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Kinetic Energy Model of Two-Phase Debris Flow

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Abstract A numerical model for two-phase debris flows is developed in this paper, on the basis of understanding of the physical characteristics of debris flows from field investigations and experiments. Employing a moving coordinate, the kinetic energy equation of gravel particles in unit volume in debris flow is developed by considering the potential energy of the particles, energy from the liquid phase, energy consumption due to inner friction-collision between the particles, energy dispersion through collisions between particles, energy for inertia force, energy consumption due to the friction with the rough bed and energy consumption at the debris front. The model is compared with measured results of two-phase debris flow experiments and the calculated velocity profiles agree well with the measured profiles. The gravel's velocity at the debris flow head is much smaller than that of particles in the following part and the velocity profile at the front of the debris flow wave is almost linear, but the profile in the main flow shows an inverse 's' shape. This is because the gravel particles in the main flow accelerate as they receive energy from the gravitational energy and flowing liquid and decelerate as they transmit the energy to the debris flow head and consume energy due to collision with the channel bed.

Key words: *Energy consumption, Kinetic energy model, Two-phase debris flow, Velocity profile, Collision*

1 INTRODUCTION

Debris flow is often triggered as a result of scour of slope deposits by torrential flood generated by intense rainfall and melting snow. Debris flow carries huge amounts of sediment, from clay finer than 10^{-3} mm to huge stones of several meters in diameter. Clay, sand, gravel and boulders move by various mechanisms, which make the problem complicated. There are two types of debris flow, namely viscous debris flow and two-phase debris flow (Wang *et al.*, 1999). Viscous debris flow consists of clay, silt, sand and gravel, and it is a non-Newtonian, pseudo-one-phase flow. In the two-phase debris flows the solid phase consists of gravel and boulders and the liquid phase consists of water, clay and silt in suspension – sometimes also sand and fine gravel. There is obvious relative movement between the solid phase and the liquid phase.

The head of debris flow usually consists of large gravel with greater height than the height of the following flow (Kang, 1985, 1996). Wang and Zhang (1990) found from experiments that the particles' velocity in the front of the debris flow wave is lower than the particles moving in the following part and the propagation velocity of the debris flow wave is

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much lower than the flow velocity of the main body of the debris wave. Moreover, Wang *et al.* (2005) found from two-phase debris flow experiments that the velocity profiles in the head and the following part are very different.

Many studies of debris flow have been made. Bagnold (1956) and Takahashi (1978, 1980, 1981) constructed a theory for two-phase debris flows that accounts for particle interactions. The central feature of their theory is the concept of grain flow dispersive stress, originally introduced by Bagnold (1954). The theory postulates for debris flow of a dilatant fluid, but shear stress is generated mainly by collision between particles. The theory provides a mechanism of supporting force for moving gravel and stones, a velocity profile distinct from water flow, and high resistance of debris flow, and seems to provide an explanation for the segregation of large and small particles that leads to the debris flow head consisting of large stones. Davis *et al.* (1986) studied the elastrohydrodynamic collision of two spheres. MeTingue (1982) developed a non-linear constitutive model for granular material based on Bagnold's concepts. Savage (1984) proposed a theory for rapid granular flows. Chen (1992) presented a generalized viscoplastic model for viscous debris flow. Wang *et al.* (1991) developed a theoretical model for two-phase debris flows based on momentum conservation. Iverson and Denlinger have reviewed and assessed these models (Iverson and Denlinger, 1993).

However, these models have essential shortcomings in omitting the energy transmission between different parts of the debris flow wave, and interaction between the two phases. The constitutive equation can be applied only if all parts of the flow behave the same rheologically, which is not true for most debris flows. Another important shortcoming of the models is neglect of the unsteadiness of the flow. In unsteady flow, the shear stress is not balanced by the driving force and the inertia or the kinetic energy that the flow possesses plays an important role in the motion, especially at the initiation stage and in maintaining the motion for a distance in the region of a very gentle slope. Therefore, none of the models can simulate the details of the debris flow and there is a lack of knowledge of the mechanism of different velocities in different parts of the debris flows.

The present study aims to develop a model that can simulate the two-phase debris flows and provide detailed information on the particle motion. For this purpose, several field investigations of the Xiaojiang Watershed were made, which is known as a museum of debris flows. There flume experiments were conducted with five types of gravel to study the mechanism of two-phase debris flows (Wang *et al.*, 2005). The model is developed on the basis of the understanding of the physical characteristics of two-phase debris flows from field investigations and experiments.

