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Relationship between grain composition and debris flow characteristics: a case study of the Jiangjia Gully in China

Abstract Debris flow occurs frequently (ten events on average per year) and displays a great variety of properties in the Jiangjia Gully (JJG) in southwest China. We find that the material of debris flow satisfies a universal grain size distribution (GSD) of $P(D)=CD^{-\mu}\exp(-D/D_c)$, and the parameters μ and D_c are closely related to the dynamical properties such as flow density, velocity, and discharge. A small μ implies a small porosity and possible high excess pore pressure in flow, reflecting high mobility and capacity of transportation, and a large D_c means a wide range of grain composition and hence a high grain concentration. A debris flow always achieves a state of certain mobility and density that can be well described by μ and D_c, and the parameters impose power law constraints on the fluctuations of debris flow surges. An upper limit of unit-width discharge is estimated as $Q_u=1.25D_c^{1.12}$. Variation of GSD parameters also describes material exchanges between debris flow and streambed sediment. Intense incision or deposition occurs when remarkable difference of grain composition exists. As the GSD is satisfied universally, the results derived from JJG are expected to be applicable for evaluating the properties and peak discharge of a potential debris flow in other conditions.

Keywords Debris flow · Grain size distribution · Flow fluctuation · Power law constraints

Introduction

Debris flow consists of grains ranging between about 0.001 and 1,000 mm and involves various effects due to variation of grains, such as the intergranular shear stress, grain collisions, and grain-fluid interactions. Therefore, debris flow goes far beyond the fluid with a fixed rheology like the Bingham fluid (Iverson and Vallance 2001; Iverson and Denlinger 2001). Various dimensionless numbers have been proposed to weight the relative significance of granular effects, including the Bagnold number (N_B) and Savage number (N_S) (Iverson 1997; Kaitna and Rickenmann 2007). However, these numbers have encountered difficulties in several respects. First, they depend greatly on viscosity and shear rate that are sensitive to the adopted materials and experiments; second, the rheology is exclusively concerned with fine grains (up to silt or clay particles), while the dynamic viscosity varies remarkably with the change in fraction of silt and clay, up to 1 or more orders of magnitude (O'Brien and Julien 1988); third, the boundary between fluid phase and solid phase is ambiguous, and the empirically estimated size varies greatly, between, say, 0.06 and 20 mm (Kaitna and Rickenmann 2007). As it is rarely possible to get a moving debris flow, the estimate is often based on artificial mixtures of several grain groups or field measurements of the deposits (Sohn 2000), which may lead to a great uncertainty. Furthermore, the numbers are insensitive to distinguish granular effects in flows. For examples, N_S is estimated between 10^{-4} and 10^{-7} and N_B between 0.4 and 4 (Iverson 1997), which are several orders of magnitude off the critical value for domination of granular effect: $N_S>0.1$ or $N_B>15$ (Iverson 1997; Vallance and Savage 2000; Iverson and Denlinger 2001). Nevertheless, the estimated values suggest that debris flow moves en masse, and the variations due to granular effects can be ignored as far as the motion of the surge is concerned. For this reason, we consider each surge of debris flow as a whole and assign it a set of characteristic quantities that can be observed in field, including flow density, depth, velocity, and discharge.

On the other hand, the extremely poor sorting of grain is crucial for the competence and mobility of flow (Pierson 1980, 1981), grain segregation plays a dominant role in levee formation that is ubiquitous in debris flow gullies (Johnson et al. 2012), and a variety of flow regimes may occur within a surge group. Describing these phenomena requires an integrated description of grain composition, which has eluded us so far. This situation is mainly caused by the lack of firsthand data from moving debris flows. Fortunately, we have an ideal site displaying a variety of debris flows in the Jiangjia Gully in southwest China, which has offered a huge dataset of dynamical quantities of debris flows (Liu et al. 2009). In this paper, we conduct a systematic study on the relationship between grain compositions based on the observation data. We propose a universal grain size distribution (GSD) for debris flow materials and then associate the GSD parameters with variation and fluctuation of the flow depth, velocity, discharge, and the impact on material exchange.

Study area and data collection

Background of the Jiangjia Gully

The Jiangjia Gully (JJG) lies in Yunnan province, southwest China. It measures 48.7 km^2 in area and extends 13.9 km, with an average slope gradient of 16 %, northward to join Xiaojiang River, a major tributary of upper Yangtze. Several faults cut through the valley in parallel to the mainstream channel. The landscape develops on Proterozoic and Precambrian strata dominated by slate, dolomite, and phyllite, which are intensely weathered and result in widespread shallow landslides, avalanches, and alluviums providing a huge amount of material supply to debris flow (Cui et al. 2005; Li et al. 2009). Interpretation of QuickBird images (2006) helps identify more than 150 landslide groups, accounting for 4.4×10^8 m^3 of loose material (Fig. 1).

Owing to the abundant material supplies, debris flows occurred frequently in the last decades, with each occurrence containing tens to hundreds of surges (Liu et al. 2008, 2009; Li et al. 2012). This makes JJG an ideal site for real-time observation of debris flows attracting attentions of the world researchers. The Dongchuan Observation and Research Station of Debris Flow of Chinese Academy of Sciences has continued a systematic observation and achieved a large dataset since its

