

Prediction of landslide-induced debris flow hydrograph: the Atsumari debris flow disaster in Japan

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Abstract

Landslides sometimes occur on mountain slopes by heavy rains. Some of them change into debris flows and then move into mountain rivers. The debris flows erode the river bed and increase their discharge. Prediction of debris flow discharge becomes important for the simulation of flooding debris flows along the river. The purpose of the present study is to develop a prediction model of the landslide-induced debris flow hydrograph. This study is composed of three steps. First, we assume a transformation model of landslide into debris flow. Second, we calculate the development process of debris flow in the middle reach and determine the debris flow discharge. Finally, we simulate the flooding process of debris flow in the downstream reach.

Keywords: Atsumari River, debris flow, landslide, bed variation.

1 Introduction

There was a continuous heavy rain in Minamata City, Kumamoto Prefecture, Japan on July 20, 2003 (fig. 1). Especially, at the Atsumari River basin in the Minamata City as shown in fig. 2, the maximum hourly and accumulated rainfall was 91 mm/h and 323 mm, respectively (fig. 3). As a result, a large-scale of landslide occurred on the right-hand side slope of the Atsumari River. The landslide changed into debris flow. During the movement in the middle reach at steep slope, the debris flow eroded the river bed and bank and increased its flow discharge. In the downstream reach at mild slopes, the debris flow caused sediment deposition and moved over river bank. The debris flow broke several



houses on the river bank and killed 15 people of residents along the river. The situation of the debris flow disaster in the Atsumari River is shown in Photo 1.

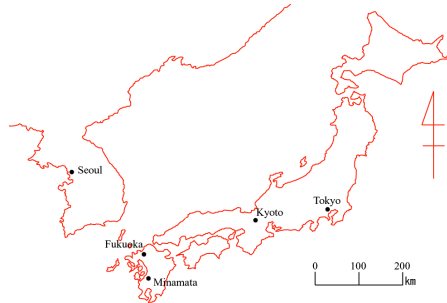


Figure 1: Location of Minamata City in Japan.

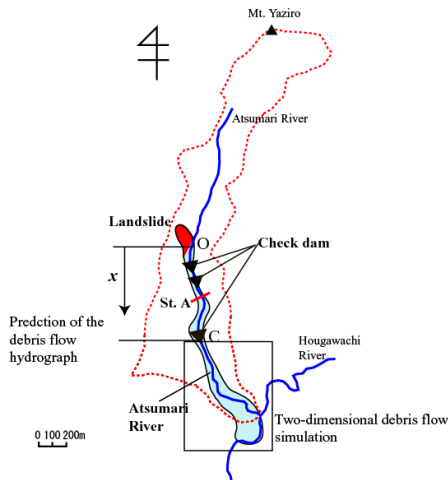


Figure 2: The Atsumari River basin.

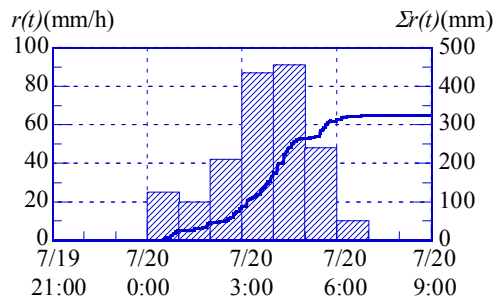


Figure 3: Rainfall measured near the Atsumari River.



Photo 1: The debris flow disaster of the Atsumari River in Minamata City.

In order to measure such disaster, we have to predict the debris flow discharge by numerical simulation. There are some studies on the prediction of debris flow discharge.

Nakagawa *et al.* [1] & [2] simulated the movement and deposition of the Harihara debris flow in Japan.

Hashimoto *et al.* [3] and Park & Hashimoto [4] proposed a prediction model for debris-flow discharge on the basis of the discussion of river bed variation.

Satofuka [5] developed a 2-D hybrid debris flow model and applied to the Atsumari debris flow disaster. However, this model does not consider erosions of river bed and bank.

Takaoka *et al.* [6] derived river bed and bank erosion rate equations for mountain rivers. Using these equations, they attempted to simulate the Atsumari debris flow disaster (Takaoka *et al.* [7]). However, satisfactory discussion is not found on a transformation of landslides into debris flows.

The present study is an extension of the work of Takaoka *et al.* [7]. First, we assume a transformation model of landslide into debris flow. Second, we calculate channel variation in the middle reach and determine the flow discharge of the Atsumari debris flow. Finally, we make a two-dimensional simulation of debris flow in the downstream reach.

