sutherland 1983; Wu and Wang 2008). To validate these models, well-documented test cases are needed. These test cases should include different flow regimes. However, majority of the researches currently focus on flat bed or mild slopes (Mohamed and McCorquodale 1992; Iervolino 2005; Savary 2007; Zech et al. 2009). The work presented here focuses on the experimental study of the transition between fixed and mobile bed in a steep-slope channel, with a slope of five percent. Data on the bed and water level evolution as well as on the velocity fields in the scour hole were collected.

The paper will be divided as follows. First, the experimental setup and the measurement techniques will be presented. Then, the results will be analyzed by isolating the different stages of the erosion process and comparing the experiment to a one-dimensional finite-volume model.

2 EXPERIMENTAL SETUP

The experiments were conducted in an 8m long and 0.25m wide flume with a slope of 5%. The 8m length was divided as follows, from upstream to downstream (see Figure 1): 2.6m of sand (mobile bed), 2m of wood (fixed bed), and 3.4m of sand (mobile bed). As the slope is steep, the length of the fixed-bed part, although

limited, is sufficient to reach uniform flow conditions before reaching the mobile bed. The sand used has a mean diameter (d_{50}) of 1.8mm and a specific weight (ρ) of 2615kg/m³. As the wooden part was much smoother than the sand bed, the resulting important discontinuity of the friction coefficient between the fixed and mobile bed would have influenced strongly the erosion process. Therefore, to ensure a better continuity of the friction factor, a layer of sand has been glued on the wood. Furthermore, the wooden part was not built as a rectangle but as a trapezoid, with angles of 60° at the base. Even though the channel is relatively narrow, the sidewalls impact on the flow can be neglected, as the depth is small and the sidewalls are made of glass and thus have a much lower friction coefficient.

The flow was controlled by a fixed discharge upstream and a 0.30m high weir downstream. The experiments were run using four different constant discharges (2, 6, 10 and 20 l/s). All tests were repeated three to five times to control repeatability.

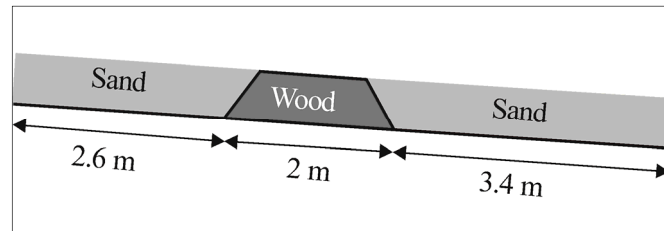


Figure 1. Experimental setup.

3 MEASUREMENT TECHNIQUE

Results were captured using two types of cameras: a classical camera capturing 12 pictures per second and a high-speed camera capturing 500 pictures per second. The first one was used to capture the bed and water level evolution during the scouring process. The second one allowed the study of the movement of the individual sand particles to evaluate the velocity field in the scour hole.

The treatment of the images was done as follows. First, the pictures were corrected by removing all the distortions due to the lenses of the camera (e.g. fish-eye effect). Then, the sediment particles positions were captured by detecting the brightness intensity peaks (Figure 2). These first two steps are used for both analyses: bed- and water-level evolution and velocity-field capture.

To detect the bed level, the picture is first divided into a rectangular mesh. For each element of the mesh, the density of points (the number of particles detected) is determined. Then, the bed level is defined as the highest particle in the highest mesh cell with a density higher than the threshold value (Figure 3). For the water level, the vertical gradient of brightness is calculated for every element of the mesh. Then, the water level is defined as the elevation with the largest gradient and located higher than the bed. The detected bed and water levels are represented in Figure 4.

