Technical Note

Effect of Bed Sediment Entrainment on Debris-Flow Resistance

Mi Tian[1]; Kai-heng Hu[2]; Chao Ma, Ph.D.[3]; and Fa-hong Lei[4]

Abstract: Entrainment of sediment from hillslope and channel usually has a significant influence on resistance of debris flow. This effect is studied by flume experiments of debris flow over rigid and erodible beds. Fifty contrast flume tests show that the flow resistance over the erodible bed is significantly larger than that over the rigid bed because of higher energy consumption resulting from sediment transport. A new formula of debris-flow resistance involving the entrainment effect is obtained from the erodible-bed data by nondimensional multiple regression analysis. **DOI: 10.1061/(ASCE)HY.1943-7900.0000805.** © *2014 American Society of Civil Engineers.*

Author keywords: Debris flow; Flow resistance; Erodible bed; Rigid bed; Entrainment of bed sediment.

Introduction

Debris flow is a gravity-driven flow of solid-fluid mixture characterized with abrupt surge fronts, high-flow velocity, great impact forces, and long run out distance (Davies 1990; Iverson 1997; Hungr et al. 2001; Jakob and Hungr 2005; Takahashi 2007), which is hazardous to residents, houses, roads, rail lines, agricultural land, and other facilities on the alluvial fans. Debris-flow resistance is an important parameter for the design of mitigation measures in calculating flow velocity or flow discharge.

Existing studies on debris-flow resistance can be roughly divided into analytical and empirical methods. The analytical methods were developed from various fluid models, such as Bingham model (Johnson and Rahn 1970); Bagnold dilatant model (Takahashi 1978, 1980); viscoplastic model (Chen 1988); dilatant plastic model (O'Brien et al. 1933); and granular flow model (Savage and Hutter 1989). Different flow resistance relationships were, thus, derived from these various constitutive models (e.g., Bagnold 1954; Johnson and Rahn 1970; Takahashi 1978; Ackermann and Shen 1982; Costa 1984; Chen 1988; O'Brien and Julien 1988; Yang and Wang 1992; Shieh et al. 1996; Egashira et al. 1997; Honda and Egashira 1997; Wang et al. 1997). The empirical methods are based on open-channel flow resistance formulas, such as Chezy, Manning, Darcy-Weisbach, and turbulents (Wang et al. 2002; Yen 2002). For example, Jin and Fread (1999) calculated the evolution process of debris flow in one-dimensional channel by Manning's formulas. Rickenmann (1994, 1999) found that the Manning's n is a function of flow rate, slope, and some characteristic grain size of channel bed. Julien and Paris (2010) compared flow resistances of Manning-Strickler, turbulent and dispersive stress models with 350 field and laboratory measurements and concluded that the best one is the turbulent model. Kang (1985) developed a power function relationship between the Manning resistance coefficient and the flow depth. Fei (2003) revealed an empirical relationship of the Manning comprehensive resistance coefficient with material composition, flow depth, and channel slope based on field data in southwestern China.

However, both the analytical and empirical methods are based on the hypothesis of nonerodible bed without the consideration of effects of bed-sediment entrainment. When debris flows descend down steep slopes, they can develop from an initially small flow to a large, hazardous flow by entraining sediment from channel bed and banks (Egashira et al. 2001), which is quite different from that over a rigid bed and greatly influences the flow resistance. At present, studies on erodible-bed resistance are mainly focused on alluvial rivers or simple open channel flow (Einstein and Barbarossa 1952; Engelund 1966; Alam and Kennedy 1969; White et al. 1980; van Rijn 1984; Yalin 1992; Wang and White 1993; Lyness et al. 2001), and little attention has been paid to debris flows.

This paper investigates the effect of bed-sediment entrainment on debris-flow resistance by flume tests. The resistance over an erodible bed is regarded as a combination of two parts: one part similar to the resistance over a rigid bed, and another part related to variation of solid volume concentration resulting from sediment entrainment. From this, a new formula of debris-flow resistance is proposed.

