Study on Shearing Force and Impact Force of a Volcanic Mud Flow on Mt. Sakurajima[1]

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Abstract: Two kinds of shearing stress meters (type A and type B) were set on the channel bottom in the Arimura River and the Mochiki River on Mt. Sakurajima. Volcanic mud flows take place there about 100 times a year. The results of the surveys demonstrated that the actual shearing force of a volcanic mud flow on Mt. Sakurajima was from 0.46 to 2.50 kgf/cm^2. The actual impact force caused by collisions of big stones, which were contained in a mud flow, with the channel bottom was calculated theoretically at about 15 times greater than the dead loads of the stones. The collision of stones in a mud flow caused great abrasion of concrete.

A great number of volcanic mud flows take place every year on Mt. Sakurajima in spite of little rainfall. They often damage both dams and channels, and also threaten the inhabitants of Sakurajima. In this study, the magnitude of the actual shearing force of a volcanic mud flow was researched in order to make clear the mechanism of the destruction and the abrasion of a dam or a concrete channel in torrents of Mt. Sakurajima. The data were analyzed by the theories of hydraulics and the collision of an elastic body. The cause of destruction and the abrasion of a dam or a concrete channel by mud flows could be clarified to some extent from the results of these surveys.

SEDIMENT YIELD ON MT. SAKURAJIMA

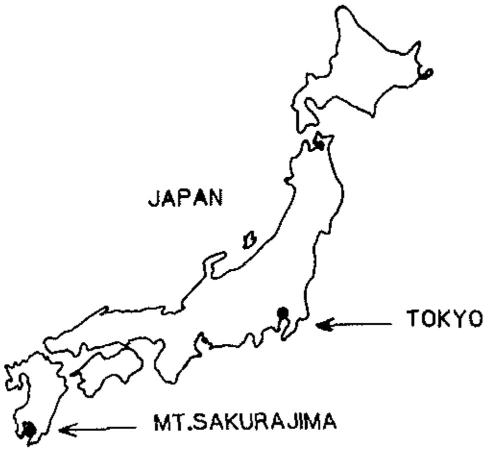

Fig. 1 Map of Japan

Mt. Sakurajima, which lies in the southern part of Japan (Fig. 1), is one of the most active volcanoes in Japan. It is located in Kagoshima Bay and has an area of 80 km^2 and circumference of 52 kilometers. There are three craters on Mt. Sakurajima: Kitadake Crater (1117 meters above sea level), Nakahake Crater (1060 meters), and Minamidake Crater (1040 meters). Minamidake Crater is currently erupting vigorously. Table 1 shows the volcanic activities of Mt. Sakurajima for the past 20 years (Osumi Public Works Office, 1986).

Lately the baring of mountain slopes has been making conspicuous progress on Mt. Sakurajima in line with the vigorous volcanic activities. The baring of the slopes has been caused by both the effect of fall from the eruptions and the action of sulphur gas from smoke emissions of the Minamidake Crater. The receding of vegetation on the slopes in the upper reaches of each torrent has continued on Mt. Sakurajima, and the baring of the g downwards year by year. A number of gullies have formed on the slopes. These slopes have been suffering from rapid erosion, and they have been producing a great amount of sediment for the last 20 years. Fig. 2 shows a picture of the slopes around the Kitadake Crater. There is no vegetation in this area, and many rills and small gullies have already formed on the slope.

Some of the geomorphological factors in reference to mud flows were analyzed by

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Table 1 Volcanic activities of Mt. Sakurajima

	number of occurances		
year	eruptions	smoke emissions	earthquakes
1965	29	36	10312
1966	44	225	17117
1967	127	511	35174
1968	37	351	30383
1969	22	128	16801
1970	19	355	18264
1971	10	45	10974
1972	108	483	31949
1973	144	673	74883
1974	362	222	122795
1975	199	709	73297
1976	176	490	64055
1977	223	447	83491
1978	231	478	88334
1979	149	307	77261
1980	277	472	37338
1981	233	188	22182
1982	413	641	29402
1983	332	388	54032

using both a series of serial photographs from 1947 to 1984 and the report on the sediment yield on the slopes of Mt. Sakurajima (Osumi Public Works Office, 1988). These results are shown in Figs. 3-6.

