Granular effects in debris flows

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Abstract: Granular effects in debris flows are usually assessed by dimensionless numbers, such as numbers of Savage, Bagnold, and Iverson, which measure the relative significance of granular interaction, and the values indicate that the granular effects are generally ignorable. But observations suggest robust phenomena pertain to grain composition in many ways. This implies that the dimension analysis does not apply to the recognition of granular behaviors in debris flows, partly because we have not really a direct description of changes in grain compositions of debris flows. We have proposed and confirmed that for debris flows the material grain size distribution (GSD) satisfies a unified function, $P(D) = C$*power(D, – μ)*exp($–D/D_c$), where $P(D)$ is the exceedance percentage of grains beyond size D (mm), and C, μ, and D_c are parameters, with a semi-log relationship between C and μ. Then the grain composition is characterized by the GSD parameters μ, and D_c, respectively representing the fine and coarse content of the materials. In this study we present a variety of appearances to illustrate how grain compositions impact on the initiation, formation, motion, and deposition of debris flow. Results indicate that debris flow occurs through a selection mechanism in which soil or sediment blocks of different grain compositions initiate in different ways and form separate surges in different flow regimes. The flow properties (X), such as the velocity, the discharge, the density, are all dependent on the GSD parameters in power laws: X ~ power(μ, $–m$) and X ~ power (D_c, n); and the power laws impose constraints on the fluctuation of the dynamical quantities. In particular, the GSD evolves from the randomly aggregated grains to the fluid with some self-organized constitute.

Key words: debris flow; grain composition; grain size distribution; dynamical properties

1. Grain size distribution for debris Flow

The debris flow and soil grains generally show a multi-peak distribution (Fig.1), but the peaks of different particle sizes are random, which is difficult to describe with a simple mathematical function. The cumulative curve shows good consistency, which can be roughly expressed as an exponential function (Fig.2). The power function can describe the distribution of fine grains, so consider using both the power function and the exponential function to describe the grain size distribution (GSD) (Fig.3).

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

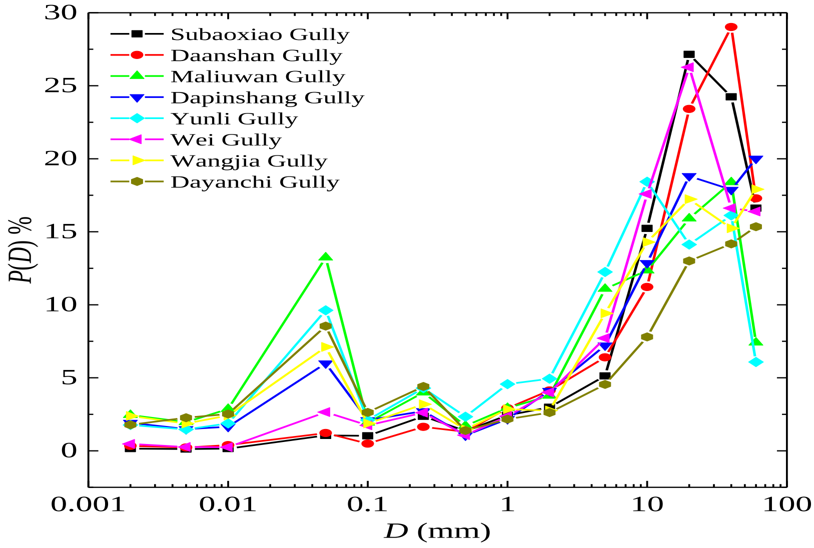

Fig.1 Grain size distribution of debris flows.

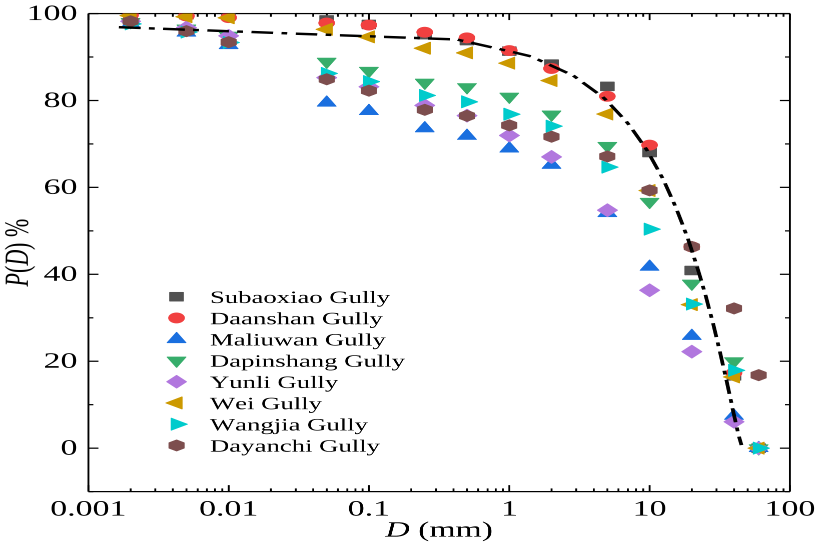

Fig.2 Exponential distribution of grain size of debris flow.

