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Motion, debris size and scale of debris flows in a valley on Mount Yakedake, Japan

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Abstract Horizontal velocity profile, concentration of gravel and gravel-size distribution were obtained from the visual data of debris flow at a field observation site of the Kamikamihori valley on the eastern slope of Mount Yakedake, in order to make clear the flow feature and the size characteristics of gravel in the flow. Three typical surface-velocity distributions, one with a plug in the central part, a smooth one with a horizontal shear, and a highly turbulent one, were found in the flows. The mobility factor defined as the ratio of surface velocity to friction velocity of the flow, was dependent on the concentration of gravel with a negative correlation coefficient. In the case of a successive occurrence of debris-flow surge, concentration of gravel in the frontal part of the later surge was lower. There was a close correlation between size characteristics of gravel and scale of the flow. and the largest size of boulder in the flow was nearly equal to the maximum of the flow depth.

THE DEBRIS FLOWS ON 12 SEPTEMBER 1988

The authors have been executing an observation of debris flows on the eastern slope of Yakedake volcano every rainy season since 1970. The data of occurrence, motion and deposition of 48 debris flows were obtained among 64 flows which occurred till the end of 1992. Motion of debris flows which occurs around the confluence point at the altitude of 1900 m are measured at the middle-reach observation site at the altitude of 1580 m as shown in Fig. 1. The rainfall as shown in Fig. 2 generated three debris flows in the night, 11 to 12 September 1988. Usually no surface runoff is found on the gully bottom due to high infiltration capacity of the slope on Mount Yakedake. Debris flow would be generated by rapid appearance of large surface runoff due to a heavy rainfall when high water content of the gully bottom are realized by preceding rainfall, even if the lower layer of gully bed is unsaturated (Suwa *et al.*, 1989).

The first debris flow deposited at the altitude of 1650 m. Second and third ones ran down forming eight surges as shown in Fig. 3. Figures 3 and 4 show surface velocity of the flows measured with an electromagnetic Doppler speedometer, and show flow depth obtained from the visual data of video camera. The flow rate was calculated as product of the cross sectional area of the flow and the mean velocity as assumed to be 3/5 of the surface velocity.

