Discussion of "Mean Velocity of Mudflows and Debris Flows" by Pierre Y. Julien and Anna Paris

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The authors predicted mudflow and debris flow velocities with 350 field and laboratory measurements and obtained a slight trend for V/u^* to increase with h/d_{50}, and the ratio of V/u^* is approximately 10 and rarely exceeds 30. The logarithmic relationship of turbulent resistance agrees reasonably well with the measurements. Good results also are obtained with the Manning-Strickler approach. The dispersive stress equation also compares well with the measurements, but only when $h/d_{50} < 50$. For individual series data such as Hashimoto and Puerco, there is a trend for V/u^* to increase with h/d_{50}. But for other individual series data, such as Davies, Rickenmann, Paris, St. Helens, Nevado del Ruiz, Wanglin, Wang, and Wenhai, there is a trend for V/u^* to decrease with h/d_{50} (Fig. 1 of the original paper). The discussers have some field data that also show the same phenomena, which are presented in Fig. 1. The database includes a total of 119 flow velocity measurements, in which each point includes flow depth, density (volume concentration), median grain diameter d_{50}, grain size of less than 10% d_{10}, and slope. The data of Jiangjia were obtained from the field measurements in Jiangjia Ravine, Yunnan, China, in 1999; the data of Hunshui were obtained from the field measurements in Hunshui Ravine, Yunnan, China, in 1976–1978; and the data of Liuwan were obtained from the field measurements in Liuwan Ravine, Gansu, China, in 1963–1964.

Debris flow is a gravity flow, and the gravity force plays an important role in the movement of debris flow. So debris flow moves on a large slope and deposits on a small slope. Fei and Su (2004) showed that the main driving force of debris flow is provided by particles, not by water. When the volume concentration $C = 0.27$ (or density $\rho = 1.46\ \mathrm{g/cm^3}$), the particle driving force is equal to the water driving force in debris flow. They defined that the minimum density of debris flow is $1.46\ \mathrm{g/cm^3}$, and 1.46–$1.80\ \mathrm{g/cm^3}$ is the range of less viscous debris flow. Therefore, the minimum density of viscous debris flow is $1.80\ \mathrm{g/cm^3}$ ($C = 0.47$) (Fei and Su 2004; Yu 2008a). Two types of shear stresses describe these two kinds of debris flows: (1) the viscous stress for viscous debris flow, and (2) the turbulent stress for less viscous debris flow (Fei and Su 2004).

As the driving force of debris flow is provided primarily by particles, the coarse particle plays an important role in the movement of debris flow, especially for viscous debris flow with a large volume concentration. So the larger particle diameter, the larger is the velocity. There is a trend for V to increase with d_{50}, and there is a trend for V/u^* to increase with d_{50}/h. Two empirical equations of mean velocity of viscous debris flow described this relationship (Wu et al. 1993; Yu 2001):

$$\frac{V}{u^*} = 27.57\left(\frac{d_{50}}{h}\right)^{0.245} \qquad (1)$$

$$\frac{V}{u^*} = 10\left(\frac{C}{S}\right)^{1/3}\left(\frac{d_{50}}{h}\right)^{1/6} \qquad (2)$$

Eqs. (1) and (2) show the trend for V/u^* to increase with d_{50}/h (Fig. 1). As Eqs. (1) and (2) were obtained from some field data of viscous debris flows, they may not be good for less viscous debris flows, mudflows, and stony debris flows.

Wu et al. (1993) summarized many field data studies of velocities of debris flows in China, and showed that there are high-speed debris flows and low-speed debris flows in different areas. Yu (2008b) found that the asymmetric coefficients (this is the ratio of midvalue grain size d_{50} and grain size of less than 10% d_{10} of the sediment in debris flow) of debris flows are quite different, and showed that debris flows with high velocities have large asymmetric coefficients, whereas debris flows with low velocities have small asymmetric coefficients. The asymmetric coefficients of debris flows could be used to classify resistance and velocity characteristics of debris flows. There is a slight trend for V/u^* to increase with d_{50}/d_{10}. An empirical equation of mean velocity of viscous debris flow described this relationship (Yu 2008b):

$$\frac{V}{u^*} = 1.1S^{-1/6}\left(\frac{d_{50}}{d_{10}}\right)^{1/4} \qquad (3)$$