There is a good coupling relationship between the parameter C and μ (Fig.4). Therefore, characterizing the composition of soil grains can be simplified into two parameters (μ, D_c). The larger the μ value, the more the fine grain content, the larger the D_c value, the wider the grain size range, and the more coarse grains. The scaling distribution of debris flow grains is universal, and can well describe the overall characteristics of debris flow grain size distribution. GSD parameters reflect the basic properties of debris flow. The difference in the distribution of different soils is manifested as the difference between the parameters μ and D_c, which just means that different debris flows can be characterized and distinguished by these two parameters.

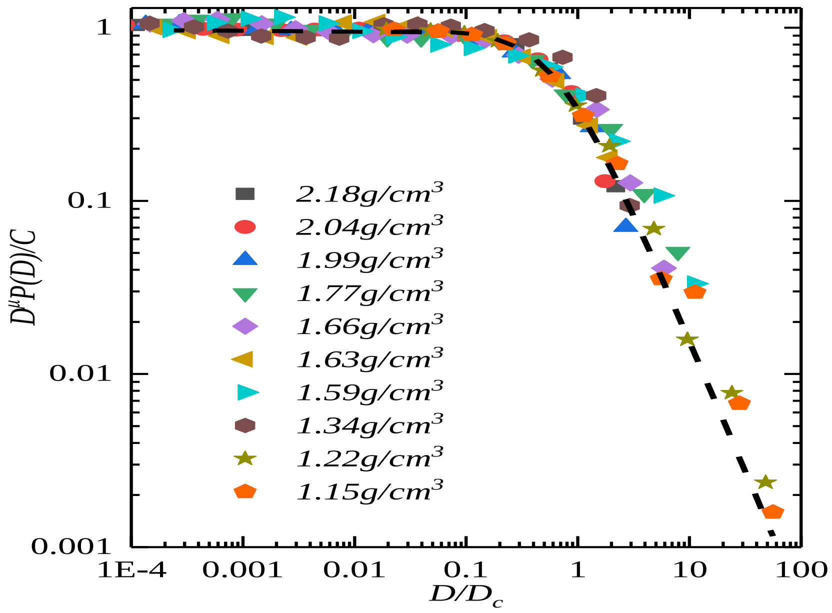

Fig.3 Rescaled GSD of debris flow surges in JJG.

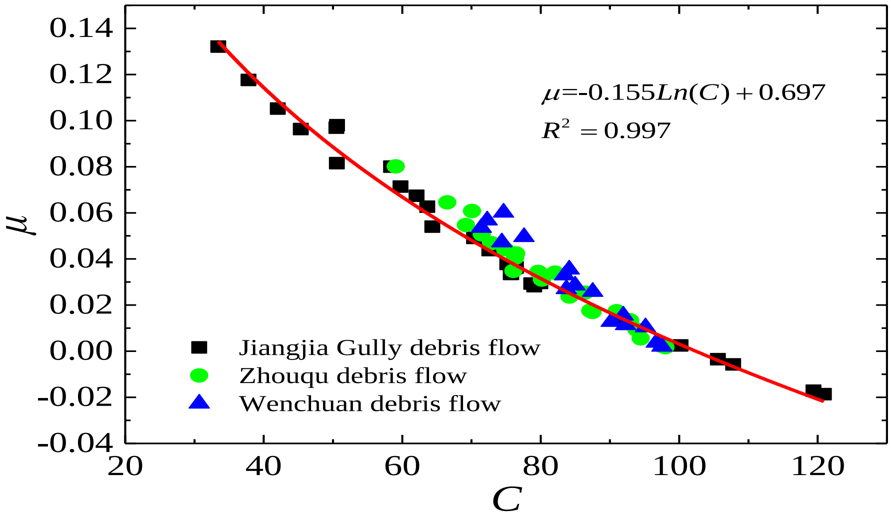

Fig.4 μ–C relationship of the GSDs.