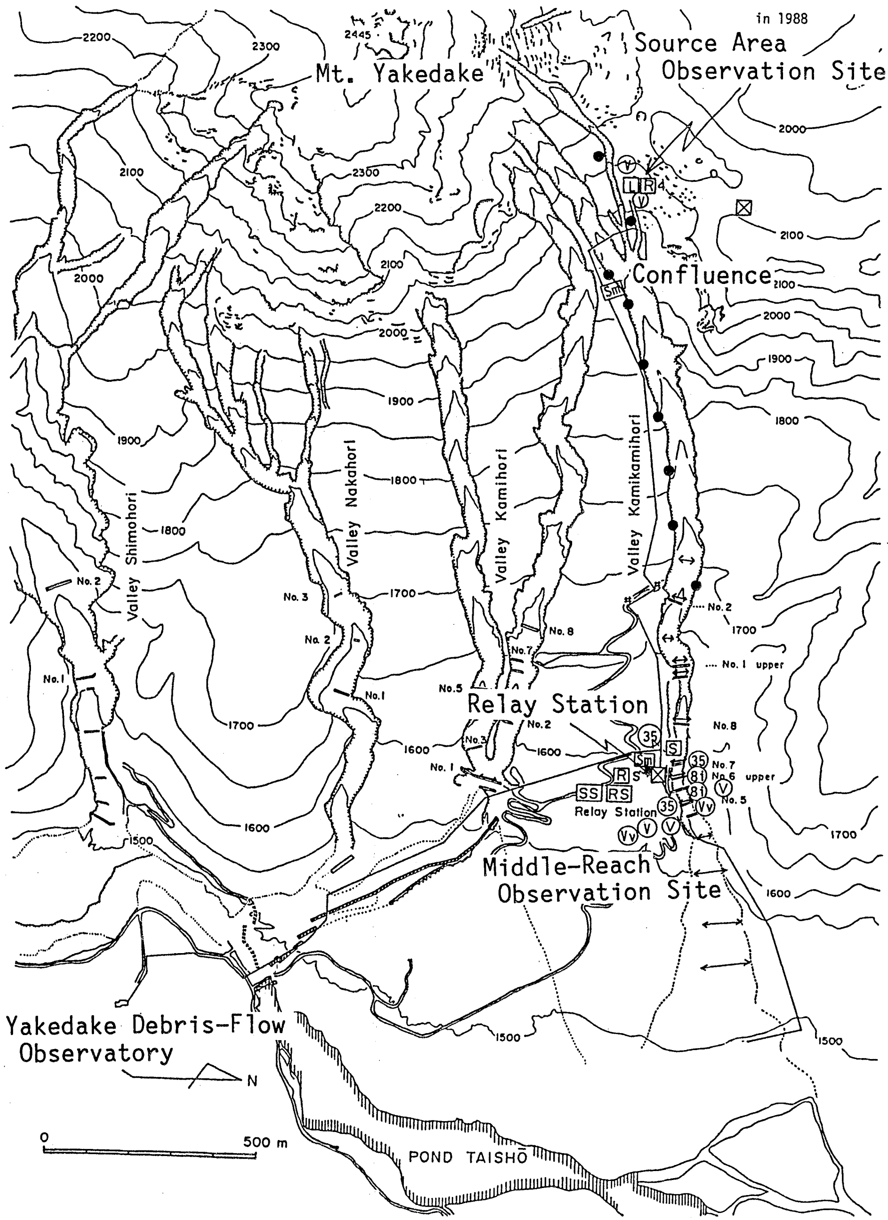

Fig. 1 Location of debris flow observation sites on the eastern slope of Mount Yakedake. R: rain gauge; L: groundwater level gauge; SS: spatial filter speedometer; RS: radar (Doppler effect) speedometer; 35: 35 mm time lapse camera; V: video camera; S: seismometer; edge arrows: wire sensor for detecting debris-flow arrival.

The field of view of the video camera looking downward as shown in Fig. 5 varies with depth of the flow. The actual position and size of each gravel in every frame were analyzed from the video data with a correction of the changes in position and magnification ratio of the view field. Through these processes, size distribution which

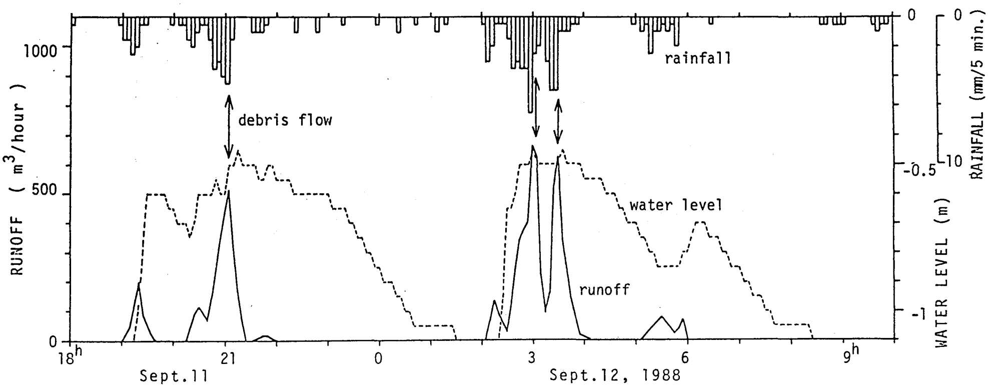

Fig. 2 Rainfall every 5 minutes, surface runoff of water (calculated) and artificially perched water level on the impervious sheet at the source area observation site. Arrows show the occurrence of debris flow.

was processed by area occupied by every gravel in each picture, and concentration of gravel which is assumed as the areal percentage occupied by gravel larger than 10 cm in diameter are shown in Fig. 4. According to this figure, the surface velocity of the frontal part of the flow is rather smaller than that of the following parts, due to its low mobility caused by an excessive concentration and an interlocking structure of boulders in the flow. After the peak of flow depth, flow rate records a peak and a little later surface velocity shows its maximum value, mainly due to the temporal changes in the composition of the flow materials. Taking the results of former observations (Ishikawa, 1985; Pierson, 1986; Suwa & Okuda, 1986; Suwa, 1988) also into consideration, it is remarkable that the peak value of the hydraulic factor of stony debris flows generally appears in an order from flow depth through flow rate to surface velocity.

