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Debris flows: Experiments and modelling

Les écoulements de débris : Les expériences et la modélisation

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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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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.

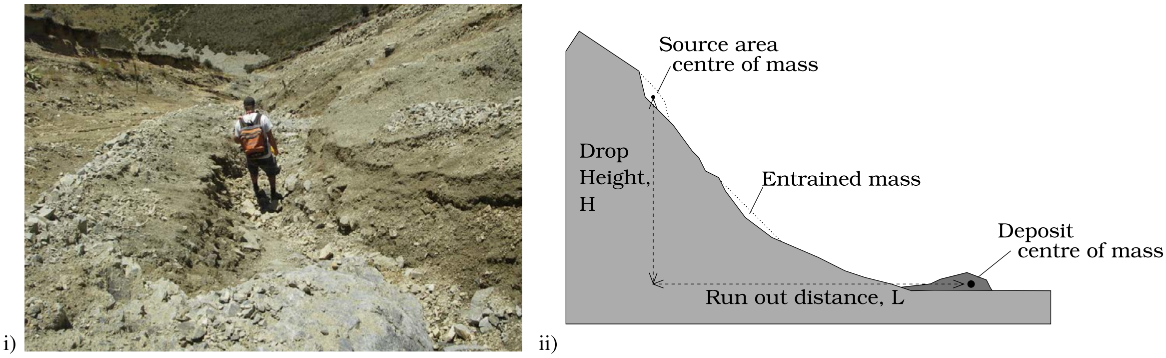

Fig. 1. i) (Colour online.) Photo (*P. Kailey*) looking down a reach of the C6 catchment in the Cass study area, near Arthur's Pass, New Zealand. The slope angle here is ≈38°. Material has been eroded from the centre of the channel, but levees have formed at the channel sides. ii) Schematic diagram of a debris flow path.

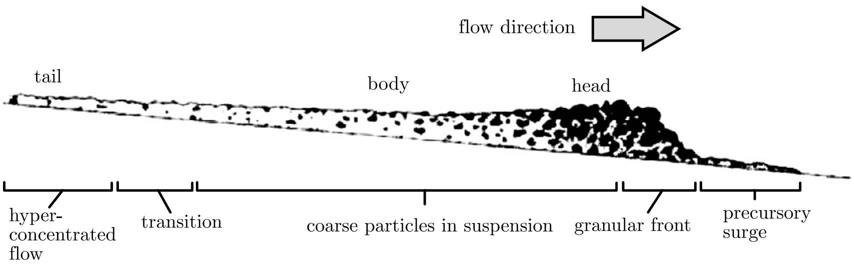

Fig. 2. Schematic of a granular front debris flow. A precursory water surge is followed by the head consisting of a mixture of large particles supported by particle contacts and fluid. After the passage of the front the average size of the particles gets smaller and the amount of suspended particles increases.

2.1. Morphology

The granular behaviour of debris flows evidences itself in some of the flows' most striking features. A debris flow will typically contain particles with sizes covering several orders of magnitude, from the finest silt to the largest boulders, exhibiting the granular segregation behaviour discussed in detail elsewhere in this volume. As the flow moves down the slope the larger particles segregate upwards and then move towards the front and sides leading to the formation of levees (see Fig. 1i), forming a channel for subsequent material to flow through. This is well documented in large chute experiments (USGS chute) [15,21], where individual particles were tracked and the deposit carefully analysed. The fine sediment and water remaining within the channel develop interesting characteristics of their own. Observers often describe a debris flow travelling as a sequence of fronts, with subsequent surges sometimes catching and overtaking previous fronts [22]. These surge instabilities have been observed in experiments with a suspension of custard powder [23].

Segregation by particle size is also considered to be partly responsible [21] for the formation of a 'snout and tail' architecture, where a relatively dry and high granular head forms at the front of the flow followed by a more fluid rich region in the bulk of the flow (see Fig. 2). We will discuss later other mechanisms that may contribute to this architecture.

2.2. Mobility

Although the overwhelming majority of debris flows are relatively small, with runout distance just a few times the fall height, that is $L/H = 1$–5, some events have much longer runouts. Developing a model that can cover both extremes without non-physical parameter fitting is challenging. The largest events are rare, but the huge amounts of material they transport and the severity of the damage they cause makes understanding them critical. The increase in runout ratio L/H with flow size has also been observed with dry rockfalls typically and Campbell (1989) [24] detailed a compelling argument based on numerical simulations that this enhanced runout resulted from a thin, low concentration layer of highly agitated particles at the base that reduced the effective friction of the flow. For wet debris flows however it is most likely that the increased runout is due to the increased suspension capability of a larger flow. In the models of Iverson for example pore pressure is governed by a diffusive process so that the timescale for its decay varies as one over the flow thickness squared. Debris avalanches can also entrain large amounts of additional material, many times their initial mass, so that an analysis based on H and L is no longer relevant.

In the following we discuss an experimental arrangement that allows some of the strongly stress-dependent processes that can occur in long runout events to enter the laboratory. Centrifuge testing, discussed in the following, allows the stresses found in field events to be replicated in small scale experiments by increasing the effective gravity. This is partic-

Table 1
Scaling laws used in geotechnical centrifuge testing [26]. N is the scale factor based on the depth of the flowing region.