2. GSD and debris flow properties

2.1. Rheology

Debris flow is the flow of mud, sand, stone and other solid grains mixed with water. The change of sediment content and grain size directly affects the change of rheological properties. According to the sampling and analysis data of Jiangjia gully (JJG) viscous debris flow, the average grain gradation of the original debris flow is obtained. For the four original samples of debris flow, the upper limit grain size is 0.25, 1, 2, 5 and 10 mm. The GSD parameters are shown in Table 1. The solid volume concentration C_{vf} and density ρ_f of each upper limit grain size debris flow slurry can be calculated by the following formula:

$$C_{vf} = \frac{C_{vc} p_f}{C_{vc} p_f - C_{vc} + 1} \tag{2}$$

$$\rho_f = \rho_w + C_{vf} (\rho_s - \rho_w) \tag{3}$$

where C_{vc} is the original solid volume concentration of debris flow; p_f is the mass content of grains smaller than the upper limit grain size in all debris flow grains; ρ_w is the density of water, kg / m^3; ρ_s is the density of solid grains, kg/m^3.

Table 1 GSD parameters of each group

D_{max} (mm)	C	μ	D_c	R^2
10	55.74	0.08	6.11	0.98
5	41.89	0.12	3.13	0.99
2	29.8	0.17	1.64	0.99
1	19.31	0.24	0.65	0.99
0.25	18.38	0.26	0.06	0.99

The instrument used for the rheological test was the MCR301 rotary rheometer produced by Anton Paar of Austria. The measuring system selects the ball system. After the test, the Herschel-Bulkley model was used to describe the rheological curve of the mud body:

$$\tau = \tau_y + m\dot{\gamma}^n \tag{4}$$

where τ_y is the yield stress, m is the consistency index, and n is the flow behavior index.

The experimental results show that the GSD parameter μ is positively correlated with yield stress and flow behavior index, and the GSD parameter D_c is negatively correlated with yield stress and flow behavior index.