An empirical equation of mean velocity of less viscous debris flow showed a different relationship of mean velocity, shear velocity, and slope (Yu 2009):

$$\frac{V}{u^*} = 1.8S^{-0.4} \qquad (4)$$

Fig. 2 shows that Eqs. (3) and (4) are close to the mean velocity of viscous and less viscous debris flows, respectively. A new relationship for V/u^* to d_{50}/d_{10} obtained from Fig. 2 is described as

$$\frac{V}{u^*} = 3.2\log\left(\frac{d_{50}}{d_{10}}\right) \qquad (5)$$

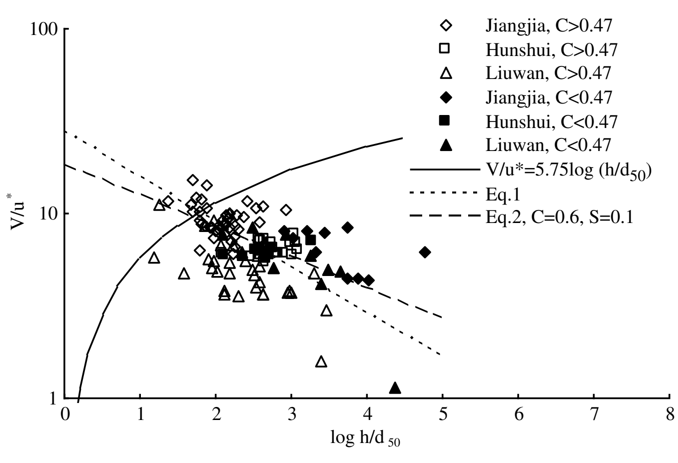

Fig. 1. Resistance to debris flow of field data with h/d_{50}

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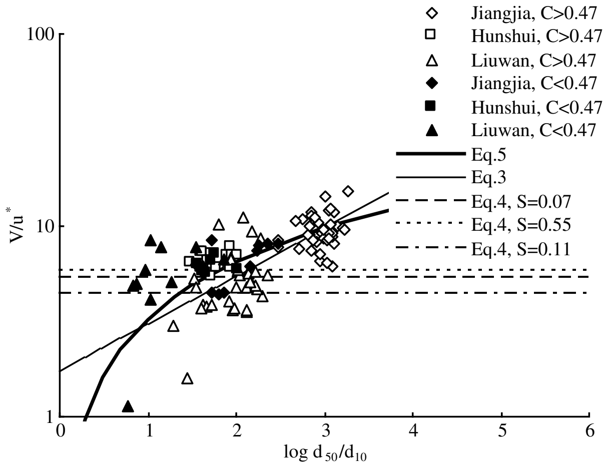

Fig. 2. Resistance to debris flow of field data with d_{50}/d_{10}

Eq. (5) may fit for mean velocity both of viscous and less viscous debris flows, but it may not fit for mean velocity of mudflows and stony debris flows.

No velocity equation can fit all velocities of field measurements because the velocities have a relatively large range. Most flows of debris flows are supercritical flows, in which the Froude number $\mathsf{F} > 1$. This phenomenon also is apparent in the high-resistance debris flow area with low velocity (Yu 2008b, 2009). The reasons for the subcritical flows of debris flows were: (1) the velocities were measured at the fans of debris flows, and the debris flows slowed down at small slope and expanded channels, and (2) there was too much sediment in debris flows, and debris flows could hardly move (Yu 2008b). To mitigate the hazards of debris flows, the supercritical flows are more important than subcritical flows in debris flows. So the component of subcritical flows can be ignored when the velocity equation cannot fit all velocities of debris flows.

Eqs. (3)–(5) were obtained from some field measurements of velocities. They may not fit for mudflows, stony debris flows, and homogeneously sized debris flows. More field and laboratory measurements are needed to discover the relationship between V/u^* and d_{50}/d_{10}. The relationship between V/u^* and d_{50}/d_{10} in this discussion helps to shed light on research on the mean velocity of debris flows.

