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RUNNING-OUT PROCESSES OF THE DEBRIS ASSOCIATED WITH THE ONTAKE LAND SLIDE

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ABSTRACT

An earthquake with a magnitude of 6.8 occurred at the southern side of Mt. Ontake, Western Nagano on the 14th of September in 1984. A catastrophic land slide, which was named the Ontake Land Slide, was triggered by this earthquake. The rock fall volume was estimated to be 3.6×10^7 cubic meters. The large amount of sediment set in motion at the slope area from 1900 to 2500 meters in altitude ran down through the Denjo River to the Nigori River and then into the Ohtaki River. The sediment motion brought about various kinds of disasters, including the loss of human lives.

The present study will discuss the debris motion triggered by the earthquake. General descriptions are made at first on the running-out processes of the slide debris, and our conclusions as to the dynamics of the movement of the side debris are presented. Theoretical calculations of fluidization as well as the movement velocity of the debris avalanche are made and compared with the results obtained in field surveys.

1. INTRODUCTION

An earthquake with a magnitude of 6.8 occurred on the southern side of Mt. Ontake, Western Nagano, on the 14th of September in 1984. Numerous slope failures were triggered by it in the Ohtaki River basin. Various disasters took place because of the earthquake and the slope failures in Ohtaki Village, including the loss of human lives and damage to houses, roads, cultivated lands, power plants and so on. Twenty-nine human lives were lost due to debris avalanches.

The largest slope failure, which was named the Ontake Land Slide, took place at an altitude of 1900 to 2500 m on the southern slope of Mt. Ontake. The rock fall volume as estimated at 3.6×10^7 m^3 is the second largest in this century in Japan. The large amount of debris produced by the slope failure ran down through the Denjo River, the Nigori River and into the Ohtaki River. Approximately seventy percent of the slide debris was deposited in the Ohtaki River bed, and the remainder was deposited in the upstream reach of the junction of the Ohtaki and Nigori Rivers. The mean speed of the debris avalanche was estimated to be 20 to 30 m/s [1]. The mean inclination along the river bed from the foot of the slope failure to the top of deposition region in the Ohtaki River is approximately 4.5 degrees (see Fig. 12). Many researchers have investigated why the debris moved at such a high speed, and the mechanism of its movement.

The present study describes the running-out processes of the debris triggered by the Ontake Land Slide. The mechanism of motion is discussed in terms of the results obtained from field

KEY WORDS: Sediment hazard, Ontake Land Slide, Debris avalanche, Debris flow, Sediment runoff
Note: Discussion open until 1 March, 1988.

surveys as well as theoretically. Theoretical calculations are made for the fluidization and movement velocity of the slide debris by our previously reported methods [2, 3, 4].

2. DESCRIPTION OF THE RUNNING-OUT PROCESSES OF THE SLIDE DEBRIS

2.1. *General Description*

Various field surveys as well as analyses were made just after the Ontake Land Slide by a number of scientists and engineers. We were members in the Project Team of Scientific Researchers, funded by the Ministry of Education and organized by Dr. K. Iida, Prof. of Aichi Institute of Technology, in order to investigate the behavior of the Ontake Land Slide.

Photo. 1 shows a distant view of the Ontake Land Slide which is 1480 m long along the slope, 480 m in maximum width, 136 m in maximum depth and 3.6×10^7 m^3 in apparent volume. The slide debris is composed of volcanic sediment. The structure of the sub-surface soil layer that

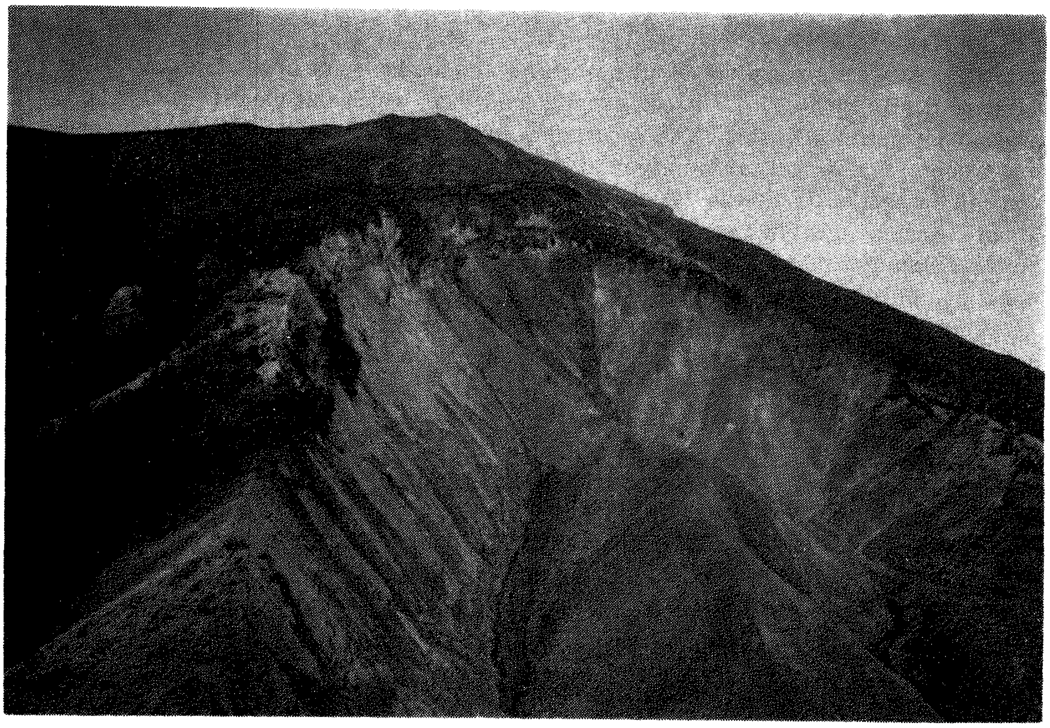

Photo. 1 Distant view of the area of the Ontake Land Slide.

Photo. 2 Surface features of the conglomerate layer overlaying the slide debris.

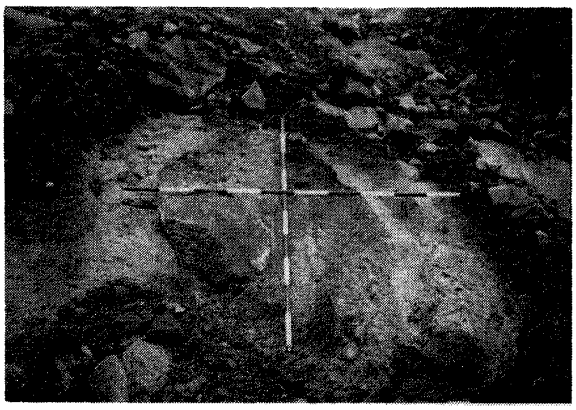

Photo. 3 Surface features of the pumice layer overlaying the slide debris.

become exposed after the slide shows alternate conglomerate and pumice layers (Photos. 2 and 3). The existence of this pumice layer is believed to be responsible for the Ontake Land Slide because the porosity in a pumice layer is large, resulting in a high water content.

