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Experimental and Numerical Study on Demarcation of the Risk Zone Due to Viscous Debris Flow

Xuelan Liu, Muneyuki Arai

Summary:

In this paper, focusing on demarcating debris flow risk zones in mountainous areas, the deposition processes of viscous debris flows what are reported in China, Japan and some other countries are discussed experimentally and numerically respectively. Two-dimensional governing equations of momentum conservation and the continuity equations of viscous debris flow are arisen. The finite upwind difference schemes of these equations are presented to calculate the stoppage of the forefront, deposition form, deposition field and so on at mouth of a torrent. The results are discussed by compared with experimental results. Furthermore, in a field scale, the different flooded areas by different types of debris flows, such as viscous, non-cohesion muddy, and stony debris flow are calculated with different resistance items respectively.

1 Introduction

Driven by gravity, debris flows transport downstream huge volumes of poorly-sorted mixtures of sediment ranging in size from clay to boulders. They may cause flood routing and deposit on sloping surfaces and/or alluvial fan. For preventing debris flow hazards, it is common to introduce structural and non structural protections such as Sabo dams, warning systems, risk prone areas zoning, emergency plans and so on. To clarify deposition process of debris flow due to abrupt change of bed slope is a fundamental approach for delimitating risk zone in mountainous areas. It is very difficult to directly observe natural debris flows deposition process, so that experimental studies are significant for building available physical debris flow deposition models.

So far many mechanistic models of debris-flow deposition have been developed by many researchers experimentally and numerically. Usually, shallow-water equations are used to describe the momentum and mass conservation equations for debris flow deposition. The main difference among the numerical models are the formulations of the resistance item, which usually is the wall friction force deduced from rheological assumptions. The differences between the rheological models have been reviewed by many researchers (Chen, 1987; O'Brien, 1993). Briefly, Takahashi et al. (1979) took account of grain contact friction, using Coulomb force as the resistance item to discuss deposit distance and deposition processes of stony debris flow. Based on a dilatant-fluid model coupled with Coulomb flow resistance, Takahashi et al. (1987) proposed a 2-D finite difference model for debris flow deposition. More recently, Takahashi and Nakagawa et al. (1997) modified the debris flow model to the Newtonian model. On the other hand, since the non-Newtonian model was proposed by Johnson (1970), some research based on the Bingham rheological model also progressed. Ashida and Egashira(1987, 1988) considered that yield stress played a key role when debris flow stopped and was deposited. Focusing on non-cohesive mud flow, Arai (1992) proposed particle settling velocity as the deposition velocity for modeling the deposition process. On the other hand, Hashimoto et al. (1985), Khrano and Hashimoto et al. (1991) discussed the one- dimension and two-dimension deposition process respectively by the Lagrangian approach experimentally. Major (1997; 1999) reported the depositional processes in large-scale debris flow experiments. By measuring the pore-fluid pressure and total bed-normal stress at the base of several debris flow experiments, Major proposed new debris-flow deposition results which contradict models that invoke widespread decay of excess pore-fluid pressure, uniform viscoplastic yield strength, or pervasive grain-collision stresses to explain debris-flow deposition.

Besides, numerical simulations based on different rheological models have been used widely in risk zoning research. O'Brien et al. (1993) used a two-dimensional finite difference model to simulate clear-water flood hazards, mudflows and debris flow on alluvial fans and urban floodplain flow. Interactive flood or mudflow routing between channel, street and floodplain flow is performed using a uniform grip system to describe complex floodplain topography. The model uses a central finite difference routing scheme (an explicit numerical technique) for the application of the equations of motion. The surface topography is discretized into uniform square-grip elements. Brufau et al. (2001) applied an upwind finite volume scheme to solve the governing equations. They used both Egashira and Ashida's, and Takahashi's equations that indicate the estimation of the erosion/deposition rate. As a result, they got the same final equilibrium state, but different transient conditions arose with these two different models. Furthermore, they also found that the variability of the mixture density in the momentum equation can be neglected. From Brufau's results, numerical experiments can be conduct ignoring the effects of spatial and temporal variations of density in the momentum equation. Nakagawa et al. (2001) estimated sediment disasters occurring in the Camuri Grande river basin, Venezuela in 1999 with 1-D and 2-D models, and adapted unstructured meshes to express the shape of the rivers, buildings, roads, and so on.

This study attempts to bring up some particular deposit characteristics of viscous debris flow. Some results of two-dimensional experimental studies on viscous debris flow process are presented, including the deposition morphology, particle distributions and deposition angles. The governing items in deposition process are discussed. Furthermore, numerical simulations are carried on; the calculation results are compared with the experimental results. The risk zones in an assumed alluvial fan with different types of debris flows, such as stony debris flows, non cohesive mud flows and viscous debris flows will be calculated and compared.

