

Experimental Study on Impact Load on a Dam Due to Debris Flow¹

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ABSTRACT

When a dam is struck by mud or debris flow, it is put under a great impact load and sometimes is destroyed. To prevent such destruction, it is important to perform basic research about the impact load on a dam due to debris flow.

Thus, we have made an experimental study and tried to establish a method to estimate such a impact load on the dam. The experiment was performed with glass beads of 5mm in diameter as bulk solid, in an open channel which is 7m in length, and 15cm in both width and depth. In these experiments, the load on the dam was measured by a dam-type load measuring device, and simultaneously the behavior of the debris flow was observed by a high speed video (200 frames per second). In the high velocity area, the load consisted of the dynamic pressure on the flow, and most agree at each point in time with the one assessed from the flow's momentum variation. However there is no method to estimate debris flow's momentum variation on an obstructed object. Consequently, a model is proposed to estimate quantitatively the deformation of the flow and the load on the dam. The results from the computer simulation of this model agree well with the experimental results.

INTRODUCTION

Debris flow is one of the most disastrous phenomena in mountain area. This is a flow of the mixture of soil, cobble, boulder, and water, that run down with great energy. The debris flow has given

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huge damage to our life. To prevent this kind of disaster, we have made great efforts, and have built a great number of dams, as one of these efforts. Dams have a certain effect on the control of sediment transportation, and usually the energy of the debris flow is attenuated or completely dissipated by the time it reaches a dam or by a dam itself. Recently in Japan, where steep mountains are close to cities, the debris flow is stopped by a dam directly. However, when such a flow strikes a dam, it generates a great impact load, sometimes destroying the dam. In such a case, the debris flow increases its energy by taking up the sediment and water on the dam and the situation becomes more dangerous. To prevent such accident, it is important to establish a method to estimate the impact load on a dam, when the debris flow strike it.

The impact load of debris flow can be roughly categorized in two groups by means of the generating mechanism (Mizuyama, 1979). One is the load generated when boulders or floodwood in the flow hit the dams (solid impact load), and the other one is the load when the hydraulic bore of the debris as a fluid hits the dam (fluid impact load). The former tends to cause partial break of the concrete dam and the latter tends to cause large scale destruction of the dam. Therefore, from the stand point of disaster prevention, it is rather important to be able to estimate the fluid impact load.

In Japan, the dynamic fluid load of the debris flow that decides the design strength of the concrete dam is accounted for from the dynamic pressure of debris flow as the steady jet flow as seen in follow equation.

$$F = Dqv = DAV \quad (1)$$

where F is the load, D is the bulk densi-

ty of the fluid, q is the discharge, v is the velocity, and A is the cross sectional area of the fluid. The dynamic pressure of the steady jet flow is the pressure on the wall during the steady jet flow changes its direction on the wall.

Several previous works on the impact load on fluid theory can be seen. But if the behavior of the debris flows different from that of regular jet flow, then reconsideration is required.

Hirao et al.(1970) made an experimental study on impulsive force on the bank due to hydraulic bore. In their experiment, the pressure on the wall, which was fixed in the channel in right angle, was measured, when it was hit by hydraulic bore of a few kind of fluid running down the channel. They reported that the measured load on the wall was 1.0-4.5 times larger than the load that calculated from the dynamic pressure of the flow as the steady jet flow. But the mechanism of load generation was not referred in this report. Miyamoto and Daido(1983) also studied on the impact load of mud-debris bore on the bank. In this work, the load was discussed theoretically and some experiments had be made. But some simplifications in their theory make it hard to apply to actual phenomena directly. Some more previous works on similar themes can be seen, but those are not enough to estimate the impact load of the debris flow yet.

In this paper, both the load and the behavior of the head part of debris flow is made clear on the basis of results of

experiments and the load is discussed with the deformation of the flow head.