Parameter	Prototype (field)	Model (centrifuge)
Gravitational acceleration	g	Ng
Stress	σ	σ
Displacement	x	x/N
Energy	E	E/N^3
Inertial time scale	t_i	t_i/N
Laminar diffusion/seepage	t_d	t_d/N^2

ularly important when considering mechanisms of initial fracture, basal erosion, material deposition and explosive particle breaking that could generate the highest levels of flow mobility.

3. Experiments

The basis for analogue experiments of large scale phenomena is satisfying all the relevant similarity criteria. However, this is impossible for debris flows, so different experimental approaches try to achieve similarity with a limited set of parameters. If particle cohesion, deformation and damage are not important, that is the particles are to be treated as an idealised granular material, then experiments in normal gravity are possible on a reduced scale and these are frequently performed in chutes or drums. However, if one wishes to study these effects at reduced scale, then the effective gravity must be increased by the use of a centrifuge to maintain stress similarity.

3.1. Centrifuge experiments

It is well known that the deformation response and shearing resistance of pseudo-static granular bodies, such as soil, is stress dependent [25]. That is at low stresses, when sheared, a consolidated dry granular material must dilate as particles ride up over each other giving rise to a large effective friction that is geometrically determined. If however the stresses are large enough for the particles to deform or break then the material need not dilate at all, resulting in a lower effective friction. Scaled physical models of pseudo-static soil and rock tested under Earth's gravitational acceleration, g, are generally unable to reproduce the stresses in a field-scale geotechnical scenario such as an unstable slope, leading to differences in the deformation behaviour and resultant predicted failure mechanisms. In contrast, in geotechnical centrifuge modelling, the field scale stresses are replicated by increasing effective gravity in proportion to the length scale reduction. That is if the field measurements are for a flow of depth h in gravity g then the centrifuge is spun fast enough to achieve an effective gravity of $g' = Ng$ where $N = h/h'$ and h' is the laboratory flow depth. Table 1 shows typical scalings used in geotechnical centrifuge modelling [26].

In addition to modelling initial slope failure to flow, centrifuge modelling is particularly useful for studying entrainment since particle deformation and cohesion is likely to be important [27]. Field scale monitoring of debris flows has shown that the front of a debris flow can entrain large quantities of bed material [11], possibly due to rapid 'undrained' loading of the saturated bed, where the pore fluid pressures rise in response to the increased overburden pressure from overriding flow and the frictional resistance to entrainment remains low [28]. Centrifuge testing of debris flows may enable this type of behaviour to be modelled more accurately because the bed stresses will be better replicated resulting in more correct dilation response (and suppression of peak resistance). However, diffusional processes in the centrifuge also need to be carefully considered.

In centrifuge testing, for fluid saturated soils such as in a debris flow, pore fluid diffusive processes scale with N^2 while velocity scales with N, Table 1. Hence, in order to match pore pressure diffusion and particle velocity timescales, either the pore fluid viscosity must be scaled up by N, or the particle size must be scaled down by $\sqrt{N}$. In a pseudo-static system, either approach may lead to the same diffusional behaviour so it is usually preferable to increase the fluid viscosity rather than to reduce the particle size because this has less influence on particle-particle contact conditions, which affect mechanical response [26]. Complete similarity cannot be achieved in any experiments; centrifuge experiments seek to operate in the regime of equivalent stresses which is important for non-ideal grain behaviour. However, in a flowing system, the method of increasing the fluid viscosity also changes the interaction with the sidewalls of the model, resulting in reduced flow rates and changing the overall flow dynamics [29]. In this case it is therefore preferable to decrease the particle size and use water as the pore fluid—an approach that has only been explored in preliminary tests thus far, due to the difficulty in controlling the particle size distribution at the scale of silt. This would also have a dramatic effect in the scaling characteristics for centrifuge experiments. That is, the values listed in Table 2 for centrifuge experiments are estimated for a high viscosity pore fluid [17] but should become much closer to typical field scale debris flow values if water is used as the pore fluid [30]. As this discussion hints, an additional important non-dimensional group, critical for dry granular flows, is the flow height divided by the particle diameter and this also should be take into account in experiment design.

Centrifuge testing can be undertaken using either a beam or drum centrifuge. A beam centrifuge has a central axis or spindle with a discrete model 'package' on one radial arm (or 'beam') and a balancing counterweight on the other, while a

Table 2
Order of magnitude estimates of the dimensionless parameters [16] describing field (one relatively small landslide—Oddstad, and one extreme debris flow—Huascarán) and experimental debris flows, indicating which experiments replicate which field processes. Note that spatial and temporal variability within a single flow can alter these estimates by one or two orders of magnitude. The variables are ϕ the solid volume fraction, ρ_s and ρ_f the solid and fluid densities respectively, d the particle diameter, h and u the flow depth and speed at the front, g the acceleration due to gravity, θ the slope angle. Data collated from [17,19,20,16,2].

