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Investigation and analysis of volcanic mud flows on Mt Sakurajima, Japan

MASAYUKI WATANABE & HIROSHI IKEYA
Sabo (erosion control) Division, Public Works Research Institute, Tsukuba Science City, Ibaraki-Pref., 305, Japan

ABSTRACT Mt Sakurajima is one of the most active volcanoes in Japan and erupts frequently. Explosive material such as rocks and ash accumulates on the mountain slope and devastates the area. Volcanic mud flows occur frequently in all the rivers around Mt Sakurajima, and in the Nojiri River volcanic mud flows occur many times every year causing serious damage. Since 1975 the Ministry of Construction has been investigating the volcanic mud flows and their flow and sedimentation mechanisms. The authors describe the field investigation techniques and present examples of analysis using data obtained in the field. The field measurements and the data analysis have proved of great value in the planning and design of disaster prevention works.

Recherches et analyse concernant les écoulements de boues volcaniques sur les flancs du Mt Sakurajima (Japon)
RESUME Le Mt Sakurajima est un des volcans les plus actifs du Japon et au cours de ses éruptions fréquentes, il projette des blocs et des cendres qui viennent s'accumuler sur les pentes de la montagne et dévastent cette région par suite d'écoulements de boues volcaniques dans les rivières en particulier dans la rivière Nojiri où elle provoque de sérieux dégats plusieurs fois par an. Depuis 1975 le Ministère de la Construction y a fait des recherches sur la boue volcanique, ses mécanismes d'écoulement et de sédimentation. Les auteurs décrivent les techniques de recherche sur le terrain et présentent des exemples d'analyses utilisant les données obtenues sur le terrain. Ces recherches sont d'une grande valeur pour la planification et la mise au point d'ouvrages pour la prévention de tels désastres.

INTRODUCTION

Motion of the material which composes mud flow has been recorded by means of VTR and movie film. These records provide good sources of data on the motion and characteristics of mud flow. The authors present methods of analysis of the motion of mud flow using 16 mm movie film of the Nojiri River on Sakurajima Island; this river generates mud flow frequently every rainy season. The data which are extracted relating to the characteristics of mud flow include the velocity of the front (hydraulic bore), the velocity of the wake, the material size distribution, the particle concentration, the vectors representing the motion of boulders, the discharge and the impact force on a dam wall. It is necessary to obtain all these data for the planning and design of disaster prevention works.

OUTLINE OF SAKURAJIMA ISLAND

Sakurajima is an active volcano which rises in the centre of Kagoshima Bay in the south of Japan and forms a small conical peninsula with an area of about 80 km^2 and a circumference of about 52 km (Fig. 1). The volcano consists of three peaks,

