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A LABORATORY EXPERIMENT ON THE EVOLUTION OF A SAND GRAVEL REACH UNDER A LACK OF SEDIMENT SUPPLY

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ABSTRACT

A flume experiment was conducted to examine the evolution of a sand-gravel reach under a lack of sediment supply. A bed composed of a bimodal sediment mixture was installed with a uniform slope and an gradual fining pattern. At the upstream end of the flume the initial bed consisted of 100% gravel, which decreased stepwise (10% steps) in downstream direction until the location where the initial bed consisted of 100% sand. The water discharge and downstream water level were constant and the sediment feed rate was equal to zero. New image analysis equipment was used to frequently measure the grain size distribution of the bed surface during the experiment over the entire length of the flume. The experiment was governed by bedload transport and subcritical flow. The flow rate was such that only sand was mobile (partial transport). This led to the washing out of sand from the upstream bimodal reach and its gradual coarsening. In this reach we observed the formation of a static armour layer, which resulted in a more abrupt transition in the mean grain size of the bed surface. The total amount of bed degradation slightly increased in streamwise direction over the bimodal reach, which was due to the streamwise increase of the sand fraction in the initial bed. The sand reach adjusted to the lack of sand supply by decreasing its slope and so its sand transport capacity (i.e. through decreasing the flow velocity). Consequently, the sand transport rate at the downstream end of the flume gradually reduced during the experiment. A morphodynamic steady state over a movable bed is generally governed by normal flow. In the present case, governed by partial transport conditions, the morphodynamic steady state is dominated by a backwater curve. This happens because under partial transport conditions the bed cannot (fully) adjust to the upstream water and sediment discharge. These experimental results were reproduced using a one-dimensional numerical model based on the St Venant-Hirano equations, although the effects of the temporal change in bed porosity were not considered in the model.

Keywords: flume experiment, bimodal mixture, partial transport, shortage of sediment supply, numerical model

1. INTRODUCTION

Rivers continuously adapt to spatial and temporal variations of water and sediment discharge to achieve a new equilibrium condition. Detailed studies of river bed evolution and the related mechanisms are fundamental to improve predictions of the response of rivers to both natural events and measures.

The difficulty of studying morphodynamic changes in natural rivers is due to the fact that these mechanisms occur over a long time scale and a large spatial scale. For this reason, it is easier to benefit also from experimental investigations. Unfortunately, a modest number of studies on morphodynamic changes in laboratory experiments are available. Laboratory experiments focused on morphodynamic changes were conducted using both unisize sediment (e.g., Newton, 1951; Suryanarayana and Shen, 1971; Soni, 1981; Alves and Cardoso, 1999) and mixed-size sediment (e.g., Ribberink, 1987; Suzuki and Michiue, 1991; Paola et al., 1992; Yen et al., 1992;).

Further laboratory studies on morphodynamic changes are therefore essential. In the present research we provide the outcomes of a laboratory experiment regarding degradation of a bed composed of mixed sediment. The results of this investigation will contribute to improve morphodynamic model predictions.

In detail, the objective of this study is to examine the influence of a shortage of sediment supply on the development of a sand-gravel reach. The provided dataset was used to simulate the experiment using a numerical model for sand-gravel morphodynamics. A new image analysis equipment was used to measure the grain size distribution of the bed surface with a high frequency and over the entire length of the flume. These measured data provided a valuable benchmark to calibrate the model and to test its prediction capability.

2. THE LABORATORY EXPERIMENT

2.1 The experimental set-up

The laboratory experiment was carried out at the Environmental Fluid Mechanics Laboratory of Delft University of Technology. The flume was 14 m long, 0.40 m wide, and 0.45 m high. The total duration of the experiment was 25 hours. Subcritical flow was maintained. The bed was composed of a sand fraction (D_{50}=1.05 mm) and a gravel fraction (D_{50}=14 mm). The image analysis technique developed by Orrú et al. (2014) was used to measure the areal grain size distribution of the bed surface. The areal fraction content of the gravel, resulting from the measurements, were converted into volumetric fractions using the model of Parker (1991a, b), as explained in Orrú et al. (2014). To use this image analysis technique the gravel particles were painted green while the sand was left with its natural colour. The initial bed was installed with a uniform slope of 0.0055 and it was composed of an upstream bimodal reach and a downstream sand reach. The bimodal reach was composed of 10 compartments, and each was 0.40 m long and 0.20 m thick (Figure 1). Each compartment was created delimiting a portion of the flume using two metal sheets of 2 mm thickness and a width of 0.39 m. These metal sheets were carefully removed before the experiment was started. At the upstream end of the flume the first compartment consisted of only gravel. Moving in streamwise direction the sand fraction increased in steps of 10% with each subsequent compartment, until the location of the sand reach (at x = 4 m).

