Dam-break waves over movable beds: a “flat bed” test case

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ABSTRACT

We present a set of experiments related to the propagation of idealised dam-break waves over movable beds, performed in the framework of the EC-funded IMPACT project. The objective is to investigate the geomorphic impacts induced by very rapid and transient floods such as those resulting from dam-breaks. The aim of this experimental work is also to serve as a basis for comparison among a range of numerical models, and to identify the key aspects that are crucial for modelling this kind of flow. The experiments were performed in a prismatic channel with a flat bed extending on both sides of the idealised dam. Additional experimental work will be performed during the IMPACT project, investigating various geometries and sediment bed levels. The experimental set-up and test conditions are described in details, and flow measurements performed using digital imaging techniques are illustrated, including velocity fields in the granular phase and interfaces separating the distinct flow regions. Expected outputs from the modellers wishing to take part in the benchmark for inter-model comparison are explained.

1 INTRODUCTION

This test case concerns a set of experimental small-scale laboratory dam-break waves over movable beds. The objective is to investigate the geomorphic impacts induced by very rapid and transient floods such as those resulting from dam-breaks. Since by nature, such geomorphic floods are not frequent and usually not very well documented, laboratory experiments offer an interesting complement to the analysis of real catastrophes. They make it possible to investigate the mechanisms of sediment entrainment and movement in very intense and transient conditions, far from the uniform conditions for which traditional sediment transport theories have been developed.

The aim of this experimental work is also to serve as a basis for comparison among a range of numerical models relying on various hypotheses, and to identify the key aspects that are crucial for modelling this kind of flow. In the present paper, the experiments are described in details with the aim of providing sufficient information to the modellers, so that it can serve as a benchmark for inter-model comparisons and validation.

The paper is structured as follows: in section 2 a detailed description of the experimental set-up is presented, including flume dimensions, initial and boundary conditions, properties of the sediments, etc. Section 3 focuses on the measurements performed: it first describes the imaging system used to acquire sequences of the flow, and then briefly presents home-made imaging methods used to derive quantitative measurements of flow elevations and granular velocities as a function of time. Finally, in section 4, the benchmark is presented: expected results from the modellers are described, as well as the standard data format they should adopt in order to facilitate inter-comparison of model outputs.


2 DESCRIPTION OF THE TEST CASE

The experiments were performed by the first author at the Department of Civil and Environmental Engineering, Université catholique de Louvain, Belgium. A horizontal flume of rectangular cross-section was used. The test reach had the following dimensions: length = 2.5 m; width = 10 cm; side-wall height = 35 cm. The principle of the tests was as follows: following the sudden raise of a narrow gate retaining an upstream reservoir of still water, an idealised dam-break wave was released over an erodible bed.

The initial conditions are sketched in Fig. 1. A sediment layer of constant thickness of approximately 5 to 6 cm extends both upstream and downstream of the idealised dam. To simulate the dam, a thin watertight sluice gate is pulled down to the flume bottom. The upstream water level is raised progressively to form a still reservoir with a depth $h_0 = 10$ cm above the top of the sediment bed. Water is also introduced in the downstream reach up to the level of the bed, in order to fully saturate the sediment layer. The rapid raise of the gate is initiated by a falling weight, linked to the gate by a system of pulleys. The gate was checked to rise entirely within less than 50 ms.

![Figure 1. Initial conditions for the erosional dam-break wave experiments. A horizontal layer of loose water-saturated sediments extends upstream and downstream of an idealised dam. A water body of depth $h_0$ is retained upstream, and released at time $t = 0$ by the sudden collapse of the dam.](image)

The bed material is composed of a light sediment analogue. Given the small scale of the tests, this choice was made to obtain a larger sediment mobility as compared to natural material, enhancing the geomorphic processes at play. The grains are small PVC pellets with a relative density $s = \rho_s/\rho_w = 1.54$. Their size is sufficient to enable resolution of individual grain movements on image sequences captured with digital cameras, using the imaging algorithms that will be briefly described in section 3. The grains are cylindrical in shape, have a diameter of 3.2 mm and a height of 2.8 mm (hence an equivalent spherical diameter of approximately 3.5 mm). The particles are mostly white in colour, mixed with a small proportion of black grains used for quick motion inspection.

