DEBRIS FLOWS AND PYROCLASTIC FLOWS

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Contents

Summary

Debris flows are classified according to the dominant stress: particle contact stress, material mixing stress, and viscous stress. Thereby, the respective criteria for the occurrence of the stony debris flow, the turbulent mudflow, and the viscous debris flow are demarcated by Reynolds number, Bagnold number, and the relative depth of flow. Characteristics of each debris flow, such as velocity, solids concentration, and the mechanism to disperse the coarse particles, are discussed. A unified theory for the inertial debris flow is given, which explains quantitative characteristics of stony, immature, hybrid, and muddy debris flows. As for viscous debris flow, a Newtonian fluid model is introduced, which explains the velocity in the actual debris flow at Jiangjia Gully, China. After a brief review of the history of research on pyroclastic flows, the classification of pyroclastic flow is given in view of the mode of occurrence as well as the volume of the total ejecta. The high mobility of pyroclastic flow is attributed to the emission of gas from the pyroclastic material itself. Characteristics of the pyroclastic flow at Mt. Fugen, Unzen Volcano, Japan, are described. A mechanical model that is able to explain the quantitative

characteristics of the granular flow stage that appears soon after collapse of the lava dome and the fluidized flow stage that follows the granular flow stage in which flow is separated into the main body and the hot ash cloud is given. The basic flow equations are incorporated into the system of equations that is necessary in the numerical simulation of pyroclastic flow. The numerical simulation reproduced the pyroclastic flow at Unzen Volcano.

1. Definition and Fundamental Mechanism of Debris Flows

Debris flow can be defined as a highly concentrated flow of the mixture of water and sediment that surges down steep slopes or ravines in response to gravitational attraction. Due to its high mobility and large density, it often brings severe disaster to the affected communities. The high mobility is caused by the motion of the solid phase as particles keep the void space between pieces large to minimize the resistance to flow. This is in contrast to landslides, within which the solid phase moves in a cluster on a slip surface resisting with the large frictional resistance. The apparent density of debris flow can be 2 tons m^{-3} or more due to the large particle dispersing mechanism within flow. This is in contrast to sediment-laden water floods in which the coarse particles are moved by the fluid dynamic forces, and the particle concentration cannot be more than a few percent. Thus, debris flow is a phenomenon intermediate between landslide and sediment-laden water flow in terms of solids concentration and fluidity.

Debris flows appear in different behavior depending on the sediment concentration, the particle size composition, thickness of flow, the gradient of slope down which they surge, etc. Possibly because of such a diversity of behavior, various nomenclatures have been used, for example, debris torrents, debris floods, mudflows, mud floods, and hyperconcentrated flows. Volcanologists sometimes call the debris flows originating in volcanic activity "lahar." Lahar is an Indonesian word. Many large debris flows occur at Indonesian volcanoes due to erosion of the pyroclastic deposit. Sometimes such a lahar is hot. All these phenomena described by the different names may be regarded as debris flows, and the classification of debris flows in terms of mechanics of flow is discussed below. The processes of occurrence and deposition are discussed in Debris Flow Forecast and Di*saster Mitigation Measures for Debris Flows*.

The difference in behavior of debris flows must be the reflection of difference in the dominant stresses among others existing within the flow. If the total shearing stress, τ, and the pressure, p, in a very highly sediment-laden plain shear flow are given by the linear sum of the constituent shearing stresses and pressures, they would be expressed as following:

$$\tau = \tau_y + \tau_\mu + \tau_c + \tau_k + \tau_s + \tau_t \qquad (1)$$

$$p = p_c + p_s + p_h \tag{2}$$

where τ_y is the yield strength of the interstitial fluid (slurry), τ_μ the viscous stress due to deformation of the mixture of slurry and the coarse particles, τ_c the shear stress due to inelastic particle collision, τ_k the kinetic stress due to plunging of particles from a layer into other layers, τ_s the static Mohr-Coulomb shear stress due to enduring contact motion between the particles, τ_t the turbulent mixing stress, p_c the pressure due to particle collision, p_s the static pressure due to enduring frictional contact between the particles, and p_h the isotropic pressure in the interstitial fluid. If $(\tau_y + \tau_\mu)$, $(\tau_c + \tau_s)$ and $(\tau_k + \tau_t)$ are written as τ_υ, τ_g and τ_m, respectively, τ_υ is considered to represent the shear stress due to viscoplasticity of the material, τ_g is that due to contact of particles and τ_m is that due to mixing of the material. As an extreme case, if the total shear is shared only by τ_υ, flow is the viscous type debris flow. If the total shear is shared only by τ_g, flow is either the stony inertial type debris flow or the quasistatic shearing motion. The latter occurs when the mean coarse particle concentration in the material is more than the threshold value of about 0.5, whereby τ_g is almost shared only by τ_s. If the total shear is shared only by τ_m, that is, the turbulent mudflow type debris flow, and the macroscale turbulence incorporated with water and sediment prevails almost in the entire depth of flow. The actual debris flows appear within the wide spectrum of these extreme cases.