Fig. 3 shows the expansion of the total area of these gullies in the 38 years from 1947 to 1984. The increase in their total area in the 26 years from 1947 to 1972 is less than that in the period since 1974. Volcanic activity became very vigorous after 1974. This fact shows that there should be a relationship between the number of mud flows and the volcanic activity since 1974. The same tendency also exists in the length of gullies (Fig. 4). This **proves that the gullies have been considerably extended, and they have also expanded in width by the failure of** sidewalls over the last 10 years (Fig. 5). An average rate of the expansion of the gullies in the 20 years from 1947 was only 0.13 m/yr. On the other hand, it increased to 0.76 m/yr in the 8 years from 1966. The latter is 5.9 times greater than the former. However, it has decreased since 1980, because fresh gullies began to form on the slopes. Fig. 4 shows the great extension of gullies. The number of gullies increased conspicuously in the 20 years from 1947 to 1966 (Fig. 6). This means that the formation of gullies had already ended during these years. Most of the sediment yield on Mt. Sakurajima is caused by the extension and the expansion of gullies. The volumetric rate of the sediment yield by the extension of gullies is 41 percent of the whole, and the expansion of them is 59 percent.

Fig. 2 Gullies on the slope of Mt. Sakurajima

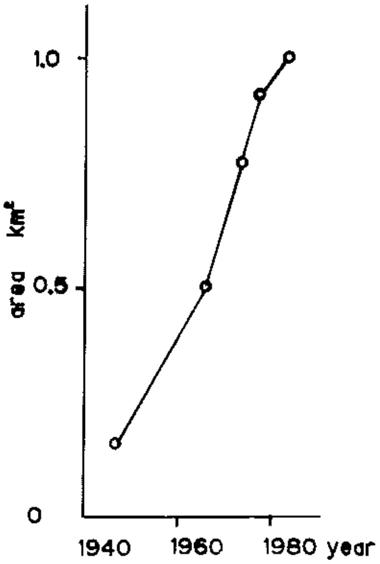

Fig. 3 Expansion of gullies

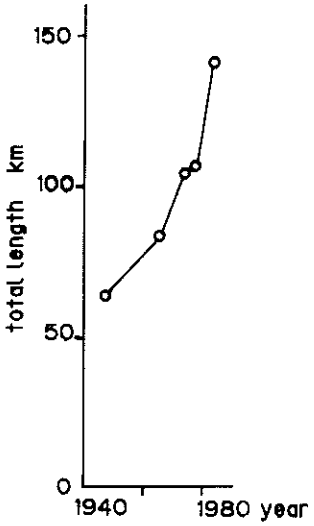

Fig. 4 Increase of total length of gullies

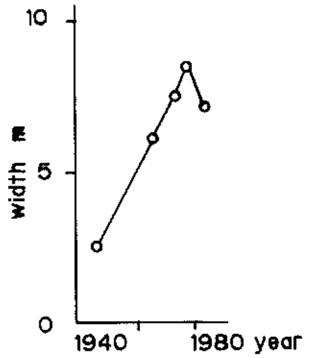

Fig. 5 Change of gully width

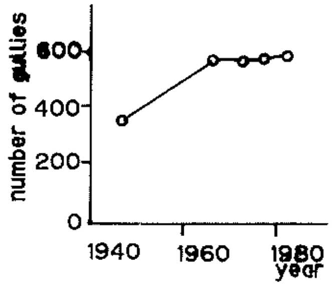

Fig. 6 Increase in number of gullies

SURVEYING METHOD

A survey of the shearing force of a volcanic mud flow acting on a channel

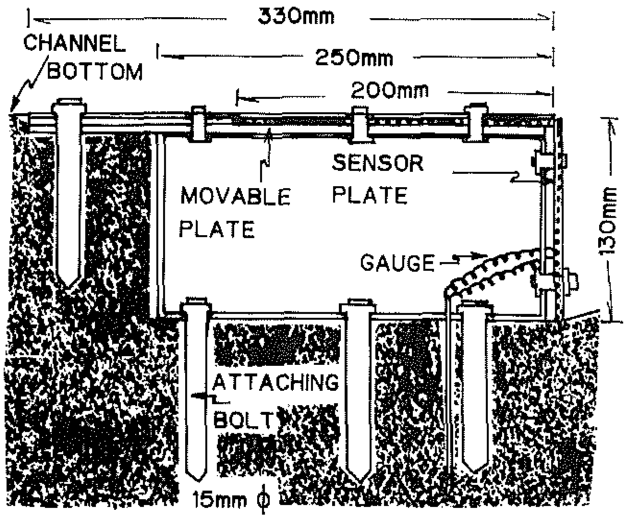

Fig. 7 Shearing stress meter (type A)

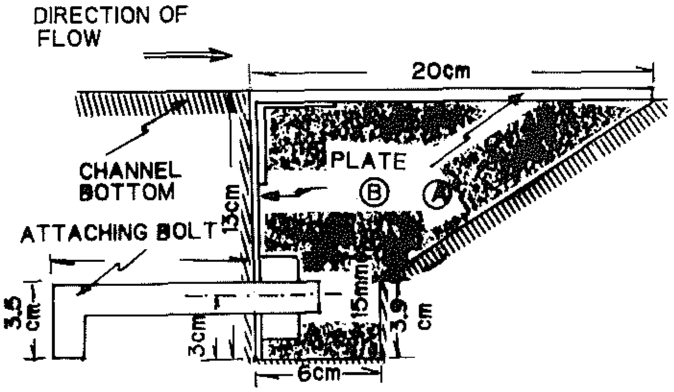

Fig. 8 Shearing stress meter (type B)