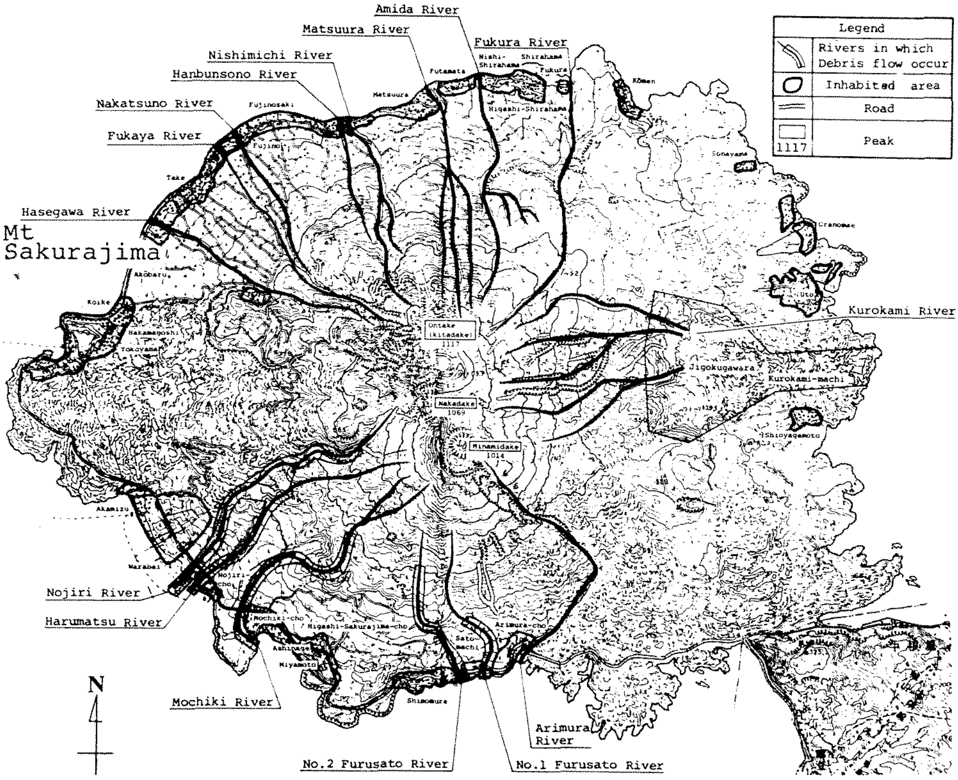

Fig. 1 Rivers on Mt Sakurajima.

namely, the Kitadake peak (1117 m), the Nakadake peak (1069 m) and the Minamidake peak (1014 m). The Minamidake peak is the only one which is still volcanically active. The summits and their vicinities are denuded and rugged due to the volcanic activities. The mid-slope area is composed of lava and covered with forest.

About 85% of the total area of Sakurajima lies within the Kirishima-Yaku National Park and the spectacular sight of the volcano is nationally famous. The area has a population of around 11 000.

Volcanic activities

Sakurajima island has an active volcano that belongs to the Kirishima volcanic zone. Ancient records show that the island came into being following the upheaval of a submarine volcano in 708 AD. Since the beginning of 1972, a third phase of volcanic activity has been going on following a first phase which began with the ejection of lava in 1946. It has been known empirically that there is a close relationship between the eruptions of Sakurajima and the occurrence of volcanic mud flow. Table 1 shows the volcanic activities from 1965 to 1975.

Table 1 Volcanic activity on Mt Sakurajima 1965-1975

Year	Frequency of eruption	Frequency of smoke emission	Frequency of earth tremors	Year	Frequency of eruption	Frequency of smoke emission	Frequency of earth tremors
1965	29	36	10 304	1971	10	45	10 974
1966	44	225	17 077	1972	108	485	31 956
1967	127	511	35 174	1973	144	673	74 878
1968	87	351	30 384	1974	362	1 226	122 805
1969	22	128	16 801	1975	198	694	73 297
1970	19	355	18 264				

Table 2 Rivers on Mt Sakurajima

Rivers	Basin area (km²)	River length (km)	Rivers	Basin area (km²)	River length (km)
Nojiri	2.99	5.4	Fukura	3.24	3.3
Harumatsu	2.09	4.3	Amida	2.94	2.8
Mochiki	1.61	4.5	Matsu-ura	2.28	4.5
No. 2 Furusato	1.40	2.9	Nishimichi	3.56	5.0
No. 1 Furusato	0.86	3.0	Hanbunzono	0.56	1.5
Arimura	3.65	3.8	Nakatsuno	0.51	2.0
Kurokami	9.80	5.9	Fukatani	3.55	3.5
Total	22.40	29.8	Hase	4.04	4.0
			Total	20.68	26.6

Rivers in Sakurajima

Sakurajima has 15 rivers, most of which originate near the mountain tops and flow into the Bay of Kinko (Table 2). These rivers usually run dry. Erosion control works have been carried out in 11 of the river basins since 1946.

As a result of the geological and topographical conditions, drastic longitudinal, lateral and surface erosion are evident at all times at altitudes greater than 400-500 m. When it rains the mud flow is flushed down the U-shaped valleys as an earth and rock avalanche, wearing away the sides of the valleys, and dispersing only when it reaches an altitude of 200-100 m. Although the rivers on Sakurajima are small (Table 2), they have vast sources of earth and sand, so that debris flow is liable to occur quickly in every heavy rainstorm, and the river bed gradients change so abruptly that the debris is liable to cause flooding and serious damage to river structures. For example in July 1977 a mud flow breached the right hand side of the Nojiri River No. 3 Dam; on 10 July 1977 a huge boulder (major and minor axes of 7 and 5 m respectively) weighing about 240 t was carried down the Nojiri River to the location of some channel works.

