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Mean Velocity Estimation of Viscous Debris Flows

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ABSTRACT: The mean velocity estimation of debris flows, especially viscous debris flows, is an important part in the debris flow dynamics research and in the design of control structures. In this study, theoretical equations for computing debris flow velocity with the one-phase flow assumption were reviewed and used to analyze field data of viscous debris flows. Results show that the viscous debris flow is difficult to be classified as a Newtonian laminar flow, a Newtonian turbulent flow, a Bingham fluid, or a dilatant fluid in the strict sense. However, we can establish empirical formulas to compute its mean velocity following equations for Newtonian turbulent flows, because most viscous debris flows are turbulent. Factors that potentially influence debris flow velocity were chosen according to two-phase flow theories. Through correlation analysis and data fitting, two empirical formulas were proposed. In the first one, velocity is expressed as a function of clay content, flow depth and channel slope. In the second one, a coefficient representing the grain size nonuniformity is used instead of clay content. Both formulas can give reasonable estimate of the mean velocity of the viscous debris flow.
KEY WORDS: debris flow, velocity, one-phase flow, two-phase flow, viscous.

0 INTRODUCTION

Debris flow velocity is a key part of debris flow dynamics. It is also one of the key parameters for the design of debris flow control structures. Debris flows are classified into five types: water-stone flow, mudflow, low-viscous debris flow, sub-viscous debris flow and viscous debris flow. The viscous type is the most common type in China. It is also among the most destructive types because of the high mobility. Thus, much attention has been paid to the velocity estimation of viscous debris flows.

Debris flow velocity can be computed in three methods. The first is numerical simulation. There are many studies associated with this work (e.g., Armanini et al., 2009; Iverson, 1997; Hungr, 1995). In these studies, mass and momentum conservation equations were established using the depth-integrated method based on the continuum theory, and debris flow propagation and deposition were then simulated. The key steps in this method are the selection of flow resistance equations and the determination of rheological parameters, which can be obtained with laboratory experiments. However, simulations with experimental parameters may produce significant errors, because large boulders are not included in the experiment (Boniello et al., 2010; Prochaska et al., 2008). Consequently, rheological parameters are usually back-analyzed with field data in practical applications, and many data are required, such as flow depth and flow velocity along the channel, inundation extent, etc.. These data are difficult to obtain in low-frequency debris flow valleys.

In the second method, debris flow velocity is computed with the superelevation height at the bend section of the channel. When a debris flow travels around a bend, the flow surface is higher at the outside wall than the inside wall. The difference, defined as superelevation height, is related with flow velocity, channel width and radius of curvature at the bend. So if the bend geometry is known, the superelevation height can be used for computing flow velocity (McClung, 2001). Nevertheless, Prochaska et al. (2008) found that radii of curvature estimates vary among different investigated approaches. It would bring a lot of uncertainty to the computed velocity.

The third method refers to the empirical formulas that mainly follow the Manning-Strickler equation or the Chezy equation and compute debris flow velocity with the channel slope, hydraulic radius or flow depth. Most of these formulas were established for a specific channel with abundant observation data (e.g., Cheng et al., 1997; Wu et al., 1990). So they are only locally effective. Some formulas have been synthetically developed with field measurements from different channels. Factors associated with sediment properties were employed to estimate Manning coefficient or Chezy coefficient in these formulas. For instance, Wang et al. (2003) employed the ratio of the cohesive fraction to the sandy fraction, Shu et al. (2003) employed the characteristic grain size D_{10}, for which 10% of the sediment material is finer in diameter, Yu (2008) employed the ratio of two characteristic grain sizes D_{50}/D_{10}, and Julien and Paris (2010) employed the ratio of flow depth to median grain size, h/D_{50}. These formulas are effective in a wider range. However, it requires further study to evaluate which factor debris flow velocity is more sensitive to.