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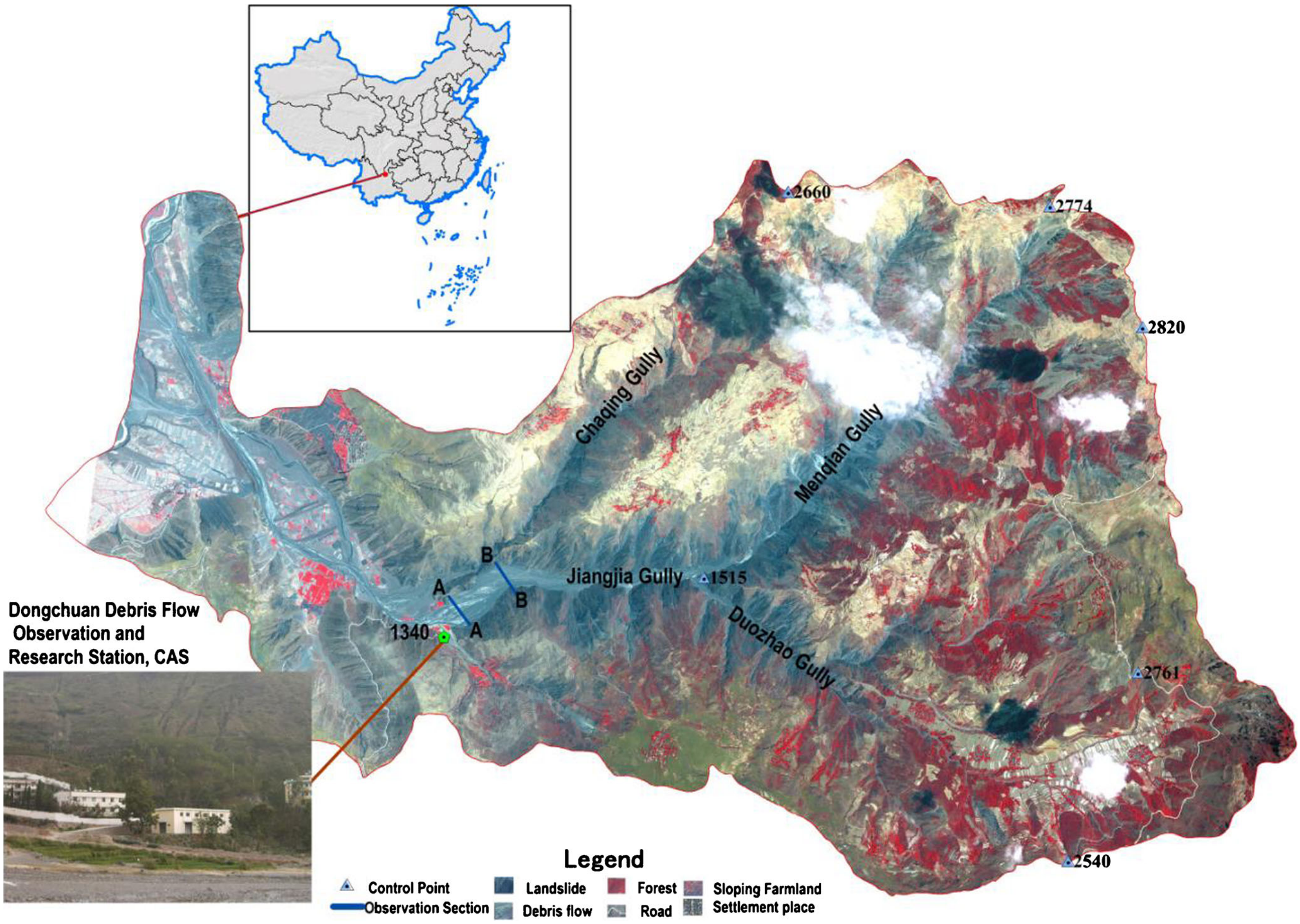

Fig. 1 Location and background of debris flow of JJG

establishment in early 1960s (Fig. 1) (for details of debris flow study of JJG, see Cui et al. (2005)).

Data collection and variety of debris flow

Real-time monitoring of debris flow is carried out every rainy season (between May and September). The measured or monitored quantities include, among other things, the flow depth, velocity, discharge, and sediment yield (Table 1). As the surge moves en masse, it can be characterized by a single flow depth and velocity. The velocity is measured as an average value of the surge passing through two fixed cross sections (i.e., the sections AA and BB in Fig. 1), and the flow depth is directly read from the level mark inscribed on concrete pile at the section. Although there is a strong fluctuation within the surge, the measured quantities are representative of the total motion. As seen in Fig. 2, a surge remains at a certain shape well throughout the course. Fluid samples are also collected from the moving surges by a suspending cable sampler, about 0.03 m^3 (30 l) in volume, and the flow density is determined directly by weighting the fluid. Since the samples are collected from surges having apparent distinctions, the measured densities are well representative, especially in statistical meaning. Comparison between different densities and the corresponding surges indicates that density difference exceeding 0.1×10^3 kg/m^3 may cause remarkable difference in motion. In this sense, the accuracy of density measurement is up to about 10 %. That is, the density of 2.0×10^3 kg/m^3 may fall into the range between $1.95\pm0.05\times10^3$ kg/m^3. (Densities are all in unit of 10^3 kg/m^3 throughout this paper. In the following, we omit the units for simplicity.)

The most conspicuous phenomenon of debris flow in JJG is the high fluctuation in discharge and velocity among the surges. Velocity varies between 2 and 12 m/s, and discharge fluctuates up to 3 orders of magnitude. Figures 3 and 4 show a typical event of 25 June 1994, including 108 surges. The high variety of surge can be ascribed to their various origins, having different material supplies, developing processes, and water conditions. All those differences result in different material compositions, which, in turn, lead to a variety of appearances of debris flow. For example, the small-scale and low-velocity surge usually has low density and viscosity, while those of high velocity are always highly viscous and concentrated. Apart from rheology or constituent relationship, there is no quantitative study of the material effect yet. So, we collect sediment samples from the surging fluid and make granular analysis and explore the relationship between material composition and the variation of flow properties.

