Technical Note

# Influence of Flow Width on Mean Velocity of Debris Flows in Wide Open Channel

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**Abstract:** Debris flow in a wide open downstream channel has a significant transverse velocity component that strongly influences its mean longitudinal velocity. Investigation of observation data of debris-flow surges at Jiangjia Ravine in China shows the dependency of Manning resistance of debris flows on the ratio of flow width to depth. Regression fit reveals a power function relationship between the Manning resistance coefficient and the width-to-depth ratio. This derives a new formula of mean velocity incorporating the influence of flow width. The result indicates that the width-to-depth ratio can be viewed as a kind of shape roughness analogous to grain roughness in the Darcy-Weisbach resistance coefficient expression. **DOI: 10.1061/(ASCE)HY.1943-7900.0000648.** 

**CE Database subject headings:** Debris; Solids flow; Coefficients; Velocity; Open channel flow.

**Author keywords:** Debris flows; Manning resistance coefficient; Mean flow velocity; Flow width.

## Introduction

Debris flows as a mixture of water, soil, and rocks, driven downslope by gravity in mountain areas, are characterized by high sediment concentration, large mobility, poor sorting, and destructive impact power (Iverson 1997; Takahashi 2007). In recent decades, large-scale debris flows happened frequently over the world, such as the tragedies of 1999 Vargas in Venezuela (Wei et al. 2000; Wieczorek et al. 2001) and 2010 Zhouqu in China (Hu et al. 2010). Until now, engineering countermeasures are still the primary approaches against debris flows.

Mean velocity of debris flow is the key parameter for designing control structures such as slot barriers, Sabo dams, and drainage canals. As pointed out by Rickenmann (1999), mean velocity often refers to either the mean translational velocity of the frontal component or the maximum (mean cross-sectional) velocity along the debris flow surge, attributable to difficulties in field observation. Studies on the mean velocity have been performed through field observations, model experiments and numerical simulations (Takahashi 1980; Okuda and Suwa 1981; Hungr et al. 1984; Costa 1984; Du et al. 1987; Rickenmann 1999; Julien and Paris 2010). Its calculation methods can be classified into theoretical and empirical types. Theoretical methods are derived from different rheological relationships that can be summarized into Newtonian laminar, Newtonian turbulent, Bingham, Dilatant, and Voellmy flows (Rickenmann 1999; Lo 2000). In practice, Newtonian turbulent and Voellmy formulas are more appropriate than the others. However, field and laboratory measurements show a disagreement with theoretical formulas for which the exponents should be constant (Costa 1984; Hungr et al. 1984; Du et al. 1987; Rickenman and Koch 1997; Koch 1998; Rickenmann 1999). In addition, resistance coefficients (e.g., that of Manning, Darcy-Weisbach or Chezy) in these equations are still empirically determined.

Alternatively, empirical methods might be more practically useful. They express the mean flow velocity as a power function of flow depth and slope gradient in the general form of $V = kH^{\alpha}S^{\beta}$, where $k$ is a comprehensive resistance coefficient reflecting the integrated influence of channel geometry, particle size, bed form, and so on. As the values of the exponents and coefficient are usually estimated by multiple regression analysis of field observatory or flume experimental data, the formula is limited to specific regions or flow conditions (Hungr et al. 1984; Johnson 1984; Du et al. 1987).

However, both theoretical and empirical formulas have not taken into account the influence of the transverse component of the velocity that is conspicuous when the downstream channel or alluvial fan is sufficiently wide, e.g., Jiangjia Ravine, Yunnan Province, southwestern China (Fig. 1). In this scenario, the flow width affects the mean longitudinal velocity primarily because of small side-wall effects and significant transverse velocity. In this paper, the influence of flow width was investigated on the basis of field measurement data at the downstream channel of Jiangjia Ravine. The data comes from 130 surges of four debris flow events in July, 1986, including mean longitudinal velocity, surface width and flow depth at the surge front (some of the data are listed in Table 1). The mean velocity was calculated by the traveling time between two control cross sections, and hence is the mean translational velocity of the frontal part. The flow depth was measured by ultrasonic sensors, and the surface width was obtained from the location of traces left by debris flows. The observed reach of the channel had no step pool, bend, and vegetation. The bed slope