The water discharge was 0.0368 m^3/s and it was maintained constant. The downstream water level was lowered in two steps over the first 3 h and after this it was maintained constant. We continuously measured the downstream water level using a laser instrument at the fixed downstream position x = 10.40 m. Longitudinal bed and water elevation profiles were measured every 30 min using two laser instruments mounted on a carriage. The sediment transport rate was measured at the downstream end of the flume where the sediment was collected in a sand trap. The samples were dried and later weighted.

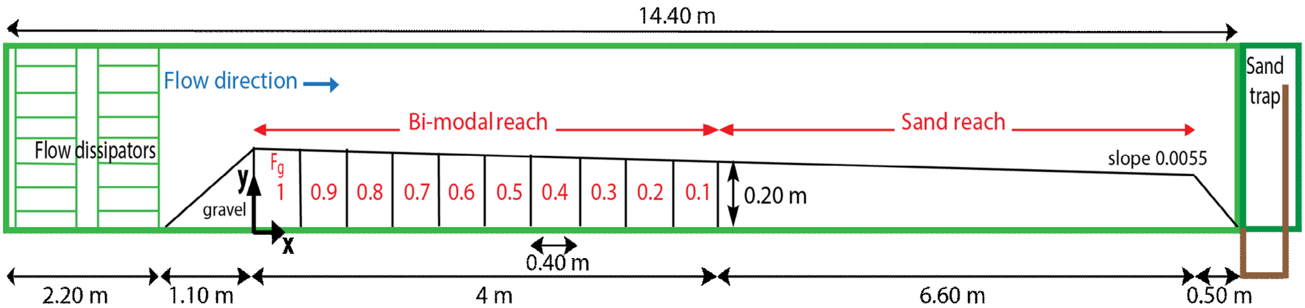

Figure 1 Initial conditions and flume set-up.

2.2 Results of the laboratory experiment

The bimodal and the sand reach responded to the shortage of sediment supply differently (Figure 2), as different transport regimes governed the two reaches.

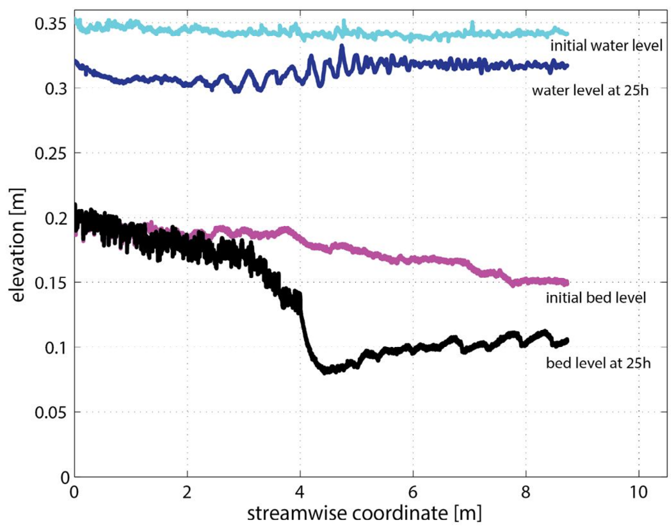

Figure 2 Measured water and bed elevations at initial (red dotted line) and final conditions at 25 h (blue line). Flow is from left to right.

Over the bimodal reach partial transport prevailed. The fine fraction (sand) was entrained by the flow whereas the coarse fraction (gravel) was immobile. The degradation of the bimodal reach was thus dependent on the content of sand available in the bed. Increasing bed degradation in downstream direction was observed (Figure 2) due to the streamwise increase in the volume fraction content of sand in the initial bed. Selective transport induced coarsening of the bed surface with time and therefore the formation of a static armour layer. These processes occurred mainly during the first hours of the experiment (Figure 3a).

The sand reach composed of fully mobile sand adjusted to the small amount of sediment supplied from upstream by reducing its slope. Initially, we observed degradation over the upstream part of the reach and deposition downstream. Afterwards, the degradation wave propagated downstream. The sand reach was bedform-dominated. The bedform height reduced during the experiment, which indicates the temporal decrease of the sediment transport rate. This decrease of the sediment transport rate was also measured at the downstream end of the flume (Figure 4). At the end of the experiment a slow adjustment was still ongoing.

The different bed response over the two reaches led to a step in bed level (Figure 2). The abrupt downstream decrease of bed elevation induced a sudden expansion of the flow, producing an increase of the water surface elevation (i.e., the Bernoulli effect).

As the bimodal reach cannot fully adjust to the lack of sediment supply because the gravel is immobile (partial transport), it is governed by the presence of a backwater curve.