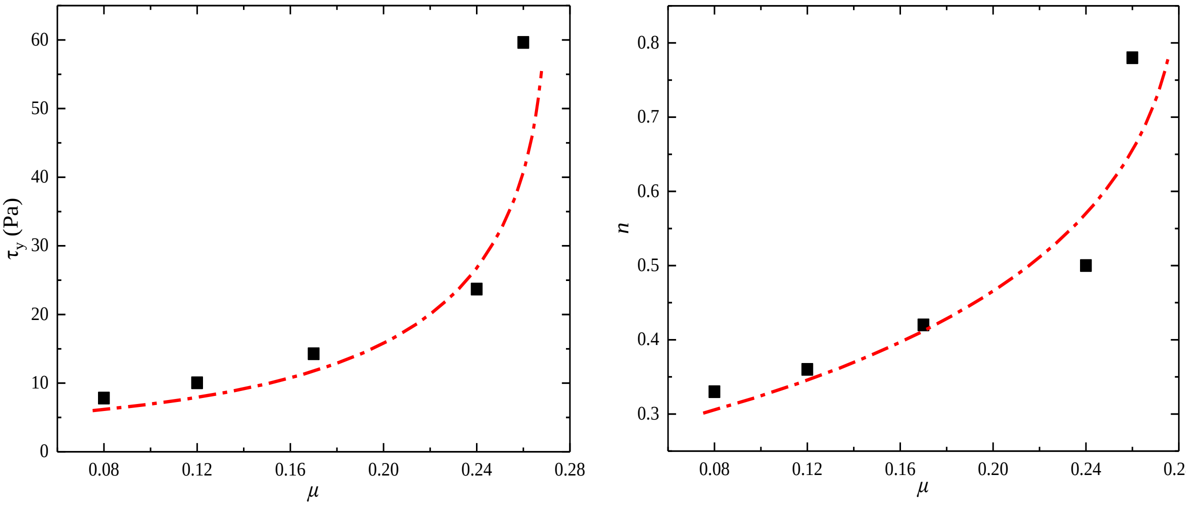

Fig.5 Relationship between μ and rheological parameters

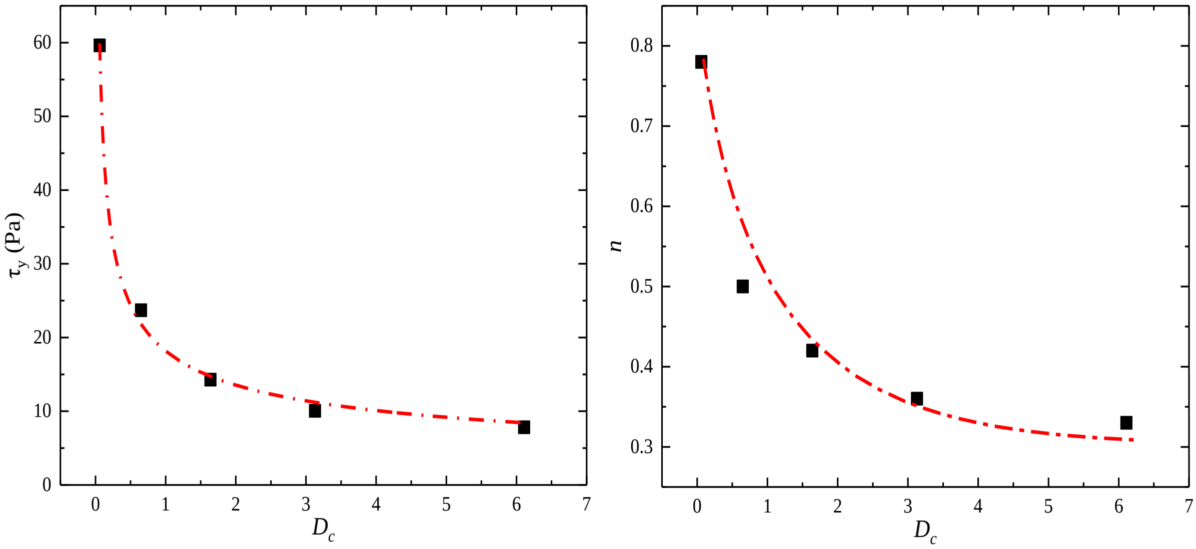

Fig.6 Relationship between D_c and rheological parameters

2.2. Density

The GSD curves of debris flow in JJG with different densities are analyzed, and it is found that the grain composition of debris flows with different densities is different (Fig.7), and the characteristics of the gradation curve are significantly different.

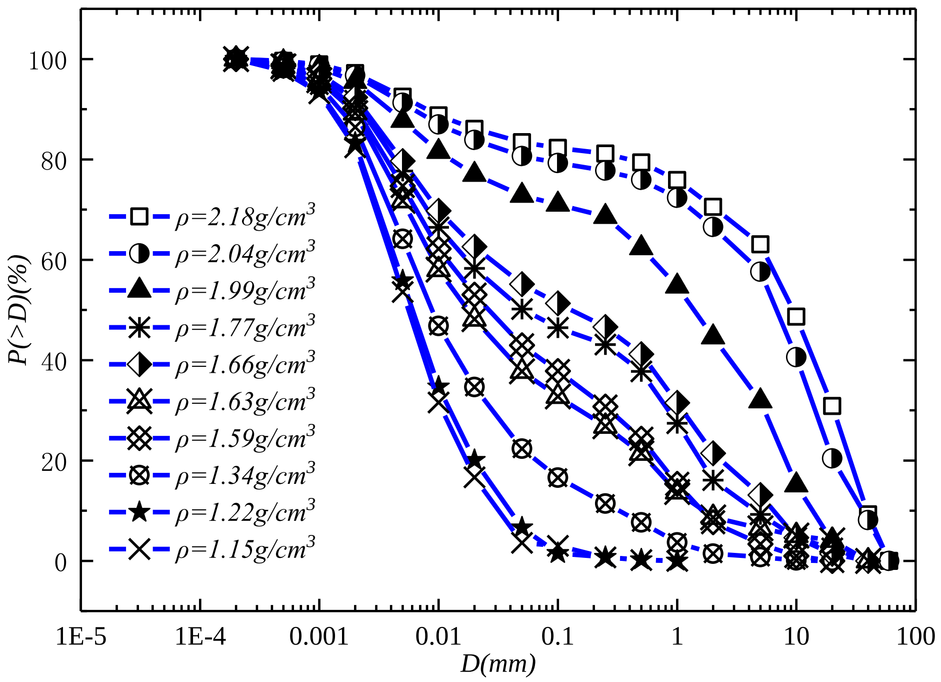

Fig.7 Partial GSD curves of debris flow in JJG

It can be seen from Fig.7 that the greater the debris flow density, the closer the corresponding gradation curve is to the top of the graph. The change of the gradation curve can be described by GSD parameters, so we selected 100 surges in JJG to study the relationship between GSD parameters and density, the research results are as follows:

$$\rho=1.26\mu^{-0.132}+0.049D_c^{0.443} \tag{3}$$

Compared with other density calculation formulas that use special grains (such as d_{50}, etc.) or a certain part of the grain content as a variable, the above formula is used to estimate the debris flow density, the accuracy is higher. Since the GSD parameter is a comprehensive parameter that reflects the change of GSD, so this formula illustrates the effect of GSD on density. At the same time, it also shows that the density can not be well estimated by a special grain or a certain part of the grain composition, and it should be considered from the whole grain composition.