Parameter	Name	Balance	Centrifuge	Notts Chute	Armanini–Larcher Chute	USGS Chute	1982 Oddstad	1970 Huascarán
L/H	Runout	Runout distance to drop height	3	2	–	2	2	20
$\dfrac{\phi\rho_s d^2 u}{(1-\phi)\mu h}$	Bagnold number	Inertial grain to viscous shear stress	0.6	2	2	400	4	>4
$\dfrac{\rho_s d^2 u^2}{(\rho_s-\rho_f) g h^3}$	Savage number	Inertial grain to frictional stress	5×10^{-4}	0.2	10^{-3}	0.2	10^{-4}	$<10^{-4}$
$\dfrac{\phi(\rho_s-\rho_f) g h^2}{(1-\phi)\mu u}$	Friction number	Frictional to viscous shear stress	10^3	9	10^3	10^3	10^4	$>10^4$
$\dfrac{\phi}{(1-\phi)}\dfrac{\rho_s}{\rho_f}$	Mass number	Solid to fluid inertia	3	1	3	4	4	4
$\dfrac{\rho_f u d}{\mu}$	Particle Reynolds number	Drag regime	10	10^4	$<10^3$	10^4	10^3	10^5
$\dfrac{u}{\sqrt{g h\cos\theta}}$	Froude number	Front to wave speed	0.6	1	1	10	3	6

drum centrifuge has a cylinder that spins around the central axis so that the scenario considered can encompass the interior of the cylinder [31]. For studies focusing on post initiation debris flow motion, drum centrifuges rather than more conventional beam centrifuges are more appropriate. This is for two reasons: first because there is far more room for the runout of the material on the drum walls of the cylinder than for a beam in which the model is constrained in a rectangular box and second because the materials can be introduced in an unconsolidated state. Debris flows may also be generated by overrunning an erodible substrate with pure fluid (water or a higher viscosity fluid as required) as shown in preliminary tests [17].

Up to now, limited model tests have been carried out on a variety of debris flow problems in centrifuges. Bowman et al. (2010) [30] and Kailey et al. (2011) [32] carried out experiments to examine the motion of and entrainment by sub-aerial debris flows under different slope and confinement conditions. Unconsolidated debris was introduced to the drum externally, via a tube feeding from the central spindle of the centrifuge, so that initiation was not considered. In some tests, the erosion of unsaturated soil beds by an overriding flow was examined. The flows tested were, in most cases, relatively viscous due to the decision to increase the pore fluid viscosity to increase the consolidation time under the enhance gravitation. In consequence, while clear trends between solid fraction, flow volume and runout were established that generally agreed with observations at $1g$ [11], the flows were quite slow and had relatively low runout overall compared to other types of test. For tests on erodible substrates within the channel, notable similarities were found between the final incision of the channel and observations made in the field.

Gue et al. (2010) [33] investigated scaling laws for submarine clay-rich debris flows on continuous shallow slopes of 6°, typical of deep sea conditions. As with Bowman et al. (2010) [30] and Kailey (2013) [17], the central spindle of the drum was used to introduce a slurry to the head of the slope. This work led to scaling laws linking flow velocity, flow height and effective gravity. Milne et al. (2012) [34] examined the initiation of sub-aerial debris flows via hill-slope erosion. Loose soil mantles with different degrees of fines (silt) were placed under suction stress on a 30° slope near its top. Failures of the mantle were produced under conditions of increasing pore pressure via basal infiltration. The results showed that siltier sands could sustain greater increases in pore water increase before failure, which concurred with observations in the field in Scotland. The study did not examine the ensuing velocity or runout of the flows.

There are a few challenges with centrifuge testing, associated with the geometry of and flow speed achieved by debris flows. A centrifuge Coriolis effect occurs as a result of soil and water moving with speed within the rotating reference frame of the centrifuge [35]. However, in all of the centrifuge model tests that have been reported using high viscosity fluids, the velocity of the flows was found to be low enough ($0.1\,\mathrm{m\,s^{-1}}$ to $1\,\mathrm{m\,s^{-1}}$) not to generate significant Coriolis accelerations (<5% of the applied g-level, Ng). In contrast, an experiment [30] in which silt-sized particles were used with water as the pore fluid developed a higher flow velocity, at $4\,\mathrm{m}\,s^{-1}$. This would result in a calculated Coriolis acceleration of approximately 20% of the total applied Ng at this velocity, which is significant. Any future work that uses water as the pore fluid along with scaled particles, and thereby develops velocities of this order, will need to take the Coriolis acceleration into account in modelling the developed runout. Fortunately, while adding a point of complexity to the boundary conditions, the Coriolis acceleration is able to be determined—and potentially included within any model of the flow—so long as the flow velocity is measured throughout a test.

The effective gravity field within a centrifuge, neglecting terrestrial gravity, is $g' = r\omega^2$, where r is the distance from the rotation axis and ω is the angular velocity. If a flow moves over a distance L at mean radius r it will therefore experience a relative change in gravity of r/L. This is usually small and can be ignored for larger centrifuges. With experiments carried out on small centrifuges in which r/L will be greater, this effect should be accounted for if an accurate comparison with a numerical model is required.