EXPERIMENT

A diagram of experimental apparatus is shown in Fig.1. The flow channel was made of steel and transparent acrylic board so that the side view of the flow can be observed. The size of the channel is 7m in length, 150mm in both width and depth. The channel bed was roughened by gluing glass beads (5mm in diameter) onto it. The channel's angle of inclination was 16 degree. Bulk solid were spherical glass beads with a diameter of 5mm and a specific gravity of 2.53. At the upper end of the channel, main and sub water supply device were attached, and at the bottom, dam-type load measuring instrument was set. The front face of the dam was at a right angle to the channel direction and the size of loading board is 120mm height and 150mm width. The load on the dam-type measuring instrument was measured by a dynamic strain meter and recorded by a oscillograph. As the same time, the side view of the flow on the dam was recorded by a high speed video recorder (200 frames per second).

The glass beads were put on the channel bed on the upper side of the dam making a movable bed 4m in length with 50mm depth. The glassbeads were saturated entirely by water from the sub water supply device, and then, the pre-determined volume of water from the main water supply device was released all at once, and this forced the glassbeads from

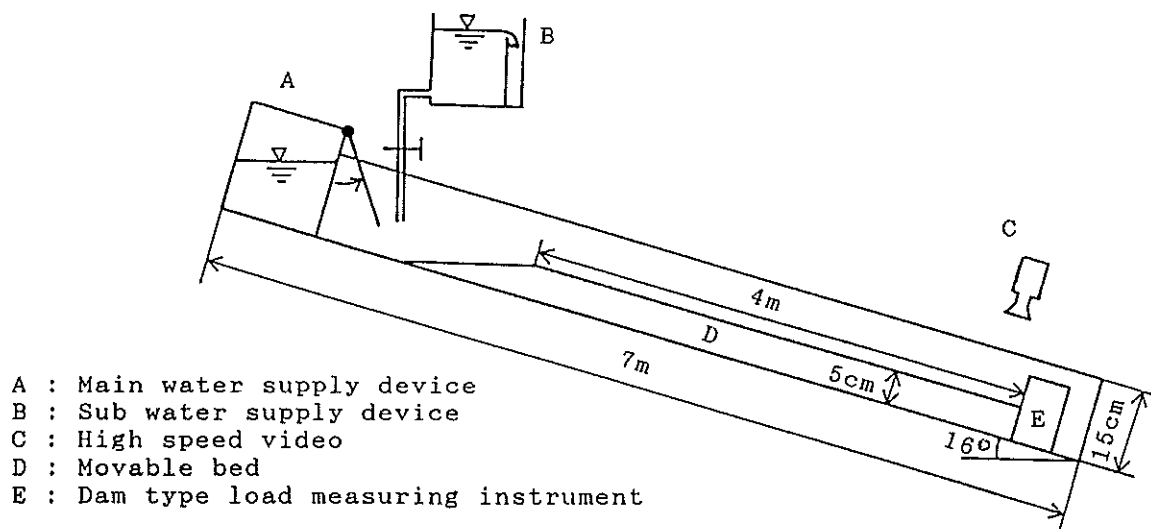


Fig.1 Diagram of experimental apparatus

the movable bed to move downstream as a debris flow. The velocity of the debris flow could be controlled by the volume of water in the main water supply device. The debris flow was checked by the dam at the bottom of the channel; the load on the dam was measured and the behavior of the flow was recorded from the channel side by the high speed video recorder. The record of both the load and the behavior of the flow were to be analyzed on the same axis of time. For this purpose, a pilot lamp was turned on in the site of the video recorder, and simultaneously in common circuit, a signal was sent to the oscillograph.

The flow's velocities were in the range of 0.4m/s to 2m/s. In all cases, distinct hydraulic bores could be observed and the flow could be considered as a steady flow at the dam point. The load on the dam measured in the experiment was recorded by the oscirograph. The measured loads can be classified in three types by the variation in time as shown in Fig.2. The load in type A has a clear peak in a very short time (from 0.01 to 0.07second) after impact; the load in type B also becomes maximum in very short time, but doesn't have a clear peak; the load in type C increases rather slowly. The relationship between the

velocities and the measured maximum loads are shown in Fig.3. The measured maximum loads increased with the velocities and each type of the load has its velocity range. The morphology of the flow on the dam, when maximum load generated, varied with the velocity or/and type of the load. Fig.4 shows the side views of the each type's typical flow, when the maximum load was recorded. In the case of type C, when the maximum load generated, the dam was filled with debris. In this case, the load is relatively small and can be explained as the static load of debris. On the other hand, in the case of type A and B, in spite of rather larger maximum load, the static load is much smaller than that of type C. This means that, in the case of type A and B, the maximum load mainly consists of dynamic load. Consequently, it is important to estimate this dynamic load so as to estimate the impact load on the dam.