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Closure to "Mean Velocity of Mudflows and Debris Flows" by Pierre Y. Julien and Anna Paris

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The writers would like to sincerely thank Bin Yu for the enlightening discussion of the article on the velocity of mudflows and debris flows. The discusser purports the view that particles drive debris flows and that V/u^* should decrease with h/d_{50}. The field measurements at three ravines (Jiangjia, Hunshui, and Liuwan) in China are presented, and the relationships derived from these data support this claim. Additionally, the discusser provides valuable information on the role of particle size gradation d_{50}/d_{10} in relation to debris flow velocity.

A priori, it is certainly worth mention that the field measurements presented in the discussion corroborate the conclusions. First, the writers had concluded that the ratio V/u^* is approximately 10 and rarely exceeds 30. The Chinese measurements are also in the range of $1 < V/u^* < 20$, with most data visibly below 10. Second, these field measurements also support the other main conclusion that the turbulent model is better than the dispersive model when $h/d_{50} > 50$. Indeed, with reference to Fig. 1 of the article, the dispersive stress approach would reach V/u^* is approximately 400 when $h/d_{50} = 1{,}000$. At the same value of h/d_{50}, the relationship $V/u^* = 5.75\log(h/d_{50})$ from the original paper predicts $V/u^* \sim 16$, whereas the field measurements in China are slightly less than 10. Thus the turbulent model is a lot closer to the field measurements than the dispersive stress.

The discusser provides a compelling argument that particles drive debris flows and therefore V/u^* should decrease as h/d_{50} increases. It is suggested that the velocity should increase with particle size at a given flow depth and slope, and the data of three ravines support this view. The Jiangjia Ravine data feature among the best debris flow sites in the world and some data had been included in the analysis. In Fig. 1 of the original paper, V/u^* for the Jiangjia Ravine did slightly decrease with h/d_{50}, as described by the discusser. The discussion is also substantiated with data from two other ravines (Hunshui and Liuwan) displaying similar decreasing trends and magnitude. However, the perspective became different from the discusser's viewpoint when the writers broadened the scope of the analysis to a wider database with a range of $\log h/d_{50}$ up to 6. Fig. 1 of this dicussion plots the entire database after highlighting the data sources examined from the Chinese literature. Overall, a perceptible increase in V/u^* with h/d_{50} is seen, even when considering only the data from China.

In an attempt to explain the discrepancies, the following elements of discussion are presented. First, the slope values presented in the discusser's Fig. 2 range from $0.07 < S < 0.55$. These are very steep channels and additional sources of energy dissipation, e.g., hydraulic jumps, are likely to increase resistance to flow far beyond that of simple turbulent shear flows. The discusser states that debris flows in China were generally supercritical and that supercritical flows are more important than subcritical flows. It has to be recognized that in near-critical flows controlled by a