Grain size distribution of debris flow

The absence of quantitative relationship of flow behavior with the material is mainly because there is not yet a useful quantitative description of grain composition of the material. Debris flow material consists of several peaks of grain size (Fig. 5, in which

Table 1 Observation quantities of debris flows in the Jiangjia Gully

No.	Density (10^3 kg/m^3)	Sediment (10^3 kg/m^3)	Yield stress (Pa)	Velocity (m/s)	Flow depth (m)	Grain composition (mm)		
						10	0.25	0.001
1	1.57	0.90	0.15	3.98	0.17	96.50	40.88	2.90
2	1.83	1.32	0.95	3.67	0.17	90.10	41.93	2.80
3	1.84	1.33	0.89	4.56	0.17	84.13	34.71	2.7
4	2.10	1.75	5.69	6.70	0.40	59.16	24.29	1.7
5	2.17	1.85	7.45	5.70	0.35	60.56	25.10	1.8
6	2.00	1.58	2.49	7.50	0.45	76.56	29.44	2.1
7	2.08	1.71	3.52	8.94	1.70	63.36	25.06	1.86
8	2.20	1.91	4.86	8.84	1.50	56.99	21.74	1.60
9	2.21	1.92	2.92	7.36	2.00	52.08	19.35	1.4
10	2.25	1.98	4.33	7.89	2.00	48.57	17.60	1.3
11	2.16	1.85	6.06	10.00	0.95	69.20	23.50	2.0
12	2.25	1.99	9.87	7.36	0.55	62.80	22.98	1.6
13	2.07	1.70	3.26	7.63	1.10	65.24	27.03	1.8
14	2.19	1.89	4.89	7.63	1.00	56.77	20.96	1.5
15	2.21	1.91	5.05	7.32	0.90	57.73	20.61	1.2
16	2.19	1.88	4.01	6.63	0.70	57.99	20.75	1.3
17	2.09	1.73	4.89	7.63	1.27	72.27	29.12	1.7

and thereafter the symbol "ρ2.0" refers to the flow density of 2.0). In the previous studies, only the fine content (e.g., silt and clay grains) has been considered as to govern the initiation and rheology of flow. However, this represents only the slurry, which differs much from the matrix of flow. A cumulative curve describes the total property of grain composition, but usually in use are some individual sizes, such as D_{10}, D_{30}, D_{60}, or their combinations (e.g., the uniformity coefficient and curvature coefficient). These are virtually empirical and more or less arbitrary. In fact, no relationship has ever been found between the bulk property and any single size of grain. Therefore, an integrated description of grain composition is needed.

We have found that fractal (i.e., power law distribution) fits well to the fine content and the exponential function fits the total composition (Li et al. 2005), but there are some discrepancies from the exponential curve at the fine content. This suggests that the fine grains might follow the power law while the coarse grains follow the exponential function. Then, we try to construct an integrated function that incorporates both the power and exponential components. Finally, we assume that the grain composition satisfies the following distribution:

$$P(D) = CD^{-\mu}\exp(-D/D_c) \quad (1)$$

where $P(D)$ is the cumulative percentage, i.e., the fraction of grains larger than D (mm). The parameters C, μ, and D_c are obtained by fitting the formula to the granular data. Using MATLAB to complete the curve fitting, we find that Eq. (1) is satisfied very well by debris flows in JJG (i.e., data of samples in Table 1), as shown in Table 2. Then, we use this for more samples from debris flows in other regions, and the results are also satisfactory.

Furthermore, when we rescale the grain size by D_c and normalize the percentage as $P(D)D^{\mu}/C$, the curves collapse on a single scaling curve of exponential function $\exp(-x)$, $x=D/D_c$ (Figs. 6 and 7).

Thus, we get a universal GSD, which naturally provides a set of characteristic parameters, C, μ, and D_c, for the material of debris flow. These parameters can be used, as in the following sections, to describe the granular effects, especially the variation of parameters corresponding to the dynamic variations of debris flow.

Fig. 2 A surge moving en masse in the mainstream channel of JJG

Fluctuation of debris flow

Granular effects are exhibited in many ways, especially the grain-grain collisions and grain-fluid interactions (Iverson 1997). However, no interior data of moving debris flow are available,

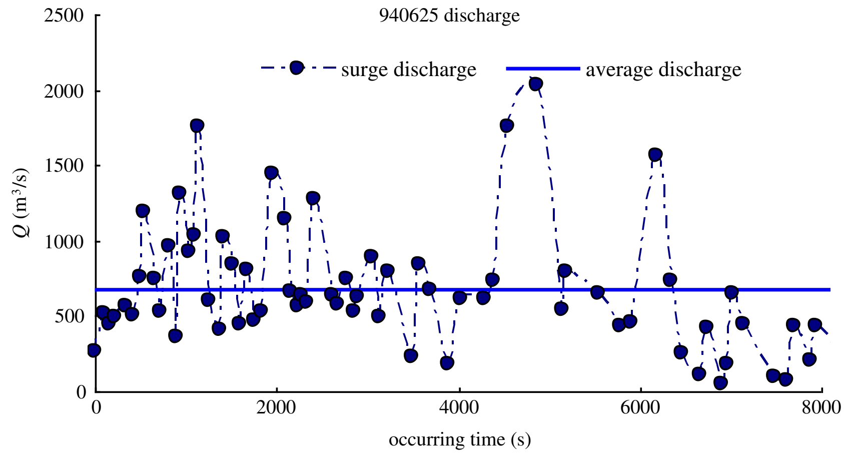

Fig. 3 Discharge fluctuation of debris flow surge

and only indirect effects are documented. As surges fluctuate conspicuously (e.g., Figs. 3 and 4), we demonstrate in the following subsections that the variation and fluctuation of surges are well associated with the granular parameters.