2 ENERGY EQUATION

Let e denote the kinetic energy of gravel particles in unit volume in debris flow, which is related to the moving velocity of the particles by:

$$e = \frac{1}{2} C_v \rho_s u_p^{\,2} \quad \text{or} \quad u_p = \left(\frac{2e}{C_v \rho_s}\right)^{1/2} \tag{1}$$

in which C_v is the volume concentration of gravel, u_p the velocity of the particles down the channel, and ρ_s the density of the particles. Changes in kinetic energy are affected by the following factors:

- E_1 – potential energy of the particles may transmit into kinetic energy moving down the slope, J;
- E_2 – particles receiving energy from the liquid phase which flows faster and possesses higher kinetic energy than the particles;
- E_3 – energy consumption due to inner friction-collision between the particles;
- E_4 – energy transmission or dispersion through collisions between particles;
- E_5 – energy for inertia force;
- E_6 – energy consumption due to friction with the rough bed;

- E_7 – energy consumed at the debris front.

For convenience of presentation of the calculations, we employ moving coordinates as shown in Fig. 1, in which the debris head is always at x = 0 and the coordinates move along the x_0 direction at a speed, u_d, which equals the debris flow wave propagation.

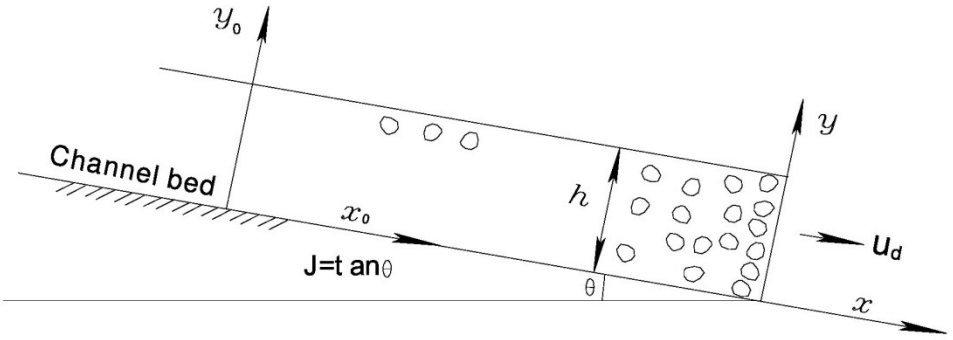


Fig. 1 Definition sketch of the moving coordinates.

The kinetic energy of a particle is the dynamic property of the moving particle and is the same in the two coordinates. In the moving coordinates, the energy flux vector is given by:

$$\vec{q} = (u_p - u_d)e\vec{i} - \varepsilon\nabla e \tag{2}$$

in which u_d is the propagation speed of the debris head, ε is the energy dispersion coefficient, $\vec{i}$ is the unit vector along the x coordinate, ∇e is the gradient of the kinetic energy.

The following equation describes the energy variation of particles in a unit volume:

$$\frac{\partial e}{\partial t} = E_1 + E_2 - E_3 - E_4 - E_5 \tag{3}$$

with boundary conditions: energy loss through the bottom boundary = E_5; and energy loss by pushing the head moving forward = E_6.

The potential energy of particles transmitting into kinetic energy in unit time is:

$$E_1 = \gamma_s J C_v u_p \tag{4}$$

in which $\gamma_s = g\rho_s$ is the specific weight of the gravel, J the slope of the debris flow gully. The equation is independent of the coordinates, or, is of the same expression in a still or moving coordinate. The concentration of particles at the bed is C_{vm} and is lower near the surface. According to the measured data of three debris flows and recommended formulae for dry sand and sand/water mixture flow by Hashimoto (1997), we can assume that the distribution of particle concentration C_v follows a linear function in equilibrium:

$$C_v = C_{vm}(1 - f\,y/h) \tag{5}$$

in which h is the depth of the flow, y is the distance from the bed, f is between 0 and 1, depending on the distance from the head. It is observed that the concentration in the head is vertically uniform and close to the bed concentration. The surface concentration reduces following the distance from the head and becomes constant, as the distance is larger than $5h$. If the matrix has a high concentration of clay and silt suspension and the median diameter of gravel is not large, f is small. If the liquid phase is water and the gravel diameter is large, f is large. As the first approximation, f is a linear function of x for $0>x>-5h$ and equals 0.4 for $x<-5h$.