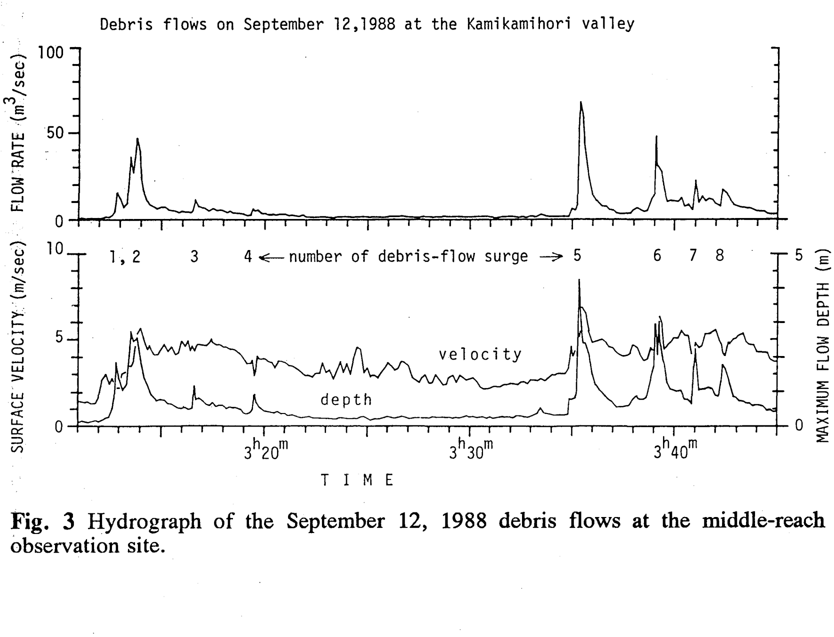

Fig. 3 Hydrograph of the September 12, 1988 debris flows at the middle-reach observation site.

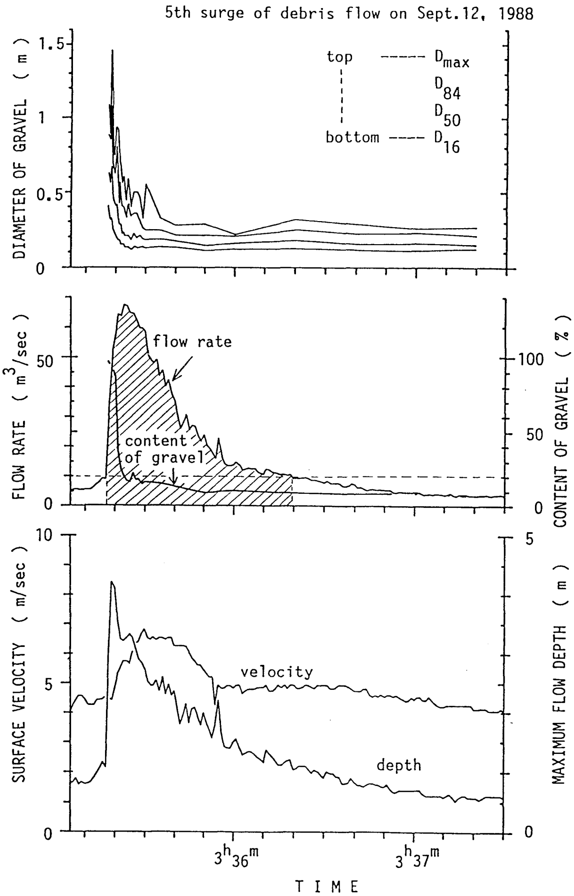

Fig. 4 Changes in the composition and the hydraulic quantities of the 5th surge of the September 12, 1988 debris flow.

RHEOLOGICAL CHARACTERISTICS SUGGESTED BY THE VELOCITY DISTRIBUTION ON DEBRIS-FLOW SURFACE

Visual record of the video camera (see Fig. 5) shows the motion of boulders, gravels, driftwood, ripple crests and muddy splash on the surface of the 12 September 1988 debris flows. Looking at this records, the material in the view field flows very smoothly almost as one body in the frontal part of each surge and whole parts of 1st and 2nd surges. But the sections behind the frontal part of 5th and 6th surges show highly turbulent flow aspects. Pierson (1986) observed the motion of debris flow with plug and that without plug in a gully on the slope of Mount St Helens. Figure 6 shows some results of the velocity profile at hydraulically typical positions in the surges whose hydrographs are shown in Fig. 3.