Many previous experimental and theoretical explorations of the constitutive relations of granular flows confirm the following forms:

$$\tau_c = \sigma d_p{}^2 f_1(C)\gamma^2 \tag{3}$$

$$\tau_k = \sigma d_p{}^2 f_2(C)\gamma^2 \tag{4}$$

$$\tau_\mu = \mu f_3(C)\gamma \tag{5}$$

where σ is the particle density, d_p is the coarse particle diameter, γ is the shear rate, μ is the viscosity of the interstitial fluid that incorporates with fine particles, and $f_1(C)$ f_2(C), and f_3(C) are the functions of the coarse particle concentration C, respectively. The shear stress due to the macroscale turbulence is given by

$$\tau_t = \rho_a l^2 \gamma^2 \tag{6}$$

where ρ_a is the apparent density of the material, and l is the mixing length.

The ratio τ_c / τ approaches 1 when the ratios τ_m / τ_c and τ_μ / τ_c become small. In the case of macroturbulent flow the kinetic stress τ_k is considered to be included in τ_m, and if C is larger than about 0.3, τ_k is far smaller than τ_c, so that from the Eqs. (3) and (6)

$$\frac{\tau_m}{\tau_c} \approx \frac{\tau_t}{\tau_c} = \left(\frac{\rho_a}{\sigma}\right)\left(\frac{l}{d_p}\right)^2 \frac{1}{f_1(C)} \tag{7}$$

The largest value of the ratio (l/d_p) will be represented by the relative depth of flow, (H/d_p), in which H is the depth of flow, and $(\rho_a/\sigma)/f_1(C)$ becomes small with increasing C. Therefore, (τ_m/τ_c) becomes small when the relative depth is small or the coarse particle concentration is large. If τ_y is neglected, as is usually justified in actual debris flow, τ_υ/τ_c is given as

$$\frac{\tau_\upsilon}{\tau_c} \approx \frac{\tau_\mu}{\tau_c} = \frac{\mu}{\sigma d_p{}^2 \gamma} \frac{f_3(C)}{f_1(C)} = \frac{1}{B_a} \frac{f_3(C)}{f_1(C)} \left[\left(\frac{C_*}{C}\right)^{1/3} - 1\right]^{-1/2} \tag{8}$$

where B_a is called Bagnold number, and C_* is the coarse particle concentration when packed. The ratio (τ_υ/τ_c) becomes small when Bagnold number becomes large. Thus, the inertial stony type debris flow appears when the relative depth is small, the coarse particle concentration is large, and the Bagnold number is large. This condition is satisfied when the comprising particles are large, the content of fine particles is small, and the particle concentration is large. The coarse particle concentration must, however, be smaller than the threshold value of about 0.5.

The ratio (τ_t/τ_μ) is given as

$$\frac{\tau_t}{\tau_\mu} = \frac{\rho_a l^2 \gamma}{\mu f_3(C)} \sim \frac{\rho_a UH}{\mu f_3(C)} = R_e \frac{1}{f_3(C)} \tag{9}$$

where R_e is the Reynolds number. The function $f_3(C)$ increases with increasing concentration. Therefore, the turbulent mudflow type debris flow will appear when Reynolds number and the relative depth are large, but the coarse particle concentration must not be too large. This condition is satisfied when the comprising particles are relatively small and the solids concentration is not so large.

The viscous type debris flow will occur when both Reynolds and Bagnold numbers are small and the coarse particle concentration is large. This condition is satisfied when the concentration of the fine cohesive particles in the interstitial fluid is large, the coarse particle concentration is also large, and the diameter of the coarse particles is not very large.

Summarizing the mentioned discussions, the domains of the existence of the respective kinds of debris flows whose coarse particle concentrations are between about 0.25 and 0.5 are given within the ternary diagram as shown in Figure 1. Hybrid debris flow in the figure means the intermediate type of the typical types of debris flows.

