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3-D AND 2-D NUMERICAL MODELING OF DAM BREAK WAVES OVER MOVEABLE BEDS

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In this paper, we report numerical simulations of dam-break waves induced sediment transport using the open source Telemac-Mascaret modeling system (www.opentelemac.org). The 3D hydrodynamic model, TELEMAC-3D, and the 2D depth-averaged hydrodynamic model, TELEMAC-2D, are used. Both models are internally coupled with the sediment transport module SISYPHE. Bed load rate is calculated using empirical formula and bed geometry is updated using the Exner equation. We simulate a laboratory experiment of dam break waves over sandy beds performed at Université Catholique de Louvain (Belgium) in the framework of the NSF-PIRE project "Modelling of Flood Hazards and Geomorphic Impacts of Levee Breach and Dam Failure". Comparisons between numerical results and measurements are based on the final bed topography after the passage of the wave as well as water level evolution recorded at selected gauging stations. Both numerical models provide reliable results: the water free-surface is accurately reproduced, with the 3D model yielding better results at the gauge stations located far downstream from the gate. Regarding the bed evolution, scouring around the location of the collapsed dam and sediment deposition further downstream are well captured, but magnitude of bed changes is underpredicted.

INTRODUCTION

Dam-break waves over movable beds are multi-physical processes that involve rapidly varying flows, liquid-granular mixtures of complex rheology, and also interactions between flow and sediment transport and between particles. Several numerical models generally based on 1- or 2-D depth-averaged shallow water equations have been used for simulating dam-break wave induced sediment transport [1]. In the classical models, the governing equations are written assuming one layer of pure water or one layer of a water-sediment mixture that behaves as a single-phase fluid with varying density [2, 3]. Other models rely on a two-layer approach (a pure water upper layer and a transport layer formed by moving water/sediment slurry) for describing the sediment transport layer [4]. Much more complex and detailed are the two-phase models, in which sediment particles are modeled as a second phase such that the drag between the sediment phase and water phase is taken into account [5].

No attempt has been made to compare 2D and 3D numerical models, although flow features are 3D in character at the earlier times following the dam break. The aim of this paper is to fill this gap. To this end, we use 3D and 2D one-layer hydrodynamic and morphodynamic numerical models. The numerical predictions are compared to measurements from laboratory experiments.

LABORATORY EXPERIMENT

Laboratory experiments of dam-break flow over moveable beds were conducted at the Civil Engineering Laboratory of the Université Catholique de Louvain (UCL) [6]. The experiments were carried out in a 3.6 m wide and 36 m long flume (Fig. 1). The dam was represented by a 1 m wide gate located between two blocks. The gate located at 12 m from the upstream end of the flume was pulled up rapidly. The flume was covered with a 0.085 m thick layer of coarse sand 1.61 mm in diameter, extending over 9 m downstream of the gate and over 1 m upstream of the gate with a bulk concentration of 58%. The initial water depth was 0.385 m upstream of the gate, while the bed was initially dry downstream of the gate. Longitudinal bed profiles were measured in a continuous way in the downstream area of the flume using a bed profiler. Profiles were measured over the whole width of the flume with a lateral space step of 0.5 m. Combination of all profiles allowed the reconstruction of a two-dimensional view of the final bed topography. Furthermore, the water level evolution in time was measured by means of 8 BaumerTM ultrasonic probes (acquisition rate 12.5 Hz) at 8 locations.

