The role of particle size in the flow behaviour of saturated granular materials

Le rôle de la distribution granulométrique du matériau dans le comportement d'écoulement des matériaux granulaires saturés

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ABSTRACT

This paper describes recent experimental research on flowing granular materials using a flume apparatus. The results show that the particle size distribution of the material has a dramatic effect on its mobility (speed and extent of flow) at a given moisture content. A wide range of particle size leads to particle size segregation during motion that is key to retaining mobility during the changing boundary conditions as a flow progresses down slope. The experimental results are discussed in light of the influence of permeability and liquefaction behaviour and of friction, viscosity and energy dissipation between solids and fluids. The results also imply that there are bounds both on the types of materials to be selected and upon the apparatuses used when considering the laboratory testing or physical modelling of such geophysical phenomena.

RÉSUMÉ

Cet article concerne une nouvelle recherche expérimentale sur l'écoulement gravitaire des matériaux granulaires en utilisant un canal incliné. Les résultats montrent que la distribution granulométrique du matériau a un effet très important sur sa mobilité (vélocité et propagation) pour un certain contenu en eau. Une large gamme de granulométries entraine pendant l'écoulement un processus de ségrégation qui est la clé pour garder la mobilité pendant les variations des conditions aux limites à mesure que l'écoulement avance. Les résultats expérimentaux sont discutés en considérant l'influence de la perméabilité, du comportement en liquéfaction et du frottement, viscosité et dissipation d'énergie entre les solides et les fluides. Les résultats obtenus indiquent aussi qu'il-y-ont des limites dans le choix des matériaux sélectionné et dans les équipements utilisés lorsque en envisage des essais de laboratoire ou une modélisation physique de ces phénomènes géophysiques.

Keywords : debris flow, physical modelling, flume study, segregation, rheology, mobility

1 INTRODUCTION

"Flow" in saturated granular materials may describe behaviour that ranges from gently moving sediments in coastal or alluvial situations, through post-liquefaction lateral spreading of sloping ground as triggered by earthquakes and finally, to fast moving mixtures of soil and rock, in the case of mud and debris flows. This paper addresses flow in the context of the high-speed movement of saturated granular materials moving down slope under the influence of gravity. Such flows as occur in nature are termed "debris flows" (Hungr et al. 2001).

Debris flows pose a major hazard in regions of mountainous terrain and high run-off. However, the mechanics of their movement remains poorly understood as a result of their temporarily and spatially evolving nature. Hence they are the subject of intense research from field, experimental and analytical perspectives.

Field evidence shows that virtually all debris flows contain a wide particle size distribution (PSD), with sizes ranging from boulders or gravel to silt and clay. The typical mean particle size D_{50} ranges between 2mm and 200mm and typical reported uniformity coefficient values $C_U = D_{60}/D_{10}$ are of the order of 100-1000 (e.g. Hurlimann et al. 2003; Pierson 1980; Takahashi 1991). A number of experimental studies have been instigated to examine the motion and arrest of flowing saturated granular materials, with a view to understanding debris flows (e.g. Itoh et al. 2000; Larcher et al. 2007). However, few previous experimental studies have explicitly considered the influence of the particle size distribution (PSD) on their behaviour (Takahashi 1991). Instead, experimental flows are typically characterized by a mean particle size (D_{50}) which is necessarily smaller than those found in the field, using a relatively uniform PSD ($C_U < 5$). Unsurprisingly, important aspects of their behaviour, such as the effects of flow segregation are unable to be replicated in such tests.

This study shows that the well-graded nature of debris flow materials is not incidental, but is key to their tendency to travel fast and far before final deposition. In addition, while there are practical limitations on the size of particles that can be used in laboratory flows, it is possible to capture the essential mechanisms behind their high mobility.

2 BACKGROUND

In the field, engineers are concerned chiefly with two aspects of granular flow, namely, how far such a flow will travel and what forces will be generated on obstacles in its path (Hungr et al. 1984). Well-graded debris flows constitute the most hazardous of these flows (Skermer & VanDine 2005), and hence are the focus of this research.

Debris flows exist where mountainous terrain and high runoff co-exist. They are often rainfall triggered, but may also occur as post-landslide, glacial outwash and dambreak events. Debris flows tend to segregate very early on in their development (Takahashi 1991), so that the largest particles in the flow move towards the front, leaving a tail comprised of finer particles. The fluid phase also segregates, so that the flow front may be unsaturated, while the tail is super-saturated or fluidized.