This study focuses on mean velocity estimation of viscous

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debris flows, introduces field data used in the present study, and theoretical equations for computing debris flow velocity with the one-phase flow assumption are reviewed and their feasibilities for viscous debris flows are discussed. Then influencing factors of debris flow velocity are determined and then new empirical formulas are proposed. Finally, conclusions are summarized.

1 DATA SOURCES

Some of the observation data used in this study are provided by the Dongchuan Debris Flow Observation and Research Station, Chinese Academy of Sciences (CAS), and the others are collected from the technical literature published by Chen et al. (1983), Kang et al. (2006), and Lanzhou Institute of Glaciology and Cryopedology, CAS (1982). These data include observations from Jiangjia Gully, Dabaini Gully, Hunshui Gully, Liuwan Gully, Niwan Gully, Huoshao Gully, Beihou Gully, and Duludr River. The first three regions are located in Yunnan Province of China. The middle four are located in Gansu Province of China, and the last one is located in the former Soviet Union. Following the classification criteria in the source literature, debris flows having a bulk density greater than 1 800 kg/m^3 are classified as the viscous type in Gansu Province, while the lowest bulk density for a viscous debris flow is 2 000 kg/m^3 in the other regions. In addition, data of Jiangjia Gully were collected in two periods, 1982 and 2004–2007. Observation instruments were different in the two periods, and it produced different magnitudes of measurement error. So these data are analyzed separately in the subsequent sections. Data collected in 1982 and in 2004–2007 are labeled JJG-I and JJG-II, separately.

Each set of data covers mean flow velocity, flow depth, channel slope and bulk density of the debris flow, some also including grain size composition of the sediment material. The number of the dataset in each region is listed in Table 1.

2 THEORETICAL EQUATIONS WITH ONE-PHASE FLOW ASSUMPTION

The velocity difference between solid particles and the interstitial fluid is negligible in a viscous debris flow. So some researchers treat the viscous debris flow as a homogeneous fluid, i.e. one-phase flow, and describe the constitutive equation with rheological models (e.g., Schatzmann et al., 2009; Coussot et al., 1998). The Herschel-Bulkley model is commonly used as follows

$$\tau=\tau_y+K\dot{\gamma}^m \tag{1}$$

where τ is shear stress, τ_y is yield stress, K is consistency coefficient, and m is flow behavior index. In Equation (1), if τ_y=0 and m=1, the fluid represents a Newtonian fluid, while τ_y=0 and m=2 a dilatant fluid, and τ_y>0 and m=1 a Bingham fluid.

Irrespective of the lateral resistance, theoretical equations for computing mean velocity of the Newtonian laminar flow, the dilatant grain-shearing flow and the Bingham fluid respectively follow.

Newtonian laminar flow

$$V=\frac{1}{3}\frac{\rho g h^2 S}{\mu} \tag{2}$$

Dilatant grain-shearing flow

$$V=\frac{2}{5}\frac{h^{3/2}}{\lambda D_{50}}\sqrt{\frac{\rho g S}{k_1\rho_s}} \tag{3}$$

Bingham fluid

$$V=\frac{\rho g H^2 S}{2\eta}\left(1-\frac{H}{3h}\right) \tag{4}$$

$$H=h-\frac{\tau_y}{\rho g S} \tag{5}$$

where ρ is debris flow density, g is gravitational acceleration, h is flow depth, S is channel slope, μ is dynamic viscosity, η is Bingham viscosity, λ is linear grain concentration, H is effective shear depth, D_{50} and ρ_s are median grain size and mass density of the solid particles, respectively, and k_1=0.013 is a coefficient.

The mean velocity of a Newtonian turbulent flow can be computed with the Manning-Strickler equation

$$V=\frac{1}{n}h^{2/3}S^{1/2} \tag{6}$$

where n is Manning coefficient.