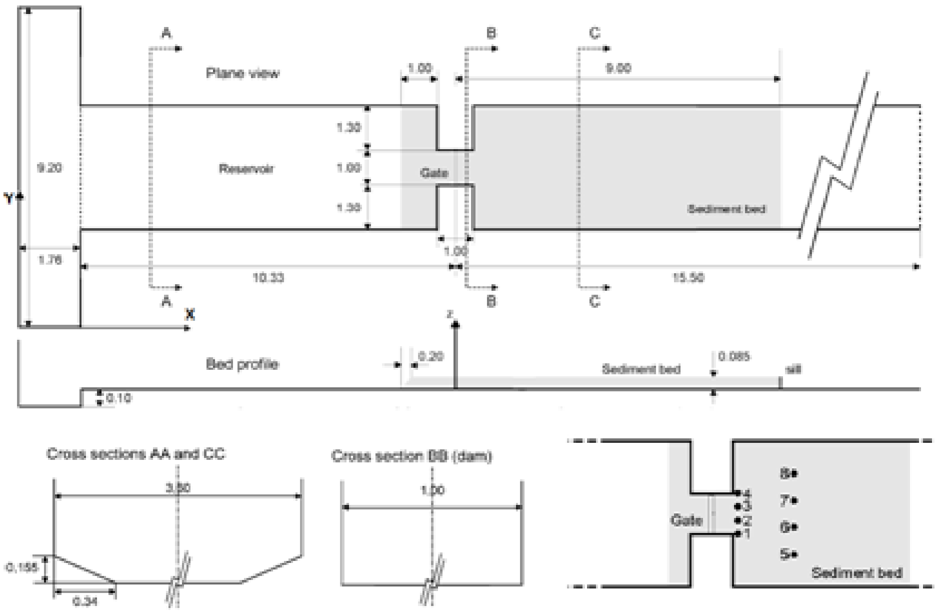

Figure 1. Sketch of the dam-break flow experiment and position of the gauge stations (GS). Dimensions are in [m] [6]

2D AND 3D NUMERICAL MODELS

To reproduce numerically the basic patterns of flow and sediment transport, 2D and 3D models of the open source Telemac-Mascaret Modeling System [7] are used.

The hydrodynamics module of the 2D morphodynamics model (module Telemac-2D) is based on the solution of the depth-averaged shallow-water equations, with a closure relationship for the turbulence and the Manning friction law to parameterize roughness effects. Both finite element and volume methods can be used [8]. The 3D hydrodynamics module (Telemac-3D) is based on the solution of the 3D continuity and Reynolds Averaged Navier-Stokes (RANS) equations with non-hydrostatic pressure approximation. Both 2D depth-averaged equations and 3D RANS equations are solved using a finite element discretization. Further details can be found in [9]. The channel bed topographic evolution due to erosion or deposition is computed from a sediment mass balance equation (module Sisyphe [10]).

At each time step, the morphodynamics model comprises two steps. First, the hydrodynamics module (Telemac-2D or Telemac-3D) calculates the flow variables in the channel, which are subsequently used by the sediment transport and bed evolution module (Sisyphe module). Second, a sediment transport capacity formula is used to compute the bed load rate, and bed evolution is determined by solving the 2D sediment continuity equation (Exner's equation).

