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Determination of the suspension competence of debris flows based on particle size analysis

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Abstract

The determination of the critical particle size between solid and fluid phases, i.e., the suspension competence, is fundamental for debris flow. A method for determining suspension competence based on particle size analysis is presented in this paper. Suspension competence of static experimental water-debris mixtures prepared with the sediment of Jiangjia Gully is ~0.025 mm if the bulk density is less than 1,800 kg m^{-3} and it increases with bulk density of more concentrated mixtures. Suspension competence of natural debris flows in Jiangjia Gully increases exponentially with the bulk density. These two data sets are compared in order to understand the suspension mechanism. It is concluded that turbulence may play a leading role in particle suspension in non-viscous and sub-viscous debris flows, while in viscous debris flows both matrix strength and excess pore water pressure play important roles.

Key Words: Debris flow, Suspension competence, Particle size analysis, Critical particle size, Particle suspension mechanism

1 Introduction

Debris flows occur when masses of poorly sorted sediment are agitated and saturated with water and surge downslope in response to gravitational effect (Iverson, 1997). In addition to being important geomorphological agents, they pose a serious hazard and have led to disasters in many mountain regions, e.g., the debris flows in Venezuela in 1999 (Pérez, 2001) and the Zhouqu debris flow disaster in China in 2010 (Hu et al., 2012). Debris flow risk analysis, leading to improved disaster preparedness, prevention and mitigation, is improved through the use of debris flow models.

Debris flow is usually considered as fluid either of single phase or two phases, depending on the homogeneity of the fluid. Single-phase models rely mainly on the rheology, e.g., the viscoplastic model (Johnson, 1970), the dilatant fluid model (Bagnold, 1954), the quadratic shear stress model (Shen, 1998), and the Voellmy-fluid friction model (Voellmy, 1955). These are limited when predicting the complex behavior of debris flows (Preisig and Zimmermann, 2010). Two-phase models, incorporating both fluid and granular effects, have advantages in this respect. Depending on the relative importance of viscous stress and inertial stress, Takahashi (1998, 2000, 2002) classified debris flows into inertial and viscous types and developed two-phase models for both types. Iverson (1997) studied the important role of interstitial fluid and presented a model based on Coulomb friction, which was improved by further work (Iverson and Denlinger, 2001; Savage and Iverson, 2003). Wang and Hutter (1999) developed a continuum theory for solid-fluid mixtures using the thermodynamic approach. Other models have been put forward employing conservation equations for mass and momentum for each phase (e.g., Pitman and Le, 2005; Preisig and Zimmermann, 2010).

In two-phase models, the fluid phase refers to water with any suspended sediment and the solid phase refers only to the unsuspended coarse particle fraction (Takahashi, 2007). Thus, determination of the critical particle size between these two phases becomes a fundamental issue, which is the so-called 'suspension competence' (Pierson, 1981). Two methods are used to determine the competence, D_0. In the first method, D_0 is estimated based on particle suspension mechanisms. For a turbulent debris flow, particles with the settling velocity w_0 smaller than the friction velocity u_* are suspended, so the

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size of the particle having w_0=u_* is equal to D_0 (Takahashi, 2007). For a viscous debris flow, the fluid phase exhibits yield strength and can support some particles. D_0 is calculated with the following formula (Shen and Xie, 1983):

$$D_0 = \frac{k\tau_y}{g\left(\rho_s - \rho_f\right)} \tag{1}$$

in which k is a coefficient relevant to the particle shape, g is acceleration due to gravity, τ_y is the yield strength of the fluid, ρ_s is the particle density and ρ_f is the bulk density of the fluid. However, this formula suffers a difficulty that both τ_y and ρ_f would increase with the entrance of particles coarser than D_0 into the fluid phase, and therefore results in a larger D_0 value until the maximum particle size is reached. Fei et al. (2004) presented an alternative formula based on the minimum stream power principle, which yielded D_0 values in 5–6 mm range for debris flows in Jiangjia Gully (Shu et al., 2008). Iverson (1997) proposed that particles with the settling time exceeding the duration time of a debris flow event belong to the fluid phase and obtained 0.05 mm for D_0. This value is consistent with Pierson's experiment (1981) in which the silt-clay-water slurry remains in a suspended state for a long time after cessation of mixing.

