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Experimental study on the rheological properties and hydrological mechanism of the occurrence of a volcanic mud flow

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Abstract In this study, the definition of a volcanic mudflow and the mechanism of its occurrence were discussed. A volcanic mudflow is characterized by its concentration and adhesive power. The occurrences of volcanic mudflows are classified into two types depending on whether or not the earth surface of a slope is covered with volcanic ash. The critical intensity of rainfall for the occurrence of a mudflow can be estimated theoretically in the case of no volcanic ash. However, in the area of an active volcano, ash falls do much to generate surface water on a slope and hasten toe failures (expansion of gullies) at the feet of the side walls of a gully. That causes the fluidization of the soil mass and greatly increases the probability of the occurrence of a volcanic mudflow, even if there is only a little rainfall.

NOTATION

θ_1	critical angle of a slope for the occurrence of a mud-debris flow in the case where sediment particles have no cohesion
θ_2	critical angle of a slope for the occurrence of a mud-debris flow in the case where sediment particles have cohesion
σ	density of a sediment particle
ρ	density of water
ϕ	frictional angle of sediment
C	volumetric concentration of a sediment deposit
h_0	height of surface water
d	mean grain diameter of sediment particles
c	adhesive power of sediment particles
C_{fs}	coefficient of correction to the real volumetric concentration (C) of a slurry
ϕ_f	concentration of floccules in a slurry
τ	shearing force
μ	coefficient of viscosity of a fluid:
(du/dr)	velocity gradient
μ_0	coefficient of the viscosity of water
μ_r	(μ/μ_0)
m	proportional coefficient to rotational speed (n) of a fluid
e	effective percentage of void
T	time from the start of rainfall to the occurrence of a mudflow

k	coefficient of permeability
θ	angle of a slope
r_m	average rainfall intensity during the time T
h	thickness of sediment deposit layer
x_1	distance
l	length of slope

INTRODUCTION

Volcanic ash is one of the most important characteristics of a mudflow in an area of an active volcano. A large scale volcanic mudflow occurred in the River Furue in Ichinomiya Town, Kumamoto Prefecture, in 1990 on account of the great size of an ash fall from the eruption of Mt Aso. Mud-debris flows have a tendency to occur more often in accordance with the voluminal increase of an ash fall. However, the mechanism of its influence on the occurrence of a volcanic mudflow is still rather unclear now. A mudflow consisting of volcanic ash and water is generally called a slurry (Pierson, 1987). However, a volcanic mudflow has not been clearly defined in terms of concentration. First, the rheological test on a volcanic mudflow was tried in various concentrations. Secondly, the influence of volcanic ash on the occurrence of a mudflow was examined using a model slope.

RHEOLOGICAL CHARACTERISTIC OF A VOLCANIC MUDFLOW

Mt Aso, shown in Fig. 1, produced a great deal of volcanic ash in the vicinity when it erupted. Mountain slopes around it were thickly covered with a fresh volcanic ash layer. A localized torrential downpour (71 mm/h) fell on the Aso district on 2 July 1990. As a result, a volcanic mudflow occurred in the River Furue, and Ichinomiya Town was seriously damaged by it. One of the causes for the mudflow might have been the influence of ash fall.

Figure 2 shows the grain size distributions of five kinds of volcanic ash. Two of them are volcanic ash collected on a mountain slope with land slides (the River Furue no. 1) and with thick vegetation (the River Furue no. 2) in the basin of the River

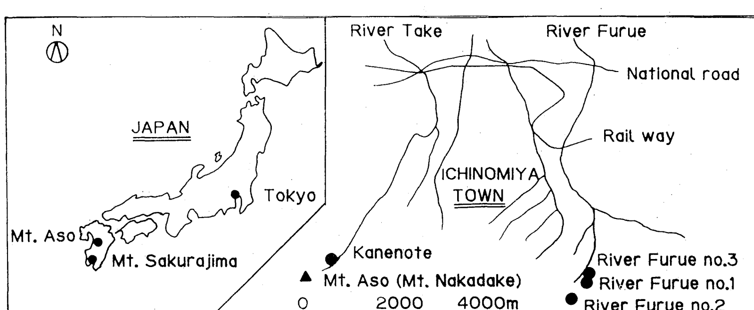

Fig. 1 A map of Ichinomiya Town.