Experimental Setup and Procedures

Fig. 1 shows the experimental flume and installation. The flume contains two parts: a 4m-long rigid-bed section with a laser sensor installed in the middle, and a 2m-long erodible-bed section with a laser sensor installed intermediately. A video camera was settled

[1]Postgraduate, State Key Laboratory of Water Resources and Hydropower Engineering Science, Key Laboratory of Rock Mechanics in Hydraulic Structural Engineering (Ministry of Education), Wuhan Univ., Wuhan 430072, Hubei, China; and Key Laboratory of Mountain Hazards and Earth Surface Processes, Chinese Academy of Sciences, Chengdu 610041, China. E-mail: tianmi0525@126.com

[2]Professor, Key Laboratory of Mountain Hazards and Earth Surface Processes, and Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China (corresponding author). E-mail: khhu@imde.ac.cn

[3]Key Laboratory of Mountain Hazards and Earth Surface Processes, and Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China. E-mail: sanguoxumei@163.com

[4]Postgraduate, Key Laboratory of Mountain Hazards and Earth Surface Processes, and Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China. E-mail: leifahong@gmail.com

Note. This manuscript was submitted on December 22, 2012; approved on July 17, 2013; published online on December 16, 2013. Discussion period open until June 1, 2014; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Hydraulic Engineering***, Vol. 140, No. 1, January 1, 2014. © ASCE, ISSN 0733-9429/2014/1-115-120/$25.00.

J. Hydraul. Eng. 2014.140:115-120.

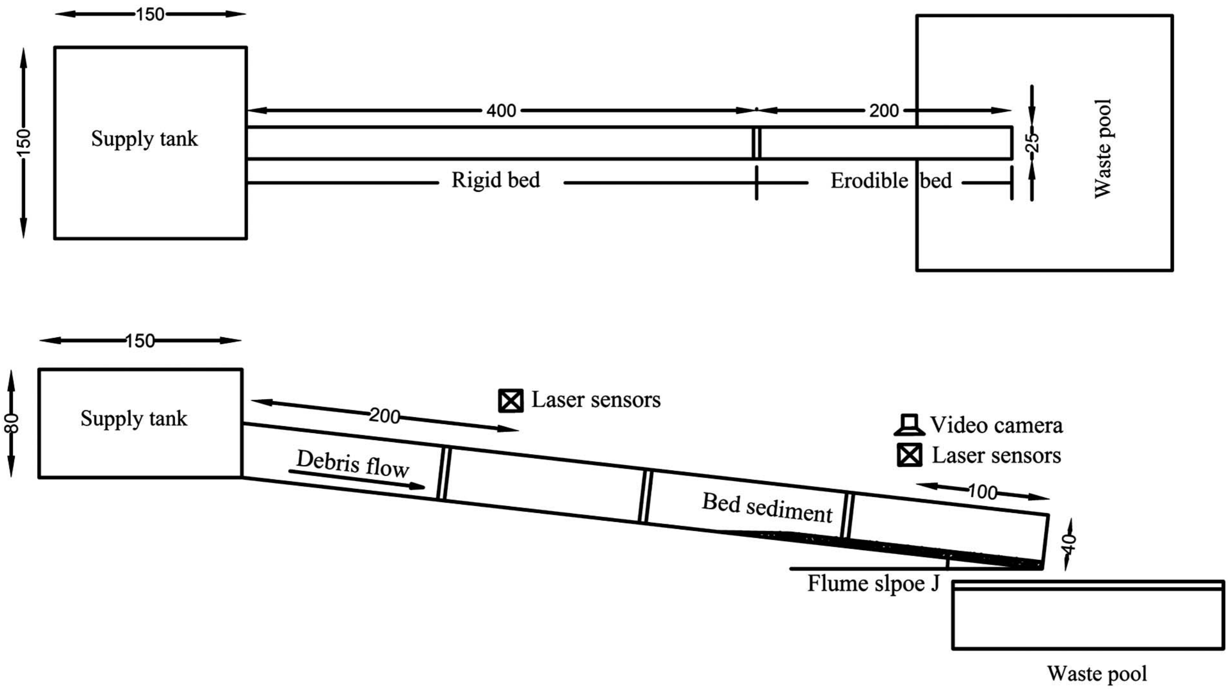

Fig. 1. Plane and side view of experimental flume and installation (all dimensions in cm)

right above the erodible bed to record the movement process. The bed sediment layer is 5.0 cm thick and four different kinds of bed sediments are used (Table 1). Considering the effect on flow regime, erodible bed stretches forward for several centimeters for smooth connection to the rigid bed. Debris-flow depositions taken from the Jiangjia ravine were used as experimental materials. The volume in each test was 0.45 m^3 and remained unchanged in the experiments. The particle grading curves of debris flow and bed materials are shown in Fig. 2. The flume slope is adjustable between 7.6° and 9.1°.