$$C_v = C_{vm}[1 + 0.4\frac{x}{5h}\frac{y}{h}] \quad for\ 0>x>=-5h \tag{6-a}$$

$$C_v = C_{vm}[1-0.4\frac{y}{h}] \qquad for\ x<-5h \tag{6-b}$$

If we denote u as the velocity of the liquid flowing down the stream, u-u_p is the relative velocity of the two phases. Assuming that the relative velocity is high enough for the flow around the particles to be turbulent, the liquid flow acts a drag force on a particle:

$$F = C_D \frac{\pi d^2}{4}\frac{\rho(u-u_p)^2}{2} \tag{7}$$

in which C_D is the drag coefficient and is equal to 0.45 for turbulent flow. There are n particles in unit volume:

$$n = (\frac{\pi}{6}d^3)^{-1} \tag{8}$$

Thus, the work that the liquid flow does on the particles, or the energy of particles in unit volume received from the liquid flow is given by:

$$E_2 = nFu_p = \frac{3C_D}{4}\frac{\rho u_p}{d}(u-u_p)^2 \tag{9}$$

The maximum relative velocity $(u-u_p)$ is equal to the fall velocity, ω. For coarse sand and gravel, the fall velocity of single particle in water is given by (Qian and Wan, 1983):

$$\omega_0 = 1.72\sqrt{\frac{\gamma_s-\gamma}{\gamma}gd} \tag{10}$$

The fall velocity is smaller if there are many particles falling together in water (also for groups of particles driven by water flow as in debris flow) because of the mutual disturbance of particles, and follows the law (Richardson and Zaki, 1954):

$$\frac{\omega}{\omega_0} = (1-C_v)^{2.39} \tag{11}$$

in which the subscript $_0$ indicates the fall velocity of a single particle.

Taking Eqs. (6-b) (10) and (11) into Eq. (9) we obtain Eq. (12):

$$E_2 = \frac{3C_D}{4}\frac{\rho u_p}{d}(u-u_p)^2 = 2.21C_D(\gamma_s-\gamma)u_p(1-C_{vm}+0.4\frac{C_{vm}y}{h})4.78 \tag{12}$$

in which C_{vm} = 0.6 in the calculation.

According to Bagnold (1988), collisions between the particles create a dispersive stress, T:

$$T = 0.013\rho_s(\lambda d)^2(\frac{\partial u_p}{\partial y})^2 \tag{13}$$

in which λ is the linear concentration proposed by Bagnold (1954):

$$\lambda = \frac{1}{(\frac{C_{v*}}{C_v})^{1/3}-1} \tag{14}$$

where C_{v*} is the maximum concentration when the particles are compactly piled, which is equal to 0.73 for round particles and about 0.65 for irregular shapes such as gravel (Bagnold, 1954).

The energy consumption due to the inner friction from the dispersive stress is then:

$$E_3 = \frac{Tu_p}{d} = 0.013\rho_s d u_p(\lambda\frac{\partial u_p}{\partial y})^2 \tag{15}$$

Like turbulence of fluid flow, collisions between particles also result in momentum exchange and dispersion of energy. The energy dispersion flux vector is given:

$$E_4 = \nabla\cdot\vec{q} = \frac{\partial(u_p-u_d)e}{\partial x} - \nabla\cdot\varepsilon\nabla e \tag{16}$$

The dispersion coefficient ε is assumed as

proportional to the times of a particle colliding with other particles in unit time, *m*, the average free path it travels between two collisions, *s*, and diameter of the particle, *d,*

$$\varepsilon = \beta msd \tag{17}$$

in which β is the ratio of the amount of the dispersed energy over the total kinetic energy. For instance, a particle of mass M and velocity $\mathbf{v_1}$ collides with a particle of the same mass but at standstill, the velocities of the two particles become $\mathbf{v_1}$' and $\mathbf{v_2}$' . The momentum conservation law yields:

$$M (v_1+v_2) = M (v_1'+v_2') \tag{18}$$

in which v_1, v_2, v_1' and v_2' are the magnitudes of the vectors $\mathbf{v_1}$, $\mathbf{v_2}$, $\mathbf{v_1}$' and $\mathbf{v_2}$'. Because $v_2 = 0$, v_1' and v_2' may be equal to each other, thus:

$$v_1=v_1'+v_2'=2\, v_1' \quad \text{or} \quad v_1'=v_2'=0.5v_1$$

The kinetic energy before the collision is $\frac{1}{2}Mv_1^{\,2}$ and after the collision becomes:

$$2\cdot\frac{1}{2}Mv_1'^{2} = \frac{1}{4}Mv_1^{\,2}. \tag{19}$$

In other words, 50% of the energy is consumed during the collision and only 50% is dispersed, or $\beta = 0.5$.