D_0 is also estimated through particle size analysis. The debris flow material in Jiangjia Gully has a bimodal distribution and the fraction of particles ~0.1 mm is scarce, hence 0.1 mm was used as D_0 by Takahashi (2007). Following Visher's (1969) study on the relationship between sediment grading curves and modes of sediment transport, Zhang and He (1981), working in the Hunshui Gully in Southwest China, concluded that D_0 is 0.063 mm and 2 mm, respectively, for debris flows with strong and weak turbulence. Wang et al. (2001) analyzed debris flow samples collected from the Xiaojiang River basin in China and from Mount St. Helens in the USA and found that sediment concentrations of particles <0.05 mm are relatively stable. Furthermore, they noted that sediment concentrations of particles <2 mm in debris flows in Jiangjia Gully are stable and they therefore used 2 mm as D_0 for Jiangjia Gully debris flows.

The first method is difficult due to the irregular shape of particles and the interaction between particles during settling. The second method is more convenient but sediment particle size distributions in the source area are not considered. Therefore, in this paper, a new method is introduced to determine D_0 based on particle size analysis. Using this method, D_0 values are obtained from static experimental water-debris mixtures and from natural debris flows in Jiangjia Gully. Finally particle suspension mechanisms are assessed with the derived D_0.

2 Suspension competence determination methodology

In debris flows, fine particles are transported as suspended load and coarse particles as bed load (Wang and Qian, 1987; Fei and Xiong, 1997), the former being more uniformly distributed than the latter. As a consequence, particles in the fraction $D<D_0$ of random samples from a debris flow produce comparable grading curves. D_0 is unknown but may be estimated from the grading curve of all the granular material in a sample. Volume fraction of particles $<D$ is denoted as $p(D)$ and then the volume fraction of particles between D_1 and D_2 is $p(D_2) - p(D_1)$. For any two positions M and N in the debris flow, the following formula is valid for $D_1<D_2<D_0$:

$$\frac{p_M(D_2) - p_M(D_1)}{p_M(D_0)} \approx \frac{p_N(D_2) - p_N(D_1)}{p_N(D_0)} \tag{2}$$

Equation (2) can be transformed to

$$\frac{p_M(D_2) - p_M(D_1)}{p_N(D_2) - p_N(D_1)} \approx \frac{p_M(D_0)}{p_N(D_0)} \tag{3}$$

This means that for any size range below D_0, the ratio of particle volume fraction in position M to that in position N remains constant and is approximately equal to the ratio of fine particle fractions in these two positions. Thus we can determine D_0 with ratios of particle volume fractions in different positions of a debris flow in different size ranges. The ratio remains nearly a constant in the range $D<D_0$, while it changes in the range $D>D_0$. Supposing that the fine particle fraction is higher in position M, then the ratio will change with particle size as shown in Fig. 1. Generally, the ratio curve contains three parts: stable in the first part, decreasing rapidly with increasing particle size in the second part and approaching zero in the third part. If D_0 is large, the curve may contain only the first or the first two parts. The turning point of the first two parts is related to D_0. The operational procedure is as follows: draw a straight line parallel to the x-axis through the first point of the curve, then draw a tangent line at the point having the maximum slope in the second part, and the corresponding particle size of the intersection of these two lines is selected as D_0, as shown in Fig. 1.

3 Suspension competence of static experimental water-debris mixtures

3.1 Experimental procedure

Jiangjia Gully, a well-known valley for its high-frequency debris flows, is located in the Xiaojiang River basin in Southwest China. The Dongchuan Debris Flow Observation and Research Station (DDFORS), Chinese Academy of Sciences, was founded in Jiangjia Gully in 1961 to conduct scientific research, observation and monitoring of debris flow. In this experiment, materials were collected from debris flow deposits in Jiangjia Gully, with particles >10 mm removed. The materials were mixed with water to produce mixtures of different densities, including: 1,600, 1,700, 1,800, 1,900, 2,000, 2,100 and 2,150 kg m^{-3}. These mixtures, each having a volume of 3.5 L, were put into 140 mm-diameter cylindrical containers one by one and were thoroughly mixed by hand. Photos were taken to record surface conditions of the mixtures at 10 min, 35 min, 2 hr, 5 hr, 8 hr, 22 hr and 46 hr intervals after mixing. Then the containers were put into an oven until all the water was evaporated and the depths of consolidated sediment, H, were measured. The top layer (0–0.05H), middle layer (0.45–0.55H), and bottom layer (0.9–1.0H) of the sediment were excavated for particle size analysis. Grains >0.25 mm were sorted by sieve analysis and the remainder was measured by MS2000 particle size analyzer.