3.2. Chute experiments

Centrifuge experiments are necessary to study behaviour at realistic stresses but once a debris flow is in motion the absolute stress level may be much less important and scaled experiments under standard gravity are applicable. These have many advantages as they are much cheaper and easier to perform, can be larger and permit a wider range of instrumentation. There are still many choices to be made when designing an experiment, which flow properties to match. Several relatively recent experimental studies, e.g. [36,37,20,14], have used innovative methods to interrogate the behaviour of continuous flows at various stages of development. Davies (1990) [36] used a moving bed to hold a debris flow steady enough to exhibit a series of surges, similar to those observed by Simpson [23] for continuous flows of custard powder suspensions flowing down a slope. Kaitna et al. (2007) [14] and the Armanini–Larcher experiments [37,20] used high-concentration granular-liquid mixtures in a vertically mounted rotating drum (with a very low fill fraction) and a re-circulating flume and to investigate the steady rheology of the front and body respectively. Rather than focusing on rheology, some chute experiments have visualised the mobilisation of bed material through boundary impacts, e.g. [38,39], underlining the variety of bed entrainment modes seen in large-scale flows [40].

To show the potential of relatively simple experiments in developing our understanding of the underlying flow mechanisms, we describe a series performed recently in Nottingham. The experiments focused on Froude and particle Reynolds number similarity, matching the sedimentation of larger solids to flow speed, ignoring the stress dependent processes [19]. In these flows the role of fine sediments is ignored and relatively large glass beads (8, 4, 2 mm diameter) were mixed with water. This mixture was released from behind a lock gate to flow down a chute inclined at 27° (Fig. 3). Some experiments were also carried out with glycerol replacing the water, to mimic the viscosity enhancement of fine sediments while re-

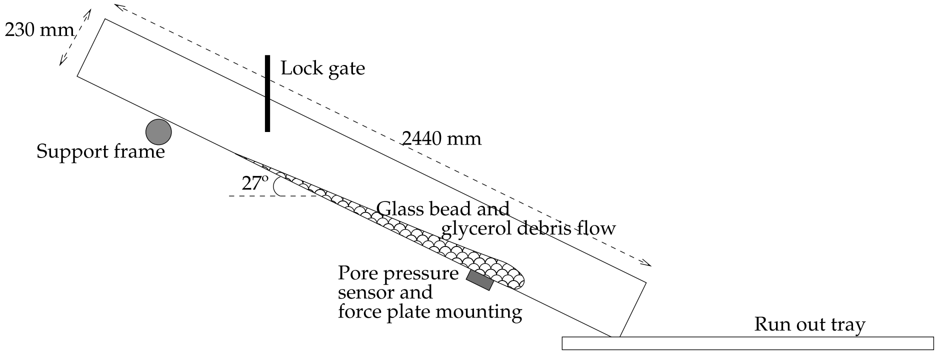

Fig. 3. Schematic illustration of a debris flow chute experiment.

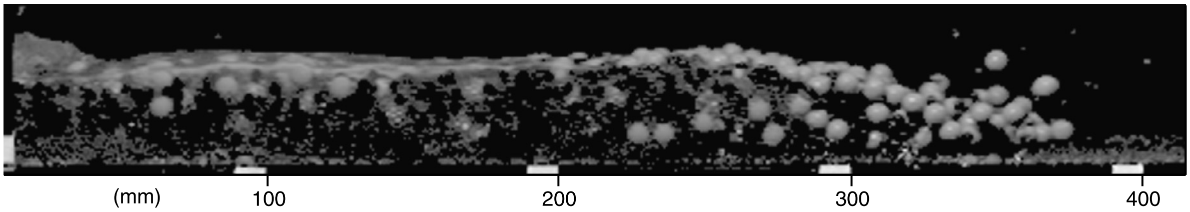

Fig. 4. Side view of 1 litre glass bead-water mixture, with solid volume fraction 0.4, released from behind a lock gate to flow down a 27° chute, $Re_p \approx 10^4$. The beads have diameters 8 mm (coloured white), 4 mm (coloured black) and 2 mm (colourless), and the chute has 8-mm-diameter beads fixed to the surface to generate roughness [19].

taining the imaging possibilities. High speed video, captured at 700 Hz through the Perspex chute sidewalls, provides image sequences (a snapshot example is shown in Fig. 4) from which velocities throughout the flow can be inferred by Particle Image Velocimetry (PIV) [41]. Normal and shear stress were measured by a force plate mounted in the chute surface. The plates were covered by an impermeable membrane to prevent fluid from seeping into the housing or to avoid particles jamming the plate motion. A differential pore pressure sensor was mounted alongside the force plates, with a thin wire mesh preventing particles from entering the saturated tapping to the chute surface. This differential transducer thus recorded the pressure in the pore fluid relative to the background atmospheric pressure.

On release from behind the lock gate, a deforming surge flowed down the chute with flow depths in the range 30–45 mm and speeds 700–950 mm s^{-1}. This indicates Froude numbers in the range 1.3–1.4, corresponding to a 1 m deep debris flow travelling at 4–5 m s^{-1}. Crucially, the flows rapidly formed distinct regions with markedly different dynamic characteristics. Although the core of the debris mixture adopted a quasi-steady, lightly shearing flow with basal slip, the fronts were largely dry and collisional with this region extending over the top surface of the surge, where individual particles break out of the fluid-filled matrix. These observations correlate well with field evidence, e.g. McArdell et al. [11], and the accepted 'snout-and-body' architecture noted earlier. Fig. 4 also qualitatively shows how the larger, 8 mm white, beads collect at the flow front with the smaller beads and fluid partitioned to the tail.

The chute experiments thus qualitatively confirm expectations from field observations, however it is much more difficult to develop repeatable methods for analysing the data quantitatively for comparison with model predictions. The main (related) reasons for this are firstly the difficulty in defining and identifying the front of the flows and secondly, dealing with unsteadiness and fluctuations of the flow.