Fluctuation of flow depth and velocity

Flow depth fluctuates between 0.2 and 4.0 m, and velocity between 2.0 and 12.0 m/s (Fig. 4). Figure 8 shows another fluctuating pattern of flow depth and velocity. Both these patterns indicate that the velocity varies positively along with flow depth, because the velocity is related to depth by the Manning formula, expressing velocity as the function of hydraulic radius and roughness coefficient (Chanson 2004). For the case of JJG, the velocity (V) can be simply related to flow depth (H) by a power law:

$$V = C_V H^p \quad (2)$$

The effect of roughness coefficient, now in almost the same flow condition, has been incorporated in the coefficient and the exponent. According to the previous studies of debris flow in JJG, the coefficient C_V=7.0 and the power exponent p=0.35 (Du et al. 1987). We have also conducted statistics on a dozen of surge groups of debris flows occurring in the last 20 years and found that C_V ranges between 6 and 8 and p has an average of 0.39 (Li et al. 2004). This also agrees with other studies on velocity of viscous debris flows (Su and Fei 2003). Moreover, the variance of the exponent is as small as 0.0035 (i.e., the standard deviation σ= 0.059), meaning that the exponent varies little with occurrences and can be taken as a constant.

Given a density, 2.0, for example, the flow depth ranges between 0.20 and 2.8 m, with an average value of 0.78 m and peak value at 0.55 m. Considering the measurement accuracy of density, the statistics is conducted on the flows with densities between 1.95 and 2.05. The Lognormal distribution is found to fit well to the data points, with average and standard variance of −0.37 and 0.50, respectively (Fig. 9). The positive skewness (1.19) means that the mode (the value at the peak of distribution) is smaller than the average, and thus, most surges have depth below the average.

Similar fluctuation patterns are also presented at other densities, but the maximal flow depth increases, and the distribution gets blunt along with the increase of density. Figure 10 displays the depth distributions at densities of 1.80, 2.00, and 2.20, showing that surges at high densities have got a relatively large depth and gentle fluctuation. This suggests that a density may have a maximal possible depth that increases with density.

Upper limit of the fluctuation

Now, we consider specifically the maximal depth (H_{max}) varying with density. In the same way we do in Fig. 10, we get maximal flow

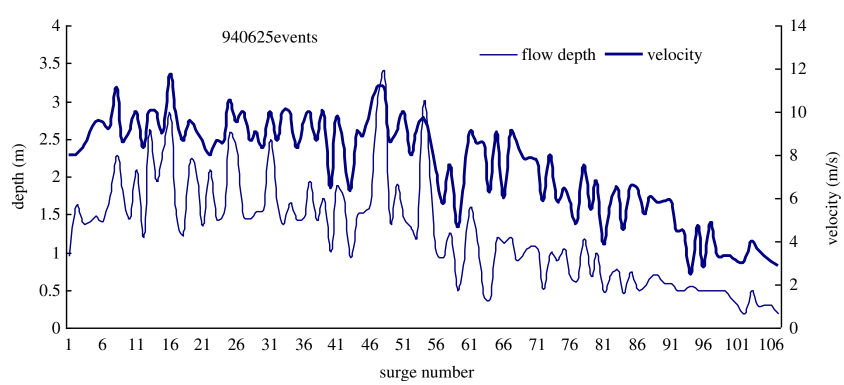

Fig. 4 Flow depth and velocity fluctuation of debris flow surge

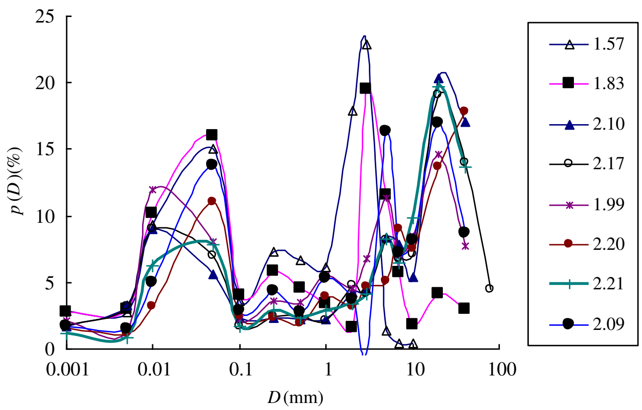

Fig. 5 Wide-graded grain composition of debris flows

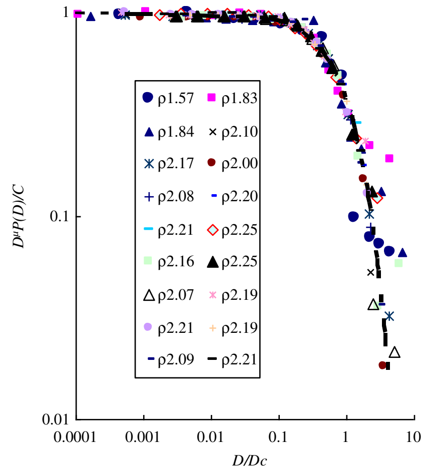

Fig. 6 The scaling GSD for debris flows of different densities in JJG

depths at various densities observed in JJG, ranging between 1.60 and 2.30 (again, densities within ±5 % are identified as the same). Statistics on nearly 6,000 debris flow surges shows that the depth increases with density by the following power law:

$$H_{\max} = C_H \rho^m \tag{3}$$

where ρ is density of debris flow, and the statistics yields C_H=0.054 and m=5.35 (R^2=0.96) (Fig. 11). This imposes the upper limit of the flow depth.

A similar limit is also imposed on velocity: $V_{\max} \sim \rho^{pm}$, following Eq. (2). As a rough estimation, the exponent of ρ is pm=0.39×5.35=2.10, in agreement with the observation (Fig. 12, which includes about 6,000 surges observed in JJG and yields an exponent value of 2.11).

Upper limit of discharge

The limits on velocity and depth naturally impose an upper limit on the discharge. As the geometry of stream channel is highly uncertain, we consider unit-width discharge, Q_u, which is the product of velocity and flow depth:

$$Q_u = VH = C_V H^{p\ +1} < C_V (C_H \rho^m)^{(p+1)} = K \rho^{m(p+1)} \tag{4}$$

This is well confirmed by the observations in JJG, as shown by Fig. 13 for two single events (910709 and 940616) and Fig. 14 for all the data points of about 6,000 surges.

