

## SEDIMENT TRANSPORT IN STEEP CHANNELS WITH A UNIFORM GRAIN SIZE

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### ABSTRACT

The sediment transport constitutes an up-to-date and challenging topic. The mathematical models are pushed forwards for including more physical characteristics which allow obtaining more accurate numerical predictions. In this work, the authors studied the influence of steep slopes over the sediment transport rate. For that purpose several one-dimensional experiments were carried out on tilting flume for where the solid and fluid discharge was varied. The transient evolution of the bed profile and also the solid discharge was recorded at several times. The influence of the slope is studied.

**Keywords:** Experimental work, steep slopes, sediment transport, uniform grain-size

### 1. INTRODUCTION

The soils and rocks which belong to the bottom of the rivers or to the coasts are exposed intensively to the water. This element is the responsible for the wearing out of the bed which provokes the mechanical breakdown of the rock mass into a cluster of particles. After having been eroded, these particles are transported and deposited downstream. In order to quantify this solid transport a number of well known theories have been developed over the last decades. Some of these formulae are based on deterministic laws (Meyer-Peter-Muller, 1948; Nielsen, 1992; Camenen et al., 1980; Ashida et al., 1972) or on probabilistic methods (Exner, 1947; Einstein, 1950). All of these laws have been validated by means of experimental work with steady flows in 1D flumes.

Since the average bed slope in the majority of the natural rivers is gentle, less than 0.01, earlier laboratory works assumed this hypothesis during the development of their experiments (Meyer-Peter et al., 1934; Williams, 1986). However, it is possible to find local areas within a river where the gradients of the bed level are significantly larger than the average bed slope. In those situations, the effect of gravity on the sloping bed has to be retained when computing the solid discharge. Being conscious of the relevance of the steep bed slopes, thorough studies have been devoted to experimentally investigate and characterize their effects (Luque et al., 1976; Smart, 1984). In these works, the measurements were focused on the determination of the transport capacity of shallow flows in high gradient channels with simulated bed roughness and various grain sizes. Then, regression analyses were performed to relate the dependent and independent variables in practical new relationships.

Two other approaches can be considered for including the gravity effects into the classical sediment transport formulae which are written in terms of the bed shear stress, and the critical shear stress for the onset of grain movement, Wu, 2004. One approach is to correct the critical shear stress using the method of Brooks, 1963, or Van Rijn, 1989. The main drawback of this approach is the fact that when the bed angle is close to the repose angle, the corrected critical shear stress usually tends to zero and thus the sediment transport capacity calculated by this formula may go to infinite, leading to unphysical values. The other approach consists in lumping the tractive force associated to the grains movement to the bed shear stress and without modifying critical shear stress as in Wu et al., 1999. The drawback of this approach is the need for tuning some parameters such as the coefficient related to the shape of the grain or the friction factor representing the portion of gravity which is affecting sediment transport.

In order to delve deeper with the physics which are involved in the sediment transport mechanics, in this work, the authors displayed several experiments over steep slopes which can be used in the future in other studies. The outline of the work is as follows: Section 2 is devoted to the description of the laboratory setup used for obtaining the experimental results. Section 3 collects the results. Conclusions are summarized in Section 4.

## 2. EXPERIMENTAL WORK

The experimental work has been conducted at the Civil and Environmental Engineering Laboratory of the Université Catholique de Louvain. A sketch of the experimental facility used is shown in Figure 1. The water-supply system works as follows: the water is stored in a reservoir located under the facility. Then, this water is pumped up to an upstream tank where there is a weir which helps to ensure a constant head. Then, water flows to the tank which feeds the flume. The flume is rectangular and it has a length of 7.6 m and 0.2 m width. The slope of the flume can be adjusted from 0 to 0.05. For the experiments considered in this work the initial slope has been fixed to 0.05. At the end of the flume a weir is placed to impose the water depth.