The experiments include fixed-bed and erodible-bed tests. For each test the fundamental quantities are measured respectively. Assuming that the debris flow head moves en masse, the velocity is calculated by measuring the travel time in each section, and laser sensors measure the flow depth. The flow samples near the outlet of the tank were taken manually by a cylindrical cup of 12 cm diameter and 12 cm height while those at the end of flume were collected by a bucket of 16 cm diameter above the waste pool. The solid volume concentrations of these samples were calculated by their mass and volume. The solid concentration before the sediment entrainment (S_{v0}) is considered to be equal to the concentration of the samples near the outlet, and the solid concentration after the entrainment (S_{v1}) to equal to that at the end of flume. A total of 50 debris-flow experiments (23 fixed-bed and 27 erodible-bed) were performed under two kinds of flume slopes. The flow concentration S_{v0} in all of the experiments ranges from 0.197 to 0.577. Four kinds of bed materials in the erodible-bed experiments were used ($D_{50} = 1.4$, 2.9, 3.9, and 6.9 mm).

Table 1. Characteristics of Bed Sediment

Bed sediment size				
Number	Maximum particle size (mm)	Unit weight (g/cm^3)	Mass water content (%)	Median particle diameter (mm)
1	20	1.928	0.32	6.9
2	15	1.633	0.64	3.9
3	10	1.771	0.41	2.9
4	5	1.640	0.55	1.4

Note: Mass water content is the ratio of water and dried soil quality.

Table 2. Experimental Data of Rigid-Bed Resistance

Number	J	H (m)	R (m)	V (m/s)	S_v	f_1
FB-1	0.133	0.040	0.030	2.40	0.494	0.055
FB-2	0.133	0.065	0.043	2.26	0.350	0.088
FB-3	0.133	0.057	0.039	2.86	0.423	0.050
FB-4	0.133	0.063	0.042	2.15	0.577	0.095
FB-5	0.160	0.067	0.044	1.99	0.588	0.138
FB-6	0.160	0.033	0.026	1.99	0.379	0.083
FB-7	0.160	0.040	0.030	1.91	0.293	0.104
FB-8	0.160	0.036	0.028	2.13	0.272	0.078
FB-9	0.160	0.035	0.027	2.07	0.340	0.080
FB-10	0.160	0.036	0.028	2.61	0.323	0.051
FB-11	0.160	0.032	0.026	2.44	0.340	0.054
FB-12	0.160	0.030	0.024	2.14	0.345	0.067
FB-13	0.160	0.025	0.021	1.73	0.317	0.087
FB-14	0.160	0.032	0.025	2.12	0.197	0.071
FB-15	0.160	0.03	0.024	1.90	0.281	0.084
FB-16	0.160	0.033	0.026	2.29	0.280	0.063
FB-17	0.133	0.033	0.026	1.97	0.366	0.070
FB-18	0.133	0.027	0.022	1.93	0.326	0.062
FB-19	0.133	0.037	0.028	1.78	0.307	0.094
FB-20	0.133	0.035	0.027	2.02	0.267	0.070
FB-21	0.133	0.034	0.027	1.78	0.244	0.088
FB-22	0.133	0.037	0.028	1.66	0.253	0.108
FB-23	0.133	0.033	0.026	1.71	0.247	0.093

Note: f_1 = fixed-bed Darcy-Weisbach resistance coefficient; H = flow depth of the head; J = flume slope; R = hydraulic radius; V = mean velocity of the head; S_v = solid volume concentration of debris flow.

J. Hydraul. Eng. 2014.140:115-120.

Results Analysis

Flow depth profiles of three erodible-bed experiments are analyzed (Fig. 3). On the fixed-bed section, the flow depth changes smoothly under the same density and slope. However, when flow moves into the erodible-bed section, the depth grows rapidly, which indicates that the flow entrained sediment from the erodible bed.

The values of debris-flow resistance obtained in these flume tests depend on which of empirical models is adopted. Over the years Manning's formula has been the most frequently used relating debris-flow velocity to resistance coefficient. However, Manning coefficient generally reflects the irregular shape and roughness of bed and sidewall, and it is not dimensionless. Therefore, Darcy-Weisbach resistance coefficient, a dimensionless coefficient, is chosen. The Manning and Darcy-Weisbach resistance coefficient can be related in the following dimensionless form:

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

where f = Darcy-Weisbach resistance coefficient; V (m/s) = mean flow velocity; R (m) = hydraulic radius; g (m/s^2) = gravitational acceleration; J = energy slope; and n (s/m$^{1/3}$) = Manning coefficient. Here, the channel slope usually substitutes J when the observed reach of the debris-flow channel is straight and smooth.