These velocity profiles represent three types of the rheologic features of debris flows. First, the flow heads of the 1st and 2nd surges show the presence of a plug. This plug seems to have been generated by Bingham fluid property which is not due

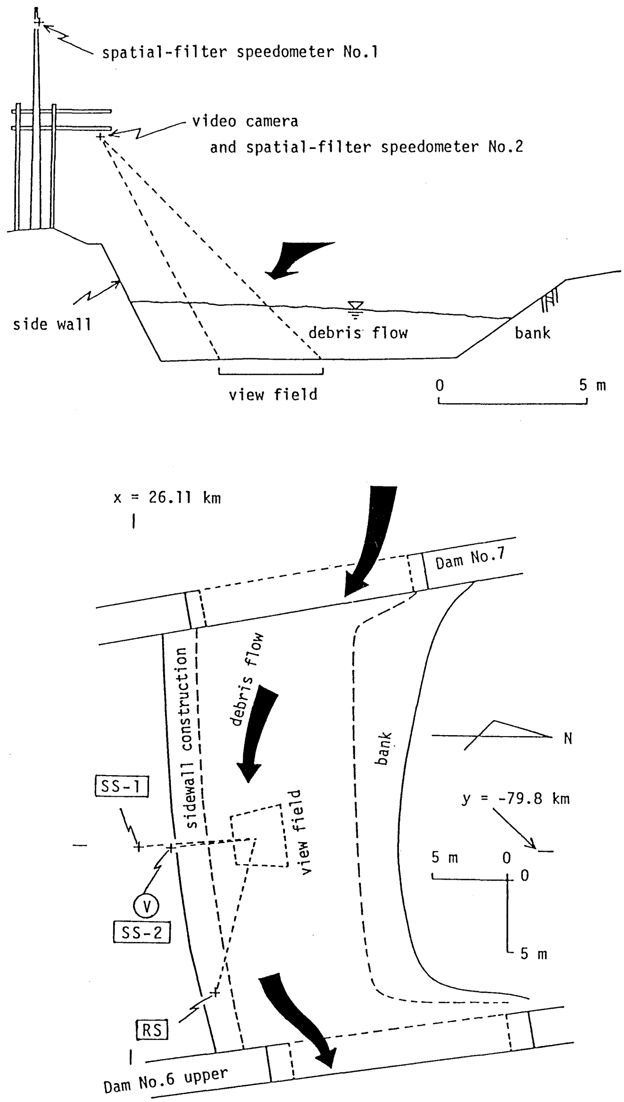

Fig. 5 Cross section (top) and plan (bottom) of the channel at the middle-reach observation site.

to high concentration of fine particle such as clay and silt, but is due to high friction structure of interlocking boulders, which structure gives the flow an yield stress strength in a macroscopic sense. Secondly, the rear part of the 2nd surge and the peak-depth part of the 5th surge show the velocity shear. But their motion is not turbulent. Thirdly, the peak-velocity part of the 5th surge shows a marked turbulence. However, it is not easy to say whether the flow regime in the latter two types is subject to dilatant flow type (Takahashi, 1980) or to the stress resistance rule in which Reynold's stress is dominant (Ashida *et al.*, 1987).

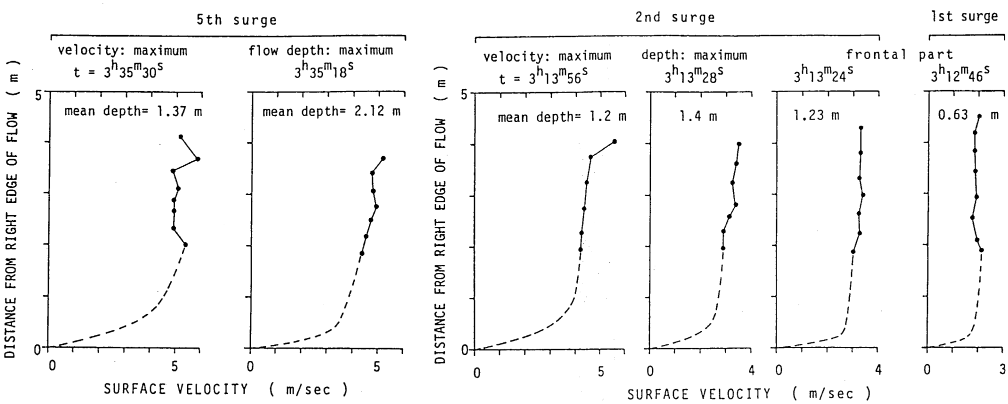

Fig. 6 Partial-width horizontal profiles of surface velocity of the September 12, 1988 debris flow at different stages of the flow.