Although the coefficient and exponent vary with event, we may take a representative estimate, using values in Eq. (2) and Fig. 11:

Table 2 GSD parameters for grain composition of debris flow

Sample	Density ρ (10^3 kg/m^3)	Coefficient C	Exponent μ	Characteristic size D_c (mm)	R^2
1	1.57	61.62	0.0691	2.2538	0.9886
2	1.83	56.29	0.0850	6.0827	0.9818
3	1.84	59.83	0.0750	9.0580	0.9880
4	2.10	74.48	0.0380	17.8731	0.9946
5	2.17	72.89	0.0418	18.8679	0.9954
6	2.00	68.96	0.0556	11.1607	0.9955
7	2.08	72.40	0.0476	17.7462	0.9926
8	2.20	75.87	0.0405	23.0733	0.9960
9	2.21	78.10	0.0364	27.4801	0.9953
10	2.25	80.07	0.0326	28.6944	0.9961
11	2.16	70.65	0.0501	13.9860	0.9933
12	2.25	76.09	0.0385	16.6834	0.9933
13	2.07	70.77	0.0506	16.0643	0.9942
14	2.19	76.81	0.0377	21.1999	0.9925
15	2.21	78.44	0.0342	19.1022	0.9963
16	2.19	76.90	0.0392	20.2429	0.9960
17	2.09	69.39	0.0538	13.1062	0.9918

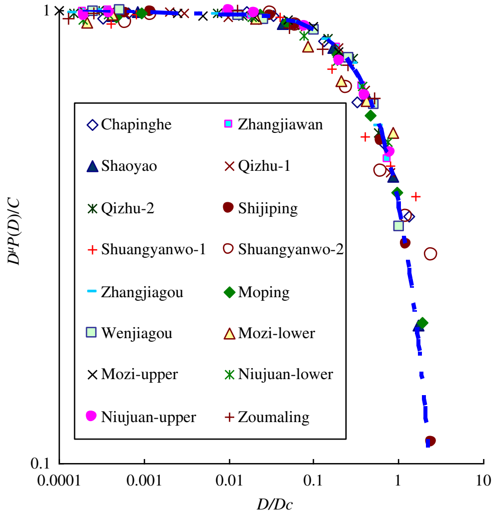

Fig. 7 The scaling GSD for debris flows in different gullies

$K=C_VC_H{}^{(p+1)}=7\times0.054^{(1+0.39)}=0.12$ and $m\ (p+1)=5.35\times(0.39+1)=7.44$. Then, Eq. (4) gives $Q_u=20.8\ \mathrm{m^2/s}$ at density $\rho=2.0$; this agrees well with the statistic result in Fig. 14, $Q_u=19.2(=0.34\rho^{5.82})$, and accounts for more than 90 % of surges with $\rho\geq2$ in JJG. Therefore, we can take $Q_u=0.12\rho^{7.44}$ as the upper limit of the possible unit-width discharge of debris flow in general conditions.

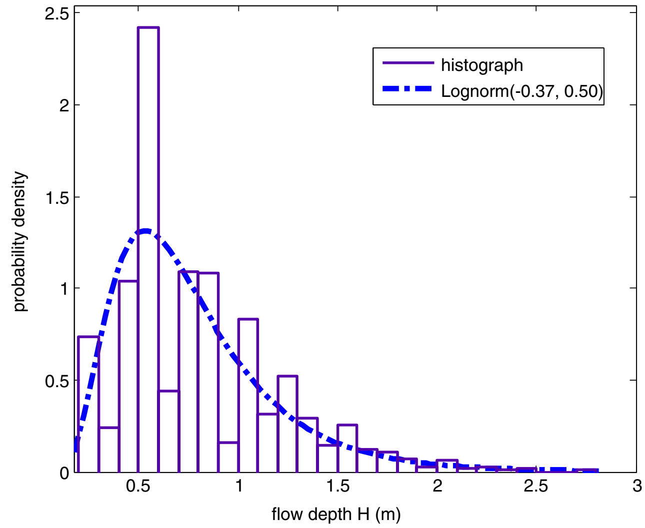

Fig. 9 Probability distribution of flow depth at a given density (2.0×10^3 kg/m^3)

Discussions: implication of GSD

Grain concentration and saturation of debris flow

The constraint on fluctuation imposed by flow density can be attributed to grain composition, and hence the GSD. As the GSD of Eq. (1) reduces to a power law $P\ (D)\sim D^{-\mu}$ when $D\ll D_c$ and to the exponent distribution $P\ (D)\sim\exp\ (-D/D_c)$ when $D\sim1$ mm,

