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Flow Convergence at the Tip and Edges of a Viscous Dam Break Wave

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Abstract

The details of the flow at the tip of a dam-break wave are important to describe the propagation of the wave, bed shear and to estimate sediment transport rates and impact forces. This paper will present novel dam-break experiments using a very viscous fluid (detergent) to slow the flow sufficiently to enable tracking of particles on the free surface streamline. The experiments are performed both up a slope and on a horizontal bed. The video tracking shows that particles converge on the tip and then rapidly decelerate, a process that will induce a high bed shear stress. Particles also converge on the wall boundaries because of the no-slip condition. At the time of writing, this flow convergence does not appear to be included in analytical modeling of the tip region and the basal resistance. The dam-break flow is also analogous to wave and tsunami run-up on beaches, so the data may contribute to improved descriptions of the run-up for those flow types.

Introduction

The flow details at the tip of a dam-break wave are of fundamental importance to describing the propagation of dam-break waves, determining the basal resistance in the tip region, and in estimating sediment transport rates and impact forces [3,4] Current models, based around the application of the Navier-Stokes shallow water equations or the Saint Venant shallow water equations, assume that the wave-tip region propagates as a solid tip with a uniform flow in the region immediately behind the tip [2]. The effects of resistance are modelled with a friction coefficient that is applied to the interface between the wave and the bed.

The dam-break wave flow has many analogies, in particular the run-up of bores on beaches [5]. For the purposes of predicting flow depths and the propagation velocity, this may be adequate, particularly with calibration. However, direct measurements of the shear stress at the tip of dam-break waves and wave run-up do not show good agreement with conventional friction coefficients [1], and the shear stress within a small tip region is large and then decreases very rapidly. Barnes and Baldock [1] suggested this might be because the no-slip condition at the bed leads to flow convergence at the wave tip, which is then overrun by the fluid behind. This leads to the constant injection of high momentum fluid into the boundary layer at the wave tip, potentially generating high bed shear stresses.

This paper considers this issue and presents new experiments that aim to illustrate the details of the flow at the dam-break wave tip. A very viscous fluid (detergent) is used to slow the flow sufficiently to enable tracking of particles on the free surface streamline.

Methodology

Dam-break Wave Flume

The dam-break flume used measured 0.4m deep, 0.4m wide and 3.0m long (figure 1). It was a glass sided flume with a PVC bed. A lever operated gate, positioned normal to the bed, divided the flume into a 1.01m long reservoir and a 2m (approximate) long 'dry' flat bed. To obtain the desired gradient, β, of the flume, the whole flume pivots about the downstream end, and a pulley system was used to raise and lower the flume (see figure 2).

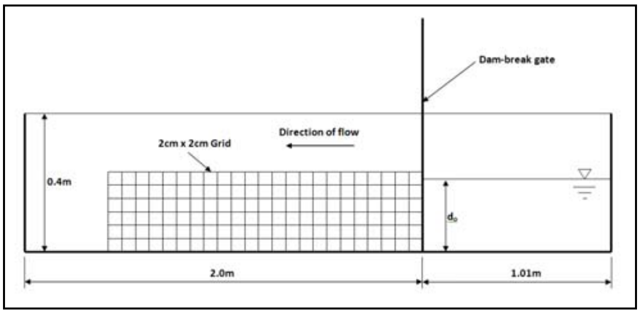

Figure 1. Schematic of dam-break flume.

A pivoting handle was attached to the gate to allow for the 'instantaneous' release of fluid. The gate was lined with rubber, silicon and grease to ensure a liquid tight seal. To aid in data analysis of the wave-tip, a 2cm x 2cm grid was placed on the near side of the flume.

Figure 2. Dam break flume with an upward sloping bed and partially filled reservoir.