RELATIONSHIP BETWEEN MOBILITY OF DEBRIS FLOW AND CONCENTRATION OF GRAVEL

The characteristics of debris-flow motion are affected strongly by some factors such as size distribution of solid particles, their concentration and scale of the flow. Size distribution of solid particles including fine particles and bulk density of debris flow were analyzed in the former paper (Okuda *et al.*, 1979). Here we focus on coarse particle in the flow, using the visual data of the September 12, 1988, the July 21, 1985, the July 27 and the September 5, 1983 debris flows. In the following, concentration of gravel and size characteristics of gravel are expressed as mean values in the head part of each flow which is defined as the part of the length 10th of the maximum depth of the flow from the flow front. And gravel whose size is larger than 10 cm is evaluated in the data processing.

Figure 7 shows a positive correlation between the peak discharge of debris flow and the concentration of gravels. The larger the scale of the debris flow, the higher the surficial concentration of gravel is. A main factor for this relationship is the higher dispersion of coarse particles due to the higher turbulence in the flow. The larger the

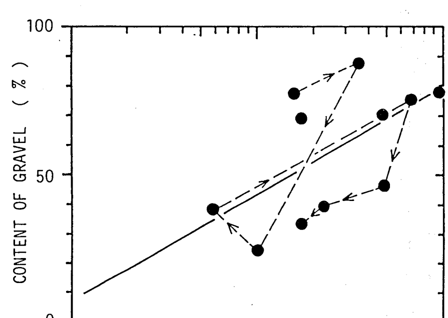

Fig. 7 Relationship between the peak runoff of debris flow and the concentration of gravel in the frontal part of the flow.

scale of the debris flow, the higher the turbulence of the flow is. Figure 7 further shows a tendency that the concentration of gravel would decrease with the order of occurrence for the successive surges.

Figure 8 shows a relationship between the concentration of gravel and the mobility of debris flow. We can call the ratio V_s/u_* as the mobility factor of debris flow which is proportional to $-1/2$ power of friction coefficient of the flow. Here V_s is the surface velocity of debris flow at the time when flow rate is maximum, $u_* = (ghI)^{1/2}$ is friction velocity, g is the acceleration of gravity, h is the flow depth, and I is the slope (sine of the slope angle). This figure shows that the mobility of debris flow would decrease with the concentration of gravel, and we can find a tendency that the mobility would increase with the order of occurrence for successive surges.

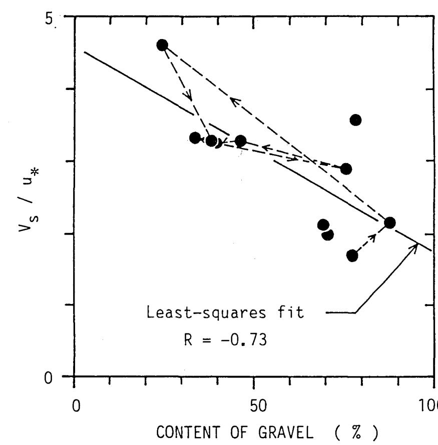

Fig. 8 Correlation between the mobility factor of debris flow and the concentration of gravel.

RELATIONSHIP BETWEEN SIZE CHARACTERISTICS OF GRAVEL AND SCALE OF DEBRIS FLOW

Representative values of the size distribution of gravel in debris flow are expected to be roughly proportional to the scale of the flow, since enough amount of debris up to the size of several meters are always prepared for debris-flow generation on the slope of Kamikamihori valley. Figures 9 and 10 show some positive correlations between size factors of gravel such as the diameter of largest boulder D_{max} and median diameter D_{50}, and the scale of debris flow such as peak runoff and total volume.

The data of maximum diameter in Fig. 9 are those from the visual records of partial width of the flows. Effective inspection of D_{max} should be done on the data from full width of the flow. Figure 11 shows a positive correlation between the peak runoff of debris flow and the diameter of largest boulder deciphered from the video records of full width of the flow. Figure 12 shows a positive correlation between the diameter of the largest boulder and the maximum of the flow depth h_{max}. From this figure, we can find that in many cases the maximum of the flow depth is nearly equal to the diameter of the largest boulder.

