Characteristics of erosion and deposition from debris flows

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Abstract Debris flows are mixtures of water and soil intermediate between sediment-laden flows and landslides in mountain areas. The transport ability of debris flow, the characteristics and values of erosion and deposition for three kinds of debris flows (micro-viscous, viscous and plastic) are analysed according to observation data from three debris flow ravines. It may be seen that debris flows have some characteristics shown by both sediment-laden flows and landslides, while there exist apparent differences between them.

INTRODUCTION

A debris flow is a mixture of water and soil midway between a sediment-laden flow and a landslide in mountain areas. The characteristics of erosion and deposition of debris flows are between those of sediment-laden flows and landslides. Table 1 shows the basic characteristics and the characteristics of erosion and deposition of sediment-laden flows, three kinds of debris flows as well as landslides (Wu Jishan, 1987). It can be seen that debris flows have some characteristics of sediment-laden flow and landslides, but apparent differences also exist. Generally, micro-viscous debris flows are closer to sediment-laden flows, while plastic debris flows are closer to landslides. This article studies the transport ability of debris flows, the characteristics and the values of erosion and deposition, according to observational data from the Heisha River in Sichuan Province, and the Jiangjia and the Hunshui Ravines in Yunnan Province.

TRANSPORTATION PATTERNS AND ABILITIES OF DEBRIS FLOWS

The erosion and deposition of debris flows is due to the transport ability of the sediments in them. Particles, including clay, sand as well as debris, are transported in three ways: suspension, suspended load and bed load. Suspension means soil particles which form networks, network-grains or lattice textures with water (Wu Jishan, 1987). When such flow is still, the particles stay suspended in the flow instead of being deposited or lifted. When the flow

Table 1 The major characteristics of a sediment-laden flow, a debris flow and a landslide.

Characteristics	Sediment-laden flow	Debris flow:			Landslide
		Micro-viscous	Viscous	Plastic	
Unit weight (t m^{-3})	<1.3	1.15-1.90	1.8-2.4	2.3-2.5	2.4-2.1
Ratio of soil volume	<0.10	0.09-0.55	0.50-0.80	0.65-0.90	0.70-0.90
Starting static shear (Pa)	0	0-5	3-500	>300	$>10^4$
Textures	textureless	loose network	close lattice	very close lattice	soil body
Rheologic characteristics	Newton body	Bingham body with turbulence	Bingham body with slipping effect	pseudo-plastic body with starting static shear	St Venant body
Erosion patterns	single particle lifting	single particle lifting	layer erosion	integral erosion	integral gravity erosion
Transportation patterns	suspended load, bed load	suspension, suspended load, bed load	suspension and bed load for some block stones	suspension	massive movement
Deposition patterns	single particle deposition	single particle deposition	layer deposition	integral deposition	integral silting

moves, the particles move at the same velocity as that of the water and unseparate from the water, known as pseudo-one-phase flow. Because ordinary sediment-laden flow cannot form a network texture, there is not suspension in such flow. The formulae for the limiting grain size of suspension are:

$$d_o = \frac{6(\alpha\tau_o)}{\gamma_s - \gamma_m} \tag{1}$$

$$d_o = \frac{6F_2 + 1.5F_3}{\gamma_s - \gamma_m} \tag{2}$$

in which γ_s is the specific gravity of soil and γ_m is the unit weight of the slurry. Formula (1) is relevant to a micro-viscous debris flow body, γ_m is slurry density of which the grain size is less than 0.02 mm. Formula (2) is relevant to a viscous debris flow, γ_m is the slurry density which has a grain size less than 2.0 mm; α is a structure strength coefficient; F_2, F_3 are respectively the resistance to unit friction and the bearing power, which are found by experiment (Wu Jishan *et al.*, 1990). For suspension, transportation needs no additional energy, so their transport ability S_1 is not impacted by the dynamic properties, but is determined by the upstream supply. All suspension material from upstream can be transported.