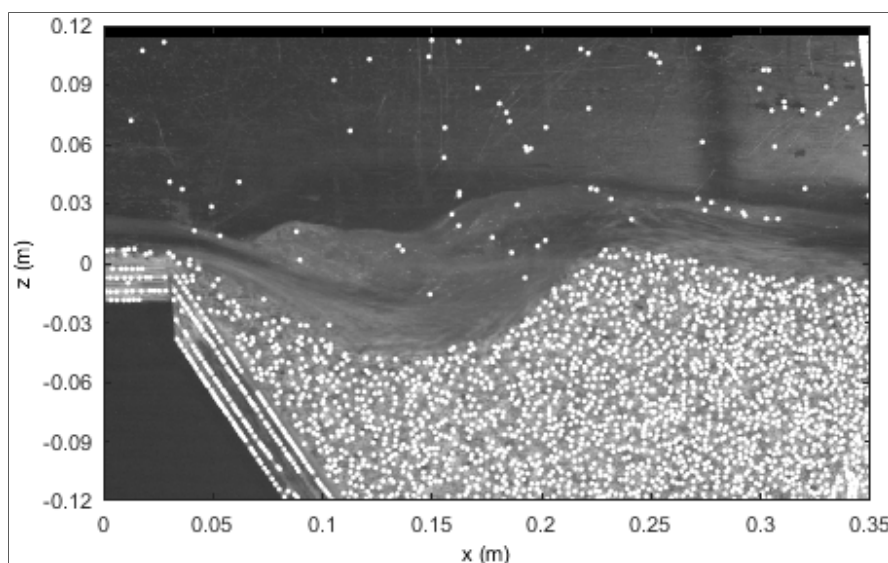


Figure 2. Particles capture.

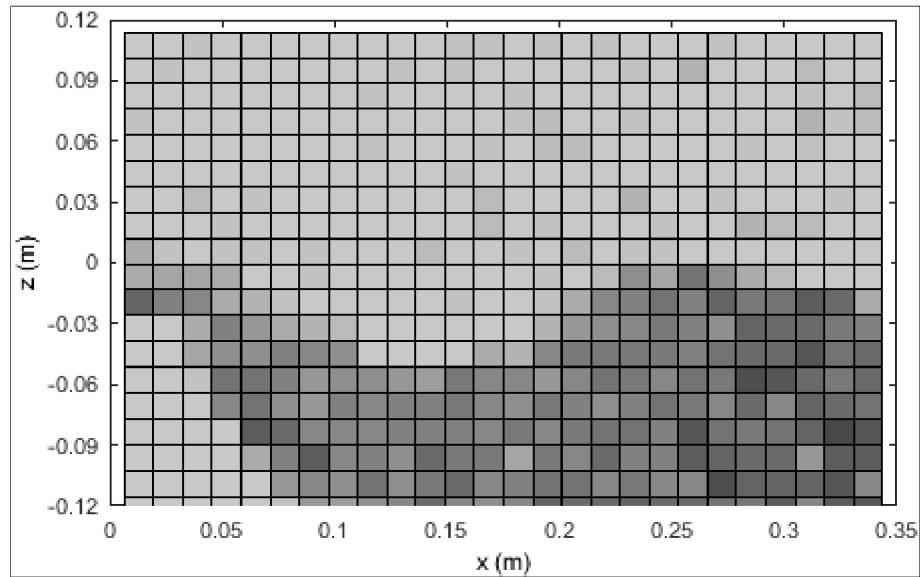


Figure 3. Density mesh to capture the bed level.