bottom has been going on in the Mochiki River since 1987 using the two kinds of shearing stress meters shown in Fig. 7 (type A) and Fig. 8 (type B). No data have been obtained from the type A survey up to the present, but some data have been gotten from the type B. In the type B, plate A is trailed downstream by the shearing force acting on its surface, and plate B is bent by the shearing force. As a result, a bending moment is generated in plate B. There should, however, be a balance between the shearing force and the bending moment. Accordingly, the shearing force acting on plate A (the channel bottom) can be easily measured by the magnitude of its deflection based on the theory of the deflection of a cantilever. The change in shearing force cannot be measured every time by this method, but the maximum shearing force can be easily measured using this meter.

When a dead load of 56.8 kilograms was applied to this shearing stress meter (type B) for the calibration of observed values, the average deflection of plate B was 8 millimeters. This meter is limited by the fact that plate B can not recover from its deflection, because a space caused by the bending moment forms between plate B and the wall of concrete to which plate B is attached (Fig. 8). This space is inevitably filled up by soil and sand which are contained in a mud flow whenever one runs down on plate A. On account of this, plate B of this meter cannot avoid increasing in deflection, whenever a bending moment acts on the plate. Of course, this happens on condition that the deflection is within the proportional limit of the strength of the material of which the plate is made.

SURVEYING RESULTS

Table 2 shows the volumetric concentration of the mud flow samples collected by the author in the Arimura River on July 18, 1987 in order to investigate the change of composition of a mud flow (Taniguchi and Takahashi, 1989).

The observed values of the shearing forces of several mud flows are shown in table 3. Some velocities of the mud flow, and the diameters of the stones in it are shown in table 4. They were measured on a video tape recorded by Osumi Public Works Office on September 24, 1988. One huge stone in the mud flow is shown in Fig. 9. These pictures were taken from that video. Fig. 10 is a picture of the measurement of the deflection of plate B in the Arimura River after the occurrence of the mud flow on October 6, 1988. No great number of huge stones gathered together at the front of that mud flow was observed.

