Technical Note

Estimation of Flood Discharge Caused by Landslide Dam Overflow Erosion and the Application of Countermeasures

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Landslide dams form in river channels due to heavy rains or earthquakes. The flood discharge generated by overflow erosion, a known common cause of dam bursts [*Schaster et al.*, 1986], must be estimated promptly to establish warning and evacuation systems downstream area residents. Previous studies [*Satofuka et al.*, 2007a ; *Satofuka et al.*, 2007b ; *Satofuka et al.*, 2007c ; *Mizuyama et al.*, 2006] have shown that the "two-layer model" proposed by *Takahama et al.* [2000] can be used to roughly estimate the peak discharge and hydrograph of a flood caused by overflow burst from a landslide dam at a given point in the downstream area. A landslide dam was formed in the Mimi River in Miyazaki Prefecture by local downpour due to the typhoon in September 2005, which burst later because of overflow erosion. The authors used "two-layer model" to simulate the flood discharge caused by the burst and worked out an approach to simple analysis of the risk associated with landslide dams when multiple landslide dams form simultaneously.

1. INTRODUCTION

Although landslide dams formed due to heavy rain or earthquakes have been studied, little information is available regarding flood discharges caused by the bursting of such dams and their flood water levels. Following heavy rains associated with Typhoon No. 14 in September 2005, a landslide dam formed in Nonoo district located on the Mimi River in Miyazaki Prefecture; this dam burst in a small period of time (Fig. 1).

The Kyushu Electric Power Co., Inc. has two power dams in the abovementioned area: Tsukabaru dam (height: 87.0 m, catchment area: 410.6 km^2) located 0.5 km upstream of the landslide dam and Yamasubaru dam (height: 29.4 m, catchment area: 598.6 km^2) located 10 km downstream of the landslide dam. The outflow and inflow data for the respective dams are recorded in detail (Fig. 2).

Chiba et al. [*Chiba et al.*, 2007] used the outflow and inflow data of two power dams in the upstream and downstream areas to estimate the flood discharge caused by a dam burst from overflow erosion of the landslide dam and compared the estimate with the results of calculation based on the "two-layer model."

The Mimi River presented a high river flood discharge due to the heavy rain. Since the Tsukabaru power dam was located directly upstream of the landslide dam, the water storage capacity upstream of the landslide dam was extremely small. As a result, the peak of the flood discharge due to the bursting of the landslide dam burst did not exceed the peak of the flood discharge due to the heavy rain. Hence, the flood marks caused by the landslide dam burst could not be confirmed on the site and another method had to be used for confirmation.

In Morotsuka district, which is approximately 5 km downstream from the landslide dam, flood discharges exceeding 3,000 m^3/s caused the flooding of roads. Flooding of roads was not observed at the time when the landslide dam burst; the time of bursting of the landslide dam was estimated by hearing, and the peak flood discharge following the landslide dam burst was estimated as 3,000 m^3/s or less.

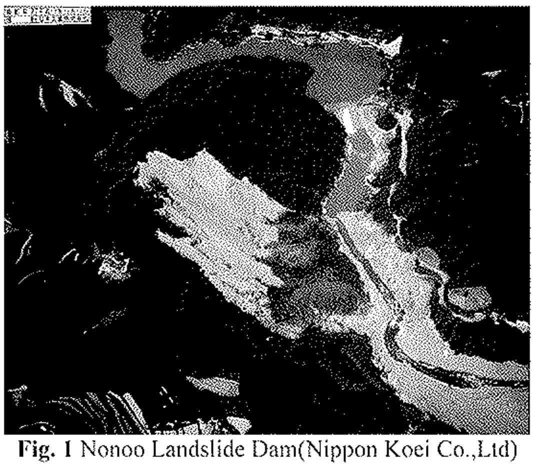

Fig. 1 Nonoo Landslide Dam(Nippon Koei Co.,Ltd)