VOLCANIC MUD FLOW AND DISASTERS

The residents and crops of Sakurajima and its vicinities are hard hit every year by a tremendous volume of volcanic ash and cinders, and the damage has been increasing year by year. On top of that, disastrous mud flows frequently occurred in the rivers due to the accumulation of ash and the increased volume of earth and sand produced by frequent collapses of the mountainsides, which were so big as to change the shape of the mountain (Table 3). Houses and public facilities have sometimes been damaged by mud flows, and in 1974, a mud flow claimed the lives of eight persons. Erosion control works to prevent such mud flow disasters have been under the administration of the Government of Kagoshima Prefecture since 1946, but in 1976 such works came under the direct control of central Government.

Table 3 Frequency of mud flows

River	1973	1974	1975	1976	1977
Nojiri	12	16	24	24	11
Harumatsu	—	—	3	4	4
Mochiki	—	—	4	4	6
No. 2 Furusato	—	—	3	2	4
No. 1 Furusato	—	—	4	3	6
Arimura	—	—	3	4	7
Kurokami	—	—	2	3	5

Table 4 Hydraulic data of mud flows (Nojiri River)

Date	Effective rainfall intensity ($mm\ h^{-1}$)	Maximum water level (m)	Maximum velocity ($m\ s^{-1}$)	Maximum discharge ($m^3\ s^{-1}$)	Total amount of mud flow ($\times 10\ m^3$)
8 April 1975	6.2	2.0	11.5	207	94.0
17 April 1975	6.0	3.2	13.6	476	194.1
29 April 1975	31.3	2.4	7.8	181	61.2
4 June 1975	9.7	2.8	10.0	287	121.2

INVESTIGATION SYSTEMS

Investigations on volcanic mud flow have been conducted on the Nojiri River since 1974 (Tahara, 1976). The location of mud flow observation systems is shown in Fig. 1. In addition to the data shown in Table 4, the grain size distribution (d_{60} = 0.4-1.0 mm) and the density (1.81-1.95) of the mud flow were obtained. Also, actual mud flows were recorded in detail by video tape recorder.

METHOD OF ANALYSIS

The analyses (Ikeya, 1979) were performed on four mud flows occurring in three rivers, namely the Nojiri River, the No. 2 Furusato River and the Arimura River; every mud flow was photographed on 16 mm film by the staff of the Ohsumi Construction Work Office, Ministry of Construction. These films are sufficiently accurate for analysis because a fixed point was used as an index of distance and the camera position was also fixed.

Projection and drawing from 16 mm cine film The projector used was a Bellhauel TQIII 1698, the distance between projector and screen was 260 cm, the size of picture 40 x 50 cm and the speed 24 frames per second. For drawing the motion of mud flows, large boulders were traced on a white paper screen by repeating a few frames several times.

Grid setting A scale is necessary for the measurement of the mud flow velocity and the diameter of large boulders. The authors set up a 1 m grid on the projection screen. The correlation between the scale and the grid is easily determined by a staff gauge at the riverbank which appears in the film.

(a) Cases 1 and 2 in the Nojiri River (Figs 2 and 3) are events which occurred on 8 and 17 April 1975. At a site 500 m from the estuary of the Nojiri River, the channel is straight and there are two gauging marks for discharge observations 30 m apart on the left bank (Fig. 4), so that it is possible to set up the grid accurately. The grid setting mechanism is as follows: in Fig. 4 the angles between the gauging marks and the bed girdle and the distance between the gauging marks and the camera are given by equations (1), (2) and (3):

$$\theta_1 = \tan^{-1}\left[(x + x_a + x_b)/12\right] \tag{1}$$

$$\theta_2 = \tan^{-1}\left[(x + x_b)/12\right] \tag{2}$$

$$\theta_3 = \tan^{-1}(x/12) \tag{3}$$

(since the perpendicular distance from the camera to the left bank of the channel is 12 m). Thus, if the distance on the projection screen between the No. 1 gauging mark and the bed girdle is A, and the distance between the bed girdle and the No. 2 gauging mark is B,

$$\frac{A}{B} = \frac{\tan^{-1}\left[(x + x_a + x_b)/12\right] - \tan^{-1}\left[(x + x_b)/12\right]}{\tan^{-1}\left[x + x_b)/12\right] - \tan^{-1}(x/12)} \tag{4}$$

Substituting the values of A and B measured from the projection screen into equation (4), the unknown x may be found. For case 1, B/A = 32.5/16.4 and x = 33.5 m and for case 2, B/A = 23.2/11.6 and x = 33.0 m. Following this, the angles θ_1, θ_2, and θ_3 may be determined, enabling the distances between the gauging marks to be related to the 1 m grid on the projection screen.