Table 2 Grain size distribution and concentration of mud flow on July 18, 1987

	Collection Time		
	10 min.	15 min.	30 min.
grain diameter	distribution rate --------(pct)-------		
over 2000 $	1.0	1.0	2.9
840	3.5	3.1	7.7
500	5.8	6.9	12.9
250	22.2	22.4	32.5
105	58.9	52.2	37.0
74	6.2	4.1	5.1
37	2.2	4.	1.8
under 37	0.2	0.2	0.1
concentration (pct)	15.6	32.0	34.3
density (g/cm^3)	1.11	1.25	1.27

Table 3 Observed shearing forces of mud flows

date observed	shearing force kgf/cm^2	river
09/24/88	2.13	Arimura
10/06/88	0.462	Arimura
02/17/89	1.402	Arimura
02/17/89	2.502	Mochiki

Table 4 Stones' diameters in the mud flow on September 24, 1988 and their velocities.

stone	diameter (cm)	velocity m/sec
1	118	2.03
2	133	1.75
3	125	4.24
4	173	3.21
5	163	3.82
6	175	9.06
7	138	8.83
8	250	8.09
9	163	7.99
10	388	6.25

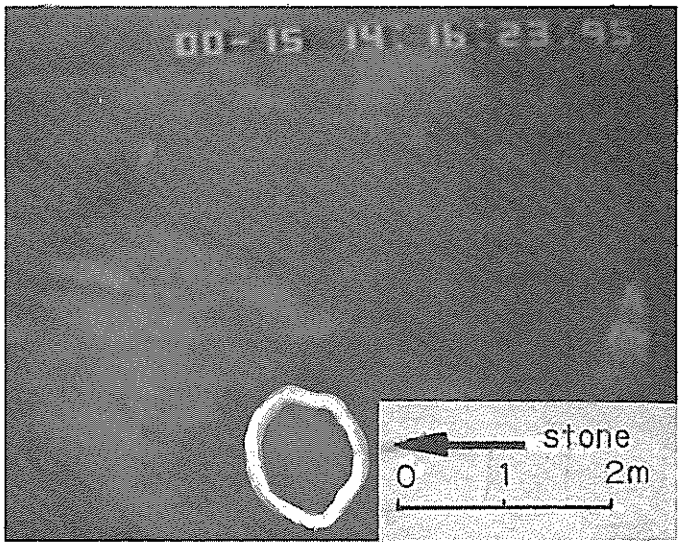

Fig. 9 **Huge stone in the mud flow on September 24**

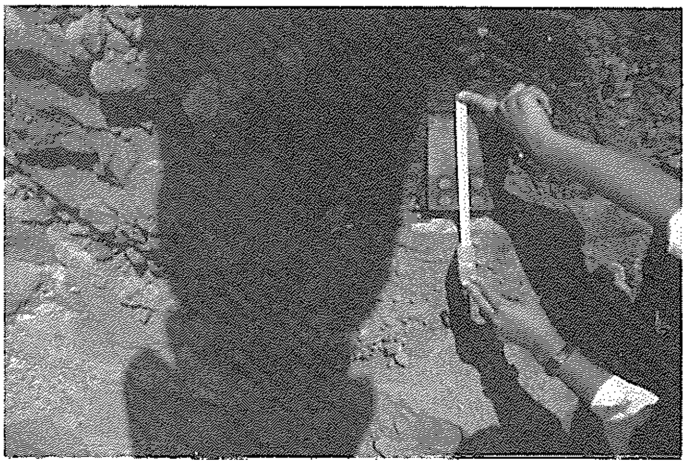

Fig. 10 **Measurement of shearing force of a mud flow**

DISCUSSION

The type B shearing stress meter is structurally a kind of cantilever. According to the theory of cantilever deflection, there should be a linearity between the shearing stress (τ) and the maximum deflection (δ) of the plate:

$$\delta \sim \tau \qquad (1)$$

If it is supposed that the magnitude of the shearing stress (τ_0) already known acts on the shear plane (plate A), and that the deflection of plate B is δ_0, there should be the following relation between τ, τ_0 and δ, δ_0, using expression (1):

$$\tau / \tau_0 = \delta / \delta_0 \qquad (2)$$

The shearing stress meter was tested by a dead load of 56.8 kilograms. As a result of that, the mean value of the deflections (δ_0) was 8 millimeters in the load test. When the above value of 8 millimeters is substituted into equation (2), the following is obtained:

$$\tau = 0.357\ \delta \qquad (3)$$

Some data (δ= 6.0 centimeters, 1.3 centimeters and 4.0 centimeters in the Arimura River mud flow which took place on September 24, 1988, October 6, 1988, and February 17,1989, and 7.0 centimeters in the Mochiki River mud flow on February 17, 1989) were obtained. When these values were substituted into equation (3), the results of computations were shown in table 3 above.