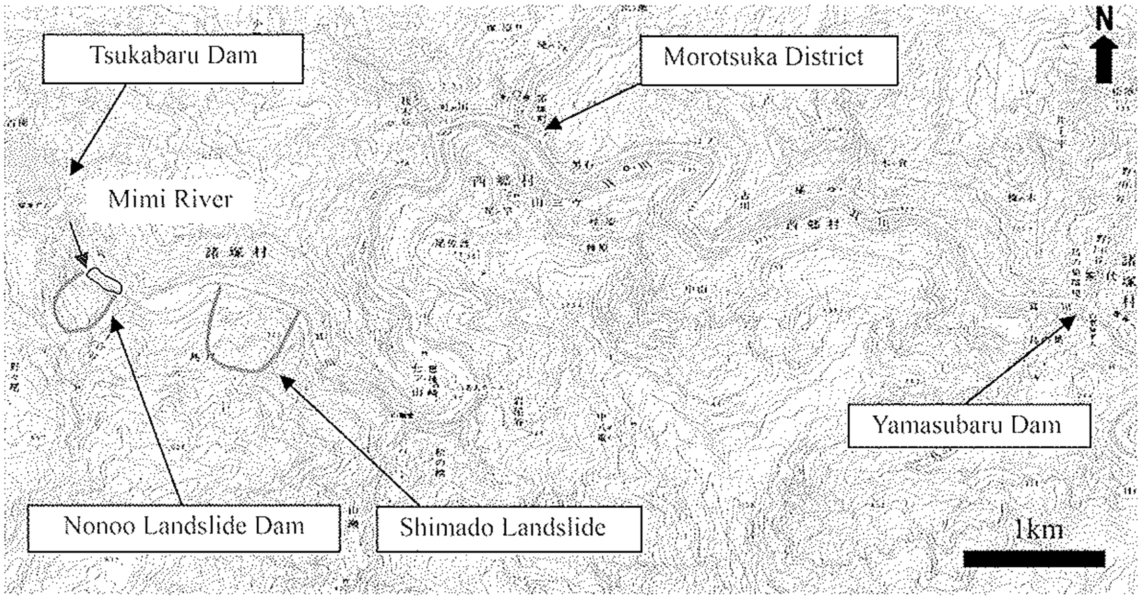

Fig. 2 Site Map of Landslide Dam and Electric Power Dams

The peak flood discharge at the Yamasubaru dam due to the landslide dam burst was estimated to be approximately 2,400 m^3/s (inflow from the remaining basin to the two power dams has been subtracted) on the basis of the records of the inflow to the dam. We validated the value calculated using the two-layer model under the abovementioned conditions.

We used a trial calculation to find the variation in flood discharge due to the differences in the average grain diameters of the sediment that constitute the landslide dams. Assuming that a new landslide dam will form and burst in a similar manner, made trial calculations to find the flood discharge using the two-layer model, on the premise of the existence of Tsukabaru dam, and we compared flood discharges for landslide dams of different heights and longitudinal profiles.

2. THE "TWO-LAYER MODEL" USED IN THE CALCULATION

For analysis of the transition process from a debris flow to a bed load transport-like collective flow, *Takahama et al.* [2000] focused on the essential difference in the constitutive law between the water flow layer and the gravel moving layer and suggested the "two-layer model" with an analysis based on a governing equation for each layer. The two- layer model analyzes the governing equation for each layer based on the conservation law resulting from the introduction of the water flow flux through the interface between the water flow and the gravel moving layers and the momentum flux according to the velocity vector of the interface, which is described in Fig. 3.

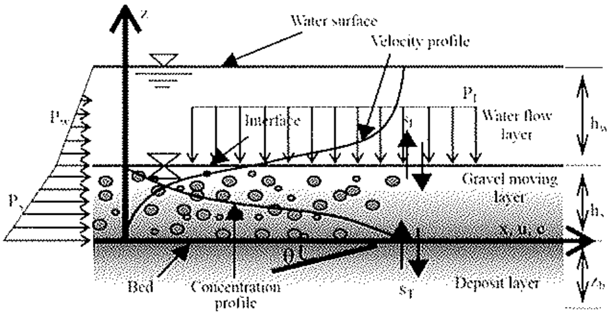

Fig.3 The two-layer model (Takahama et al., 2000, partialy revised)

Here, θ: bed slope,

h_w: water flow layer thickness,

h_s: the moving gravel layer thickness,

s_i: volume of the water flow layer through the interface per unit time per unit area; calculated as $c_s = c_*/2$ for the two-layer condition,

$c_*(= 0.6)$: concentration of deposit layer,

s_T: yield through the bed surface into the gravel layer (erosion rate),

z_b: bed height,

P_w: pressure on the water flow layer integrated over the interface through the water surface,

P_s: pressure working on the gravel moving layer integrated from the bed through the interface, and

P_i: pressure on the interface.