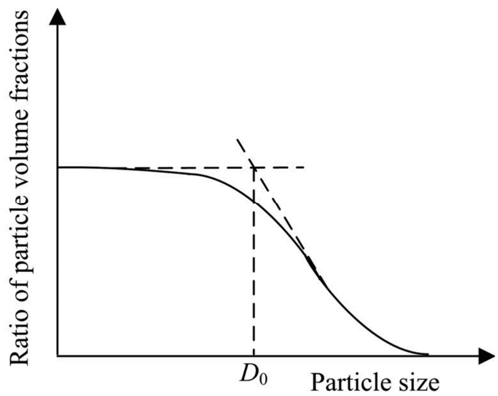

Fig. 1 Graph for the determination of suspension competence on the basis of sediment particle size analysis in two positions of a debris flow

3.2 Observations in the experiment

During the mixing and settling periods, a number of observations were made as listed in Table 1. The seven mixtures are labeled A through G. Generally, as a mixture became more concentrated, coarse particles were more easily suspended and more time was required for clarification of the topmost layers. A water-mud interface was visible for all but the most concentrated mixture and it descended gradually, suggesting compression settling. Coarse particles were visible only for mixtures F and G.

Table 1 Observations in the mixing/settling experiment

Mixture	Density (kg m^{-3})	Observations
A	1,600	Coarse particles settled during mixing.
B	1,700	Coarse particles settled during mixing. The topmost layer became clear 10 min later.
C	1,800	Coarse particles settled during mixing. The water-mud interface was visible 10 min later.
D	1,900	The same as mixture C.
E	2,000	Coarse particles were suspended during mixing and disappeared from the surface 10 min later. The topmost layer seemed like a slurry 10 min later and became clear 35 min later.
F	2,100	Coarse particles were visible at the surface in a long time after mixing, but some disappeared 5 hr later. The topmost layer became clear 5 hr later.
G	2,150	The surface was rugged after mixing. A fracture appeared at the boundary due to evaporation 15 hr later.

3.3 Experimental results

Samples were collected from the top, middle, and bottom layers which were labelled I, II, and III respectively. The particle size distributions are illustrated in Fig. 2. At the top layer (I), particle size distributions of the three mixtures having a density of $\rho_m \leq 1{,}800$ kg m^{-3} are similar, and the maximum particle size is ~0.1 mm. Both mean particle size and the maximum particle size increase with ρ_m for mixtures >1,800 kg m^{-3}. At the middle (II) and bottom layers (III), mean particle size decreases with increasing ρ_m, though the change is small as compared with the top layer. Therefore, the difference between the particle size distribution at I and those at II and III is greatest for mixture A and becomes less for more concentrated mixtures until it vanishes for mixture G.

Ratios of particle volume fractions between the top and middle layers (I/II) and bottom layers (I/III) were computed in different size ranges, as shown in Fig. 3, where 0.001 in the x-axis represents the range of 0–0.001 mm and 0.002 represents the range of 0.001–0.002 mm and so on. On all ratio curves values of I/II and I/III show very little variation over the fine components and decrease rapidly over the coarse components. This suggests that the vertical distribution of fine particles is relatively uniform, while coarse particles concentrate in the lower part of the column. Generally, values of I/II and I/III at the stable stage decrease with increasing ρ_m. They are largest for mixture A and reach 11–13 while approaching 1 for mixture G. Using the method discussed earlier, suspension competences are determined using curves I/II and I/III, which present a slight difference, as listed in Table 2. Fine particles should distribute uniformly everywhere in the mixture, so the smaller value is selected as D_0.