A large amount of slide debris ran off along the river course. Figure 1 shows the trace of movement of the slide debris, which ran down the Denjo, Nigori and Ohtaki Rivers. In the running-out processes part of the debris, the volume of which was negligibly small, was forced to overflow over both sides of Mt. Komikasa, leading to the Mizoguchi and Suzukasawa Rivers, in which debris flows were formed by the supplied debris. At a section about 2 km downstream of Mt. Komikasa, part of the moving debris, flooded into the Nigorisawa River because of the curvature of the river course, but the main motion of the debris was nevertheless into the Denjo River. The flooded volume was estimated to be much smaller than that of the main motion. After each flow of the debris joined, the debris then entered the Nigori River and reached the confluence of the Nigori and Ohtaki Rivers. It partly overflowed one bank because the river course bends to left as much as ninety degrees, owing to a ridge with a relief of 50 m. The debris continued in motion in the Ohtaki River, and ceased at last its avalanche motion at Korigase, 3.7 km downstream of the confluence of the Nigori and Ohtaki Rivers. The travel distance was 12 km from the beginning of movement to the point of ceasing.

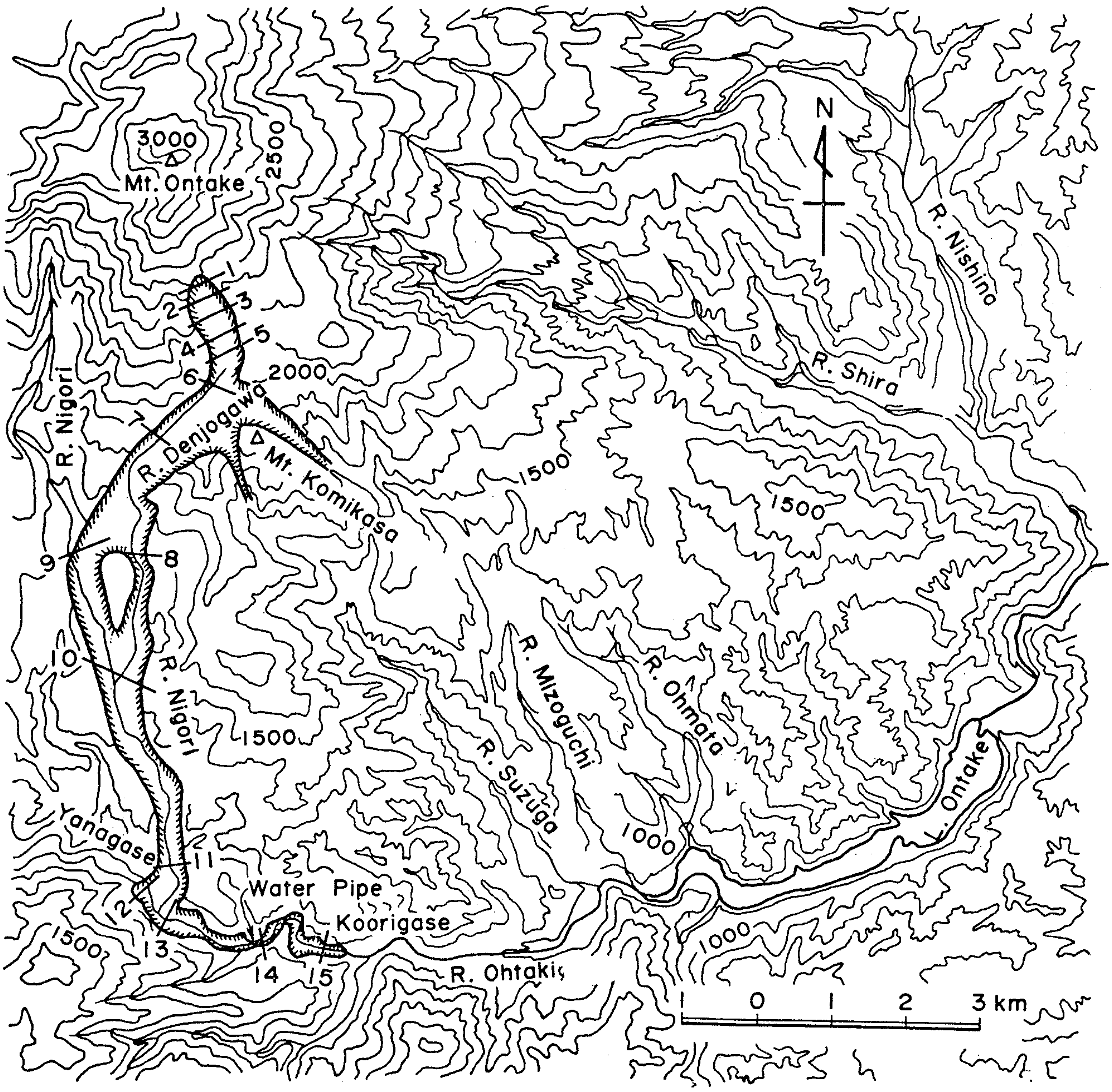

Fig. 1 Trace of the debris avalanche triggered by the Ontake Land Slide.

2.2. *Erosion and Deposition of the Debris Avalanche*

The debris movement produced fairly big changes in the area's geomorphological features. Figure 2, in which the section number is indicated in Fig. 1, shows several cross-sectional shapes before and after the slide. Sections 1 to 5 show the area of the Ontake Land Slide. The maximum width was in Sec. 3, and the maximum depth in Sec. 2. The rock fall volume calculated from these cross-sections is 3.6×10^7 m^3.

Sections 6, 7 and 8 are of the Denjo River. Their profiles show that erosion dominates in these sections, although local deposition of the debris is found. The depth of the debris motion from these cross-sections may be inferred to be more than 100 m. In addition, the speed of