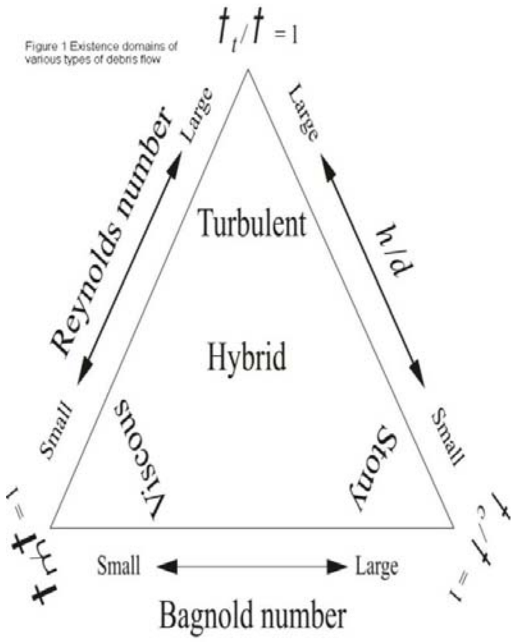

Figure 1. Existence domains of various types of debris flow

2. Characteristics of Stony Debris Flow and Modeling As a Dilatant Fluid

Figure 2 shows a stony debris flow passing through a channel consolidating structure in Kamikamihori Gully, Japan. Generally, stony debris flow surges down the gully setting up a bore-like front, which swells with gathering big boulders. The size of particles in the front is the largest and particle size decreases toward the rear; water content in the front is low and the rear part contains more water. The particle size in the whole debris flow material distributes from a few meters to the clay size, but the content of fine particles smaller than 0.1 mm is normally less than a few percent. The big stones on the surface that often seem to float, proceed faster than the translation velocity of the forefront. Those stones tumble down to the gully bed, arriving at the tip of the snout, the smaller particles are then caught under the snout. Thus, the biggest stones accumulate at the front.

Debris flows build a fan at the mouth of the gully. This is steeper than the usual alluvial fan and consists of poorly sorted mixture of particles. An individual debris flow forms a lobe deposit on the fan. The lobe that is composed of numerous boulders has a semicylindrical shape, just as if flow is suddenly frozen, and this type lobe deposits on the upper part of the fan where the slope angle is more than three degrees. In this kind of deposit, the there is often inverse grading (i.e., from top to bottom, the particle size decreases). The deposit that is rich in sand size particles forms flatter lobe and it reaches the lower part of the fan. Sometimes, a debris flow overflows from the incised channel on a fan and makes the natural levees with big boulders along the channel.

Figure 2. A stony debris flow passing through a gully consolidating structure at Kamikamihori, Kamikochi, Japan
Figure by H. Suwa

For the first approximation of the motion of stony inertial debris flow, let us assume that τ_c balances with the external driving force due to gravity, and use the Bagnold's constitutive relation in Eq. (3). Then, we obtain the following equation:

$$(a\sin\alpha)\sigma d_p{}^2\left[\left(\frac{C_*}{C}\right)^{1/3}-1\right]^{-2}\left(\frac{du}{dz}\right)^2=g\sin\theta\int_z^H\left[(\sigma-\rho)C+\rho\right]dz \qquad (10)$$

where u is the velocity at the height z measured from the bottom of flow, g the acceleration due to gravity, θ the channel gradient, ρ the density of the interstitial fluid (water), and $(a\sin\alpha)$ is a constant. A conceptual fluid within which the shearing stress is proportional to the square of the shear rate is a kind of dilatant fluid. Therefore, Eq. (10) means that debris flow is modeled as a dilatant fluid flow. If a homogeneous distribution of solids throughout the entire depth is assumed, Eq. (10) is easily integrated to give the vertical velocity distribution and finally the formula of resistance to flow as

$$\frac{U}{u_*}=\frac{2}{5d_p}\left\{\frac{1}{a\sin\alpha}\left[C+(1-C)\frac{\rho}{\sigma}\right]\right\}^{1/2}\left[\left(\frac{C_*}{C}\right)^{1/3}-1\right]H \qquad (11)$$

where U is the cross-sectional mean velocity, and $u_*=(gH\sin\theta)^{1/2}$. The previous experimental data show that $a\sin\alpha$ is approximately 0.02, and Eq. (11) well predicts the mean velocity of the stony debris flow if $H/d_p \leq 30$. Substitution of the larger H/d_p value than 30 into Eq. (11) gives unreasonably fast velocity, because in such a large relative depth the debris flow is no more the stony type but the turbulent mudflow type.