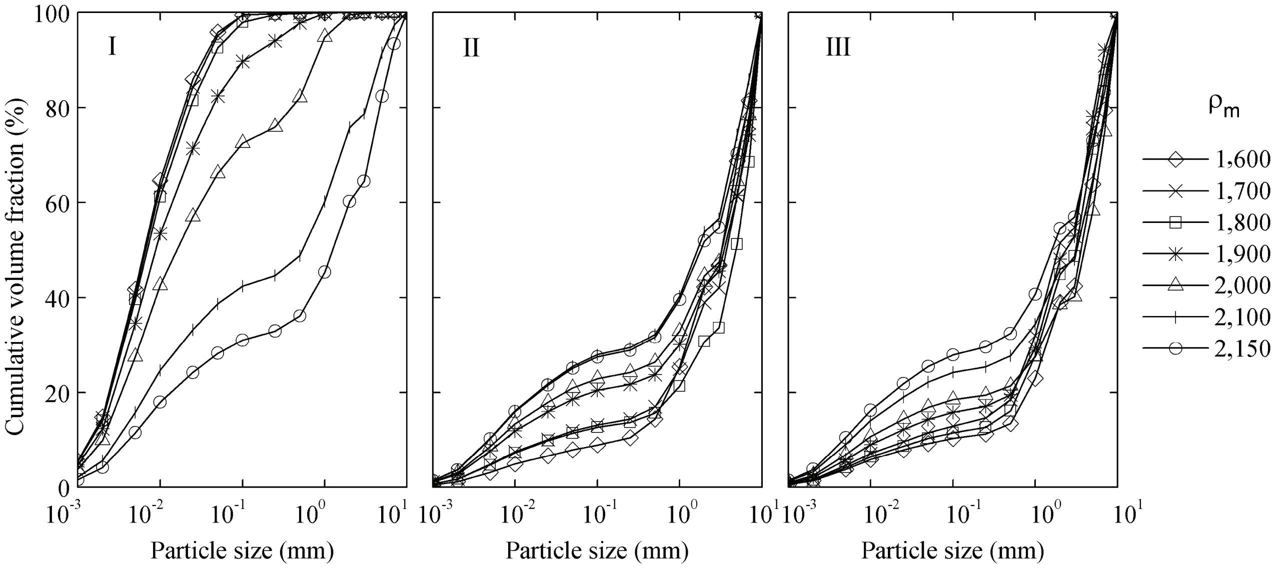

Fig. 2 Particle size distributions of samples collected from the top (I), middle (II) and bottom (III) layers of each experimental mixture following 46 hr after mixing

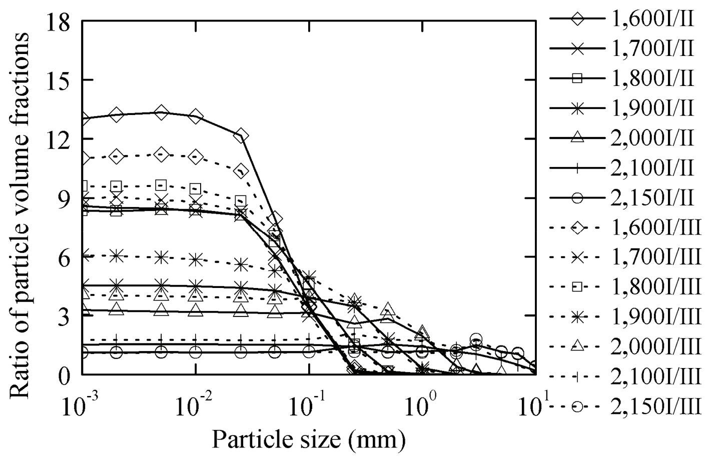

Fig. 3 Ratios of particle volume fractions between the top and middle layers (I/II) and bottom layers (I/III) for each experimental mixture

Table 2 Suspension competence of static experimental water-debris mixtures

Mixture	A	B	C	D	E	F	G
D_0(I/II) (mm)	0.023	0.027	0.032	0.160	0.552	2.128	6.658
D_0 (I/III) (mm)	0.026	0.024	0.025	0.111	0.435	2.274	6.928
D_0 (mm)	0.023	0.024	0.025	0.111	0.435	2.128	6.658

As shown in Table 2, D_0 remains nearly constant (~0.025 mm) in the range $\rho_m \leq 1{,}800$ kg m^{-3} and increases exponentially with ρ_m at higher values of ρ_m (Fig. 4). This is consistent with observations during the experiment: particle settling occurred during mixing and only very fine particles remained suspended in low-density mixtures. According to Wang et al. (2001), clay minerals in debris flows exist as flocs between 0.01 and 0.05 mm in size, and D_0 would fall within this range if the mixture has a low density. More flocs are formed as the mixture becomes more concentrated and they begin to connect forming networks that increase matrix strength. As the matrix strength increases, larger particles are supported. Coarse particles in mixture G did not settle during the experiment. However, particle size analysis showed that the fraction of particles in the 7–10 mm range in the top layer was less than that in the other two layers. This may have been induced by sampling error. Sampling depth in the top layer was ~10 mm, while it was ~20 mm in the middle and bottom layers. Thus, the fraction of particles in the 7–10 mm range may not be representative of the top layer.

4 Suspension competence of natural debris flows

In practice, it is hard to obtain samples through a vertical section of an active debris flow and a substitute method is necessary. In the debris-flow source area, fine particles flow with water and they do not deposit in the travel. Coarse particles, on the other hand, are transported at a slower velocity and some will deposit. Thus, the particle size distribution of the fine fraction reflects the situation in the source area, while the coarse fraction is relatively small. The suspension competence therefore may be estimated by comparing particle size distributions between debris flow sample and the source soil.