The mean free path *s* is given by Bagnold (1954):

$$s = \frac{d}{\lambda} = [(\frac{C_{v^*}}{C_v})^{1/3} - 1] \tag{20}$$

The collision times is given by Wang and Qian (1985) as follows:

$$m = k\frac{\lambda u_p}{d} \tag{21}$$

in which *k* is a constant. Taking Eqs. (17, 20 and 21) into Eq. (16) we obtain:

$$E_4 = \frac{\partial(u_p - u_d)e}{\partial x} - \beta kd[\frac{\partial}{\partial x}(u_p\frac{\partial e}{\partial x}) + \frac{\partial}{\partial y}(u_p\frac{\partial e}{\partial y})] \tag{22}$$

Debris flow always exhibits acceleration or deceleration, and therefore acts by inertia force. The inertia force on the particles in unit volume is:

$$F_I = C_v\rho_s\frac{\partial u_p}{\partial t} \tag{23}$$

and the energy needed for the acceleration in unit time is:

$$u_pF_I = C_v\rho_s u_p\frac{\partial u_p}{\partial t} = \frac{\partial e}{\partial t} \tag{24}$$

With the expressions of E_1, E_2, E_3, E_4, E_5 in Eq. (4) (12) (15) (22) and (24), the energy Eq. (3) then takes the form:
in which u_p is coupled with *e* by Eq. (25).

$$\frac{\partial e}{\partial t} = \gamma_s JC_v u_p + 2.21C_D(\gamma_s - \gamma)u_p$$
$$(1 - C_{vm} + 0.4C_{vm}\frac{y}{h})^{4.78} - 0.013\rho_s du_p(\lambda\frac{\partial u_p}{\partial y})^2$$
$$- C_v\rho_s u_p\frac{\partial u_p}{\partial t} - \frac{\partial(u_p - u_d)e}{\partial x} +$$
$$\beta kd[\frac{\partial}{\partial x}(u_p\frac{\partial e}{\partial x}) + \frac{\partial}{\partial y}(u_p\frac{\partial e}{\partial y})] \tag{25}$$

3 BOUNDARY CONDITIONS AND INITIATION CONDITIONS

The boundary conditions can be formulated as follows:
On the surface $\vec{q}\cdot\vec{j} = 0$, or

$$\varepsilon\frac{\partial e}{\partial y} = 0 \,..or..\, \frac{\partial e}{\partial y} = 0, \text{ at } y=h \;\; and \;\; x<=0 \tag{26-a}$$

There is no motion for the particles at and

below y = 0, or

$u_p=0$ and $e=0$ at $y=<0$ (26-b)

It is observed that particles move over the head, fall down to the bed and stop moving or bounce up a little. Assume the particles lose their energy after fall down on the bed, the energy loss per time at the head is then:

$$E_6 = u_p e \tag{27}$$

The energy flux through the head gives the following condition: $\vec{q} \cdot \vec{i} = E_6$, or,

$$(u_p - u_d)e - \beta k d u_p \frac{\partial e}{\partial x} = u_p e \text{ at } x=0 \tag{28}$$

It can be simplified as:

$$-\beta k d u_p \frac{\partial e}{\partial x} = u_d e, \text{ at } x=0 \tag{29}$$

We suggest the following empirical formula for the vertical velocity distributions for the initiation conditions:

$$\frac{u_p}{u_{ps}} = \frac{y}{h} - \Gamma \sin(\frac{2\pi y}{h}) \tag{30}$$

in which u_{ps} is the maximum particles' velocity ($=2u_d$) and occurs on the top of the head, Γ is a dimensionless coefficient and equals 0.1 in most cases (it is taken as 0.1 in the paper). Because the average velocity of the head equals the wave propagation speed u_d, the maximum velocity u_{ps} must be equal to $2u_d$.. Then Eq. (29) is rewritten as:

$$\frac{\partial e}{\partial x} = -\frac{C_v}{\beta k}\frac{\rho_s u_d^2}{d}[\frac{y}{h} - 0.1\sin(\frac{2\pi y}{h})] \text{ at x=0} \tag{31}$$

in which u_d is the propagation speed of the debris flow wave and equals the average of the u_p at the head.

If the equation is used directly as the boundary condition at x= 0, the partial derivative $\partial e / \partial x$ is not continuous and that causes problems of calculation. We assume

$$\frac{\partial e}{\partial x} = -\frac{C_v}{\beta k}\frac{\rho_s u_d^2}{d}[\frac{y}{h} - 0.1\sin(\frac{2\pi y}{h})](1+\frac{x}{h})^2,$$

for –h<x<=0 and t=0 (32)

and

$e=0$ *for* $x=+0$ *and* $t=t$.