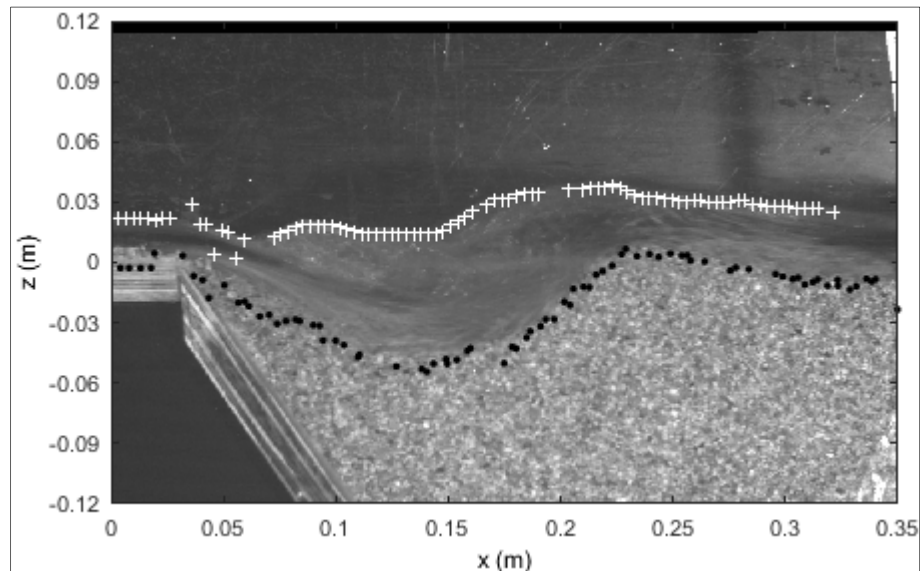


Figure 4. Bed level (black dots) and water level (white cross).

The velocity fields are determined using the Particle Tracking Velocimetry, also known as PTV. This method, unlike the Particle Image Velocimetry (PIV), tracks individual particles from one picture to the other. To track one particle, three methods are mainly used in the literature: nearest neighbor, pattern tracking and path tracking. The first method considers that the particle in the next frame is simply the particle nearest to the previous position. It is the simplest method of the three however, in rapid and dense flows, the results are not always accurate. The second method was developed by Capart et al. (2002). Instead of matching individual particles, group of particles, described by their Voronoi diagrams, are matched. The third and last method was first developed by Sethi and Jain (1987). It uses a sequence of pictures to find the trajectories of the particles and then correct the tracking by checking the coherence and the continuity of the calculated trajectories.

To check that the results are repeatable, the measured water and bed levels for three different tests at 10 l/s after 40s are compared (Figure 5). It can be observed that, even though there are small differences, a good repeatability is obtained.

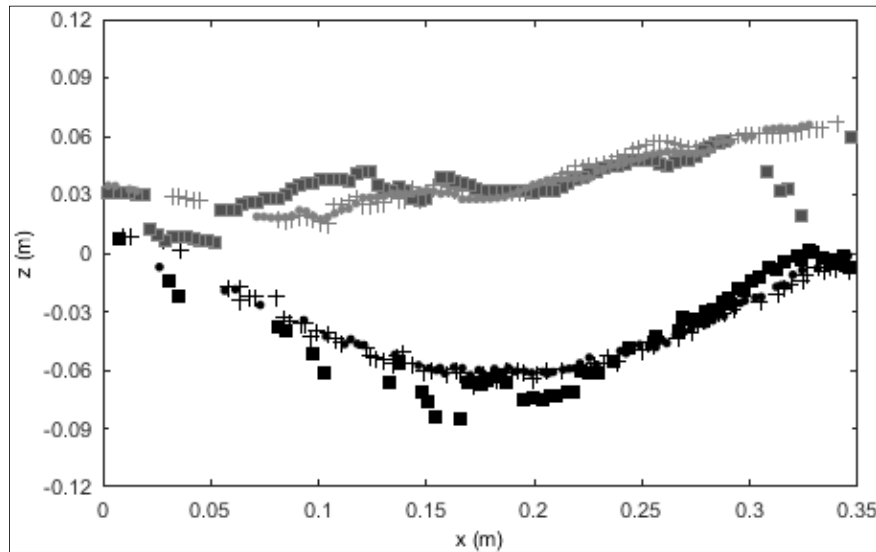


Figure 5. Repeatability: results obtained with three different tests at 10 l/s.

4 EXPERIMENTAL RESULTS

When the fast supercritical flow reaches the mobile bed, the erosion process progressively starts, and a hydraulic jump forms when the scour hole reaches a given depth. This jump rapidly evolves to a submerged jump with a complex velocity distribution and cyclic flow patterns. This process can be described by four distinct stages described below: (1) Attached flow, (2) Stationary hydraulic jump, (3) Surface jet and (4) Moving hydraulic jump.

