The effects of bed soil parameter variation on granular debris flow behaviour: an experimental investigation

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ABSTRACT

Small-scale debris flow tests using erodible beds were conducted in a flume to determine the influence of the flow and test bed on the bed erosion and subsequent debris flow runout area. This paper focuses on one model test where erosion of the bed was greatest. High-speed images of the test flows were analysed to produce shear and volumetric strain fields for the test at particular points in time. These were compared with image analysis of the saturation front from the flow into the bed to examine the influence of saturation on bed mobility. The results show that the test bed moisture content plays a major role in determining the final run-out area, while saturation of the test bed over the course of a debris flow's motion leads to entrainment of the bed into the body of the flow, through shearing in accordance with classical soil mechanics theory.

1 INTRODUCTION

A granular debris flow is a long-running motion of granular debris material saturated with water, which moves down slope in a highly agitated state. Granular debris flows can travel for several kilometres from their source area (Lu & Cruden 1996; Lavigne & Suwa 2004) and in the process inundate large areas with debris material. Landslide material or accumulated debris may be converted to a debris flow via water arising from the breaking of a naturally built dam or the appearance of a surface water stream during heavy rainfall (Johnson 1984). The resulting debris flow not only comprises the original landslide material but also the additional entrained water and bed material. This study discusses the strain profiles that were found to develop in a small-scale model granular debris flow during a test to observe this erosion behaviour.

2 TEST PROCEDURE

The test described in detail below formed part of a wider laboratory-based study to investigate the influence of moisture content (W_b), relative density (I_d) and saturation (S) of the bed on its erosion and entrainment and the subsequent debris flow runout area (Mahoney 2006). In the larger study the amount of fluid in the flow and bed were varied for each test, while the total mass of solids and fluids in the whole system were kept constant.

The experimental debris flows were produced using a flume and test procedure described in detail in earlier work (Rombi et al. 2006). For each test saturated granular material was released from a hopper, 1.15m above the run-out area, onto a 0.7m long by 0.2m wide curved aluminium chute. The debris material then flowed from the chute onto a 1m long by 0.2m wide test slope, set at an angle of 24° to the horizontal. The test slope was covered with an erodible bed made of the same granular material as the debris material. Once the debris material flowed down the test bed it proceeded to flow onto the 1m long by 0.4m wide run-out area at the base of the flume (Figure 1). For each test, 8kg of dry subrounded sandy-silt was used in the flow, with 8kg additional dry material in the bed. Only the water content of the bed and flow material and relative density of the bed was changed between tests. During the test, the side view of the debris flow was recorded through the Perspex sidewall via a high-speed camera at 1200frames/s for three seconds. The final run-out area and shape were recorded by digital camera.

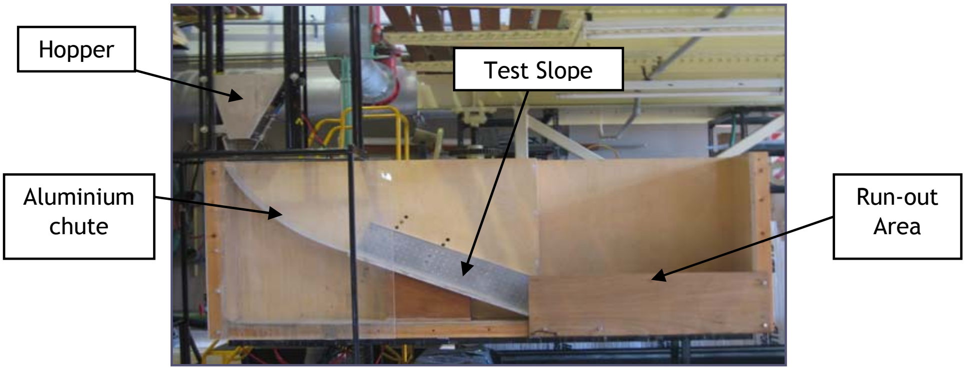

Figure 1: Testing Flume

After the test, images of the flow were post-processed using image analysis software to produce shear and volumetric strain plots of the model flows. In addition, the saturated-unsaturated boundary in the test bed was observed using grey-scale intensity measuring software.