In general, the dynamic load of debris flow has been discussed in comparison with the dynamic load of the steady jet flow in the same profile. Fig.5 shows the relationships between the velocities and the maximum measured load per cross section of the bore. The broken line "P" in Fig.5 is the dynamic pressure of the steady jet flow, calcu-

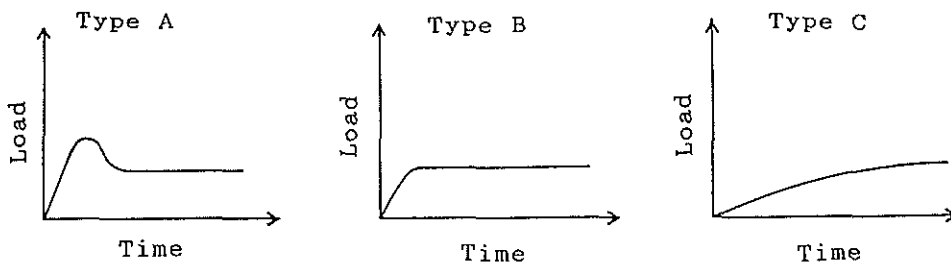


Fig.2 Type of load

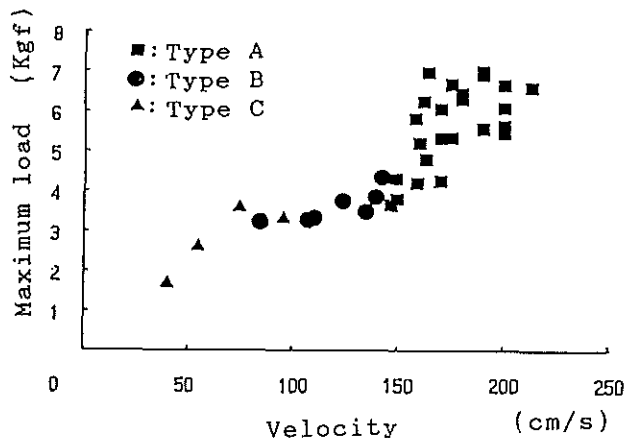


Fig.3 Relation between velocity and measured load

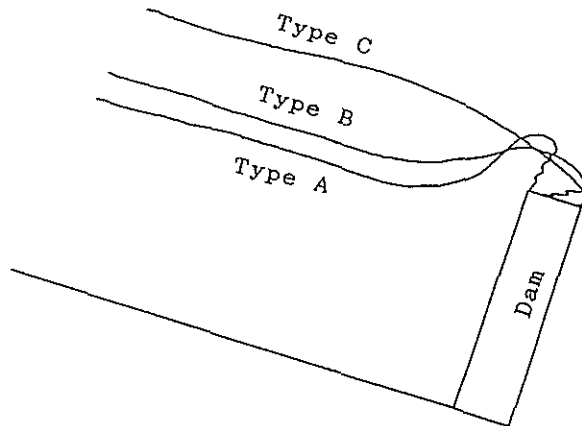


Fig.4 Flow morphology when maximum load generated

lated in the relationship of eq.(2).

$$P = Dv^2 \quad (2)$$

The bulk density was determined to be 1.4 gf/cm^3 from results of preliminary experiments. This figure shows that the maximum load is larger than the one due to the dynamic pressure of steady jet flow at each velocity.

Fig.6 and Table 1 shows the variation of the form of flow's head part and the measured load. After impact, the debris flow change its direction along the dam-front surface just like the behavior of the jet flow. From 0.05 to 0.06 second after impact, the head part jumps up above the dam, and makes overflow. The maximum load measured at this point. Then the debris begins to stop and makes sedimentation from the corner between the channel bed and the dam face, and static part grows to the final sedimentation. The sedimentation makes the impact angle larger between the flow and the dam face and the load on the dam becomes smaller.