(b) Case 3, an event on the No. 2 Furusato River on

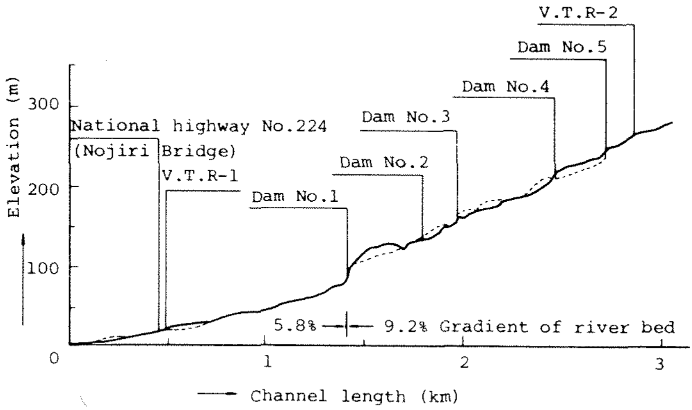

Fig. 2 Location of mud flow monitering equipment on the Nojiri River.

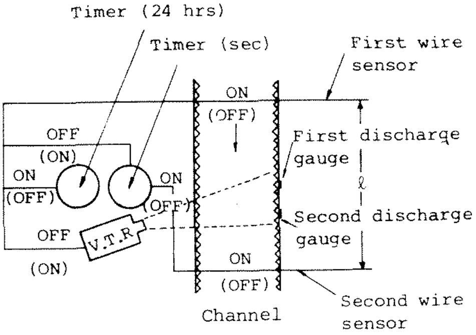

Fig. 3 Observation system.

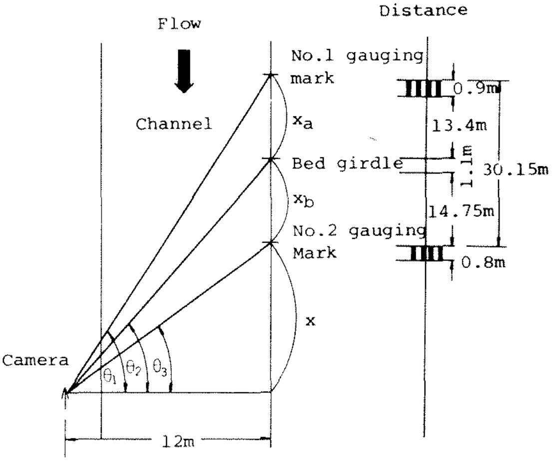

Fig. 4 Nojiri River observatory (500 m from river estuary).

17 September 1975. A mesh was set up at the site of the entrance to a box culvert which has a 1/500 scale plane and 1/100 longitudinal section and which had already been surveyed by the Ohsumi Construction Work Office.

(c) Case 4, an event on the Arimura River on 17 September 1975. At a point 300 m from the estuary of the Arimura River there are three gauging marks for discharge observations at 20 m intervals, but their alignment is curved, so that the grid method used for the Nojiri River is unsuitable. In this case, the scaling factor r is found from lengths on the plane, and the grid interval follows from this.

RESULTS

Front velocity of mud flow and its plane shape The front velocity of the mud flow (cases 1, 2 and 4) was measured by film frame numbers as it passed two gauging marks. The front velocity for case 3 was determined using Rand's formula for a drop structure (Henderson, 1966). The results were as follows:

Case	*Front velocity* ($m\ s^{-1}$)	*Wake velocity* ($m\ s^{-1}$)
No. 1	12.7	13.2
No. 2	13.0	12.3
No. 3	6.5	-
No. 4	4.8	7.4

The plane shapes of the mud flow fronts were also of interest, as these are not generally known at present. These shapes are illustrated in Fig. 5.