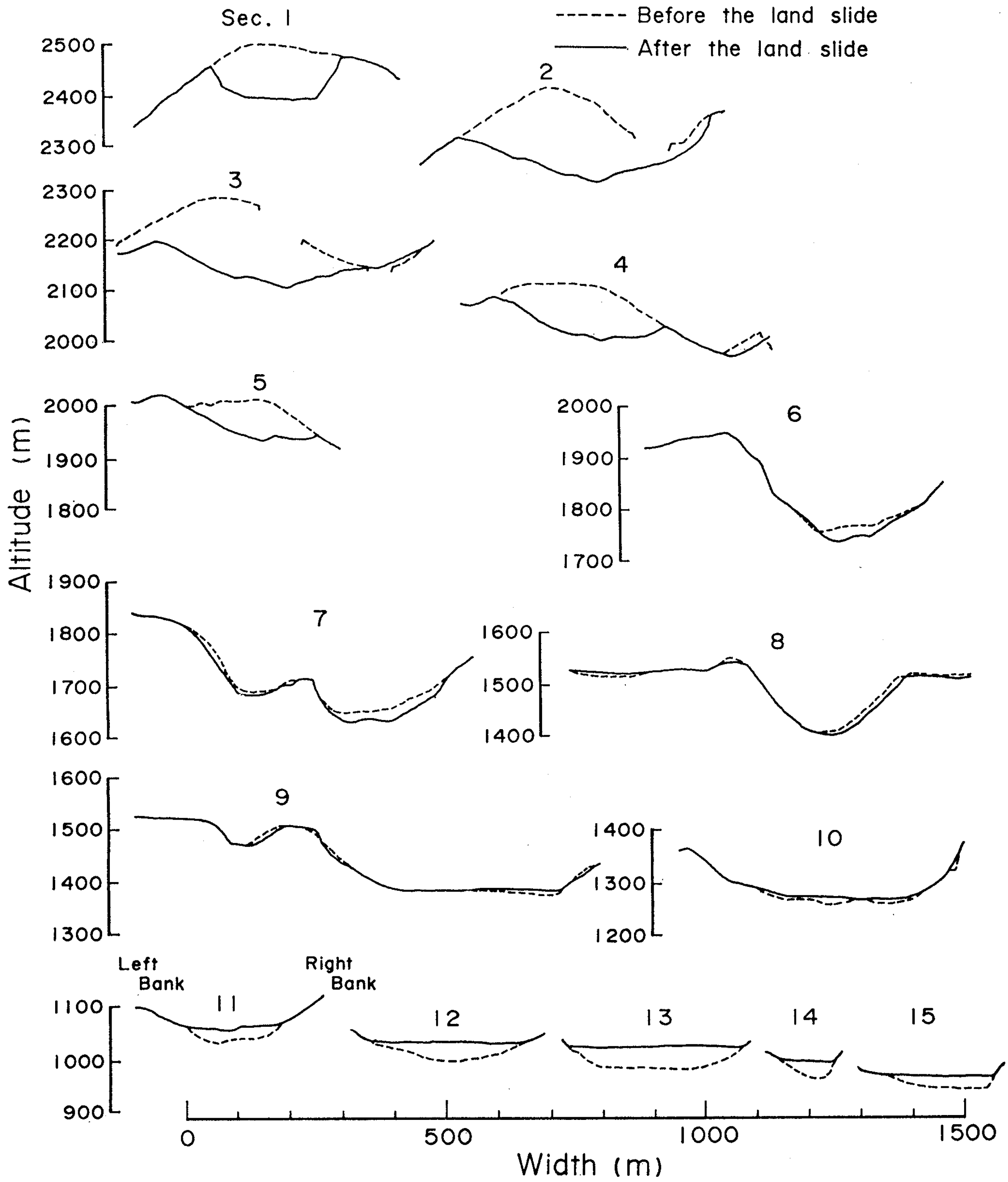

Fig. 2 Cross sections of areas before and after the Ontake Land Slide. The number shown in each cross section is given in Fig. 1.

debris avalanche must have been fairly high, because scouring was as much as 25 m deep in section 7. Note that the bed inclination in the river course is 7 to 8 degrees (see Fig. 12).

Section 9 is of Nigorisawa Creek, into which part of the slide debris overflowed. The left bank is eroded, but debris deposition is found locally in the vicinity of the right bank.

Sections 10 and 11 are of the Nigori River. The mean inclination of the reach is 3.6 degrees between the two sections. From section 10 downstream, deposition processes are dominant, as is indicated in these cross-sectional profiles; the maximum depth of debris deposition is up to 15 m in section 10 and 30 m in section 11. Several flow mounds, some of which were larger than 10 m in diameter, were found in the deposited debris.

Sections 12 to 15 are of the Ohtakı River. A large amount of slide debris was deposited in its reach. Especially in the vicinity of section 13, the width of debris deposition was up to 300 m, and the maximum depth was not less than 40 m. A fairly large number of flow mounds, which were smaller than those in Nigori River, were found in the reach. The surface features of deposited debris looked astonishingly smooth in this area, except in areas where there were flow mounds. The surface inclination of the deposit was 1.7 degrees, as compared to an original bed slope of 1.0 degree.

2.3. *Sediment Transported by the Debris Avalanche*

The water content of the sediment, except of the flow mounds, was so high that one could not walk on it. Unfortunately no analysis was made of this water content. The debris was a mixture of silt, sand, gravel and rock, and no sediment sorting was found. Figure 3 shows the

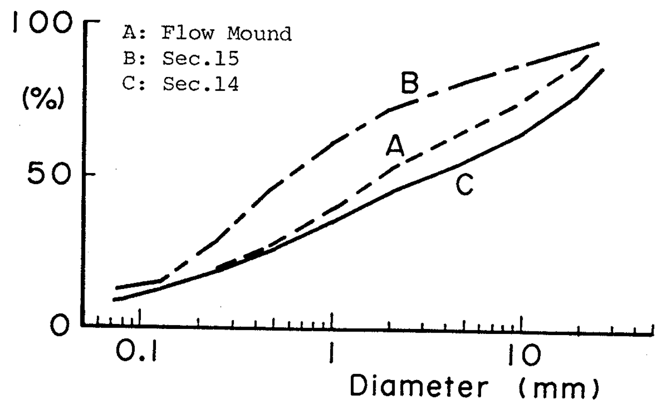

Fig. 3 Particle size distributions of the sediment transported by the debris avalanche.

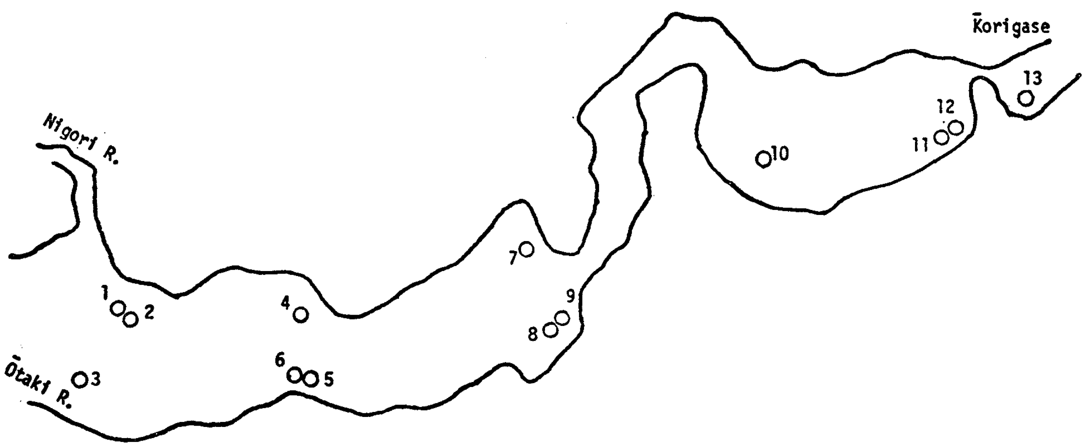

Fig. 4 Sites of boring stations at which deposited debris layers were surveyed. Provided by the Ministry of Construction.

size distributions of sediment, sampled at sections 14 and 15 and at a flow mound, particles of which are finer than 25.4 mm in diameter. Upon comparing each of them, no representative differences could be found in these distribution curves.

Table 1 Description of the deposit layering at boring stations 1, 4, 12 and 13.