Fig.3 is a schematic diagram of the two-layer model. The details of equation of motion for this model see references [*Mizuyama et al.*, 2006] and [*Takahama et al.*, 2000]. The characteristics of this two-layer model are as follows.

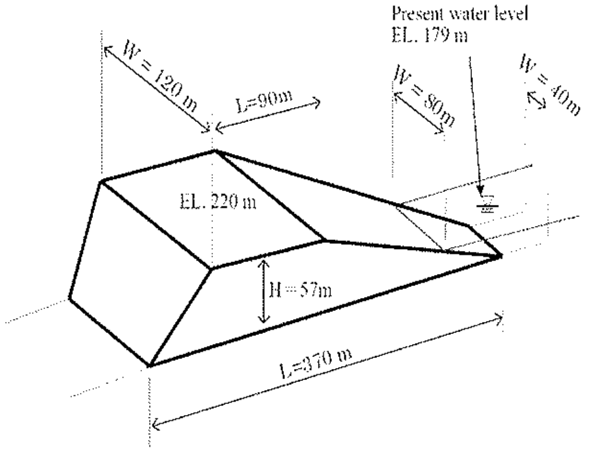

Fig. 4 Estimated Configuration of Nonoo Landslide Dam

Point 1 is the approach to the fluid above the river bed, which is divided into two layers: the "water flow layer" containing water only and the "gravel moving layer", which is a mixture of sediment and water.

Point 2 is concerns the versatility. Two-layer model is applicable continuously to everything from debris flow to bed load transport and is suitable for dealing with the overflow erosion of landslide dams.

Point 3 is the model's applicability to flood analysis. Past literature and research dealt with flood discharge directly below dams and did not extend to the creation of hydrographs. This model, however, allows hydrographs of any given spot to be created. Flood analysis for downstream areas can then be made based on these hydrographs.

3. FLOOD DISCHARGE FROM LANDSLIDE DAM OVERFLOW BURST IN RELATION TO AVERAGE GRAIN SIZE

The configuration of the landslide dam formed in Nonoo district has been estimated from field investigations, as shown in Fig. 4. The outflow

Table 1 Parameters used in the calculation

Mark	Value	Unit	Description
g	9.8	m/s^2	Gravity acceleration
σ	2650	kg/m^3	Gravel density
ρ	1000	kg/m^3	Water density
φ	35	°	Internal friction angle
c*	0.6		Accumulation layer concentration
n	0.05	$m^{-1/3}s$	Roughness coefficient

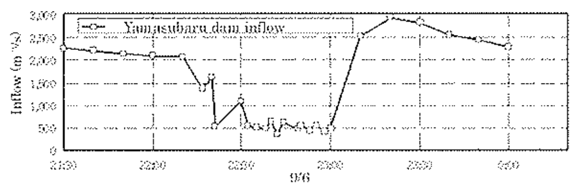

Fig. 5 Inflow to Yamasubaru dam

from Tsukabaru dam, which is directly upstream, has been considered as is the inflow to the landslide dam.

The values of various parameters used in the calculations are listed in Table 1. For numerical calculations, the leap-frog scheme has been used; here, dx (step increment) = 10 m and dt (time increment) = 0.01 s. Calculations are made for three cases of average grain size of the constituent materials of the landslide dam: 40 mm, 100 mm, and 400 mm.

The inflow from the remaining basin between Tsukabaru dam and Yamasubaru dam is considered as 502 m^3/s on the basis of records of the inflow to Yamasubaru dam due to the landslide dam during the damming period (Fig. 5). Regarding the flood discharge caused by the landslide dam burst, the inflow from the remaining basin is subtracted and compared with the calculated value.