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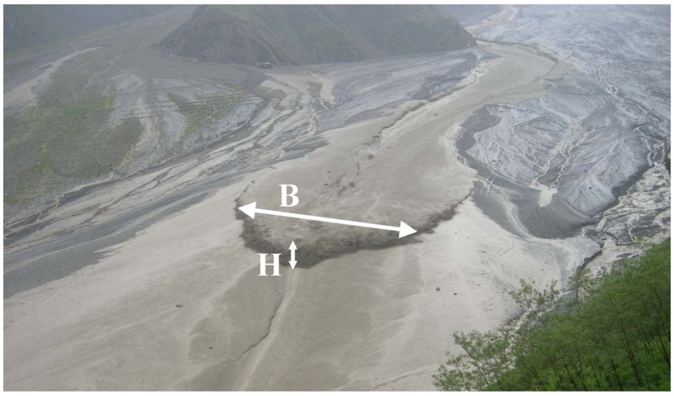


**Fig. 1.** Typical surge's profile at Jiangjia Ravine on July 11, 2008 (surge's front is approximately 2 m high and 50 m wide, and its flow width changed greatly along the downstream channel)

slightly changed from 5.7–5.6% during the events. Detailed description on Jiangjia debris flows can be found in Kang and Zhang (1980), Li et al. (1983), and Cui et al. (2005).

## Manning Resistance Coefficient from Jiangjia Data

The most frequently used resistance coefficients—Manning, Darcy-Weisbach, and Chezy—are related to each other through the following:

$$\sqrt{\frac{f}{8}} = \frac{n}{R^{1/6}}\sqrt{g} = \frac{\sqrt{g}}{C} \tag{1}$$

in which $n$ [s/m$^{1/3}$], $f$, and $C$ [m$^{1/2}$/s] are the Manning, Darcy-Weisbach, and Chezy resistance coefficients, respectively; $R$ = hydraulic radius; and $g$ = gravitational acceleration. In principle, the value of one coefficient can be used to derive the other two from Eq. (1). However, it is well known that $C$ exhibits a dependence on flow depth in a natural channel and $f$ is often treated as point resistance related to the velocity distribution, whereas $n$ is nearly a constant independent of flow depth, and more appropriately regarded as cross sectional and reach resistance (Yen 2002). Therefore, $n$ is more suitable to represent the comprehensive resistance to debris flow than the other two, with respect to the cross-sectional averaged velocity and the fixed reach in the Jiangjia's measurements.

