Experimental Study on the Mobility of Channelized Granular Mass Flow

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Abstract: Granular mass flows (e.g., debris flows/avalanches) in landslide-prone areas are of great concern because they often cause catastrophic disasters as a result of their long run-out distances and large impact forces. To investigate the factors influencing granular mass flow mobility, experimental tests were conducted in a flume model. Granular materials consisting of homogeneous sand and non-homogeneous sandy soil were used for studying particle size effects. Run-out tests with variable flow masses, water contents, and sloping channel confinement parameters were conducted as well. The results indicated that granular mass flow mobility was significantly influenced by the initial water content; a critical water content corresponding to the smallest flow mobility exists for different granular materials. An increase in the total flow mass generally induced a reduction in the travel angle (an increase in flow mobility). Consistent with field observations, the travel angles for different granular materials decreased roughly in proportion to the logarithm of mass. The flume model tests illustrate that the measured travel angles increase as the proportion of fine particles increases. Interestingly, natural terrain possesses critical confinement characteristics for different granular mass flows.

Key words: granular mass flow, mobility, water content, flow mass, fine particle, channel confinement

1 Introduction

Granular mass flow (e.g., debris flows/avalanches) are geological phenomena with significant economic impacts in mountainous regions of China and the world. They occur when masses of poorly sorted sediment, agitated and mixed with water (saturated debris for “debris flows” and partially or fully saturated debris for “debris avalanches”), surge down slopes in response to gravitational attraction (cf. Iverson, 1997; Hungr et al., 2014). Granular mass flows are different from sediment-laden water floods (e.g., Pan et al., 2014) in that both solid and fluid forces influence the motion and govern their rheological properties (cf. Iverson, 1997). Stresses caused by solid particle collisions, contact friction and solid-fluid interactions generally govern the kinematic properties of granular mass flows. Fine particles (e.g., silts and clays) in debris flows even can be considered as pore fluid components when the timescale required for viscous settling (without particle interactions) exceeds the flow duration (Iverson, 1997; Iverson and Denlinger, 2001). The apparent viscosity of the pore fluid in a debris flow is much larger than that of water. Meanwhile, coarse particles (e.g., gravel) interact during transportation and significantly influence the kinematic properties of debris flows/avalanches.

The phenomenon of gravity-driven flows, composed of an assembly of cohesionless granular particles, has begun to attract increasing research interest for the purpose of improving understanding of a wide variety of geomorphological and industrial processes (Armanini et al., 2005). Within the scope of civil engineering, a specific field where granular flow mechanisms are now widely applied, is the dynamics of debris flows (Armanini et al., 2008). Debris flows/avalanches usually develop along natural slopes and pose a major threat to local populations and infrastructure due to their long run-out distances and
large impact forces (cf. Feng et al., 2013; Ni et al., 2014). Field instances of natural debris flows commonly involve heterogeneous solid particles in a non-Newtonian fluid (Armanini et al., 2005; Tian et al., 2015). Granular materials vary significantly, depending on the geometry of the constituent particles and the nature of their interactions. The interaction between pore fluid and solid particles is complex: not only does the existence of fine particles affect the viscosity of the fluid phase, but the volumetric deformation of the granular phase also has a significant effect on liquid pore pressure (Iverson, 1997).

For simplicity, research attention has been focused on assemblies of spherical cohesionless particles, slightly polydispersed, and without interstitial fluid (Da Cruz et al., 2005). Despite this, research on dry granular flows remains challenging. The complex interactions between solid particles govern the rheological properties of granular flows; an understanding of these properties is fundamental to explaining their behavior.

Predicting the run-out lengths ($L$) of large, dry granular mass flows (i.e., granular flows) has long been the focus of research, primarily due to their significant destructive potential. One parameter that has been studied in detail is the increase in mobility ($M$) of a rock avalanche, defined as the ratio of the run-out distance to the fall height, given a certain volume, $V$. The physical nature of this lubrication mechanism remains unclear. Sturton and Lajunesse (2009) analyzed field data and conducted discrete numerical simulations of granular flows, demonstrating the geometrical basis of the apparent enhancement of mobility with increasing volume. Their study discussed the interaction between volume and topography and their effects on the run-out distance; this can be classified into two flow regimes: one dominated by sliding, in which the run-out distance is independent of $V$, and another dominated by spreading, in which the run-out distance is strongly dependent on $V$.

