Mean Velocity of Mudflows and Debris Flows

Pierre Y. Julien, M.ASCE[1]; and Anna Paris[2]

Abstract: Models to predict mudflow and debris flow velocities are tested with 350 field and laboratory measurements. Overall, the turbulent model performs best while the dispersive stress approach only compares well with the measurements when the flow depth h is less than 50 times the median particle diameter d_{50}. The analysis of field measurements shows that the ratio of mean flow velocity V to shear velocity u^* is approximately 10, rarely exceeds 30, and increases slightly with relative submergence h/d_{50}. The best overall agreement with laboratory and field velocity measurements is obtained with $V=5.75u^* \log h/d_{50}$.

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Introduction

Worldwide occurrences of mudflows and debris flows in mountain areas have garnered increasing attention in recent decades. In mountain areas, mudflows and debris flows are usually triggered by exceptional combinations of rainfall, snowmelt, and/or volcanic eruptions. The destructive momentum forces generated during mudflows and debris flows threaten living communities, particularly on alluvial fans. The devastating consequences are often without warning and handled with emergency rescue operations. For instance, the debris flow disaster in Venezuela (Lopez 2000) provides yet another example of the magnitude of the natural forces generated from surface runoff and sediment transport in very steep mountains. In this perspective, the need to pursue international research on the mean velocities of mudflows and debris flows becomes evident.

Hyperconcentrated sediment flows have been classified by the National Research Council (NRC) (1982) as mudfloods, mudflows, and debris flows. Distinct physical processes differentiate these types of hyperconcentrations based on the rheology of the water-sediment mixture (O'Brien and Julien 1985; Julien and Lan 1991). Four types of shear stresses describe hyperconcentrations: (1) the yield stress; (2) the viscous stress; (3) the turbulent stress; and (4) the dispersive stress. Julien and Leon (2000) proposed a classification for hyperconcentrated sediment flows and mitigation structures based on the dominant shear stress from these four components. Accordingly, the turbulent shear stress is dominant in mudfloods, the yield and viscous stresses are dominant in mudflows, and the dispersive stress is dominant in debris flows. Other nomenclatures have been proposed and more detailed information on the physical processes of mudflows and debris flows can be found in Takahashi (1991), Wan and Wang (1994), Contreras and Davies (2000), and Iverson (1997, 2005). Several videos and reports from the flume experiments on debris flow at the USGS Cascades Volcano Observatory from 1992 to 2006 have been compiled by Logan and Iverson (2007) and are available on line at http://pubs.usgs.gov/of/2007/1315/. Valuable recent reviews also include that of Rickenmann and Koch (1997), Coussot (2005), Ancey (2007), and Griswold and Iverson (2008).

The primary objective of this study is to develop engineering guidelines to estimate the mean flow velocity of mudflows and debris flows. The topic of resistance to flow is addressed through a comparison of turbulent and dispersive stress models with field and laboratory measurements. Methods to estimate flow velocities are tested with a substantial database on field and laboratory measurements for mudflows and debris flows.

Resistance to Flow

Resistance to flow relationships define the mean flow velocity V of open channels as a function of the stream slope S, the mean flow depth h, and the size of sediment particles d_s describing channel roughness. A simple force balance in wide open-channel flows gives bed shear stress as $\tau_o=\rho_m ghS$, where g=gravitational acceleration. This allows the definition of a shear velocity $u^*=\sqrt{\tau_o/\rho_m}=\sqrt{ghS}$. Resistance to flow is typically presented in a dimensionless form with the Darcy–Weisbach friction factor f defined as $f=8u^{*2}/V^2$. Alternatively, Manning n can be defined from $n=h^{2/3}S^{1/2}/V$ in International System of Units (Le Système International d'Unités (SI) units. The Manning–Strickler approach shows Manning n proportional to the 1/6 power of grain diameter, as described in Julien (1995, 2002). Resistance to turbulent flows can generally be described by a logarithmic relationship written as

$$\frac{V}{u^*}=\sqrt{\frac{8}{f_t}}=5.75\log\frac{\alpha h}{d_s} \qquad (1)$$

where f_t=Darcy-Weisbach friction factor for turbulent flows. The well-known reference value for α is 12.2 when roughness ele-

[1]Professor of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523-1320 (corresponding author). E-mail: pierre@engr.colostate.edu

[2]Engineering Research Center, Colorado State Univ., Fort Collins, CO 80523-1320; and, Univ. of Trento, I-38122 Trento, Italy. E-mail: annaparis.italy@gmail.com

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ments are glued to plane boundaries. In natural channels, empirical values of $\alpha=3$ can be used when the grain diameter refers to d_{90} of the bed material, and $\alpha=2$ represents resistance of the upper regime plane bed with sediment transport (Julien and Raslan 1998).

