Prediction and Analysis of Debris Flow

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I. Introduction

The debris flow is a shape of fast mass movement of a body of granular solids, water, and air, with flow properties varying with water and clay content, sediment size and sorting. Natural disasters caused by debris flow, as shown in Fig. 1, brings lots of sacrifices of people and wealth compared to natural disaster by land slide, erosion and so on, because debris flow may come suddenly without the sign before occurred. Therefore, the debris flow has been feared for its potential to cause heavy disaster. Studies on occurrence and intensity of debris flow are, therefore, required to prevent the disasters. In the past, occurrence criteria of debris flow have been defined by two parameters, cumulative rainfall from its beginning and a rainfall just before the occurrence of debris flow. But this method is not satisfactory in accuracy as well as in deciding the cumulative rainfall practically the lack of theoretical clarity.

In this study, the occurrence conditions of debris flow are analyzed to obtain the critical rainfall needed to cause a debris flow, and a mathematical model of runoff which predicts the intensity of debris flow is derived.

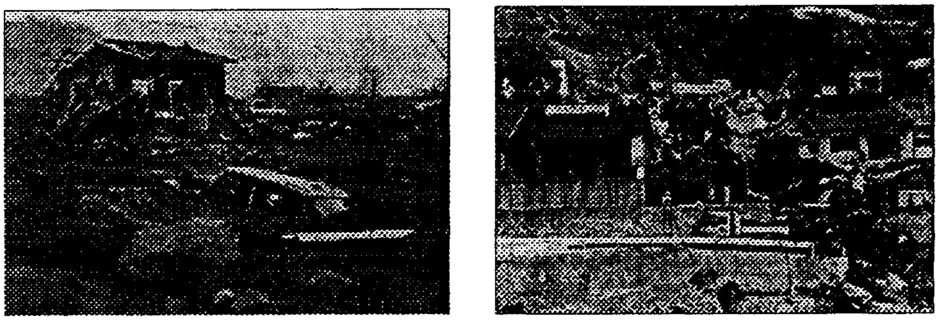

Fig. 1 Natural Disaters Caused by Debris Flow

II. The Critical Rainfall for Occurrence of Debris Flow

1. Occurrence Condition of Debris Flow

On a slope of deposits as shown in Fig. 2, the shear stress τ at a point in the deposit is given

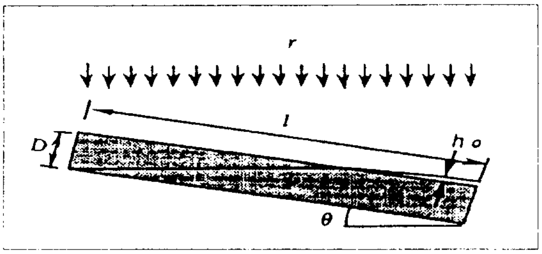

Fig. 2 Schematic sketch of a slope.

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$$\tau = \{ C_*(\sigma - \rho)a + \rho(h_0 + a)\} g \sin\theta \qquad (1)$$

where, C* is the concentration of deposited material, σ and ρ are the densities of the deposits and water, respectively, a is the distance from the surface, h_0 is the depth of the surface flow, g is the gravitational acceleration, and θ is the angle of the slope. The resisting stress τL at the point is expressed by

$$\tau L = c + C_*(\sigma - \rho) a g \cos\theta \tan\phi \qquad (2)$$

where c is the adhesive force, and ϕ is the angle of internal friction.

Since the critical condition is $\tau = \tau L$, the critical angle of a slope θ_c for the occurrence debris flow is obtained by Eqs. (1) and (2) as

$$\tan\theta_c = \frac{\dfrac{c}{\rho g a \cos\theta_c} + C_*\left(\dfrac{\theta}{\rho} - 1\right)\tan\phi}{C_*\left(\dfrac{\sigma}{\rho} - 1\right) + 1 + \dfrac{h_0}{a}} \qquad (3)$$

By substituting ordinary values of C* =0.6, $\tan\theta$ =1.0, σ/ρ =2.65 and c = 0 for sandy materials to Eq.(3) and considering that a and h_0 should be larger than grain size d to cause a debris flow(1), one obtains ϕ_c =14.8°. This has been supported by field data as well as flume data.