Pyroclastic flows, debris flows and debris avalanches commonly develop along natural sloping channels (Fig. 1), which mostly exert non-uniform channel confinement on dense, shearing granular mixtures with solid concentrations of around 60% (v/v). Despite variation in their origins, particle types and interstitial fluids, they are all prone to segregation based on particle size, as a result of which their deposits tend to be morphologically similar. Their mobility, or effective friction, however, can differ widely and is influenced by diverse factors (Kokelaar et al., 2014). Gaseous and aqueous pore-fluid pressures are important in conferring mobility via fluidization and liquefaction to pyroclastic flows and debris flows, respectively. In addition, the relatively fine-grained components (fines) of natural dense flows can reduce their

Fig. 1. Natural terrain landslides where debris flows/avalanches have occurred and developed along a non-uniform sloping channel.
(a), Rhone Valley of the Southern France on October 14th, 2000 (from www.quanterra.org); (b), Lantau Island of Hong Kong in November 1993 (courtesy of Wong et al. 1996).
tendency to deposit and thus increase mobility, for example, by acting as an interstitial medium for coarser particles. This hinders packing of these large particles and reduces inter-particle friction; ball-bearing-like effects can also occur (Iverson, 1997; MIDI, 2004; Phillips et al., 2006; Druitt et al., 2007; Linares-Guerrero et al., 2007; Iverson et al., 2010).

To investigate the factors influencing granular mass flow (e.g., debris flow/avalanche) mobility, we conducted experimental tests in a flume model, which was constructed by equipping an inclined chute with side walls and a horizontal deposition plane. This flume was designed for the parametric study of debris flow/avalanche mobility. Debris materials comprising uniform sands (Leighton Buzzard (LB) sand fractions C & E) and non-uniform sandy soils (completely decomposed granite, CDG) were used for studying particle size effects. Run-out tests with variable flow masses and water contents were conducted to investigate their effects on flowing mobility. In addition, the influences of variable channel widths and critical confinement angles are discussed in this paper.

2 Flume Model Tests

2.1 Experimental setup

Fig. 2 depicts the setup of flume model tests for studying the mobility of granular mass flows. The model, constructed from plywood, comprised a transportation zone and a deposition zone; the former was an inclined slope channel 1.4 m long and 0.4 m wide. The slope angle was fixed at 45°. The deposition zone was a flat channel 1.2 m long and 0.4 m wide. Both zones were coated with self-adhesive plastic sheets to ensure a uniform, low coefficient of friction. Silicone sealant was injected into the joints of side walls and between zones to ensure that all surfaces were water-proof and smooth. A Perspex window (transparent PVC plate) was cut into one side of the model, for the purpose of installing a video camera to record flow behavior. For convenient observation and analysis of the experimental results, the transparent PVC plate and the deposition zone were marked with grids as a reference before they were covered with self-adhesive plastic. Furthermore, the side walls of the sloping channel were adjustable, in order to vary the confinement conditions (see Fig. 3). This aspect was included to simulate natural terrain (Fig. 1), where the channel width along the flow direction tends to be variable (i.e., $\alpha \neq 0$).

The source mass was held at 1.2 m above the ground in a sand hopper, with dimensions of 360 mm × 230 mm × 310 mm (W × L × H). Prepared granular mixtures were placed in the sand hopper just before each test, in order to minimize the risk of consolidation and segregation. A pneumatically operated trapdoor to the hopper controlled the release of the granular materials into the slope channel. When highly compressed air was released into the actuator, the valve rotated and opened to allow the debris mass to descend along the inclined plane of the trapdoor smoothly and then to enter the channel. After reaching a certain run-out distance, the debris mass was deposited on the horizontal plate.