Two video recording cameras were used in the capturing of dam-break wave footage. These sampled at 25 Hz and were mounted looking side-on to the flume and focused on the tip region for different test conditions. Three Microsonic MIC+25 ultrasonic non-contact distance sensors were used to record the depths of the dam-break wave at a time after the dam failure had been initiated. Two forms of detergent were used in the experiments so that observations of particle movements could be made both on the surface and within the interior of the flow. However, this paper will focus on the surface particles only. A standard domestic grade detergent was used, Kwikmaster Manual

Dishwash Liquid, colour green, density 1020-1040kg/m^3, surface tension 34 mN/m, and viscosity 0.8-0.9 Pa.s.

Experimental procedure

The flume was set to the desired angle of tilt and the reservoir was filled to the desired level, with the depth of the reservoir at the gate (d_o) measured perpendicular to the bed. Plastic beads and Styrofoam balls were used for particle tracking. They were placed at a regular spacing, generally 25-50mm apart, on the reservoir side of the gate. To improve the range of data attainable, variations of the size and density of the balls were trialled. Styrofoam balls were used to track the surface particles as they floated particularly well. A sketch of the layout of the particles is provided in Figure 3.

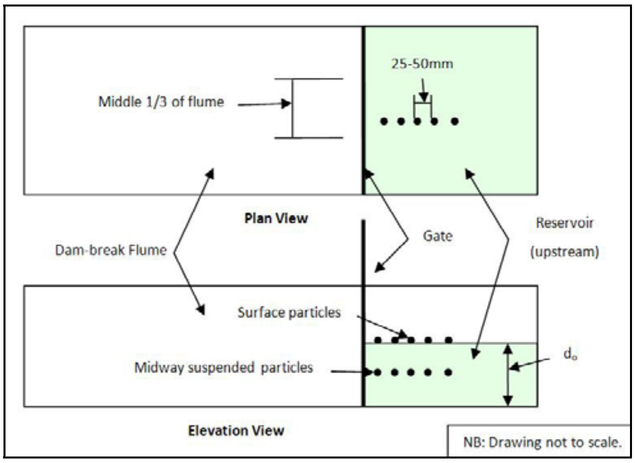

Figure 3. Illustration of initial positions of particles for video tracking. Surface particles were also placed in three lines parallel to the flume walls to investigate boundary wall effects.

Before running each test the downstream side of the gate was cleaned of excess fluid and any small seepage just downstream of the gate was wiped out just before the gate opening. The gate opens using the lever arm to a height of 0.2m in about 0.15s, which provides near instantaneous release conditions. Multiple re-runs were performed if high quality video records were not obtained. The maximum wave run-up along the centreline of the flume was also measured.

Data and video analysis

A MATLAB script was produced to allow for the quick, efficient and accurate analysis of the digital video footage recorded of the dam-break experiments. Analysis involved importing the video footage into the script, defining the time interval over which analysis was to be performed, setting reference co-ordinates in the image and defining the number of points that required tracking. By manually clicking on each particle in a defined order (see figure 4), the script progressed through the footage at the desired frame rate, recording the position locations of the particles relative to the reference co-ordinates and output the data for post-processing.

Only a few of the 95 tests involving green detergent, clear detergent and water are discussed here. The data are displayed by showing displacement versus time, displacement relative to the wave tip versus time and, in some instances, average velocity versus time. Displacement is measured parallel to the bed surface and time is measured from the instant of the initial gate opening. Instantaneous particle velocities were determined using the change in displacement between each time step, with averaging over 5 frames. The gradients of the relative displacement versus time curves were used to determine the relative velocity of particles with respect to the wave-tip, where a positive slope indicated that the particle was gaining on the wave-tip, a negative slope indicated that the particle was falling behind the wave-tip and a horizontal line indicated that the particle was travelling at the same speed as the wave-tip. Data can be non-dimensionalised as follows if required:

$$t = t^* \sqrt{\frac{g}{d_o}}, x = \frac{x^*}{d_o}, v = \frac{v^*}{\sqrt{gd_o}}$$

where the dimensional variables are starred.