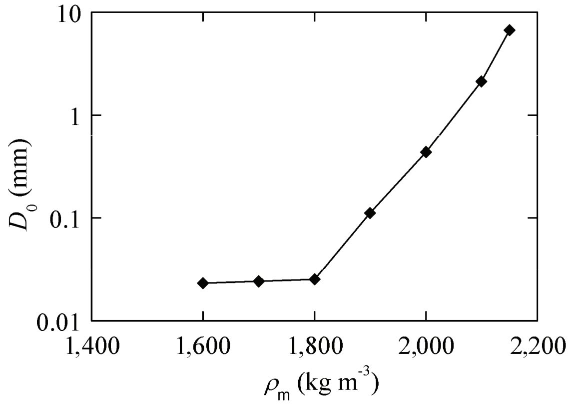

Fig. 4 The relationship between suspension competence and water-debris mixture density in the static experimental case

4.1 Data of debris flows

24 debris flows occurred in Jiangjia Gully between 2004 and 2007, with densities varying between 1,062 and 2,280 kg m^{-3}. The data used here come from 102 debris-flow surges. Of these, 34 surges occurred in 2004, 12 in 2005, 16 in 2006 and 40 in 2007.

4.2 Data of the source soil

In Jiangjia Gully, granular material in debris flows is supplied by colluviums, landslide deposits and old debris flow deposits. During 1984–1985, 48 soil samples were collected in the debris-flow source area by DDFORS. The particle size distributions vary over a wide range. Figure 5 illustrates their mean value, upper and lower limits.

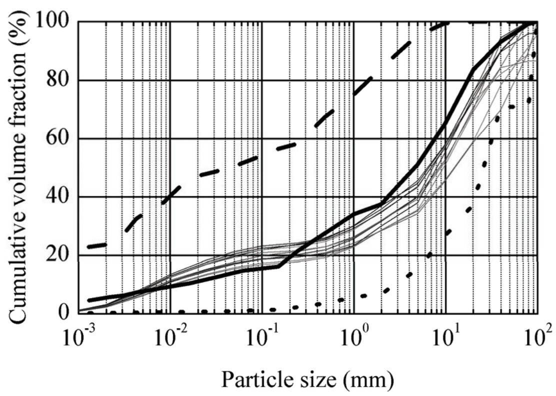

Fig. 5 Particle size distributions of the source soil (bold curves) and debris flow samples with the bulk density exceeding 2,200 kg m^{-3} during 2004–2007 (fine curves) in Jiangjia Gully. The bold dashed curve, bold dotted curve and bold solid curve represent the upper limit, lower limit and mean value respectively of the 48 particle size distributions of soil samples collected from the debris-flow source area.

In Jiangjia Gully, debris flows are non-Newtonian and exhibit high yield strength at the bulk density exceeding 2,200 kg m^{-3}, in which case the granular material is very poorly sorted during start-up and movement. There are 11 samples having ρ_m>2,200 kg m^{-3} in the study period whose grain size distributions are illustrated in Fig. 5. The range of variation is relatively small and the curves are close to the mean of the 48 source soil samples. This suggests that debris materials from different tributaries are agitated during movement and samples from high-concentration debris flows may represent the general characteristics of the source soil. Particle size analyses were performed by different researchers each year at DDFORS and error levels varied. Therefore, we calculated the mean value of particle size distributions for high-concentration debris flows (ρ_m>2,200 kg m^{-3}) each year and they are used as reference values to represent particle size distributions of the source soil.

4.3 Analytical results

For each debris flow sample, particle volume fractions in different size ranges were divided by the reference values from the corresponding year, and then the ratio curve was obtained. Some of the curves are shown in Fig. 6. The curves remain horizontal in the range D<0.1 mm and many fluctuate in the ranges of 0.1–0.25 mm and 40–80 mm. It is induced by the large variance in corresponding reference values (Fig. 7). Particle volume fraction in the 0.1–0.25 mm range is small (0.6–2%). Besides, 0.25 mm is the cutoff point between manual sieving and analysis by MS2000. So operational error may be large in the 0.1–0.25 mm range and produces a large variance in its volume fraction. The sampling device used for natural debris flows is relatively small and the sample generally has a volume of less than 15 L. Volume fractions of coarse particles are not so representative and lead to a large variance in the range of 40–80 mm. There is only one high-concentration debris flow sample in 2005. The reference value of particle volume fraction in the 5–10 mm range derived from this sample is much smaller than those from the other three years and gives rise to an abrupt decrease in ratio curves of that year. In order to reduce error, this reference value (18.17%) was substituted by the mean of the other three years (13.39%) and the ratio curves were correspondingly updated.