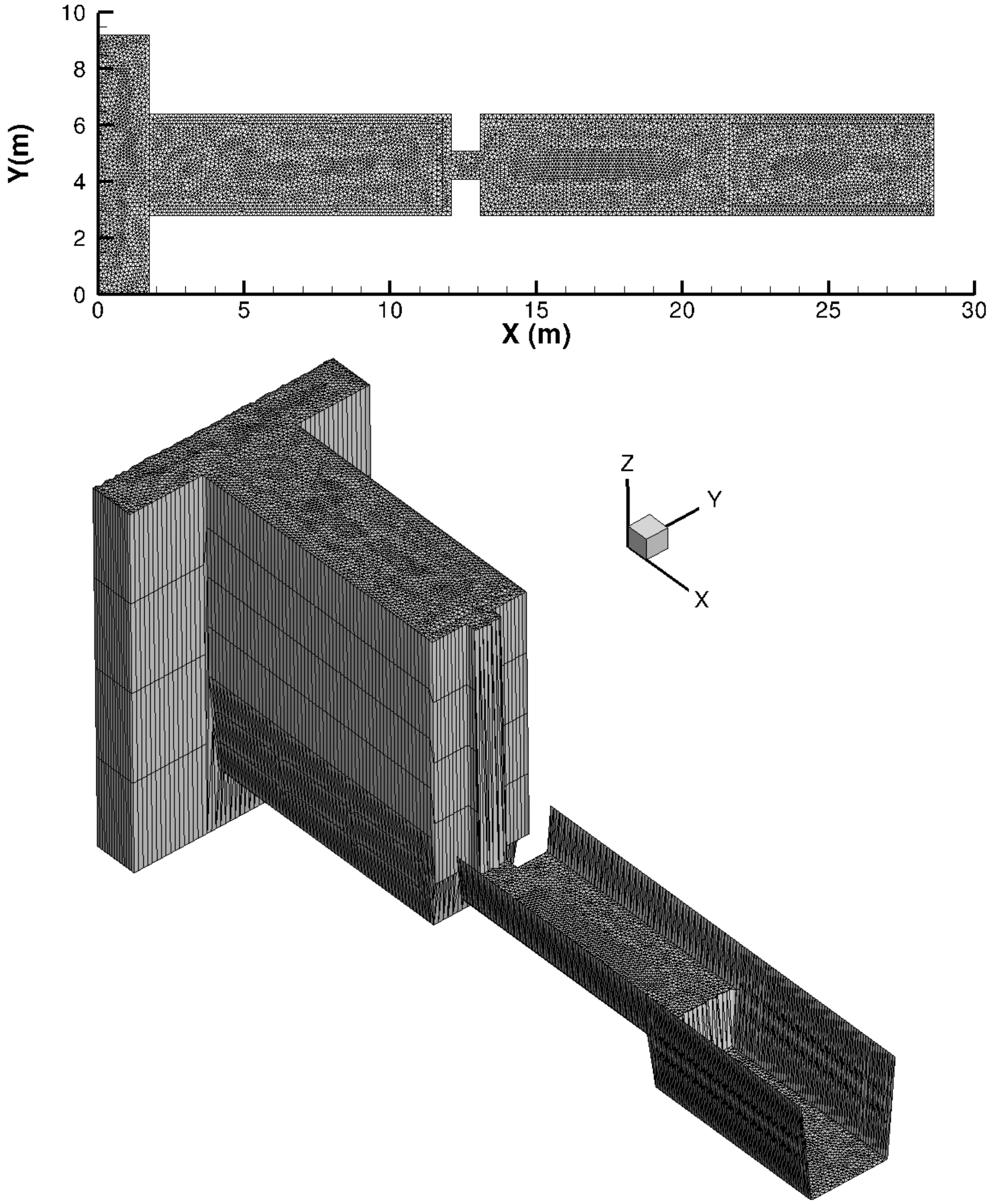

Figure 2. 2D and 3D corresponding meshes (mean horizontal element size is 0.10 m)

In the numerical simulation, an unstructured triangular mesh is used with 13684 elements (Fig. 2). The time step is 0.05 s. Only bed load is considered, using the Meyer-Peter and Müller formula [11], with a critical dimensionless shear stress value of 0.047. The roughness Manning coefficient is estimated on the basis of the bed material diameter and thus set at 0.0165 [7]. For the 2D numerical modeling, the upstream boundary condition is a closed wall. A Neumann-type boundary condition (i.e. free height and velocity) is imposed on the downstream end. The $k-\epsilon$ turbulence model is used. The finite element method is used.

For the 3D numerical modeling, the computational domain was discretized with prismatic elements, obtained by first dividing the 2D domain with non-overlapping linear triangles and then by extruding each triangle along the vertical direction into linear prismatic columns that exactly fitted the bottom and the free-surface. Then, each column was partitioned into non-overlapping layers, requiring that two adjacent layers comprised the same number of prisms. For the simulations presented in this section, five superimposed layers were used in the vertical direction. Solutions computed with an increasing number of layers showed no perceptible differences on the results. For the 3D simulations, similar boundary conditions and turbulence model as the 2D case are specified.