The transport ability of suspended load S_2 and that of bed load S_3 can be obtained by correcting the formula for bed load given by Qian Ning (Wu Jishan *et al.*, 1990). In viscous flow, particles with grain size larger than d_o move by rolling or sliding. The rolling particles are mainly spheroids or close to spheroids. The sliding particles are mainly cubes or close to cuboids. The limiting grain sizes between them d_r, d_s can be given by correcting Bertui's formulae (Wu Jishan *et al.*, 1990):

$$d_r = \frac{3\rho_c v_c^2(C_f - C_x - C_v + C_z f'\cos\alpha) - 6\tau_\rho'\cos\alpha}{4k_r(\gamma_s - \gamma_m)f'\cos\alpha} \tag{3}$$

$$d_s = \frac{\rho_c v_c^2(C_f - C_x - C_v + C_z f\cos\alpha) - 2\tau_\rho\cos\alpha}{2k_s(\gamma_s - \gamma_m)f\cos\alpha} \tag{4}$$

in which C_f is the thrusting coefficient; C_x is the contraction coefficient; C_v is the viscosity resistance coefficient determined by the viscosity resistance to the stones; C_z is the lifting force coefficient; τ_ρ and τ'_ρ are the limiting values of block stones rolling and sliding due to their inertia. It will disappear when the stones begin to move; f and f' are respectively the friction coefficients of spheroid stones and cube stones with the bed interface; k_r and k_s are respectively the corrected coefficients of stone profiles. When a stone is a sphere or a cube, k_r and $k_s = 1$. When all the stones in the debris flow are not spheres or cubes, the determination of k_r and k_s is based on how much the stones deviate from a sphere or a cube.

Suspension, suspended load and bed load exist in micro-viscous debris flows. The total transport ability of sediments S is the sum of S_1, S_2 and S_3. In viscous debris flow, most particles are in suspension but there are also a few stones rolling and sliding as bed load. In plastic debris flow, all particles are in suspension.

THE EROSION AND DEPOSITION OF DEBRIS FLOW

For different debris flows the patterns and abilities of transportation cause the differences in erosion and deposition. Generally, there are three patterns.

The pattern of micro-viscous debris flow is the lifting or deposition of a single particle which is similar to that in sediment-laden flow, meanwhile, because the medium of transportation in micro-viscous debris flow is a slurry with a network texture between fine grains and water, in the same conditions, the degree of erosion and deposition is larger than in the case of sediment-laden flow. Generally, when the concentration of soil is less than S, a debris flow exhibits erosion, and when the concentration is more than S, it exhibits deposition.

Layer erosion and deposition are the main characteristics of viscous debris flow, but there are also a few stones which move by rolling and sliding. The particles are in suspension, with a close lattice texture. When the drag force of debris flow τ_c is used to balance the resistance of bed surface τ_f, a debris flow will move forward as a mass; when τ_c is larger than the resistance of internal friction of sediments in bed τ_b, especially when weak faces exist, the sediments are transported layer by layer; when τ_c is smaller than τ_f, the sediments are deposited layer by layer on the bed surface; when τ_c is smaller then τ_o, a debris flow exhibits mass deposition. While the grain size is more than d_o but less than d_r or d_s, rolling or sliding occurs and sediments erode; those stones which are larger than d_r or d_s stop moving and deposit.

Plastic debris flows exhibit mass erosion and deposition. Because a close lattice texture exists, all particles are in suspension. When τ_c is more than τ_f but less than τ_b, a debris flow moves as a mass, but it is different from a landslide in that it has a velocity gradient; when τ_c is more than τ_f while τ_f is more than τ_b, the sediments on the bed are carried away through the weak interface as a mass; when τ_o is less than τ_f, a debris flow stops moving as a mass, τ_c, τ_f and τ_b are given as follows:

$$\tau_c = \gamma_c h \sin\theta = \gamma_c h i \tag{5}$$

$$\tau_f = f_o \gamma_c h \cos\theta \tag{6}$$

$$\tau_b = k_b(\gamma_s h_b \tan\phi + C) \tag{7}$$

in which θ is the bed angle; f_o is the coefficient of friction between the bed and the debris flow; h_b is the height of sediments on the bed; ϕ is the internal friction angle; C is cohesion; k_b is a correction coefficient.