Debris flows tend to travel down a series of confined channels or reaches, eroding and entraining or depositing

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material as they proceed. Whether they erode or deposit is a function of the channel geometry, flow constituents and bed constituents. The runout zone may be considered as the final deposition area. For well-established debris flow channels, a relatively shallow deposition fan at the base of steeper terrain may mark this point, hence it is often also where human habitation commences and where the interest of engineers begins.

Research has shown that the velocity of the flow head of a debris flow at the point at which it exits a confined reach is relatively well correlated to the final runout distance of the flow on level ground or a gently sloping fan for a particular geoclimatic situation (Hungr et al. 1984; Takahashi 1980). So that:

$$X_0 = f\left(v_i^2\right) \quad (1)$$

were X_0 is the runout length in the deposition zone and v_i is the exit velocity of the previous reach.

Equation [1] shows that, as well as the gravity force that acts on all landslides that begin their motion from a standstill position, momentum is a major driver of debris flows within the zone of interest to most engineers. However, as noted by Rickenmann (2005), several variations on the form of this equation exist, while coefficients of correlation depend in the field on the specific region or catchment. In addition, quite different empirical correlations have been determined for experimental arrangements (Bagnold 1954; Takahashi 1980). While it appears that this equation captures essential elements of debris flow behaviour, the two types of data (field and laboratory) are thus unable to be directly related.

It should be noted that a debris flow may be arrested at any point (either within a confined channel or unconfined zone) by friction at flow margins. A debris flow will therefore travel furthest over a particular reach either if the entry velocity is high or if the friction is low.

The experiments described here consider the final reach of a debris flow channel before an unconfined deposition zone.

3 EXPERIMENTAL PROCEDURE

Fig.1 shows the experimental apparatus. The flume measures 3.7m in length by 1m in height and has a metal hopper supporting the debris flow material before its release. The section of the channel containing the straight portion of slope is 1000mm long by 180mm wide and can be varied from test to test. The channel floor is artificially roughened by glued sand and the outward facing wall is made from Perspex through which a high-speed digital camera can view the downslope flow behaviour. A grid of calibration markers of 30mm centres is dotted on the Perspex face to assist in imaging measurements. The base of the marine ply runout area, which is sealed but otherwise not roughened, is marked with a 50mm grid so that the final runout can be easily compared between tests.

In all the tests described, the flume angle was kept constant at 23°. Using alluvial material collected from the Waimakariri River bed in the South Island of New Zealand, artificial particle size distributions were created where C_U and D_{50} were systematically varied (Table 1). The total solid mass was 8kg for each test. Immediately before a test, the prepared granular material was saturated with 2.24kg of water to obtain an average flow moisture content of 28%. The saturated flow material was placed in the hopper, 1.08m above the runout area, and continually agitated to ensure that the least possible segregation and consolidation took place before release of the material. The pneumatically-operated hopper trapdoor was linked by a microswitch to the high speed camera to ensure a coordinated time-delay between the release of the material and recording of the flow. Recording was at 800 fs^{-1}, with 2400 still frames of 1280 × 512 pixels. Measurements of runout were collected and recorded: length, area, and deposit thickness. Analysing high speed camera footage allowed the determination of the dynamic characteristics within the flume including the flow velocity and the flow height just before (i.e approx. 15 cm from) the exit point to the runout area.

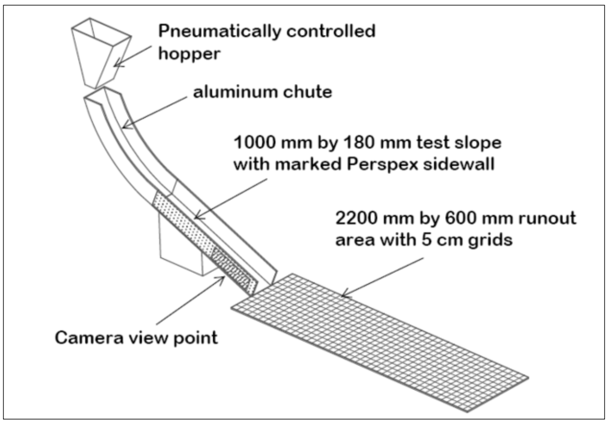

Figure 1 Experimental apparatus.

Table 1. Experimental Conditions. D_{10} and D_{50}, effective and mean grain size; D_{90}, particle size for which 90% of the particles are finer; Cz, coefficient of curvature; Cu, coefficient of uniformity.