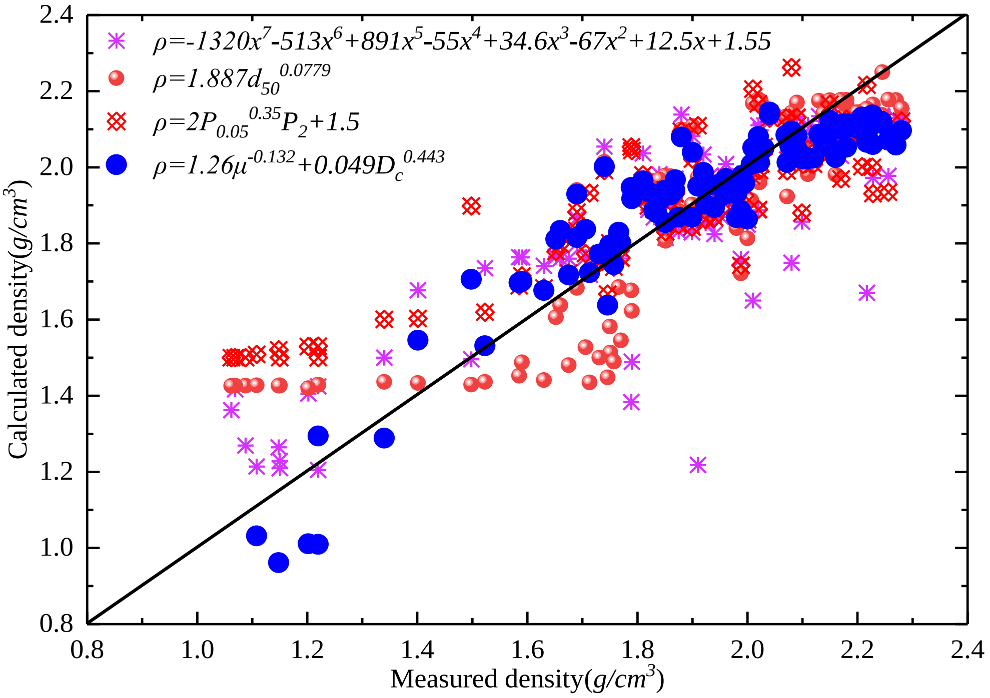

Fig.8 Comparison between densities measured and estimated by different formulas

2.3. Velocity

We use JJG observation data, through dimensional analysis, to focus on the effect of grain composition on flow velocity, and established such an empirical formula (Fig.9).

$$v = p\exp(2.59\mu)(\frac{H}{D_c})^{\frac{1}{6}}\sqrt{gHJ} \tag{4}$$

Then the data from Hunshui gully and Liuwan gully were used for verification. We found that the value of parameter p in this formula takes different values in different regions. In order to determine the method of p value, we use the observation data of these three gullys to inversely calculate the parameter p, and found that the parameter p has a good linear relationship with the F_r of the flow (Fig.10). But in the field investigation, we can only investigate flow depth by the mud mark method, the GSD data is obtained by sampling the debris flow, and the parameter p cannot be determined by the relationship between the parameter p and F_r. Further analysis shows that the parameter p also changes with the fluctuation of H/D_c, when the fluctuation of H/D_c is large, the value of parameter p is small; when the fluctuation of H/D_c is small, the value of parameter p is large. Fig.11 clearly shows that there is a good negative power exponent relationship between $(H/D_c)_{\max}$ and parameter p, indicating that we can obtain the grain composition of mud depth and debris flow through field investigation, and then pass $(H/D_c)_{\max} \sim p$ relationship to roughly determine the value of the parameter p. Therefore, the average velocity formula of JJG can be expressed as.:

$$v = 4.04\exp(2.59\mu)(\frac{H}{D_c})^{\frac{1}{6}}\sqrt{gHJ} \tag{5}$$

We compared formula (5) with several typical empirical formulas in JJG, Yunnan. The results are shown in Tab.2.