The results of the calculations made by using the two-layer model for the three average grain sizes are shown in Fig. 6. The calculated value for the Morotsuka district is approximately 3,000 m^3/s. The flood peak discharge to Yamasubaru dam is approximately 2,400 m^3/s; this confirms the validity of the two-layer model.

As clearly indicated in Fig. 6, the discharge is significantly greater for smaller grain sizes at points directly downstream of the landslide dam. This is because a decrease in grain size causes a decrease in the shear stress in the bed surface, and this results in an increased fluid momentum, thereby increasing the discharge. However, in Morotsuka district,

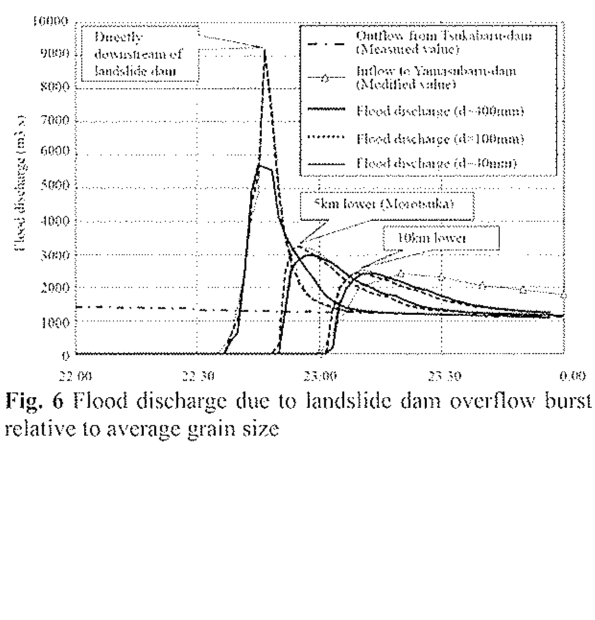

Fig. 6 Flood discharge due to landslide dam overflow burst relative to average grain size

which is approximately 5 km downstream, there was almost no difference in the discharge resulting from the difference in the grain sizes. In the case of the Mimi River, the large inflow from all basins may be an important factor. When the target protection area is near the downstream of a landslide dam, it is important to identify the grain size of the constituent materials of the dam. However, this factor is not very important for distant target areas. In other words, investigative action for such areas is not worth risking danger.

4. DIFFERENCES IN FLOOD DISCHARGE DUE TO DIFFERENCES IN THE LONGITUDINAL PROFILE OF THE LANDSLIDE DAM

In Shimado district, which is located downstream of Nonoo District, the flood discharge, which was generated following the overflow and bursting of the landslide dam, directly downstream of the dam site, has been calculated for six cases: landslide dam heights of 20, 40, and 70 m, and with longitudinal lengths of 200, 410, and 720 m (Fig. 7).

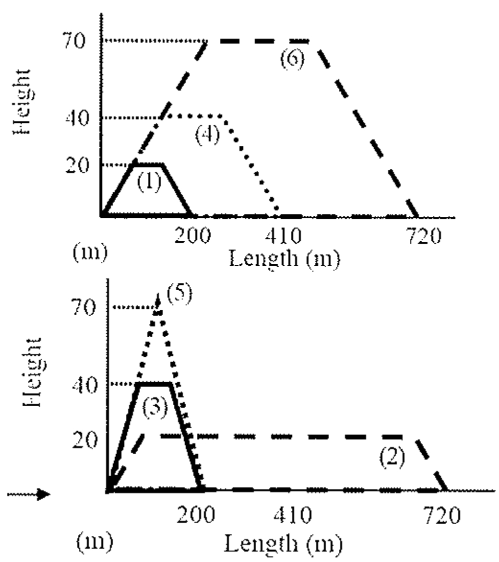

Fig .7 Longitudinal profiles used for calculations

Table 2 Calculation of peak discharge at time of overflow burst

Case	Landslide dam length (m)	Landslide dam height (m)	Inflow to landslide dam (m^3/s)		
			1,000	2,000	3,657
(1)	200	20	1,913.1	3,005.3	4,891.8
(2)	720		1,023.3	2,039.4	3,768.3
(3)	200	40	4,252.0	5,487.7	7,233.4
(4)	410		2,119.0	3,361.3	5,389.6
(5)	200	70	25,494.6	26,540.7	27,145.2
(6)	720		1,784.7	3,175.4	5,110.0