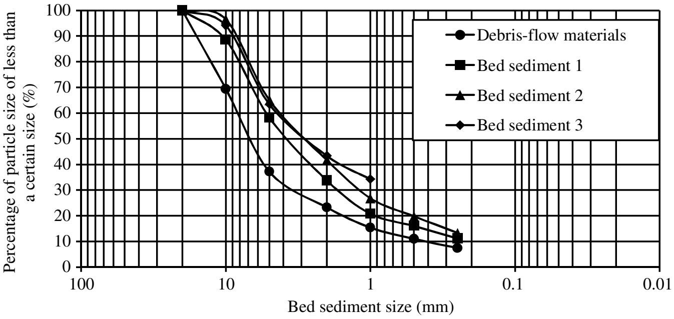

Fig. 2. Particle grading curves of debris-flow materials and bed sediments

The Darcy-Weisbach coefficient in the rigid-bed tests ranges from 0.050 to 0.138 with the mean value = 0.08 and the standard deviation $\sigma = 0.021$ (Table 2), while the value of the erodible resistance ranges from 0.123 to 0.372 with = 0.204 and $\sigma = 0.073$ (Table 3). The resistance over erodible bed is significantly larger than that over fixed bed (Fig. 4).

The nonzero variation of solid volume concentration (Table 3) suggests that bed sediments are involved and entrained into the flows. In this material exchange process, particle collisions are the main mechanism of momentum and energy transformation or dissipation for rapid debris flows.

Other factors are also influential. For erodible bed, debris-flow resistance can be affected by inflow, boundary conditions, and sediment entrainment. Accordingly, the flow resistance can be divided into two parts: the fixed-bed resistance f_1 and the flow resistance f_2 attributable to sediment entrainment. So the erodible-bed resistance can be written as

$$f = f_1 + f_2 \tag{2}$$

Generally, the fixed-bed resistance of debris flow is influenced by the cross-sectional profiles and the solid concentration of debris flow. The flow resistance increases with the flow depth (Wu et al. 1993). Solid concentration of debris flow has dual effects on the flow resistance. On the one hand, the internal resistance of viscous debris flow increases with the solid concentration. On the other hand, the fall velocity of particles and the internal resistance would reduce rapidly when the concentration is very high. The dimensionless ratio of flow depth to flow width is chosen to reflect the influence of the channel cross-sectional shape. Because of sidewall effects for debris flows, the flow depth is replaced with the hydraulic radius. The dimensionless parameter $S_v(1 - S_v)$ reflects the dual effects of debris-flow solid concentration on the flow resistance. The fixed-bed resistance f_1 can be expressed as

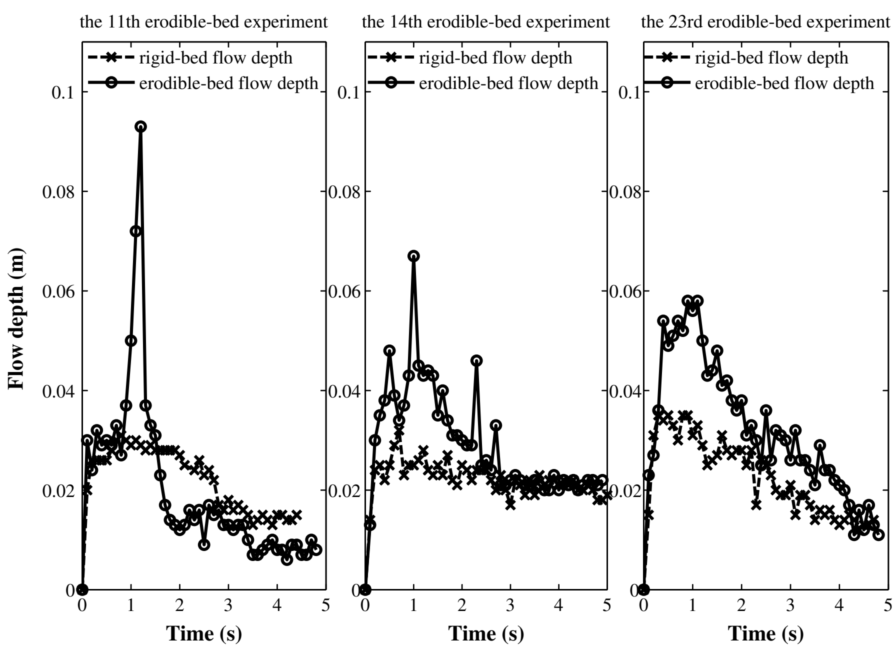

Fig. 3. Curve of flow depth on the fixed bed and erodible bed in the erodible-bed test