To separate the unsteadiness of the mean flow from the rapid fluctuations the following technique was developed. By capturing the flows at a high frame rate it was possible to find averages over 14 frames—a time frame (≈0.02 s) short enough that variations in the mean flow were negligible. This method effectively ensemble averages velocity information from an intermittent but quasi-steady flow. Deviation from these local ensemble averages thus effectively discriminates between plug-like regions with low intermittency and collisional regions with high intermittency. Fig. 5 shows these regions in light and dark grey respectively, together with local ensemble averaged velocity profiles through the flow depth at two positions for mono- and polydisperse flows of particles.

One of the most striking features of Fig. 5 velocity maps, is the existence of a dilute, collisional regime, where the stresses are all supported by binary particle collisions. Note that this occurs even for monodisperse flows so it does not require segregation to occur. Sometimes this is called a *fluid starved front*. This finding is supported by pore pressure measurements from one of those monodisperse flows, which shows a significant lag behind the shear and normal stress signals that peak as the front of the flow passes the sensors (see Fig. 6). A delay in pore pressure indicates that the front of the flow is not saturated with fluid. This is somewhat surprising since the formation of a dry snout is usually attributed to particle size segregation and the role of fine sediments, e.g. [16]. The formation of snout architecture in monodisperse flows with relatively high particle Reynold's numbers, suggests that there are alternative fluid–particle processes at play.

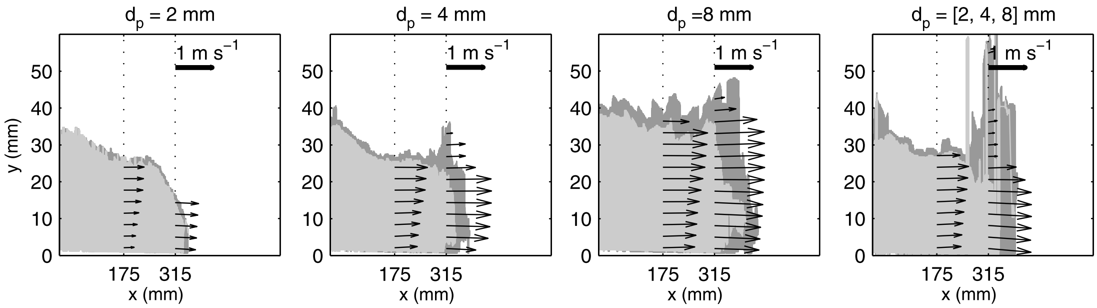

Fig. 5. Debris flows of (from left to right) $d_p = [2, 4, 8]$ mm diameter glass beads and a mixture of those sizes in water over a rough surface formed of 4-mm-diameter beads. The flow front is at the position of the pressure sensors, around 9 times the length of the release volume down the slope. Quivers show the magnitudes of the velocities at 10% and 50% of the flow length from the head averaged over 14 video frames. Pale grey indicates regions with low standard deviation from this mean, and dark grey regions are those with high standard deviations from the mean [19]. The bold reference quiver corresponds to a local velocity of $1\,\mathrm{m\,s^{-1}}$. (Note the different scales in the chute parallel and normal directions.)

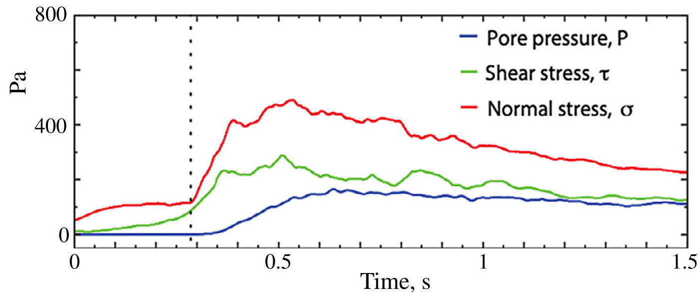

Fig. 6. (Colour online.) Pore pressure history, with normal and shear stresses, from a monodisperse flow of 4-mm glass beads in water over a rough surface of 4-mm-diameter beads. The dashed line indicates the arrival of the flow front at the sensors [19].

These experiments test just one aspect of debris flows mechanics, i.e. the role of fluid–particle interaction. The simple chute allows the snout to develop naturally from the body and this behaviour appears at least in part attributable to the fluid–particle interaction. However, if also configured continuously, after Davies, Armanini, Larcher and Kaitna [36,37,20,14], a more complete picture of the long-term snout or body behaviour could be developed.

4. Multiphase models

The mathematical models for debris flows are similar to those used for avalanches and rockfalls. Although these flows have many differences they all give rise to equations with a similar structure, that is mass conservation for the different components and momentum conservation that is a balance between inertia, gravity and drag. If the surface over which the flow occurs is sufficiently smooth then gravity also acts to smooth out the flow and eventually the shape of the flowing body exhibits a shallow flow geometry, meaning that properties vary much more slowly parallel to the slope than perpendicularly. All debris flow models make this assumption and since boulders may span the depth of a flow it is doubtful whether it makes sense to have a continuum model that is depth resolved. In theory there is no difficulty in going from one-dimensional models to two-dimensional models in arbitrary topography, and we shall only discuss the former here, though in practise there are many complexities. For a solution that can cope with curvatures similar to the flow depth, the equations must be integrated normal to the slope and expressed in general curvilinear coordinates which is rather complicated. There are no widely used codes that currently do this though there are several in development.