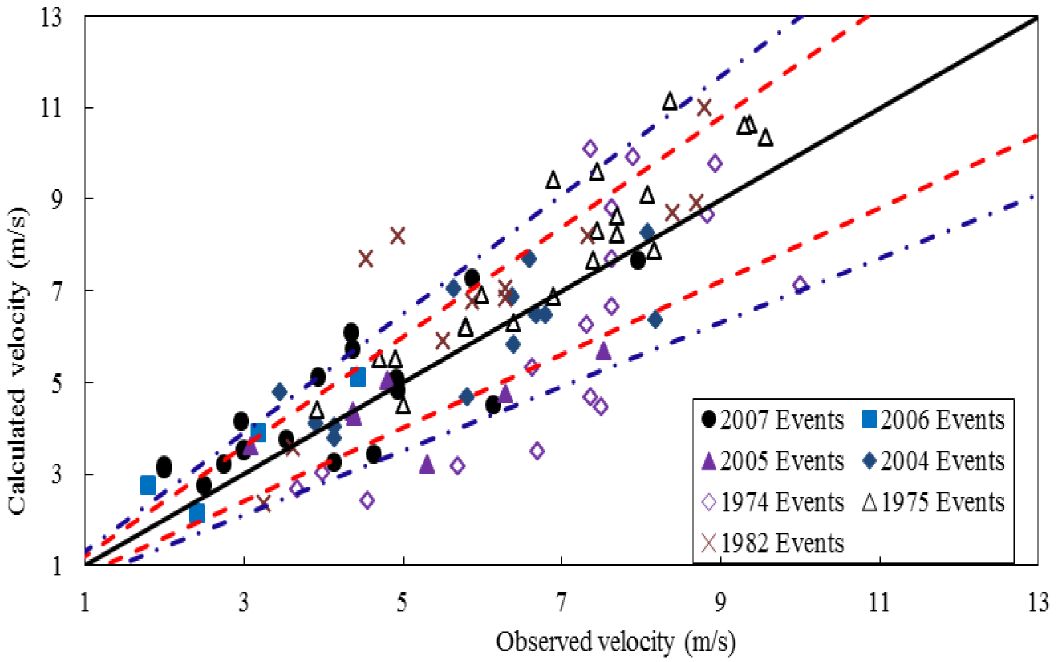

Fig.9 Comparison of observed and calculated mean flow velocities at JJG. The red dash line is error bars of 20%, and the blue dot-dash line is error bars of 30%

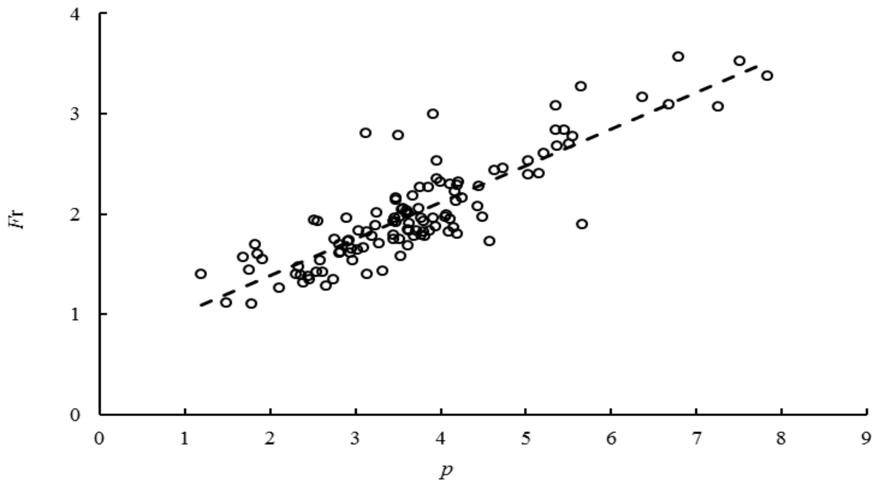

Fig.10 Relationship between p and F_r.

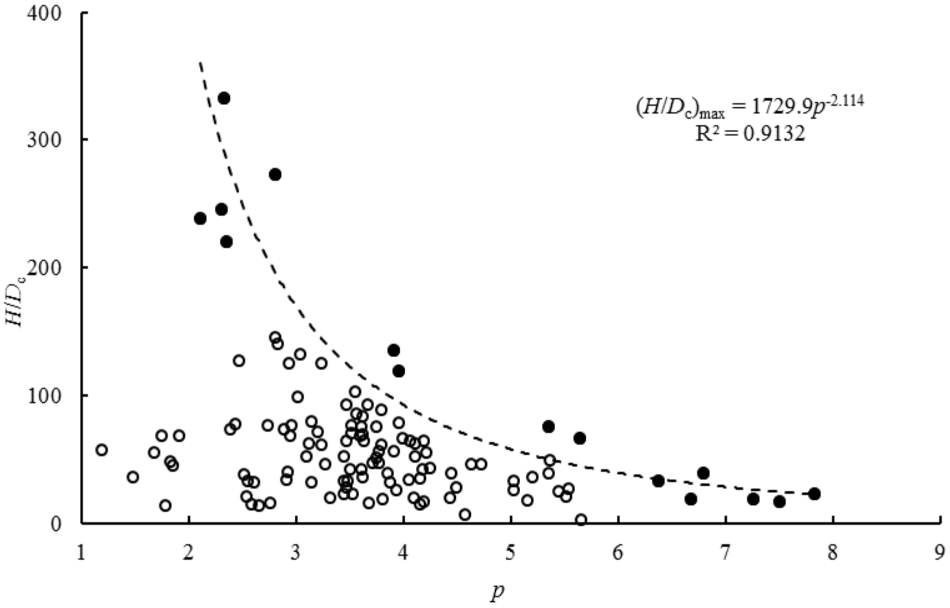

Fig.11 Relationship between H/D_c and p.