During the first stage, the flow remains attached to the bed with low erosion and shallow depth. The flow field was not captured during this stage, as the water depth is too shallow to allow a correct measurement.

Rapidly, after the initial formation of the scour hole (in less than one second), a stationary jump is created just downstream of the transition (stage 2). This is the main stage of the erosion process, as it lasts uninterrupted for 100 s in average. This stage is also the main cause of the intense scouring. As observed in Figure 6, the water flows mainly along the bed with a recirculation (the jump) near the water surface. These high velocities, close to the bed, have a very strong erosion capacity.

When the scour hole becomes too deep, the main velocity vectors detach from the bed and become horizontal, and a recirculation zone appears at the bottom, close to the bed (Stage 3, Figure 7). The erosion is greatly reduced during this regime and the upstream slope becomes milder because, due to the recirculation at the bottom, the sand particles are transported upstream. In addition, the length of the scour hole is increased. After 2-3 s, when the upstream slope is sufficiently mild again, the flow reattaches to the bed and a new hydraulic jump is formed at the downstream end of the scour hole (Stage 4, Figure 8). The erosion process is similar to Stage 3, with a low erosion rate and sand particles close to the bed moving in the upstream direction. This jump then proceeds to move upstream where it becomes stationary, resulting in the situation of Stage 2 again (Figure 6) and the whole process, from Stage 2 to Stage 4, starts again in a cyclic way.

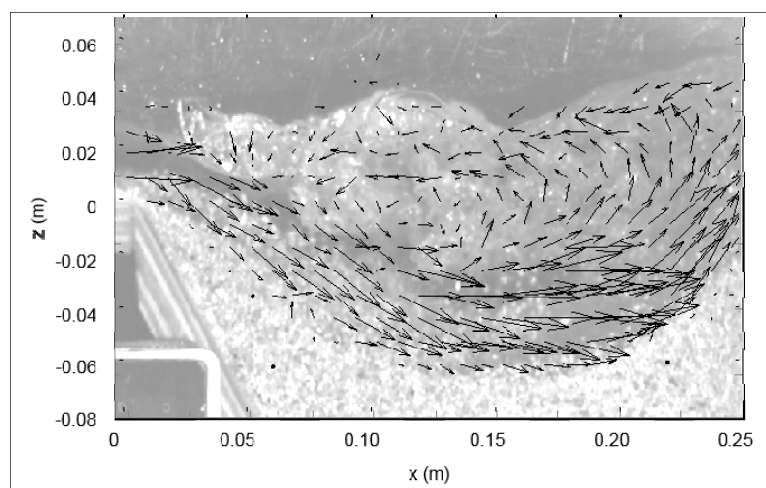


Figure 6. Velocity field during stage 2 of the erosion process.

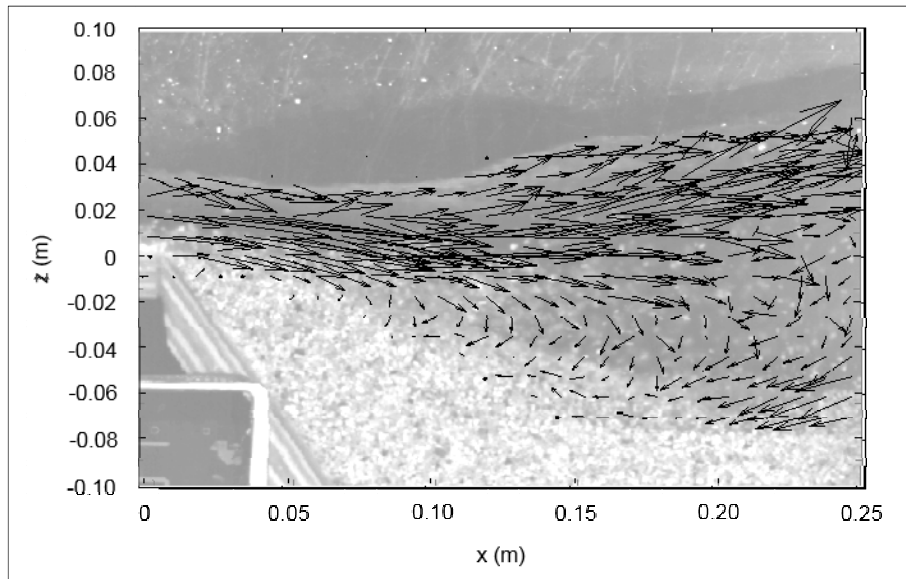


Figure 7. Velocity field during stage 3 of the erosion process.