Given the very short duration of the experiments and the relatively long test reach, upstream and downstream boundary conditions need not to be specified very precisely. It may reasonably be assumed that the upstream reservoir has an infinite length and a constant width equal to that of the test reach, which might be implemented numerically either as a solid wall far upstream or as a supply section where a constant water level is imposed. On the downstream side, the channel is terminated by a weir whose crest coincides with the top of the granular bed. This watertight weir insures full saturation of the sediment bed before the start of the test, and acts like a free outfall during the test. In numerical models, the wave may be assumed to propagate over a sediment bed of infinite length, placing boundary conditions out of the region of interest, or a far-field boundary condition may be imposed at the downstream end. Regarding the evolution of the sediment bed, the erosion never attained the solid wall at the bottom of the sediment layer, hence an infinite thickness of this layer may be assumed in numerical models. As a summary, any set of boundary conditions may be assumed, as long as they do not influence the development of the wave for the considered duration of the tests.
3 DESCRIPTION OF THE MEASUREMENTS

The flume and measurement apparatus used for the tests are sketched in Fig. 2, along with a photograph of the set-up. Visual access to the flume is possible through the transparent sidewalls. The flows are filmed using two synchronized fast CCD cameras, operating at frame rates of 200 frames per second. The grey level images have a resolution of 256 by 256 pixels and a colour depth of 8 bits. To guarantee a detailed and accurate observation of the individual grain movements, a minimum of a few pixels per particle is required. As a consequence of the limited sensor resolution, the maximal width of view for one camera is about 15 cm, i.e., 30 cm for the two cameras put aside each other. To be able to capture the full spatial extent of the waves, tests are repeated a number of times with the gate displaced upstream or downstream by multiples of 30 cm. Previous experiments had revealed the very good reproducibility of the tests, giving confidence in the results obtained by this method. This was also verified by filming separate tests in the exact same configuration. Moving the gate instead of the cameras offers the great advantage of leaving the imaging system unperturbed: the image sequences resulting from separate runs can be easily merged together in coherent mosaic images, avoiding separate camera calibration procedures and complex post-processing transformations for image reassembling.

Figure 2a,b. Flume and experimental apparatus: a schematic top-view; b side view of the laboratory set-up moments after release of the wave. The components of the device are: (1) prismatic flume with transparent side-wall and translucent back-wall; (2) sluice gate; (3) synchronised CCD cameras; (4) spot heads; (5) back-illumination. Lighting is supplied from two frontal spot heads oriented at an angle of 45 degrees with respect to the camera axis. To avoid projected shadows and uneven illumination, a translucent panel placed on the opposite side of the flow provides diffuse back lighting. The camera axis was located slightly under the sediment bed level, to avoid ambiguous location of the bed and water levels on the images. All this yields clear images on which the white sediment grains stand out saliently from the surrounding darker fluid, and the flow free surface contrasts well with the background. Reconstituted image mosaics of the flow are shown in Fig. 3.
Figure 3a-e. Reconstituted image mosaics for the erosional dam-break wave experiments. Selected instants are, from top to bottom: a $t = 0$; b $t = 0.25$ s; c $t = 0.50$ s; d $t = 0.75$ s; e $t = 1.00$ s.
A quick phenomenological description of the flow can be derived from the analysis of those mosaic images. The collapse of the water body initially forms a wave front propagating downstream and eroding very intensively the underlying sediment bed. Bulking of sediments into the flow forms a bore at the front of the wave, made of a mixture of water and densely packed grains. Sediment entrainment is so intense that, by mixing with the flow, it forms an active transport layer of finite thickness. The very presence of the granular phase itself influences in turn the flow dynamics. Hence, the rheology of the wave propagation is more connected to that of a two-phase fluid-granular flow, rather than to that of a pure fluid flow with passive sediment transport. Following Capart (2000), three different flow regions can be identified: a pure water layer, a transport layer made of a mixture of water and grains, and the motionless sediment bed. Separating those flow regions are three interfaces, whose positions can be tracked in time on the digital images of the flow.