Particle Size Distribution	C_U	C_Z	D_{90} (mm)	D_{50} (mm)	D_{10} (mm)	Number of tests
PSD9	21	1.1	11.88	1.76	0.14	4
PSD10	10	1.1	14.50	3.78	0.54	3
PSD11	10	1.1	7.13	1.76	0.26	3
PSD12	10	1.1	3.77	0.95	0.14	3
PSD13	6.4	0.7	7.13	1.76	0.40	3
PSD14	10	1.1	2.13	0.52	0.08	3
PSD15	4.8	1.0	1.63	0.52	0.14	2
PSD16	3.3	0.9	4.35	1.76	0.66	2

4 RESULTS

Figure 2 shows a comparative group of tests to examine the influence of a change in mean particle size D_{50} for C_U=10. Figure 3 shows comparative tests for a change in C_U at a particular D_{50} of 0.52mm or 1.76mm.

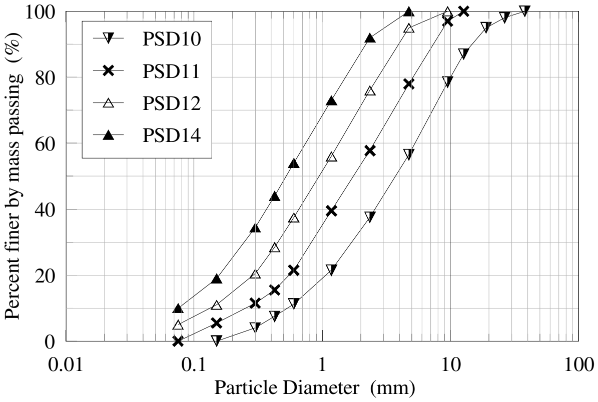

Figure 2 Particle size distributions for tests with same C_U=10.

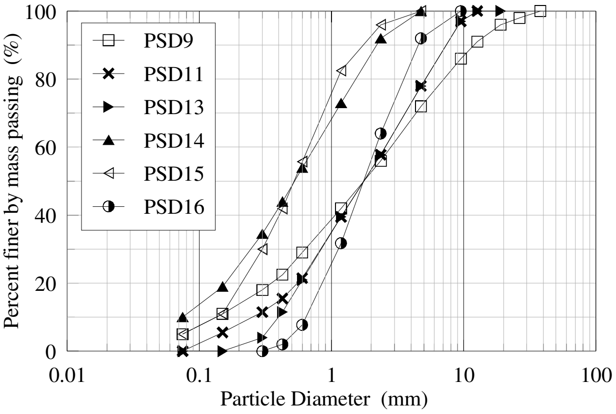

Figure 3 Particle size distributions for the tests with same D_{50}. For PSD14 and 15, D_{50}=0.52 mm, for PSD9, 11, 13 and 16, D_{50}=1.76 mm.

4.1 *Deposit morphology*

Figure 4 shows the shape of the runout fan on the horizontal deposition area at the base of the slope for tests at the same D_{50} with different C_U. The runout length is greatest for PSD9, with the highest C_U – i.e. the most well-graded material. In addition, while PSD9 displayed the greatest overall segregation during flow and deposition, with coarser particles being shunted to the deposit margins, the deposit appears most uniform in terms of plan area distribution. The deposits become progressively more pear-shaped with a greater deposit area at the proximal end of the deposit as the soil becomes more uniformly graded.

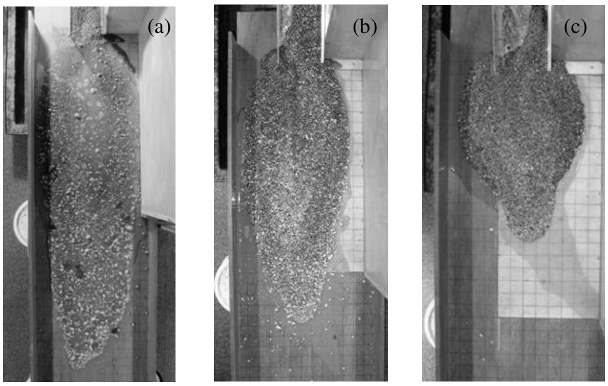

Figure 4 Test depositions for particle size distributions with same D_{50} but different C_U: a) PSD9; b) PSD13; c) PSD16

This behaviour is reflected in other tests. That is, in general a lower runout is observed for tests of lower C_U for a given mean particle size D_{50}, as shown in Figure 5. D_{50} is found to have an influence also on runout, with larger mean particle size resulting in shorter runout lengths, as discussed in more detail later.