In the equation, C_v is given by Eq. (6-b). For $t=0$, the equation gives the distribution of e in the zone of $-h<x<0$.

$$e = \frac{1}{3}\frac{C_v}{\beta k}\frac{h\rho_s u_d^2}{d}[\frac{y}{h} - 0.1\sin(\frac{2\pi y}{h})][1-(1+\frac{x}{h})^3],$$

for $-h<x<=0$ and $t=0$ (33)

for $x<-h$ and $t=0$

$$e = \frac{1}{3}\frac{C_v}{\beta k}\frac{h\rho_s u_d^2}{d}[\frac{y}{h} - 0.1\sin(\frac{2\pi y}{h})],$$

for $x<-h$ and $t=0$ (34)

A debris flow wave is usually composed of a head, a body and a tail. The head moves like a bulldozer and consumes a lot of energy, and liquid and particles in the body move at higher velocity and transport energy to the head. The tail part can only follow the flow and transport no net material and energy to the body and head. Observation and measurement of debris flows show that the main body of a debris flow wave is about 100 times the depth. Therefore,

$$\frac{\partial e}{\partial x} = 0 \text{ at } x=-100h,\ t=t \tag{35}$$

4 CALCULATION RESULTS

Table 1 presents the constant parameters in [cm.g.s] system:

Table 1 Values of parameters used in the calculation.

Parameter	Symbol	Unit	Value
Slope*	J	–	0.2, 0.3
Drag coefficient	C_D	–	0.45
Constant	βk	–	0.2
Concentration of particles on the bed	C_{vm}	–	0.6
Maximum concentration of compactly piled particles	C_{v*}	–	0.65
Diameter of particles	d	cm	1
Depth of the debris flow	h	cm	40,80,100
Propagation speed of debris flow head	u_d	cm/s	100, 400
Density of water	ρ	g/cm^3	1
Density of particles	ρ_s	g/cm^3	2.65
Specific weight of water	γ	g/cm^2s^2	981
Specific weight of particles	γ_s	g/cm^2s^2	2600

* The slope maintains constant in the calculation for gravel C_D is constant

Fig. 2 shows the calculated velocity profiles for J=0.2 and h=0.4 m, and Fig. 3 shows the velocity profiles for J=0.3 and h=0.8 m and 1 m. The velocity profiles of particles in the head are nearly linear and those of particles at x=–1 h, 2.5 h and 5 h are different and gradually change to an inversed 's' shape, or concave in the upper part and convex in the lower part. The difference in velocities and velocity profiles between the particles in the head and in the following part can be explained by the fact that the particles in the main flow receive energy from the flowing liquid and accelerate to a high velocity. They catch up with the head and collide with and transfer their energy to the particles in the head, then decrease their velocity. The collisions between the particles and with the bed consume much energy, so that the head is subjected to great resistance and moves at a much lower velocity.

Wang *et al.* (2005) conducted experiments of two-phase debris flows in a tilting flume 10 m long and 50 cm wide with glass-sided walls (Fig. 4a). The bed slope of the flume was adjusted within a range of 0–30 degrees. Five types of natural gravel were used for the experiments, with various median diameters: (I) D_{50} = 7.3 mm; (II) D_{50} = 10.3 mm; (III) D_{50} = 20 mm; (IV) D_{50} = 26 mm; and (V) D_{50} = 34 mm. Before the experiments, the gravel was put on the bed, forming a mobile bed 20 cm deep; then a water or clay suspension flowed down the flume from the upstream entrance. The flow rate was controlled by means of a motor valve and measured using an electromagnetic flow meter.

As the slope and the discharge of the flow were large, many particles were removed from the bed and rolled in the front part of the flow. Individual particles in the main liquid flow moved faster than those in the front; subsequently more and more particles came to the front, forming a growing head. Particles in the flow collided with each other and with the bed, consuming much energy. The velocity of debris flow is much lower than water flow under the same conditions. Fig. 4b shows the collisions between particles, which consumed most of the energy. Therefore, the moving velocity of the debris flow (velocity of the head) was smaller than the velocity of particles (velocity in the main flow). The particles in the main flow caught up with the head. The head grew until it reached an equilibrium height, which was several times higher than the largest gravel's diameter. The head rolled down the flume like a bulldozer. The concentration of particles in the head was as high as 1100–1600 kg/m^3.

The velocity profiles of solid particles are analyzed by digitalizing the video recordings of the debris flow experiments. Fig. 5 shows the velocity profiles of gravel measured in the experiments, which were obtained by digitalizing the video recordings of the debris flow experiments. The velocity profiles at the heads and at about $x = -3$ h and -5 h are similar to those of the calculation. The mechanism of the different velocity and velocity profiles at the head and the following part is that the energy is consumed largely at the head and the particles in the flow receive energy from the liquid flow and transmit to the head as they catch up with it. The numerical model incorporates the mechanism and, therefore, agrees well with the measurements.