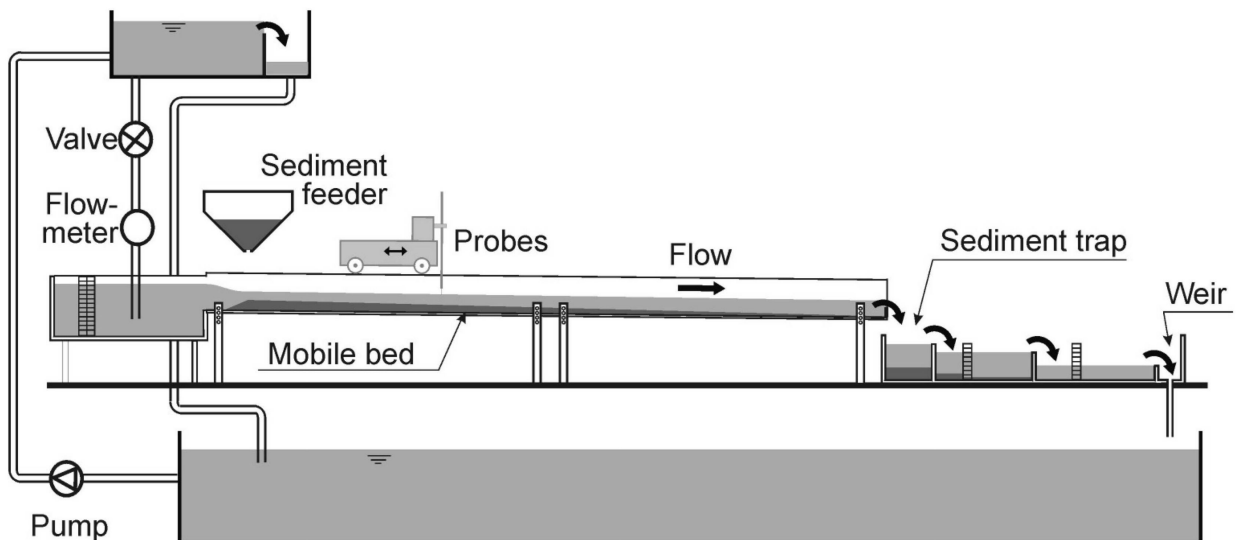


Figure 1. Experimental setup of the experiment

With respect to the sediment, a sediment supply is located over the flume for feeding it with dry sand at a constant rate. A vibrating system is fixed to the sill in order to facilitate the fall of sediments and additionally, it allows to regulate the solid discharge. At the end of the flume a sediment trap is placed for collecting all the outgoing particles. The grain-size distribution is considered quasi-uniform, the mean diameter is equal to 1.82 mm, with an internal friction angle of 30° and the porosity is 0.42.

Two different experiments were carried out at the laboratory with the sand properties described above. In all the experiments the morphologic changes occurs by means of bedload and no geomorphologic collapse of the material has been observed. In the following subsections each set of experiments is described.

### 2.1 Tests over steep uniform slope

In steep catchments and mountainous rivers, erodible bed channels are modified through the sediment transport which takes place as bedload. From a geomorphological and engineering point of view, it is interesting to characterize the response of a channel bed to changes in upstream loadings. Considering a steady water flow and a stable sediment supply the channel suffers from an overloading or underloading amount of material leading to channel aggradation or degradation. The system tends to evolve towards a morphological equilibrium where a constant slope is achieved. Bearing in mind these ideas, four aggradation experiments have been designed. The three first tests keep constant the solid discharge although the water flow is modified in each one. In the last case, the sediment supply is enhanced. In all the experiments the initial bed slope is equal 0.05. Each experiment has been reproduced three times. The characteristics of each experiment, in terms of water flow discharge ( $Q$ ) and sediment discharge ( $Q_s$ ), are summarized below:

- Test SU1:  $Q=3$  l/s and  $Q_s=112$  gr/s
- Test SU2:  $Q=6$  l/s and  $Q_s=112$  gr/s
- Test SU3:  $Q=8$  l/s and  $Q_s=112$  gr/s
- Test SU4:  $Q=6$  l/s and  $Q_s=208$  gr/s

During the experiments, water levels have been measured by means of two ultrasonic probes which were fixed on a trolley moving along the flume. The same technique was used in Bellal et al., 2002. The ultrasonic probes were located in opposite corners of the trolley to check that the erosion process within the channel follows a 1D pattern. The behavior of the ultrasonic probes is the following: an ultrasonic wave is emitted from the probe, the distance between the water surface and the wave emitter can be deduced from the measurement of the time taken by the wave to reflect and return to the emitter. Without any intrusion in the flow, the probe measures the level of a surface with a precision of 0.1 mm

when it is located in a range of 0.1 m to 0.2 m from the concerned surface. In this range, the linearity between the measured voltage and the level is ensured.