As initial condition, a zero velocity field is imposed. The initial water depth is 0.385 m upstream of the gate, whereas the bed is initially dry downstream.

RESULTS

Figures 3 and 4 depict the dam break wave propagation using the 2D and 3D codes, respectively. Both numerical runs illustrate the observed flow features, namely the wave expansion immediately downstream of the gate and reflections against the lateral walls of the flume. Using the 3D model, the wave propagation downstream is quite slow in comparison with the wave propagation given by the 2D model.

The computed and measured stage hydrographs at 4 gauge stations are shown in Figure 5. Both models reproduce accurately the laboratory measurements. At gauge stations GS1 and GS2, which are placed near the initial location of the gate, similar results are given by Telema2D and Telemac3D. Far downstream, the 3D model provides slightly better results at intermediate and late times following the dam break. The correlation coefficient between the measured and computed data is on the range 0.82-0.93 for both models, indicating good model-data agreement. The average deviation between the computed and measured water levels is between 0.008 m and 0.011 m, depending on the considered gauge, with a standard deviation in the range from 0.005 m to 0.010 m. These values are in the same order as the measured mean standard deviation (which ranges between 0.006 m and 0.016 m).

Figure 6 depicts the measured and calculated final bed topographies. In the numerical results, the bed scouring occurring immediately around the area of the collapsed dam can be clearly identified as well as the sediment deposition area with a typical shape of a tongue propagating downstream with crests near the walls. All these features are consistent with those observed in the laboratory. In the 3D numerical run, the deposit takes place on a distance longer than the 2D numerical simulation, and thus much more in agreement with the experimental observations. However, the magnitude of erosion and deposition is still underestimated by both numerical models. The mean error between the computed and measured bed elevations is approximately 0.03 m and 0.027 m using the 2D and 3D models, respectively. Discrepancies may be attributed to a very rough calibration of the friction coefficient as well as the sediment transport capacity formula.