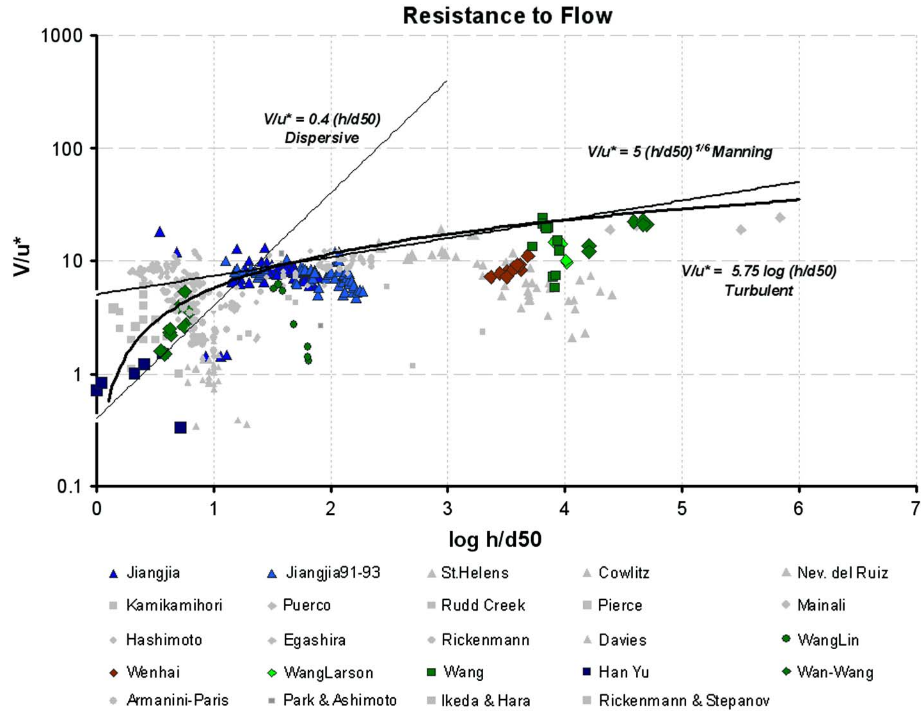

Fig. 1. Resistance to flow for sediment hyperconcentrations highlighting data sources from China

constant Froude number, resistance to flow becomes a function of channel slope S. Given the fundamental relationship $S = (f/8)\ \mathrm{F}^2$ with $\mathrm{F} = 1$, the Darcy-Weisbach friction coefficient f must be equal to 8 times the friction slope, and thus $V/u^* = S^{-0.5}$. This will cause resistance to flow in steep channels to become very large. The point here is that Yu's Eq. (4) defines the relationship between the slope and the Froude number. Specifically using Yu's relationship $V/u^* = 1.8S^{-0.4}$ at slopes ranging from $0.07 < S < 0.55$ implies the following: (1) the corresponding Froude number is $1.38 < \mathrm{F} < 1.7$; (2) the Darcy-Weisbach friction factor is $0.29 < f < 1.52$; (3) and $2.3 < V/u^* < 5.2$. Essentially, values of $V/u^* < 5$ in steep channels are often suspicious because they often describe supercritical flows.

Second, it is interesting that when using the quadratic rheological model of O'Brien and Julien (1985), the yield and viscous stresses need to be subtracted from the total shear stress (e.g., Julien 2010, p. 243). In other words, the presence of yield strength and high viscosity will effectively increase resistance to flow. Consequently, highly viscous debris flows like the field observations at Jiangjia Ravine are expected to be found mostly below the curve $V/u^* = 5.75 \log(h/d_{50})$.

Third, this point is probably not the case in the discusser's calculations, but it is nevertheless worth mention. The analysis of resistance to flow requires an adequate definition of shear velocity, and this deserves clarification in sediment hyperconcentrations. In clear water, the value of mass density for water $\rho = 1{,}000\ \mathrm{kg/m^3}$ is used to determine the shear velocity from $u^* = (\tau_0/\rho)^{0.5}$, where τ_0 is the bed shear stress. However, the mass density of the mixture ρ_m should be used in the calculation of shear velocity $u^* = (\tau_0/\rho_m)^{0.5}$ in sediment hyperconcentrations (Woo and Julien 1990). At such high volumetric concentrations $C_v >$ 0.47 (or $\rho_m > 1{,}800\ \mathrm{kg/m^3}$), the use of ρ instead of ρ_m produces artificially high resistance to flow values or low values of V/u^*.

Finally, the discusser's Fig. 2 showing the increase in V/u^* with d_{50}/d_{10} is a true gem. It is well-known that debris flows are well-graded, but the data shown here with d_{50}/d_{10} approximately 1,000 is truly remarkable. This is reminiscent of Fig. 9.3 in Julien (2010), in which the bedload particle velocity V_p varies with the ratio between the rolling bedload particle diameter and the bed roughness size. The range $5 < V/u^* < 15$ presented in Yu's Fig. 2 is very similar to the range of bedload particle velocities V_p on rough surfaces $3 < V_p/u^* < 12$ in Julien (2010). This similarity between debris flows and bedload motion seems to corroborate the discusser's view that the particles are driving debris flows.

In closing, the writers appreciate the increased interest in sediment hyperconcentrations and are truly grateful for Bin Yu's discussion. Mudflows and debris flows have adversely affected most mountainous countries around the world. Better predictions of the velocities of mudflows and debris flows can lead to improved design of mitigation structures. The writers are hopeful that this article and discussion will contribute to advances in the development of appropriate remediation structures for hazard reduction and disaster prevention.

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