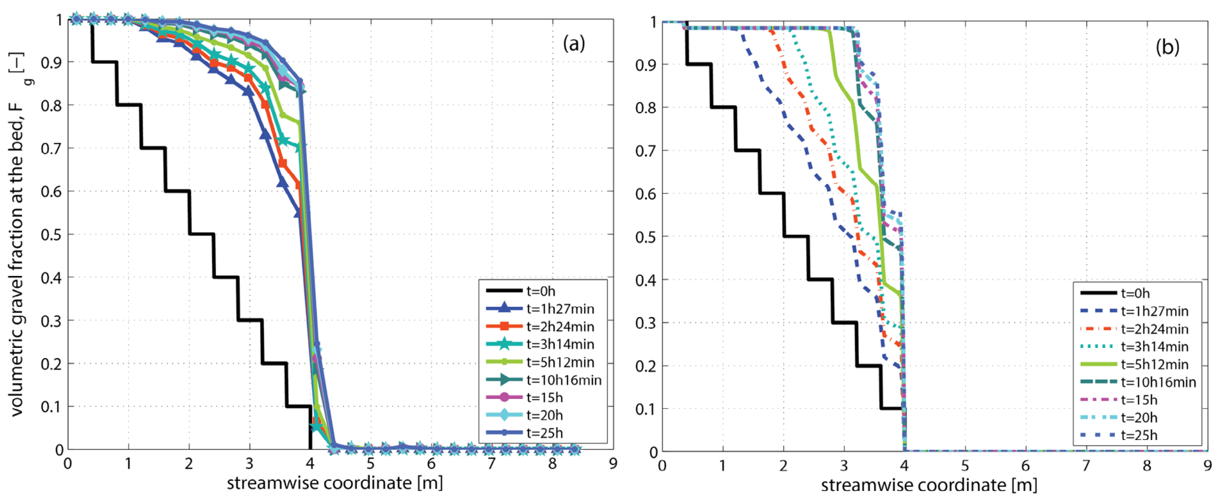

Figure 3 Development of measured (a) and predicted (b) volumetric fraction content of gravel at the bed surface at various times.

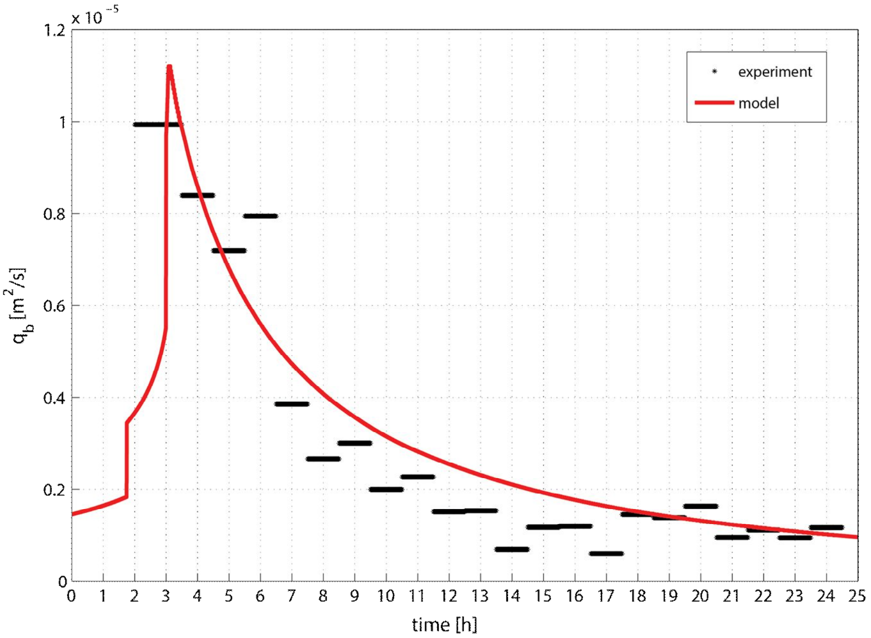

Figure 4 Measured and predicted sediment transport rate at the downstream end of the flume. Please note that measurements began only two hours after the start of the experiment as then a sufficient amount of sand had reached the sediment trap.

3. THE NUMERICAL MODEL

3.1 The set-up of the numerical model

A one-dimensional model for mixed sediment morphodynamics is used to simulate the laboratory experiment. The model can be ideally decomposed into three submodels for (1) flow, (2) changes in bed elevation, and (3) sorting. The flow submodel is based on the St. Venant shallow water equations. The submodel for the development of bed elevation resolves the Exner equation. Finally, the sediment sorting submodel is based on the active layer approach proposed by Hirano (1971). Bedload sediment transport rates are predicted using the relation of Ashida and Michiue (1972). A hiding–exposure correction was incorporated in the latter relation using the method presented by Viparelli et al. (2010a). The boundary and initial conditions are the same as imposed in the laboratory experiment.