Table 1 (a) St. 1

1 (m)	2	3	4	5	sample description
		YB	DF	SS	water content low. Wood and andecite breccia(d=0.5 -1.0cm) present.
5		DB		SG	Content of andesite breccia(d=0.5-1.0cm) as much as 40%. The matrix is poorly sorted. Trees and roots in pieces.
10		RB	DF with MFH	TBR	Matrix composed of andesite breccia(d=2-10cm) and volcanic sand; gravel content 40 to 60%. Matrix composed of poorly sorted volcanic sand with soft and weak materials.
15					Content of andesite breccia(d=1-5 cm) 40 to 50%. Matrix composed of poorly sorted coarse sands with silt. Silt content higher in the upper than the lower layer. Many fragments of trees and roots.
20		DG	DF	SG	Content of andesits breccia(d=1-10 cm) is as much as 50%. Matrix composed of coarse volcanic sand which predominates in the middle layer.
25		DG DRG	DF with MFH	TBR	Content of andesite breccia(d=1-7 cm) 30 to 60%. Matrix composed of poorly sorted sands and a large amount of silt. Many fragments of trees and roots.
30		DBG	DF	SG	Water content of deposit 30 to 60%. Pebbles of larger than 10cm in diameter predominate. Materials smaller than 10 cm in diameter are subrounded breccia. Matrix composed of medium to coarse sands. Sands predominate from 37.25 to 38.4 m and from 38.8 to 39.5 m.
35, 40		DG	ORB	SG	

1=Depth (m), 2=Deposit layering, 3=Color tone, 4=Type of deposition, 5=Qualty of material
Color tone: YB= Yellow-brown, DB= Dark brown, RB= Reddish brown, DG= Dark grey, DBG= Dark brownish grey, GG= Green-grey, YG= Yellow-grey, G= grey, Type of deposition: DF= Debris flow, MFH= Mud-flow hill, ORB= Original river bed
Qualty of material: SS= Silty sand, S.G= Sand and Gravel, TBR= Tuff breccia rocks, S= Sand, R= Rhyolite

Although little information could be obtained about the surface layer just after the event, boring surveys were made by the Ministry of Construction after three months. The boring stations are shown in Fig. 4. The boring surveys revealed some features of the subsurface layers of the deposited sediment. The results obtained from the surveys at stations 1, 4, 12 and 13 are shown in Table 1 (a) to (d). The results indicate that the debris material is poorly sorted, with a large amount of tree wood found in it; however, some flow mounds are still found in the subsurface layer. This means that the debris experienced fairly high shear stresses in the running-out processes, and gained a high speed.

Table 1 (b) St. 4

1 (m)	2	3	4	5	Sample description
0–35 (5, 10, 15, 20, 25, 30)		DB	DF	S.G	Gravel content 30 to 50%. Hard to subrounded breccia (d=2-10cm) composed of andesite and andesite with rhyolite in rare cases. Matrix composed of poorly sorted sandy soil. Many fragments of trees and roots. Gravel content low in the layer of 0 to 9.5m, in which the matrix is composed of silt. Gravel content as much as 70% in the layers from 30 to 34.7m. Except in the above layers, dominant gravels are present from 9.9 to 10.8 m 17.0 to 17.65m 18.0 to 19.45m 23.5 to 24.00m Large pieces of wood are present from 18.15 to 18.65m.
35	L L L L	GG		R	Comparatively hard rocks are present. Cracks developed randomly in the core samples. The color of these cracks turned brown.
40					

Table 1 (c) St. 12

1 (m)	2	3	4	5	Sample descriptior
		DG	DF	S.G	Content of gravels with andesite breccia is as much as 40%. Matrix poorly sorted.
5		RB	DF with MHF	TBR	Andesite breccia 2 to 5cm with a matrix of volcanic sand. Gravel content 30 to 50%. No wood present.
10		DBG	DF	S.G	Andesite breccia 1 to 3cm with poory sorted matrix of sandy soil. Wood fragments present from 9.6 to 9.8m.
		YG	ORB	S	Median sands, comparatively well sorted, predominate. Wood fragments present in the upper part.
15		G	ORB	S.G	Subrounded breccia 3 to 5cm. Gravels composed of andesite and rhyolite. Matrix composed of coarse sand.

Table 1 (d) St. 13

1 (m)	2	3	4	5	Sample description
		DG	DF	S.G	Andesite breccia to subangular breccia; diameter 2 to 6cm. Matrix composed of poorly sorted coarse sand.
5		DBG DB	DF	S.G	Andesite breccia and subangular breccia; diameter 3 to 10cm. Gravle content 30 to 50%. Matrix composed of poorly sorted sandy soil with dominant silt. Tree and root fragments present.
10			ORB	S.G	Gravel content 50 to 80%. Subangular and subrounded breccia present. Gravels composed of various kinds of andesite and rhyolite. Matrix composed of poorly sorted medium to coarse sand. Water springs out below 9.0m.

The water content of the debris was tested during the boring surveys, but the original content could not be accurately determined because the test was made three months after the event. The results from these tests are, however, significant. The results obtained from the test indicated that the water content of subsurface layer, except flow mounds, was 10 to 20%, with that of the flow mounds as low as 10%. Supposing the debris to be saturated with water, water contents from 10 to 20% would be in accord with porosity of 22 to 35%. Note that the level of the water table was shallower than 5 m from the surface.

2.4. *Water Volume in the Debris Avalanche*

The description up to this section provides an outline of the running-out processes of the slide debris. Some researchers think the existence of water plays an important role in the process, and on the other hand others hold the converse to be true. Let us consider first the water balance relating to the process, before proposing our opinion as regards this problem.

The amount of rain-fall from the beginning of September to the earthquake was 177 mm at the Ontake rain gage station and 48 mm at the Makio dam rain gage station. These rain gage station are shown in Fig. 5 together with those of dams and water intake. The flow discharge in the Ohtaki River could be estimated easily from the inflowing discharge into Makio Reservoir, which drains an area of 304 km^2, 2 to 3 m^3/s from the 1st to 8th of that month, 19 m^3/s on the 9th, 10 m^3/s on the tenth, and on just before the earthquake, 3 m^3/s. Flow discharges inflowing into Makio Reservoir may have been much less than usual due to discharging through the power plants. Water intake were in operation at most tributaries of the Ohtaki River, and moreover the power plant of Miura dam, which drains 73.5 km^2, was also in operation.