The front velocity for mud flow in the Nojiri River is more than twice that in the Arimura River. In the case of mud flow in the Nojiri River, there is no concentration of large boulders but

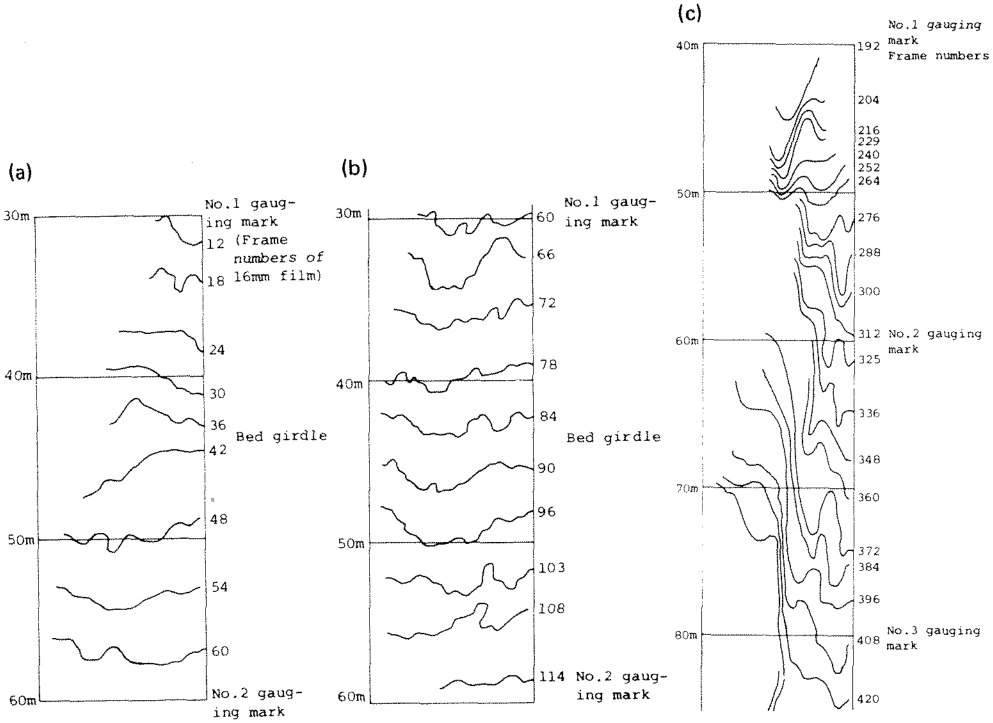

Fig. 5 Plane shape of mud flow fronts: (a) case 1, Nojiri River; (b) case 2, Nojiri River; and (c) case 4, Arimura River.

it does have a hydraulic bore. On the other hand, in the case of mud flow in the Arimura River, there is a bore with large boulders. Therefore it is suspected that the type of material in the mud flow affects its velocity. In the case of the No. 2 Furusato River, the velocity lies between that in the Nojiri River and that in the Arimura River, and there are few boulders but many cobbles in the flow, therefore the mud flow in the No. 2 Furusato River is similar in type to that in the Nojiri River. Here, the difference in velocity may be caused by the effects of river characteristics such as the river bed slope. Comparing the velocity values which had already been observed at each river (Tahara, 1976; Ikeya, 1979) with the calculated velocities, the data for the Nojiri River agree very well, but calculated velocities for the Arimura River and the No. 2 Furusato River are slightly less than the observed values.

In Figs 5(a) and (b), the plane shape of the mud flow front in the Nojiri River shows parallel movement of the front line, due to a constant velocity at the front as would be found in viscous flow. Comparing front velocities at ¼ s intervals, case 2 shows a constant value (about 12 m s^{-1}), but in case 1 the flow velocity varies between 5 and 20 m s^{-1}. This is a phenomenon which requires further research. In the Arimura River, in case 4, the mud flow did not occupy the complete width of the channel (Fig. 5(c)), and the front velocity was affected by the movement of large boulders.

Velocity of wake There are few data about the velocity of the wake, because the measurement of the wake is difficult. However, many disasters were in fact due to the wake, so it is desirable to determine the wake velocity. Therefore, the authors measured the wake velocity from pieces of wood and waves on the surface of the flow (see Table 4). These results show that the wake has a higher velocity than the front, so it is clear that large quantities of sediments flowed down with the wake. This method of measurement is not very accurate because of errors caused by vertical movements of the wood, therefore further research is required.

Distribution of gravel sizes and velocities of large boulders There are no data relating to the distribution of gravel diameters in mud flow, apart from those at Mt Yakedake, where it is easy to take measurements, because the flow consists of debris which does not have such a high velocity, being composed of gravels and boulders. It is difficult to measure the distribution of gravel diameters in mud flow, because mud flow has a high velocity and it is not easy to see the gravels and boulders contained in it. Table 5 shows the number of gravels and their shapes in a sample of about 44 m^3 from a mud flow front; these data give valuable information about the specific gravity of a mud flow.

