SURGE WAVE DEVELOPMENT IN DEBRIS FLOWS

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ABSTRACT

Surge waves often form on the free surface of debris flows. These surge waves have the form of a hump that moves down slopes at speeds that are greater than those recorded for the free surface and the front of the debris flows. Surge waves can be very destructive. In the present study, a theoretical analysis is proposed to explain the formation and the velocities developed by these surge waves. The analysis models the debris flow material as one having a frictional-viscous resistance to flowing down slopes. Using this model, it was determined that surge waves travel on the free surface of debris flows at a speed that is two times greater than that recorded for the free surface and three times greater than the mean velocity of the debris flow. The theoretical findings were substantiated by velocity measurements on a debris flow in Sakurajima, Japan.

Key words: debris flows, granular materials, slope stability, surge waves (IGC: E6)

INTRODUCTION

Surge waves have been observed to form on the surface of active debris flows (Johnson, 1965; Johnson, 1970; Morton and Campbell, 1974; Takahashi, 1981, 1991; Davies, 1986; Hikida, 1990) (Fig. 1). According to Morton and Campbell (1974), the surge waves “have the form of

humps or translatory waves that are several inches in amplitude, and move on the surface of the debris flows at approximately twice the speed of the free surface of the flows.” Figure 2 shows a typical surge wave moving on the surface of a debris flow at speed, V_c , that is greater than the speed, V_0 , of the surface of the flow as well as greater than the mean velocity, V_m , of the debris flow.

Fig. 1. Surge waves in debris flows (Johnson, 1965)

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Fig. 2. Velocities of waves in debris flows

Surge waves effectively move material from the rear to the front of a debris flow, and because of their high velocities of travel (between 0.5 m/s to 20 m/s according to Takahashi, 1981) they can cause severe damage to structures in their path (Mileti et al., 1991).

Davies (1986), Hikida (1990), and Takahashi (1991) have stated the conditions necessary for the formation of surge waves in debris flows using the Froude number, F , and the Reynolds' number, R_e , of the flow. The Froude number, F , can be obtained from the following relationship (Davies, 1986):

$$F = \frac{V_m}{(gh)^{1/2}} \quad (1)$$

where V_m and h are the mean flow velocity and depth respectively (Fig. 2), and g is the acceleration due to gravity. The Reynolds' number can be obtained from the following relationship (Davies, 1986):

$$R_e = \frac{V_m h \rho}{\eta} \quad (2)$$

where ρ is the density and η is the viscosity of the material forming the debris flow, and V_m and h are the mean flow velocity and depth respectively (Fig. 2).

According to Davies (1986), surge waves form in debris flows that travel on infinitely wide channels if the Reynolds' number, R_e , is smaller than 600 and the Froude number, F , is equal to 0.6.

The model that will be used in the present study in order to explain the development of surge waves and their velocities in debris flows is the Coulomb-Viscous model developed by Johnson (1970).

MODEL USED TO EXPLAIN SURGE DEVELOPMENT AND ITS VELOCITY

Debris flows are highly deformable masses consisting of a mixture of a solid phase and a fluid phase. The solid phase is represented by rock particles of different sizes and shapes. The fluid phase is represented by a combination of water and fines (silt and clay) (Pierson, 1980). If the fluid phase has a volume concentration of clay in excess of 13%, it will have a shear strength that influences the stability of the mixture when located on a slope (Ham-

pton, 1975). According to Lowe (1979) and Vallejo (1989), this type of mixture is classified as a mudflow. Conversely, if the fluid phase has no shear strength, the resistance of the mixture to flow on slopes is provided by the effective frictional forces between the large particles and the viscosity of the grains-fluid mixture (Johnson, 1970; Rodine and Johnson, 1976; Enos, 1977). Mixtures that have frictional and viscous resistances when moving down a slope are classified by Lowe (1979) as debris flows. The present study is concerned only with instabilities associated with debris flows.