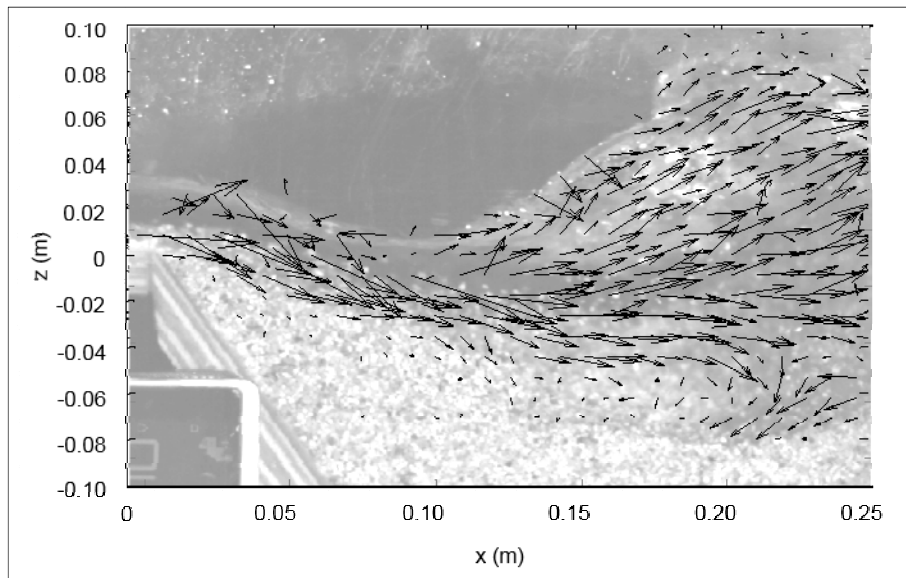


Figure 8. Velocity field during stage 4 of the erosion process.

The evolution of the scour geometry is summarized in Figure 9 to Figure 11 for the tests with 10 l/s. It can be observed that the shape of the scour hole is similar for each time step, the downstream and upstream slopes being constant (Figure 9) until the scour depth reached the fixed channel bed ($t = 600$ s). In addition, the maximum scour depth evolves linearly (Figure 10). The longitudinal position of the deepest point, illustrated in Figure 11, also evolves almost linearly, showing that the extent of the scour hole progressively increases. The influence of stage 3 and 4 on the deepening on the scour hole cannot be observe on Figure 10 because the deepest scour position reaches the end of the measurement frame before stage 3 appear.