2 Transformation model of landslide into debris flow

From mass conservation of sediment, we obtain the relationship between landslide sediment volume V_s and sediment discharge in initial debris flow $Q_{s0}(t)$:



$$\int_0^T Q_{s0}(t)dt = V_s \tag{1}$$

where V_s = landslide sediment volume and $Q_{s0}(t)$ = sediment discharge of initial debris flow.

Rewriting eqn (1), and denoting $Q_{s0}(t)/V_s$ by $u(t)$, we have

$$\int_0^T u(t)dt = 1 \tag{2}$$

where $u(t)$ corresponds to a response function for the transformation from landslide into debris flow. Therefore, we can have the following relationship:

$$\int_{-\infty}^{\infty} V_s \delta(t - \tau)u(\tau)d\tau = V_s u(t) = Q_{s0}(t) \tag{3}$$

where $\delta(t - \tau)$ is Dirac delta function. Landslide sediment volume V_s can be regarded as the input of the system at time $t = \tau$ and sediment discharge $Q_{s0}(t)$ as the output.

Since the evaluation of $u(t)$ is very difficult, we assume four cases as the response function. The response functions are shown in fig. 4. Cases A and B express the response function as rectangular waves, and Cases C and D as triangular.

$Q_{s0}(t)$ is also expressed as

$$Q_{s0}(t) = C_0 Q_0(t) \tag{4}$$

where C_0 = sediment concentration and $Q_0(t)$ = the initial debris flow discharge.

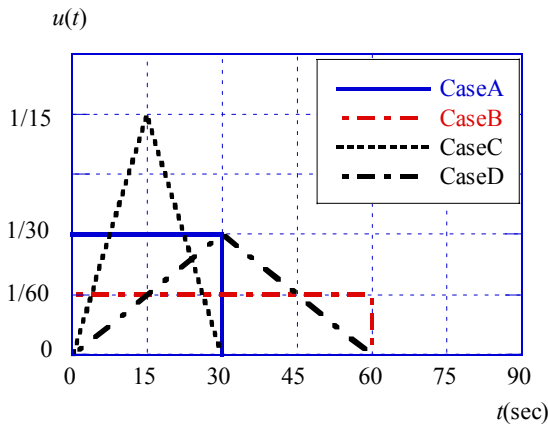


Figure 4: Assumed response functions.

3 Prediction of the Atsumari Debris Flow Hydrograph

Simulation is composed of two parts; one is prediction of hydrograph from the middle river reach and the other two-dimensional simulation of flooding debris flow on the deposition area. The former is the boundary condition for the latter.

Therefore, using the hydrograph based on the river bed variation calculation, we can simulate numerically flooding debris flow. The study area is Atsumari River basin (fig. 2). There were three check dams in the Atsumari River.

We calculate river bed variation from the landslide position "O" to the most downstream check dam position "C", as shown in fig. 2. St. A indicates the position where we measured the channel cross section.

3.1 Basic equations

The cross section of the river reach is approximately trapezoidal and the angle of both side banks is 30 degrees. We assume that the river banks are eroded in lateral direction with constant angle of repose 30 degrees.

The equations of mass and momentum conservation govern the flow in the middle reach from station A to C:

the one-dimensional equation of motion

$$\frac{\partial Q}{\partial t} + \frac{\partial vQ}{\partial x} \cos \theta = -gA \cos \theta \left[\frac{\partial(h + z \cos \theta)}{\partial x} \right] - \left(B + \frac{2h}{\sin \beta} \right) \frac{v^2}{\phi^2} \quad (5)$$

the continuity equation of sediment-water mixtures

$$\frac{\partial(A + A_s)}{\partial t} + \frac{\partial Q}{\partial x} \cos \theta = q_{in} + h \frac{\partial B}{\partial t} \quad (6)$$

the continuity equation of sediment

$$\frac{\partial(CA + C_s A_s)}{\partial t} + \frac{\partial(C_T Q)}{\partial x} \cos \theta = q_{sin} + C_s h \frac{\partial B}{\partial t} \quad (7)$$