Fig.7 shows the relationship between the velocity and timelag (the difference of time between the moment at which flow's head touch the dam face and at which the load become maximum). The timelag seems to be in inverse proportion to the velocity. In other words, the length of the head part of the flow, that reach the dam until maximum load arises, is constant (about 10cm in this experiment), in spite of the difference in velocity. This means that the shape of the flow's head has an important role in the mechanism of load generation and that this part's properties should be adopted in estimating the impact load.

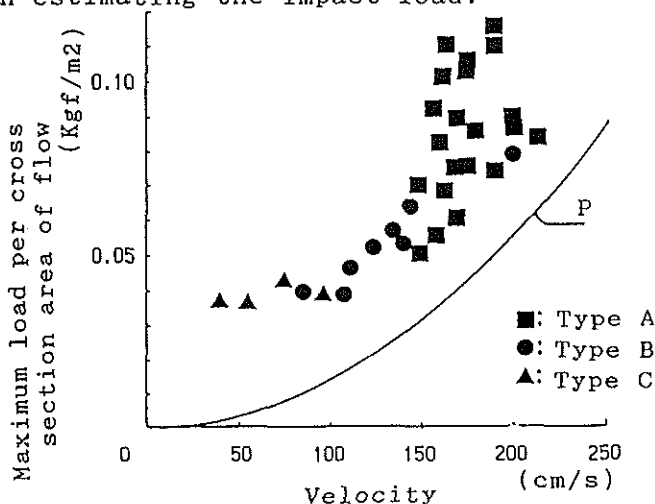


Fig.5 Relation between velocity and maximum load per cross section area of flow

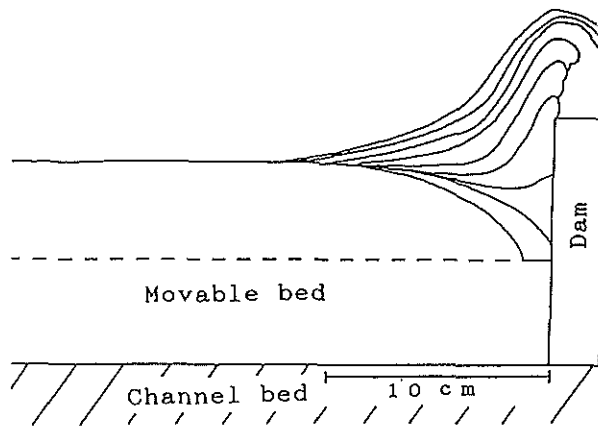


Fig.6 Morphological variation of debris flow's head at intervals of 0.01 second

Time (sec)	Load (Kgf)
0.01	1.66
0.02	4.04
0.03	4.26
0.04	4.78
0.05	5.21
0.06	5.46
0.07	5.15

Table 1 Variation of impact load with time

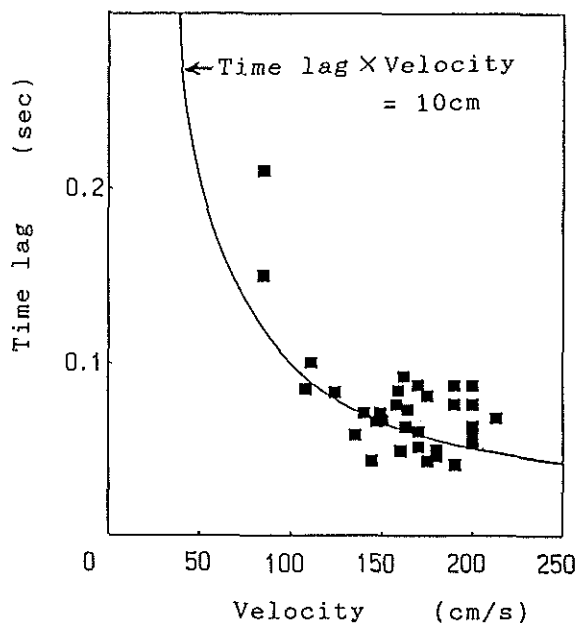


Fig.7 Relation between velocity and time lag

A DISCUSSION OF THE LOAD ON THE BASIS OF MOMENTUM VARIATION OF THE FLOW HEAD

In this chapter, the mechanism of load generation will be discussed in the relation with the variation of the load and the deforming process of the flow head.