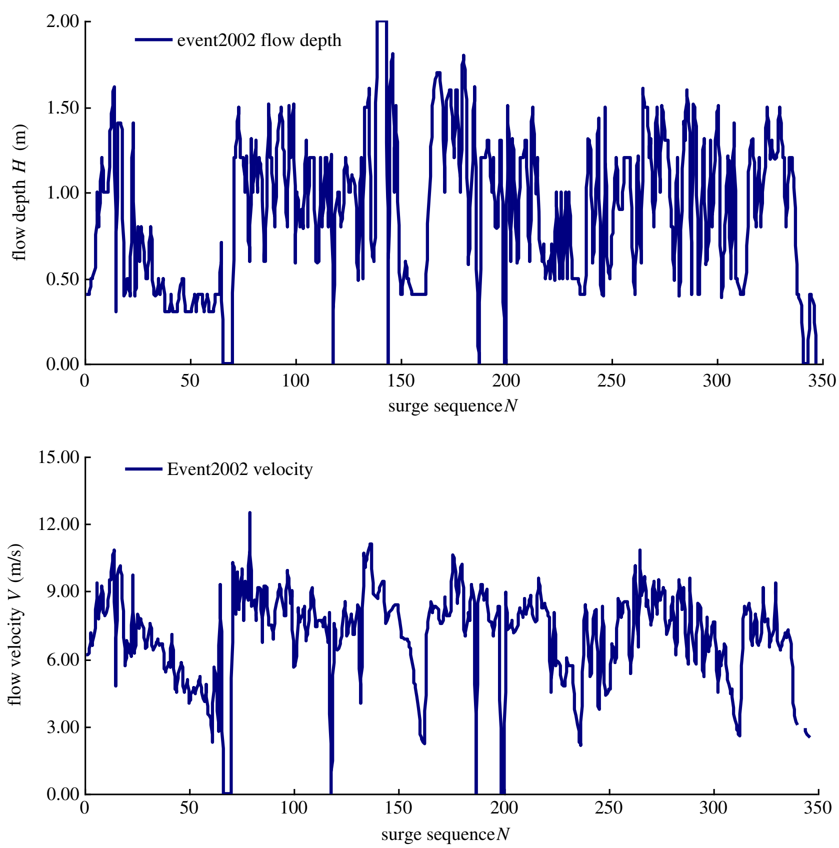

Fig. 8 Fluctuation of flow depth and velocity of a surge group in JJG, 2002

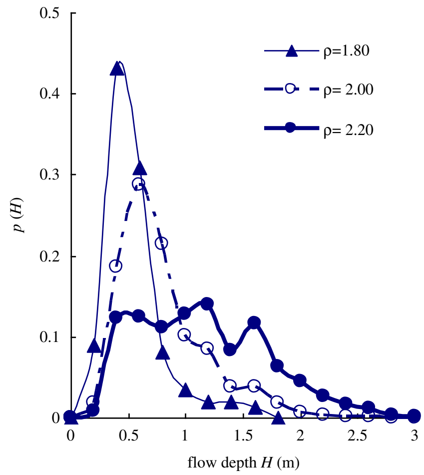

Fig. 10 Flow depth fluctuation at different densities

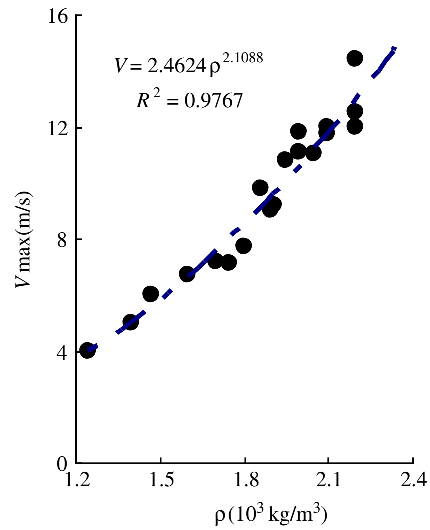

Fig. 12 Upper limit of velocity imposed by flow density

then, μ and D_c, respectively, describe the fine and coarse component. The power law distribution for fine grains is associated with a fractal of porosity (Hunt 2004; Li et al. 2005). When μ is small, the porosity is small; this may increase the excess pore pressure in flow and hence the mobility and capacity of transportation (Pierson 1981; Iverson et al. 2000).

On the other hand, when D_c increases, more coarse grains will join the fluid phase and increase the sediment concentration. Therefore, combination of μ and D_c determines the mobility, capacity, and density of debris flow. The existence of upper limit on discharge implies that there should be a saturated concentration of the fluid. Such a saturated concentration may be in parallel to the concept of Takahashi (1981), which is also influenced by the stream gradient and internal friction. Actually, observation in JJG shows that the sediment concentration increases with D_c by a power law (Fig. 15).

Correspondingly, the flow density ρ is related to D_c in the same way (with D_c in unit of mm):

$$\rho = kD_c^{\ a} \tag{5}$$

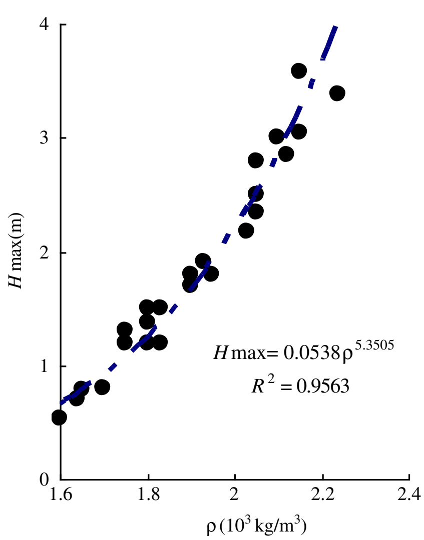

Fig. 11 Upper limit of flow depth imposed by density

This can be well confirmed by observations in JJG. As shown in Fig. 16, the fitting curve of JJG 1974 is drawn from the data in Table 1 (for measured density) and Table 2 (for characteristic size D_c), and the curve of JJG 1975 is drawn from another group of debris flows. As the two curves are statistically independent, their comparison is meaningful. Using $\rho=1.34D_c^{\ 0.16}$ (the JJG 1975 curve) to the samples in Table 1 (i.e., events in 1974), we find that the calculated densities are in good agreement with the measured values, with the relative errors, $\delta\rho/\rho_m=(\rho_e-\rho_m)/\rho_m$, being below 5 % (Table 3). Combining the two fitting curves, we get the average of the density estimation: $k=(1.40+1.34)=1.37$ and $a=(0.1459+0.1616)/2=0.15$, meaning that $\rho=1.37D_c^{\ 0.15}$. The average estimated densities are also compared in Table 3.