2.2 Test preparation

To study debris flow/avalanche mobility, four flume model tests were conducted. First, the influence of water content on the granular materials (with different mean particle sizes and particle size distributions) was studied. Samples of LB sands (fractions C & E) and CDG were released into the channel; their particle size distributions are shown in Fig. 4. The water contents of the samples ranged from 0% through 15%, 20% and 25%, to 30% (i.e. from dry to fully saturated), while the total soil mass was kept constant at 5 kg. Secondly, the effect of soil mass on
flow mobility was investigated. Dry LB sands (fractions C & E) and CDG were released individually while the total soil mass was varied from 2 kg through 4 kg, 8 kg, 16 kg and finally, 24 kg. Thirdly, the effects of fine particles in dry granular mass flows were studied. Mixtures of coarse LB sand (fraction C) with fine sand (fraction E) were released into the slope channel. The percentage of fraction E in the mixture was varied from 0% through 30%, 50%, 70% and finally, 100%, while the total mass of the mixture was kept constant at 10 kg. Lastly, we assayed the effects of variation in the confinement angle, $\alpha_c$ (from 0° to 8.5°), using different granular materials with identical masses (i.e., 10 kg). The run-out distance for each type of material was then recorded. A summary of the flume model tests is provided in Table 1.

### 3 Results and Discussion

#### 3.1 Definition of the travel angle and its physical meaning

According to Lo (2000), the run-out distance of a landslide is usually estimated through assessment of the damage. To study the mobility of different landslides systematically, the energy line concept was applied to define a travel angle (Cruden and Varnes, 1996). The travel angle is considered to be the most suitable parameter for assessing granular mass flow mobility, as it can characterize the rate of energy loss during movement as well as the effect of the slope gradient. Fig. 5 indicates that the travel angle is measured from the crest of the scarp to the distal end of the debris flow/avalanche. Accordingly, Eq. 1 can be derived:

$$\tan \phi_o = \frac{H}{L}$$

where $\phi_o$ is the travel angle; $H$ is the vertical elevation of the debris flow/avalanche source above the deposit; $L$ is the horizontal distance from the source to the deposit. Determining the travel angle is an easy method to describe and compare granular mass flow geometry. However, the physical meaning of the travel angle and energy line concept, and their limitations, tend to be ignored.

The simplest model of mass movement is that of a rigid block driven by gravity sliding down an inclined plane (see Fig. 6). As Straub (1996) illustrated, there is only one inclined slope angle, $\alpha_i$ at which the frictional sliding force, $F_r$, is in equilibrium with the driving force, $F_D$, which results in steady motion with a constant velocity. The tangent of the inclined slope angle is equal to the coefficient of dynamic contact friction, $\mu$:

$$F_r = -F_D = \mu F_N = \mu mg \cos \alpha_i$$

where $m$= mass and $g$= acceleration due to gravity. In most instances, the slope angle, $\alpha_i$, is greater than $\alpha_c$; consequently, the block accelerates on an inclined slope and then decelerates on a horizontal plane, finally coming to rest with a certain run-out distance, $L_D$ (Fig. 6a). The initial potential energy of the block is given by the following equation:

$$E_{pot} = mgh$$

On the way downhill, potential energy is partly converted into kinetic energy, while the remainder is converted into heat, expressed as work, $W_e$, due to contact friction:

<table>
<thead>
<tr>
<th>Series</th>
<th>Materials</th>
<th>Water Content (%)</th>
<th>Mass (kg)</th>
<th>Confinement angle $\alpha_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LB sands (fractions C &amp; E) and CDG</td>
<td>0-30</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>LB sands (fractions C &amp; E) and CDG</td>
<td>0</td>
<td>2-24</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>LB sands (fractions C &amp; E) and CDG</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>30</td>
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<tr>
<td></td>
<td>0</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>LB sands (fractions C &amp; E) and CDG</td>
<td>0</td>
<td>10</td>
<td>0°-8.5°</td>
</tr>
</tbody>
</table>