**Table 1.** Part of the Observational Data at Jiangjia Ravine in 1986

| Surge's order | Date | Time | Flow depth $H$ (m) | Flow width $B$ (m) | Width-to-depth ratio | Channel slope $S$ | Mean velocity $V$ (m/s) | Froude number F |
|---|---|---|---|---|---|---|---|---|
| 1 | 1986.7.22 | 13:17:03–13:17:40 | 0.75 | 33.30 | 44.40 | 0.057 | 6.50 | 2.40 |
| 2 | 1986.7.22 | 13:17:48:13:18:26 | 1.52 | 38.15 | 25.10 | 0.057 | 6.49 | 1.68 |
| 3 | 1986.7.22 | 13:21:11–13:21:52 | 1.04 | 32.69 | 31.43 | 0.057 | 7.15 | 2.24 |
| 4 | 1986.7.22 | 13:22:03–13:22:26 | 0.75 | 33.30 | 44.40 | 0.057 | 6.90 | 2.55 |
| 5 | 1986.7.22 | 13:22:39–13:23:06 | 0.97 | 34.02 | 35.07 | 0.057 | 7.25 | 2.35 |
| 6 | 1986.7.22 | 13:24:21–13:24:50 | 3.82 | 52.08 | 13.63 | 0.057 | 6.90 | 1.13 |
| 7 | 1986.7.22 | 13:25:28–13:25:57 | 0.58 | 31.89 | 54.98 | 0.057 | 5.30 | 2.22 |
| 8 | 1986.7.22 | 13:26:08–13:26:38 | 0.61 | 31.96 | 52.39 | 0.057 | 6.30 | 2.58 |
| 9 | 1986.7.22 | 13:27:23–13:27:51 | 1.45 | 37.93 | 26.16 | 0.057 | 7.80 | 2.07 |
| 10 | 1986.7.22 | 13:28:56–13:29:30 | 1.64 | 39.63 | 24.16 | 0.057 | 7.40 | 1.85 |
| 34 | 1986.7.23 | 09:18:13–09:19:10 | 2.32 | 47.80 | 20.60 | 0.056 | 8.01 | 1.68 |
| 35 | 1986.7.23 | 09:19:33–09:20:37 | 2.52 | 48.80 | 19.37 | 0.056 | 7.32 | 1.47 |
| 36 | 1986.7.23 | 09:20:50–09:21:30 | 2.32 | 47.80 | 20.60 | 0.056 | 8.54 | 1.79 |
| 37 | 1986.7.23 | 09:22:12–09:22:54 | 2.81 | 51.60 | 18.36 | 0.056 | 8.52 | 1.62 |
| 38 | 1986.7.23 | 09:23:57–09:24:35 | 2.37 | 45.90 | 19.37 | 0.056 | 9.04 | 1.88 |
| 39 | 1986.7.23 | 09:26:05–09:26:57 | 1.36 | 37.50 | 27.57 | 0.056 | 8.80 | 2.41 |
| 40 | 1986.7.23 | 09:29:02–09:30:09 | 2.94 | 50.00 | 17.01 | 0.056 | 9.59 | 1.79 |
| 41 | 1986.7.23 | 09:32:50–09:33:40 | 1.66 | 39.75 | 23.95 | 0.056 | 9.03 | 2.24 |
| 42 | 1986.7.23 | 09:34:10–09:35:40 | 1.77 | 41.20 | 23.28 | 0.056 | 9.32 | 2.24 |
| 43 | 1986.7.23 | 09:37:00–09:38:00 | 2.29 | 45.85 | 20.02 | 0.056 | 11.27 | 2.38 |
| 89 | 1986.7.28 | 20:26:31–20:27:45 | 1.05 | 42.85 | 40.81 | 0.056 | 7.75 | 2.42 |
| 90 | 1986.7.28 | 20:31:53–20:32:31 | 2.73 | 56.04 | 20.53 | 0.056 | 9.25 | 1.79 |
| 91 | 1986.7.28 | 20:32:52–20:33:46 | 2.17 | 52.53 | 24.21 | 0.056 | 10.85 | 2.35 |
| 92 | 1986.7.28 | 20:34:34–20:35:15 | 0.80 | 46.25 | 57.81 | 0.056 | 7.88 | 2.81 |
| 93 | 1986.7.28 | 20:36:35–20:37:14 | 0.68 | 39.70 | 58.38 | 0.056 | 7.65 | 2.96 |
| 94 | 1986.7.28 | 20:37:19–20:37:51 | 1.1 | 43.63 | 39.66 | 0.056 | 8.6 | 2.62 |
| 95 | 1986.7.28 | 20:39:05–20:39:28 | 0.66 | 39.39 | 59.68 | 0.056 | 7.27 | 2.86 |
| 96 | 1986.7.28 | 20:39:59–20:40:23 | 1.88 | 50.53 | 26.88 | 0.056 | 10.3 | 2.40 |
| 97 | 1986.7.28 | 20:42:08–20:43:00 | 2.49 | 54.61 | 21.93 | 0.056 | 11.15 | 2.26 |
| 98 | 1986.7.28 | 20:45:50–20:46:16 | 2.42 | 54.13 | 22.37 | 0.056 | 10.05 | 2.06 |
| 117 | 1986.7.31 | 19:13:32–19:14:00 | 2.2 | 60 | 27.27 | 0.056 | 12.15 | 2.62 |
| 118 | 1986.7.31 | 19:15:02–19:15:31 | 0.4 | 52.5 | 131.25 | 0.056 | 7.02 | 3.55 |
| 119 | 1986.7.31 | 19:24:06–19:24:57 | 1.77 | 57.62 | 32.55 | 0.056 | 9.85 | 2.37 |
| 120 | 1986.7.31 | 19:28:27–19:29:59 | 2.27 | 60.35 | 26.59 | 0.056 | 9.15 | 1.94 |
| 121 | 1986.7.31 | 19:30:52–19:31:59 | 1.1 | 53.4 | 48.55 | 0.056 | 8.68 | 2.64 |
| 122 | 1986.7.31 | 19:34:44–19:34:57 | 0.34 | 47.05 | 138.38 | 0.056 | 6.33 | 3.47 |
| 123 | 1986.7.31 | 19:35:25–19:35–45 | 1.06 | 52.83 | 49.84 | 0.056 | 8.3 | 2.58 |
| 124 | 1986.7.31 | 19:38:53–19:39:17 | 0.71 | 50.7 | 71.41 | 0.056 | 7.13 | 2.70 |
| 125 | 1986.7.31 | 19:41:30–19:41:39 | 0.58 | 48.27 | 83.22 | 0.056 | 6.15 | 2.58 |
| 126 | 1986.7.31 | 19:42:45–19:42:55 | 0.4 | 47.5 | 118.75 | 0.056 | 5.56 | 2.81 |