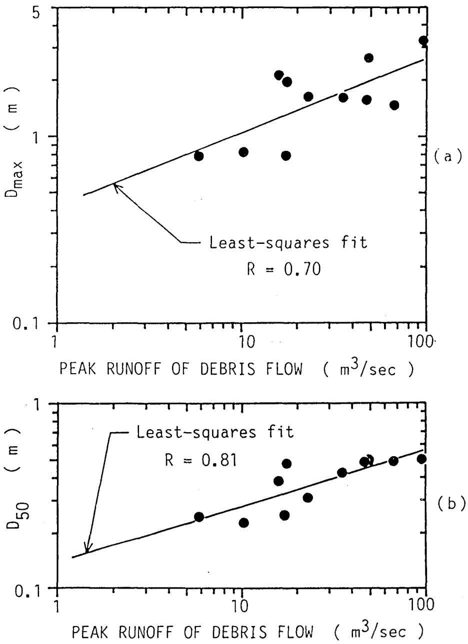

Fig. 9 Correlation between the size characteristics D_{max} and D_{50}, and the peak runoff of debris flow.

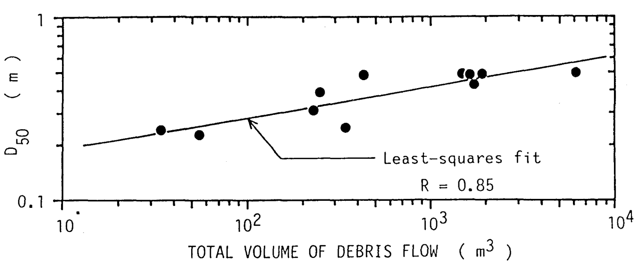

Fig. 10 Correlation between D_{50} and the total volume of debris flow.

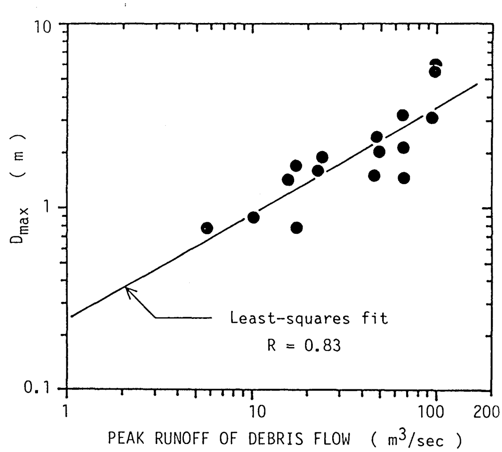

Fig. 11 Correlation between the diameter of the largest boulder and the peak of debris flows.

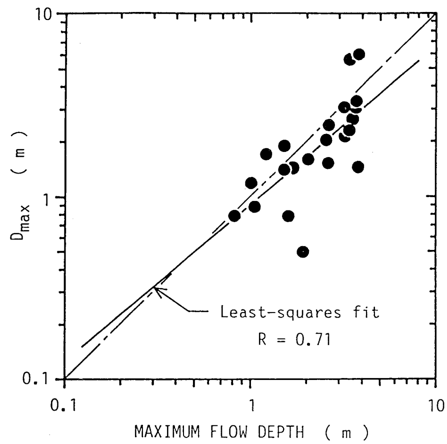

Fig. 12 Correlation between the diameter of the largest boulder and the maximum of the flow depth.

Considering the processes of the entrainment of boulders to the flow and those of individual deposition of boulders (Suwa, 1988), the diameter of the largest boulder in the flow is expected to be proportional to the 2nd power of flow velocity. But we could not find any good correlation between them. This seems to be due to two factors. One is the fact that the observation site of the motion at the outlet of the valley is in the equi-velocity domain for some flows and is in the deceleration domain for other flows. The other is the fact that the size of the largest boulder in the flow would be strongly affected by contingency.

FUTURE WORK

Rheological property of debris flow changes remarkably from the flow front through the backward part to the tail part with the changes in debris concentration and size factor of debris. Then it is necessary to make clear the characteristics of motion of individual gravels and the processes of contact and collision among the gravels. There is a possibility of underestimation for the concentration of gravel in the backward part of the flow, so a new contrivance is necessary for the evaluation of the concentration of gravel in the flow.

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