Another balance of force equation in terms of pressure that is transmitted directly from particle to particle must also be satisfied as

$$(a\cos\alpha)\sigma d_p^{\,2}\left[\left(\frac{C_*}{C}\right)^{1/3}-1\right]^{-2}\left(\frac{du}{dz}\right)^2 = g\cos\theta\int_z^H(\sigma-\rho)C\,dz \qquad (12)$$

Integration of Eq. (12) also results in a resistance law formula. This result and Eq. (11) must be the same one, and this condition requires the following relationship:

$$C = \frac{\rho\tan\theta}{(\sigma-\rho)(\tan\alpha-\tan\theta)} \qquad (13)$$

The previous experiments on the stony debris flow show that the equilibrium condition, in which neither erosion nor deposition on an erodible bed occurs, is satisfied if C is equal to C_∞,

$$C_\infty = \frac{\rho\tan\theta}{(\sigma-\rho)(\tan\phi-\tan\theta)} \qquad (14)$$

where $\tan\phi$ is the internal friction coefficient of the stable solids layer, which must be approximately equal to $\tan\alpha$ in a highly concentrated debris flow. This would be the reason why Eq. (11) is valid.

Eq. (14) calculates small concentration when the channel inclination is small. However, to disperse the particles throughout the entire flow layer by the action of interparticle collisions, it needs comparatively high concentrations. Actually, under a concentration less than the limit value of about 0.25, the particles are no longer dispersed throughout the entire depth, but are concentrated in the lower part of the flow. Above this particle mixture layer a water layer appears. This kind of flow is named "immature debris flow." In immature debris flow, the particle concentration in the mixture layer is held almost constant of about 0.25, but the thickness of the layer increases with increase in channel inclination. Thus, immature debris flow can appear in the channel slope range from about 13° to about 3°.

According to the authors experiments the equilibrium transport concentration, $C_{s\infty}$, for immature debris flow is given by

$$C_{s\infty} = 6.7 C_{\infty}{}^{2} \tag{15}$$

The transport concentration is defined by q_s / q, where q_s is the sediment discharge per unit width, and q is the discharge of water plus sediment per unit width. It must be noted that Eq. (15) is valid in the range about $0.02 < C_{s\infty} < C_{\infty}$ corresponding to the above mentioned channel slope range. The empirical formula of the resistance to flow obtained by the author's experiments is

$$\frac{U}{u_*} = 0.4 \frac{H}{d_p} \tag{16}$$

Although Eqs. (14) and (15) suggest that the equilibrium sediment concentration in the mature and immature debris flows are determined uniquely corresponding to the channel inclination, the actual existence fields of the mature and the immature debris flows overlap each other. The process of deposition of a mature debris flow is an inertial phenomenon, and depending on the longitudinal profile of the ravine, the boulder rich front of the mature debris flow sometimes arrives to a mildly inclined area whose slope angle well falls in the domain of immature debris flow. In such a case, the successive flow that overpasses the deposit made by stopping of the debris flow front becomes immature debris flow.

3. Characteristics of Turbulent Mudflow

At the active volcanic area the frequent ash-falls and/or pyroclastic flows cover the mountain slope, and this cover hinders the infiltration of rain into the ground. Thus, even a weak rainfall produces the surface water flow containing highly concentrated pyroclastic particles whose size distributes from about that of silt to a few millimeters. Such muddy flow concentrates on the gully system and erodes the channel to develop to a debris flow. This type debris flow is usually very much turbulent, and although it contains many big boulders they do not gather around the front contrary to a stony debris flow, the boulders are transported by the fluid dynamic force rather than due to particle colliding effect.

The typical turbulent mudflows occurred at Mt. Unzen, Kyushu, Japan, originating from the deposit of a large number of pyroclastic flows. More than 114 debris flows occurred in the Mizunashi River during the activity of the volcano from 1991 to 1995, resulting in the deposition of more than 8×10^6 m^3 of debris and destroying about 1000 buildings on the fan area. Many debris flows passed through the reach steeper than 2.9° and deposited in the reach whose slope is between 2.0° and ~1.5°.

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