The two variables, μ and η, are positively correlated with debris flow density ρ. Manning coefficient n is closely related with channel bed roughness as represented by D_{50}. As a result, when a debris flow is defined as a Newtionian laminar flow or a Bingham fluid, V/h^2 is negatively correlated with ρ. For the dilatant grain-shearing flow case, $V/h^{3/2}$ is negatively correlated with λD_{50}, and for the Newtonian turbulent flow case, $V/h^{2/3}$ is negatively correlated with D_{50}.

The datasets of Jiangjia Gully, Hunshui Gully and Liuwan Gully are more complete than those of the other regions, and are thus used to analyze the fluid property of viscous debris flow. Correlation coefficients of V/h^2 and ρ, $V/h^{3/2}$ and λD_{50}, $V/h^{2/3}$ and D_{50} were calculated respectively for each gully and are listed in Table 2. The maximum packing fraction of the

Table 1 The number of datasets of viscous debris flows from each region

Region	JJG-I	JJG-II	Hunshui Gully	Liuwan Gully	Niwan Gully	Huoshao Gully	Beihou Gully	Dabaini Gully	Duludr River
N_1	8	26	11	14	14	10	4	29	13
N_2	8	26	8	10	3	3	0	0	0

Note: N_1 represents the number of dataset only consisting of mean flow velocity, flow depth, channel slope, and bulk density; N_2 represents the number of dataset with grain size composition included.

Table 2 Correlation coefficients between some variables

Region	$R(V/h^2, \rho)$	$R(V/h^{3/2}, \lambda D_{50})$	$R(V/h^{2/3}, D_{50})$
JJG-I	-0.539	-0.469	-0.609
JJG-II	-0.336	-0.291	-0.446
Hunshui Gully	0.244		0.068
Liuwan Gully	-0.218		0.232

sediment material is required for estimating λ. There is no information about this parameter in Hunshui Gully and Liuwan Gully. So there are no correlation coefficient values of $V/h^{3/2}$ and λD_{50} in these two gullies. Overall, in Table 2 only one correlation coefficient value, $R(V/h^{2/3}, D_{50})$ for JJG-II, passes the significance level p=0.05. The other values are too small to show any correlation between the analyzed variables. It means that the viscous debris flow is difficult to be classified as a Newtonian laminar flow, a Newtonian turbulent flow, a Bingham fluid, or a dilatant fluid in the strict sense. If we have to select one from these four types of flow, the Newtonian turbulent flow may be more reasonable.

3 EMPIRICAL FORMULAS FOR VELOCITY ESTIMATION

As analyzed above, the viscous debris flow is difficult to be classified as any type of the four typical flows. So the theoretical equations listed in the previous section are unsuitable for estimating mean velocity of the viscous debris flow, and empirical formulas are still necessary.

3.1 Analysis of Potential Influencing Factors

Factors influencing debris flow velocity were discussed in the previous section with the one-phase flow assumption. They include h, S, ρ and D_{50}. Besides, viscous debris flows have been treated as a two-phase flow in more and more studies. In order to determine the influencing factors more comprehensively, it is necessary to review current typical two-phase flow models for the viscous debris flow before establishing new empirical formulas.

3.1.1 Bed load+suspension load

Fei and Shu (2004) carried out their studies on viscous debris flows with the sediment transport theories. They took the fine fraction of the sediment as suspension load while the coarse fraction as bed load, and proposed a two-phase flow model. In the model, the fluid phase consists of the fine fraction and water. It distributes uniformly and turbulent stress dominates in the flow. The solid phase refers to the coarse fraction which concentrates at the flow bottom and frictional stress is the dominant resistance. The variable representing flow intensity, Θ, and the variable representing sediment transport intensity, Φ, are usually employed in the studies of bed load transport. They are expressed as (Qian and Wang, 1984).

$$\Theta=\frac{\rho_f RS}{(\rho_s-\rho_f)D_b} \tag{7}$$

$$\Phi=V_b hC_b\left(\frac{\rho_f}{\rho_s-\rho_f}\right)^{1/2}\left(\frac{1}{gD_b^3}\right)^{1/2} \tag{8}$$

where ρ_f is bulk density of the fluid phase, R is hydraulic radius, V_b, C_b, and D_b are mean velocity, volume concentration and representative grain size of the bed load respectively.