Fig. 5. Definition of travel angle (Lo, 2000).
where $F_{FA}$ = frictional force downhill and $L_s$ = sliding distance along the slope. During the deceleration phase on the horizontal plane, the remaining kinetic energy is converted into heat:

$$W_D = -F_{FD}L_D$$  \hspace{1cm} (5)

where $F_{FD}$ = force of contact friction on the horizontal plane. Considering Eqs. (3), (4) and (5) together, a summarized energy equation can be obtained:

$$E_{pot} + W_A + W_D = 0$$  \hspace{1cm} (6)

The total work due to friction, $W$, can be expressed as:

$$W = -E_{pot} = W_A + W_D = -F_{FA} \cdot L_s - F_{FD} \cdot L_D = -\mu mg \cdot L_s \cos \alpha - \mu mg \cdot L_D$$  \hspace{1cm} (7)

For $L_s \cos \alpha = L_A$ (Fig. 6a); Eq. (7) can then be substituted and simplified by

$$W = -\mu mg(L_A + L_D) = -\mu mgL$$  \hspace{1cm} (8)

Inserting Eq. (8) into the energy equation Eq. (6) yields

$$E_{pot} + W = mgH - \mu mgL = 0$$  \hspace{1cm} (9)

Equation (9) provides a simple expression for the coefficient of friction:

$$\mu = H / L$$  \hspace{1cm} (10)

The horizontal travel distance, $L$, is only dependent on the drop height, $H$, and the coefficient of friction, $\mu$. In addition, $L$ is independent of the mass and path of the sliding block. Heim (1932) constructed a straight line linking the uppermost point of the breakaway rim with the farthest flow front of the landslide (Fig. 6b); this represents the (apparent) energy line of the moving mass. The tangent of the inclination angle, $\phi_{an}$, is the travel angle (cf. Fig. 5).

It must be noted that the definition of the travel angle in Eq. (1) is the same form as that of Eq. (10) and that the physical meaning of the travel angle is the angle of apparent friction for the entire flow path. This does not take into account the geomorphology of slopes (e.g., roughness, bumpiness and erosion). Additionally, the reciprocal value of $\mu$ represents the net efficiency, which describes the conversion of gravitational potential energy to work done during debris flow/avalanche movement. The more efficiently this conversion occurs, the less vigorously energy degrades to irreversible forms such as heat, and the farther the flow travels before stopping (Iverson, 1997).

Although the concept of the energy line as suggested by Heim (1932) has been frequently applied in research studies, it is often prone to errors due to physical limitations (Straub, 1996). Granular mass flows are a system of many granular materials; therefore, the equation should be based on the center of mass of the system (Fig. 6b). The inherent error in the equation results in a lower, incorrect apparent coefficient of contact friction being calculated (Hayashi and Self, 1992; Straub, 1994). Furthermore, Lau and Woods (1997) suggested that the travel angle method may not be appropriate for the practical analysis of landslides in nature. The accuracy of estimating the run-out distance using this method decreases rapidly when the slope angle at the final point of debris deposition approaches the angle of reach of the landslide.

Given the aforementioned considerations, application of the corrected energy concept generates low coefficients (Straub, 1996), and the center of mass is difficult (or nearly impossible) to determine. Therefore, this concept is not practical for hazard assessment of landslides in nature. The concept of travel angle is generally reasonably accurate in predicting landslide travel distance and thus is still effective in practice as a measurement of flow mobility, for the purpose of hazard assessment and mitigation. Because several factors interact to influence granular mass flow mobility, several tests were conducted in our study, such that each test focused on the effects of only one parameter.

3.2 Effects of water content
As illustrated in Fig. 7, we compared the measured travel angles of CDG and LB sand (fractions C & E) with varying water contents. The measured travel angle of LB sand (fraction C) increased from 32° to around 41° when the water content increased from 0% to 20%. However, the travel angle decreased when the water content increased beyond 20%. A similar trend was observed for CDG, although the water content corresponding to the largest travel angle (smallest run-out distance) was 25%. When much finer particles (fraction E sand) were
involved, increasing the water content beyond 30% did not increase the run-out distance, because most of the sand perched on the slope. This mechanism is unclear and requires further elucidation.