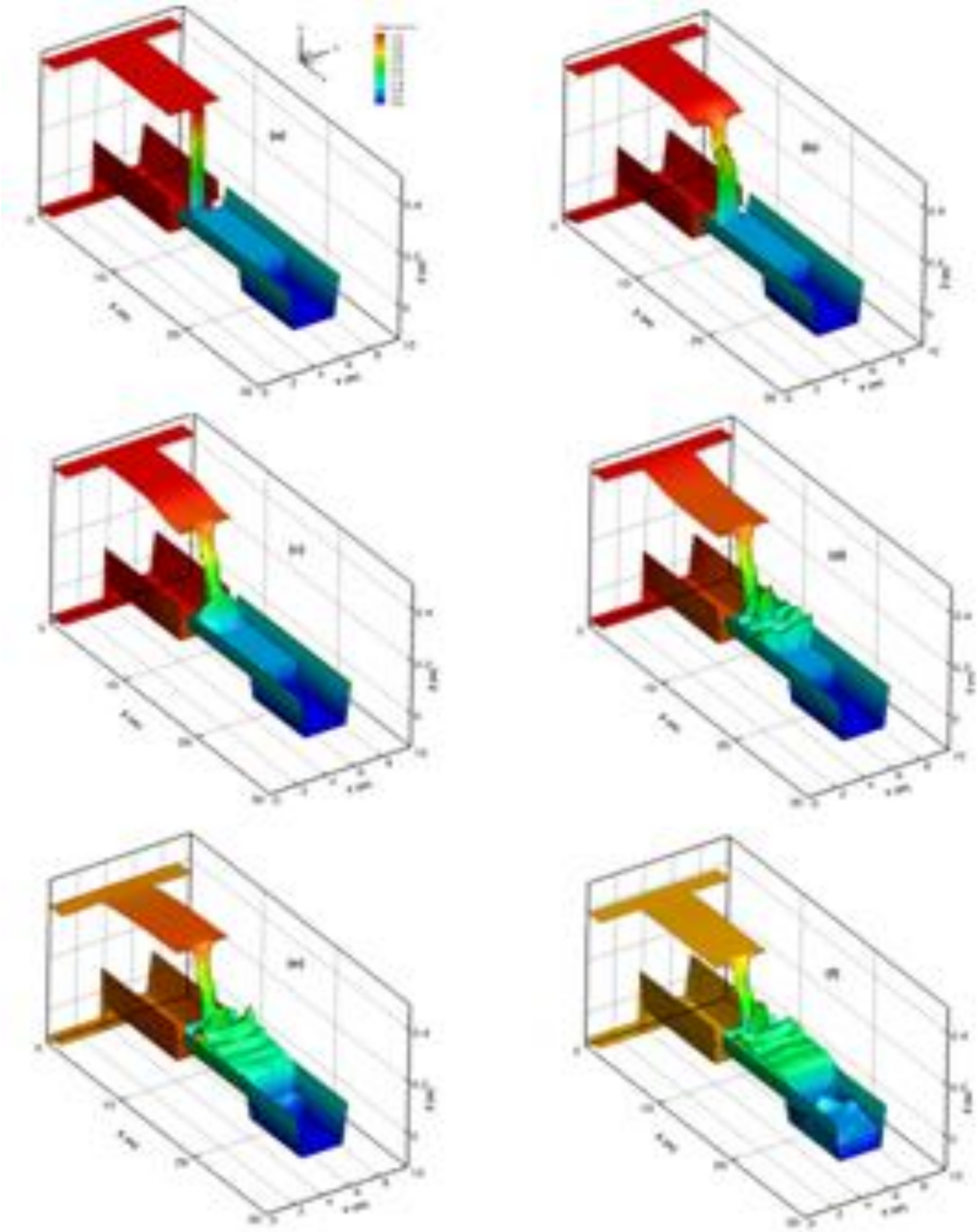

Figure 3. Dam break wave propagation using Telemac2D at different times following the dam collapse. (a) 0s, (b) 1s, (c) 2s, (d) 5s, (e) 10s, (f) 15s