J. Hydraul. Eng. 2014.140:115-120.

Table 3. Experimental Data of Erodible-Bed Resistance

Number	J	H (m)	R (m)	D_{50} (m)	V (m/s)	S_{v0}	S_{v1}	S_{Δ}	K	F	f
MB-1	0.133	0.057	0.039	0.0069	1.786	0.317	0.357	0.040	0.176	2.88	0.128
MB-2	0.133	0.047	0.034	0.0069	1.036	0.364	0.465	0.101	0.202	1.791	0.333
MB-3	0.133	0.055	0.038	0.0069	1.117	0.461	0.534	0.073	0.181	1.826	0.320
MB-4	0.133	0.047	0.034	0.0069	1.020	0.554	0.620	0.065	0.202	1.764	0.343
MB-5	0.160	0.054	0.038	0.0069	1.653	0.378	0.473	0.096	0.183	2.719	0.173
MB-6	0.160	0.051	0.036	0.0069	1.429	0.373	0.483	0.110	0.190	2.398	0.223
MB-7	0.160	0.052	0.037	0.0069	1.754	0.353	0.465	0.112	0.188	2.924	0.15
MB-8	0.160	0.062	0.041	0.0069	1.724	0.245	0.356	0.111	0.166	2.705	0.175
MB-9	0.160	0.073	0.046	0.0014	1.681	0.340	0.427	0.087	0.031	2.506	0.204
MB-10	0.160	0.088	0.052	0.0014	1.538	0.323	0.413	0.090	0.027	2.165	0.273
MB-11	0.160	0.093	0.053	0.0014	1.681	0.340	0.438	0.098	0.026	2.325	0.237
MB-12	0.160	0.064	0.042	0.0014	2.041	0.345	0.446	0.100	0.033	3.171	0.127
MB-13	0.160	0.069	0.045	0.0029	1.227	0.317	0.430	0.113	0.065	1.855	0.372
MB-14	0.160	0.067	0.043	0.0029	1.786	0.197	0.294	0.097	0.067	2.737	0.171
MB-15	0.160	0.038	0.029	0.0029	1.667	0.281	0.355	0.074	0.099	3.107	0.133
MB-16	0.160	0.064	0.042	0.0039	1.818	0.318	0.422	0.104	0.092	2.820	0.161
MB-17	0.160	0.045	0.033	0.0039	1.481	0.280	0.415	0.135	0.119	2.610	0.188
MB-18	0.160	0.065	0.043	0.0039	1.504	0.369	0.452	0.083	0.091	2.318	0.238
MB-19	0.133	0.059	0.040	0.0039	1.429	0.366	0.467	0.102	0.097	2.279	0.205
MB-20	0.133	0.048	0.035	0.0039	1.212	0.326	0.413	0.087	0.112	2.079	0.247
MB-21	0.133	0.057	0.039	0.0039	1.333	0.322	0.413	0.091	0.100	2.153	0.23
MB-22	0.133	0.055	0.038	0.0029	1.802	0.307	0.406	0.099	0.076	2.947	0.123
MB-23	0.133	0.058	0.040	0.0029	1.802	0.267	0.341	0.074	0.073	2.884	0.128
MB-24	0.133	0.069	0.045	0.0029	1.869	0.244	0.319	0.075	0.065	2.830	0.133
MB-25	0.133	0.067	0.044	0.0014	1.835	0.205	0.298	0.093	0.032	2.801	0.136
MB-26	0.133	0.066	0.043	0.0014	1.515	0.253	0.343	0.090	0.033	2.332	0.196
MB-27	0.133	0.063	0.042	0.0014	1.695	0.247	0.339	0.092	0.034	2.650	0.152

Note: D_{50} = median particle diameter of bed sediment; F = Froude number; f = erodible-bed Darcy-Weisbach resistance coefficient; H = flow depth of the head on the erodible-bed section; J = flume slope; $K = D_{50}/R$, relative roughness of the erodible bed; R = hydraulic radius of the erodible-bed-section debris flow; S_{v0} = solid volume concentration of debris flow before entering the erodible bed; S_{v1} = solid volume concentration of debris flow after entrainment happened; $S_{\Delta} = S_{v1} - S_{v0}$, solid volume concentration variation before and after getting through the erodible bed; V = mean velocity of the erodible-bed-section head.

$$f_1 = k\left(\frac{R}{B}\right)^x [S_v(1-S_v)]^y \tag{3}$$

where B (m) = width of the flume; R (m) = hydraulic radius; S_v = solid volume concentration; and k, x, and y = undetermined coefficients.