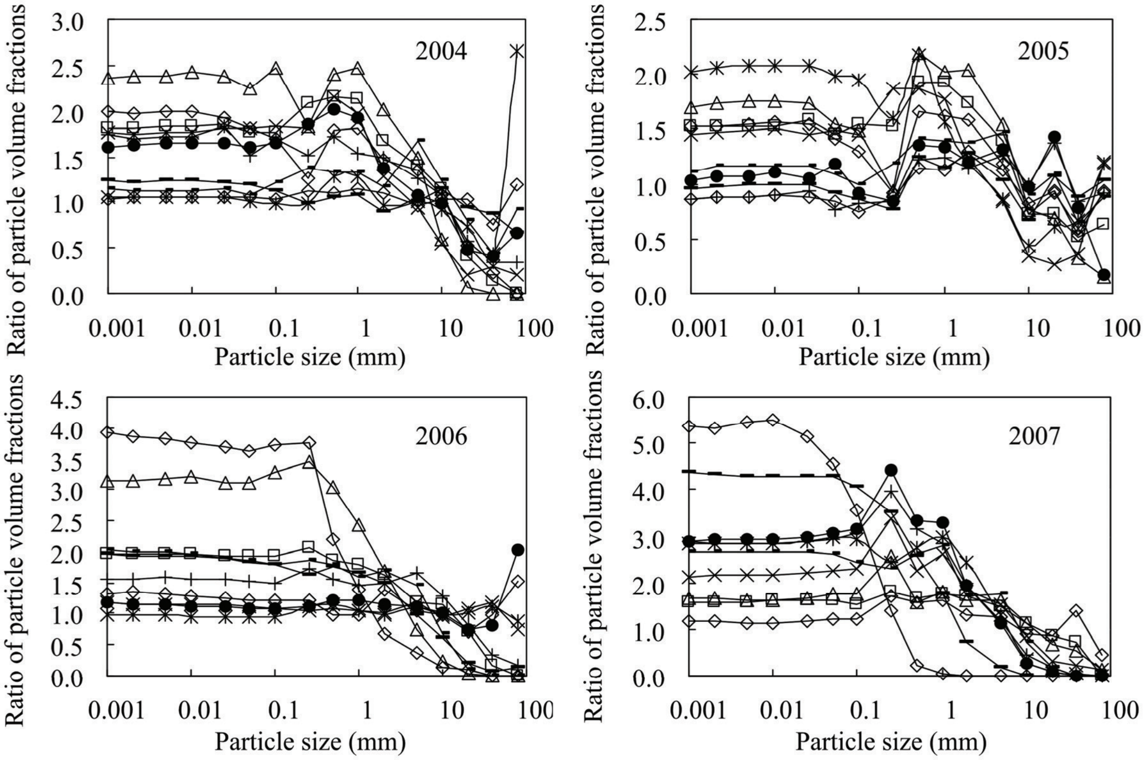

Fig. 6 Ratios of particle volume fractions of some natural debris flows to the reference values in the period 2004–2007 in Jiangjia Gully

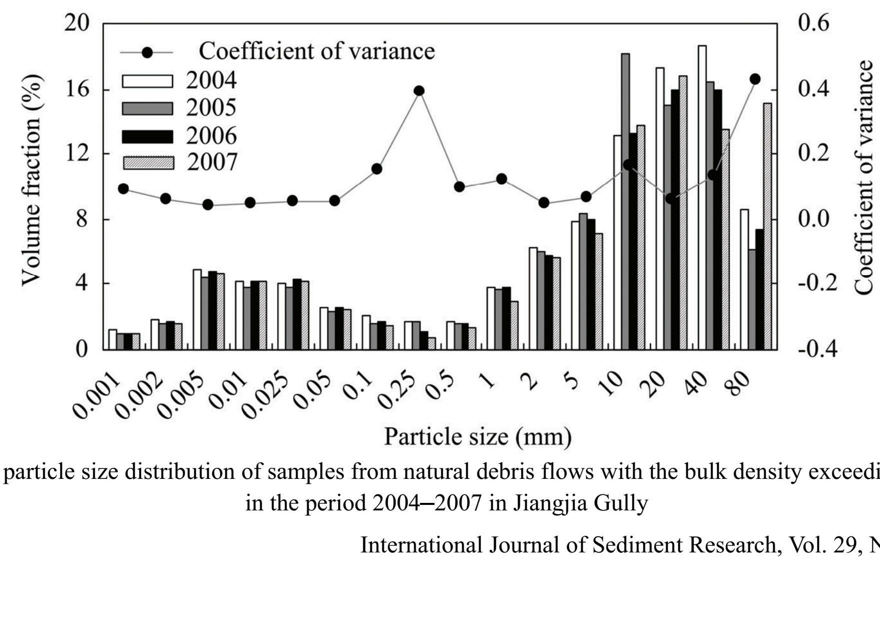

Fig. 7 Mean particle size distribution of samples from natural debris flows with the bulk density exceeding 2,200 kg m^{-3} in the period 2004–2007 in Jiangjia Gully