As Θ and Φ are positively correlated, V_b is positively correlated with S and negatively correlated with C_b.

3.1.2 Newtonian fluid with inhomogeneous vertical distribution of particle concentration

Phillips et al. (1992) proposed a constitutive equation for computing the distribution of particle concentration in a neutrally buoyant suspension. On this basis, Takahashi (2007) took into account the effect of gravity and established a heterogeneous fluid theory for viscous debris flows. Moving particles in adjacent shearing layers can collide with each other and generate a particle flux perpendicular to the main flow direction. In a steady flow, particle flux induced by collision is balanced by that induced by gravity. Then the vertical distribution of particle concentration can be simulated and flow velocity at different depths can be computed with the Newtonian laminar flow equation. Relationships between the computed mean velocity and fluid factors are analyzed with this theory. The following relationship is found.

$$V\propto\frac{h^2S}{\mu} \tag{9}$$

3.1.3 Excess pore water pressure+granular flow

Iverson et al. (2010), Iverson and Vallance (2001), and Iverson (1997) carried out fruitful studies on debris flow movement, deposition, and erosion with large-scale flume experiments. Granular friction was considered as the dominant resistance in debris flow. If permeability of the sediment material is low, the excess pore water pressure generated by particle rearrangement will retain in the duration of a debris flow event and reduce the frictional resistance. It dissipates more slowly with the decrease of sediment permeability. So it can be deduced that resistance of debris flow is negatively correlated with the sediment permeability. Since sediment permeability has been found to be associated with sediment properties, such as porosity, grain size nonuniformity, and clay content (Zheng, 2010), debris flow velocity may be positively correlated with particle concentration, C, clay content, p, and grain size nonuniformity represented by D_{50}/D_{10} here.

Furthermore, the magnitude of frictional resistance is also related with the friction coefficient. Iverson et al. (2010) adopted the latest achievement in granular flow research that the effective friction coefficient, μ_{eff}, is positively correlated with the inertia index, I (Forterre and Pouliquen, 2008; MiDi, 2004). I is expressed as

$$I=\frac{VD}{h\sqrt{gh\cos\theta}} \tag{10}$$

where θ is inclination angle of the channel. So for granular flows with the same μ_{eff} value, inertia indexes are equal, and the following relationship exists among V, h and D

$$V\propto\frac{h^{1.5}}{D} \tag{11}$$

3.2 Selection of Influencing Factors

According to the above analysis, ρ, h, S, p, D_{50}, D_{50}/D_{10}, and h/D_{50} are potential factors influencing debris flow velocity. Besides, D_{10} is also adopted as a potential influencing factor based on the research of Fei and Shu (2004). Datasets of Jiangjia Gully, Hunshui Gully, and Liuwan Gully were used once again to analyze the correlation coefficients between debris flow velocity and these factors. The results are listed in Table 3.

If the relationship between debris flow velocity and any factor is significant, the significance level is given in Table 3. Overall, debris flow velocity is positively correlated with flow depth in all the three regions. It is unimaginable that the statistical results manifest that flow velocity has no correlation, or a negative correlation, with channel slope. This phenomenon is induced by the small range of channel slope values in a specific Gully. So the correlation coefficient between V and S in an individual gully has little meaning. In addition, the dataset of Jiangjia Gully shows that flow velocity is positively correlated with h/D_{50}. It is mainly induced by the high correlation coefficient between h and h/D_{50}, 0.625 and 0.714 for JJG-I and JJG-II, respectively. As a result, h and S are used as main factors for establishing empirical formulas in the subsequent section, and then the relationship between key parameters of the formula and the other factors will be analyzed.