Automated imaging algorithms are used to characterise the flow pattern, by tracking grain motions in time and identifying the position of the interfaces separating the three distinct flow regions. Designing digital particle tracking velocimetry (DPTV) algorithms to track individual grain motions in dense, rapidly sheared particle dispersions, like is the case in the present experiments, is far from being a trivial task. Resolving motion ambiguities in such cases is a challenge, and the originality of the approach used for the present experiments lies in adopting a robust pattern-based principle to perform correspondence between sets of particle positions on successive frames. The principle of the method is illustrated in Fig. 4. Convolution of the digital images with radial filters is first used to highlight particles and locate their centroid positions to subpixel accuracy (Fig. 4a). Voronoï diagrams are then constructed on the sets of particle centres identified on one frame and on the next (shown respectively in thin and thick lines in Fig. 4b). While particles themselves are identical, their Voronoï polygons are not and reflect the local arrangement of neighbouring grains. This arrangement turns out to be quite stable over successive frames. By matching polygons of similar shapes, it is possible to pair positions corresponding to one and the same physical particle but sampled at two separate times. Once such a pairing is obtained, the inter-frame displacement vectors of the individual particles approximate the velocity field (Fig. 4c). Full details of the methods are given in Capart et al. (2002) and Spinewine et al. (2002).

Figure 4a-c. Steps of the pattern-based Voronoï particle tracking velocimetry algorithm (Capart et al. 2001): a image detail with particle centroid positions; b Voronoï diagrams constructed on the sets of particle centres identified on one frame (thin lines) and the next (thick lines); c displacement vectors obtained by matching particles according to their local Voronoï patterns.

Obtained using those automated algorithms, particle tracking results are presented in Fig. 5. The only manual intervention involved in obtaining the new velocity results is a post-processing step in which some manifestly incorrect vectors (around 2 % of the total number of vectors) are pruned out.

Besides particle velocities, semi-automated imaging procedures were developed to locate the three experimental profiles of interest, separating the three distinct regions of the flow: $\Gamma_w$, $\Gamma_s$ and $\Gamma_b$, separating respectively the successive layers of air, pure water, moving sediments and immobile granular substrate. They are extracted from the mosaic images in the following way. Taking benefit of the good contrast between the two regions, the flow free surface $\Gamma_w$ separating the water layer or water-granular
Figure 5a-d. Flow interfaces and velocity fields obtained from particle displacements tracked over 4 successive frames (15 ms) for 
\( t = 0.25 \text{ s}, \; b \; t = 0.50 \text{ s}, \; c \; t = 0.75 \text{ s}, \) and \( d \; t = 1.00 \text{ s}. \) Estimated interfaces \( \Gamma_w, \Gamma_s \) and \( \Gamma_b \) overlain as thick lines.
mixture from the overlying ambient air is obtained using a succession of custom low-pass and high-pass filters similar to the ones used to pinpoint particle positions in Fig. 4a. Interface $\Gamma_s$, dividing the flow into a sediment-free water sub-layer and a transport layer of water mixed with densely packed sediments, is acquired manually: while it is not impossible that an automated procedure similar to the one used for $\Gamma_w$ could be designed, it was found more straightforward to trace the interface silhouette directly from the images by manually picking points belonging to the interface. Finally the location of bed interface $\Gamma_b$ distinguishing the moving transport layer from the underlying motionless bed is estimated on the basis of the PTV displacement fields. Roughly, the interface position is chosen as the location where a linear extrapolation of the upper velocity profile intercepts zero, leaving a decaying tail of small velocities below the interface. The three boundaries are overlain onto the displacement fields shown in Fig. 5. Some degree of judgment is involved in tracing these various curves, hence they are not to be interpreted too literally. As the reader can judge for himself based on the raw images and displacement fields, however, the interfaces usefully highlight the main aspects of the flow structure.