At high concentrations of coarse material, the dispersive stress approach has been used to describe resistance to flow. Based on the early contributions by Bagnold, Takahashi (1991), Hashimoto (1997), Hashimoto and Hirano (1997), and Egashira et al. (1997) demonstrated that dispersive stress yields a linear relationship between V/u^* and h/ds. For instance, Takahashi (1991) and Hashimoto (1997), respectively, proposed

$$\sqrt{\frac{8}{f_d}}=\frac{V}{u^*}=\frac{2h}{5d_s}\left[\frac{1}{a_1}\left\{C_v+(1-C_v)\frac{1}{G}\right\}\right]^{1/2}\left\{\left(\frac{C_v^*}{C_v}\right)^{1/3}-1\right\} \quad (2)$$

$$\sqrt{\frac{8}{f_d}}=\frac{V}{u^*}=0.4\frac{h}{d_s} \quad (3)$$

where f_d=Darcy-Weisbach friction factor for dispersive stress. The similitude between these two relationships, Eqs. (2) and (3), is apparent when considering a given sediment concentration C_v given that a_1, C_v^*, and G are constants. Both formulations yield parallel lines on resistance diagrams because the terms in brackets and accolades of Eq. (2) are constants. In debris flows, the median grain diameter d_{50} is suggested for dispersive stress calculations.

Testing with Field and Laboratory Measurements

Field and laboratory measurements of hyperconcentrated open-channel flows are used to test the applicability of resistance relationships. The data set compiled by Hussain (1999) includes laboratory measurements by Tsubaki et al. (1982), Takahashi (1980), Mainali (1993), Mainali and Rajaratnam (1994), Davies (1994), Hashimoto (1997), Hashimoto and Hirano (1997), Scotton and Deganutti (1997), and Egashira et al. (1997). More recent data from Park and Hashimoto (2003), Rickenmann et al. (2003), and Paris (2008) have been subsequently added. Additional field measurements include the Hanyu and Luohui irrigation canals in China (Xu and Wan 1985; Wan and Wang 1994; Wang and Zhang 1990; Hong et al. 1985), the Jiangjia ravine data (Wan and Wang 1994; Hamilton and Zhang 1997), the Yellow River (Wu, personal communication), the Kamikamihori valley at Mt. Yakedake (Suwa 1989), Mount St.-Helens (Pierson 1985; Julien and O'Brien 1997), Rudd Creek (Pierson 1985; O'Brien et al. 1993), Prince Creek and Hope Creek (Jakobs et al. 1997), and Kitamata Valley (Ikeda and Hara 2003). The database includes a total of 350 flow velocity measurements where each point includes flow depth and slope, from which the shear velocity $u^*=(ghS)^{0.5}$ can be determined, and the median grain diameter d_{50} of the transported material. Field studies that did not have these parameters could not be included in the analysis.

Fig. 1 shows the results of the resistance to flow analysis in terms of V/u^* as a function of the relative submergence h/d_{50}. Despite the complexity of mudflows and debris flows, the ratio of V/u^* is approximately 10 and rarely exceeds 30. There is a slight trend for V/u^* to increase with h/d_{50}. Logarithmic relationship Eq. (1) with $\alpha=1$ agrees reasonably well with the measurements. Good results are also obtained with the Manning-Strickler approach. Dispersive stress Eq. (3) shown as a straight line in Fig. 1 also compares well with the measurements, but only when