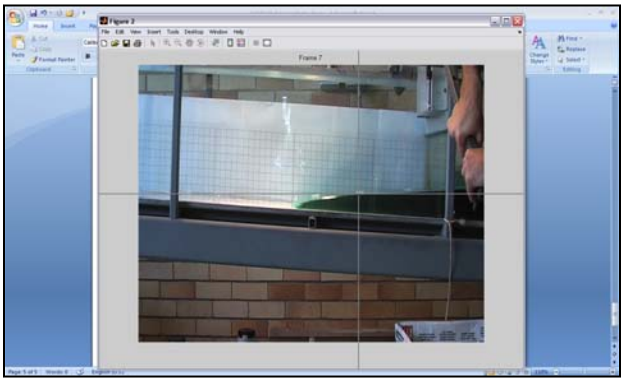

Figure 4. Illustration of image processing within Matlab to track the particle positions over time. The white Styrofoam particles are visible on the surface of the green detergent, and the cross-hairs are centred on one of the particles.

Results

To illustrate the convergence of the flow at the tip, a sequence of three still images from the video are shown in figures 5a-c. While the particles appear slightly blurred, tracking their position is straightforward. In figure 5a, five particles are visible behind the tip of the wave, and this reduces to four and three particles visible behind the tip in figures 5b and 5c, respectively. The “missing” particles have converged on the tip and remain there or, because they float, are caught in a recirculating eddy.

To illustrate the dimensional data, the displacement time-history of five particles are illustrated in figure 6. The first three of the five particles tracked can be observed to approach the wave-tip. Note that the wave tip and the particles are both slowing since the wave is progressing upslope. The third particle does not quite reach the tip before flow reversal occurs at the tip. Particles 4 and 5 were observed to progress forward at a rate similar to that of the wave-tip. Hence, the convergence occurs over a finite distance behind the tip for a wave propagating up-slope.

Figure 7 shows the velocity of the wave tip and particle 1 from figure 6, which is initially the closest particle to the wave tip. The velocity of the particle is initially slower than that of the tip, consistent with inviscid dam-break theory, but the particle velocity soon exceeds the velocity of the tip and therefore converges on the tip, as demonstrated in figure 6. The latter behaviour is not explained by theoretical models to the authors’ knowledge. Indeed, for inviscid dam-break, or swash flows on upward sloping beaches, theoretically, the flow is always diverging behind the wave tip during the uprush phase of the motion. For real flows on beaches, foam patches can be seen to similarly converge on the run-up tip. At $t \approx 1.5$s the particle reaches the wave tip (figure 6), and then decelerates very rapidly (figure 7). The rapid deceleration of the fluid particles due to the no slip condition at the bed imparts momentum transfer to the bed, and is therefore likely to generates a strong localised bed shear stress, as proposed by Barnes and Baldock [1].

a)

b)

c)

Figure 5. Snapshots of surface particles behind the dam-break tip progressing up a 1:10 slope. d_o=0.09m.

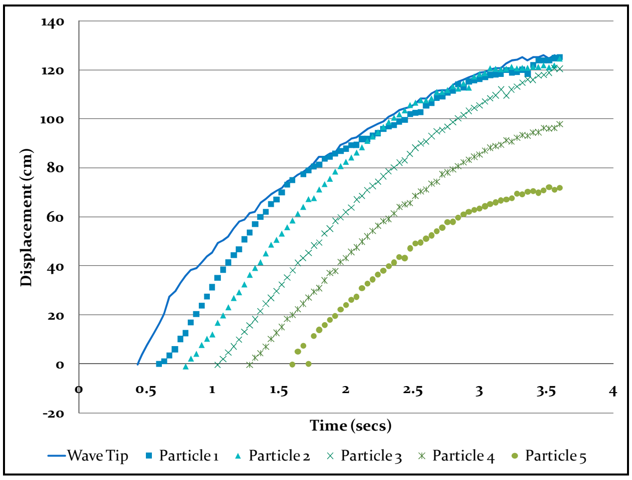

Figure 6. Displacement time-history for five particles behind the wave tip. β=0.05, d_o=0.12m.