According to Eq. (1), x can be chosen as $1/6$. Through multiple regression analysis, the value of y is -0.785, which is closed

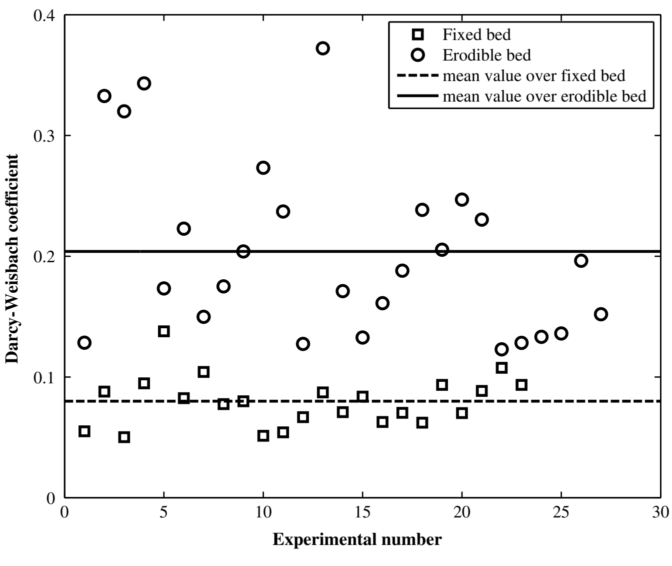

Fig. 4. Flow resistance over erodible and rigid bed

to $-2/3$. Based on Fei's empirical resistance equation (Fei 2003), y is selected as $-2/3$. The fixed-bed resistance is put forward as follows:

$$f_1 = k\left(\frac{R}{B}\right)^{1/6} [S_v(1-S_v)]^{-2/3} \tag{4}$$

Under the erodible-bed conditions, the debris-flow resistance increases with surface roughness, and the sediment transportation will bring about great energy or resistance loss. Variation of solid volume concentration is the index of mass exchange. Besides, the characteristic of debris flow itself has direct impact on the resistance. Accordingly, the flow resistance due to the bed sediment can be represented as

$$f_2 = g(K \cdot S_{\Delta} \cdot \mathsf{F}) \tag{5}$$

where K = relative roughness for the wall surface resistance; $S_{\Delta} = S_{v1} - S_{v0}$, variation of solid volume concentration over the erodible bed; and F = Froude number.

Further regression analysis gives the function among the dimensionless resistance coefficient f_2, the Froude number, relative roughness, and solid volume concentration variation. The formula of erodible-bed flow resistance is proposed

$$f = 0.04\left(\frac{R}{B}\right)^{1/6} [S_v(1-S_v)]^{-2/3} + 8.56 S_{\Delta}^{0.479} K^{0.068} \mathsf{F}^{-3.39} \tag{6}$$

The coefficient of determination R-square is 0.888.

This formula is verified by comparing with the formula of Kang (1985) and Fei (2003) as follows:

J. Hydraul. Eng. 2014.140:115-120.

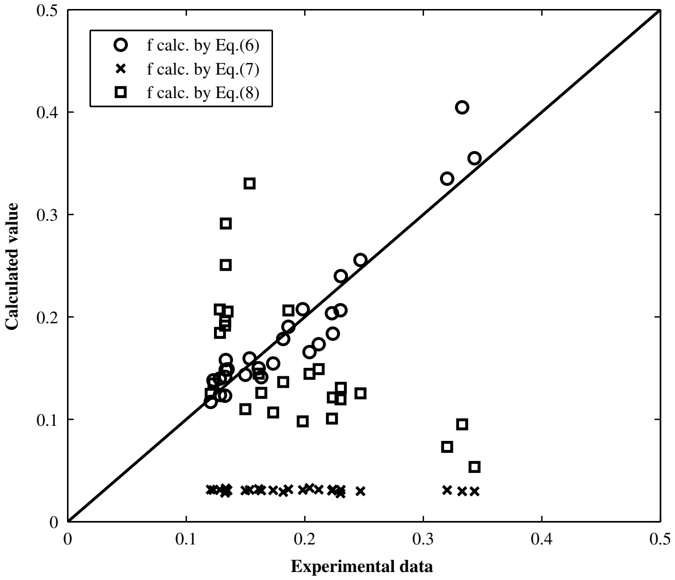

Fig. 5. Comparison of measured and calculated Darcy-Weisbach f

$$n = 0.035H^{0.34} \tag{7}$$

$$\frac{1}{n} = 1.62\left[\frac{S_v(1-S_v)}{\sqrt{HJ}d_{10}}\right]^{2/3} \tag{8}$$

where H (m) = flow depth; and d_{10} (m) = grain size for which 10% of the bed material is finer.