It is, however, doubtful whether a linearity between these shearing forces and deflections of the plate might strictly exist in this case, because these observed deflections are conspicuously large.

However, seeing that these deflections began to occur in the test when the acting load had gone over 57 kilograms, it was evident that a shearing force at least greater than 0.29 kgf/cm^2 acted on the shear plane.

The shearing force of a mud flow acting on a channel bottom can be expressed as follows, taking the flow model of a mud flow shown in Fig. 11 into consideration:

$$\tau = \rho_D gH\sin\theta \qquad (4)$$

where ρ_D is the density of a mud flow; H is its water height; and θ is the angle of the channel slope. When the actually observed values of a density of 1.27 g/cm^3 and a water height of 1.0 meters in the mud flow of the Arimura River on July 18, 1987 are substituted into equation (4), the shearing stress (τ) becomes about 9 gf/cm^2. The computed value from equation (4) cannot prove that a large shearing stress as great as 0.5 ~ 2.5 kgf/cm^2 should occur even if there is a very large scale of a mud flow. Judging from that, it can be inferred that such a large shearing stress must be caused by the friction between stones and the channel bottom, because these stones are dragged along the channel bottom at a rather high speed.

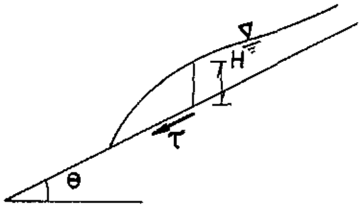

Fig.11 Flow model of a mud flow

Using the actual shearing force acting on the channel bottom, the size of a stone contained in the mud flow which took place in the Arimura River on September 24, 1988 could be estimated. When it was supposed that the density of a stone was 2.7 g/cm^3 and its frictional coefficient was 0.7, the size of a stone corresponding to the above shearing force of 2.13 kgf/cm^2 was calculated at about 60 centimeters in length for one side of a cube, or about 80 centimeters in the diameter of a sphere. Many stones corresponding to such sizes were observed on the video. Judging from that, it can be seen that the calculated value of the size of a stone is proper compared with the actual sizes. However, the maximum size of a stone in the Arimura River mud flow on September 24 was 3.8 meters. This proves that the concept of shearing force in the case in which a mud flow is regarded as only a fluid like water cannot be used for the solution of an actual problem like the abrasion of a concrete channel bottom.

When a mud flow accompanied by many stones flows on a channel bottom, its abrasion is very conspicuous, because the stones are dragged along the channel bottom. A great friction between the surface of the channel bottom and stones is generated.

The hydraulic drag force of a stone (a perfect cube or sphere) in fluid can be expressed as follows:

$$F = (1/2)\ C_D\rho_D\ V^2A \qquad (5)$$

where F is the drag force; C_D is the coefficient of the drag force; V is the relative velocity between fluid and a stone; and A is the area of the application of the drag force. The value C_D became about 8 from the results of the computations on the mud flow which took place on July 18, 1987 in the Arimura River.

Supposing that C_D was 8, the density of a mud flow was 1.27 g/cm^3 (the value in table 2), the stone's diameter was 3.8 meters (the maximum diameter in the mud flow on September 24, 1988 in the Arimura River), and the relative velocity was 5.1 m/sec., the drag force of the mud flow could be estimated at 50 tons by equation (5). On the other hand, the frictional resistance of a stone on the channel bottom is estimated at 40 ~ 50 tons, using the value 0.76 as the coefficient of its friction. Judging from the above result, it can be seen that a mud flow with a water height of about 1 meter and a relative velocity of about 5 m/sec can easily carry a huge stone as large as 3 meters in diameter. The great friction is caused by many stones dragged along a channel bottom by a mud flow. There is another report that the temperature rose about 0.5 ~ 1.5°C in the Mochiki River when a mud flow ran down in the channel (Hirano, 1989). This shows that the frictional heat stated above might have a relation to the friction which was generated between the concrete channel bottom and the stones.