3 SOFTWARE ANALYSIS

3.1 General

Here we discuss three sets of five frames that were taken from the high-speed digital camera images at particular phases of the model debris flow development. These images were analysed using two separate software packages. The first, GeoPIV, was used to produce volumetric and shear strain plots at points in time during the model debris flow. The second, ImageJ®, was used to estimate the position of the fully saturated to partially saturated boundary in the erodible test bed at each point. These were combined to examine the influence of the bed saturation on its mobility though the course of the model debris flow progression.

3.2 Strain Plots

GeoPIV is a Matlab® module, which implements Particle Image Velocity (PIV) in a way suited to geotechnical testing (White et al. 2003). PIV is a particle velocity-measuring procedure originally developed for fluid mechanics. GeoPIV uses the principles of PIV to gather displacement data from a sequence of digital images collected during geotechnical testing, in this case from the high-speed camera used to record the model debris flows. This in turn allows for the determination of strain and/or velocity fields of the debris flow. Strains produced during the debris flows are necessarily larger than those typically tracked during slow soil deformation. Strain rates are reported here, since each set of analyses is undertaken over a particular segment of time.

3.3 Bed Saturation Interface

In order to visually assess the state of saturation of the test bed, ImageJ image analysis software was used to determine the grey-scale intensity of a series of vertical cross-sections taken through images of the model test bed with time. Where the erodible test bed transforms from being fully saturated to partially saturated (i.e. vertically through the bed as water from the flow seeps downwards), the image cross-section transforms rather abruptly from being smooth and lighter-grey in appearance, indicating full saturation, to a darker grey and spikier, grainer image, indicating incomplete saturation. The series of analysed cross-sections are used to define the fully saturated to partially saturated interface for each of the different stages. A typical grey-scale intensity profile, from ImageJ, showing the transition between partially and fully saturated soil is shown in Figure 2. Twenty grey-scale intensity cross-sections were taken for each image to identify the interface. A smoothed line was then used to interpolate between the points to produce the transition line, indicated by the white line overlying the images in Figures 3 to 5.

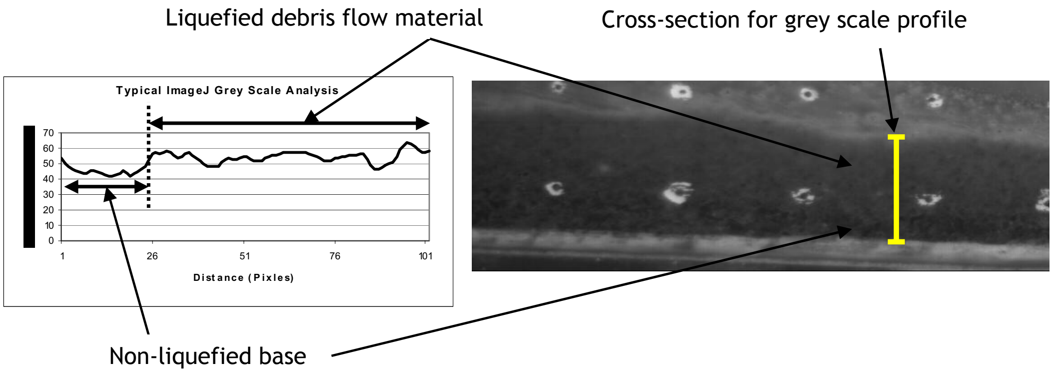

Figure 2: Grey scale intensity plot for non-saturation / saturation interface

4 RESULTS

From the series of model debris flow tests carried out by Mahoney (2006), Test 2, which exhibited complete bed erosion and entrainment as the model flow passed, is singled out here for detailed strain and saturation interface analysis. Test 2 had debris and bed properties as shown in Table 1.