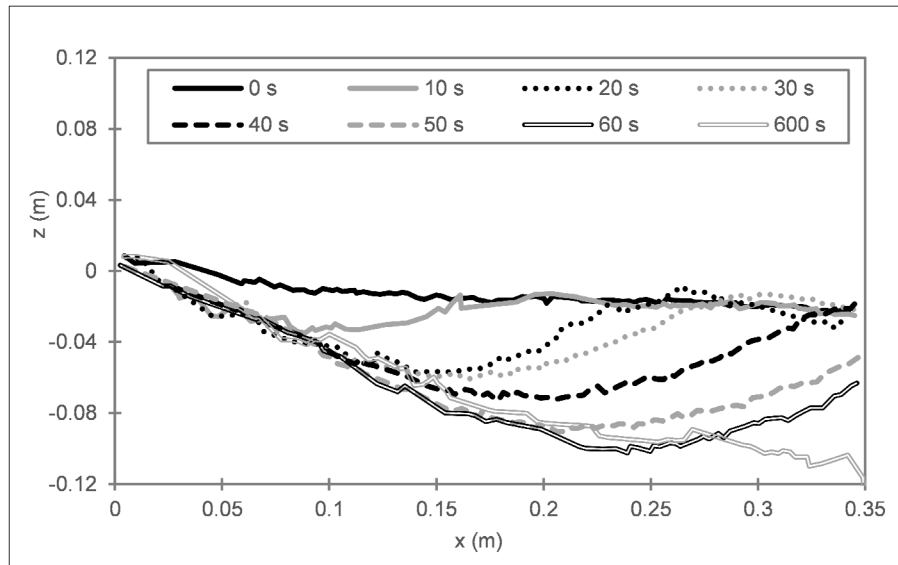


Figure 9. Evolution of the scour hole geometry with 10l/s.

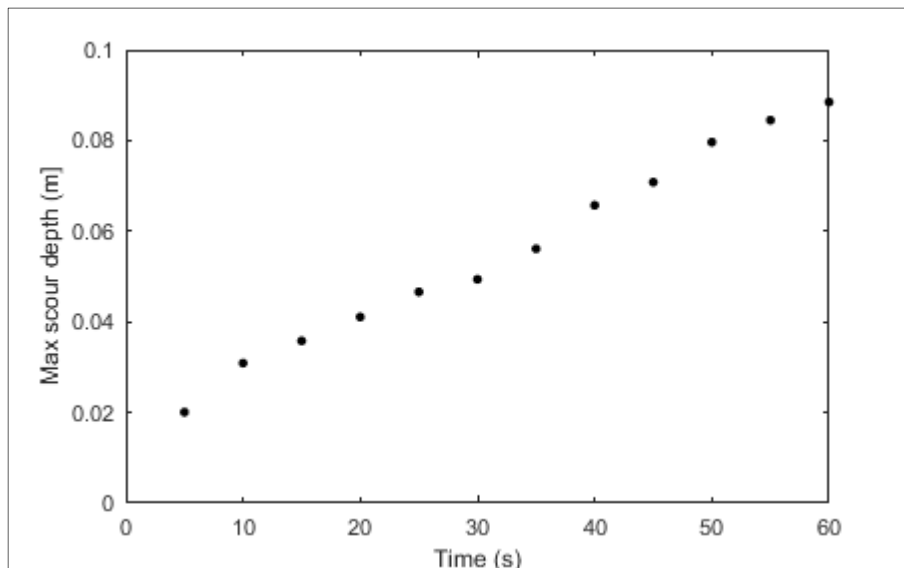


Figure 10. Evolution of the max scour depth for 10l/s.

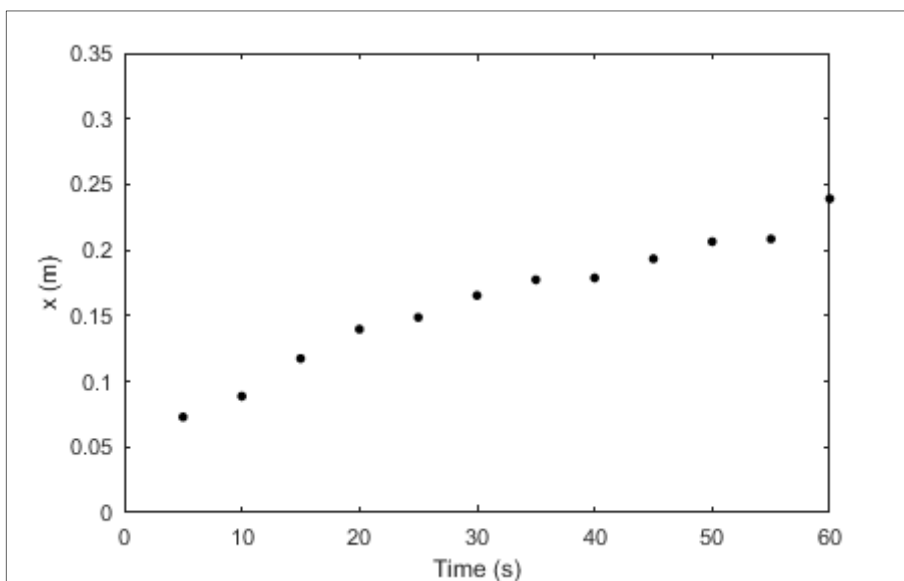


Figure 11. Evolution of the position of the bottom of the scour hole for 10l/s.