The interesting measurements in this experiment was the bed level profile evolution which was tracked by a camera located in the lateral. Photos were taking each 30 s. Then, these photos were post-processed by several image treatment techniques as in Figure 2.

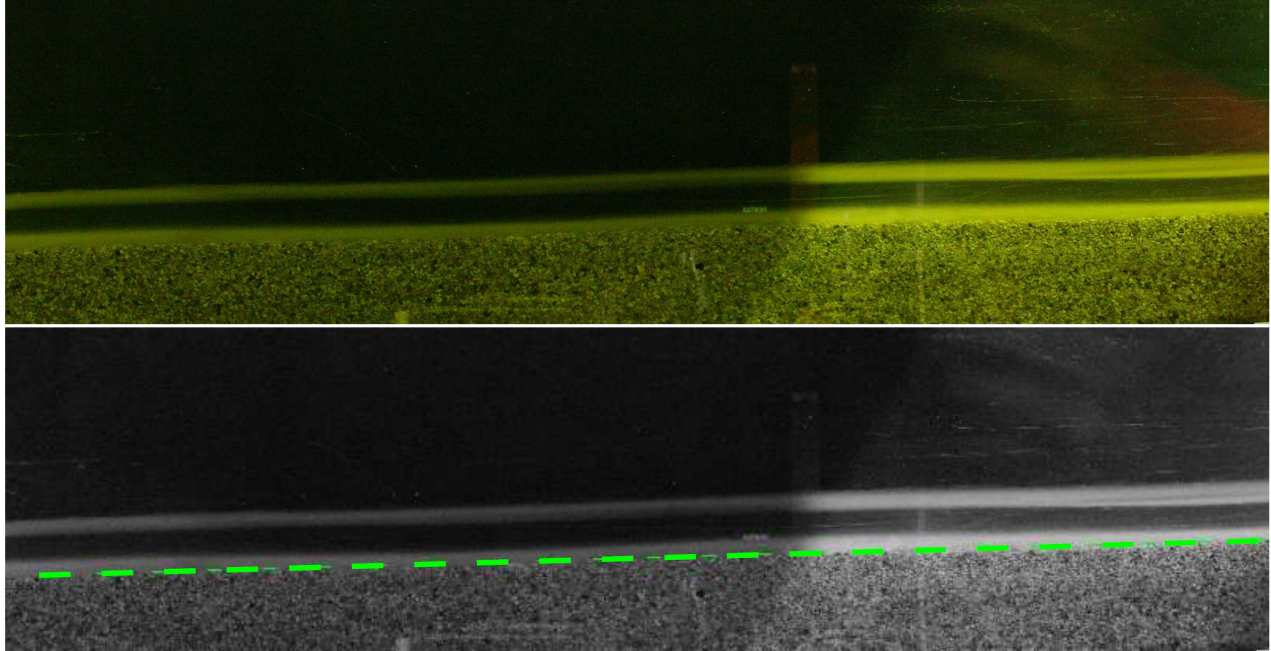


Figure 2. Original (upper) and treated gray image (below) with the points detected at the bed level

Test repeatability was checked by comparing the measured bed level and the solid outflow from different but identical experiments. Then for each measurement and for each time instant, the mean experimental value was calculated. Figure 3 shows the satisfactory level of repeatability achieved for each experiment. For the sake of brevity only the measurements for the final slope of the experiment are showed.