Current models can be divided into two categories, those geared towards practical work that have seen widespread use in the engineering community and those more focused on understanding the underlying physics. In the first category is DAN [42] and its developments DAN3D [43]. The model has been in use for nearly twenty years and applied to more than 100 case histories. Generally good agreement is found, with flow deposits but only after calibrating the parameters. It is a meshless Lagrangian method either based on blocks in one dimension or Smooth Particle Hydrodynamics in two dimensions. This approach copes well with complicated topography and a wide variety of rheological models can be applied. However, such models do not cope well with shocks, are only first order accurate and it is not possible to introduce additional evolution equations for other flow variables such as pressure.

The RAMMS software package [8] also has a long history. It was originally developed for avalanches, but has recently been applied to debris flows. It uses a two-parameter Voellmy model which must be calibrated for each event by fitting the parameters. It is a Lagrangian shock capturing method, but it is not clear from the published papers if it correctly deals with arbitrary topography.

These models are based on equations for the conservation of the depth integrated mixture mass m and the momentum mU,

$$\partial_t \begin{pmatrix} m \\ mU \end{pmatrix} + \partial_x \begin{pmatrix} mU \\ \alpha m U^2 + \beta g_y m^2/\rho \end{pmatrix} = \begin{pmatrix} 0 \\ m g_x - F \end{pmatrix} \tag{1}$$

where α is a constant that depends on the velocity profile and is usually taken equal to one. $\beta = 1/2$ for an isotropic pressure distribution and ρ is the bulk density. Here we have ignored the complication of any erosion or deposition which would be included by a source term on the right. At this level of modelling a constant solids fraction is assumed and the only substantial difference between models is the choice of frictional force F. This is a poor representation of the underlying physics except in very limited cases. The first improvement is straightforward and that is to incorporate a separate conservation equation for the solids mass fraction c which can be written

$$\partial_t(cm) + \partial_x(\delta c m U) = 0 \tag{2}$$

where again we have ignored any possible erosion or deposition. The bulk density is no longer constant but given by $\rho = c\rho_{\mathrm{s}} + (1-c)\rho_{\mathrm{f}}$, where ρ_{s} and ρ_{f} are the constant intrinsic material densities of the solid and fluid phases respectively. The coefficient $\delta > 1$ is a shape factor that comes from integrating the product of the velocity profile and the solids profile and when $\delta > 1$ the solid material moves towards the front of the flow can give rise to a fluid starved front.

These simple models cannot correctly model the pore pressure which critically influences the dynamics. This dependence is clearly seen in the experiments of Iverson and observations from Illgraben. When the particles are not suspended the excess pore pressure is zero and they contribute a large Coulomb-friction-like component to F. When the particles are suspended the excess pore pressure is high and F is much lower and viscous-like. The work of Iverson and co-workers has developed over many years to address this problem by formulating an equation for the pore pressure p [44,45]. This can be written

$$\partial_t p + U\partial_x p + (m g_y \gamma)\partial_x U = \mathrm{rhs} \tag{3}$$

where the rhs source terms derive from the compaction or dilation of the granular material. The frictional force contains a direct correction due to the pore pressure and solid and fluid stresses

$$F = \frac{m}{\rho}(1-\beta)\partial_x p - UDc(\rho_{\mathrm{s}} - \rho_{\mathrm{f}}) + \partial_x(\tau_s + \tau_{\mathrm{f}}) \tag{4}$$

where D is the granular dilation rate and is given by the difference between basal pore-fluid pressure and hydrostatic pressure. The fluid stress τ_{f} is straightforward and proportional to the shear and pore fluid viscosity. The key innovation, and what makes the model a powerful representation of the underlying physics, is in the closure for the solid basal stress τ_s. They use a Coulomb–Terzaghi equation for granular friction and allow a dependence on strain rate but this multiplies the difference between the pore pressure and the hydrostatic pressure, $m g_y - p$. Therefore when $p = m g_y$ there is no solid friction and the flow will be highly mobile and capable for travelling large distance over shallow terrain.

A different approach to this problem was developed by Kowalski and McElwaine [6]. They study the detailed vertical equation of motion for the solid particles and show how this can be well approximated by an evolution equation for the centre of mass of the solid particles h_{p}. Their fourth transport equation, rather than one for pore pressure (3), is then

$$\partial_t h_{\mathrm{p}} + \partial_x(h_{\mathrm{p}} U) + \partial_x\left[cmUH\gamma\left(\frac{1}{12} - h_{\mathrm{p}}'^2\right)\right]/cm = \left(h_{\mathrm{p}}^{(s)} - h_{\mathrm{p}}\right)/T_{\mathrm{p}} \tag{5}$$

where $h_p^{(s)}$ is an equilibrium height, and T_{p} is a relaxation time, which depends on the flow variables. $h_{\mathrm{p}}' = h_{\mathrm{p}}\rho/m - 1/2$ is a non-dimensional measure of whether the particles are higher or lower in the flow than average. The pore pressure at the base is then a function of the flow variables including h_{p} and exactly the same basal stress closure as the Iverson model can be used. Indeed because there is a linear relation between p and h_{p} the model equations are largely equivalent though developed in different ways. This is not surprising as they represent the same underlying physics reflecting the extent to which the particles are influenced by the fluid or by their own motion and interactions. Perhaps the most significant difference is that since the particles maybe higher or lower in the flow then when there is a velocity shear there will be differential motion. The equation for particle motion can be written as Eq. (2) with

$$\delta = 1 + \gamma h_{\mathrm{p}}'(1 - c\rho_{\mathrm{f}}/\rho_{\mathrm{p}}) \tag{6}$$

where γ is a measure of the shear. If the particles are higher in the flow $h_{\mathrm{p}}' > 0$ then they advect faster than the mean motion U and this can allow the formation of a dry granular front as is often seen in natural flows and experiments.