2. Critical Rainfall for Occurrence of Debris Flow

According to the theory mentioned above, a debris flow will occur on a slope steeper than θ_c when depth of the surface flow exceeds the grain size. There are two approaches to obtain the critical rainfall based on this theory.

One is to assume the discharge of surface flow in which the depth is equal to the grain diameter of the deposits as the critical discharge. Ashida et al.(2) derived the critical discharge Q_c by introducing h_0 = d and Q_c = Buh_0 as

$$Q_c = \sqrt{\frac{8\sin\theta}{f_0} B^2 g d^3} \qquad (4)$$

where, B is the width of the flow, u is the velocity of surface flow, f_0 is the resistance coefficient, k is the ratio of h_0 and d close to unity, and d is the grain diameter of the deposits.

Applying the rational formula to Eq. (4), one obtain the critical rainfall intensity as

$$r_T = \frac{1}{T}\int_0^T r\,dt \geq \frac{Bd}{fA}\sqrt{\frac{\sin\theta}{f_0 K^3} g d} \qquad (5)$$

where, T is the time of concentration, r is the rainfall intensity, f is the runoff coefficient, and A is the catchment area.

The other is to assume the occurrence of surface flow to be the occurrence condition of debris flow. Since irregularity of the slope surface is larger than the grain size, depth of the surface flow will exceed in some part of the slope when surface flow appears on the slope. Consequently, a debris flow will occur as soon as surface flow appears on a slope due to the heavy rainfall. The criteria for the surface flow are given as follows:

On a slope as shown in Fig. 1, the momentum and continuity equations of subsurface flow are expressed by

$$\frac{\partial(\lambda h)}{\partial t} + \frac{\partial(v h)}{\partial x} = r\cos\theta \quad \text{and} \quad v = k\sin\theta \qquad (6)$$

where, λ is the porosity, h is the depth of the subsurface flow, t is the time, v is the velocity of the flow, x is the coordinate taken in the downstream direction, and k is the hydraulic conductivity.

By solving Eq. (6) by using the kinematic wave theory, one obtains the occurrence conditions of surface flow as

$$l \geq kT\frac{\sin\theta}{\lambda} \quad \text{and} \quad \lambda D \geq \int_0^T r\cos\theta dt \qquad (7)$$

where, l is the length of the slope, and D is the depth of the deposits.

Assuming that debris flow occurs when surface flow appears on a slope, the occurrence condition of debris flow is derived from Eq.(7) as

$$rT = \frac{1}{T}\int_0^T r dt \geq \frac{Dk}{l}\tan\theta \qquad (8)$$

The applicability of this equation was verified by the experiments[(3)] as shown in Fig. 3.

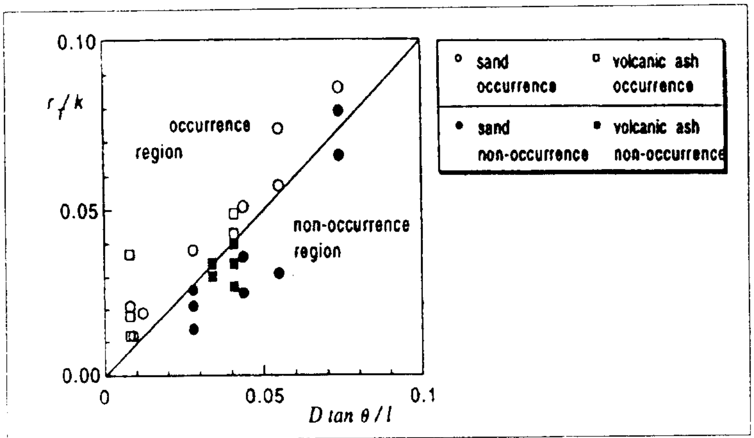

Fig. 3 Comparison between theoretical and experimental results.

In spite that Eqs. (5) and (8) are derived from the different basis, right hand sides of the equations are the same. These equations indicate that a debris flow will occur when rainfall intensity within the time of concentration exceeds a certain value determined by the properties of the slope.