For most landslides in nature, flowing granular materials on a sloping bed (i.e., surge heads and coarse margins) are unsaturated and exhibit little to zero pore water (see Fig. 8). Considering that the sliding of a granular body and pertinent granular flows is essentially a combination of shearing processes of multiple solid particles, it would be expected that the mobility of unsaturated debris avalanches is governed by the unsaturated shear strength (resistance acting on the slope bed, cf. Fig. 8b). For simplicity, the shear strength of unsaturated soils may be expressed as a function of the water content and matric suction (Vanapalli et al., 1996; Ng and Menzies, 2007) as follows:

$$\tau = c' + (\sigma_s - u_w)\tan\phi' + (u_r - u_w)(\Theta^s)\tan\phi'$$

(11)

Where \((u_r-u_w)\) is the matric suction, \(\Theta\) is the normalized volumetric water content, \(\kappa\) is a fitting parameter, \(\phi'\) is the effective friction angle, and \(c'\) is the effective cohesion.

The peak travel angles in Fig. 7 reveal the existence of a maximum resistance to flowing materials for some soils; this phenomenon may be explained as follows. Although the matric suction decreased with a small increase in water content from completely dry conditions (high suction) in sand and CDG samples, the soil-water contact area increased as the normalized volumetric water content, \(\Theta\), continued to increase. The coupled effects, \((u_r-u_w)\Theta^s\), increase the shear strength, \(\tau\), and reduce debris avalanche mobility (the travel angle is increased). With a further increase in the water content to saturation, matric suction is eliminated (i.e., \(u_r-u_w=0\)) and \(\tau\) attains a minimum value. Therefore, between these two extreme conditions (dry and saturated soils), there exists an optimum water content at which the matric suction \((u_r-u_w)_{opt}\) is highest; this corresponds to a peak in the value of the shear strength, \(\tau_{max}\) (Fig. 9). In addition, high pore pressures in saturated debris flows help sustain debris mobility (Iverson, 1997). Thus, decreased travel angles are observed with high water contents; inflections (critical water contents) are observed on the corresponding curves.

Fig. 7 also reveals that granular materials with different mean particle sizes have different critical water contents. A reasonable explanation for this is that during slope failure and sliding, pore water pressure is affected by the permeability of the soil (Wang and Sassa, 2003). The lower the permeability, the lower the dissipation rate of the pore pressure. In unsaturated debris avalanches, the relatively low permeability results in the matric suction being sustained, which in turn generates a higher resistance to flow. Experimental results indicated that the smaller the mean particle diameter, \(d_{50}\) (LB sand fraction E in this study), the higher the water content. Soils with non-uniform particle size distributions (in this study, CDG) exhibited higher critical water contents than did uniform soils.

In addition, when a solid-water mixture flows down a slope channel, segregation of solid particles along the travel direction usually occurs. The flow front generally displays unsaturated behavior, even when the water content inside the granular body is high. Fig. 10 depicts a deposited CDG that was initially saturated before being released. The flow front and margins were unsaturated; the longitudinal segregation of solid particles was very apparent. Coarse particles tended to concentrate at the flow front, leaving fine particles and fluid fractions in the tail. This phenomenon is consistent with observations in large flume model tests (cf. Fig. 8a); concentrated coarse particles typically form a dam that impedes and eventually halts the motion of more liquefied debris flows containing finer particles with higher pore pressures.

### 3.3 Effects of flow mass

In the case of man-made slopes where the slope gradient is usually flat, the correlations (between travel angles and flow volumes) obtained from a landslide database are generally sufficient to enable reasonably accurate prediction of debris travel distances. However, natural terrain typically involves relatively steep slope profiles, and data available on these slopes tends to be incomplete. This relatively poor resolution of the correlations usually fails to predict travel distances accurately because of the small difference between the slope angle and the travel angle (Wong et al., 1997). Empirically recorded \(L/H\) values can be compared in only the broadest sense because these data are typically collected from debris flows/avalanches with diverse origins and flow path geometries, by investigators with diverse objectives. Although any observed trends are noteworthy, it is questionable to make predictions on run-
out distances on the basis of only $L/H$ data (Iverson, 1997). To systematically study the effects of total flow mass on debris mobility, we kept the slope length and inclination angle constant in the flume model test. Based on run-out distances, travel angles were calculated.