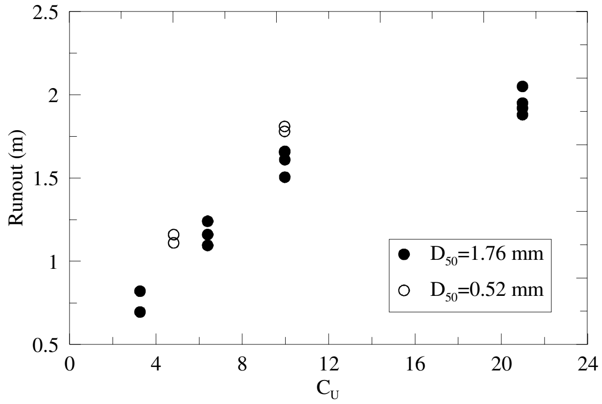

Figure 5 Runout against C_u for tests with same D_{50}.

Figure 6 shows the effect of varying D_{50} of the flow at a fixed value of C_U. The runout length reduces as D_{50} increases, however, there appears to be a maximum limit of runout that can be obtained with decreasing particle size, so that PSD12 and 14, with D_{50} of 0.95mm and 0.52mm, respectively, give similar final results.

This may be due to the “grain settling” limit, as suggested by Iverson (1997), whereby using Stokes Law, it can be shown that in the typical time taken for debris flow to occur, free-falling grains in water that are finer than sand (<50μm) will remain effectively suspended due to fluid viscosity effects. Such particles are not considered by Iverson as being part of the solid phase, but rather, serve to increase the fluid viscosity. Accordingly, he considers particles smaller than the silt-sand boundary as belonging to the fluid phase in his 2-part stress partitioning model. The results here show that the onset of viscous effects are occurring at a D_{50} of 500μm and a D_{10} of 80μm for test PSD14. The D_{10} value is far closer to Iverson’s theoretical one, hence it would appear that, while D_{50} is often used to characterize debris flows (Iverson 1997; Takahashi 1991), D_{10} may play a far more important role in terms of mechanical behaviour. This would be in agreement also with the consideration of permeability (Hazen 1892) as a prime factor in controlling debris flow motion.

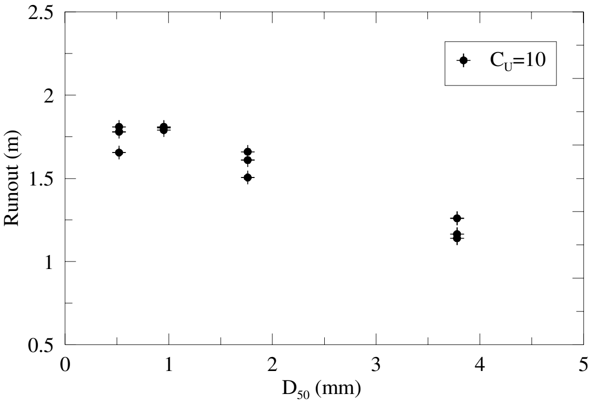

Figure 6 Runout against D_{50} for tests with same C_U.

4.2 *Velocity relationships*

Figure 7 shows a plot of the square of the front velocity against runout extent for tests of the same C_U=10 but different mean particle size (i.e. Figure 2). A linear relationship, in agreement with the form of Equation [1], is found. The influence of D_{50} is clear, so that as the particle size increases for a given uniformity, the velocity decreases as does the runout.

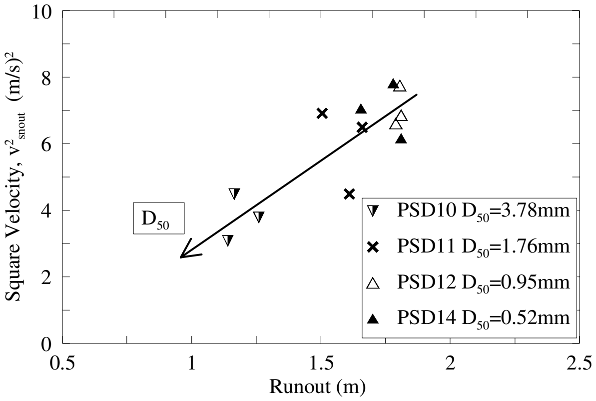

Figure 7 Square value of front velocity against runout for tests with same C_u=10.