Several parameters were calibrated against the experimental results. The total friction coefficient was tuned by applying only the flow submodel in combination with the measured bed elevation profiles and comparing predicted water surface profiles to the measured ones. The resulting hydraulic friction coefficient thus accounts for skin friction, form drag, and side wall friction. Various morphodynamic parameters were then tuned using the complete hydrodynamic-morphodynamic model: (a) a prefactor for the sediment transport relation of Ashida and Michiue (1972), (b) the porosity of the sediment bed, (c) the power of the hiding coefficient in the correction by the Viparelli et al. (2010a) relation, (d) the constant in the relation for the roughness height that is applied in the Manning-Strickler relation for skin friction, which is used in the computation of the sediment transport, and (e) the thickness of the active layer.

The availability of the new measured data regarding the development of the grain size distribution of the bed surface with time appeared to be fundamental to tune the model parameters.

3.2 Results of the numerical model

We observe an overall agreement between the measured and predicted water and bed surface profiles (Figure 5). Figure 5 shows the results of both the model and the experiment after 25 run hours. We notice that the model overpredicts the degradation of the bed between 2 m and 4 m, which is the downstream part of the bimodal reach. This is due to the fact that the model does not consider the temporal change of the bed porosity during the experiment. In the laboratory experiment the washing out of sand led to an increase of the bed porosity with time. Instead, for the numerical model a constant bed porosity is assumed. The neglect of the increase of the bed porosity with time makes the model overpredict the total degradation. This overprediction also results in a slight overestimation of the water surface elevation over the reach.

The overall decreasing trend in the sediment transport rate is well represented by the model (Figure 4). We obtain a reasonable agreement to reproduce the coarsening of the bed surface (Figure 3). During the initial part of the simulation the rate of coarsening is slightly underpredicted by the model. After 25 hours of simulation the model predicts a coarsening pattern comparable to the one observed for the experiment (Figure 3).

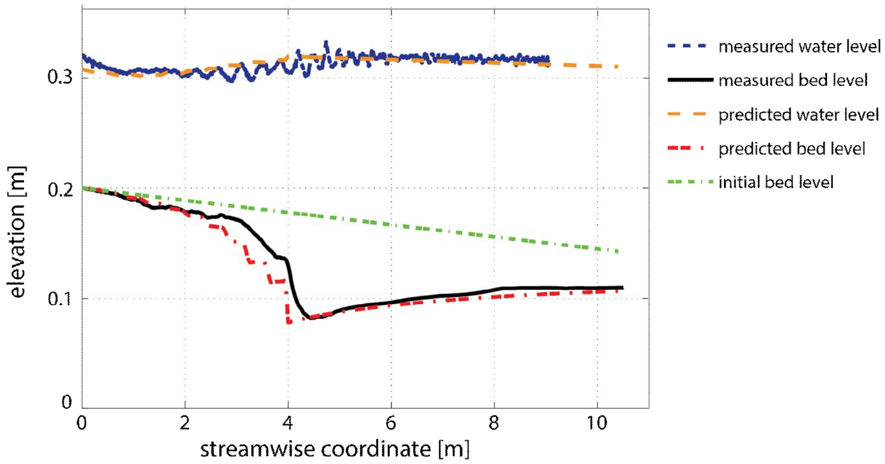

Figure 5 Measured and predicted water and bed surface elevation after 25 hours. Flow is from left to right.

4. CONCLUSIONS

A laboratory experiment was conducted in order to study the effects of a lack of sediment supply over a sand-gravel reach. The experimental data was used to calibrate a morphodynamic numerical model. New measured data were used regarding the evolution of the grain size distribution of the bed surface with time.

The partial transport over the bimodal reach and the fully mobile transport over the sand reach led to a different response to the lack of sediment supply. The bimodal reach responded with a spatial increase of the bed degradation. The amount of degradation increased in downstream direction due to the fact that the sand content in the initial bed increased in streamwise direction. The bed surface coarsened and a static armour layer formed. The sand reach adjusted by reducing its slope through degradation. The larger degradation at the sand reach led to a step in bed elevation between the two reaches. The corresponding expansion of the flow caused a Bernoulli effect and so a downstream increase in the water surface elevation.

A morphodynamic steady state is generally governed by normal flow. Yet, although the experiment was not continued until a steady state was reached, we expect that here it is governed by the presence of a backwater curve. This was due to the partial transport conditions dominating the bimodal reach. Under such conditions the bed cannot (fully) adjust to the upstream water and sediment discharge.

A numerical model was used to simulate the laboratory data, achieving fairly-comparable results. The model represented the hydrodynamic and the morphodynamic adjustment and the coarsening of the bed surface reasonably well. However, the neglect of temporal change in bed porosity may have caused a slight overestimation of degradation in the numerical results. Moreover, capturing the time scale of coarsening of the bed surface was more challenging for the model.

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