The robustness of the ρ-D_c relationship implies the intrinsic dependence of flow density on grain composition, and thus, it is expected to be universally valid. In fact, observations of debris flows in various places indicate that the parameters fall into three groups, corresponding to the hyperconcentrated flow, low-density debris flow, and high-density debris flow, respectively (Table 4). As it is rarely possible to catch a moving flow in field, such an estimate is helpful in evaluating a past or potential debris flow.

Following Eq. (5), the upper limit of unit-width discharge (Eq. (4)) can be expressed in terms of D_c:

$$Q_u = K\rho^{m(p+1)} = AD_c^{\ n} \tag{6}$$

where the coefficient $A=Kk^{m(p+1)}$ and the exponent $n=am(p+1)$. This is just in parallel to the power law relationship between the concentration and D_c. Using the parameter values in Eqs. (2)–(5), we have

$$Q_u = 0.12\rho^{7.44} = 0.12\left(1.37D_c^{\ 0.15}\right)^{7.44} = 1.25D_c^{\ 1.12} \tag{7}$$

For a typical example, D_c=15 mm, we have Q_u=26.0 m^2/s. Using D_c instead of ρ is practically important for evaluating a potential debris flow because the flow density is unknown before the occurrence. This means that we can estimate the possible maximal discharge by the grain composition of the material.

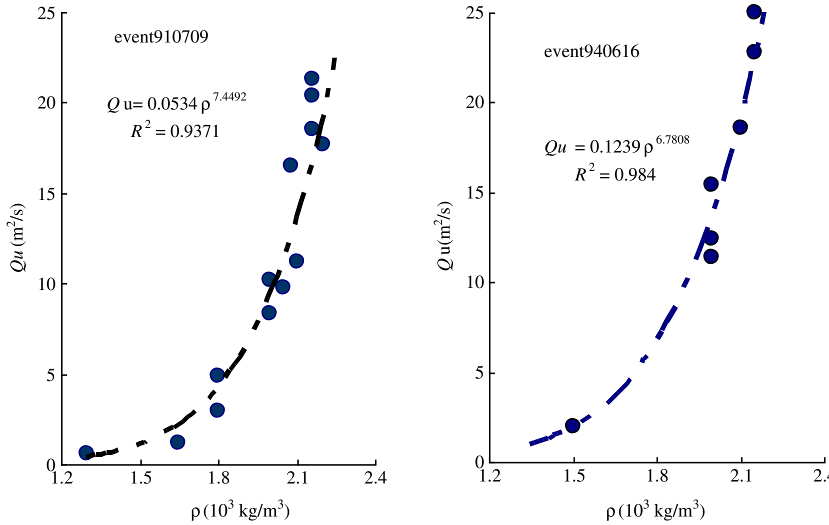

Fig. 13 Upper limit of unit-width discharge for individual events

Material exchange between flow and streambed

Just as granular structure is crucial in river flow (Buffington and Montgomery 1997; Church et al. 1998; Dade and Friend 1998), grain composition is important for material exchange between debris flow and streambed sediment. As GSD parameters change with grain composition, they provide indices describing the material exchange. Indeed, the solid density ρ_s can be expressed by GSD:

$$\rho_s = \int \rho_D(D) p(D)\, dD \tag{8}$$

where ρ_D (D) is the grain density at size D, and p (D) is the fraction in Fig. 5. Taking some ρ_c as the average of ρ_D (D), we have

$$\rho_s = \rho_c \int p(D)\, dD = \rho_c (1 - P(D)) \tag{9}$$

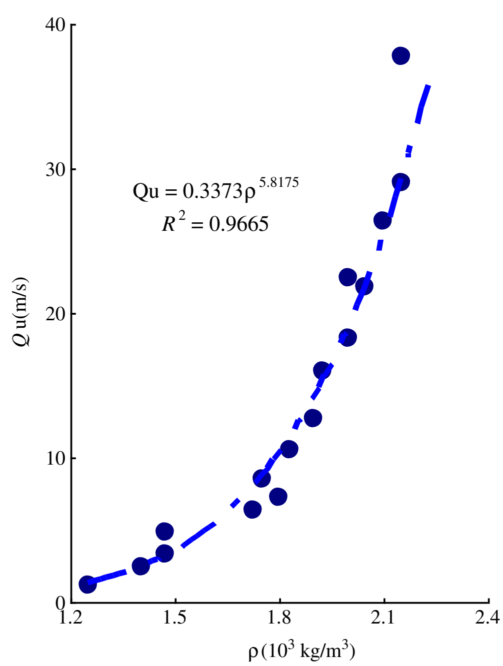

Fig. 14 Upper limit unit-width discharge for all observed events

where P (D) is just the GSD function defined by Eq. (1). Then, the material change corresponds to the variation of μ and D_c. For conceptual simplification, we consider material exchange between the bottom flow and the streambed sediment through convection due to density gradient (White 1974):

$$\nabla \rho_s / \rho_s \sim \nabla \ln P(\mu, D_c, .z) \sim (\partial \mu(z)/\partial z - \partial D_c(z)/\partial z) \tag{10}$$

where z is the vertical depth of flow. This implies that intense exchange occurs at the locations of high gradient of the GSD parameters, where the basal sediment differs much from the material of flow.

Observation in JJG indicates that intense incision occurs coincidently with intense deposition. As shown in Fig. 17, the incision and deposition by different debris flows coincided at 16 cross sections in the stream channel. A natural explanation following Eq. (10) is that grain composition at those sections is in favor of the material exchanges, either through deposition or incision.