It is useful to know the vector of motion of moving boulders when collecting data relating to the impact force of boulders on some structures. In the Arimura River (case 4) the velocity of boulders and their course of movement were measured in a similar manner to the mud flow (Fig. 6). The maximum velocity observed for a boulder with a diameter of 1 m was about 8-16 m s^{-1}, and this boulder moved at a fixed speed in the flow. In contrast, a boulder with the same diameter which was out of the flow stopped in a short distance. The direction of motion of the boulders was parallel to the flow direction.

Water depth and discharge The water depth can be measured using the grid projection; the discharge of mud flow front may then be calculated from the water depth of the mud flow, the velocity data described above, and the cross section of the river as shown in Table 6. Compared with values which have been measured previously, the values for case 1 and for case 4 agree

Table 5 Gravel size data (No. 2 Furusato River: 44 m^3 sample)

Data no.	Major axis (m)	Minor axis (m)	Data no.	Major axis (m)	Minor axis (m)
1	1.2	0.5	15	0.5	0.3
2	1.0	0.5	16	0.5	0.4
3	0.8	0.4	17	0.7	0.5
4	1.2	0.4	18	0.7	0.4
5	1.1	0.7	19	0.7	0.4
6	0.9	0.6	20	0.7	0.4
7	1.1	0.6	21	0.7	0.5
8	0.5	0.3	22	0.8	0.4
9	0.6	0.4			
10	0.8	0.6	Mean diameter	0.75	0.43
11	0.4	0.2			
12	0.8	0.3	Median diameter		0.59
13	0.3	0.2			
14	0.6	0.4			

Table 6 Water depth and discharge

Case no.	Water depth (m)	River width (m)	Velocity (m s^{-1})	Discharge (m^3 s^{-1})
1	2.4	9.3	12.7	284
2	2.3	10.0	13.0	299
3	0.8	3.8	6.5	20
4	2.2	4.5	4.8	48

Table 7 Calculated impact force of mud flows

	Mud flow front		Large boulders		
Case no.	Velocity of mud flow (m s^{-1})	Impact force (t m^{-2})	Diameter of large boulders (m)	Velocity of large boulders (m s^{-1})	Impact force (t weight)
1	12.7	64.5	–	–	–
2	13.0	67.6	2.4	4.95	1 803
3	6.5	16.9	1.2	6.5	633
4	4.8	9.2	2.1	4.9	1 381

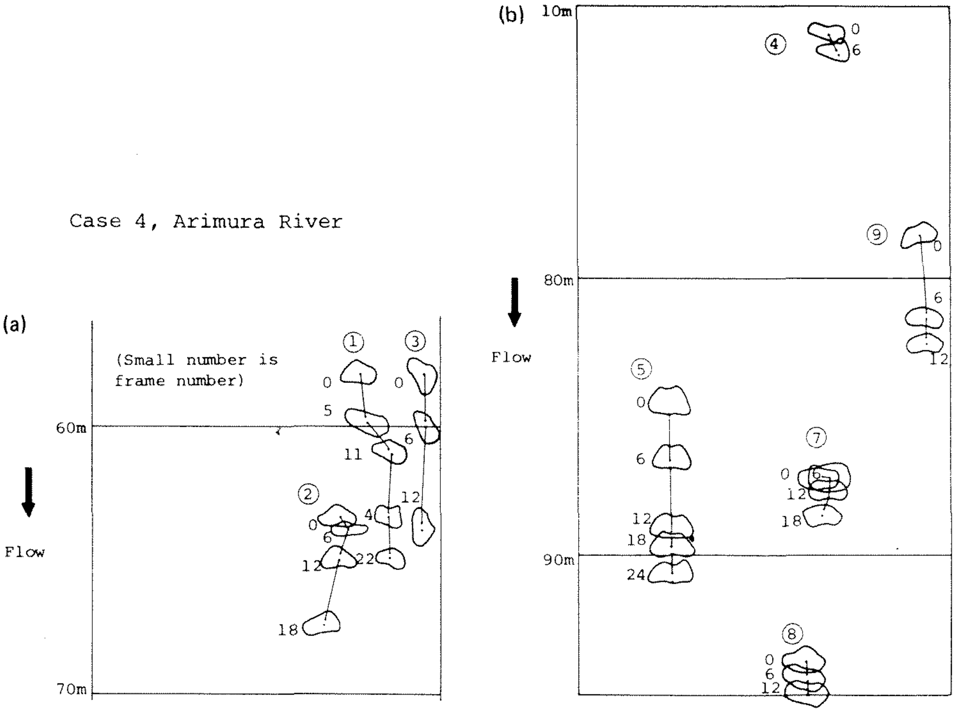

Fig. 6 Vector of motion of moving boulders.

very well, but the value for case 2 was only 68% of that given in earlier data and the value for case 3 was 30% of the corresponding measurement.