3.3 Foundation of Empirical Formulas

3.3.1 Form of the Formula

The analysis in section 2 shows that the viscous debris flow more approximates a Newtonian turbulent flow than the other types of flow. However, the stream surface of a viscous debris flow usually appears stable, and looks like a laminar flow. So first of all the dataset of Jiangjia Gully, which includes the most complete observation elements, were used to evaluate the flow regime of viscous debris flows. Data used here were collected in 2004–2007.

Reynolds number, Re, was used for the estimation of flow regime

$$Re=\frac{4hV\rho}{\eta} \tag{12}$$

The viscosity of a debris flow is difficult to measure in laboratory due to the presence of large boulders. So it was estimated with the Krieger-Dougherty equation (Krieger, 1972) together with the viscosity of the slurry. Then Reynolds number was computed. It varies in the range $4\,860<Re<246\,971$.

For a yield stress fluid, the critical Reynolds number, Re_c, is not a constant. It depends on the relative depth of flow core, r_h, as follows (Fei and Shu, 2004)

$$Re_c=\frac{2\,100}{1-\frac{3}{2}r_h+\frac{1}{2}r_h^3} \tag{13}$$

$$r_h=\frac{\tau_y}{\rho g h S} \tag{14}$$

Wu et al. (2003) computed the yield stress of debris flow in Jiangjia Gully with the depth of deposits, and developed an empirical relationship between τ_y and ρ. Values of τ_y computed with this relationship were used to derive Re_c following equations (13) and (14). Figure 1 shows the result.

There is a trend for Re to decrease with increasing values of ρ while Re_c shows an inverse trend. For ρ=2 000 kg/m^3, $Re>>Re_c$. For ρ>2 220 kg/m^3, Re is close to or even smaller than Re_c. Overall, Re is greater than Re_c for 21 surges out of the total 26 surges, indicating that the viscous debris flows are mainly turbulent. Thus, we can establish the empirical formula following the form of Equation (6)

$$V=Ah^bS^c \tag{15}$$

It is also the general form for computing debris flow velocity in the literature.

3.3.2 Determination of parameters in the formula

In order to guarantee the physical meaning, parameters in Equation (15) were not determined simultaneously through data fitting. Instead, they were determined step by step.

There are many reports about parameters b and c in the literature. In the Chezy equation, b=c=1/2. In the Manning-Strickler equation, b=2/3 and c=1/2. These two equations are used for the steady uniform flow in open channels. In the formulas specially developed for debris flows, Shu et al. (2003) used b=1/3 and c=1/6; Yu (2008) used b=1/2 and c=1/3; some researchers used b=0.3 and c=0.5 (Rickenmann, 1999). Since the three values, 1/6, 1/3 and 1/2, are usually assigned to

Table 3 The correlation coefficient between debris flow velocity and each factor

Region	N_1	N_2	$R(V, \rho)$	$R(V, h)$	$R(V, S)$	$R(V, p)$	$R(V, D_{10})$	$R(V, D_{50})$	$R(V, D_{50}/D_{10})$	$R(V, h/D_{50})$
JJG-I	8	8	0.538	0.964 (0.001)	-0.730 (0.05)	-0.311	0.278	0.223	-0.474	0.732 (0.05)
JJG-II	26	26	0.208	0.577 (0.01)	0.162	-0.245	0.235	0.186	0.049	0.505 (0.01)
Hunshui Gully	11	8	-0.157	0.951 (0.001)	0.000	-0.576	0.408	0.623	0.004	0.465
Liuwan Gully	14	10	0.205	0.615 (0.02)	-0.159	0.180	-0.615	-0.582	-0.340	0.354

Note: N_1 and N_2 have the same meanings as in Table 1. Data in the bracket represent the significance levels, which are classified into four grades: 0.05, 0.02, 0.01, and 0.001.