The average grain size used for the calculation is 400 mm; the internal friction angle, 35 degrees; and the roughness coefficient of the downstream river channel, 0.05. In relation to the inflow to the landslide dam, discharges corresponding to 1-, 10-, and 100-year probability scales (1,000, 2,000 and 3,657 m^3/s, respectively) have been used as the outflow from Tsukabaru dam. The results of the calculation are listed in Table 2 and shown in Fig. 8 to Fig. 13 (for 10-year probability, 2,000 m^3/s).

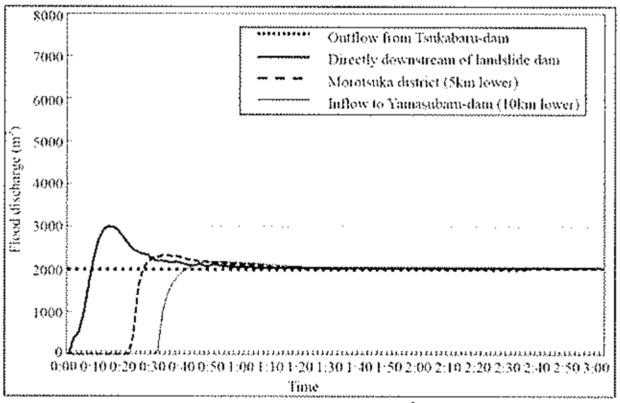

Fig. 8 Case (1) (2,000 m^3/s)

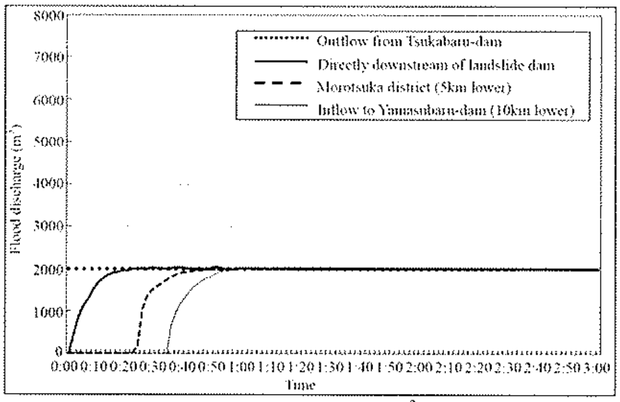

Fig. 9 Case (2) (2,000 m^3/s)

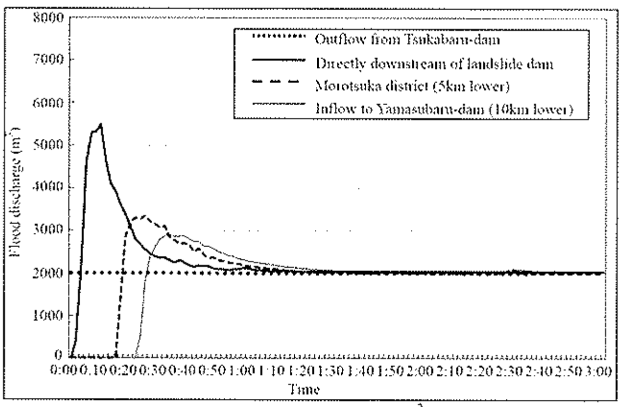

Fig. 10 Case (3) (2,000 m^3/s)

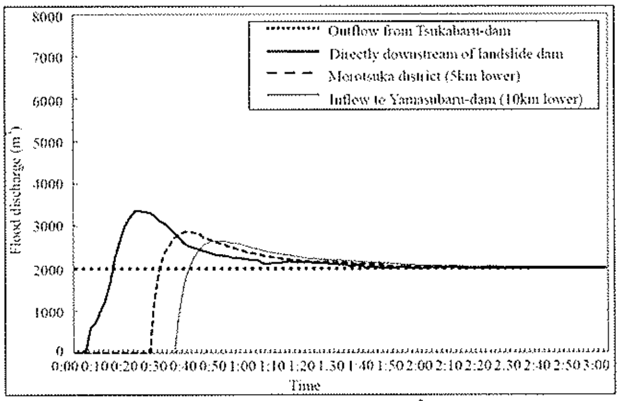

Fig. 11 Case (4) (2,000 m^3/s)