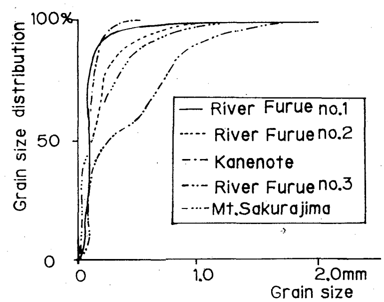

Fig. 2 Grain-size distribution of the volcanic ash of Mt Aso.

Furue. Another is volcanic ash collected in the stream bed of the River Furue (the River Furue no. 3), and the others are volcanic ash from the basin of the River Take of Mt Aso (Kanenote), where it accumulated the most thickly, and from Mt Sakurajima.

Table 1 shows the physical properties of the volcanic ash of Mt Aso and Mt Sakurajima. The coefficient of permeability of Kanenote's volcanic ash in Table 1 is (1/10) times as great as that of the River Furue no. 1, and (1/100) times as great as that of the River Furue no. 2. As seen in Fig. 2 and Table 1, these coefficients of permeability correspond to the grain sizes of these two. The volcanic ash consisting of grains of small size accumulated most thickly in the basin of the River Take. These mountain slopes were coated with a substance like cement mortar by this volcanic ash. Although this accumulation of volcanic ash was produced at the same time from Mt Aso, their physical properties are considerably different on each different mountain slope. One of the differences is their cohesion. The adhesive power of Kanenote's volcanic ash is 3 times as great as that of the River Furue no. 1.

The following equation is given for the occurrence of a mud-debris flow where sediment has no cohesion and is thoroughly saturated by water (Ahida *et al.*, 1983):

$$\tan\theta_1 = \{C(\sigma-\rho)\}\tan\phi/\{C(\sigma-\rho)+\rho(1+h_0/d)\} \qquad (1)$$

On the other hand, the equation of the critical angle of a slope for the occurrence of a mud-debris flow is expressed as follows where sediment has cohesion:

$$\tan(\theta_2) - c/\{C(\sigma-\rho) + \rho\}gh\cos\theta_2 = \tan\theta_1 \qquad (2)$$

Table 1 Physical properties of the volcanic ash of Mt Aso.

Location	Kanenote	River Furue no. 1	River Furue no. 2	River Furue no. 3	Mt. Sakurajima
Coefficient of permeability	2.58×10^{-4}	1.83×10^{-3}	1.09×10^{-2}	1.17×10^{-2}	7.60×10^{-2} (cm/sec)
Adhesive power	7.8	2.8 (gf/cm^2)			
Friction angle	35	35 (degree)			

The relationship between θ_1 and θ_2 can be obtained as follows, using equations (1) and (2):

$$\tan(\theta_2/2) = [\{1-(c/\{C(\sigma-\rho)+\rho\}gh)^2+(\tan\theta_1)^2\}^{1/2}-1]/[\tan\theta_1-c/\{C(\sigma-\rho)+\rho\}gh] \quad (3)$$

The value of C and other physical constants must be determined in order to calculate the value of θ_2 of the River Furue's volcanic mudflow using equation (3). However, the actual value of C of the River Furue's volcanic mud flow was unclear. When 0.75 as the value of C obtained from the experimental result, h = 1 m, and other physical constants of the volcanic ashes of Kanenote (the River Take) and the River Furue no. 1 in Table 1 were substituted into equation (3), their angles were calculated at 24° (Kanenote's volcanic ash) and 22° (the River Furue's volcanic ash no. 1), respectively. It is necessary to consider why the volcanic mudflow did not occur in the basin of the River Take, but occurred in the basin of the River Furue where there was less volcanic ash. Average grades of both mountain slopes are 23° (the River Take) and 40° (the River Furue). It shows that the critical angle of a slope for the occurrence of a volcanic mudflow in the basin of the River Take became 1° larger than that of the mountain slope through the influence of the adhesive power of the volcanic ash. On the other hand, the gradient of the mountain slopes in the basin of the River Furue is far above this critical angle.

The difference in erodibility by surface water between the volcanic ash of Mt Aso (the River Furue's and the River Take's volcanic ash) and that of Mt Sakurajima (the River Nojiri's one) was examined in order to find out how it was related to the occurrence of volcanic mudflows in those areas. Figure 3 shows the experimental results. The speed of erosion of the volcanic ash of the River Furue no. 1 is 10 times greater than that of Kanenote (the River Take). But it is 1/7-1/8 times as great as that of Mt Sakurajima (the River Nojiri). Table 1 shows that the volcanic ash of the River Furue no. 1 contained more water than that of Kanenote during the rainfall because of its greater permeability. The erodibilities and coefficients of permeabilities must have a connection with the probability of the occurrences of volcanic mudflows.