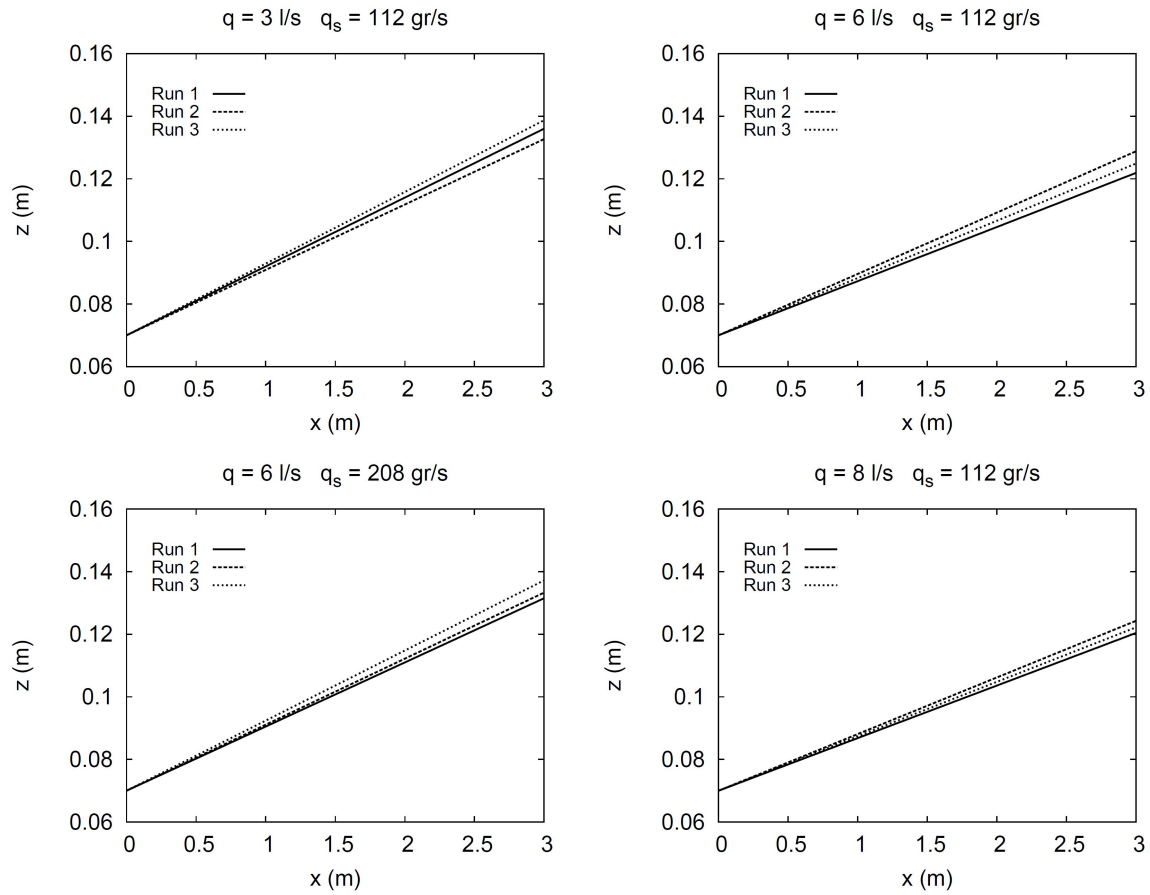


Figure 3. Repeatability of the bed slope for three different rounds and for the four experiments at time 1800 s

## 2.2 Tests over non-uniform slope: knickpoint configuration

Knickpoints in channels with a longitudinal uniform slope appear at a particular location where the slope changes abruptly. Several knickpoint configurations exist in nature and they are governed by bedload capacity and hydraulic conditions. Such a configuration was studied in Bellal, et al., 2002, and it allows to observe the bed evolution in the transition between the two planes with a different slope. A sketch of the experiment, with the initial conditions for the water and the sediment is displayed in Figure 4. This experiment was carried out with a initial zero water discharge that was progressively increased to 1 l/s in 10 s. The wetting front progressively migrated towards the knickpoint and started eroding it. From that moment, the evolution was very fast and the downstream steep slope was rapidly softened to an equilibrium value.