If the flow is in a fully steady state before the impact point, the debris flow' head, that include enough part concerning the generation of the impact load, can be treated as a series of momentum points. On the assumption that the flow depth of this part is equal in each section, the discussion can be made in two dimension. Then, this part is expressed as a plane with some mass on X-Y two dimensional axis, as shown in Fig.8, and the surface line is described as a function $h(x,t)$. At the time t , this fluid part exists in $0 < x < x_e$, and the center of gravity on X axis x_g is in the relation of

$$\int_0^{x_g} h(x,t)(x_g-x)dx = \int_{x_g}^{x_e} h(x,t)(x-x_g)dx \quad (3)$$

The center of gravity given by this equation varies with the deformation of the flow head, and is defined as a function of time $x_g(t)$. Then, the acceleration of the gravity center is also defined as a function of time $a_g(t)$ as

$$a_g(t) = \frac{d^2 x_g(t)}{dt^2} \quad (4)$$

It is the dam that gives the force which makes this acceleration, thus the load on the dam is described as follow.

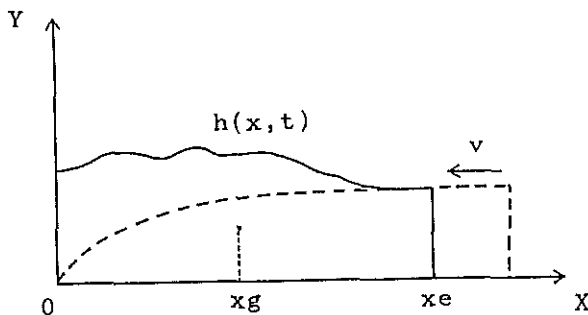


Fig.8 Model of flow head as a system of material points

$$F = DB \int_0^{x_e} h(x,t)dt \cdot \frac{d^2 x_g(t)}{dt^2} \quad (5)$$

where, B is the width of channel. As a consequence, the load on the dam is regulated by the function $h(x,t)$ that express the surface line of the flow head.

These way of analysis was applied in results of the experiment. In this analysis, the head part of the flow, that include enough part concerning the generation of the impact load, is considered to be cut off and be independent from the following flow, as shown by the broken line in Fig.9(a). Fig.9(a) shows the morphology of the flow head at each 0.01 second interval after impact on the dam, that was observed in the experiment by the high speed video. The variation of the flow' gravity center is calculated from this morphological variation and the average loads that should be generated on the dam during each 0.01 second are

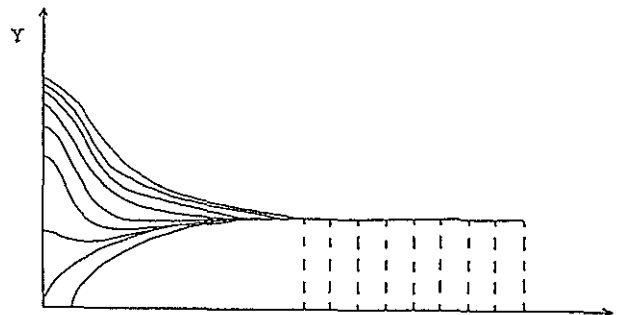


Fig.9(a) Behavior of the system of material points in flow's head at interval of 0.01 second

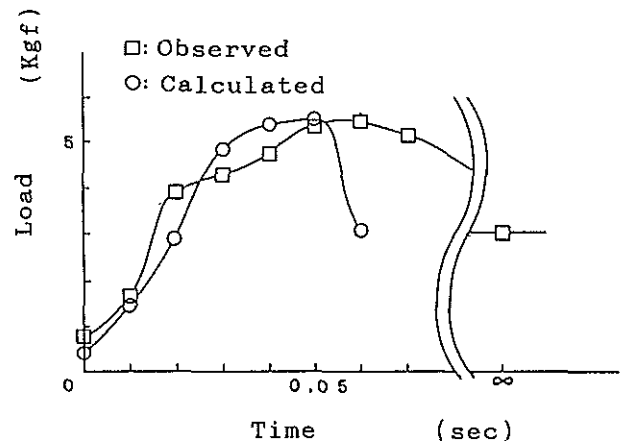


Fig.9(b) Relation between measured and calculated load

calculated from this and the bulk density. It is determined that the bulk density used in the calculation is to be 1.4g/cm^3 .