2 Governing Equations

Viscous debris flows are solid-liquid mixtures flows. They can be taken as a continuous flow before they stop. According to the shallow wave theory, the two-dimensional motion equations are

(1) $$\frac{\partial M}{\partial t}+\beta\frac{\partial(MU)}{\partial x}+\beta\frac{\partial(MV)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho_m}$$

(2) $$\frac{\partial N}{\partial t}+\beta\frac{\partial(NU)}{\partial x}+\beta\frac{\partial(NV)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho_m}$$

the two-dimensional mixture constitutive equation is

(3) $$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=i$$

and solid mass constitutive equation is

$$\frac{\partial(Ch)}{\partial t}+\frac{\partial v(CM)}{\partial x}+\frac{\partial v(CN)}{\partial y}=iC_* \tag{4}$$

where, M and N are the fluxes in x and y directions respectively. u and v are the mean velocities in x and y directions respectively. C is the dimensionless volumetric concentration of sediments in the mixture, C_* is the volumetric sediment concentration on a static bed just after deposition, $H = z + h$, is the flow evolution, z is the bed level respects to an arbitrary horizontal reference, g is the acceleration due to gravity, i is the bed erosion/deposition velocity, and β is the momentum correction coefficient. ρ_m is the density of mixture, τ_x and τ_y are shear stress in x and y directions respectively, and they are given as follows:

$$\frac{\tau_x}{\rho_m}=fu\sqrt{u^2+v^2} \tag{5}$$

$$\frac{\tau_y}{\rho_m}=fv\sqrt{u^2+v^2} \tag{6}$$

For viscous debris flow, the friction coefficient f is suggested by Takahashi(1997) as

$$f=8\left[\frac{1}{3}\frac{u_*}{\nu_m}(1-\frac{\overline{C}}{C_*})^{1.82}(1+\varepsilon\overline{C})h\right]^{-2} \tag{7}$$

where $u_* = \sqrt{gh\sin\theta}$ is the shear velocity, ν_m is the kinematics viscosity, $\overline{C}$ is the mean volumetric sediment concentration of the coarse particles in a cross section, dimensionless parameter $\varepsilon = (\sigma-\rho)/\rho$, σ, ρ are the sediment and water density respectively.

The bed erosion/deposition velocity is proposed as

(8) $$i = \frac{3\nu_m(\frac{\sigma}{\rho} - 1)(C - C_e)\tan\phi}{2\alpha h \tan\theta}$$

where C_e is equilibrium volumetric sediment concentration of the coarse particles, ϕ is the angle of repose.

3 Experiments

For discussing the viscous debris flow stoppage and deposition mechanism, some experiments are generated with a 25°inclined steel flume. A wooden plane with size of 180cm×90cm is set at the end of the flume. The inclined angle of the plane is 3°. Six experiments are conducted. The compositions of sediment and water mixture used in these experiments are shown in Table 1.

Table 1 Experimental Sediment Mixtures

No□	Volume concentration C	Clay:gravel:water (Weight ratio)
B-1	0.443	0.47:0.2:0.33
B-2	0.425	0.45:0.2:0.35
B-3	0.416	0.442:0.2:0.358
B-4	0.407	0.43:0.2:0.37
B-5	0.390	0.417:0.2:0.383
B-6	0.373	0.4:0.2:0.4

4 Experiment Results and Discussions

4.1 Deposition angle

Generally, viscous debris flow are well mixed flow, the deposition angle γ can be represented as

(9) $$\tan\gamma = \frac{C_*(\sigma-\rho)}{C_*(\sigma-\rho)+a\rho}\tan\phi$$

Here, a is an unknown parameter. The critical deposition angle θ_c can be given as

(10) $$\tan\theta_c = \frac{(\sigma-\rho)c_{du}}{(\sigma-\rho)c_{du}+\rho}\tan\alpha$$

where, c_{du} is the equilibrium concentration, α is the dynamic friction angle between the moving particles.

By comparing the angle of bed slope θ, deposition angle γ and critical deposition angle θ_c, the debris flow deposition condition can be shown as follows:

(1) $\theta \le \gamma$: Debris flows deposit with angle of γ;

(2) $\gamma < \theta < \theta_c$: Part of debris flows deposit and part of debris flow move down continually;

(3) $\theta \ge \theta_c$: Debris flows move down slope without deposition.