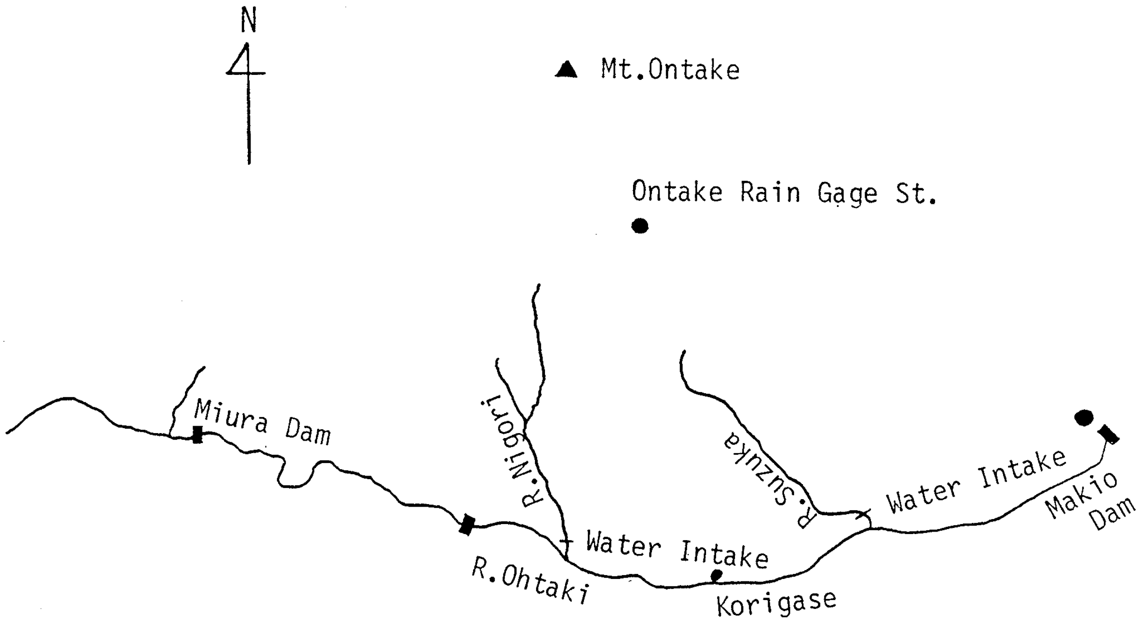

Fig. 5 Sites of the dam, water intake and rain gage.

The water intake had been in operation in the Nigori River (21 km^2) until the moment of the event. From the intake, no more than 2 m^3/s, had been discharged. Judging from this fact, the flow discharge could be estimated not exceeding 2 m^3/s in the Nigori River. The total daily volume of water discharge in the Nigori River is thus found to be 170000 m^3. This water volume would not be increased so much even if the discharge of the Ohtaki River is added to that of the Nigori River.

The water volume of the slide debris was, on the other hand, so large that the debris pores could be saturated except in the flow mounds and a debris flow could be formed, judging from the results of field surveys. The restricting the water volume in sediment deposited in the Ohtaki River bed alone, was estimated as 8×10^6 m^3, supposing that the apparent sediment volume is 2.5×10^7 m^3, 5×10^6 m^3 of which is composed of flow mounds, and the porosity is 40%.

A major question arises as to what supplies such a large amount of water to the debris avalanche. A possible idea is to consider that so much water was included in the body of the mountain or slope itself; however, a clear answer could not be specified to this question. Pumice soils as well as volcanic debris generally have a large porosity. Considering this fact, and supposing that the upper layer composing 30 to 40% of slide soil block, with volume 3.6×10^7 m^3, is in a fairly dry state, but the lower soil is saturated by water, with a porosity of 40%, the water volume existing in the body of the slope could be estimated as from 8×10^6 to 10^7 m^3.

3. MECHANISM OF THE DEBRIS AVALANCHES

Investigations of equivalent frictional coefficient are frequently made in order to understand the behavior of debris avalanches [5]. Figure 6 shows the coefficient of the Ontake Land Slide together with historical events in Japan and in foreign countries. It is well known that the coefficient defined in this figure decreases with increasing rock-fall volume. A comparison of each value in Fig. 6 reveals that the coefficient for the Ontake Land Slide is the smallest. This means that this debris avalanche behaved as a body with high mobility. In fact, the debris avalanche ran down with high speed, for a long distance, along a river course where the mean inclination was not very steep.

The equivalent coefficient gives thus valuable information, although it depends on the debris material, water content, dynamic variables and the rock-fall volume. Investigations on the mechanism of debris avalanches are, therefore, necessary to specify the equivalent frictional coefficient. What makes such a motion possible? Judging from the results mentioned above, a kind of "flow" was surely formed somewhere in the running-out process. The phases composing the multiphase flow could be classified as follows;

(1) solid particles and "fluid" and
(2) solid particles and "dry fluid".

"Fluid" refers not only to the water phase without solid particles, but to a mixture of water and solid particles which behaves as a "fluid". "Dry fluid" refers to a mixture composed of air and solid particles.

The flow structure posited above is classified from the viewpoint of two-phase flow. Shifts of phase may take place depending on the characteristics of the flow. We are thinking about that the turbulence due to a high shear stress causes a particle suspension in the pore fluid and the mixture of suspended solid and fluid behaves as a "fluid", resulting in a phase shift. The phase shift is, therefore, apt to occur much easier not only in water than in air, but also in finer particles of the debris materials. The idea of phase-shift has already been applied to the analysis of debris avalanches and debris flow by Takahashi [6], but no phase-shift machanism was specified.

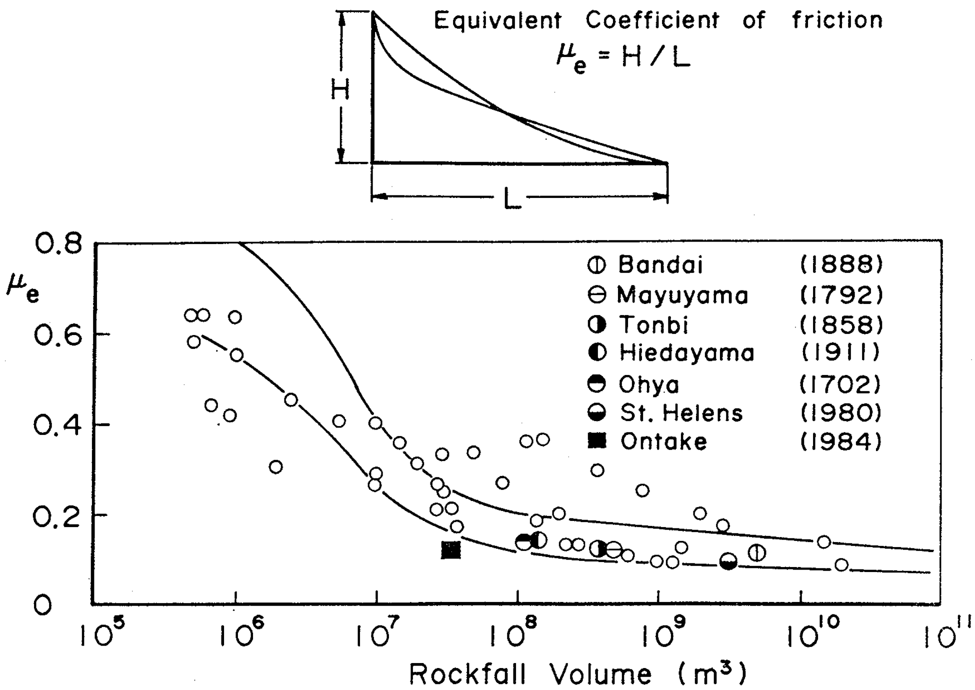

Fig. 6 Relation of equivalent friction coefficients to rock fall volumes in past debris avalanches in Japan and foreign countries [5].