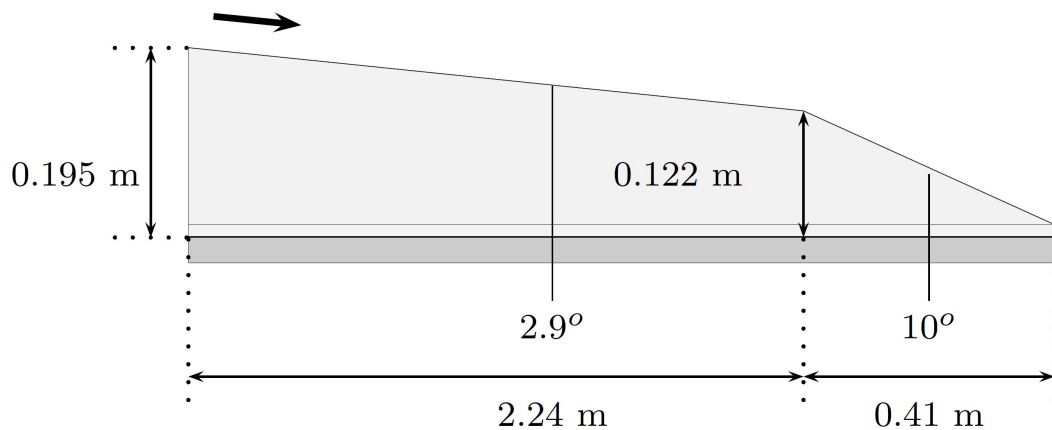


Figure 4. Knickpoint configuration

Comparing the slopes here to the slopes in Bellal's experiments where the knickpoint tended to migrate upwards, in this case, the knickpoint is eroded quickly by the flow due to the large flow energy which results from the steep condition. Since the peak erosion took place in just a few seconds, a speed camera along with a laser was used for recording the evolution of the bed profile, Figure 5. The camera was able to record the images at 12 frames per second. Newly, trolley

with the probes was considered for checking a 1D evolution of the phenomenon and the experiment was repeated four times for a latter averaged of the results. From Figure 6 it can be observed that a satisfactory level of repeatability is obtained for both levels, water and bed level. For the sake of brevity, only one of the first instants of time and the last one are showed.