A mud flow also has the same characteristic as a debris flow. It greatly vibrates the earth around the stream when it flows at a high speed. The vibration is caused by the collision of stones with the concrete channel bottom or sidewalls of the stream. There are some reports that the vibrations caused by collisions between huge stones and the channel bottom have accelerated slope failures along torrents. This collision is also another important factor in the destructive damage of dams or concrete channels in torrents. The vibration caused by the collision of a huge stone in a mud-debris flow was surveyed on the slopes of Mt. Yake in order to estimate the occurrence of a slope failure when the flow ran down in a torrent. An acceleration of 0.1 gal was observed at a point 15 meters from the centre of the torrent in cross section (Matsumoto Public Sabo Works Office, 1975). There might have been a great vibration near the centre. This problem should be taken into consideration to prevent dams or channels from being damaged in torrents.

The relationship between the strength of the concrete of a channel and the abrasion caused by the collision of stones contained in a mud flow is unclear even now. The impact force caused by the collision of an elastic body with concrete can be expressed as follows (Okubo, 1963):

$$(\sigma^2 / 2E) A \mathit{l} = W_0 (S + \lambda) \qquad (6)$$

where σ is the impact stress per unit area; E is the coefficient of the modulus of concrete; A is the area of the application of a force; l is the length of a body; W_0 is a dead load S is the falling height of a body from a level; and λ is the compressed thickness of concrete. By solving equation (6), σ is obtained:

$$\sigma = \{2EW_0 (S + \lambda) / A \mathit{l}\}^{1/2} \qquad (7)$$

On the other hand, σ can also be expressed as follows:

$$\sigma = E(\lambda / \mathit{l}) \qquad (8)$$

By substituting equation (8) into equation (6), σ can be solved:

$$\sigma = (W_0/A)(1 + \sqrt{1 + 2SEA/W_0 \mathit{l}} \qquad (9)$$

When it is supposed that λ_0 is the thickness corresponding to a dead load (W_0), λ_0 can be expressed as follows:

$$\lambda_0 = W_0 \mathit{l} / AE \qquad (10)$$

When equation (10) is substituted into equation (9), σ can be solved:

$$\sigma = (W_0/A)(1 + \sqrt{1 + 2S/\lambda_0} \qquad (11)$$

The strain (λ) caused by the impact fo of a stone which is contained in a mud can be solved, using equations (8) and (10):

$$\lambda = \lambda_0 (1 + \sqrt{1 + 2S/\lambda_0} \qquad (12)$$

The dead load corresponding to the above strain can be estimated, using equations (8) and (12):

$$W/W_0 = 1 + \sqrt{1 + 2S/\lambda_0} \qquad (13)$$

When it is supposed that D_0 is the actual stone's diameter, the converted diameter (D), defined here as the diameter of an imaginary stone which is assumed to be equal to the impact force caused by an actual stone with the diameter (D_0) stated above, can be calculated as follows, using equation (13) and both expressions of $W = \pi\rho_s D^3/6$, $W = \pi\rho_s D_0{}^3/6$:

$$D/D_0 = (1 + \sqrt{1 + 2S/\lambda_0})^{1/3} \qquad (14)$$

where D is the converted diameter defined above; ρ_s is the density of a stone. When it is supposed that S is 10 centimeters, λ_0 is 1 millimeter, and stone's diameter is 3.8 meters (the maximum diameter in the Arimura River mud flow on September 24, 1988), the diameter (D) of an imaginary stone (the converted diameter corresponding to the impact force caused by an actual stone with a diameter of 3.8 meters is estimated to be about 9.4 meters. This means that the impact force has the same effect as a huge stone loaded on the channel bottom. It shows that channel works should be designed safely enough to prevent a concrete channel from destruction, because a channel may be attacked by a very high impact force.