Table 1: Soil Parameters

Bed Moisture Content (W_b)	Flow Moisture Content (W_d)	Bed Dry Density (kg/m^3) (ρ)	Bed Relative Density (I_d)	Bed Saturation Ratio (%)	Flow Solids Concentration (C)
0.20	0.28	1,740	0.46	100*	0.57

* Note the bed saturation of 100% was the value during initial test bed preparation. Downward migration of moisture, taking place between bed preparation and testing, will have reduced the saturation to less than this value.

The three stages discussed in detail here are: the initial debris flow arrival at 0ms, the initial bed erosion at 333ms, and the advancing bed erosion at 1,000ms – Figures 3 to 5, respectively. Analysis was carried out over 5 frames (corresponding to strains developed over 4.2ms).

In Figures 3 to 5, from the GeoPIV and ImageJ analysis, the bed saturation interface is laid over the camera image for each stage (top of each figure). In addition, shear strain and volumetric strain plots are produced (middle and bottom of each figure, respectively). The strain plots are over ranges of 0mm to 250mm for the x-axis and –20mm to 40mm for the y-axis. The strain deformation values in the plots in Figures 3 –5 are calculated over a 1mm by 1mm grid spacing.

5 ANALYSIS AND DISCUSSION

In viewing the plots in Figures 3 to 5 and the slow-motion video of the model debris flow (not shown) the following points are observed:

- Bed saturation progresses upslope (right to left) with time, as the model debris flow test progresses, as indicated by the dropping of the bed saturation interface line to the non-erodible flume base.
- Bed erosion and entrainment progresses upslope (right to left) with time. The advancement of the bed erosion and entrainment appears to closely follow the advancement of the bed saturation interface line.

The test analysed in this paper, Test 2, had the highest bed moisture content (20%) of all six model debris flow tests conducted (Mahoney 2006). It also had the highest theoretical bed saturation (100%, which by the time of testing would have reduced due to moisture loss during the test set up), given the relatively high density of the bed. Test 2 was the only test to exhibit complete bed erosion and entrainment, and it had the largest runout area of the model debris fan. When combining the computer aided analysis discussed here with the runout data it suggests that there is a direct link between increased bed saturation and increased bed erosion and entrainment.

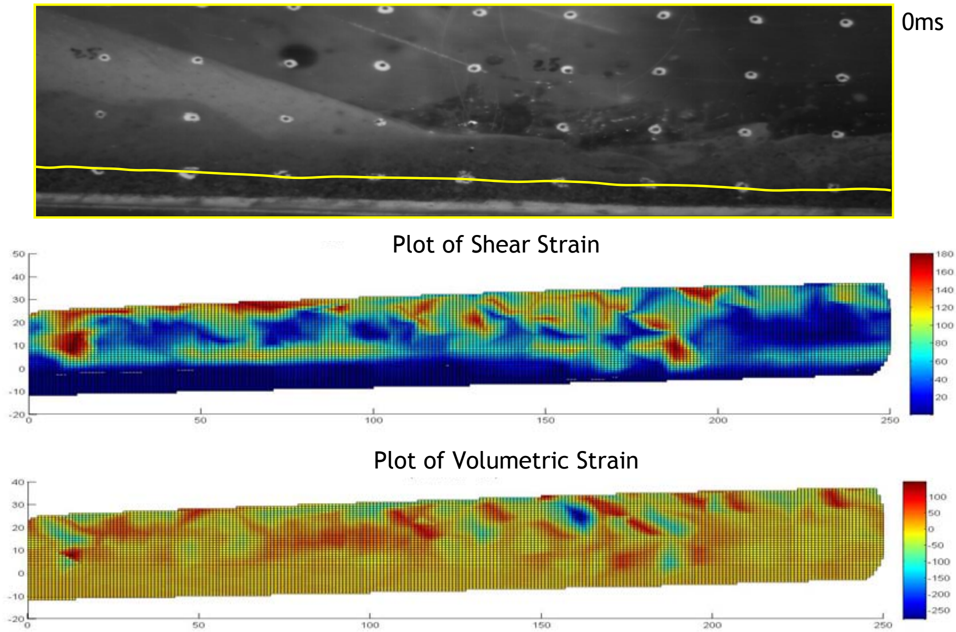

Figure 3: Saturation Interface and Strain Plots – Initial debris flow arrival (0ms)