bed erosion rate equation

$$\frac{\partial z}{\partial t} = -k_b (C_{T\infty} - C_T)^p v \quad (8)$$

for $C_{T\infty} > C_T$ or

$$\frac{\partial z}{\partial t} = k_b (C_T - C_{T\infty})^p v \quad (9)$$

for $C_{T\infty} < C_T$

lateral erosion rate equation

$$\frac{\partial B}{\partial t} = k_s v \quad (10)$$

where ρ_t = density of the mixture; Q = discharge of the mixture flow; v = average velocity; h = flow depth; z = bed level; B = river bed width; A , A_s = cross section area of mixture flow and sediment; β = bank slope angle; θ = river bed angle ϕ = nondimensional average velocity; C = sediment concentration in the flow; C_T = flux-averaged sediment concentration; $C_{T\infty}$ = equilibrium sediment concentration; k_b = coefficient for bed erosion rate; k_s = coefficient for lateral erosion rate; q_{in} , q_{sin} = lateral inflow rate of the mixtures and sediment from the slopes (Park and Hashimoto [4]) and x = distance measured in the flow direction from the upstream end of the river reach. We have the values of $k_b = 0.01$ and $p = 0.7$ for eqn (8) and (9), and $k_s = 0.01$ for eqn (10) (Takaoka *et al.* [6]). We can



have the value of nondimensional average velocity $\phi = 5$ (Takaoka *et al.* [8]). The schematic figure of channel cross section is shown in fig. 5.

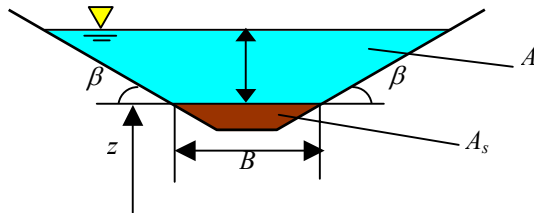


Figure 5: Schematic figure of cross section.

Denoting sediment and fluid density by σ and ρ , we have $\rho_t = \sigma C + \rho(1-C)$. In the discussion we assume sediment concentration profile uniform. Therefore we can have the relation of $C_T = C$. Indicating friction velocity by u_* , we have $\phi = v/u_*$.

Denoting equilibrium sediment discharge by q_s , we can express the equilibrium sediment concentration as

$$C_{T\infty} \approx \frac{Bq_s}{Q} \quad (11)$$

We use the equilibrium sediment discharge formula for q_s in eqn (11). The equilibrium sediment discharge formula proposed by Hashimoto *et al.* [9] & [10] is appropriate for various kinds of sediment transport in steep rivers.

$$\frac{q_s}{\sqrt{sgd^3}} = \frac{\bar{u}_\delta}{u_*} \tau_*^{3/2} \left(1 - \frac{\tau_{*c}}{\tau_*}\right) \frac{1}{(\alpha - I_f) \cos \theta} G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) \quad (12)$$

where $s = (\sigma - \rho)/\rho$; τ_* = the nondimensional shear stress; τ_{*c} = the critical nondimensional shear stress; θ = bed slope angle; I_f = the friction slope; w_0 = the fall velocity of sediment grains in water; $\alpha = 0.875$ and $\bar{u}_\delta/u_* = 4.7$.

According to Hashimoto *et al.* [9] & [10], G is a function of I_f , h/d and w_0/u_* and is approximated as

$$G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) = 1 + 0.1 \left(\ln\left(\frac{h}{d}\right)\right)^2 (I_f)^{-0.8} \exp\left\{-2.5\left(\frac{w_0}{u_*}\right)^{0.5}\right\} \quad (13)$$

We assume that river bed was composed of cohesionless sediments 2 m thick (Takahashi *et al.* [11]).

3.2 Boundary condition

The boundary conditions at $x = 0$ (the landslide position) are given by

$$Q = Q_0(t), \quad h = \left(\frac{Q_0}{\phi B \sqrt{g \sin \theta_0}}\right)^{2/3}, \quad \text{and} \quad C_T = C_0 \quad (14)$$

for $0 \leq t \leq T$ and



$$Q = Q_{w0}(t), h = \left(\frac{Q}{\phi B \sqrt{g \sin \theta_0}} \right)^{2/3}, \text{ and } C_T = 0 \quad (15)$$

for $T < t$.

Here $Q_0(t)$ = initial flow discharge and C_0 = initial sediment concentration and T = landslide duration. The value of C_0 is assumed 0.5. $Q_{w0}(t)$ denotes flow discharge determined by runoff analysis. From the discussion of Chapter 2, we have

$$Q_0(t) = \frac{V_s}{C_0} u(t) \quad (16)$$

where the landslide sediment volume V_s was estimated as 21,000 m³ by Kumamoto Prefectural Government and four kinds of response functions $u(t)$ is assumed, as shown in Fig. 4.