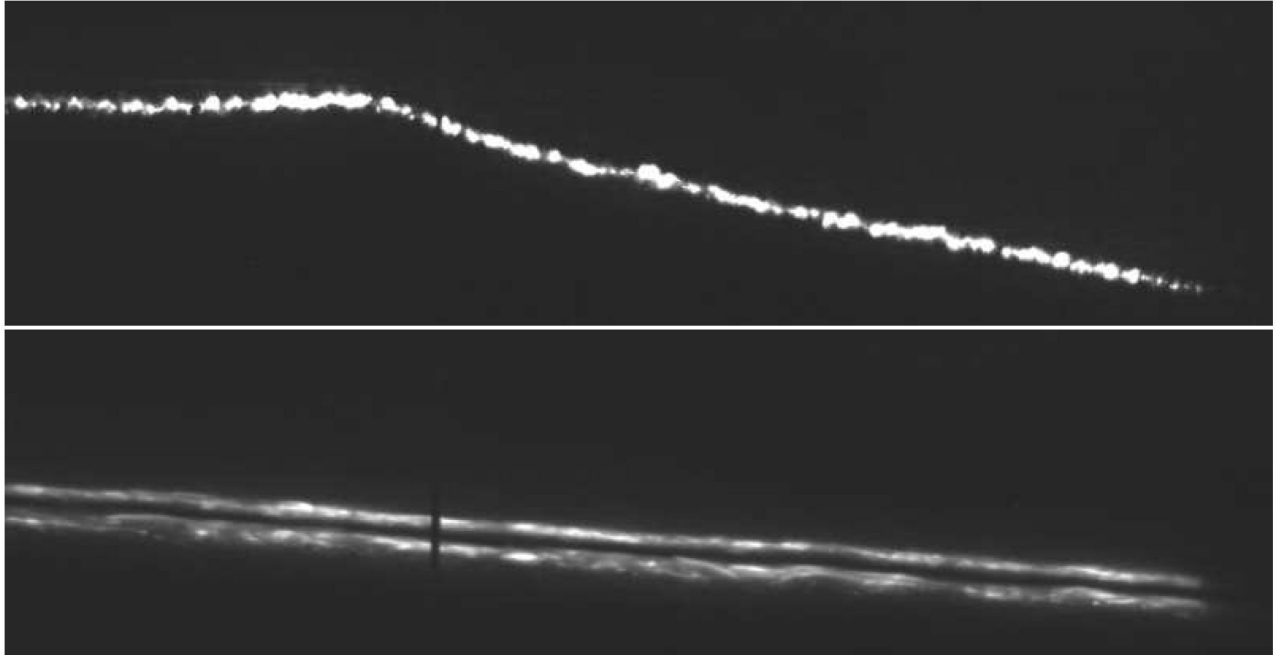


Figure 5. Initial situation of the experiment with the laser (upper) and at the end of the experiment (below)

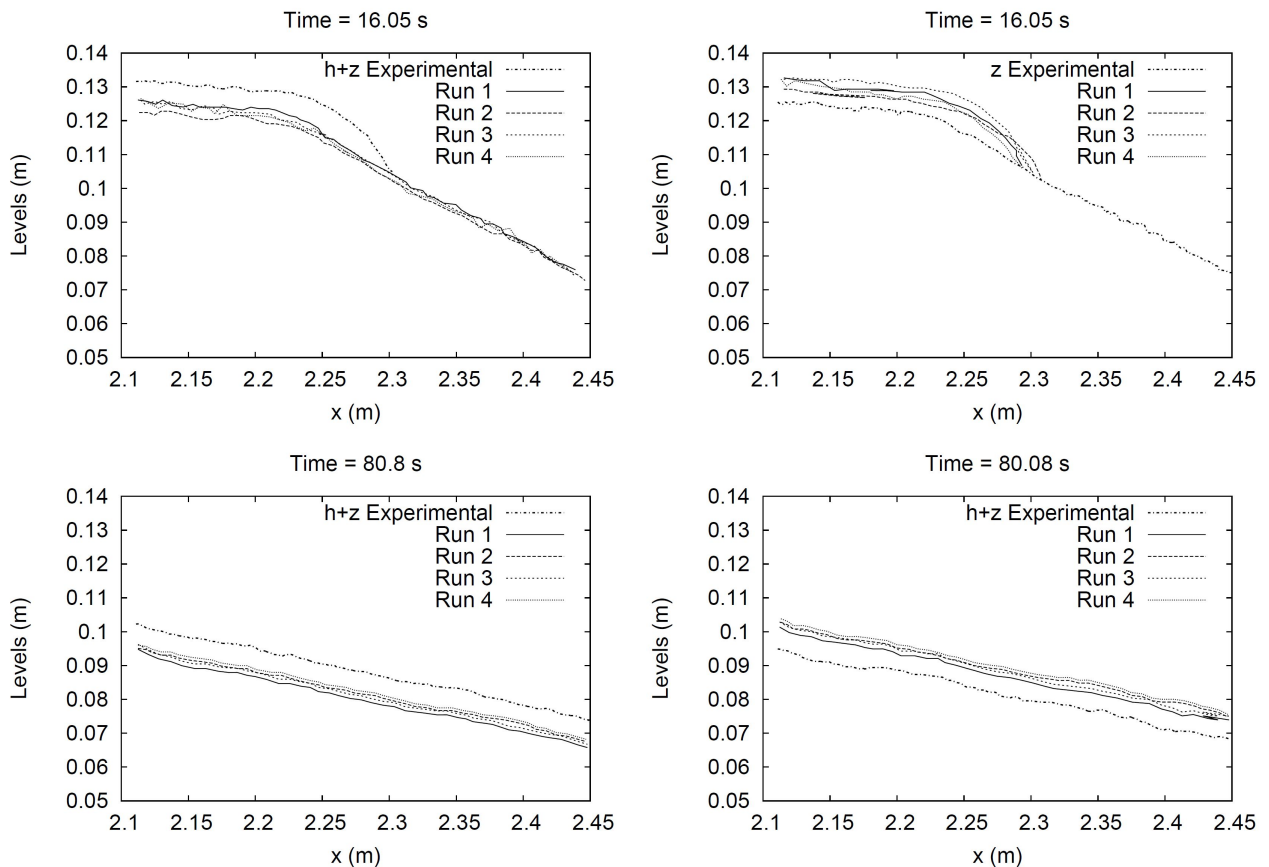


Figure 6. Repeatability of the bed level (left) and water level (right) for four different rounds at times 16.05 and 80.8 s

### 3. RESULTS

#### 3.1 Tests over uniform slope

The bed evolution profile is showed for all the tests at Figure 7. As it can be observed, each experiment provides a different final equilibrium bed slope depending on the solid and liquid discharge.

