C. R. Physique 16 (2015) 86–96

Contents lists available at ScienceDirect

Comptes Rendus Physique

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Granular physics / Physique des milieux granulaires

Debris flows: Experiments and modelling

Les écoulements de débris : Les expériences et la modélisation

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ARTICLE INFO

Article history:
Available online 31 December 2014

Keywords:
Debris flows
Debris avalanches
Centrifuge experiments

Mots-clés :
Écoulements de débris
Avalanches de débris
Expériences en centrifuge

ABSTRACT

Debris flows and debris avalanches are complex, gravity-driven currents of rock, water and sediments that can be highly mobile. This combination of component materials leads to a rich morphology and unusual dynamics, exhibiting features of both granular materials and viscous gravity currents. Although extreme events such as those at Kolka Karmadon in North Ossetia (2002) [1] and Huascarán (1970) [2] strongly motivate us to understand how such high levels of mobility can occur, smaller events are ubiquitous and capable of endangering infrastructure and life, requiring mitigation. Recent progress in modelling debris flows has seen the development of multiphase models that can start to provide clues of the origins of the unique phenomenology of debris flows. However, the spatial and temporal variations that debris flows exhibit make this task challenging and laboratory experiments, where boundary and initial conditions can be controlled and reproduced, are crucial both to validate models and to inspire new modelling approaches. This paper discusses recent laboratory experiments on debris flows and the state of the art in numerical models.

RÉSUMÉ

Les écoulements et avalanches de débris sont des courants gravitaires complexes de roche, d'eau et de sédiments, qui peuvent être hautement mobiles. Leur composition produit une morphologie riche et une dynamique inhabituelle, possédant des attributs de matériaux granulaires et de courants gravitaires visqueux. Bien que des incidents extrêmes tels que ceux survenus à Kolka Karmadon, en Ossétie du Nord, en 2002 [1], et à Huascarán, en 1970 [2], nous motivent fortement pour comprendre comment une telle mobilité peut être atteinte, des écoulements plus petits et ordinaires, qui sont également à même de menacer les infrastructures et les personnes, doivent être eux aussi confrontés. De récents progrès dans la modélisation de ces écoulements ont produit des modèles multiphases qui peuvent fournir des indices sur les origines de leur phénoménologie unique. Cependant, leurs variations spatiales et temporelles compliquent cette tâche. De ce fait, les expériences en laboratoire, où les conditions initiales et aux limites peuvent être contrôlées de façon reproductible, sont cruciales à la fois pour valider les modèles et pour inspirer de nouvelles

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http://dx.doi.org/10.1016/j.crhy.2014.11.006

approches théoriques. Cet article décrit des expériences récentes sur des écoulements de débris en laboratoire et résume l'état de l'art en matière de modèles numériques.

1. Introduction

Debris flows are gravitational mass movements of rock incorporated in a fluid matrix of fine sediments suspended in water [3,4]. Often the term *debris avalanche* is used to refer to the largest, most rapid events. In this paper we are using the term *debris flow* to refer to any subaerial flowing mixture of particles in water where the particle can range from sediments to boulders. Rainfall triggered landslides, debris avalanches, glacial outbursts and lahars all fall within this description. What distinguishes debris flows from rock falls and dry processes is that the water has a substantial influence on the dynamics, though debris flows also exhibit some features of dry granular flows, such as lateral levees and segregation. The suspended sediment increases the effective viscosity of the water so that debris flows also have some characteristics of a viscous gravity currents. With the particle and fines concentration profiles varying in space and time as the flow evolves, a single event can at any instant display wide variations in rheology and character [5].

Typically these flows move with speeds of the order of $10\,\mathrm{m\,s^{-1}}$ and travel 100–1000 m, but extreme events [1,2] have achieved speeds of $80\,\mathrm{m\,s^{-1}}$ and have travelled tens of kilometres. Typical debris flows are triggered by land instability and heavy rainfall, occurring in the same locations repeatedly so that historical data is effective for hazard mapping and risk management. However, volcanic activity depositing ash, land-use changes such as deforestation, and climate change can render this past data unrepresentative, generating new vulnerabilities. Predictive numerical models are necessary not only to test our understanding of the underpinning physical processes but also for the estimation of runout distances and impact pressures of potential events.

Various modelling approaches have been employed [6–10] with the aim of reproducing front velocities, runout distances and deposition patterns. Since the length and time scales normal to the slope are very small compared to the scales down and across the slope, depth-averaged models are typically employed. These models assume equilibrium profiles in the slope-normal direction, which are derived from a rheological model. Because of these necessary assumptions, developing a model that covers a wide-ranging parameter space is very challenging and requires systematic validation and calibration with high quality experiments. Field-scale data is crucial, but the lack of reproducibility and control of boundary and initial conditions make obtaining such data very challenging. Small scale experiments are therefore extremely useful since, though they cannot satisfy complete similarity, they are reproducible and detailed parametric investigations are possible.

In a depth-averaged model the momentum equation is a balance between inertia, pressure gradients, gravity and the shear stress on the bottom boundary. Relating the shear stress to the flow velocity near the bottom boundary is the key difficulty in modelling debris flows. It only depends weakly on the assumed constitutive law, but there is little experimental or theoretical evidence for a satisfactory description. Although field observations [11] have shown the presence of an almost entirely dry granular flow front, theoretical and laboratory modelling approaches have focused upon the fluid-filled core of the flow [12–14], which replicate bulk dynamics surprisingly well. But this approach cannot tell us about the peak velocities, impact pressures and flow heights that will occur within the highly energetic dry granular regions of the flow.

Field measurements are still quite rare, with regular observations limited to specific sites (e.g., Dorfbach Mattertal and Illgraben test sites in Switzerland [11]), and post-event photogrammetry analysis, e.g. [2,1], typically restricted to the very largest (and hence atypical) flows. The chief difficulty in devising small scale laboratory experiments is in replicating the dynamic similarity criteria. In contrast, the 90 m long outdoor USGS chute [15,16] provides excellent dynamic similarity to the field scale (particularly when considering frictional phenomena), however control over the boundary and initial conditions is somewhat limited. Different experiment designs are needed to match different combinations of similarity criteria, providing insight into different processes within the flow.

In the following we describe some of the most interesting morphological features of debris flows and a range of idealised, simplified experimental systems that exhibit some of these characteristics. These are systems that are tractable for mathematical and physical modelling, but by their nature can only capture some elements of a real debris flow. The challenge remains to find new ways to capture the full complexity of debris flows in an effective manner.

2. Processes in debris flows

Fig. 1 shows i) a photo of a debris flow deposit at Cass near Arthur's Pass in the Southern Alps of New Zealand, together with ii) a schematic of a typical path profile. Studies of such, relatively small, debris flow catchments offer an excellent link between field scale processes and laboratory scale ones. Few studies focus on such small scale flows, but those that do, (e.g. [17,18]), offer valuable insight since good statistics can be collected. The figure shows the definitions of H and L as the changes in the horizontal and vertical centre of the initiating mass from start to finish. This is the correct definition for studying effective friction, that is the runout ratio H/L, but more typically these lengths are calculated from its distal limits, which are easier to measure. This is the idealised case since both erosion and deposition can occur over substantial portions of the track.