Note: Presented are 40, not all, debris-flow surges of four events in July 1986.

According to the Manning formula in one-dimensional open channel flow, the coefficient $n$ can be estimated by the following:

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

where $S$ = channel slope; and $V$ [m/s] = mean longitudinal velocity. Assuming that the channel of Jiangjia was rectangular and the debris flows completely limited by side banks, the hydraulic radius can be calculated by the following:

$$R = \frac{H}{\left(1 + 2\frac{H}{B}\right)} \tag{3}$$

where $H$ [m] = flow depth; and $B$ [m] = flow width. When the width-to-depth ratio is large enough, the hydraulic radius can be approximated by the flow depth. In the scenario for which there is no side-wall or bank limitation for debris flows, especially in wide open channel, the hydraulic radius can be replaced with the flow depth. In such a scenario, $B$ is represented as flow-surface width and $H$ as frontal flow depth (Fig. 1). To evaluate the influence of substituting hydraulic radius with flow depth on the Manning coefficient, the values of the resistance coefficient are computed respectively with hydraulic radius and flow depth (Fig. 2). Maximum relative error between the two is 8.7% (at the sixth surge). Thus, the flow depth is used instead of the hydraulic radius in the subsequent analysis.

Using the observed data of debris-flow surges in 1986, the Manning resistance value calculated with the flow depth ranges between 0.0148 and 0.0846 $s/m^{1/3}$, with the mean $\mu = 0.0333$ $s/m^{1/3}$ and the standard deviation $\sigma = 0.0106$ (Fig. 2). The variation cannot be simply attributed to grain size or bed form that remains almost constant during the flow courses. However, debris-flow surges spread transversely with a significant velocity component over a wide channel (Fig. 1), indicating that the flow width varies greatly along with the moving surges, which apparently differs from a confined flow in narrow midstream channel. Therefore, the effect of the flow width should be taken into account.