Tab.2 Other empirical equations for the area of Yunnan province, in China

Formulas	R^2	Percentage within 20% error	Percentage within 30% error	Authors
$v = 4.04\exp(2.59\mu)(\frac{H}{D_c})^{\frac{1}{6}}\sqrt{gHJ}$	0.69	62	80	In this paper
$v = 8.94H^{0.15}B^{0.35}J^{0.5}$	0.46	53	70	Hu (2012)
$v = \frac{1}{n}H^{\frac{2}{3}}J^{\frac{1}{2}},\ \ n = 0.035H^{0.34}$	0.70	61	75	Kang (1985)
$v = 1.62[\frac{S_v(1-S_v)}{d_{10}}]^{\frac{2}{3}}H^{\frac{1}{3}}J^{\frac{1}{6}}$	0.28	32	47	Fei (2003)

2.4 Impact force

A series of impact experiments were carried out (Fig.11), and use SPI TACTILUS built-in pressure distribution measurement sensor to measure the impact force data to explore the relationship between the temporal and spatial distribution characteristics of impact force and the relationship between dynamic pressure coefficient k and grain composition when debris flows interact with structures(Fig.12, Fig.13).

Fig.11 Real picture of experiment flume

The impact force calculation formula $F=k\rho v^2H$ under the single width of the structure can be regarded as the area enclosed by the longitudinal distribution coefficient λ, the normalized flow depth H_c/H and the coordinate axis, so the dynamic model of the dynamic pressure of the debris flow considering the impact effect can be obtained.

$$F=\int_0^a f(\lambda)d\lambda\rho v^2=0.5ab\rho v^2H=k\rho v^2H \tag{6}$$

The relationship between the correction coefficient k and the particle parameters (μ, D_c) (Fig.14**)**:

$$k=0.28\mu^{-0.83}+0.95\exp(0.085D_c) \tag{7}$$

Therefore, we can estimate the value of the dynamic correction coefficient *k* value through the particle parameters.

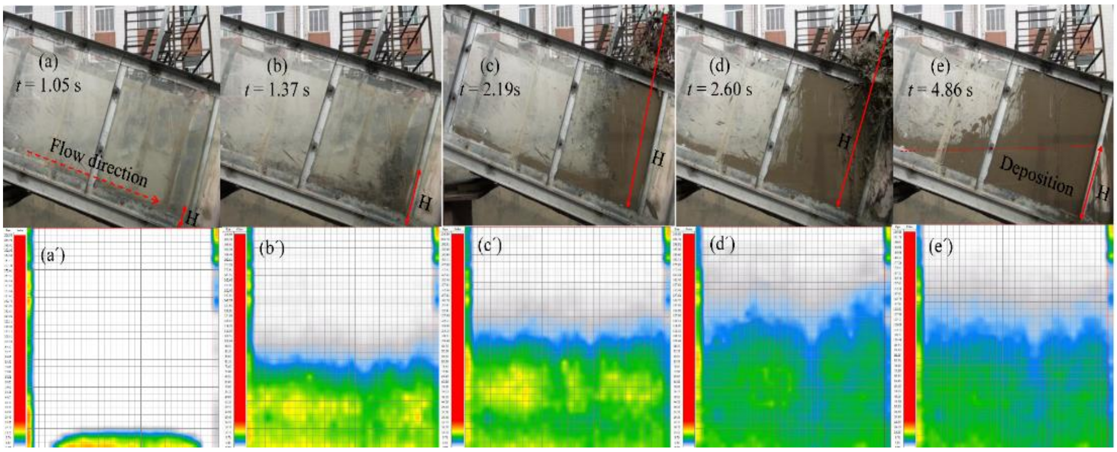

Fig.12 Debris flow impact process and impact spatial distribution with density 1.7g/cm^3