To study the rheological characteristic of a volcanic mudflow, the relationship between shearing resistance force and the concentration of a slurry consisting of volcanic ash and water were examined. Figure 4 shows the experimental device used. In the experiment, volcanic ash and water were placed into a cylinder. The shearing

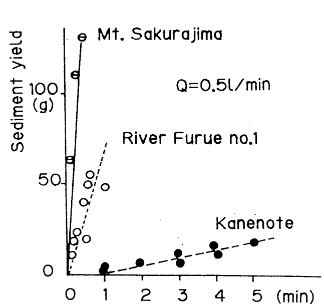

Fig. 3 Speed of erosion of volcanic ash.

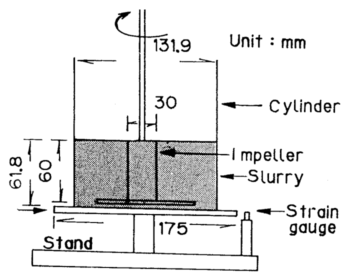

Fig. 4 Device for a rheological test of a volcanic mudflow.

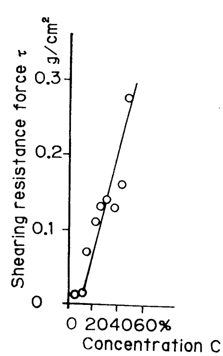

Fig. 5 Relationship between the concentration of a mudflow and shearing force.

resistance force of the slurry acting on the surface of this cylinder was measured after a uniform and rotational flow of the slurry had been produced by the impellers in Fig. 4. Figure 5 shows the relationship between the shearing force and the concentration of the slurry.

The relative viscosity (μ_r) of a slurry composed of volcanic ash and water can be expressed as follows (Daido, 1970):

$$\phi_f = C_{fs} \cdot C \quad (4)$$

$$\mu_r = 1 + [3/\{(1/\phi_f) - (1/0.52)\}] \quad (5)$$

Figure 6 shows the computed result of μ_r of the slurry using equation (5). If a volcanic

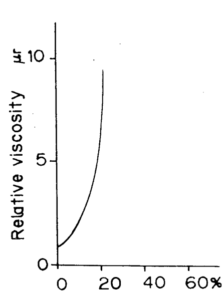

Fig. 6 Relationship between the concentration of a mudflow and its relative viscosity.

mudflow is an ideal Newtonian fluid and a laminar flow, the rheological equation can be expressed as follows:

$$\tau = \mu(\mathrm{d}u/\mathrm{d}r) \tag{6}$$

Substituting equation (5) into equation (6), the following can be derived:

$$\tau = \mu_0\{1 + [3/\{(1/\phi_f) - (1/0.52)\}] (\mathrm{d}u/\mathrm{d}r) \tag{7}$$

Using equation (7), the following can be obtained:

$$\tau/\mu_0(\mathrm{d}u/\mathrm{d}r) = 1 + [3/\{(1/\phi_f) - (1/0.52)\}] \tag{8}$$

Assuming that the value of (du/dr) in equation (8) is in proportion to the rotational speed (n) of the fluid, equation (8) becomes as follows (Taniguchi, 1991):

$$\tau/an = 1 + [3/\{(1/\phi_f) - (1/0.52)\}] \tag{9}$$

$$a = m\mu_0 \tag{10}$$

Assuming the rotational speed (n) is constant, equation (9) is expressed as follows:

$$\tau/[1 + (3/\{(1/\phi_f) - (1/0.52)\})] = A \tag{11}$$

The value of the left side of equation (11) should be constant, because the value of A in equation (11) is constant. However, it was found that the observed values were not constant. They decreased in proportion to the increase in the concentration of the slurry. It can be inferred that the reason why the value of A decreased lies in the assumption that the value of C_{fs} is constant. However, the value of ($C_{fs}C/0.52$) becomes close to one where the concentration of a slurry is rather high (Taniguchi, 1974). When the value of C is about 0.3, the value of C_{fs} becomes about 1.73. The value of C_{fs} is not always constant, but decreases in relation to the increase of the concentration of a slurry. Equation (7) shows that the shearing resistance force of a slurry is a function of its concentration and increases in relation to its rise. The definite single point of critical concentration for identifying the distinct characteristics of a volcanic mudflow cannot be found in Fig. 6, which was obtained from equation (5). It was found in Fig. 5 and Fig. 6 that the observed shearing resistance forces and the computed relative viscosities increased conspicuously together at a point about 15% in concentration. Judging from the above, it may safely be said that a slurry consisting of volcanic ash and water with a concentration over about 15% can be defined as a complete volcanic mudflow rheologically. This is consistent with the result of Fig. 6. The slurry, with the volumetric concentration of about 25%, presented the obvious characteristics of a highly viscous fluid like oil.