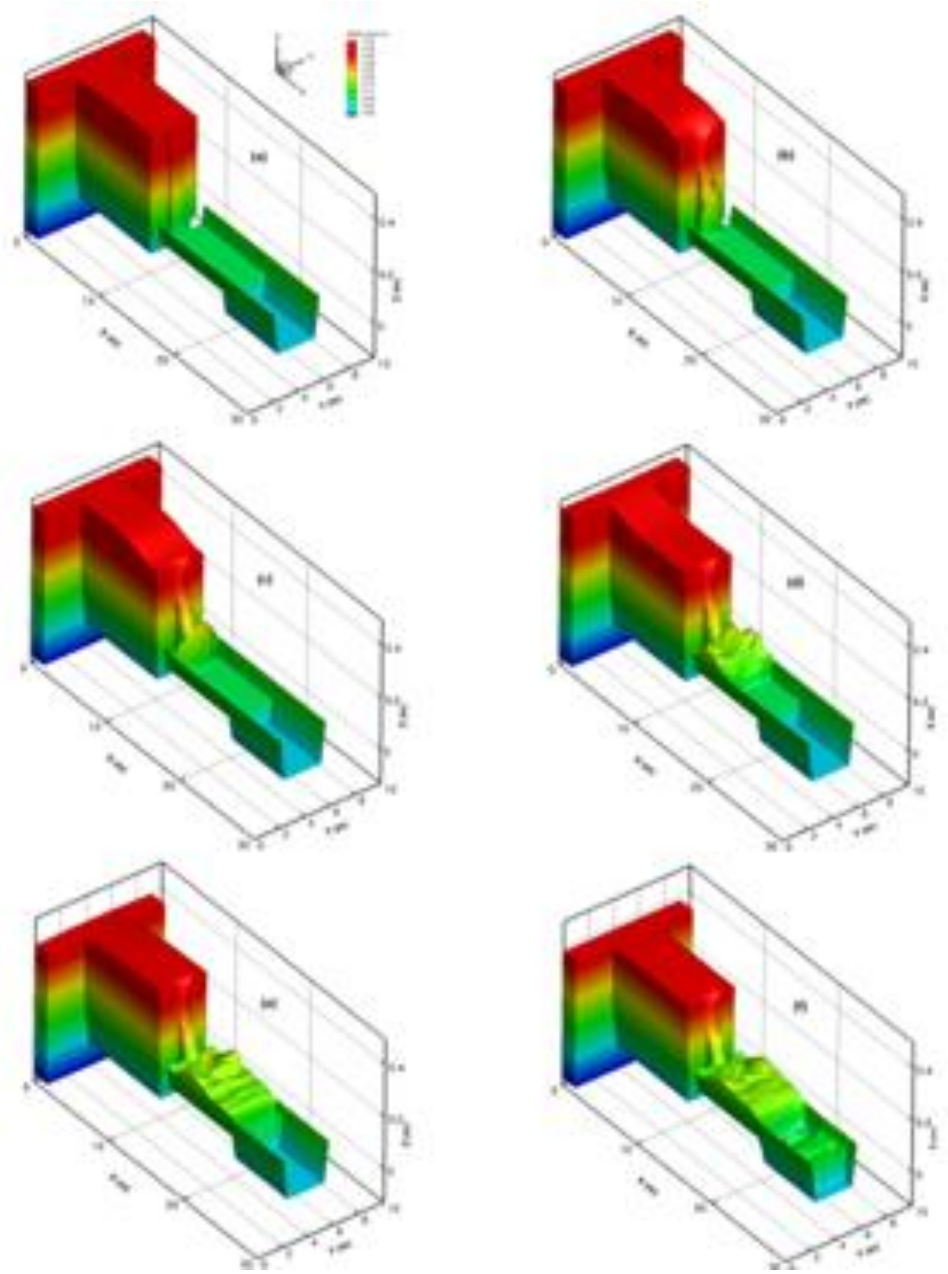

Figure 4. Dam break wave propagation using Telemac3D at different times following the dam collapse. (a) 0s, (b) 1s, (c) 2s, (d) 5s, (e) 10s, (f) 15s

