Formation of dry granular fronts and watery tails in debris flows

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Abstract. Debris flows are particle-fluid mixtures that pose a significant hazard to many communities throughout the world. Bouldery debris flows are often characterized by a deep dry granular flow front, which is followed by a progressively thinner and increasingly watery tail. The formation of highly destructive bouldery wave fronts is usually attributed to particle-size segregation. However, the moving-bed flume experiments of Davies (*N. Z. J. Hydrol*., vol. 29, 1990, pp. 18-46) show that discrete surges with dry fronts and watery tails also form in monodisperse particle-fluid mixtures. These observations motivate the development of a new depth-averaged mixture theory for debris flows, which explicitly takes account of the differing granular and phreatic surfaces, velocity shear, and relative motion between grains and fluid to explain these phenomena. This poster presents the theory of Meng et al. (*J. Fluid Mech.*, vol. 943, 2022, A19), which consists of four coupled conservation laws that describe the spatial and temporal evolution of the grain and water thicknesses and depth-averaged velocities. This system enables travelling wave solutions to be constructed that consist of (i) a large amplitude dry flow front that smoothly transitions to (ii) an under saturated body, (iii) an oversaturated region and then (iv) a pure water tail. It is shown that these solutions are in good quantitative agreement with Davies' experiments at high bed speeds and slope inclinations. At lower bed speeds and inclinations, the theory produces travelling wave solutions that connect to a steady-uniform upstream flow, and may or may not have a bulbous flow front, consistent with Davies' observations.

1 Introduction

One of the most destructive parts of a debris flow is the initial surge or front, which is usually deeper, drier and richer in boulders and other large debris, than the rest of the flow. Following the passage of this front, many debris flows wane and transition to a fluid-saturated tail, with suspended sediment that is finer-grained than the front [3]. It is common for successive surges, with similar boulder-rich fronts, to follow the first.

Since water and fluid-saturated grains usually experience less friction than dry grains, it would be natural to suppose that the grains would be left at the back of the flow, with the faster-moving water travelling in front – and indeed several multi-phase debris flow models predict this, in contradiction to observations. Another mechanism must therefore be responsible for the formation of dry granular fronts in debris flows.

The laboratory experiments of Davies [1] show that a simple mixture of monodisperse grains and water flowing down an inclined plane develops a pronounced dry granular front, followed by a thinner watery tail as shown schematically in Figure 1. These experiments demonstrate that the dry front forms even in a very simplified analogue flow, in which particle size segregation is not present.

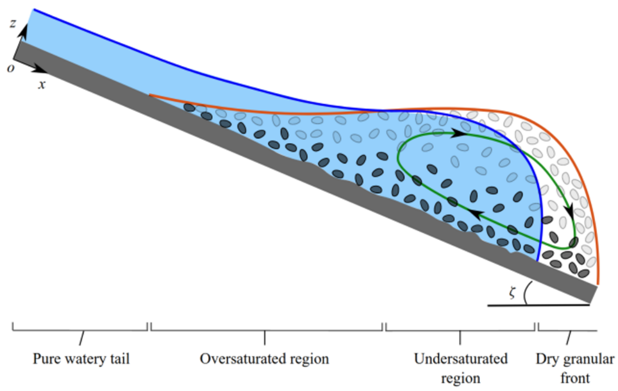

Fig. 1. Schematic diagram of a debris flow front, based on a solution of the two-phase model of Meng et al. [2]. The grains lie below the red line in the region partially filled with schematic grains. The phreatic (water) surface is shown with a blue line and the water saturated region is shaded blue. The green arrow indicates the recirculation of grains, with the light grey ones being sheared towards the front and darker grey ones moving back relative to it.

2 Modelling of Meng *et al.* (2022)

Motivated by the experimental results of Davies, Meng *et al.* [2] derive a two-phase depth-integrated flow model, in which grains and water satisfy separate mass