THE OCCURRENCE OF A VOLCANIC MUDFLOW BY RAINFALL

A mudflow only occurs when a sediment deposit layer is thoroughly saturated by water during rainfall, and surface water is generated on it. Considering the above assumption, the condition for the generation of surface water at a distance x_1 from the upper end of the slope can be expressed as follows (Hirano, 1988):

$$ex_1 = kT\sin\phi \tag{12}$$

The value of x_1 can be obtained from equation (12):

$$x_1 = (kT\sin\phi)/e \tag{13}$$

The total volume of water supplied by rainfall during the time T is expressed as follows:

$$r_m \cos\theta\, T = eh \tag{14}$$

Using equations (13) and (14), the condition for the generation of surface water at the distance 1 on a slope can be expressed as follows:

$$r_m/k = h\tan\phi/1 \tag{15}$$

The following expression also may be necessary for the occurrence of a mudflow on a slope (Takahashi, 1977):

$$\tan\theta \geq C(\sigma-\rho)\tan\phi/\{(\sigma-\rho) + \rho\} \tag{16}$$

Using equations (15) and (16), the following inequality can be derived:

$$r_m \geq KI* \tag{17}$$

$$K = [kC(\sigma-\rho)/\{C(\sigma-\rho)+\rho\}]\tan\phi \tag{18}$$

$$I* = h/I \tag{19}$$

Experimental method and result

Figure 7 shows the experimental equipment for the occurrence of a volcanic mud flow by artificial rainfall. It consisted of two systems: the equipment for producing artificial rainfall and a model channel (a model slope). The channel had two sections: the first where sediment was deposited and a second below it where the mudflow ran down. It was 4 m in length, and 20 cm in width and height. Five sediment deposit layers were used in this experiment. One of them was a single layer consisting only of sand. The sand was deposited 1.3 cm-4.0 cm thick within a distance of 1 m from the upper end of the channel (this was the section for sediment deposit and the occurrence of a mudflow). The other model slopes had double sediment deposit layers consisting of sand and volcanic ash. The sand layer (3.0 cm thick) was covered with volcanic ash layers 0.5 cm, 1.0 cm, 2.0 cm and 4.0 cm in thickness, respectively.

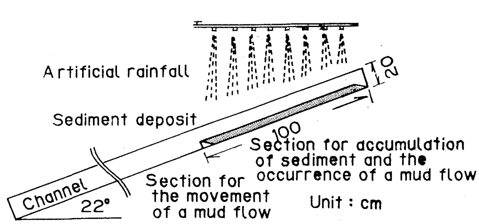

Fig. 7 Model channel for the occurrence of a mudflow.

The occurrence of a volcanic mudflow was examined experimentally when artificial rainfall was applied to each model slope. This experiment was carried out under conditions in which the intensity of the artificial rainfall was over 40 mm/h. It was measured by the discharge of running water at the lower end of the channel during the time from the start of the artificial rainfall to the time when a volcanic mudflow occurred. The moisture percentage of the sediment deposit has been measured before the artificial rainfall was applied. Samples of the sediment in the channel were collected at the same time as the occurrence of the volcanic mudflow, and their voluminal concentrations were measured. Table 2 shows some of the physical properties of the volcanic ash used in this experiment. Table 3 shows the experimental results. The term "collapse" in Table 3 is one of the types of occurrences of a mudflow. A volcanic mudflow of this type was caused by a collapse (a slope failure). It was generally large scale and occurred suddenly. All of these collapses (slope failures) immediately changed into mudflows. The term expansion identifies another type in which the activity of formation and expansion of a rill or a gully went ahead of the occurrence of a collapse (a slope failure). In this case, the sediment was generally yielded continually be a toe failure at the feet of the side walls in a gully while it rained. In this case, a large scale collapse hardly ever occurred. The term 'nothing' identifies non-occurrence of a mud flow. In this case, any types of mudflows did not occur.