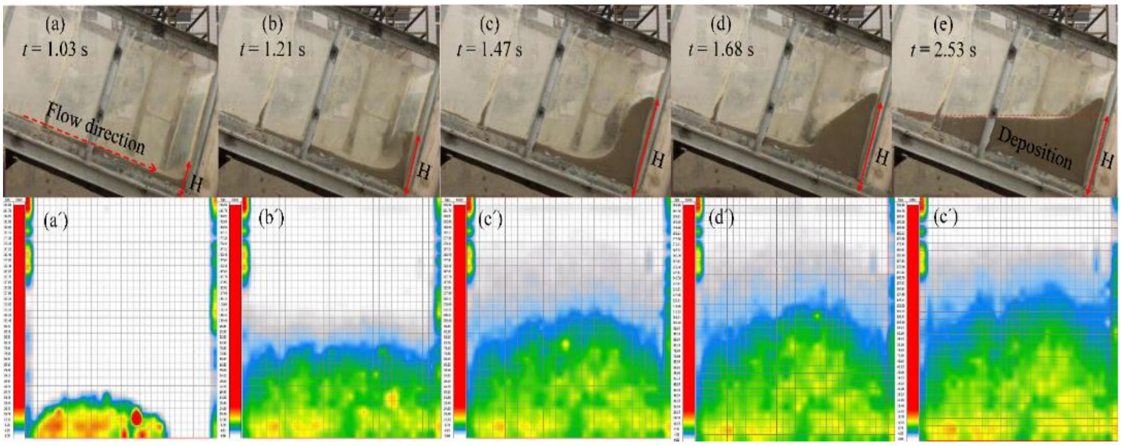

Fig.13 Debris flow impact process and impact spatial distribution with density 2.1g/cm^3

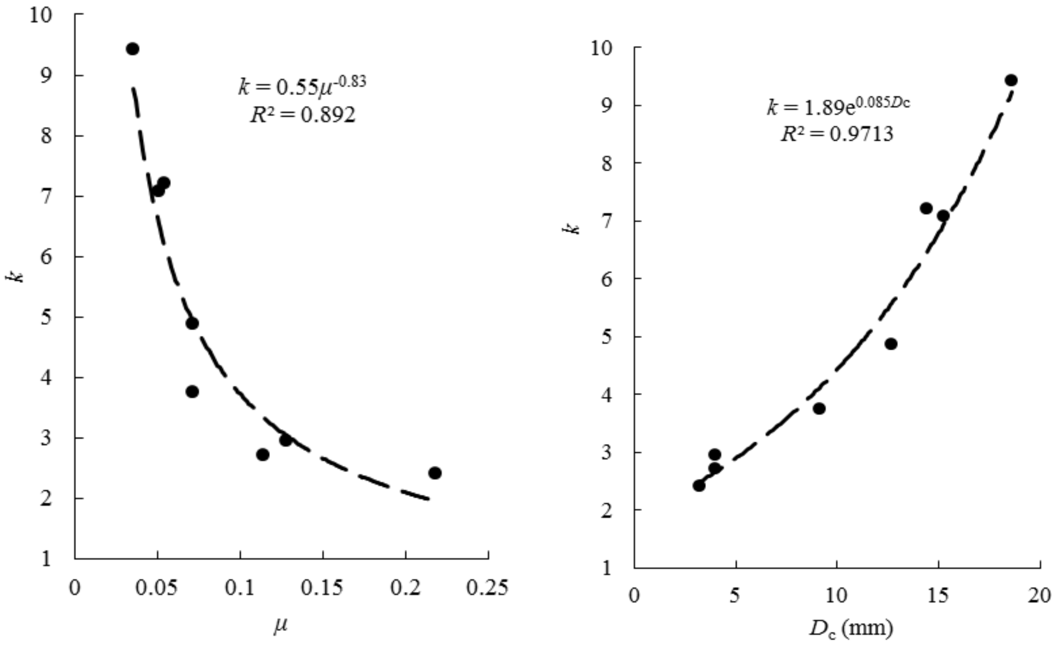

Fig.14 Relationship between k and GSD parameters (μ, D_c)

In fact, when μ is larger and D_c is smaller, the fluid is more uniform and the interaction between grains is weaker. The impact process is closer to the impact process of the slurry, so the value of the dynamic correction coefficient k is smaller. With the increase of D_c and the decrease of μ, the non-uniformity of the grain composition in the fluid increases, and the interaction between the grains also gradually increases, which leads to an increase in the non-uniformity of the entire fluid, which in turn increases the dynamic correction coefficient k. On the other hand, an increase in D_c and a decrease in μ also result in an increase in fluid density and a decrease in F_r, which causes more debris flow material to accumulate in front of the dam, increasing the proportion of static earth pressure, which also leads to dynamics An important reason for the increase of the correction coefficient k.

3. Summary

The effects of grain composition on debris flow related properties are studied through GSD parameters. The results show that GSD parameters are more sensitive to the change of debris flow grain composition, which is a comprehensive reflection of the characteristics of debris flow GSD. The close relationship between GSD parameters and debris flow rheological parameters, density, velocity and impact force shows that debris flow is a special fluid with obvious granular effect, it is necessary to study the grain composition characteristics and formation mechanism of various debris flows with different properties.