When a debris flow moves down a slope, the gravity induced shear stress, τ , is opposed by the combined effect of the frictional and the viscosity resistances of the mixture. In an equation form, for debris flows the following relationship applies (Johnson, 1970; Lowe, 1979):

$$\tau = \sigma'_n \tan \phi' + \eta \left(\frac{dv}{dy} \right) \quad (3)$$

where σ'_n is the effective internal normal stress between the rock particles, ϕ' is the effective angle of friction between the rock particles, η is the viscosity of the particles-fluid mixture, and dv/dy is the velocity gradient in the flow that is obtained using the x - y coordinate system shown in Figs. 2 and 3.

In the right-hand side of Eq. (3), the first term represents the effective frictional resistance in a debris flow, the second term represents the viscosity resistance. According to Grace (1970) and Davidson et al. (1977), the viscosity resistance is the result of: (a) the shearing stresses resulting when the particles collide with one another, and (b) the viscosity of the fluid and granular phases in the mixture. Equation (3) defines the Coulomb-Viscous model for debris flow; it applies to debris flows that: (a) are saturated by the fluid phase, (b) are of great length and move on a slope that has a rough surface, (c) have a laminar flow type, (d) are two dimensional, (e) have a free surface, and (f) have a velocity profile as shown in Fig. 3 (Johnson, 1970; Lowe, 1979).

Fig. 3. Coordinate system and velocity profile for the Coulomb-Viscous model

SURFACE AND AVERAGE VELOCITIES IN DEBRIS FLOWS

The surface and average velocities in debris flows are calculated using the coordinate system shown in Fig. 3. Using this coordinate system, the velocity gradient has a negative value. Taking this into consideration, Eq. (3) becomes after some rearrangements,

$$-\frac{dv}{dy} = \frac{1}{\eta} (\tau - \sigma'_n \tan \phi') \quad (4)$$

In Eq. (4) the following relationships apply:

$$\tau = \gamma y \sin \alpha \quad (5)$$

and

$$\sigma'_n = \gamma' y \cos \alpha \quad (6)$$

where γ is the bulk unit weight of the material, γ' the effective unit weight of the granular phase, y is the depth, and α is the inclination of the free surface and the rough surface on which the debris flow moves.

Replacing Eqs. (5) and (6) into Eq. (4) the following relationship is obtained

$$-\frac{dv}{dy} = \frac{1}{\eta} (\gamma y \sin \alpha - \gamma' y \cos \alpha \tan \phi') \quad (7)$$

From the integration of Eq. (7) the following is obtained

$$v = \frac{1}{\eta} \left[\frac{y^2}{2} (\gamma' \cos \alpha \tan \phi' - \gamma \sin \alpha) \right] + \text{constant} \quad (8)$$

The value of the constant can be obtained knowing that at $y=h$, $v=0$ (Fig. 3). The parameter h represents the thickness of the flow. Therefore,

$$\text{constant} = \frac{1}{\eta} \left[\frac{h^2}{2} (\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi') \right] \quad (9)$$

Replacing Eq. (9) into Eq. (8) the following is obtained

$$v = \frac{1}{\eta} \left[\left(\frac{h^2 - y^2}{2} \right) (\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi') \right] \quad (10)$$

When $y=0$, $v=v_0$ (Fig. 3), where v_0 is the free surface velocity of the flow. Thus, using Eq. (10) the value of v_0 is equal to

$$v_0 = \frac{h^2 [\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi']}{2\eta} \quad (11)$$

The mean velocity of the flow, v_m , is obtained from Eq. (10) as follows

$$v_m = \frac{1}{h} \int_0^h \frac{1}{\eta} \left[\left(\frac{h^2 - y^2}{2} \right) (\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi') \right] dy \quad (12)$$

or

$$v_m = \frac{h^2 [\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi']}{3\eta} \quad (13)$$

SURGE WAVE DEVELOPMENT AND THEIR VELOCITY IN DEBRIS FLOWS

Surge Waves in Water Flows

From laboratory studies conducted by Ippen and Kuling (1954), Benjamin (1957), Mayer (1959), and Longuet-Higgins (1981) on water channel flows, they determined that when the laminar type of flow on the channels was disturbed, the flow developed surge or translational waves on its free surface as shown in Fig. 4. The flow disturbances used included: (a) placing obstructions at the base of the flow, (b) a sudden pressure exerted over a limited area of the free surface of the flow, and (c) the rapid addition or subtraction of material from the flow. The speed of the surges or translational waves (v_c) were higher than the free surface (v_0) and average (v_m) velocities of the flow (Fig. 4).