5 COMPARISON WITH NUMERICAL SIMULATIONS

A one-dimensional model based on the Saint-Venant equations and the Exner equation for the bed evolution is used to represent the flow. These equations are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad [1]$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A} + gl_1 \right) = gA(S_0 - S_f) \quad [2]$$

$$\frac{\partial A_b}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_s}{1 - \varepsilon_0} \right) = 0 \quad [3]$$

where Q is the discharge, A the wetted area, S_0 the bed slope, A_b the area of the sediment bed, Q_s the sediment transport rate and ε_0 the bed porosity. The integral gl_1 represents the hydrostatic pressure thrust.

The sediment transport rate is determined by the Meyer-Peter and Müller (1948) equation:

$$Q_s = 8B \sqrt{g(s-1)d_{50}^3} \left(\frac{RS_f}{(s-1)d_{50}} - \theta_{cr} \right)^{1.5} \quad [4]$$

where s is the specific gravity of the sediments, d_{50} the median bed sediment diameter, R the hydraulic radius (defined as $R = A/P$), and θ_{cr} the non-dimensional shear stress for initial sediment motion (here the value is set at 0.047). According to Garcia (2008), the sediment transport over the entire cross-section is obtained by multiplying the unit-width sediment transport by the width B of the channel at the level of the free surface. The sediment transport is always considered to be at capacity, equal to the value of [4], if sediments are available.

The system of equations [1] to [3] is written in vector form as

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \mathbf{H} \frac{\partial \mathbf{U}}{\partial x} = \mathbf{S} \quad [5]$$

with,

$$\mathbf{U} = \begin{bmatrix} A \\ Q \\ A_b \end{bmatrix} \quad [6]$$

$$\mathbf{F} = \begin{bmatrix} Q \\ \frac{Q^2}{A} + gl_1 \\ \frac{Q_s}{1 - \varepsilon_0} \end{bmatrix} \quad [7]$$

$$\mathbf{S} = \begin{bmatrix} 0 \\ -gAS_f \\ 0 \end{bmatrix} \quad [8]$$

$$\mathbf{H} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{gA}{B} \\ 0 & 0 & 0 \end{bmatrix} \quad [9]$$

The finite-volume scheme is then solved using a Roe solver with a lateralized treatment of the source terms (Franzini and Soares-Fraza submitted).

$$\mathbf{U}_i^{n+1} = \mathbf{U}_i^n + \frac{\Delta t}{\Delta x} (\mathbf{F}_{i-1/2}^{*R} - \mathbf{F}_{i+1/2}^{*L}) \quad [10]$$

$$\mathbf{F}_{i+1/2}^{*L} = \mathbf{F}_i + \sum_{\lambda_m < 0}^m ((\lambda\alpha - \beta)\mathbf{e})_{m,i+1/2} \quad [11]$$

$$\mathbf{F}_{i+1/2}^{*R} = \mathbf{F}_{i+1} - \sum_{\lambda_m > 0}^m ((\lambda\alpha - \beta)\mathbf{e})_{m,i+1/2} \quad [12]$$

with α the wave strength and β the projection of the source terms defined as:

$$\alpha = \mathbf{E}^{-1}\delta\mathbf{U} \quad [13]$$

$$\beta = \mathbf{E}^{-1}\mathbf{S} \quad [14]$$

The matrix $\mathbf{E}$ is the matrix of the eigenvectors $\mathbf{e}$ and λ are the eigenvalues (wave celerities). The eroded area, A_b , is uniformly distributed along the section width.