If it is supposed that both areas of the application of forces, the dead load (W_0) and the impact load (W), are equal, W_0 and W can be expressed as follow:

$$W_0 = A\sigma_0 \qquad (15)$$

$$W = A\sigma \qquad (16)$$

When expressions (15) and (16) are substituted into equation (13), the following equation can be obtained:

$$\sigma/\sigma_0 = 1 + \sqrt{1 + 2S/\lambda_0} \qquad (17)$$

σ_0 in equation (17) is the stress by the dead load derived from an actual impact stress (σ). The stress (σ) must be within the allowable strength of the concrete. It is generally said that the limit of the strength of concrete is about 250 kgf/cm^2. Accordingly, the maximum (σ) must be about 250 kgf/cm^2. If the same values as the above (λ_0 = 1 millimeter and S = 10 centimeters) are used here, σ_0 can be derived from equation (17):

$$250/\sigma_0 = 15$$

$$\therefore\ \sigma_0 = 16.\mathrm{kgf/cm^2}$$

When the area of the application of a force is about 10 cm^2, the whole force becomes 167 kilograms, and a stone's diameter corresponding to this allowable force is calculated at 50 centimeters. However, the actual compressed thickness of the concrete of a channel must be less than the 1 millimeter assumed above. Then the value of σ_0 becomes smaller than 16.7 kgf/cm^2. Accordingly, the allowable diameter of a stone in a mud flow to prevent the destruction of a concrete channel must be less than 50 centimeters.

The above is a discussion from the point of view of the compressive strength of concrete. Shearing force is also a very important factor in the destruction of a concrete channel. It is generally said that the shearing strength of concrete is 1/4 ~ 1/7 of its compressive strength (Okada and Muguruma, 1989). Accordingly, the allowable size of a stone should be even smaller than 50 centimeters in diameter. It can be foreseen that the destructive action against a concrete channel will increase even more by dint of the shearing force caused by the friction of stones with a channel bottom, in addition to the compressive force by the impact. The Osumi Public Works Office began to carry out a survey of the abrasion of the channel concrete in the Mochiki River in 1988. That concrete channel was constructed to the strength of 160 kgf/cm^2. The mixing proportion of that concrete is shown in the following.

slump	water	aggregate			additive	cement
		fine	coarse			
			A	B		
(cm)	(kg)					
8	158	700	600	600	2.5	252

A mud flow took place on October 6, 1988, a week after the channel works had been completed, and it abraded the concrete in the survey section. That mud flow could not be recorded on video tape, because it took place at night. The abrasion of the concrete was 2.5 centimeters in depth. The result of the strength test of the concrete reported that the strength on the 7th day after the mixing of that concrete was 110 kgf/cm^2.

Taking into consideration the fact that the shearing strength of concrete is about 1/7 of the compressive, the allowable compressive strength of 110/ kgf/cm^2 corresponds to an allowable shearing strength of 15.7 kgf/cm^2. The shearing force of the mud flow which took place on the Mochiki River on February 17, 1989, was 2.5 kgf/cm^2. As the mud flow on October 6, 1988, could not be recorded on video tape, its scale was unknown, but the marks of the water height in the channel after this flow nearly equal to the marks of the mud flow on February 17, 1989, in the same river. As both scales were almost equal, the value of 2.5 kgf/cm^2 was substituted for its shearing force. It resulted in the calculated value (the allowable shearing strength of the material, 15.7 kgf/cm^2) being larger than the observed ones. However, in the case in which such shearing force acts actually on a channel bottom as a repeated force, the shearing force of 2.5 kgf/cm^2 is not small as compared with the allowable shearing strength of the concrete (15.7 kgf/cm^2) stated above.

CONCLUSION

The results of surveys in the Arimura River and the Mochiki River showed that the actual shearing force of a mud flow on the surface of a channel bottom was about 0.5 ~ 2.5 kgf/cm^2. According to the theoretical calculations, the frictional force which should be caused by a stone of about 80 centimeters in diameter corresponded to the force of 2.13 kgf/cm^2 in the Arimura River mud flow on September 24, 1988. Such sizes of stones could be observed on the video. The impact force caused by huge stones in a mud flow was derived from the theory of the collision of an elastic body, and it proved that the impact force of a stone was several times greater than the dead load caused by that stone. When a shearing stress of about 2.5 kgf/cm^2 acted on a concrete channel with a compressive strength of 110 kgf/cm^2, the abrasion of that concrete was 2.5 centimeters in depth.

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