#### 3.2 Tests over non-uniform slope

The temporal evolution of the bed level is displayed in Figure 8. An erosion recession propagates upwards quickly during times  $t=16.05s$  and  $t=17.3s$ . As a consequence, the bed profile starts a morphological evolution. After these starting times the knickpoint is completely vanished and the steep plane decreases progressively its slope until reaching a milder slope at time  $t=80.8s$ .

### 4. CONCLUSIONS

In this work bed load transport has been studied over steep slopes. Two 1D configurations have been addressed and a wide range of hydraulic conditions are present in these experiments. The results will be useful for enhancing the mathematical equations which are used for describing transient flows over erodible beds. A careful analysis of the gravity effects over the sediment transport remains as a future work.

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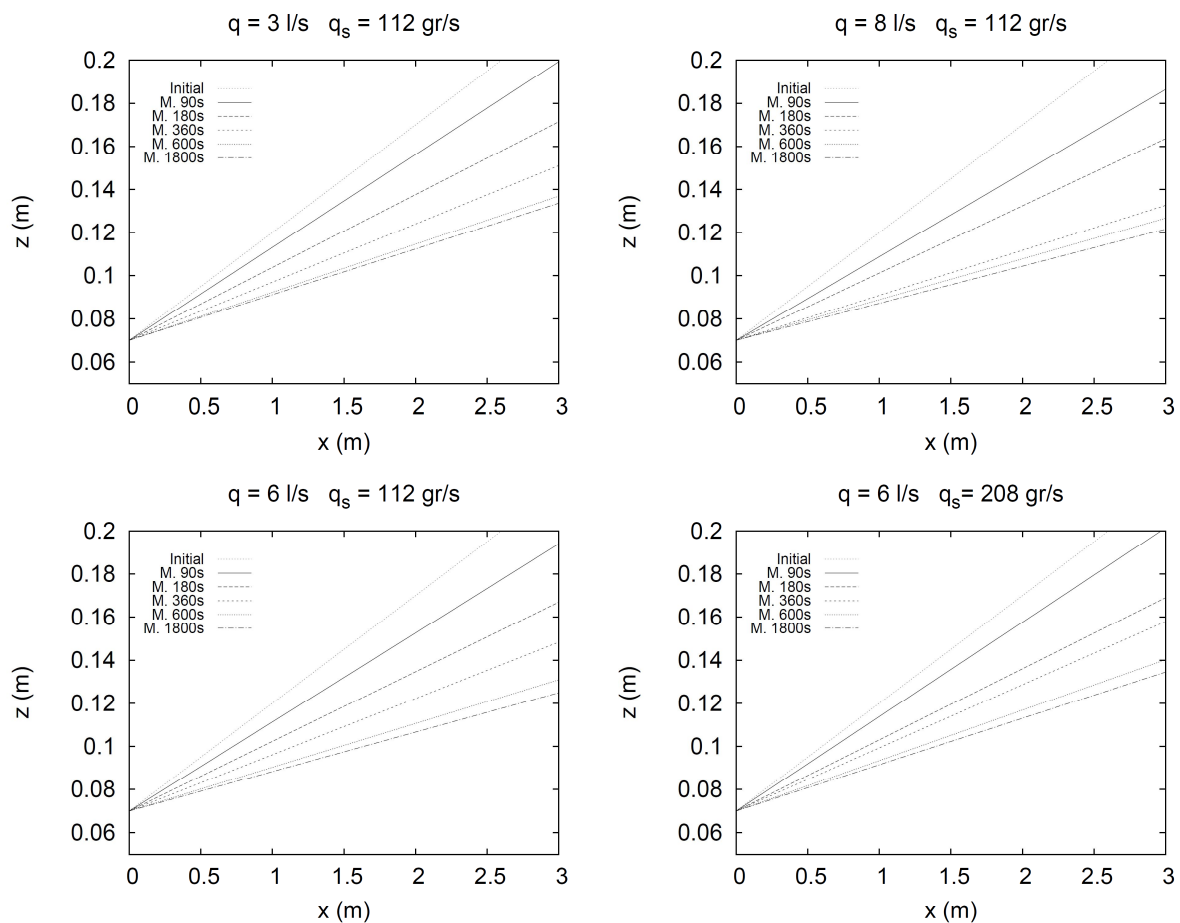