Error! Reference source not found. show the numerical results and the experiments after 30s. It can be observed that, even though the model is able to capture the creation and deepening of the scour hole, the complete erosion occurs on the wooden part and the scour hole is much shorter than observed during the experiments. Similar results were presented by Zech et al. (2009) for a case of local scouring on a horizontal bed. The shorter scour hole occurs because the sediment transport is considered to be at capacity all the time. However, in the reality, some distance is required before the sediment transport rate reaches its full capacity. In addition, the model is unable to capture the vertical velocities, being cross-section averaged. Yet, in this experiment, the majority of the erosion is created by the 3D velocities, as illustrated in Figures 6, 7 and 8.

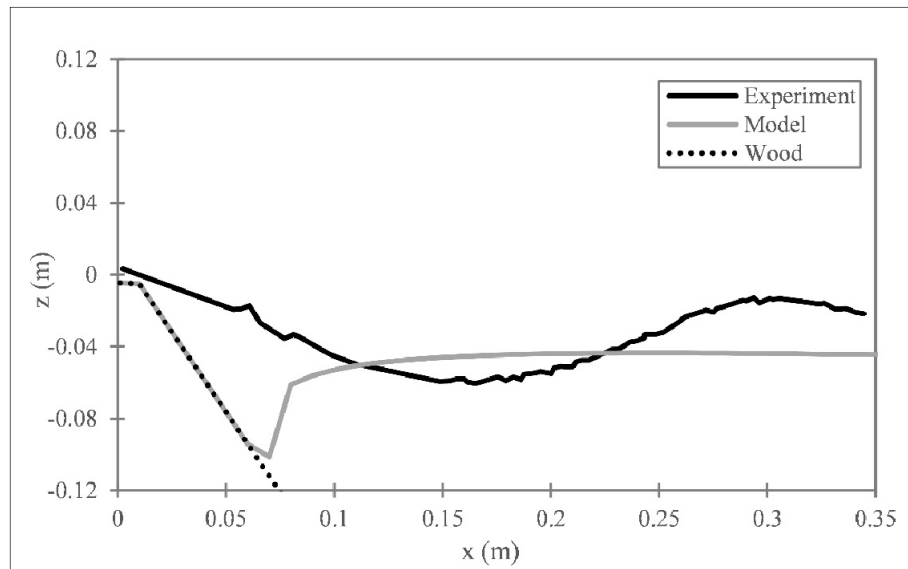


Figure 12. Comparison between the numerical model and the experiment for 10l/s after 30s.

6 CONCLUSIONS

Experiments of scouring at the transition between fixed and mobile in a steep-sloped channel have been presented. During the experiments, the evolution of the bed and water levels were filmed through a side window using a suitable digital video camera. It was shown that the scour hole progressively evolves during the whole erosion process keeping constant upstream and downstream slopes. The deepest point of the scour hole was tracked and it was observed that both the depth and the position of this point evolved linearly; the position being progressively pushed in the downstream direction.

A high-speed camera (500 fps) was used to capture the movement of the sand particles in the scour hole. This tracking achieved using PTV (path tracking) allowed to determine the velocity fields during the erosion process. Four different stages were observed during the experiments: (1) attached flow, (2) stationary hydraulic jump, (3) surface jet and (4) moving hydraulic jump. The first stage, the attached flow, only occurred during the first instants of the experiments as long as the erosion remained limited. The second and most important stage, both in terms of duration and erosion capabilities, presented a stationary hydraulic jump with

the main flow field close to the bed surface. Then, the third and fourth stages were relatively short and the main flow field became horizontal before returning to the second stage, starting a new cycle of stages 2-3-4.

Finally, the experimental results were compared to a one-dimensional finite-volume model computing the sediment transport using the Meyer-Peter and Müller formula and considering equilibrium sediment transport. The comparison showed that the model was able to capture the creation and deepening of the scour hole. However, the length of the scour hole was not well predicted, the scour hole being too short and located too close to the transition between the fixed and mobile beds.

Future work will focus on an appropriate lag formulation for the sediment transport rate in order to better represent the progressive evolution of this transport rate towards the full transport capacity.

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