A change in the apparent solid friction coefficient would be caused by phase shift. Figure 7 shows a schematic of particle size distribution, in which particles finer than a critical size d_c behave as a fluid. Suppose that a phase shift occurs between the static and moving states as shown in Fig. 8, in which the portion indicated by λ represents a fluid phase or the porosity of the mixtures. Figure 9 shows a uniform, two phase flow. From the above assumptions and by definitions, the mean bulk density of the moving layer is written as

$$\rho_b = \lambda_s \rho_{fs} + (1-\lambda_s)\rho_s \tag{1A}$$

or

$$\rho_b = \lambda_m \rho_{fm} + (1-\lambda_m)\rho_s \tag{1B}$$

in which ρ_b is the bulk density of the moving layer or that of the layer to be moved, λ_s the porosity in the static state, λ_m the porosity in the moving state, ρ_s the mass density of solid particle, ρ_{fs} the mass density of the fluid in static state and ρ_{fm} the mass density of the fluid phase in moving state. λ_m and ρ_{fm} are expressed by

$$\lambda_m = (1-F)\lambda_s + F \tag{2}$$

and

$$\rho_{fm} = \{\lambda_s \rho_{fs} + F(1-\lambda_s)\rho_s\}/\{\lambda_s + F(1-\lambda_s)\} \tag{3}$$

in which F is the rate at which solid particles are shifted in the fluid phase. From Fig. 9, the driving force per unit length and width is

$$F_d = \rho_b g H \sin\theta \tag{4}$$

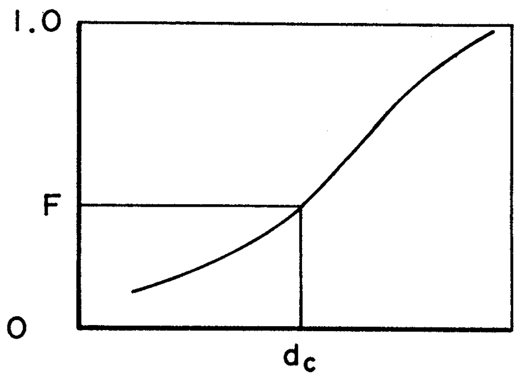

Fig. 7 Diagram of particle size distribution. Particles finer than d_c could behave as "fluid".

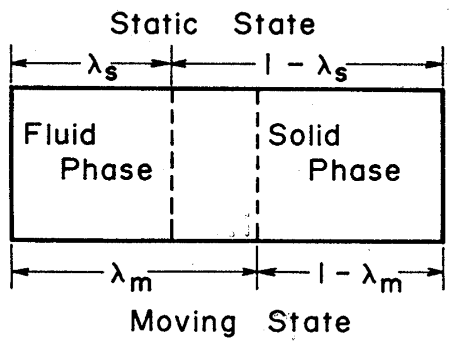

Fig. 8 Diagram of the phase shift.

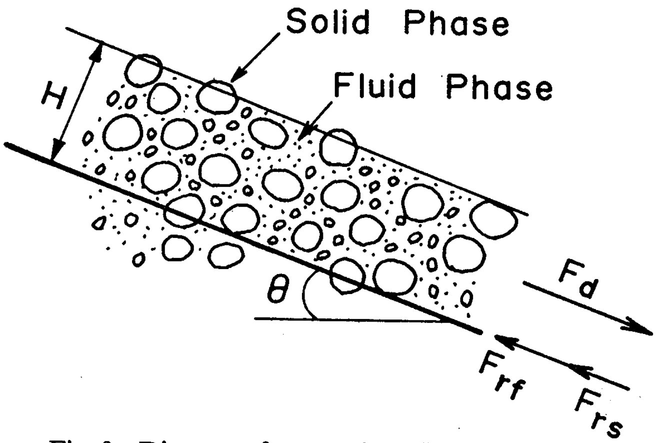

Fig. 9 Diagram of a two phase flow on a slope.

in which F_d is the driving force, H the flow depth and θ the inclination of the bed. Resisting forces on the bed are produced in two ways; by solid to solid friction and by deformation of the fluid phase. Using the quasi-Bingham plastic mode by Ashida, Egashira et al. [4], these two forces at the bed are

$$F_{rs}=\{(1-\lambda_m)(\rho_s-\rho_{fm})gH\cos\theta\}\mu_k \qquad (5)$$

$$F_{rf}=\rho_{fm}\varepsilon_f\left.\frac{du}{dz}\right|_{\text{bed}}=\rho_{fm}u_*^2 \qquad (6)$$

in which μ_k is the kinematic friction coefficient for solid to solid, ε_f the eddy viscosity of the fluid phase and u_* the shear velocity of the fluid phase. Equation (5) represents the yield stress at the bed which decreases with increasing the rate of phase shift F, and Eq. (6) is equivalent to the viscous or Reynolds stress. The state of uniform flow must satisfy the relation:

$$\rho_b gH\sin\theta=\{(1-\lambda_m)(\rho_s-\rho_{fm})gH\cos\theta\}\mu_k+\rho_{fm}u_*^2 \qquad (7)$$

Let us consider the change of the apparent friction coefficient in treating a phase shifting phenomenon. In this case, Eqs. (5) to (7) should be written as

$$F_{rs}=\{(1-\lambda_s)(\rho_s-\rho_{fs})gH\cos\theta\}\mu_{ka} \qquad (8)$$

$$F_{rf}=\rho_{fs}U_*^2 \qquad (9)$$

$$\rho_b gH\sin\theta=\{(1-\lambda_s)(\rho_s-\rho_{fs})gH\cos\theta\}\mu_{ka}+\rho_{fs}u_*^2 \qquad (10)$$

in which μ_{ka} is the apparent friction coefficient for solid to solid. From Eqs. (7) and (10);

$$\{(1-\lambda_s)(\rho_s-\rho_{fs})gH\cos\theta\}\mu_{ka}=\{(1-\lambda_m)(\rho_s-\rho_{fm})gH\cos\theta\}\mu_k+(\rho_{fm}-\rho_{fs})u_*^2 \qquad (11)$$

In our theory [3, 4], the second term on the right hand side of Eq. (11) becomes negligible compared to the first term when the bed slope decreases. The ratio μ_{ka}/μ_k reduces to

$$\mu_{ka}/\mu_k=(1-F)\lambda_s/\{F+(1-F)\lambda_s\} \qquad (12)$$

when the second term is neglected. Figure 10 shows the curve calculated from Eq. (12).

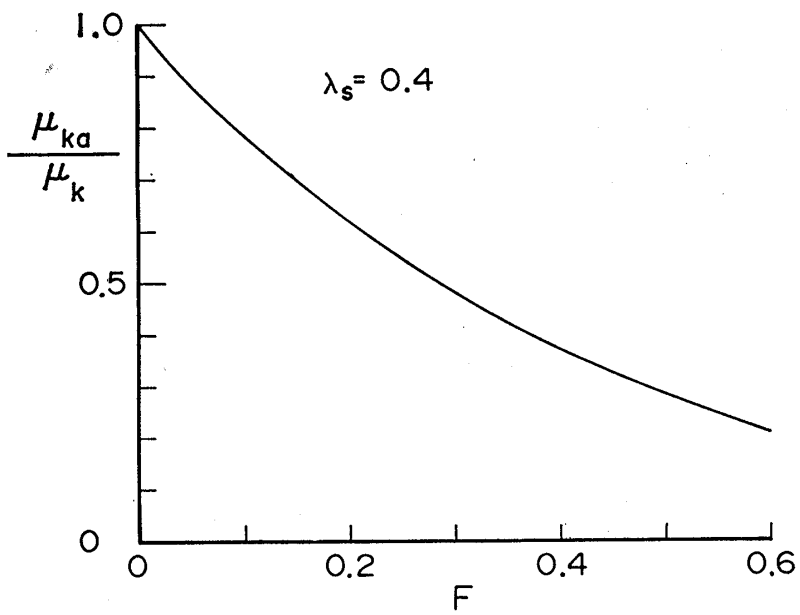

Fig. 10 Apparent solid to solid friction coefficient curve calculated from Eq. (12).