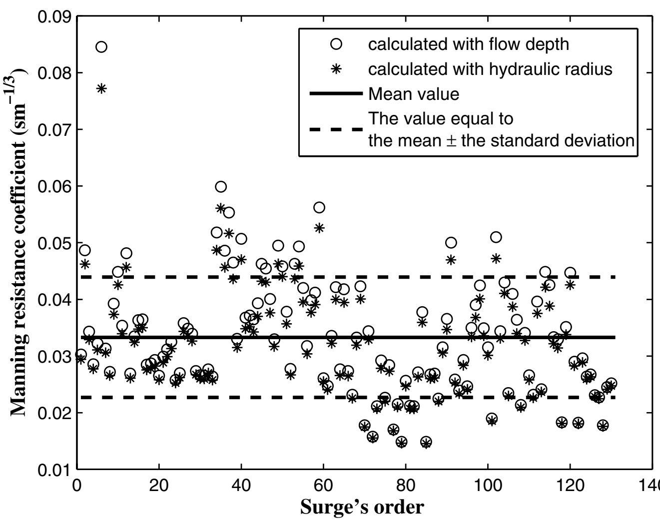


**Fig. 2.** Manning resistance coefficient from Jiangjia data in 1986 (surge's order is the sequence number of debris-flow surges ordered by their occurrence time; 28.5% of surges do not fall in the interval $[\mu - \sigma, \mu + \sigma]$)

## Relationship between Manning Resistance and Flow Width

For wide open flow, there are two length scales: flow depth and width. A simple dimensionless variable is the ratio of flow width to flow depth. The ratio $B/H$ of the observed 130 surges ranges from 13.63–138.38 (Table 1). The Manning resistance with its dimensionless form $n/H^{1/6}g^{1/2}$ exhibits an obvious decreasing relationship with increasing $B/H$ (Fig. 3). Further regression analysis gives the following empirical function between the two dimensionless variables:

$$\frac{n}{H^{1/6}} \sqrt{g} = 0.35 \left(\frac{B}{H}\right)^{-0.35} \tag{4}$$

The fit $R$-square is 0.72, and the root mean squared error (RMSE) is 0.012. The 95% confidence intervals of the coefficient and the exponent in Eq. (3) are (0.29, 0.40), and (−0.40, −0.31).

Combining Eqs. (2) and (4), the following empirical formula of mean flow velocity can be obtained:

$$V = \frac{\sqrt{g}}{0.35} H^{0.15} B^{0.35} S^{0.5} = 8.94 H^{0.15} B^{0.35} S^{0.5} \tag{5}$$

This formula is verified by the Jiangjia data of 1990 and 1991 (the authors have no data on debris flow width in other regions). Although the flow width data were roughly estimated by eyewitness, the observed velocities show a reasonable agreement with the calculated values (Fig. 4). Moreover, Eq. (5) appears to overestimate the mean velocity within 2 and 8 m/s and underestimate it beyond 8 m/s.

## Discussion

Eq. (5) presents a general formula for mean flow velocity, although the values of the coefficient and exponents are estimates that are specific to Jiangjia Ravine. Debris flows in Jiangjia have a high volumetric concentration of fine sediment particles <2 mm up to 35%, leading to a different behavior from stony debris flows. Therefore, the formula is limited to mudflow or muddy-debris flow such as in Jiangjia. The Froude number of the surges is larger than 1.0 (Table 1), which implies that there are local head losses in front

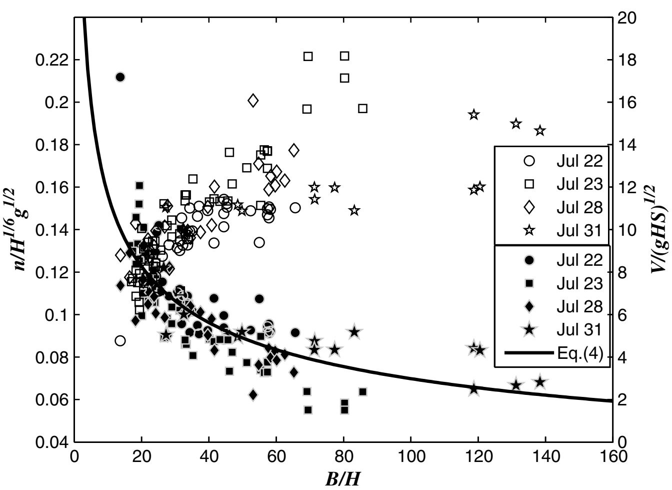


**Fig. 3.** Width-to-depth ratio versus the dimensionless Manning resistance coefficient (solid symbol) and the dimensionless mean velocity (open symbol)