Among all the 102 samples analyzed, only 90 samples have a decreasing part in the corresponding ratio curves. So they were used to determine the suspension competence following the procedure described in section 2. D_0 is plotted against ρ_m in Fig. 8 where it is clear that it increases exponentially with ρ_m:

$$D_0 = 0.000018\exp(0.00645\rho_m) \tag{4}$$

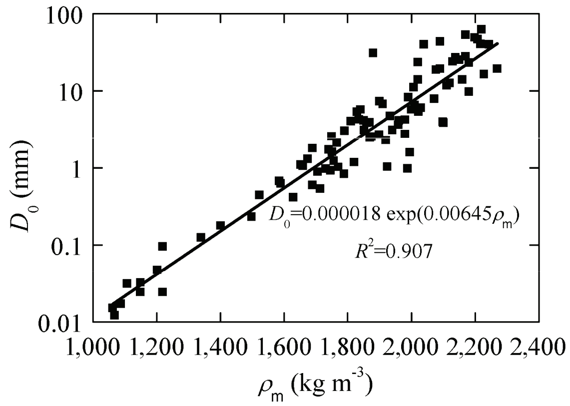

Fig. 8 The relationship between suspension competence and bulk density of natural debris flows in Jiangjia Gully

5 Discussion of the particle suspension mechanism in debris flows

Discussions above (section 3.3) indicate that particles finer than 0.025 mm belong to the fluid phase regardless of sediment concentration of the mixture. This qualitatively agrees with Iverson (1997) using 0.05 mm as the critical particle size. A slurry consisting of particles <0.025 mm and water is taken as a fundamental slurry with matrix strength. Its bulk density, $\rho_{0.025}$, is derived as follows:

$$\rho_{0.025} = \frac{C_v p_{0.025}\rho_s + (1-C_v)\rho_w}{C_v p_{0.025} + 1 - C_v} \tag{5}$$

where $p_{0.025}$ is the volume fraction of particles <0.025 mm, ρ_w=1,000 kg m^{-3} is the mass density of water, and C_v is volume concentration of the granular material in the debris flow. C_v is computed with the following formula

$$C_v = \frac{\rho_m - \rho_w}{\rho_s - \rho_w} \tag{6}$$

$\rho_{0.025}$ was computed for both experimental water-debris mixtures and natural debris flows. It was plotted against D_0 as obtained in sections 3.3 and 4.3 in Fig. 9. For natural debris flows, D_0 increases with $\rho_{0.025}$ in the range $\rho_{0.025}$<1,200 kg m^{-3}, while there is no significant relationship between them in the range $\rho_{0.025}$>1,200 kg m^{-3}. This is contrary to our experiments. Natural samples having $\rho_{0.025}$<1,200 kg m^{-3} were all collected from sediment-laden flows. When a strong rainfall event occurs in Jiangjia Gully, flow in the main channel is first sediment-laden flow, followed by debris flow and finally reverts to sediment-laden flow. For natural sediment-laden flows, debris material supply is limited by the erosional capacity of water flow on the slope surface and in the channel, whereas debris material supply can be abundant in an experimental mixture. Therefore, D_0 values for some natural sediment-laden flows are less than 0.025 mm but lie in the 0.01–0.05 mm range of the floc size. In the case of $\rho_{0.025}$>1,300 kg m^{-3}, suspension competence of the experimental

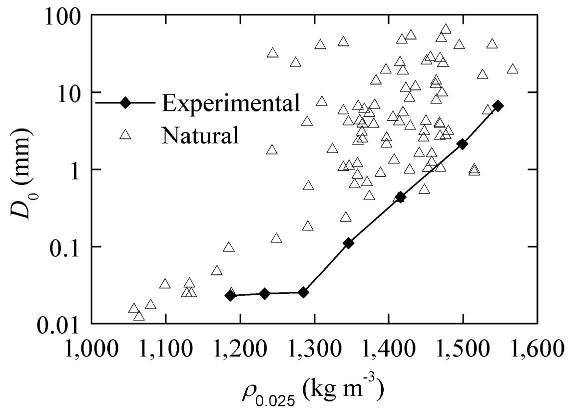

Fig. 9 The relationship between suspension competence and bulk density of a fundamental slurry for the static experimental case and for natural debris flows. The fundamental slurry is composed of water and particles finer than 0.025mm.