There have been many reports that the kinematic friction coefficient μ_k, does not depend on the state of motion, and maintains an approximately constant value. A previous experiment of ours [3] shows that μ_k is in the range of

$$0.7 \tan \phi_s < \mu_k < 0.85 \tan \phi_s$$

in which ϕ_s is the angle of repose of the material. Soil tests made on Ontake soil [7] indicate that ϕ_s falls in the range of

$$30° < \phi_s < 40°$$

The above material allows for the specification of the phases of the debris avalanche mentioned earlier in this chapter. Let us consider the possibility of debris motion based on the results obtained by applying some numerical constants to the formulas. The numerical constants are assigned as follows; $\theta = 7.3°$, $\mu_k = 0.49$ $(= 0.7 \tan \phi_s,\ \phi_s = 35°)$, $\rho_s = 2.65$ g/cm³, $\rho_{fs} = 1.0$ g/cm³ (water), or $\rho_{fs} = 0$ (air), $\lambda_s = 0.4$, in which the inclination angle referred to is the mean value of the Denjo River. The possibility of debris movement can be evaluated by the mobility defined as F_d/F_{rs}, resulting in the following:

	Mixture of solid particles and "fluid" F_d/F_{rs}	Mixture of solid particles and "dry fluid" F_d/F_{rs}
$F=0$	0.526	0.261
$F=0.25$	0.962	0.478
$F=0.5$	1.838	0.917

If the mobility, F_d/F_{rs}, is smaller than unity, the debris has no possibility to move. The results shown above suggest the possibility that the debris avalanche triggered by the Ontake Land Slide ran off as "debris flow", where in this case, "fluid" means a mixture of water and part of the solid particles.

Although the mechanism of the debris avalanche has been shown fairly well, the question remains as to what is the mechanism of the phase shift. Extensive studies on hyperconcentrated flow are necessary to clarify that mechanism. It is, however, possible to estimate roughly the shifting phenomenon, by applying available knowledge concerning sediment suspension produced by turbulence. On the basis of our previous results [8], phase shift could be evaluated by the particle suspension due to turbulence in the "fluid".

4. FLUIDIZATION AND MOVEMENT OF THE DEBRIS AVALANCHE

Fluidization and velocity of the debris can be analyzed by our method. We have presented a formula to predict the critical movement distance for the fluidization of the soil block [2];

$$\frac{x_c}{h_{max}} = 37\left\{\frac{\cos(\pi/4+\phi_{sa}/2)\tan\phi_{sa}}{3\mu_{ka}} + \frac{1}{\mu_{ka}(1-\lambda_s)(1-\rho_{fs}/\rho_s)}\frac{c}{\rho_s g h_{max}}\right\} \tag{13}$$

in which x_c is the critical distance, h_{max} the maximum depth of slope failure, ϕ_{sa} the apparent angle of repose of material, g the gravitational acceleration and c the cohesion of the material. Equation (13) shows that fluidization takes place when the movement distance becomes x_c. In Eq. (13), use of the "apparent" value ϕ_{sa} instead of the true one is why the phase shift rate can not be determined in detail.

The formula for the movement velocity [3, 4] is

$$\frac{U}{\sqrt{gh}} = \left\{\frac{U_0^2}{gh}e^{2ax/h} - \frac{a}{b}(1-e^{2ax/h})\right\}^{1/2} \tag{14}$$

$$a = -2(\rho_{fs}/\rho_b)f \tag{15}$$

$$b = \cos\theta\{\tan\theta - \mu_{ka}(1-\lambda_s)(\rho_s - \rho_{fs})/\rho_b\} \tag{16}$$

in which U is the movement velocity, U_0 the initial or boundary value of that velocity, x the moving distance and f the friction coefficient due to the deformation of the fluid phase.

Numerical constants must be specified in order to calculated the critical distance, x_c. $\theta = 12.2$ (see Fig. 12) is applied to Eq. (13), considering that fluidization takes place in the early stage of the running-out process. The other assigned constants are $\lambda_s = 0.4$, $\rho_{fs} = 1.0$ g/cm^3, $\rho_s = 2.65$ g/cm^3 and $\mu_{ka} = 0.7 \tan\phi_{sa}$ ($\phi_{sa} = 10°$, $14°$).

The curves predicted by Eq. (13) and shown in Fig. 11 give the relation between the nondimensional critical distance x_c/h_{max} and the cohesion. To know the critical distance, therefore, one must specify the cohesion and the maximum depth of slope failure. The value 1900 kgf/m^2 used as the cohesion is the same as the value used in the analysis of the Nagasaki disaster [9], because not enough information has yet been obtained on the cohesion of the Ontake Land Slide. The value 136 m was assigned as the maximum depth.

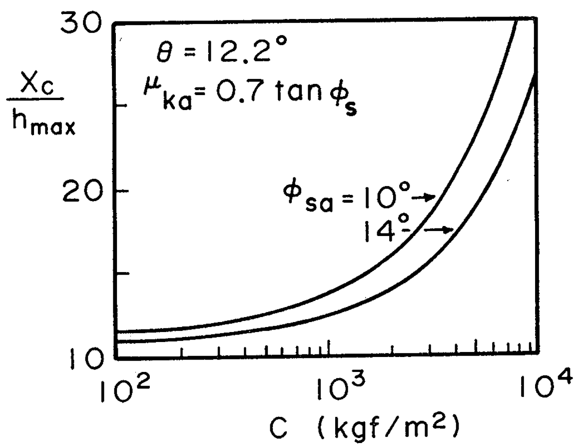

Fig. 11 Nondimensional critical distance for the fluidization of slide debris as predicted by Eq. (13).

Applying these values to the calculated curves, the critical distances are found to be

$$x_c = 1900 \text{ m} \quad (\phi_{sa} = 14°,\ x_c/h_{max} = 14)$$

and

$$x_c = 2200 \text{ m} \quad (\phi_{sa} = 10°,\ x_c/h_{max} = 16)$$

These critical distances may be much longer than the real ones because the actual cohesion may likely be smaller than that of the value used in the calculations. Consequently, fluidization could occur in a shorter distance than the calculated values, and the debris avalanche could run down as a debris flow, except for the dry portion, i.e. the upper-most layer of slide debris. This dry portion might be crushed into pieces during the running-out. Each piece then would be transported as a flow mound by the debris flow.

Figure 12 shows the distributions of movement velocity predicted by Eq. (14) for two values of ϕ_{sa}, with $f = 0.02$ as well as the same numerical constants used in the calculations of the critical distance for fluidization. In the figure, the longitudinal bed profiles before and after the slide as well as the divided reaches, and the mean inclination used in our calculations are given.