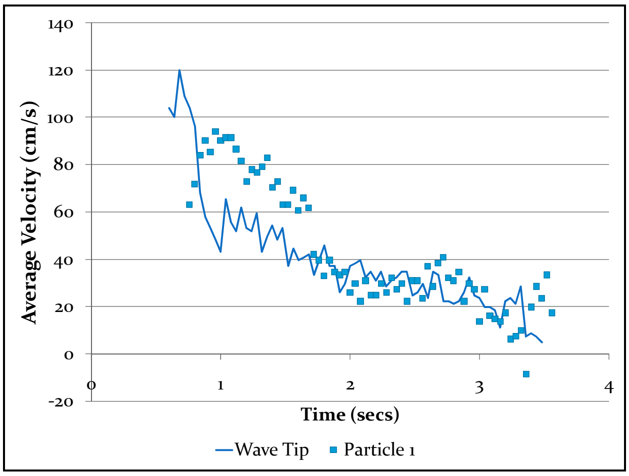

Figure 7. Velocity of wave tip and particle 1 in figure 6. β=0.05, d_o=0.12m.

For this trial, the particles that reach the tip of the wave converge on the tip at a relatively constant rate (figure 8), although the rate of convergence slows as the time of flow reversal approaches. This does not happen on a horizontal or downward sloping bed. Clearly, sediment, or debris, in suspension in such a wave tip boundary region will also converge on the tip prior to deposition.

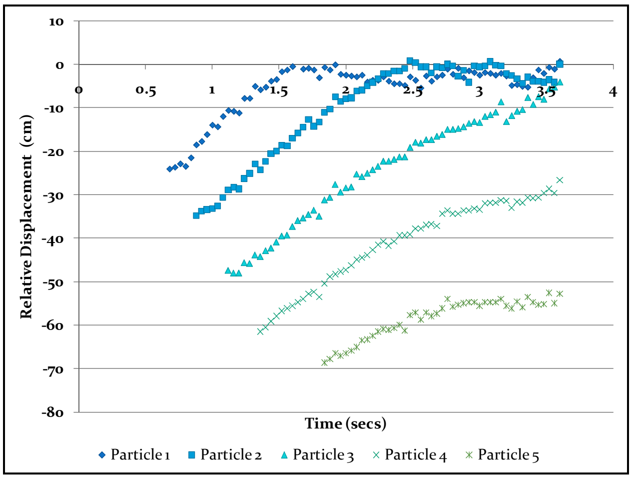

Figure 8. Relative displacement of wave tip and particles 1-5 in figure 6. β=0.05, d_o=0.12m.

The convergence of the flow on the tip region appears due to the no-slip condition retarding the fluid at the wet-dry interface, which is then overrun by the fluid above and behind the tip region [1]. The same effect occurs along the side-wall boundaries; the no-slip condition retards the fluid in the wall boundary layer and the adjacent interior fluid overruns the wall layer at the wet-dry interface. Fluid particles therefore also converge on the walls from the centre part of the flow. This is illustrated in figures 9a-b, which shows snapshots taken from the downstream end of the flume, looking back toward the reservoir, and demonstrates the effects of the wet-dry wall boundary on lines of particles placed along the flume. These effects will be demonstrated more clearly at the conference using video images.