The data of f observed show a better agreement with the values calculated from the new formula (Fig. 5). Eq. (7) only considered the flow depth and empirical coefficient and index are determined by the measured data from the Jiangjia gully. It did not consider the influence of the movable bed. Although Eq. (8) contains various comprehensive factors, it did not consider the boundary conditions and it isn't dimensionless. It appears that the new formula is better in that it incorporates the bed sediment transportation and dimension parameters, which are usually ignored in debris-flow resistance.

Conclusions

Debris-flow resistance is of practical importance for debris flow control works. Experiments on rigid- and erodible-bed resistance show that the resistance coefficients increase significantly over erodible bed due to entrainment of bed sediment. A new formula estimating the erodible-bed flow resistance is derived from nondimensional multiple regression analysis, $f = 0.04(R/B)^{1/6}[S_v(1-S_v)]^{-2/3} + 8.56S_{\Delta}^{0.479}K^{0.068}\mathsf{F}^{-3.39}$. The calculated results presented a good agreement with the observed data. However, there are still other factors contributing to resistance coefficient, which should be incorporated in a more satisfactory calculation.

Acknowledgments

This work has been funded by the Key Research Program of the Chinese Academy of Sciences (Grant No. KZZD-EW-05-01), the National Basic Research Program of China (973 Program) (Grant No. 2011CB409902), and the Hundred Young Talents Program of the Institute of Mountain Hazards and Environment. The authors thank the Dongchuan Debris Flow Observation and Research Station, CAS, for providing the laboratory and experimental setup. Special thanks are due to Professor Yong Li for his careful revision.

Notation

The following symbols are used in this paper:

B = flume width, m;
D_{50} = median particle diameter of erodible bed, m;
d_{10} = characteristic grain size for which 10% of the bed material is finer in diameter, m;
F = Froude number;
f = Darcy-Weisbach resistance coefficient;
f_1 = fixed-bed Darcy-Weisbach resistance coefficient;
f_2 = Darcy-Weisbach resistance caused by bed sediment;
g = gravitational acceleration, m/s^2;
H = flow depth, m;
J = slope;
K = relative roughness;
n = Manning coefficient, s/m$^{1/3}$;
R = hydraulic radius, m;
S_v = solid volume concentration of debris flow;
S_{v0} = solid volume concentration of debris flow before entering the erodible bed;
S_{v1} = solid volume concentration of debris flow after entering the erodible bed;
S_{Δ} = solid volume concentration variation; and
V = mean debris-flow velocity, m/s.

References

Ackermann, N. L., and Shen, H. (1982). "Stresses on rapidly sheared fluid-solid mixtures." *J. Eng. Mech. Div.*, 108(1), 95–113.

Alam, A. M., and Kennedy, J. F. (1969). "Friction factors for flow in sand-bed channels." *J. Hydraul. Div.*, 95(6), 1973–1992.

Bagnold, R. A. (1954). "Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear." *Proc., Roy. Soc. A*, 225(1160), 49–63.

Chen, C. L. (1988). "General solutions for viscoplastic debris flow." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1988)114:3(259), 259–282.

Costa, J. E. (1984). "Physical geomorphology of debris flows." *Developments and applications of geomorphology*, J. E. Costa and P. J. Fleischer, eds., Springer, Berlin, Germany, 268–317.

Davies, T. R. H. (1990). "Debris-flow surges–Experimental simulation." *J. Hydrol.*, 29(1), 18–46.

Egashira, S., Honda, N., and Itoh, T. (2001). "Experimental study on the entrainment of bed material into debris flow." *Phys. Chem. Earth C*, 26(9), 645–650.

Egashira, S., Miyamoto, K., and ltoh, T. (1997). "Constitutive equations of debris flow and their applicability." *Proc., 1st Int. Conf. on Debris-Flow Hazard Mitigation, Mechanics, Prediction, and Assessment*, ASCE, New York, 340–349.

Einstein, H. A., and Barbarossa, N. L. (1952). "River channel roughness." *Trans. Am. Soc. Civ. Eng.*, 117(1), 1121–1132.

Engelund, F. (1966). "Hydraulic resistance of alluvial streams." *J. Hydraul. Div.*, 92(HY2), 315–326.

Fei, X. J. (2003). "Velocity and solid transportation concentration of viscous debris flow." *J. Hydraul. Eng.*, 15–18 (in Chinese).