THE MAIN FACTORS AFFECTING EROSION AND DEPOSITION OF DEBRIS FLOW AND HOW TO DETERMINE THE AMOUNT OF EROSION AND DEPOSITION

For different debris flows the main factors affecting erosion and deposition of debris flows vary, thus the formulae for erosion and deposition also vary.

The erosion and deposition of micro-viscous debris flow is similar to that of sediment-laden flow. It is affected by the velocity and coarse grains of the bed as well as the medium of transportation. According to the observational data of micro-viscous debris flows in the Heisha River, the depth of erosion is as follows:

$$t_d = 0.0114 \left[\frac{V_c^{2/3}}{d_{90}^{1/2}}\right] \left[\frac{\gamma_s - 1}{\gamma_s - \gamma_m}\right]^{1/2} - 0.028 \qquad (t_a \leq 0.06 \text{ m}) \tag{8}$$

$$t_d = 0.0649 \left[\frac{V_c^{2/3}}{d_{90}^{1/2}}\right] \left[\frac{\gamma_s - 1}{\gamma_s - \gamma_m}\right]^{1/2} - 0.405 \qquad (t_d > 0.06 \text{ m}) \tag{9}$$

in which d_{90} is the diameter of particles, the weight concentration of which is 90%. The erosion and deposition of a viscous debris flow is related to i (the bed gradient), Q (discharge of debris flow), drainage area and the process of movement. Generally, when the bed gradient is sufficient, a debris flow will move forward. When the bed gradient is less than a limited gradient i_k, it will stop moving and become a deposition fan. According to the observational data from the Heisha River, the Jiangjia Ravine, the Hunshui Ravine and its tributaries, when the drainage area F increases, i_k will decrease. When the density is about 2.2 t m^{-3}, the following results:

$$i_k = 0.105 - 0.163 \log F^{0.2} \tag{10}$$

According to the observational data from the Jiangjia Ravine, when a viscous continuous debris flow appears, the bed is eroded. A single viscous continuous debris flow can incise the bed by over 16 m. For a viscous shooting debris flow, if the discharge is more than 1000 m^3 s^{-1} or the mud depth is more than 1.7 m, then erosion is the main phenomenon. The larger the discharge or depth the larger is the depth of erosion. If the discharge or depth is less than these values, erosion and deposition can appear at the same time, but the smaller Q_c or h_c, the larger the probability of deposition, or the smaller is the probability of erosion. The relationship between them is:

$$t_d = 0.163 - 5.67 \times 10^{-4} Q_c \tag{11}$$

$$t_d = 0.38 - 0.421 h_c \tag{12}$$

but the scatter is large. Meanwhile, there does not exist any apparent relation between velocity and erosion or deposition. At any velocity, erosion or deposition can occur. In the Jiangjia Ravine, if V_c is more than 12 m s^{-1}, the probability of erosion is about equal to that of deposition.

The erosion and deposition of plastic debris flows are mainly affected by the bed gradient and the scale of a debris flow. The latter replaces the drainage area F or the total discharge of a debris flow W_c. According to the data from the Heisha River and the Jiangjia Ravine, the limit of the bed gradient at which a debris flow stops moving i_k is given below:

$$i_k = 0.083 - 0.262 \log F^{0.2} \qquad (F \le 1 \text{ km}^2) \tag{13}$$

$$i_k = 0.098 - 0.113 \log F^{0.2} \qquad (F > 1 \text{ km}^2) \tag{14}$$

$$i_k = 0.324 - 0.306 \log W_c^{0.3} \qquad (W_c \le 200 \text{ m}^3) \tag{15}$$

$$i_k = 0.199 - 0.119 \log W_c^{0.3} \qquad (W_c > 200 \text{ m}^3) \tag{16}$$

REFERENCES

Wu Jishan (1987) *Analysis of Debris Flow Characteristics. Soil Wat. Conservation in China* **62**, 2-8.
Wu Jishan *et al.* (1990) *Observation and Research of Debris Flow in Jiangjia Ravine, Yunnan Province,* 185-201, Science Press.