There has also been considerable progress in extending kinetic theories of granular matter to include fluid interactions. This approach [9,46] attempts to derive equations without any free parameters and can include sidewalls and erosion and deposition and has been compared in detail with experiments. However, so far the depth-averaged theories that have been derived using this approach are the same form as those previously discussed but do not allow include a non-equilibrium pore pressure or debris centre of mass and so cannot be expected to accurately deal with out of equilibrium conditions. Nevertheless this remains a promising approach that is developing rapidly.

5. Conclusions

This review has described recent approaches to modelling debris flows, both physically and numerically. Two contrasting experimental methods are described aimed at capturing different aspects of debris flow dynamics. Experiments in a high *g* centrifuge generate insight into the stress-dependent processes involved in initial slope failure, flow progression and erosion, highlighting the importance of fluid–particle scaling in flow dynamics. Chute experiments under standard gravity contrast with previous laboratory studies by maintaining particle Reynolds number similarity. These experiments have shown that polydispersity is not necessarily a requirement for the formation of characteristic debris flow snouts. Well-controlled and observed experiments in which the physics is well understood can be used to develop and calibrate new models. As this paper discusses, recent progress in multiphase modelling shows that the differential motion between fluid and particle fields can lead to particles being advected faster than the mean flow. This provides a mechanism by which, even in monodisperse fluid–particle mixtures, particles can collect at the front to form a dry snout. The on-going development and calibration of improved numerical models that include such complex processes is something we should look forward to in future work.

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References

[1] C. Huggel, S. Zgraggen-Oswald, W. Haeberli, A. Kääb, A. Polkvoj, I. Galushkin, S. Evans, et al., The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery, Nat. Hazards Earth Syst. Sci. 5 (2) (2005) 173–187.
[2] S.G. Evans, N.F. Bishop, L. Fidel Smoll, P. Valderrama Murillo, K.B. Delaney, A. Oliver-Smith, A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970, Eng. Geol. 108 (1) (2009) 96–118.
[3] J.W. Vallance, Volcanic debris flows, in: Debris-flow Hazards and Related Phenomena, Springer, 2005, pp. 247–274.
[4] T. Takahashi, Debris flow, Annu. Rev. Fluid Mech. 13 (1) (1981) 57–77.
[5] R.M. Iverson, The debris-flow rheology myth, in: Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, vol. 1, 2003, pp. 303–314.
[6] J. Kowalski, J.N. McElwaine, Shallow two-component gravity-driven flows with vertical variation, J. Fluid Mech. 714 (2013) 434–462.
[7] S.P. Pudasaini, Some exact solutions for debris and avalanche flows, Phys. Fluids 23 (2011) 043301.
[8] M. Christen, J. Kowalski, P. Bartelt, RAMMS: numerical simulation of dense snow avalanches in three-dimensional terrain, Cold Reg. Sci. Technol. 63 (1) (2010) 1–14.
[9] D. Berzi, J. Jenkins, A theoretical analysis of free-surface flows of saturated granular–liquid mixtures, J. Fluid Mech. 608 (2008) 393–410.
[10] R.M. Iverson, R.P. Denlinger, Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory, J. Geophys. Res., Solid Earth 106 (B1) (2001) 537–552.
[11] B.W. McArdell, P. Bartelt, J. Kowalski, Field observations of basal forces and fluid pore pressure in a debris flow, Geophys. Res. Lett. 34 (7) (2007) L07406.
[12] D. Berzi, J.T. Jenkins, M. Larcher, Debris flows: recent advances in experiments and modeling, Adv. Geophys. 52 (2010) 103–138.
[13] C. Ancey, N. Balmforth, I. Frigaard (Eds.), Visco-plastic fluids: from theory to application, J. Non-Newton. Fluid Mech. 158 (2009) 1–3.
[14] R. Kaitna, D. Rickenmann, M. Schatzmann, Experimental study on rheologic behaviour of debris flow material, Acta Geotech. 2 (2) (2007) 71–85.
[15] C. Johnson, B. Kokelaar, R. Iverson, M. Logan, R. LaHusen, J. Gray, Grain-size segregation and levee formation in geophysical mass flows, J. Geophys. Res., Earth Surf. 117 (F1) (2003–2012).
[16] R.M. Iverson, The physics of debris flows, Rev. Geophys. 35 (3) (1997) 245–296.
[17] P. Kailey, Debris flows in New Zealand Alpine catchments, PhD thesis, University of Canterbury, Canterbury, UK, 2013.
[18] R. Fannin, M. Wise, An empirical-statistical model for debris flow travel distance, Can. Geotech. J. 38 (5) (2001) 982–994.
[19] P. Paleo Cageao, Fluid particle interaction in geophysical flows: debris flows, PhD thesis, University of Nottingham, Nottingham, UK, 2014.
[20] M. Larcher, L. Fraccarollo, A. Armanini, H. Capart, Set of measurement data from flume experiments on steady uniform debris flows, J. Hydraul. Res. 45 (Suppl. 1) (2007) 59–71.
[21] R.M. Iverson, Debris flows: behaviour and hazard assessment, Geol. Today 30 (1) (2014) 15–20.
[22] E. Bryant, Natural Hazards, Cambridge University Press, Cambridge, UK, 2005.
[23] J.E. Simpson, Gravity Currents: In the Environment and the Laboratory, Cambridge University Press, Cambridge, UK, 1999.
[24] C.S. Campbell, Self-lubrication for long runout landslides, J. Geol. 97 (1989) 653–665.
[25] M. Bolton, The strength and dilatancy of sands, Géotechnique 36 (1) (1986) 65–78.
[26] J. Garnier, C. Gaudin, S. Springman, P. Culligan, D. Goodings, D. Konig, B. Kutter, R. Phillips, M. Randolph, L. Thorel, Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling, Int. J. Phys. Model. Geotech. 7 (3) (2007) 1–23.
[27] H. Chen, G. Crosta, C. Lee, Erosional effects on runout of fast landslides, debris flows, Géotechnique 56 (5) (2006) 305–322.
[28] J. Hutchinson, R. Bhandari, Undrained loading, a fundamental mechanism of mudflows and other mass movements, Géotechnique 21 (4) (1971) 353–358.
[29] E. Bowman, W. Take, K. Rait, C. Hann, Physical models of rock avalanche spreading behaviour with dynamic fragmentation, Can. Geotech. J. 49 (4) (2012) 460–476.
[30] E.T. Bowman, J. Laue, B. Imre, S.M. Springman, Experimental modelling of debris flow behaviour using a geotechnical centrifuge, Can. Geotech. J. 47 (7) (2010) 742–762.
[31] R. Taylor, Centrifuges in modelling: principles and scale effects, in: R.N. Taylor (Ed.), Geotechnical Centrifuge Technology, W.W. Norton, Boston, 1995, pp. 19–33.
[32] P. Kailey, E. Bowman, J. Laue, S. Springman, Modelling debris flow processes with a geotechnical centrifuge, Ital. J. Eng. Geol. Environ. 13 (2011) 339–349.
[33] C. Gue, K. Soga, M. Bolton, N. Thusyanthan, Centrifuge modelling of submarine landslide flows, in: S. Springman, J. Laude, L. Seward (Eds.), Proceedings 7th International Conference on Physical Modelling in Geotechnics, Zurich, Taylor and Francis, London, 2010, pp. 1113–1118.
[34] F. Milne, M. Brown, J. Knappett, M. Davies, Centrifuge modelling of hillslope debris flow initiation, Catena 92 (2012) 162–171.