In the experiments, a rolling head moved down the flume and the main flow followed the head. Fig. 5a,b shows the velocity profiles in the head and the main flow of two experiments. The velocity profiles of particles in the head are quite different. The particles' velocity in the head is only half that of the particles' velocity in the main flow. The shapes of the velocity profiles are also different. The velocity profiles of particles in the head were nearly linear and those of particles in the main flow had an inverse 's' shape.

The difference in velocity between the particles in the head and in the main flow can be explained by the fact that the particles in the main flow receive energy from the flowing liquid and accelerate to a high velocity. They catch up with the head and collide with and transfer their energy to the particles in the head, then decrease their velocities. The concentration of particles in the head is higher than that in the main flow. The collisions between the particles and with the bed consume much energy, so that the head is subjected to great resistance and moves at a much lower velocity.

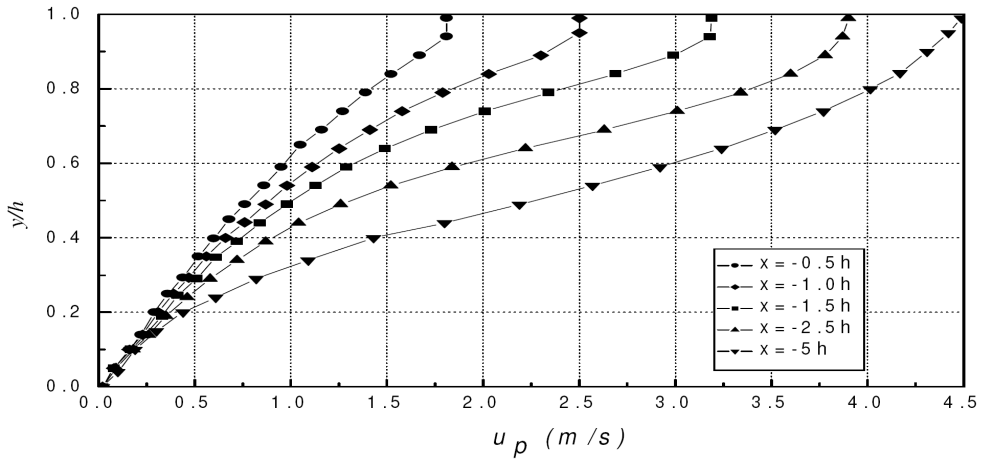


Fig. 2 Calculated velocity profiles at different distance behind the head for $J = 0.2$ and $h = 0.4$m. (The calculated propagation velocity of the debris flow wave is 1 m/s.)