4 BENCHMARK DESCRIPTION

Following the quick phenomenological description of the flow presented in the previous section, the wave can be schematised as a succession of three sub-layers separated by relatively sharp interfaces. Fraccarollo and Capart (2002) proposed an analytical description of their related set of flow equations, describing the flow as a series of shocks and expansion waves separating regions of constant states, like is illustrated on the bottom of Fig. 6. If this particular description depends on its constitutive assumptions and is valid only for a given mathematical model, it has the merit of highlighting some major flow features similar to those observed during the experiments.

Figure 6a-b. Wave structure of the erosional dam-break flow: a characteristic paths of the rarefaction fan and shock wavefront; b schematic flow pattern as depicted by the three interface profiles $\Gamma_w$, $\Gamma_s$ and $\Gamma_b$. 
Depending on the respective mathematical and numerical models, flow features may vary substantially. However, any model should at least capture the front wave propagation speed and the evolution of water levels and bed levels in time. Therefore, the proposed simulation results to be compared with the benchmark data comprise the propagation speeds of the front shock-wave downstream \((x_f(t))\) and of the upstream rarefaction wave within the reservoir \((x_b(t))\), and the temporal evolution of the interface levels \(z_w, z_b\) (and \(z_s\) if relevant) at different locations \(x\) along the channel. Those variables are defined in Fig. 6.

Modellers wishing to take part in the benchmark are invited to present their models and modelling results in a coherent way to guarantee easiness and objectiveness of inter-model comparisons and validation.

Expected results from the modellers include:

- short description of the numerical simulation covering
  - the system of equations used for describing flow dynamics and sediment movements, along with the phenomenological assumptions leading to this mathematical framework;
  - the numerical methodology, or a reference where a description of the method can be found;
  - the type of mesh used, the number of computational cells or points, the duration of the simulation in terms of CPU usage;
  - comments regarding the simulation and the results, if any.

- Required simulation results, presented in the following format
  - Position of the wave front \(x_f(t)\) and of the rarefaction wave \(x_b(t)\), presented as a single text file with the following format:

    | Col 1 | Col 2 | Col 3 |
    |-------|-------|-------|
    | Time  | \(x_f(t)\) \[m\] | \(x_b(t)\) \[m\] |
    | \(t\) \[s\] | \(\ldots\) | \(\ldots\) |

    It is proposed to use time increments \(\Delta t = 0.05\) s., corresponding to intervals of 10 images. Note that the origin of the horizontal axis is located at the gate position, and that the vertical reference level is taken at the top of the initial sediment bed.

  - Evolution of the interface elevation for \(z_w, z_b\) and \(z_s\) at 6 specific cross-sections along the channel: \(x = -0.50, -0.25, 0.00, 0.25, 0.50, \) and \(0.75\) m, each presented in a separate text file with the following format:

    | Col 1 | Col 2 | Col 3 | Col 4 |
    |-------|-------|-------|-------|
    | Time  | Free surface elevation | Bed level elevation | Transport layer elevation |
    | \(t\) \[s\] | \(z_w(t)\) \[m\] | \(z_b(t)\) \[m\] | \(z_s(t)\) \[m\] |
    | \(\ldots\) | \(\ldots\) | \(\ldots\) | \(\ldots\) |

    Note that the fourth column referring to the elevation of the top of the transport layer is of relevance only for numerical models adopting a multi-layer approach. This column should be left empty if not relevant for a particular model.

- Additional simulation results could be provided and will be compared with experimental data: full profiles of the flow and its various interfaces, velocity maps (only the velocities in the transport layer will be compared with experimental data through particle tracking), \(\ldots\) Presentation of those results is left to the spontaneity of the modeller.
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