The comparison between the measured and the calculated load is shown in Fig.9(b). The two loads are in good agreement until the maximum point, and this means that the impact load of the debris flow is regulated by the deformation of the debris flow head. After the maximum point, the measured load becomes larger than the calculated one. This difference may be caused by the static load due to sediment of the debris.

FLOW MODELING AND COMPUTER SIMULATION

The impact load of the debris flow is regulated by the deformation of the debris flow head, as described in previous chapter. Therefore, the best method to roughly calculate the impact load is by estimating the deformation process of the flow head quantitatively using the initial conditions (flow velocity, flow depth, bulk density). Although $h(x,t)$ may have complex form affected by many factors, here a simple model is proposed that is analogous to the behavior of a jet flow checked by a perpendicular wall.

In this model, some functions are prepared. The original flow depth is to be described as a function of the distance from the flow front $H(x)$. The bulk density in each part of the flow is also to be described as a function of the distance from the flow front too, to take up the effect of the density distribution in x direction. As shown in Fig.10, the debris flow flows from x direction to y axis which represent the dam face with keeping initial velocity. The flow come to y axis and shift its position on the surface of original flow at each time in order from the front and, as a result of

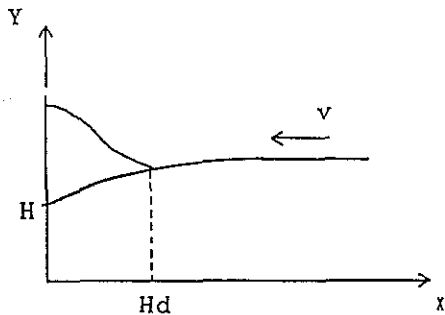


Fig.10 Flow deformation model

a series of this behavior, the fluid goes up to y direction along y axis. when the fluid shifts its position, each part of the flow changes its flow depth from H to H_d . H_d at each time is decided by R which is the ratio of H_d and H ($R=H_d/H$). R is also a function of the distance from the flow front. These functions of the distance from the flow front can be transformed to the functions of the time by means of velocity. Therefore the load on the dam and the morphology of the flow head at each time can be obtained by completing these functions of time as $H_t(t)$, $D_t(t)$, $R_t(t)$. The load can be described as a function of time as

$$F_t(t) = D_t(t)H_t(t)Bv^2 + \frac{Bv}{2} \cdot \frac{d}{dt}(D_t(t)H_t(t)^2R_t(t)) \quad (6)$$

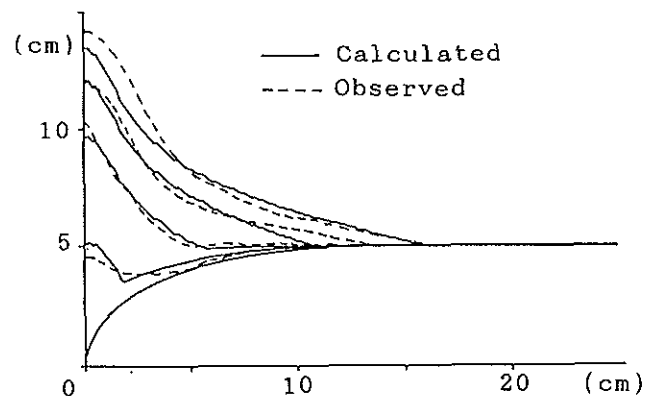


Fig.11(a) Comparison between observed and calculated morphology of debris flow head. (Each line indicates 0,0.1,0.3,0.5,0.7 second after impact)

