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Simulation of initiation, transport, and deposition of granular avalanches: Current progress and future challenges

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Abstract

Since 1989 models to route debris flows and avalanches for hazards mitigation have been constructed using the seminal work of Savage and Hutter. With this approach a Saint Venant model for wet or dry granular flow is constructed by depth integrating equations for mass and momentum conservation, evaluating stress using bulk mixture values and a Coulomb failure criterion. Such models rely on just three forces to determine whether motion will occur: the force giving downslope acceleration, drag along the bed during flow, and the stress gradients derived from variations in thickness of the flow. With this construction most avalanche models simply begin with a force imbalance set large enough to reproduce the runout and deposits observed. However research into granular flow mechanics has advanced our knowledge considerably in recent years, allowing construction of a new and more powerful class of models that incorporate the effects of changes in internal structure in the flow, and explicitly include phenomenon such as fluid-solid coupling during rapid deformation of saturated granular mixtures. The defining feature of these more sophisticated models is that they can evolve from a stable stress state into an unstable state such that, given certain conditions, an initially stable rock or soil masscanbegin to creep or deform slowly well before it eventually accelerates rapidly andflows downhill. The contrast between simple and sophisticated models is illustrated by comparison of a simple model for an estimated rockfall hazard in California using a Savage and Hutter approach with a sophisticated, fully coupled fluid-solid model that successfully simulated initiationand transport of experimental debris flows without arbitrarily adjusting any model parameters.

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1. Introduction

Early studies in granular flow noted the fluid like behavior in chutes and channels [1]. This qualitative similarity to fluid flows motivated development of a depth-averaged Saint Venant or shallow water model

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for granular flow [1] that opened the door to development of routing models for debris flows and avalanches. In the intervening years, there has been development of numerous routing models (for example; Titan2d (http://en.wikipedia.org/wiki/TITAN2D), Flo2d (https://www.flo-2d.com/), Fldwav (http://www.dodson-hydro.com/software/hydro-cd/programs/fldwav.htm), [3–7]) based on the approach [2] as well as numerous experimental and theoretical studies into the dynamics of granular flow.

Much of the recent theoretical and experimental work has greatly expanded our knowledge of granular flow, but until recently this knowledge has not translated into more sophisticated routing models. In particular, experiments that define the details of the relationship between stress and deformation in granular flows have produced a large, yet remarkably consistent body of results that converge toward common relationships between stress, solids volume fraction, and shear rate. Both stress and solid volume fraction are related to the same ratio of the time for microscopic rearrangement of grains in the solid matrix to macroscopic shear rate, emphasizing the influence that local stress states in the deforming material have on the bulk continuum [8]. This is in contradiction to the assumptions embodied in original approach of [2] to model rock avalanches, in which depth-averaging of conservation equations for mass and momentum ignores details of the dynamic internal structures or mechanisms in the flow. Unfortunately our knowledge of granular flow mechanics is still insufficient to produce a full set of constitutive equations on which to base a complete model for flow of dry or wet granular materials. Nonetheless, progress in the last five years has allowed for significant advances in understanding of granular flow and fluid-solid coupling in mixtures, and new flow models that use the results of recent research produce much more realistic environmental hazards assessments than are possible with any of the models listed above.

In this paper I will contrast the standard application of a depth-averaged or Saint Venant model for hazards assessment of debris flows and avalanches with a more advanced approach. In particular I will contrast the approach used in two different flow simulations; one that uses standard methods to predict possible outcomes for a rock avalanche that may occur in California, and one that uses a more sophisticated model to analyze experimental data for debris flows. The California example is typical of current hazards assessment and is subject to limitations of the [2] formulation. In contrast, the latter example explicitly includes coupling between fluid and solid phases in the flowing debris, incorporating knowledge gained from recent research in granular flows and mixtures to accurately simulate experimental debris flows without arbitrarily adjusting parameters. The full inclusion of a fluid-solid coupling model allows for realistic initiation scenarios as well as an explicit model for the changing structure of flowing granular debris. This type of mixture model is a significant advance over traditional approaches and represents the future of environmental flow hazards assessment.

2. Simple routing models

The seminal work of [2] has been useful as the basis for a wide range of models constructed to route debris flows and avalanches. All of these models rely on depth-averaging of the 3d conservation equations for mass and momentum. These are, for conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{v} = 0 \ , \tag{1}$$

and for conservation of momentum (with $\boldsymbol{g}$ the acceleration of gravity)

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \rho \boldsymbol{v}\boldsymbol{v} = \rho \boldsymbol{g} + \nabla \cdot \boldsymbol{T} \ , \tag{2}$$

in which the velocity vector $\boldsymbol{v}$, the bulk density ρ, and the stress tensor $\boldsymbol{T}$ are defined for a fluid-solid mixture, as discussed in [9]. Stress is assumed to be defined by the bulk properties and is constrained to satisfy a Coulomb criterion between shear stress and bulk confining stress. For dry granular flow down a uniformly-sloping channel, depth-averaging in slope normal coordinates results in equations for mass conservation