Figure 7. Temporal bed level evolution for each experiment

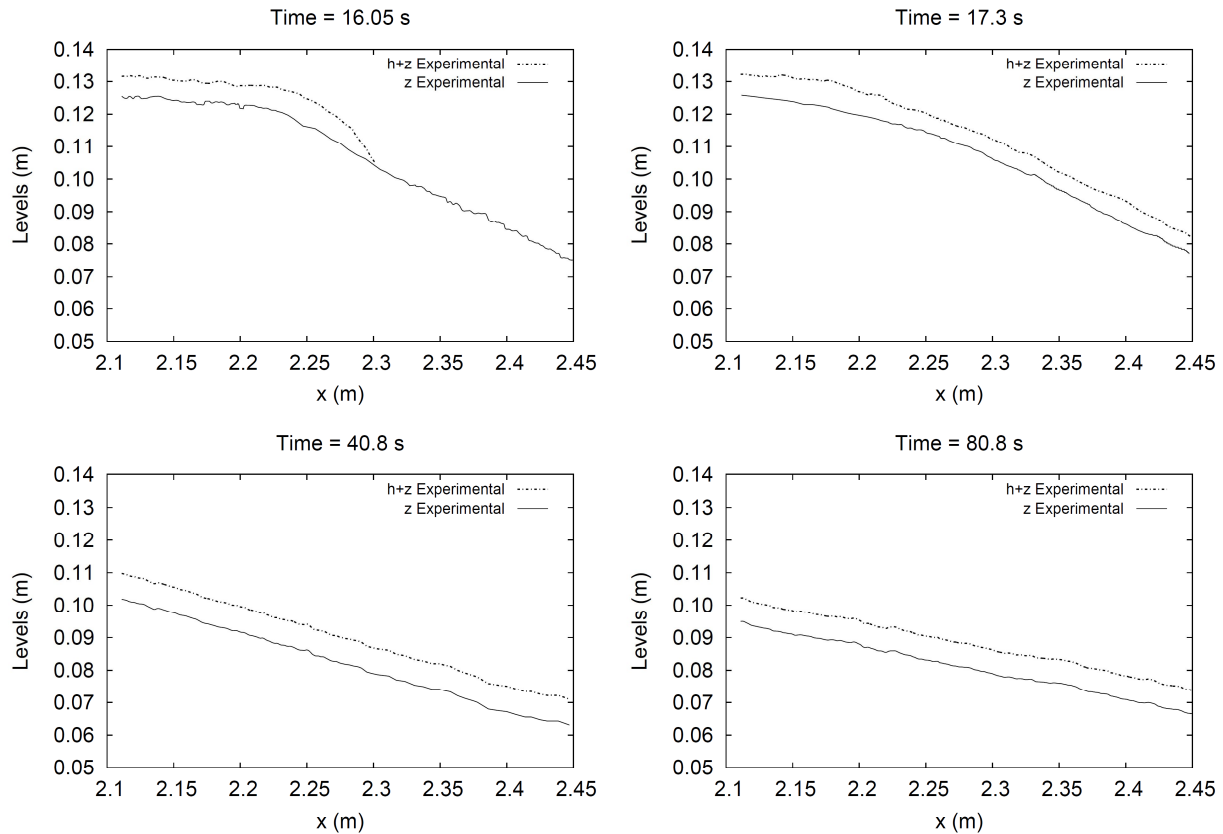


Figure 8. Temporal bed level evolution for knickpoint experiment

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