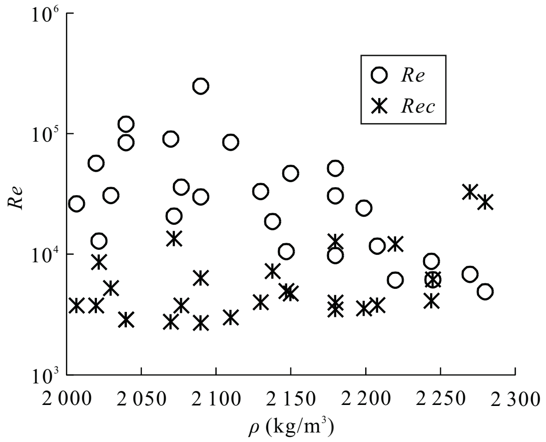

Figure 1. The Reynolds number and critical Reynolds number of viscous debris flows in Jiangjia Gully.

parameter c, all of the 129 sets of data summarized in Table 1 were used to fit V/S^c and h according to Equation (15) using c=1/6, c=1/3 and c=1/2, respectively. The results are listed in Table 4. No matter which value is assigned to parameter c, the regressed value of parameter b is around 0.5. So parameter b was determined first, i.e., b=1/2.

$V/h^{1/2}$ is plotted against S in Fig. 2. Most of the data points concentrate in the zone S<0.1, where $V/h^{1/2}$ increases with S. $V/h^{1/2}$ decreases instead in the zone S>0.1. The other factors may be at work. So it is difficult to determine parameter c with Fig. 2.

Parameter A in Equation (15) was derived for each dataset with the combination of b=1/2 and c=1/6, c=1/3 and c=1/2, respectively. Then the correlation analysis was performed between A and the potential influencing factors mentioned in section 3.2 using the datasets having grain size information (totally 58 sets of data). Table 5 lists the result. It shows that there is no significant correlation between A and ρ. Significance levels of the correlation coefficients between A and p, D_{50}, D_{50}/D_{10}, h/D_{50} are all less than 0.01. Out of them, the correlation coefficients between A and p, D_{50}/D_{10} even pass the significant level of 0.001. So factors p and D_{50}/D_{10} were used for the further analysis.

Parameter A was regressed as a power function of p and D_{50}/D_{10} separately with c=1/6, c=1/3 and c=1/2, respectively. The regressed values of A were then employed to estimate debris flow velocity. The mean absolute relative error (MARE) between estimated velocities and observations was computed for each gully and for all the datasets as listed in Table 6. If c=1/6, though the overall error is the smallest, values of MARE are greater than 30% for Niwan Gully. If c=1/3, values of MARE are within 30% for each gully. If c=1/2, the error is relative large for Huoshao Gully. So c=1/3 is recommended. Then the empirical formula using p is

$$V = 6.54p^{0.39}h^{1/2}S^{1/3} \tag{16}$$

The formula using D_{50}/D_{10} is

$$U = 7.04\left(D_{50}/D_{10}\right)^{0.11} h^{1/2}S^{1/3} \tag{17}$$

Equation (17) is similar with Yu's result (Yu, 2008). The difference is that the flow depth is used in Equation (17) and it is easier to get in field investigation than the hydraulic radius used by Yu. In addition, more observation data were used for the derivation of Equation (17), leading to a different value for the exponent of D_{50}/D_{10}, 0.11 here and 0.25 in Yu's result.

Equations (16) and (17) reveal some movement behaviors of the viscous debris flow. The significant correlation of debris flow velocity with flow depth means a vertical gradient in the flow velocity. It agrees with the field observation that the front part of a debris flow surge usually rolls from top to bottom, which means a larger velocity at the surface. S is a factor related with energy. It reflects the role of gravity as a driving force for the debris flow. p and D_{50}/D_{10} reveal the influence of the solid phase. Solid concentration is high for a viscous debris flow, and particles contact with each other in the movement. Excess pore water pressure can be generated by grain rearrangement at the initiation stage or by turbulent fluctuation in movement (Hotta, 2012; Iverson, 1997). With the increase of clay content and nonuniformity of grain size composition, the dissipation of pore water pressure is retarded and the frictional resistance is reduced.