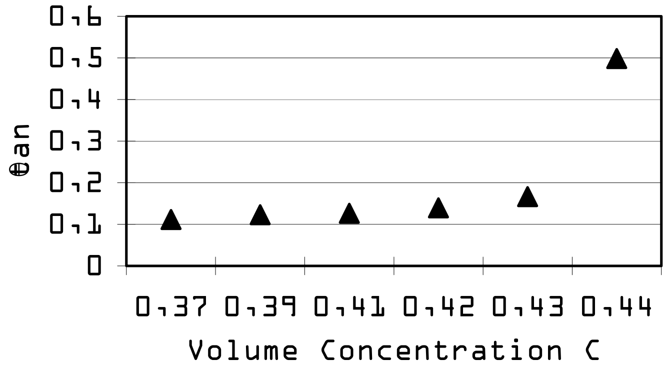

Figure 1 The relationship between volume concentration and deposits' angle

It is clear that deposition angles change with solid volume concentration of debris flows. Figure 1 shows the experimental relation between deposition angles and volume concentrations. It is illustrated that the higher the volume concentration C is, the bigger the deposit angle γ is.

4.2 Viscous Debris Flow Front Arrival Range

Figures 2 to 7 show the 2-D deposition profiles for 6 experiments, respectively. They illustrate the tendency that the higher the volume concentration C is, the further debris flow front arrival range is.

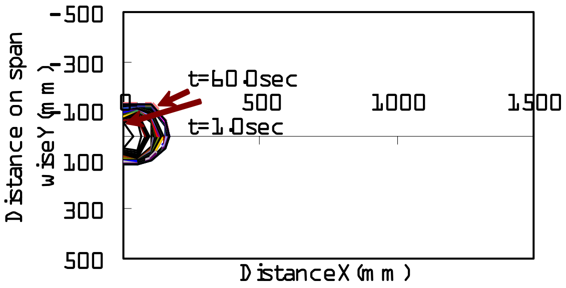

Figure 2 (No.B-1 C=0.443)

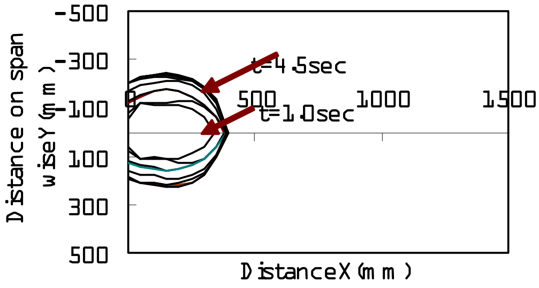

Figure 3 (No.B-2 C=0. 425)

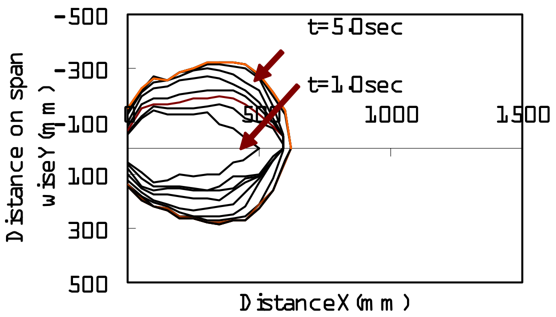

Figure 4 (No B-3 C=0.416)

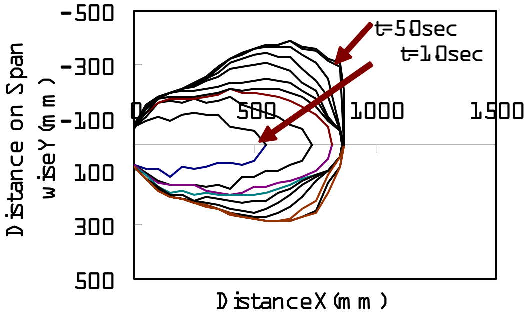

Figure 5 (No.B-4 C=0.407)

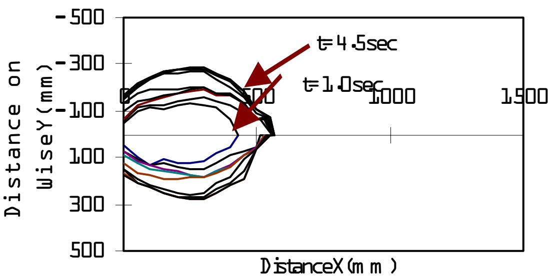

Figure 6 (No.B-5 C=0.390)

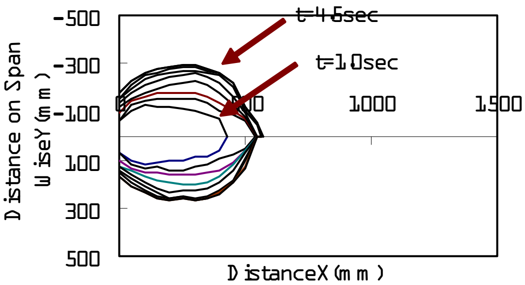

Figure 7 (No.B-6 C=0.373)

5 Numerical Calculations

6 Numerical Calculation Results and Discussions

7 Conclusions

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