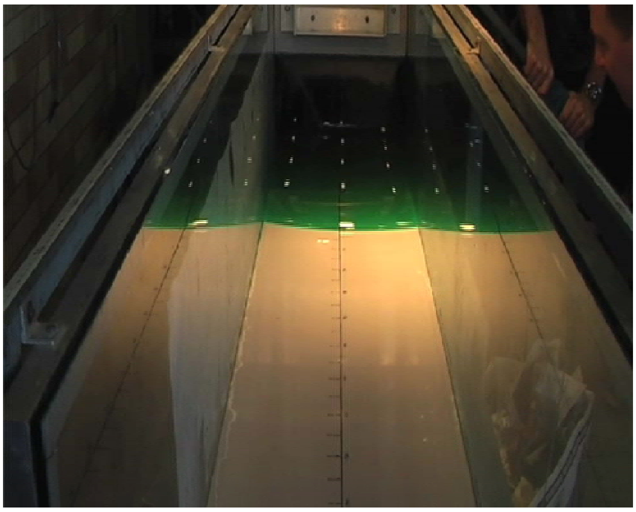

Figure 9a. Three lines of surface particles toward the start of the run-up. Initially, the particles in each line are the same distance from the walls.

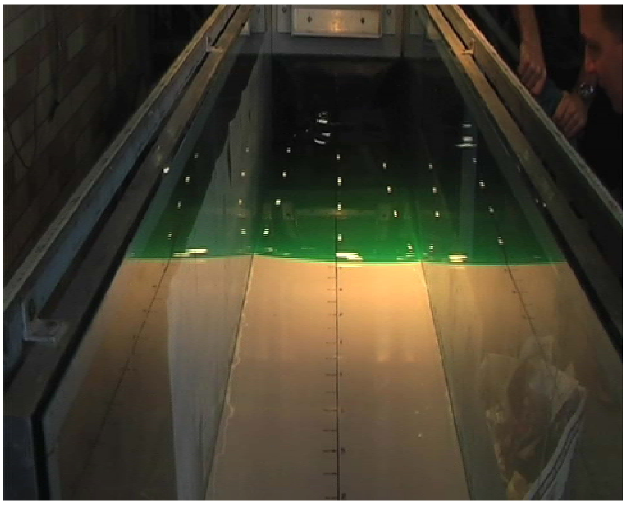

Figure 9b. Same particles a few moments later. The particles have converged on both the wave front and the side walls.

Based on the observations over many such tests, schematic diagrams of the particle paths are shown in figures 10a and 10b. We also note that because the fluid behind the tip is over running the tip this may explain the relative insensitivity of dam-break and swash run-up to changes in bed roughness [1].

Conclusions

Novel experiments are performed to track the motion of surface particles close to the wet-dry interface at the bed and walls during dam-break flows. The experiments clearly show that the no-slip condition at the bed and walls leads to flow convergence at wet-dry interface at the wave tip. Fluid converging on the tip decelerates rapidly, which may generate the high localised bed shear stresses observed in recent experiments.

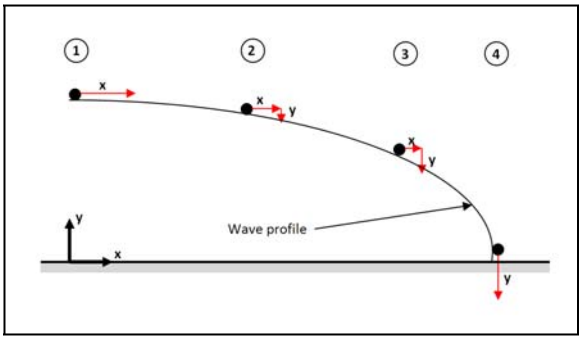

Figure 10a. Particle paths due to the wet-dry bed boundary; vectors show velocity relative to the celerity of the wave tip.

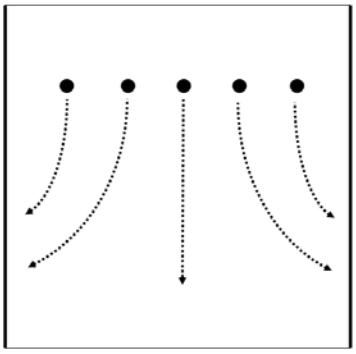

Figure 10b. Particle paths due to the wet-dry wall boundary.

Acknowledgments

Graham Illidge designed the dam gate that seals near perfectly without side-wall fixings that could lead to flow disturbance.

References

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