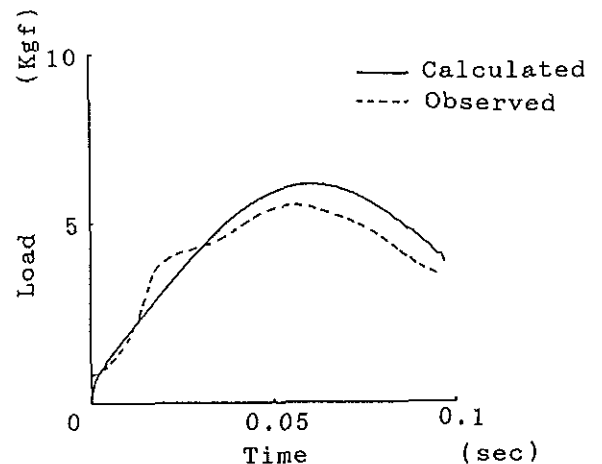


Fig.11(b) Simulated result of impact load on high velocity(1.70m/s).

After some transformations are made on this equation, the maximum load can be expressed by giving each value of composing functions D_t , H_t , R_t and their time differential functions (D'_m , H'_m , R'_m , D''_m , H''_m and R''_m respectively) at that time.

$$F_m = K D_m H_m B v^2 \quad (7)$$

$$K = 1 + \frac{H_m R'_m}{2v} + \frac{R_m H'_m}{v} + \frac{D'_m}{2D_m v} \quad (8)$$

Where K is a coefficient that mean the ratio between the maximum load and the load by dynamic pressure of a steady jet flow in same profile.

Now this modeling is applied to the experiment. The composing functions are decided as follow.

$H(x)$, the function that represents the flow depth, is to be described in a simple form that suits the morphology of the flow head in each experimental run, as follow

$$H(x) = \frac{H_{10} + 10a}{10^b} \cdot x^b - ax \quad (9)$$

where, H_{10} is the flow depth at 10cm from the front; a and b are the parameters that are decided in each run for better suitabilities, which have the range of 0.5-0.7 and 0.6-0.7 respectably. This function is applied to about 20cm length in the flow front. $D(x)$, the function that represents the bulk density in each part of the flow, is decided on the basis of the preliminary experiment, as a empirical equation.

$$D(x) = 0.4 + (0.15x)^{0.5} - 0.025x \quad (10)$$

$R(x)$ is the function that represents the deforming property of the flow, and also considered to express the ratio between the velocity components rise along the dam face and these which turn back to upstream after impact. This function is also decided so as to suit the experimental result.

Fig.11 is the comparison between the observed and the calculated morphology of the flow's head and the load on the dam. The velocity of this flow is 170cm/s and the flow depth at 10cm from the front is 4.8cm and parameter a and b in equation (9) are 0.5 and 0.6 respectively. The function $R(x)$ used in this calculation is

$$R(x) = 1.7 + 0.07x - 1.1 \cos(0.2x) \quad (11)$$

In this function, the x is given in cm unit. This function of the distance is

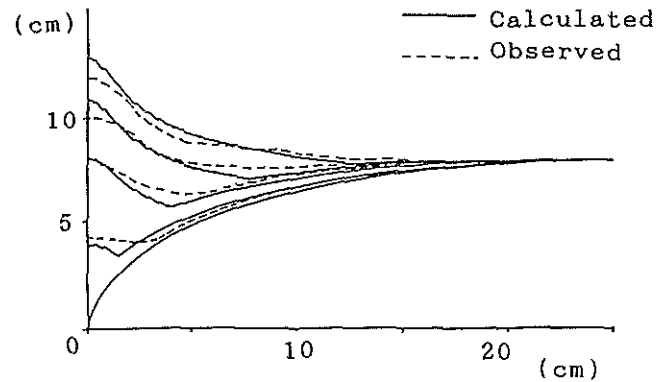


Fig.12(a) Comparison between observed and calculated morphology of debris flow head. (Each line indicates 0, 0.1, 0.3, 0.5, 0.7 second after impact.)