This effect is related to mixture permeability, such that, as the grain size increases, so does the permeability and hence the drainage time of fluid from the mixture decreases. The overall result is an increase in Coulomb friction between the particles and at the flow margins, resulting in a lower velocity being attained during downward motion on the slope and lesser momentum-driven runout.

Figure 8 shows a plot of the square of the front velocity against runout for tests where C_U is varied at the same D_{50}. It is found that as C_U increases, so does the velocity and the runout. However, the relationship is non-linear between the square of the velocity and runout. That is, as C_U increases, the square of the velocity increases at a reducing rate in comparison with the runout.

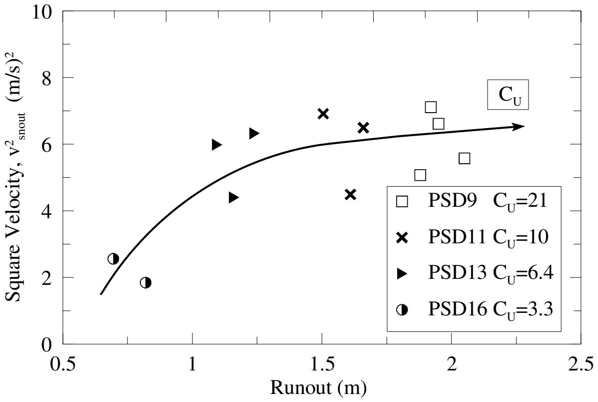

Figure 8 Square value of front velocity against runout for tests with same D_{50}=1.76 mm.

The reason for this may be that, in a closed solid-fluid system, the segregation of particles and fluid within a flow comprised of well-graded materials may assist in generating low frictional resistance within the flow body (i.e. where fine particles and fluid dominate, permeability is reduced and pore pressures may be greater than hydrostatic (Iverson 1997) to the extent that liquefaction occurs and effective stress reduces to zero), while not contributing as much to increased friction at the flow margins (where coarse particles dominate with increased permeability and reduced fluid pressures) during runout over a flat surface. It is well-understood that, during deposition, the interior of flows tends to shunt forward and sideways the coarser frontal fraction (Major and Iverson 1999), which forms levees confining the still-liquefied core, post-arrest. Conversely, in a uniformly-graded flow, no segregation can occur, so the whole body of solids and fluid maintains a uniform steady frictional resistance throughout. During runout, momentum is lost more rapidly, since the fluid is more evenly distributed over the whole, resulting in a shorter stoppage distance as fluid pressures drop and interparticle contact forces are regained.

Such behaviour may explain why field scale debris flows possess such long runout distances for relatively low attained velocities, in comparison to laboratory experiments; so that scaling between them does not appear feasible. That is, as they become larger and more well-graded (i.e. with larger particles becoming available at the upper end of the distribution), greater segregation leads to greater runout distances at a given exit velocity. This point has been used in arguments against the use of small scale flume studies – i.e. that with small laboratory-scale experiments, despite the high velocities that may be attained by the flow, the high overall mobility of field-scale events is not attained (Iverson 1997).

5 CONCLUSIONS

Field evidence suggests that fast granular flows that possess a range of particle sizes larger than silt tend to be more mobile (i.e. travel faster and further) than either flows dominated by clay-sized particles or those consisting of uniform materials.

Experimental research shows that the particle size distribution has a dramatic effect on the mobility of flowing granular materials at a given moisture content. Segregation of particle sizes results in a relatively fine-grained flow rear or interior that is maintained in a liquefied state in a process similar to seismic liquefaction, with a coarser-grained flow front and exterior that acts to contain and define the flow margins. On steep, confined slopes, the larger, inertial particles move to the head of the flow, while on shallow, unconfined slopes they are shunted by the liquefied core. Such interplay results in flows with somewhat greater speed and far greater average runout for well-graded soils in comparison to uniformly graded soils.

The mean particle size also has an influence on mobility, with flows comprising of larger particles than fine sand producing less mobile flows due to increasing permeability and particle friction. However, for flows comprised of particles smaller than medium-fine sand, viscous effects lead to a reduction of flow mobility with decreasing particle size.

The results reported here show that careful laboratory testing can inform the mechanisms behind debris flow behaviour observed in the field. However, there are upper and lower bounds on the grading of materials selected and limits on the size of flume apparatuses that should be used when considering the modelling of such geophysical phenomena.

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