As shown in Fig. 11, we compared the measured travel angles of both dry CDG and LB sand (fractions C & E), involving different flow masses. Similar linear relationship curves are obtained for all materials, using a semi-logarithmic coordinate system. Noted the void ratio of the granular mass is usually kept constant, these experimental results support and clarify previous research findings that an increase in the debris volume (or the flow mass) generally results in a reduction in the travel angle (Lo, 2000). In addition, they are consistent with field observations (Fig. 12) that suggest that the travel angle decreases roughly in proportion to the logarithm of volume for landslides. Although Eq. (10) indicates that the mass of a debris avalanche should not affect the travel angle or run-out efficiency, both test data and field
observations suggest that the mobility increases with the scale of the debris avalanche. Therefore, it can be postulated that debris-avalanche mobility is a function of flow mass.

Iverson (1997) emphasized that debris flows and avalanches can undergo changes in their mass and composition while in motion, and can spread longitudinally, which would change their mass distribution (Davies, 1982). Some debris flows can witness increases in their mass of well over 100%, owing to bed and bank erosion (Pierson et al., 1990), while others may witness a substantial decline in the concentrations of solid components as a result of mixing with stream or river water (Pierson and Scott, 1985). Changes in debris flow/avalanche mass independent of changes in composition may significantly influence run-out efficiency. Attempts to use elementary energy balances to predict the effects of changes in mass on debris flow/avalanche efficiency has encountered challenges (Iverson, 1997). Entrainment of additional granular materials would increase the flow mass and thereby enhance the pertinent potential energy ($mgH$). Assuming that the work done by resisting forces is constant or increases at a relatively low rate, the debris flow/avalanche mobility will increase significantly. This assumption would be correct if the apparent friction angle, $\mu$ ($H/L$), was dependent only on internal forces, but $\mu$ depends also on external forces that change the flow mass. The occurrence of changes in debris flow/avalanche mass requires that work be done by the flow on the bed and its banks to entrain additional granular materials. This work eliminates the work that would be done over the same path length in the absence of entrainment. The critical question is whether the additional work done is smaller or greater than the energy savings accrued by the entrained mass. It is unlikely that this question has a universal answer. Any change in mass is dependent on work done during exchange of momentum with the bed and its banks; the nature of this exchange may vary significantly among locations. Despite these confounding factors, it is important to recognize the fundamental effects of external forces on the debris flow/avalanche efficiency, $\mu$. Otherwise, differences in run-out distances may wrongly be assumed to be caused solely by differences in flow.
composition and rheological properties (Iverson, 1997).

3.4 Effects of fine particle content

Fig. 13 indicates the measured travel angles of flowing materials consisting of different mixtures of dry LB sand (fractions C & E) (see Table 1). The mass of the soil mixture used in each test was 10 kg. The original travel angle of dry LB sand (fraction C) was around 26°. An increase in the percentage of fraction E (fine sand) resulted in an increase in travel angles. This suggests that fine particles in granular bodies may reduce flow mobility.

In granular bodies, a solid particle flowing down along a slope moves due to the acceleration due to gravity, G. This force is proportional to $D^2$ ($D$ being the particle diameter). Frequent contacts between solid particles (shearing or collisions) with neighboring particles dissipate kinetic energy (Fig. 14). Based on the theory of Bagnold (1954) for inertial granular flows, the following conclusions can be drawn:

(i) The change in particle momentum perpendicular to the mean flow direction is $2m\delta U \cos \alpha f(\lambda) \frac{\delta U}{s} \frac{1}{(bD)^2}$.