3. Estimation of the Critical Rainfall

3.1 Estimating Method

Equation (8) is rewritten as

$$R(t,T) = \int_{t-T}^{t} r(\tau)d\tau \geq \frac{Dk}{l}\tan\theta = R_c \qquad (9)$$

where, t is the time, and R_c is the critical rainfall. Equation (9) shows that debris flow will occur when cumulative rainfall within the time of concentration exceeds a certain value related to the properties of the slope. Two parameters, the time of concentration T and critical amount of rainfall Rc , should be estimated to obtain the criterion for occurrence of debris flow. It may be possible to estimate the value of R_c by measuring the value of D, l and θ, however, the estimated value will not be accurate enough for practical use due to the large errors in the measurements. This is the reason that the method of system analysis will be commendable to identify the parameters.

To estimate the time of concentration and critical rainfall, T and R_c, cumulative rainfall $R(t,t_0)$ defined as below is calculated.

$$R(t,t_0)=\int_{t-t_0}^{t} r(\tau)d\tau \qquad (10)$$

The maximum values of $R(t,t_0)$ for each time, $R\max(t_0)$, are plotted against t_0. If there are no errors in the data as well as in the theory, the plotted lines should exceed the point (R_c,T) when debris flow occurred, and not exceed the point when debris flow did not occur as schematically illustrated in Fig. 4.

Consequently, the upper limit line of non-occurrence and the lower limit line of occurrence should cross at the point (R_c,T) as schematically shown in Fig.5(a). Because of the errors in the data and the unsteady field conditions, however, the upper limit of non-occurrence and the lower limit of occurrence will be like two lines shown in Fig. 5(b). The point where the difference between two curves is minimum is estimated to be the time of concentration.

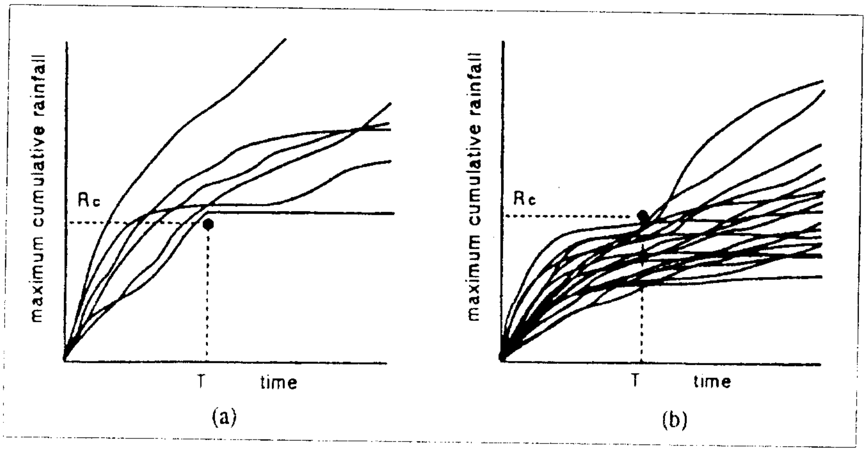

Fig.4 Cumulative rainfall when debris flow occurred(a) and not occurred(b).

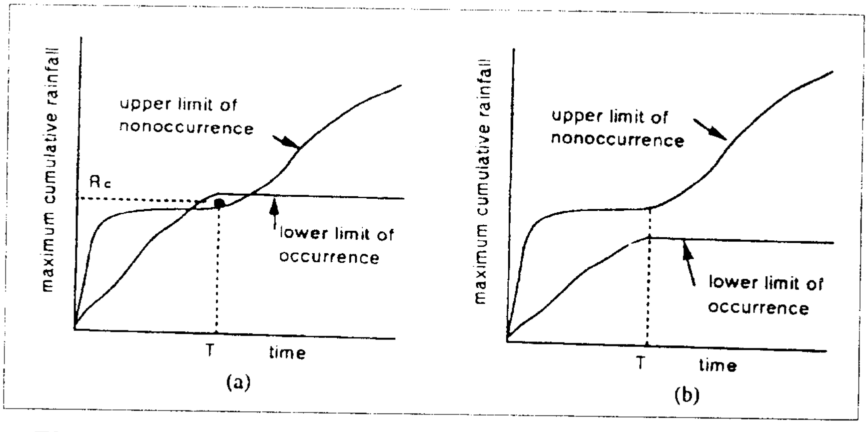

Fig. 5 Upper limit of non-occurrence and lower limit of occurrence.