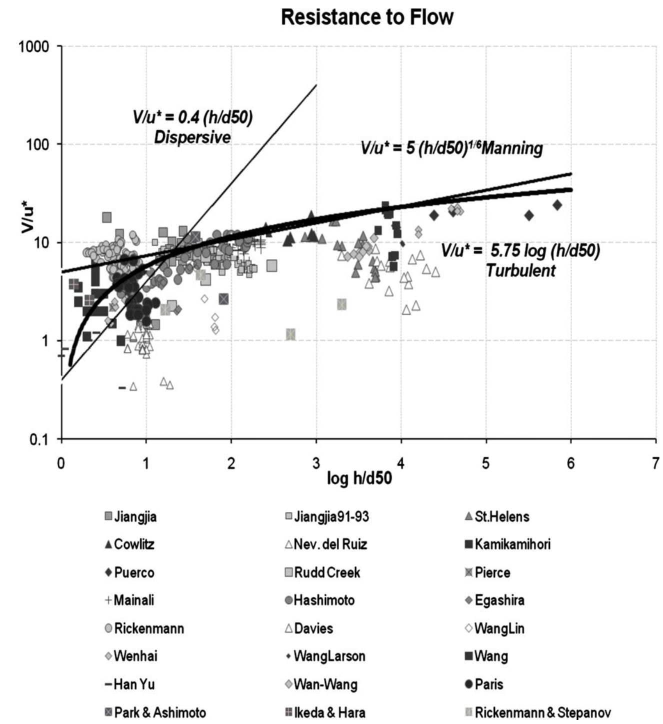

Fig. 1. Resistance to flow for sediment hyperconcentrations

$h/d_{50}<50$. However, the dispersive approach clearly underestimates resistance to flow when h/d_{50} is larger than 50. This implies that using the dispersive stress approach when $h/d_{50}>50$ would largely overestimate the mean flow velocity.

Discrepancy Ratios

The discrepancy ratio (DR) describes calculated to measured mean flow velocities. Four methods are used for direct comparisons with the field and laboratory measurements. Two methods describe dispersive stress from Takahashi [Eq. (2)] and Hashimoto [Eq. (3)], and two methods describe turbulent flow with the logarithmic equation [Eq. (1)], with $\alpha=12.2$ and 1, respectively. Cumulative distribution functions of the logarithmic values of the DRs are shown in Fig. 2. The line of perfect agreement is a

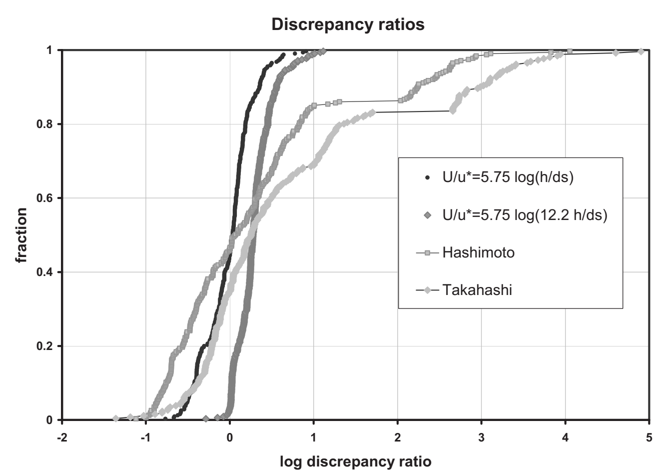

Fig. 2. DRs between calculated and measured flow velocities

vertical line where log DR=0. It is found that the dispersive stress approach has about 15% of DR values larger than two orders of magnitude, which means that 15% of the predictions give calculated velocities more than 100 times larger than the measured flow velocity. Comparatively, the logarithmic equation for turbulent flows with $\alpha = 12.2$ always overestimates the measured flow velocities. The results of the logarithmic equation with $\alpha = 1$ are well centered with about 80% of the calculated velocities within 50 and 200% of the measurements. It is concluded from Figs. 1 and 2 that the logarithmic equation with $\alpha = 1$ provides better overall agreement with field and laboratory velocity measurements than the dispersive stress approach.

Conclusions

This analysis of the mean velocity of mudflows and debris flows points to the following conclusions: (1) When flow depth and slope are available, the mean flow velocity of mudfloods and debris flows is approximately $10u^*$ and rarely exceeds $30u^*$; (2) when the median particle diameter is also known, the mean velocity V of mudflows and debris flows can be estimated from $V = 5.75u^* \log h/d_{50}$; and (3) approximately 80% of the flow velocities calculated using $V = 5.75u^* \log h/d_{50}$ fall within 50 and 200% of the measured flow velocities.

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Notation

The following symbols are used in this technical note:

- a_1 = empirical constant in Bagnold's equation ($a_1 = 0.01$);
- C_v = volumetric sediment concentration;
- C_v^* = maximum volumetric sediment concentration $C_v^* = 0.625$;
- d_s = grain diameter;
- d_{50} = median grain diameter;
- d_{90} = grain diameter for which 90% of the material by weight is finer;
- f = Darcy-Weisbach friction factor;
- f_d = dispersive Darcy-Weisbach friction factor;
- f_t = turbulent Darcy-Weisbach friction factor;
- G = specific gravity of sediment;
- g = gravitational acceleration;
- h = flow depth;
- n = Manning n;
- S = friction slope;
- u_* = shear velocity;
- V = mean flow velocity;
- α = coefficient in the logarithmic resistance equation, $1 < \alpha < 4$;
- ρ, ρ_m, ρ_s = mass densities of water, mixture, and sediment, respectively; and
- τ_0 = total and bed shear stress, respectively.

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