Impact force of a mud flow

(a) Impact caused by mud flow front. The impact force of a mud flow front is given by

$$P = K\ (wv^2/g) \tag{5}$$

where P is impact force, w is density of flow, v is velocity, g is gravitational acceleration, and K is a coefficient. K changes with flow material, for clear water K has been found to be between 1 and 2, and for bentonite, K = 2. In this analysis the authors assumed K = 2 and the density of flow w = 1.95 was taken from a field survey (Tahara, 1976). Thus equation (5) may be written as

$$P \doteq 0.4v^2 \tag{6}$$

Results of calculations for each river are shown in Table 7. The value for the Nojiri River is about 70 t m^{-2}, and this is reasonable for the impact force of a mud flow front, as it is 4 times the impact force due to a jet flow.

(b) Impact caused by large boulder. Using the impact theory of elastic bodies it can be shown that (Okuda, 1978):

$$P_{max} = 1.92\ (\rho s + \frac{\rho w}{2})^{3/5} \cdot (K_1 + K_2)^{-2/5} \cdot R_i^2 \cdot v^{6/5} \tag{7}$$

where, ρs is density of boulder, ρw is density of fluid containing boulders, K_1 is modulus of elasticity of boulders, K_2 is modulus of elasticity of the structure, R_1 is radius of boulder, v is velocity of boulder, and P_{max} is maximum impact force.

From this, supposing $\rho s = 2.65$ g cm^{-3}, $\rho w = 1.95$ g cm^{-3} (both from a field survey of the Nojiri River), $K_1 = K_2 = 1.18 \times 10^{-12}$ cm s^2 g^{-1} (from Okuda, 1978), the impact force of a large boulder was calculated as shown in Table 7. The impact force from a large boulder thus calculated is very large, but this is because equation (7) results from the assumption that the boulder and the structure are perfectly elastic bodies, leading to an overestimate of the force. Takahashi (1971) has reported that the impact force of a hydraulic bore is about twice that of a jet flow, but the impact force of a boulder is about 6 times that of a jet flow. The velocity of a large boulder is smaller than that of a mud flow but the impact force of a boulder is large even if it is not a perfectly elastic body. If the mud flow includes large boulders as in the case of mud flows in the Arimura River, it is necessary to consider sufficiently large impact forces from large boulders when designing structures.

Table 8 summarizes the results.

Table 8 Results of analyses

Case no.	Discharge (m^3 s^{-1})	Velocity (m s^{-1}) upper : front lower : wake	Water depth of mud flow front (m)	Impact force upper : front (t m^{-2}) lower : large boulder (t weight)	Distribution of gravels and flow condition
1	284	12.7 13.2	2.4	64.5 —	There are no large boulders at the front, and boulders flow down in the wake
2	299	13.0 12.3	2.3	67.6 1 803	Large boulders (ϕ = 2.4 m) flow down in the wake
3	20	6.5 —	0.8	16.9 633	Boulders in the front and the wake, and drift wood also in the flow
4	48	4.8 7.4	2.2	9.2 1 381	Big boulders in the front and in the wake

CONCLUSIONS

(a) Using 8 mm or 16 mm cine film, the front velocity, the water level of the front (hydraulic bore) and the diameter of a boulder and its vector of motion may be measured accurately; other factors such as the wake velocity and the distribution of gravels may be estimated with less accuracy.

(b) The mud flow discharge, the impact force of the front and the impact force of a large boulder may be analysed using measured factors. In particular, the mud flow discharge and the front impact force are adequate for use in the design of structures, but the impact force of a large boulder is not sufficiently well modelled to be used with certainty.

(c) The front velocity of mud flows in the Nojiri River is about 13 m s^{-1} and the discharge about 300 m^3 s^{-1}.

(d) Large boulders which moved in the same direction as the main stream of mud flow give a large impact force on structures.

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