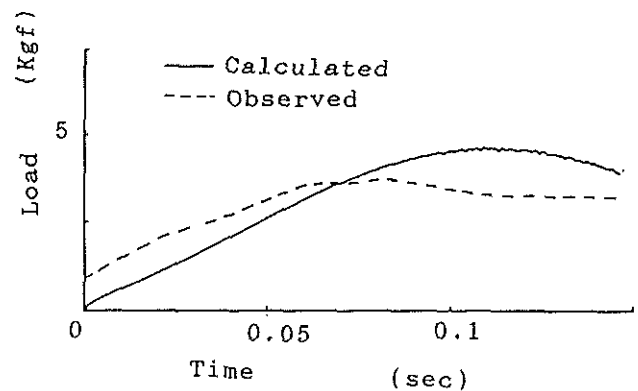


Fig.12(b) Simulated result of impact load on low velocity.

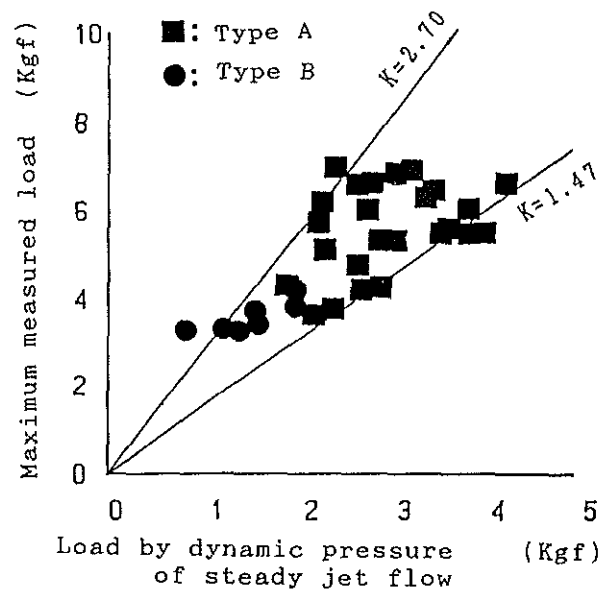


Fig.13 Relation between load by dynamic pressure of steady jet flow and measured load.

transformed to function of the time with the velocity (170cm/s) as

$$R_t(t)=1.7+11.9t-1.1 \cdot \cos(34t) \quad (12)$$

Both the deforming process of the flow and the load on the dam are well simulated. Fig.12 is the simulated result of another experimental run, by same $R(x)$. The velocity of this flow is 108cm/s, and the flow depth at 10cm from the front is 6.3cm, and the parameters of the flow depth function a , b are 0.7 and 0.7. The calculated results can be said to agree well with the observed one in spite that function $R(x)$ is decided to suit for other experimental run. The difference of the load between the calculated and the observed after the maximum point is most likely caused by the effect of overflow above the dam, which is ignored in this model.

The estimation of the maximum load is one of the most important problem in the practical aspect. The maximum load can be estimated with the model and the functions above. With these functions and the condition that the maximum load arises when $vt=10$ cm in this experiment (see Fig.7), eq.(9) is transformed to

$$K = 1.013+2.86a(b-1)+(0.135+0.286b)H_m \quad (13)$$

Since H_m is in the range of 4.1-6.3 and parameter a is 0.5-0.7, b is 0.6-0.7 as the results of the experiments, K should be in the range of 1.47-2.70. Fig.13 is the relationship between the load by the dynamic pressure of steady jet flow and the maximum measured load. The calculated value of K expresses the entire tendency of the experimental results.

CONCLUSION

The impact load on the dam when debris flow strikes it was measured and the behavior of the flow was observed in

the experiment. In the low velocity area, the measured load could be explained as the static load by the sediment of debris. On the other hand, in the high velocity area, the measured load was rather great and corresponded to the momentum variation of the debris flow head. Then a model was proposed that estimate the characteristic momentum variation of the debris flow. Both the load on the dam and the deformation process of the flow could be well simulated by means of this model. The measured maximum load was 1.47-2.70 times larger than the load by the dynamic pressure of the steady jet flow in same profile of each debris flow.

In this way, the impact load on the dam due to debris flow has been made clear and, although more investigation will be required to apply this model to practical situations, the impact load can be estimated at least on an experimental level.

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