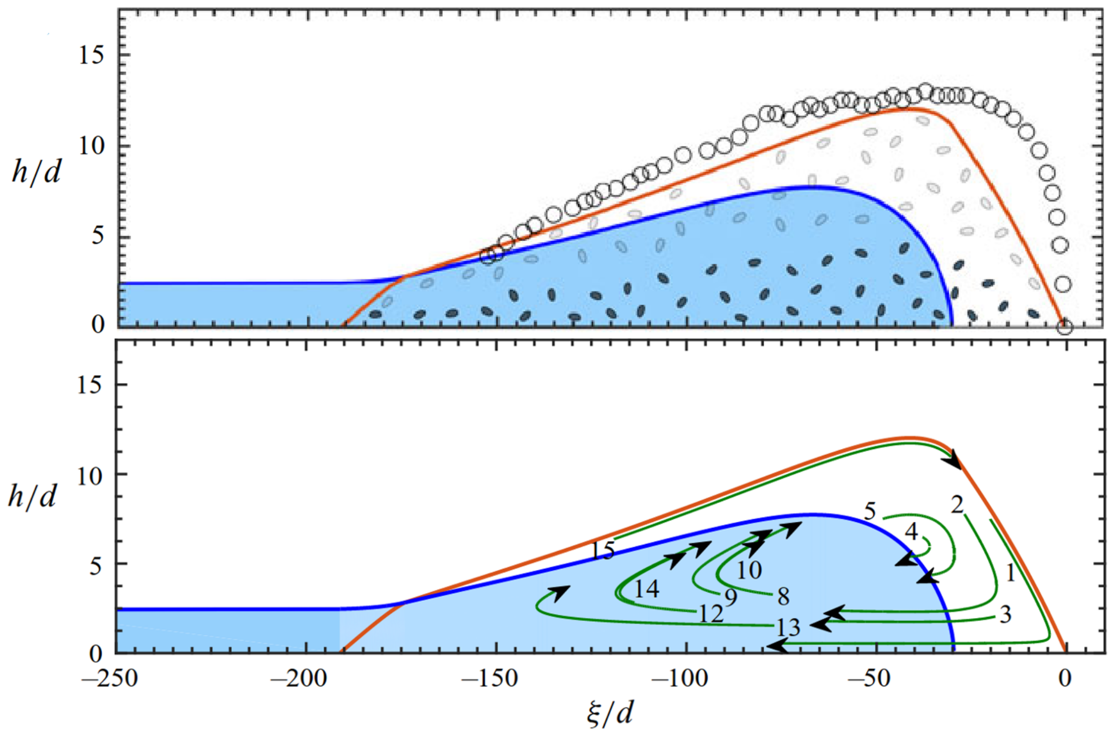

Fig. 2. Plot of the granular free surface (red) and water free surface (blue), predicted by the Meng et al. [2] model for parameters corresponding to an experiment of Davies [1]. Circles in the top panel indicate the granular free surface measured in experiments. Green lines in the bottom panel indicate particle paths predicted by the model, which are in qualitative agreement with the experiment.

and momentum equations. They demonstrate that that velocity shear plays an essential role in the formation of dry fronts. When the flow is under saturated, the composition of the flow varies vertically, with the volume fraction of water near the free surface less than that in the bulk of the flow. Velocity shear then transports the grains near the surface faster than the depth-averaged velocity, towards the flow front. Meng *et al.* [2] demonstrate a travelling wave solution in which a bulbous dry granular front is followed by a flowing body with a mixture of grains and water, and finally a streamflow of water, matching both the experimental observations of Davies [1] and descriptions of natural debris flows in the field [3] (figure 1).

Solutions of the Meng *et al.* [2] model accurately reproduce the shape of the bulbous flow in the experiments of Davies [1] (figure 2, top panel), and additionally capture the recirculation observed by Davies, where grains at the surface approach the flow front, are buried, carried back through the flow near its base, and rise in the body of the flow to be carried towards the front once more (figure 2, bottom panel).

This transport by velocity shear is extremely effective at carrying grains to the front of the flow and forming a dry flow front, even when the water is more mobile than the grains. That is, even when water is locally percolating downslope through the granular matrix, the *depth-averaged* speed of grains may nonetheless be faster than that of the water in an under saturated flow, due to the fastest-flowing layer at the flow surface being predominantly granular.

3 Conclusion

A characteristic feature of bouldery debris flows is the spontaneous development of a dry granular front, the presence of which significantly increases the thickness and thereby the hazard posed by such flows. Meng *et al.* [2] showed that velocity shear is essential to the formation of this dry front. The overwhelming majority of current depth-integrated debris flow models assume a plug-flow velocity profile (that is, no velocity shear), and in doing so, are unable to properly capture the physical mechanisms leading to the formation of the dry region at the debris-flow front.

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