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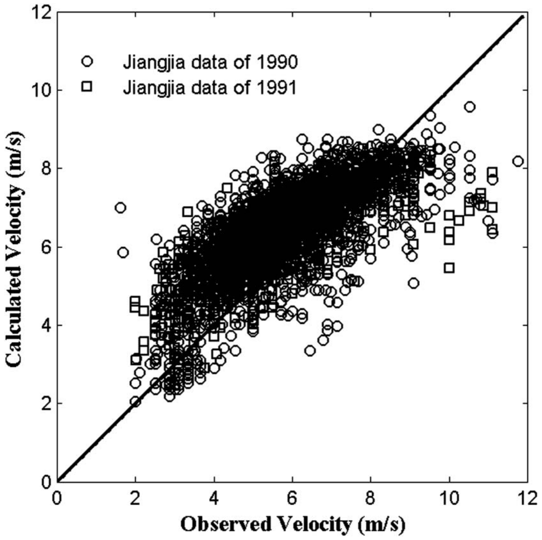


**Fig. 4.** Comparison of observed and calculated mean flow velocities [1990 and 1991 data of Jiangjia Ravine come from Zhang and Xiong (1997)]

of the unsteady flow surge. However, the Jiangjia data show that the Manning coefficient decreases with increasing width-to-depth ratio, which indicates that the losses are not so considerable when the flow is wide and shallow and the increasing flow width is able to reduce the head losses to some extent.

An implication of Eq. (5) can be revealed if it is rewritten in the Darcy-Weisbach form, as follows:

$$\frac{V}{\sqrt{gHS}} = \frac{\mathbf{1}}{\mathbf{0.35}}\left(\frac{H}{B}\right)^{-0.35} \tag{6}$$

For a narrow channel, the flow resistance depends on grain roughness $d_s$, such as $d_{50}$ or $d_{90}$. However, for a wide channel, Eq. (6) implies that the resistance also depends on flow width to a large extent. Considering the similarity between Eq. (6) and the Manning-Strickler formula, the $H/B$ is intuitively viewed as some kind of shape roughness analogous to $H/d_s$. The additional resistance attributable to transverse spreading is significant only in wide and shallow channels with a large aspect ratio. In such a scenario, the relative error between the hydraulic radius and flow depth should be sufficiently small. Provided that the error is below 10%, the value of $B/H$ must be larger than 20 according to Eq. (3), which corresponds to the lower limit of Eq. (6). In contrast, the empirical formulas in this paper would be unavailable if debris flow surges are too wide or too shallow. Julien and Paris (2010) reported that the ratio of mean flow velocity to shear velocity is rarely larger than 30 for mudflows and debris flows. The authors of the present manuscript found that the ratio rarely exceeds 20. This indicates that the reasonable upper limit value of $B/H$ in Eq. (6) may be approximately 260.

## Conclusions

Debris flow as a mass movement of solid-fluid mixture is more complex than water flow. The resistance to debris flow is affected by many factors, such as channel geometry, bed form and grain size distribution. Analysis on Manning resistance coefficient using debris-flow surges at Jiangjia Ravine indicates that the transverse spread in a wide channel exerts a strong influence on the mean velocity of the mainstream flow. The Manning coefficient decreases with increasing the flow width-to-depth ratio. Regression analysis yields a power function relationship between the coefficient and the ratio with an acceptable $R^2$. The relationship derives a new formula of calculating mean flow velocity $V = 8.94H^{0.15}B^{0.35}S^{0.5}$, which includes the influence of flow width. The formula may exhibit a general form of the resistance to debris flows in wide open downstream channels.

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## Notation

*The following symbols are used in this paper:*

$B$ = flow width, m;
$H$ = flow depth, m;
$n$ = Manning resistance coefficient, $s/m^{1/3}$;
$Q$ = discharge of debris flow, $m^3/s$;
$S$ = channel slope; and
$V$ = mean debris-flow velocity, m/s.

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