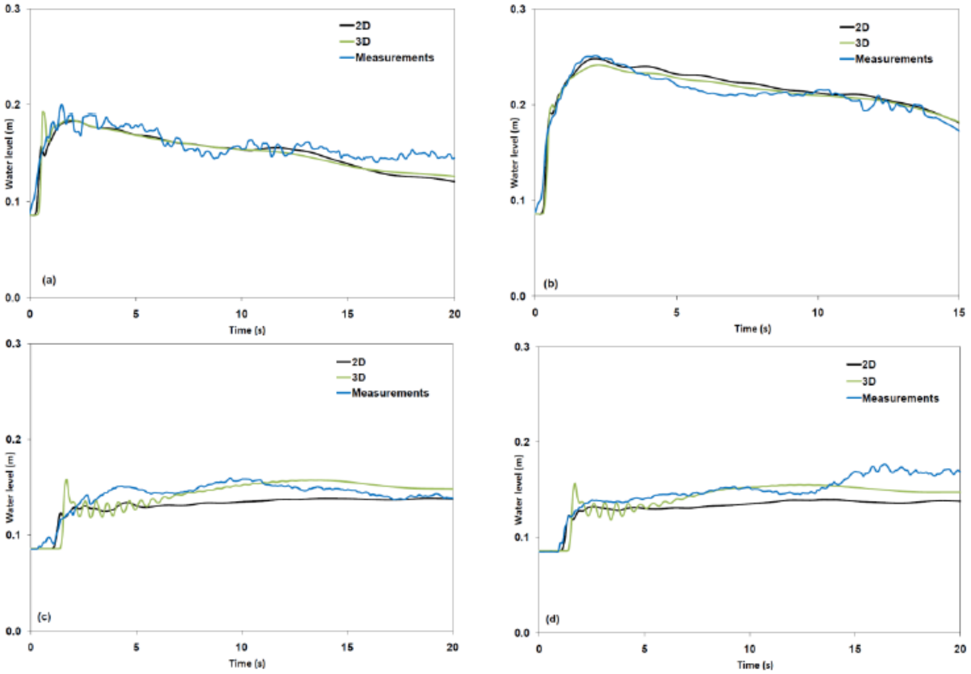

Figure 5. Measured and computed water levels at four gauge stations. (a) GS1, (b) GS2, (c) GS5, (d) GS8. See locations on Fig. 1

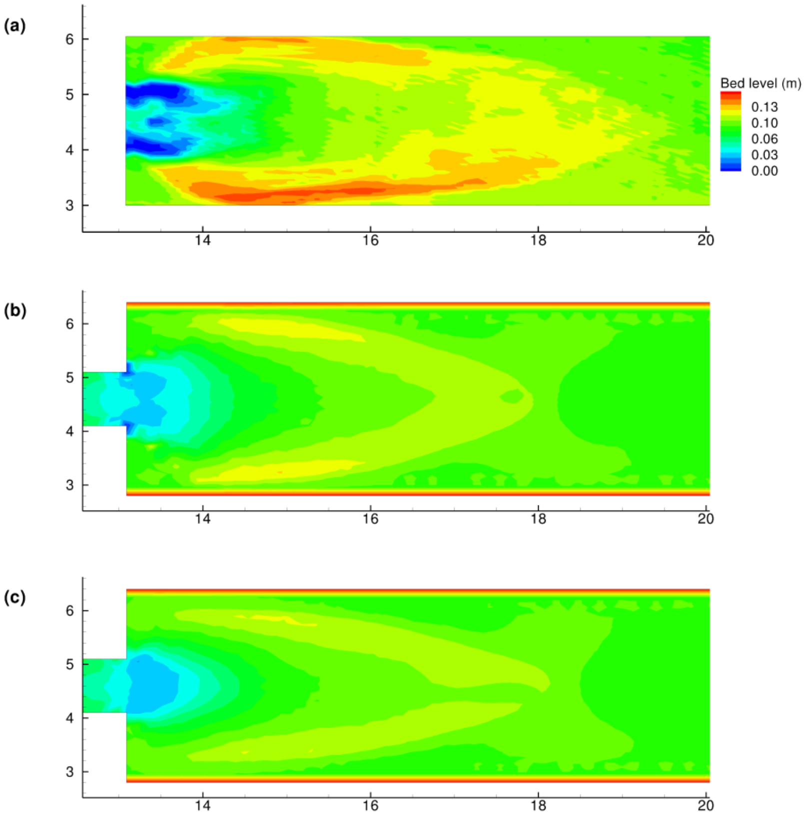

Figure 6. Bed topography at the end of the experiment. (a) Measurements, (b) 2D simulation, (c) 3D simulation. The initial bed level is 0.085 m in this area.

CONCLUSIONS

The dam-break flow over moveable bed was simulated using 3D and 2D numerical models (www.opentelemac.org). The main features experimentally observed were captured by both models. In particular, the water level evolution at different gauge stations were very well reproduced by the numerical models, with the 3D numerical model yielding slightly better results at intermediate and late times following the dam collapse. Regarding the bed evolution, both models reproduced scour at the dam location and deposition further downstream. However, discrepancies were observed in the amplitude of scouring and deposition. The ongoing work includes a sensitivity analysis of the numerical results to several parameters, such as turbulence model, mesh refinement, roughness, critical shear stress as well as sediment transport capacity formula.

ACKNOWLEDGMENTS

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