Generally, empirical formulas are only effective in a specified range. In the present study, p varies in the range 2%<p<14% while D_{50}/D_{10} varies in the range 40<D_{50}/D_{10}< 1 500, as shown in Figs. 2 and 3. In the cases of p=0% and p=100%, values of A will be respectively 0 and 39.41 according to Equation (16). The former value of A is evidently unreasonable. The minimum value of D_{50}/D_{10}, 1.0, corresponds to a value of A=7.04 based on Equation (17). This value of A is still reasonable. In this perspective, Equation (17) performs better than Equation (16) in extensibility.

Table 4 The fitting results of Equation (15) for different values of c

c	A	b	R^2
1/6	7.83	0.488	0.516
1/3	12.43	0.475	0.502
1/2	19.71	0.462	0.468

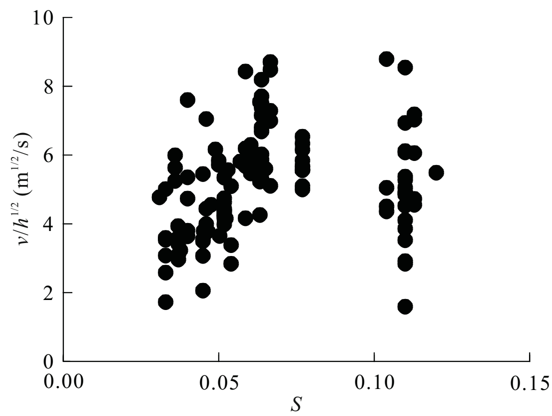

Figure 2. The relationship of $V/h^{1/2}$ and channel slope S.

Table 5 The correlation coefficient, *R*, between parameter *A* in Equation (15) and each influencing factor

c	$R(A, \rho)$	$R(A, p)$	$R(A, D_{10})$	$R(A, D_{50})$	$R(A, D_{50}/D_{10})$	$R(A, h/D_{50})$
1/6	0.201	0.559	-0.327	0.392	0.544	-0.354
1/3	0.225	0.581	-0.270	0.411	0.557	-0.405
1/2	0.239	0.587	-0.215	0.417	0.555	-0.442

Table 6 Mean absolute relative error for each gully with estimated values of *A* (%)

Region	A is expressed as a function of p			A is expressed as a function of D_{50}/D_{10}		
	c=1/6	c=1/3	c=1/6	c=1/6	c=1/3	c=1/2
JJG-I	7.6	8.1	3.6	3.6	3.3	4.7
JJG-II	15.5	15.6	17.0	17.0	16.7	17.2
Hunshui Gully	11.5	10.5	6.9	6.9	8.7	14.2
Liuwan Gully	15.5	18.7	16.6	16.6	24.6	30.6
Niwan Gully	32.7	25.7	34.6	34.6	29.9	22.1
Huoshao Gully	24.1	28.6	22.4	22.4	28.8	31.3
Overall	15.2	15.6	14.9	14.9	16.4	18.4

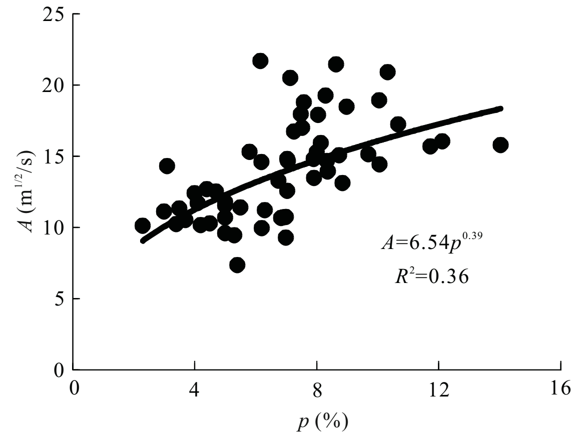

Figure 3. The relationship of parameter *A* in Equation (15) with clay content *p*.