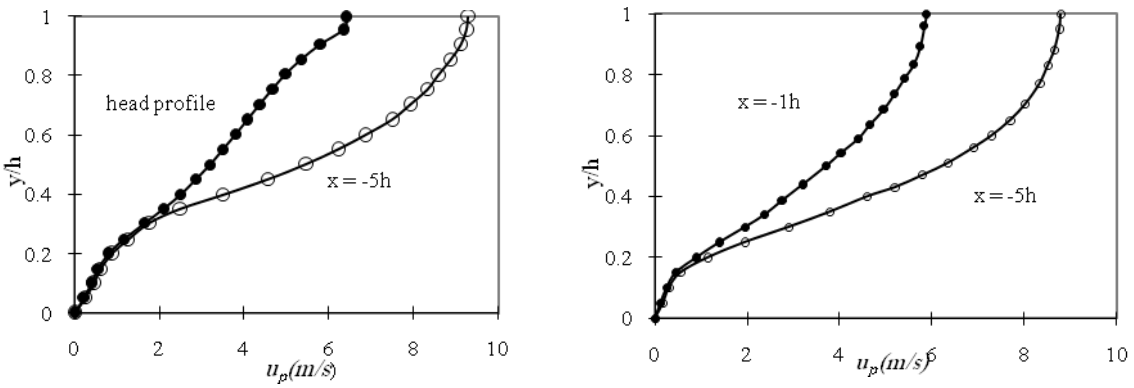
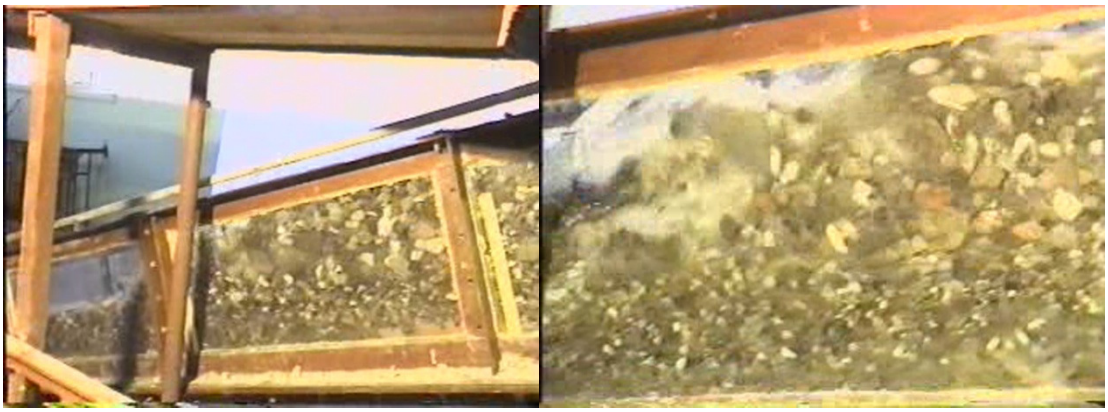
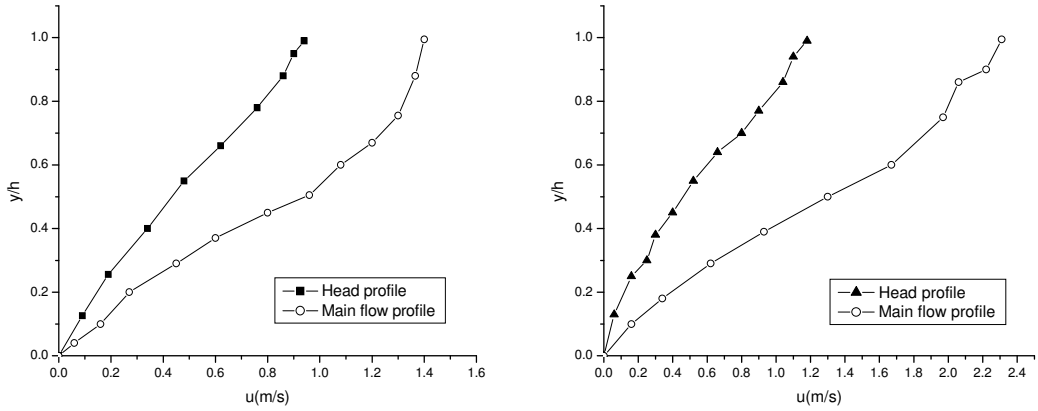


Fig. 3 Calculated velocity profiles for $J = 0.2$, $h = 1.0$ m (left) and $J = 0.2$, $h = 0.8$ m (right). The head profile is the velocity profile of the front particles.



(a) (b)

Fig. 4 (a) Experiment of two-phase debris flow in a tilting flume. (b) Collisions between particles and velocity distribution.



(a) (b)

Fig. 5 Velocity profiles of particles in the head and the main flow measured in the two-phase debris flow experiments: (a) $D_{50} = 20$ mm, $J = 0.278$, $h = 0.09$ m and propagation velocity of the debris flow wave is 0.6 m/s. (b) $D_{50} = 20$ mm, $J = 0.278$, $h = 0.12$ m and the propagation velocity of the debris flow wave is 0.7 m/s.

5 CONCLUSION

Solid particles in two-phase debris flows carry, receive, transmit and consume energy. They accelerate as they receive energy from the gravitational energy and flowing liquid and decelerate as they transmit the energy to the debris flow head or consume energy due to collision with other particles and the channel bed. A numerical model for two-phase debris flow is developed on the basis of the understanding of the physical features. An equation of the kinetic energy of gravel particles in unit volume in debris flow is established. In this equation the potential energy of the particles, energy from the liquid phase, energy consumption due to inner friction-collision between the particles, energy dispersion through collisions between particles, energy for inertia force, energy consumption due to the friction with the rough bed and energy consumption at the debris front are considered. The calculated velocity profiles agree well with the measured profiles. The gravel's velocity at the debris flow head is much smaller than that of particles in the following part. Also, the velocity profile at the head is almost linear but the profile in the debris flow body shows an inverse 's' shape. This is because the kinetic energy of particles is consumed largely at the head and the particles in the flow receive energy from the liquid and transmit it to the head.

6 REFERENCES

Bagnold, R. A. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proc. Roy. Soc. London 1954;225:49–63.

Bagnold, R. A. The flow of cohesionless grains in fluids, Phil. Trans. Roy. Soc. London, Series A, 1956;249:235–297.

Bagnold, R. A. The Physics of sediment Transport by Wind and Water. 1988, ASCE Press.

Chen, C. L. Generalized viscoplastic modeling of debris flow. J. Hydraulic Engineering 1988; 114:237–258.

Davis, R. H., Serayssol, J-M. and Hinch, E. J. The elastrohydrodynamic collision of two spheres. J. Fluid Mech. 1986;163:479–497.