3.2 The critical rainfall of debris flow in the Mizunashi River

Unzen Volcano began to erupt in November 1990 after 198 years of dormancy and has been in violent activity. Continuous growth of lava dome and falls of lava rocks have resulted in frequent pyroclastic flows. As a great volume of volcaniclastic material has been deposited and scattered by the pyroclastic flows, debris flows have frequently occurred along the Mizunashi River and damaged many houses.

The cumulative amounts of rainfall were calculated using the rainfall data collected by the Unzen Meteorological Observatory, both when debris flows had occurred and when they had not.

In case when debris flow occurred, the amount of rainfall up until the time of occurrence was computed, and in case without debris flow, whole data were used. In Fig. 6, the upper limit of non- occurrence and lower limit of occurrence are illustrated.

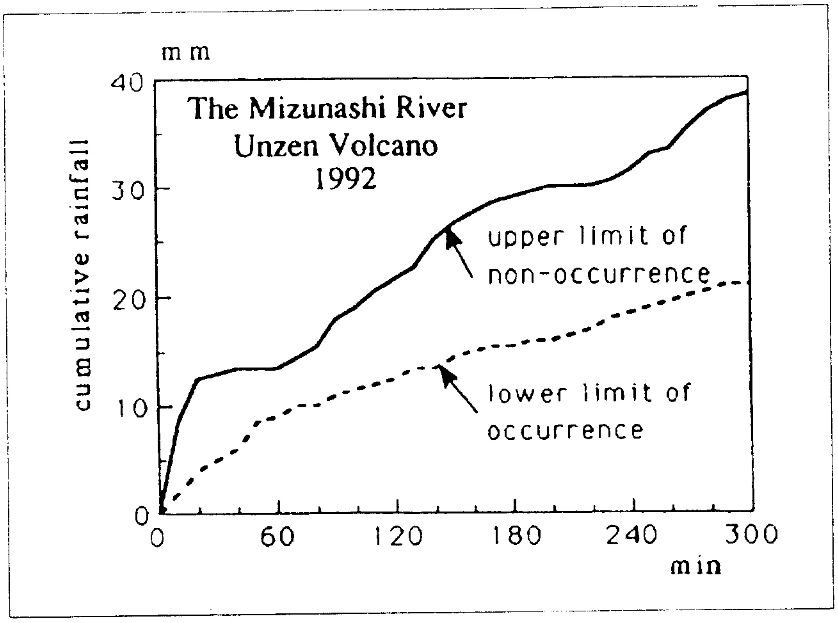

Fig. 6 Upper limit of non-occurrence and lower limit of occurrence of debris flow in the Mizunashi River, Unzen Volcano.

From the Fig. 5, the following are confirmed: 1) the time of concentration is estimated to be about an hour on average; 2) the occurrence of debris flows is possible when the amount of rainfall per hour rises over the limit of 9 mm; and 3) debris flows will definitely occur when this amount rises over the limit of 14 mm. At Sakurajima Volcano, which has been in violent activity in this 20 years, debris flow have been generated by rainfall from 7 to 13 mm over a period of forty minutes. By comparison, the debris flows in the Mizunashi River show the typical property of volcanic debris flow which is possible by a small amount of rainfall.

III Conclusions

The occurrence condition of debris flow due to heavy rainfall and runoff analysis of debris flow were studied. Results obtained are as follows:

(1) Debris flow will occur on a slope when amount of rainfall within the time of concentration exceeds a certain value which is peculiar to the slope. The time of concentration and the critical amount of rainfall is obtained by analyzing the data of rainfall and debris flows.

(2) A mathematical model for runoff of debris and water flows is derived. This model results in the instantaneous unit hydrograph when no debris flow occurs. The applicability of this model was verified by adopting to the debris flows in Sakurajima and Unzen Volcanoes.

(3) The derived equation for debris flow discharge gives the theoretical basis to an empirical method which uses the cumulative rainfall and rainfall intensity at the moment to forecast the

occurrence of debris flow.

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