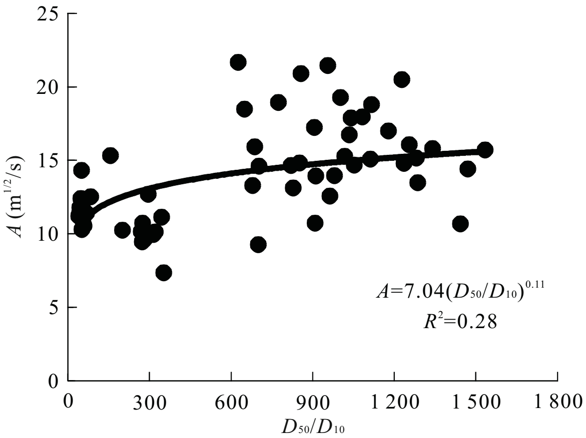

Figure 4. The relationship of parameter *A* in Equation (15) with D_{50}/D_{10}.

4 CONCLUSIONS

The following conclusions can be drawn though analyzing the field data of viscous debris flows.

(1) It is difficult to classify the viscous debris flow as a Newtonian laminar flow, a Newtonian turbulent flow, a Bingham fluid, or a dilatant fluid in the strict sense. However, we can establish empirical formulas to compute its mean velocity following equations for the Newtonian turbulent flow, because most viscous debris flows are turbulent.

(2) Mean velocity of the viscous debris flow has a significant correlation with flow depth and channel slope. In addition, it is influenced by the sediment properties represented by clay content and grain size nonuniformity, because the increase of these two variables can enhance retaining excess pore water pressure.

(3) Two empirical formulas have been developed. In the first one, clay content, flow depth and channel slope were used to estimate the mean velocity of a viscous debris flow. In the second one, D_{50}/D_{10} was used instead of clay content. Both formulas can give reasonable results with an error of about 16%.

Grain size composition varies with the sampling time and the sampling position for a debris flow event. So estimates with equations (16) and (17) can be used together for comparison in practical application.

The observation data of debris flow movement are rare in the world. All the observation data of different debris flow valleys in China have been used to set up the empirical formulas in this study. So errors of these formulas are analyzed with these observation data. Observation data from debris flow valleys in the other countries can be found in the literature. However, grain size information is usually absent. So it is difficult to test the empirical formulas with these data. If new data are available, the formulas will be further tested.

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2004–2007 were provided by the Dongchuan Debris Flow Observation and Research Station, CAS.

NOTATION

A	Constant in velocity Equation (15)
b	Exponent of h in velocity Equation (15)
C	Solid volume concentration of debris flow
c	Exponent of S in velocity Equation (15)
C_b	Volume concentration of the bed load
D_{10}	Characteristic grain size for which 10% of the sediment material is finer in diameter
D_{50}	Median grain size
D_b	Representative grain size of the bed load
g	Gravitational acceleration
H	Effective shear depth
h	Flow depth
I	Inertia index
K	Consistency coefficient in the Herschel-Bulkley fluid model
k_1	Constant in velocity Equation (3)
m	Flow behavior index in the Herschel-Bulkley fluid model
n	Manning coefficient
p	Clay content of the sediment material
R	Hydraulic radius
Re	Reynolds number
Re_c	Critical Reynolds number
r_h	Relative depth of the flow core
S	Channel slope
V	Mean flow velocity
V_b	Mean velocity of the bed load
C_b	Volume concentration of the bed load
Θ	Flow intensity
Φ	Sediment transport intensity
$\dot{\gamma}$	Shear rate
η	Bingham viscosity
θ	Inclination angle of the channel
λ	Linear grain concentration
μ	Dynamic viscosity
μ_{eff}	Effective friction coefficient
ρ	Debris flow density
ρ_f	Bulk density of the fluid phase of debris flow
ρ_s	Mass density of the solid particles
τ	Shear stress
τ_y	Yield stress

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