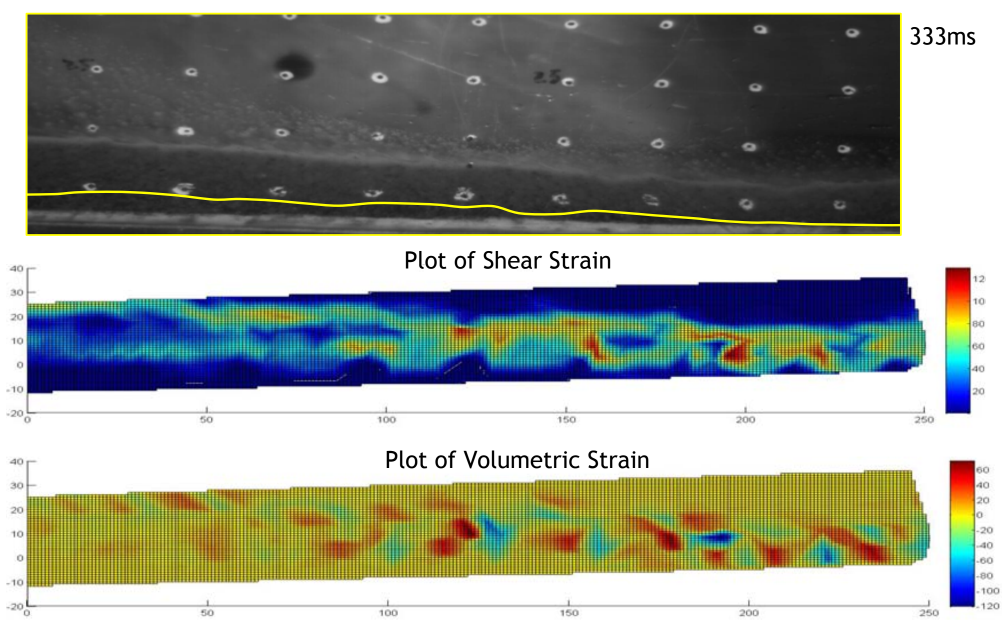

Figure 4: Saturation Interface and Strain Plots - Initial bed erosion (333ms)

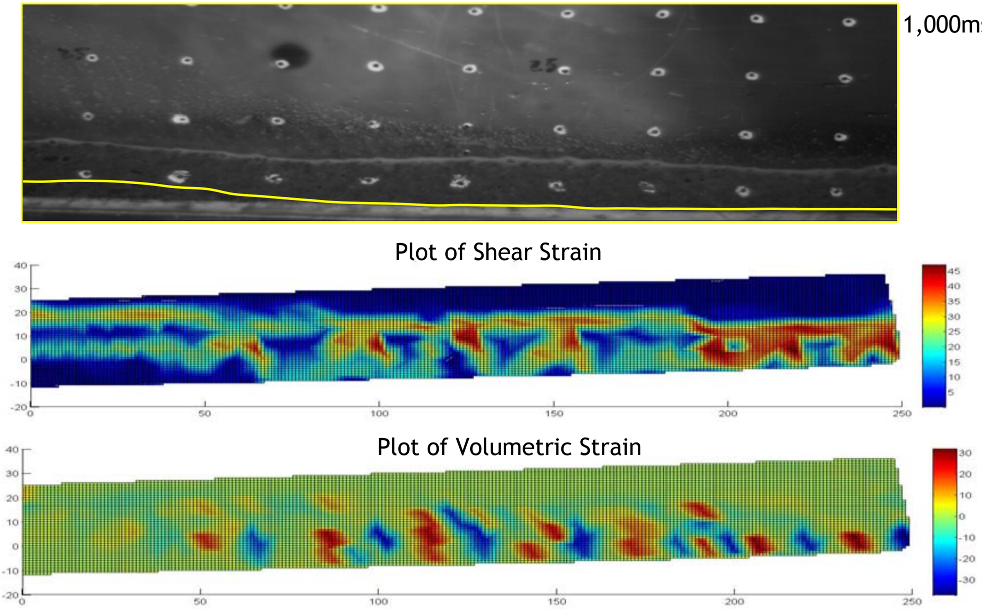

Figure 5: Saturation Interface and Strain Plots - Advancing bed erosion (1,000ms)