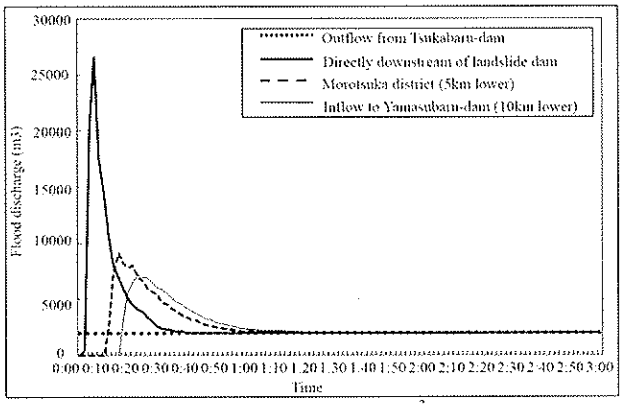

Fig. 12 Case (5) (2,000 m^3/s)

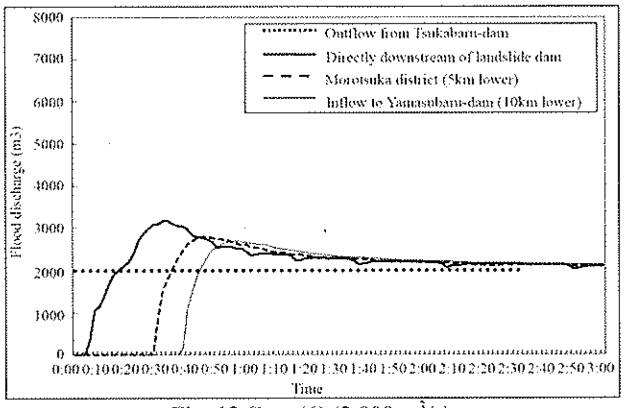

Fig. 13 Case (6) (2,000 m^3/s)

From shape of the hydrograph, we observed the following:

a) Of the six cases, Case (5) shows the sharpest shape with the largest dam height and smallest dam length and the shortest time until the peak discharge was reached.
b) For all cases, the discharge after the peak approximates to the inflow to the landslide dam.
c) For Case (2), with a small dam height and long dam length, the peak of the hydrograph barely rises, even after the landslide dam overflows, and is almost the same as the inflow discharge.
d) For all cases, the peak of the hydrograph varies depending on the inflow discharge but the differences between the peak and inflow discharges are similar.

With a focus on the peak discharge, we observed the following:

e) A comparison between Cases (1), (4), and (6) shows that the dam height has little impact if the longitudinal profiles are similar
f) What has the most impact on the peak discharge is the longitudinal profile of a landslide dam. A short longitudinal length, results in the peak discharge increasing. This may be explained by the fact that the dam height rapidly decreases with overflow erosion and a large volume of the stored water overflows.
g) The discharge becomes extremely large with a triangular shape Case (5).

5. CONCLUSION

The flood discharge caused by overflow erosion from a landslide dam in the Mimi River has been estimated by using the two-layer model, and has been checked by considering the outflow and inflow data of the power dams in the upstream and downstream areas. The results confirm that the estimates obtained by using the two-layer model provide fairly reasonable values.

Recent examples including the Chuetsu Earthquake, Iwate-Miyagi Nairiku Earthquake, and Wenchuan Earthquake in Sichuan China have shown that many landslide dams often form simultaneously due to earthquakes. From the perspective of crisis management and for the establishment of a warning and evacuation system, the degrees of risk associated with the simultaneous formation of many landslide dams must be quickly analyzed in order to take appropriate measures.

Authors think that investigates the longitudinal profile of the landslide dams as early as possible, we can grasp flood discharge by overflow erosion using two-layer model and analyze the degrees of many landslide dams. Hence, development of technology that will enable the prompt acquisition of site information is required.

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