Hashimoto, H. A comparison between gravity flows of dry sand and sand water mixtures. In: Armanini and Michiue, editors. Recent Development on Debris Flows. 1997, Springer, pp. 80–85.

Iverson, R. M. and Denlinger, R. P. The physics of debris flow: a conceptual assessment. In: Beschita, Blinn, Grant, Ice and Swanson, editors. Erosion and Sedimentation in the Pacific Rim, IAHS Publication No. 165. 1993, IAHS, pp. 155–165.

Kang, Z. Characteristics of the flow patterns of debris flow at Jiangjia Gully in Yunnan. Memoirs Lanzhou Inst. of Glaciol. Cryopedol. 1985;4:97–100. (In Chinese)

Kang, Zhicheng. Debris Flow Hazards and their Control in China. 1996, Science Press of China. (In Chinese.)

MeTingue, D. F. A non-linear constitutive model for granular material. J. Appl. Mech. Trans. ASME 1982;49:291–296.

Qian Ning (Chien Ning) and Wan Zhaohui. Mechanics of Sediment Movement. 1983, Chinese Science Press. (In Chinese.)

Richardson, J. F. and Zaki, W. N. Sedimentation and Fluidization, Part I. Trans. Inst. Chem. Eng. 1954;32:35–53.

Savage, S. B. The mechanics of rapid granular flows. Adv. Appl. Mech. 1984;24:289–366.

Takahashi, T. Mechanical characteristics of debris flow. J. Hydraulic Div. ASCE 1978;104:1153–1169.

Takahashi, T. Debris flow on prismatic open channel. J. Hydraulic Div. ASCE 1980;106:381–386.

Takahashi, T. Debris flow. Annu. Rev. Fluid Mech. 1981:57–77.

Takahashi, T. Dynamics of the inertial and viscous debris flows. In: Recent Developments on Debris Flows, 1997.

Wang Guangqian. Two-phase fluid model and basic equations for debris flows. Post-Doctoral Theses of China, No. 4. 1991, Peking University Press. (In Chinese)

Wang Zhao-Yin, Wai Onyx W. H. and Cui Peng. Field investigation on debris flows. Int. J. Sediment Res. 1999;4:10–23.

Wang Zhaoyin, Wang Guangqian and Liu Cheng. Viscous and two-phase debris flows in Southern China's Yunnan Plateau, IWRA. Water Int. 2005;30:14–23.

Wang, Z. Y. and Zhang, X. Y. Initiation and laws of motion of debris flow, Hydraulic/Hydrology of Arid Land, ASCE 1990;596–601.

مدل انرژی جنبشی در جریان‌های نخاله‌ای دومرحله‌ای

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چکیده در این مقاله یک مدل عددی برای جریان‌های نخاله‌ای دو مرحله‌ای بر اساس تفسیر تصاویر فیزیکی حاصل از آزمایشات و تحقیقات صحرایی تهیه شده است. با بکارگیری مختصات متحرک، رابطه انرژی جنبشی برای ذرات شن در یک واحد از حجم جریان نخاله‌ای با توجه به انرژی پتانسیل ذرات، انرژی فاز مایع، تحلیل انرژی به علت برخورد و اصطکاک داخلی بین ذرات، انتشار و تفرق انرژی در حین برخورد ذرات، انرژی صرف شده برای نیروی اینرسی، تحلیل انرژی به علت اصطکاک با بستر زبر و تحلیل انرژی در بخش جلویی جریان نخاله‌ای تهیه شده است. نتایج مدل با نتایج اندازه‌گیری شده در آزمایشات جریان نخاله‌ای دو مرحله‌ای مقایسه و مشخص گردید که پروفیل‌های محاسبه‌ای و اندازه‌گیری شده سرعت با یک‌دیگر تطابق مناسبی داشتند. سرعت ذرات شن در قسمت سر جریان نخاله‌ای نسبت به ذرات موجود در دنباله جریان بسیار کم‌تر و پروفیل سرعت در بخش جلویی موج جریان نخاله‌ای غالباً خطی بوده درحالی‌که در بخش اصلی جریان شکل "s" معکوس را نشان داده است. دلیل اختلاف در پروفیل سرعت این است که شتاب ذرات شن در جریان اصلی با دریافت انرژی از نیروی ثقل و جریان مایع بیش‌تر بوده حال آن‌که شتاب ذرات شن در سر جریان با انتقال و تحلیل انرژی به علت برخورد با بستر کانال، کم‌تر بوده است.

کلمات کلیدی: تحلیل انرژی، مدل انرژی جنبشی، جریان نخاله‌ای دو مرحله‌ای، پروفیل سرعت، برخورد