[35] R. Steedman, X. Zeng, Dynamics, in: R. Taylor (Ed.), Geotechnical Centrifuge Technology, Blackie Academic & Professional, London, 1995, pp. 168–195.
[36] T.R. Davies, Debris-flow surges—experimental simulation, J. Hydrol. (NZ) 29 (1) (1990) 18–46.
[37] A. Armanini, H. Capart, L. Fraccarollo, M. Larcher, Rheological stratification in experimental free-surface flows of granular–liquid mixtures, J. Fluid Mech. 532 (2005) 269–319.
[38] B. Yohannes, L. Hsu, W. Dietrich, K. Hill, Boundary stresses due to impacts from dry granular flows, J. Geophys. Res., Earth Surf. 117 (F2) (2003–2012).
[39] L. Hsu, W.E. Dietrich, L.S. Sklar, Experimental study of bedrock erosion by granular flows, J. Geophys. Res. Earth Surf. 113 (F2) (2003–2012).
[40] J.D. Stock, D.R. Montgomery, B.D. Collins, W.E. Dietrich, L. Sklar, Field measurements of incision rates following bedrock exposure: implications for process controls on the long profiles of valleys cut by rivers and debris flows, Geol. Soc. Am. Bull. 117 (1–2) (2005) 174–194.
[41] S. Dalziel, DigiFlow, Dalziel Research Partners, 2002.
[42] O. Hungr, A model for the runout analysis of rapid flow slides, debris flows, and avalanches, Can. Geotech. J., http://dx.doi.org/10.1139/t95-063.
[43] O. Hungr, Numerical modelling of the dynamics of debris flows and rock avalanches, Geomech. Tunn. 1 (2008) 112–119.
[44] R.M. Iverson, D.L. George, A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. Physical basis, Proc. R. Soc., Math. Phys. Eng. Sci. 470 (2170) (2014) 20130819.
[45] D.L. George, R.M. Iverson, A depth-averaged debris-flow model that includes the effects of evolving dilatancy. II. Numerical predictions and experimental tests, Proc. R. Soc., Math. Phys. Eng. Sci. 470 (2170) (2014) 20130820.
[46] D. Berzi, J. Jenkins, Steady inclined flows of granular-fluid mixtures, J. Fluid Mech. 641 (2009) 359–387.