mixture represents the size of the largest particles suspended by matrix strength of the fundamental slurry. Size distributions of particles <0.025 mm are the same for experimental material and natural debris flows, as a consequence fundamental slurries of identical densities have the same matrix strength in the two cases. However, Fig. 9 shows that D_0 values for natural debris flows are greater than those for experimental mixtures, and they have no obvious relationship with $\rho_{0.025}$. This suggests that matrix strength may not be the dominant factor in the suspension of particles in reality and factors such as turbulence, particle dispersion and excess pore water pressure may be of greater significance.

Particles can be suspended by turbulence if the settling velocity ω_0 in the flowing medium does not exceed the friction velocity $u_*=\sqrt{gRJ}$, with R the hydraulic radius and J the hydraulic gradient. (Takahashi, 2007):

$$\omega_0 \leq u_* \tag{7}$$

Then the critical particle size, defined as satisfying $\omega_0=u_*$, can be derived by calculating ω_0 at different sizes.

Calculation results for 55 surges are plotted against ρ_m in Fig. 10, showing that D_0 increases with ρ_m. According to the classification of Du et al. (1986), bulk densities for non-viscous (violently turbulent), sub-viscous (slightly turbulent) and viscous (laminar) debris flows are 1,500–1,800 kg m^{-3}, 1,800–2,000 kg m^{-3}, and >2,000 kg m^{-3} respectively. Mean values of D_0 determined by particle size analysis are 1.2 mm, 4.8 mm, and 22.9 mm for the three types of flows. As calculated by Eq. (7), the respective mean values are 2.7 mm, 4.3 mm, and 9.1 mm .The first two values are relatively close to those determined by particle size analysis while the third value is comparatively small, suggesting that particle dispersion may be at work and causing particles coarser than 9.1 mm to be suspended in viscous debris flows. However, field observations indicate that some boulder-sized clasts stay at the surface when flow ceases. Because both turbulence and particle dispersion stop in this case, other factors are required to support these clasts. As concluded earlier, matrix strength alone is not adequate to support these clasts and therefore, we can only turn to excess pore water pressure to explain this phenomenon. Excess pore water pressure may be generated when shear shrinkage occurs during debris flow initiation or motion (Iverson and LaHusen, 1989; Iverson, 2003). Once generated, it is difficult to dissipate in the limited duration (tens of minutes) of debris flows because of the high viscosity and low permeability of viscous debris flows.

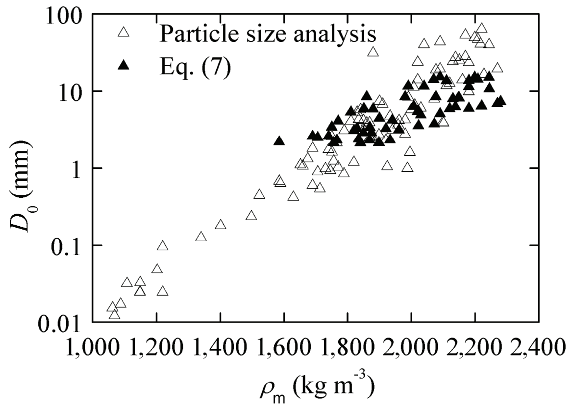

Fig. 10 Suspension competences for natural debris flows in Jiangjia Gully determined using different methods

6 Conclusions

The following conclusions may be drawn from the study:

(1) Suspension competences for static experimental water-debris mixtures composed of particles <10 mm are closely related to the mixture density. If the density is less than 1,800 kg m^{-3}, suspension competence is ~0.025 mm, which is close to the size of the flocs formed by clay minerals. If the density is greater than 1,800 kg m^{-3}, suspension competence increases exponentially with the density. If the density reaches 2,150 kg m^{-3}, the mixture appears as a homogenous material and particle settling does not occur.

(2) Suspension competence increases exponentially with the density of debris flow in Jiangjia Gully.

(3) Suspension competence results not only from matrix strength of the slurry, but also from turbulence for non-viscous debris flows and from excess pore water pressure for viscous debris flows.

Since it is difficult to collect samples through a vertical section from active debris flows, we determined suspension competence by comparing the particle size distribution of debris flow samples with that of soils in the source area, which were represented by high-concentration debris flows. In future research, we will collect samples from debris flow deposits and along the lognitudinal direction of active debris flows (front, body, and tail of a surge). More accurate results about suspension competence may be achieved through further analysis.

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