When viewing the video footage only without further processing, the flow appears relatively laminar and well behaved. But when observing the results from the computer aided processing, the following interesting features are observed:

- During the initial debris flow arrival phase (0ms time lapsed) the shear strain rate ranges from 0%/ms to +43%/ms, with the volumetric strain rate ranging from –65%/ms to +24%/ms. During the initial bed erosion phase (333ms time lapsed) the shear strain rate ranges from 0%/ms to +31%/ms, with the volumetric strain rate ranging from –29%/ms to +19%/ms. During the advanced bed erosion phase (1,000ms time lapsed) the shear strain rate ranges from 0%/ms to +12%/ms, with the volumetric strain rate ranging from –8%/ms to +8%/ms. Hence, the strain rates decrease in magnitude as the test progresses, due to the model debris flow losing momentum and slowing down.
- The flow above the unsaturated sections of the test bed shows “plug-flow” behaviour. This is indicated by constant shear strain above the area of the test bed that is not fully saturated. This area of constant shear strain is evident at all stages for flow upstream of the bed erosion and entrainment.
- The flow begins to show rotational zones in areas above where the bed is fully saturated and is beginning to erode and entrain into the passing flow, as indicated by the areas of high shear strain surrounding regions of near-zero shear strain.
- As the test progresses, the bed exhibits stationary zones between sections that are being entrained into the flow. This differential erosion is indicated by adjacent areas of positive and negative volumetric strain near the bed which otherwise shows zero strain. These pairs of alternating zones of positive and negative volumetric strain shown correspond directly to translational shortening of the flow, followed by translational lengthening (not shown here).
- As the flow progresses, the rotational and stationary zones do not progress horizontally along the test bed, but remain fixed in position. However more rotational and stationary zones form upstream as the test progresses with the bed entrainment moving uphill.
- When viewing the model debris flow from above, the surface of flow does not show the aforementioned effects. Therefore it is not possible to simply look at the surface of flows to view this aspect of flow behaviour.

The tests indicated that the amount of erosion is influenced by the bed saturation, so that the more saturated the test bed the more erosion and subsequent entrainment into the passing debris flow. The erosion and entrainment process appears to be non-laminar in nature, with vortices (as indicated by dilation and contraction in the volumetric strain plots) “chewing” into the bed. This is contrary to the classical concept that erosion is a linear stripping of layers under an average shear stress (Takahashi 1991).

This limited study of model debris flows results in further questions arising. For example, it is not known whether these stationary zones exist in plane strain alone, or whether there is there a spatial (3D) effect away from the glass window. It is equally unknown what influences the spacing of the zones (particle size, slope angle etc.) and in fact, whether this mechanism of erosion would exist in a "real" debris flow. Perhaps the most important issues are how this behaviour affects our overall understanding of erosion and entrainment and whether we need to be able to model this behaviour numerically. If we do, how will it be done? Further experimental research is required.

6 CONCLUSIONS

A series of small-scale model debris flow tests were conducted in a model debris flow flume. These tests varied the moisture content of the debris material and the erodible test bed that the model debris flow travelled over. The tests were filmed with a high-speed digital video camera and the images were analysed to produce volumetric and shear strain plots and to identify the interface between fully saturated and partially saturated soil in the erodible test bed. From the analysis of Test 2, which exhibited complete bed erosion and entrainment, the following key points are noted:

- The strain rates decreased in magnitude as the test progressed, due to the model flow losing momentum.
- The trigger for bed erosion and entrainment appeared to be the bed becoming fully saturated, while the erosion process appeared to be non-laminar in nature, with zones of positive and negative volumetric strain and zones of rotation.
- The zones of positive and negative volumetric strain and zones of rotation remained stationary as the flow progressed. Additional zones of rotation formed as the bed proceeded to erode upstream, rather than the zones progressing upslope following the erosion front.

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