Table 2 Physical properties of sand and volcanic ash used in the experiment.

Experimental material	Sand	Volcanic ash
Specific gravity	2.63	2.60
Coefficient of permeability(cm/sec)	1.05×10^{-1}	1.09×10^{-2}
Friction angle (degree)	36	35

Discussion concerning rainfall

Based on the assumption that a mudflow occurs when the whole sediment deposit layer on a long and uniform slope is completely saturated by water and its mechanical stability is lost, the critical intensity of rainfall for the occurrence of a mudflow could be theoretically determined by equation (17) derived from a two-dimensional analysis. Equation (17) shows that a volcanic mudflow will never occur under conditions where the intensity of rainfall is below the value KI^*. The correctness of this equation was proved by the experiment using a model slope with a single layer of sand. The result of Table 3 shows that a mudflow hardly ever occurs if the intensity of rainfall is below the value of KI^* in equation (17) where a mountain slope is composed of coarse grains like sand. However, in the experiment, where the slope was covered with volcanic ash, it was often seen that almost all volcanic mudflows were caused by expansions of rills or gullies. The occurrence of a mudflow depends on whether the grain sizes of sediment particles which compose a mountain slope are large or small. The mechanism of the occurrence of a volcanic mudflow of the small-grain type is quite different from that of the large-grain type. The small-grain type is more complicated than the other.

Table 3 The influence of ash fall on the critical intensity of rainfall in the occurrence of a mud flow.

Run No.	Sand layer (cm)	Volcanic ash layer (cm)	Concentration (%)	Critical intensity of rainfall (calculated value) (mm/h)	Intensity of artificial rainfall (observed value) (mm/h)	Type of occurrence
1	1.3	0	57.8	17.6	115.0	Collapse
2	2.0	0	55.6	26.1	197.0	〃
3	4.0	0	60.0	54.3	36.7	Nothing
4	3.0	0.5	60.0	0.7	207.5	Collapse
5	3.0	0.5	57.5	0.7	139.0	〃
6	3.0	0.5	57.3	0.7	204.5	〃
7	3.0	0.5	60.6	0.7	207.5	〃
8	3.0	0.5	58.1	0.7	139.5	〃
9	3.0	0.5	58.9	0.7	189.7	〃
10	3.0	0.5	61.1	0.7	39.1	Expansion
11	3.0	1.0	57.5	1.3	204.5	〃
12	3.0	1.0	54.3	1.3	204.5	〃
13	3.0	1.0	61.0	1.4	171.1	〃
14	3.0	1.0	58.7	1.3	202.2	〃
15	3.0	1.0	58.8	1.3	169.1	〃
16	3.0	1.0	60.5	1.4	150.7	〃
17	3.0	2.0	58.7	2.7	52.1	〃
18	3.0	2.0	57.5	2.6	178.5	〃
19	3.0	2.0	57.0	2.6	230.6	〃
20	3.0	2.0	60.0	2.7	174.8	〃
21	3.0	4.0	59.0	5.3	39.1	〃
22	3.0	4.0	58.4	5.3	163.6	〃

In this case, surface water will be generated as soon as it begins to rain, and sediment will be vigorously yielded on account of that. A deep gully will be formed on a slope, and the heights of side walls of the gully will increase still more. It is natural that they will be very unstable in mechanics. As a result, a toe failure will never fail to occur at the feet of these side walls during rainfall, and the occurrence of a volcanic mudflow would follow (Taniguchi, 1985). In this case, therefore, the generation of surface water has a very important role in the occurrence of a volcanic mudflow.

FUTURE WORK

Volcanic ash has important effects on the occurrence of mudflows in areas of active volcanoes. One is its adhesive power. The critical angle of a slope for the occurrence of a volcanic mudflow in the basin of the River Take became 1° larger than that of the mountain slope by its influence. Volcanic mudflows did not occur there on account of its adhesive power. Another effect is its rheological and dynamic role in a volcanic mudflow. It is necessary to study the rheological and dynamic behavior of a highly concentrated slurry consisting of volcanic ash and water. The third is its influence on sediment yield. Volcanic ash is clearly related to the sediment yield in areas of active volcanoes. The critical intensity of rainfall for the occurrence of a mudflow should be more thoroughly investigated in the field, and the mechanisms of sediment yield in areas of active volcanoes should be clarified.

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