(ii) The collision frequency, $K$ (number of encounters per unit time) between any two spheres, A and B, can be described by $K = f(\lambda)\delta U/s$ (l is the linear particle concentration defined as the ratio of particle diameter to the mean free dispersion distance and is related to volumetric concentration, $C$, by $\lambda = \frac{D}{s} = \frac{1}{(C_0/C) - 1}$ where $C_0$ is the maximum possible static volumetric concentration).

(iii) Number of particles, $N$, that are contained per unit area in a layer, is proportional to $1/(bD)^2$.

Thus, the dispersive stress perpendicular to the mean direction of motion is:

$$P = 2m\delta U \cos \alpha f(\lambda) \frac{\delta U}{s} \frac{1}{(bD)^2}$$ (12)

Similarly, the resistance force (shear stress), $f_r$, acting on the particle surface is

$$f_r = 2m\delta U \sin \alpha f(\lambda) \frac{\delta U}{s} \frac{1}{(bD)^2}$$ (13)

The shear rate $\dot{\gamma}$ between neighboring layers is

$$\dot{\gamma} = \frac{dU}{dy} = \frac{\delta U}{kbD}$$ (14)

Therefore, Equation (13) can be expressed as:

$$f_r = \rho \dot{\gamma} f(\lambda) \frac{dU}{dy} \sin \alpha$$ (15)

Equation (15) indicates that the resistance is proportional to the surface area (i.e., $f_r \propto D^2$). The ratio of the resistance to the driving force, $f_r/G$, is dependent on $1/D$ and governs flow mobility. Comparing the respective $f_r/G$ ratios for LB sand fractions C and E, the ratio for the former was observed to be relatively low. This implies that the coarse fraction exhibited greater mobility (Fig. 13). In other words, when the total flow mass is kept constant, an increase in the percentage of fine particles reduces the mean particle diameter $D$ of the granular flow. This

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**Fig. 13.** Effects of the proportion of fine particles on travel angles.

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**Fig. 14.** (a), Cross-section of equidistant particle arrangement (three-dimensional); (b), Two-dimensional sketch of possible statistically preferred particle arrangements (non-equidistant) which might allow dispersive pressure proportional to shear stress, in a viscous fluid (Bagnold, 1954)
promotes interactions between the particles. Thus, the resultant increase in energy loss reduces the mobility of dry granular mass flows.

3.5 Effect of channel confinement

Fig. 15 illustrates the effect of channel confinement on granular mass flow mobility. For different granular materials, a slight narrowing of the sloping channel along the flow direction essentially reduced the travel angles and thus increased global flow mobility. Further increases in the channel confinement angles resulted in increasingly larger amounts of granular materials jamming the channel mouth. This resulted in a significant decrease in the run-out distances (i.e., flow mobility) of the granular mass flows, and a significant increase in the corresponding measured travel angles. Fig. 15 indicates that for different granular materials, there exists a critical confinement angle which corresponds to the smallest travel angle and the highest flow mobility. Importantly, the coarse granular materials assessed in this study (LB sand fraction C and CDG) possessed larger critical confinement angles than did the finer materials (LB sand fraction E). The mechanisms accounting for the observed channel confinement effects on granular mass flow mobility necessitate further elucidation.

4 Conclusions

Through flume model tests, we modeled granular mass flows to study their dynamic properties and the factors that influence them. The key conclusions drawn from this study are:

1. The mobility of granular mass flows is significantly influenced by the initial water content. A critical value for the initial water content, corresponding to the lowest value of flow mobility, exists for each type of granular material.
2. An increase in the total flow mass for dry granular flows generally induces a reduction in the travel angle (an increase in the flow mobility). Consistent with field observations, the travel angles for different granular materials decrease roughly in proportion to the logarithm of mass.

3. Fine particles can generally be considered as a part of the fluid phase for saturated debris flows. They can influence flow viscosity and thus have an appreciable effect on flow mobility. Furthermore, the flume model tests indicated that the fine particle content can significantly influence the mobility of dry granular mass flows. The measured travel angles increase as the proportions of fine particles increase.

4. There exists a critical confinement angle of the slope channel, which corresponds to the largest value of granular mass flow mobility. Typically, coarse granular materials possess larger critical confinement angles.

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