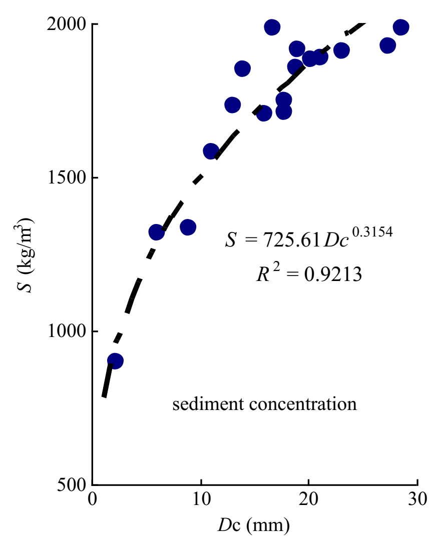

Fig. 15 Sediment concentration varying with D_c

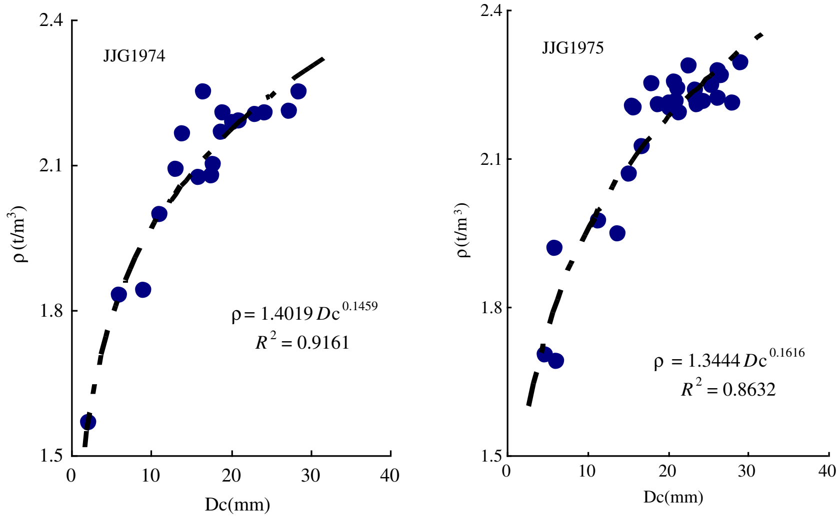

Fig. 16 Relationship between flow density and D_c

Table 3 Comparison between estimated and measured density of debris flow

Sample	Characteristic size D_c (mm)	Measured density ρ_m (10^3 kg/m^3)	Estimated density ρ_e (t/m^3)			
			$\rho_e=1.34D_c^{0.16}$	$\delta\rho/\rho_m$	$\rho_e=1.37D_c^{0.15}$	$\delta\rho/\rho_m$
1	2.25	1.57	1.53	−0.027	1.55	−0.014
2	6.08	1.83	1.79	−0.020	1.80	−0.019
3	9.06	1.84	1.91	0.040	1.91	0.036
4	17.87	2.1	2.14	0.017	2.11	0.005
5	18.87	2.17	2.15	−0.007	2.13	−0.019
6	11.16	2	1.98	−0.011	1.97	−0.016
7	17.75	2.08	2.13	0.025	2.11	0.014
8	23.07	2.2	2.23	0.011	2.19	−0.003
9	27.48	2.21	2.29	0.036	2.25	0.019
10	28.69	2.25	2.31	0.024	2.27	0.007
11	13.99	2.16	2.05	−0.050	2.04	−0.058
12	16.68	2.25	2.11	−0.061	2.09	−0.071
13	16.06	2.07	2.10	0.014	2.08	0.004
14	21.20	2.19	2.20	0.002	2.17	−0.011
15	19.10	2.21	2.16	−0.023	2.13	−0.035
16	20.24	2.19	2.18	−0.005	2.15	−0.018
17	13.11	2.09	2.03	−0.028	2.02	−0.036

Table 4 Debris flow classification by GSD parameters

Flow nature	Density (10^3 kg/m^3)	C	μ	D_c (mm)
Hyperconcentrated flow	1.2–1.5	10–20	0.20–0.30	<2
Low-density debris flow	1.6–1.9	30–60	0.05–0.10	2–15
High-density debris flow	>2.0	60–80	<0.05	~20

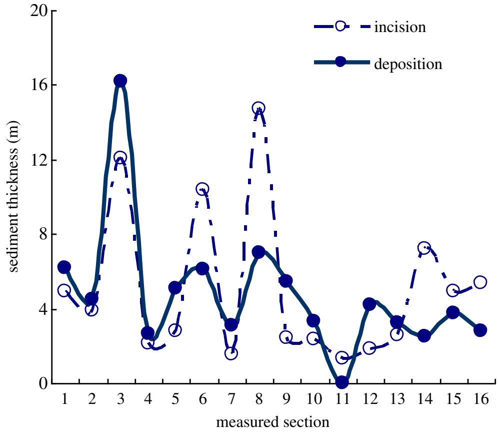

Fig. 17 Incision and deposition of debris flows in JJG

Conclusions

The GSD of debris flow satisfies $P(D)=CD^{-\mu}\exp(-D/D_c)$, with parameters μ and D_c, respectively, describing the fine and coarse components. A small μ implies a small porosity and high excess pore pressure, reflecting high mobility and capacity of flow, and a large D_c means a wide range of grain size and hence a high concentration of sediment. These two parameters determine the mobility, capacity, and density of debris flow. The flow density can be estimated by D_c to high accuracy.

The grain composition has imposed power law limits on the fluctuations of debris flow surges. An upper limit of unit-width discharge is derived from the observation data in JJG, $Q_u = 1.25D_c^{1.12}$. The upper limit implies the existence of a saturated concentration of sediment in debris flow.

Grain composition also controls material exchanges between debris flow and streambed sediment. Using GSD parameters to describe the exchange indicates that the incision or deposition is likely to occur at the positions having a high gradient of the parameter.

As these characteristics are primarily governed by the flow dynamics rather than environmental factors and the proposed GSD is universally satisfied by various debris flows, the results derived from JJG are expected to be applicable for debris flows in other conditions. In practice, we can use these relationships to evaluate a possible debris flow from the source soils or sediments, and in theory, we hope that a complete model of debris flow should incorporate the GSD parameters to illustrate the granular effects.

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