According to Benjamin (1959), the velocity of the surge waves in the water flows can be obtained if the following relationship is used,

$$v_c = \frac{dQ}{dh} \quad (14)$$

where Q is the mass flow rate which can be obtained from

$$Q = v_m h \quad (15)$$

where v_m and h are the average velocity and the depth of the flow (Fig. 2)

Surge Wave Velocity in Debris Flows

The value of the surge wave velocity, v_c , for the case of debris flows can be obtained by the use of Eqs. (13), (14) and (15). First, the value of v_m given by Eq. (13) is introduced in Eq. (15), and then the differentiation outlined by Eq. (13) is performed. After this is done, the following relationship is obtained for the surge wave velocity,

$$v_c = \frac{h^2 [\gamma \sin \alpha - \gamma' \cos \alpha \tan \phi']}{\eta} \quad (16)$$

Relationships Between Surge, Free Surface and Average Velocities

By the use of Eqs. (11), (13) and (16), relationships be-

Fig. 4. Translational wave and velocities in open channel water flow experiment (Ippen and Kuling, 19954).

tween the surge wave velocity, v_c , the free surface velocity, v_0 , and the average or mean wave velocity, v_m , for the case of debris flows can be obtained. These relationships are:

$$\frac{v_c}{v_0} = 2 \quad (17)$$

and

$$\frac{v_c}{v_m} = 3 \quad (18)$$

SUBSTANTIATION OF THE THEORETICAL ANALYSIS

In order to check the validity of the theoretical analysis, the relationships expressed by Eqs. (17) and (18) are applied to an actual debris flow in Japan. Hikida (1990) established a center of observation for debris flows on the slopes of the Sakurajima mountain in Japan. Using a set of video cameras, Hikida recorded the the formation and the velocity acquired by surge waves on the surface of the debris flows. The free surface velocity of the flows was measured by recording the velocity of travel of pebbles that were in suspension and were visible on the surface of the debris flow. Figure 5 shows the velocity, v_c , of one surge wave during one and a half hour observation period. Figure 5 also shows the ratio of the surge wave velocity, v_c and the free surface wave velocity, v_0 . Figure 5 indicates that at the time of the formation of the surge wave in the debris flow (about 9:15), the velocity of the surge wave, v_c , was about 10 m/s, and the v_c/v_0 ratio was equal to 2. As time progressed beyond the time the surge wave formed, it experienced damping and a decay in its velocity. The damping and decrease in velocity of surge waves have also been recorded to take place in channel water flows (Keulegan, 1948).

When the surge wave formed on the surface of the debris flow, the ratio of the surge wave velocity, v_c , and

the free surface velocity, v_0 , was equal to 2. This ratio was predicted by the theoretical analysis expressed by Eq. (17). Field observations on debris flows in California conducted by Morton and Campbell (1974) also established the same ratio between the surge wave velocity and free surface velocity. Thus, the field findings corroborate the theoretical analysis presented in this study.

CONCLUSIONS

A theoretical analysis designed to explain the formation and velocity reached by surge waves in debris flows was presented. The ratio of the surge wave velocity and the free surface wave velocity in two actual debris flows was predicted by the theoretical analysis.

NOTATION

h = thickness or depth of flow
 v = velocity throughout the depth of flow
 v_c = surge wave velocity
 v_m = mean velocity of flow
 v_0 = velocity of free surface of flow
 x = distance along the flow
 y = distance along the depth of flow
 Q = mass flow rate
 α = inclination of base over which the flow moves
 η = viscosity of the fluid-rock mixture
 ϕ' = angle of friction between the rock particles
 γ = bulk unit weight of the fluid-rock mixture
 γ' = effective unit weight of rock particles in the flow
 σ'_n = effective internal normal stress between particles
 τ = shear stress induced by gravity on the flow

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Fig. 5. Surge wave velocity, v_c , and velocity ratio v_c/v_0 for a debris flow in Japan (Hikida, 1990)

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