Honda, N., and Egashira, S. (1997). "Prediction of debris flow characteristics in mountain torrents." *Proc., 1st Int. Conf. on Debris-Flow Hazard Mitigation: Mechanics, Prediction, and Assessment*, ASCE, New York, 707–716.

Hungr, Q., Evans, S. G., Bovis, M., and Hutchinson, J. N. (2001). "A review of the classification of landslides of the flow type." *Environ. Eng. Geosci.*, 7(3), 221–238.

J. Hydraul. Eng. 2014.140:115-120.

Iverson, R. M. (1997). "The physics of debris flows." *Rev. Geophys.*, 35(3), 245–296.

Jakob, M., and Hungr, O. (2005). *Debris flow hazards and related phenomena*, Praxis Publishing, Chichester, U.K., 1–202.

Jin, M., and Fread, D. L. (1999). "1D modeling of mud/debris unsteady flows." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1999)125:8(827), 827–834.

Johnson, A. M., and Rahn, P. H. (1970). "Mobilization of debris flows." *Zeitschrift fur Geomorphologie*, 9(Suppl.), 168–186.

Julien, P. Y., and Paris, A. (2010). "Mean velocity of mudflows and debris flows." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000224, 676–679.

Kang, Z. C. (1985). *A velocity analysis of viscous debris flow at Jiangjia gully of Dongchuan in Yunnan*, Memoirs of Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences, Science Press, Beijing, 108–118 (in Chinese).

Lyness, J. F., Myers, W. R. C., Cassells, J. B. C., and O'Sullivan, J. J. (2001). "The influence of planform on flow resistance in mobile bed compound channels." *Water Maritime Eng.*, 148(1), 5–14.

O'Brien, J. S., and Julien, P. Y. (1988). "Laboratory analysis of mudflow properties." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1988)114:8(877), 877–887..

O'Brien, J. S., Julien, P. Y., and Fullerton, W. T. (1993). "Two-dimensional water flood and mudflow simulation." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1993)119:2(244), 244–261..

Rickenmann, D. (1994). "An alternative equation for the mean velocity in gravelbed rivers and mountain torrents." *Proc., Int. Conf. on Hydraulic Engineering: Hydraulics of Mountain Rivers*, ASCE, Buffalo, NY, 672–676.

Rickenmann, D. (1999). "Empirical relationships for debris flows." *Natural Hazards*, 19(1), 47–77.

Savage, S. B., and Hutter, K. (1989). "The motion of a finite mass of granular material down a rough incline." *J. Fluid Mach.*, 199(1), 177–215.

Shieh, C.-L., Jan, C.-D., and Tsai, Y.-F. (1996). "A numerical simulation of debris flow and its application." *Natural Hazards*, 13(1), 39–54.

Takahashi, T. (1978). "Mechanical characteristics of debris flow." *J. Hydraul. Div.*, 104(8), 1153–1169.

Takahashi, T. (1980). "Debris flow on prismatic open channel." *J. Hydraul. Div.*, 106(3), 381–396.

Takahashi, T. (2007). "What's debris flow." Chapter 1, *Debris flow mechanics, prediction and countermeasures*, Taylor & Francis/Balkema, The Netherlands, 3–32.

Van Rijn, L. C. (1984). "Sediment transport, Part III: Bed forms and alluvial roughness." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1984)110:12(1733), 1733–1754.

Wang, G.-Q., Shao, S.-D., and Fei, X.-J. (1997). "Particle model for alluvial fan formation." *Debris Flow Hazards Mitigation*, 143–152.

Wang, S., and White, W. R. (1993). "Alluvial resistance in transition regime." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1993)119:6(725), 725–741.

Wang, X. K., Shao, X. J., and Li, D. X. (2002). *Fundamental river mechanics*, China Water Power Press, Beijing, 163–194 (in Chinese).

White, W. R., et al. (1980). "The frictional characteristics of alluvial streams: A new approach." *Proc., Inst. Civ. Eng.*, 69(3), 737–750.

Wu, J. S., Kang, Z. C., Zhang, Y. F., and Liu, J. (1993). *Debris flow and its comprehensive measures*, Science Press, Beijing, 165–175 (in Chinese).

Yalin, M. S. (1992). *River mechanics*, Pergamon Press, New York, 1–217.

Yang, M. Q., and Wang, L. X. (1992). "A laminated load model of debris flow and its experimental investigation." *J. Sediment Res.*, 9(3), 21–29 (in Chinese).

Yen, B. C. (2002). "Open channel flow resistance." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2002)128:1(20), 20–39.

J. Hydraul. Eng. 2014.140:115-120.