Let us focus on the two curves for $\phi_{sa} = 10°$ and $14°$. Both show acceleration in the upper reach of the Denjo River, and attain an equilibrium state along the lower reach of the Denjo River, with a speed of 60 to 65 m/s for $\phi_{sa} = 10°$ and 50 m/s for $\phi_{sa} = 14°$. The two debris flows

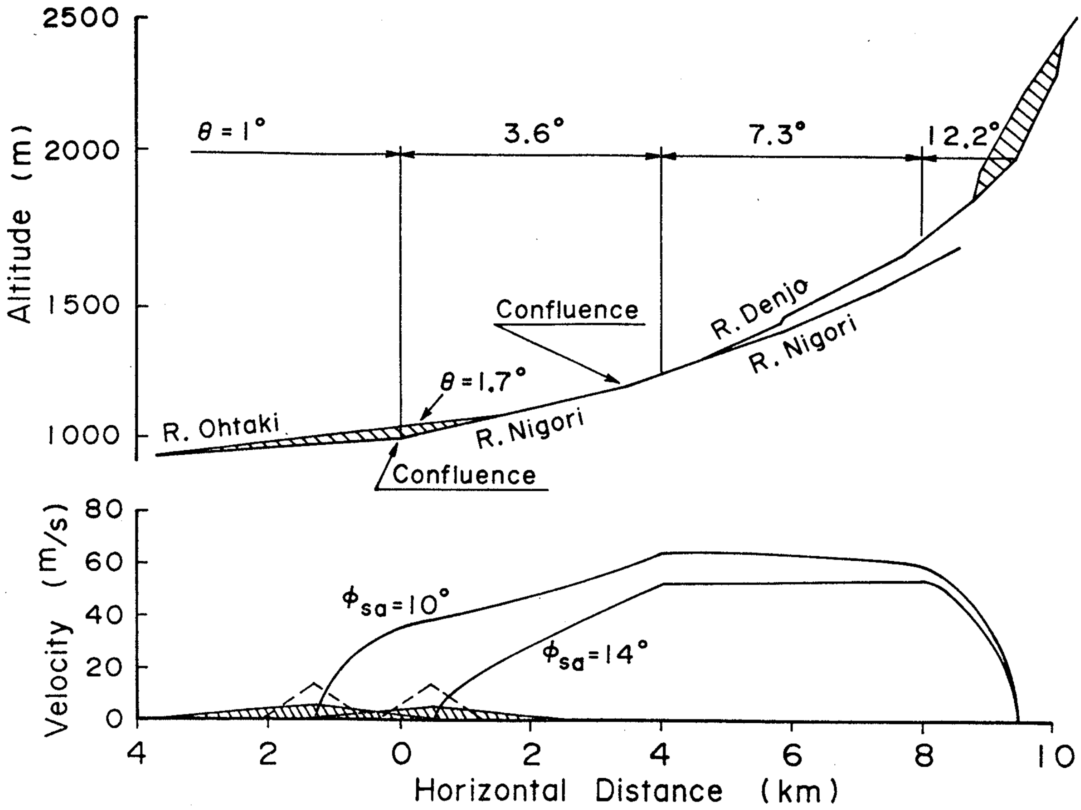

Fig. 12 Longitudinal profiles of the river beds and velocity distributions along the river courses as predicted by Eq. (14).

predicted by Eq. (14) are decelerated as soon as they enter the reach of the Nigori River. The debris flow calculated with $\phi_{sa}=14°$ comes to a halt at a section 500 m upstream of the junction of the Nigori and Ohtaki Rivers. The flow calculated with $\phi_{sa}=10°$ does not come to a halt in the Nigori River, and can continue its motion for 1.3 km more in the Ohtaki River. As compared with such calculated results, the center of deposited debris estimated from the field surveys is 200 to 300 m downstream from the junction of the Nigori and Ohtaki Rivers.

The calculation with $\phi_{sa}=10°$ overestimates the running out distance, and that with $\phi_{sa}=14°$ underestimates it. Using $\phi_{sa}=12°$, the center of deposited debris is predicted well. In addition, the time mean velocity calculated with the same coefficient yields

$$U=35 \text{ m/s}$$

versus the velocity of 20 to 30 m/s found by observation. U is defined by $\int_0^T Udt/T$, and T is the duration of debris movement.

From the viewpoint of debris motion, erosion is considered to be dominant in the area where the movement is accelerated or keep its equilibrium; whereas, deposition generally takes place during the decelerating motion. Taking such processes into account, we found that the velocity distribution of debris flow along the river course corresponds fairly well with observal pattern of erosion and deposition shown in Fig. 2.

In our calculation, we did not take into account the deformation process of the soil block. It should be noted, therefore, that the results obtained from the analysis refer to speeds and distances of center of the sliding debris mass.

5. CONCLUSIONS

The running-out process of the Ontake Land Slide have been discussed on the basis of data

from a field survey and from a theoretical analysis. The results of our study show
(1) The Ontake Land Slide occurred on the south slope, at an angle of 24 degrees. The rock fall volume of the slide debris was 3.6×10^7 m^3, the maximum length 1480 m, the maximum width 480 m and the maximum depth 136 m.
(2) The slide debris ran through the Denjo River to the Nigori River and into the Ohtaki River. During the running-out, part of the slide debris overflowed on both sides of Mt. Komikasa and at sections where the direction of river course changes abruptly, although the overflow volume is negligibly small to that of the main motion.
(3) Erosion was dominant along the reach of the Denjo River, in which the maximum depth of erosion was estimated as up to 25 m. Deposition was dominant in the reaches of the Nigori and Ohtaki Rivers, particularly in the Ohtaki River, in which the maximum width and depth were 300 and 40 m. The surface of the debris deposited in the Ohtaki river bed is a very smooth except in areas having flow mounds, and the inclination angle is 1.7°.
(4) The debris avalanche moved down along the river course in the running-out as a "debris flow" composed of solid particles and "fluid", where "fluid" implies a mixture of water and part of the solid particles. A large number of flow mounds transported by the debris flow were found in the deposited debris. These flow mounds are composed of fairly dry soil blocks, formed when the surface layer of the slide debris broke into pieces that then were transported by the debris flow.
(5) Our calculations of the critical distance for the fluidization of the slide debris indicates that the debris flow formed in the early stages of the running-out.
(6) The velocity distribution of the debris flow along the river reach was calculated by our method, on the assumption of an apparent solid-solid friction coefficient of $\phi_{sa}=10°$ or 14°. The results show that the debris flow accelerated in the upper reach of the Denjo River and attained a steady velocity in the lower reach. The debris flow decelerated in the reaches of the Nigori and Ohtaki Rivers. Our predicted behavior of the debris flow corresponds fairly well to the actual pattern of erosion and deposition.
(7) The time mean moving velocity predicted by our method compares well with the velocity estimated from the observation.

The Ontake Land Slide provides much valuable information for the study of natural disasters, but various questions about the phenomena involved remain to be answered. In the field of sediment hydraulics, further study is required to explain the phenomena from small scales to such large scales as those associated with the motion of debris avalanches, in which phase shifting is an important phenomenon.

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