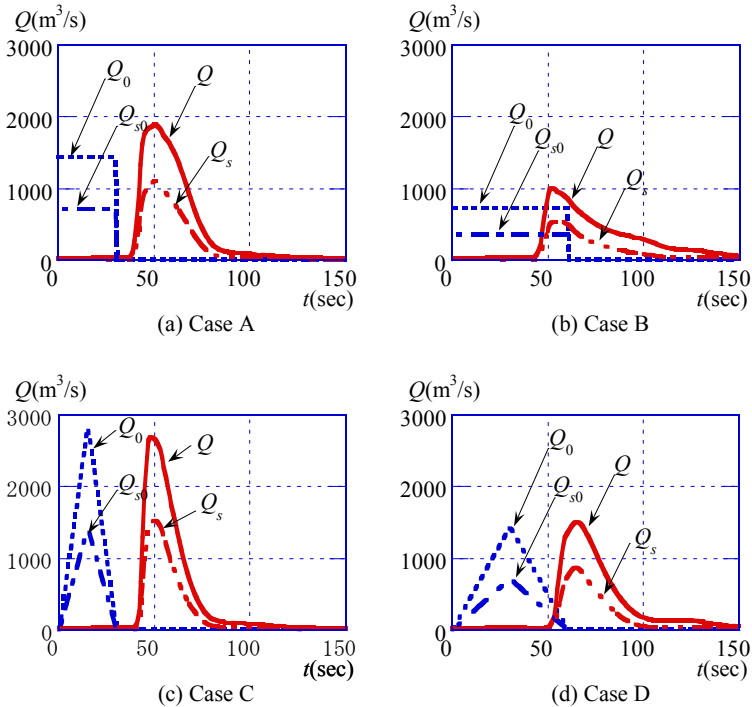


Figure 6: Debris flow hydrograph assumed at the landslide position and calculated at the most downstream check dam.

3.3 Prediction of debris-flow hydrograph

Figs. 6 (a), (b), (c) and (d) show the discharge hydrograph calculated at the most downstream check dam in Case A, B C and D, respectively. We can find the peak discharge 1,000 - 2,500 m³/s. The peak time is in 50 to 60 seconds after the initiation of landslide. Kumamoto Prefectural Government found the peak



discharge 1,300 - 4,700 m³/s. The calculation results agree with the investigation of Kumamoto Prefectural Government. When the different response functions have the same landslide duration, we can find the predicted peak discharge almost same. The total sediment outflow volume from the most downstream check dam is found 43,000 m³ from the calculation result. Kumamoto Prefectural Government found the sediment outflow volume 64,000 m³.

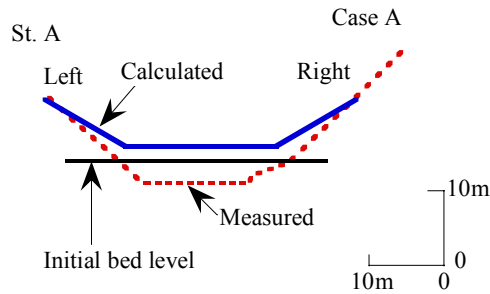


Figure 7: Comparison between measured and calculated channel cross section.

Fig. 7 shows the comparison of channel cross sections calculated and measured at St. A (fig. 2). The calculated channel width agrees with measured one. The calculation shows bed level increase, and measurement shows bed erosion. This is why initial sediment concentration $C_0 = 0.5$ becomes larger the equilibrium sediment concentration estimated with eqn (11).

4 Two-dimensional debris flow simulation

Two-dimensional debris flow simulation is made for the region from the most downstream check dam (fig. 2) to the confluence of the Atsumari and Hougawachi River. We select hydrograph calculated in Case A (fig. 6 (a)) as the boundary condition.

The initial river bed condition of the study area is dry. The boundary conditions at the check dam are given by fig. 6 (a). We simulate the debris flow behavior for the period of 300 seconds from the initiation of the debris flow to its termination.

Fig. 8 shows the plan view of the calculated flow depth. There are several houses on hills of both sides of the downstream reach. Position E indicates the river channel and Positions F and G indicate houses on the left-hand and right-hand side of the river bank, respectively. The houses at positions F and G were broken by the debris flow. We find that the debris flow overflowed river bank near the village and inundated houses, especially on the bank of the right-hand side.

The deposited sediment volume is found 37,000 m³ from the calculation result. On the other hand, Kumamoto Prefectural Government found deposited sediment volume 53,000 m³.

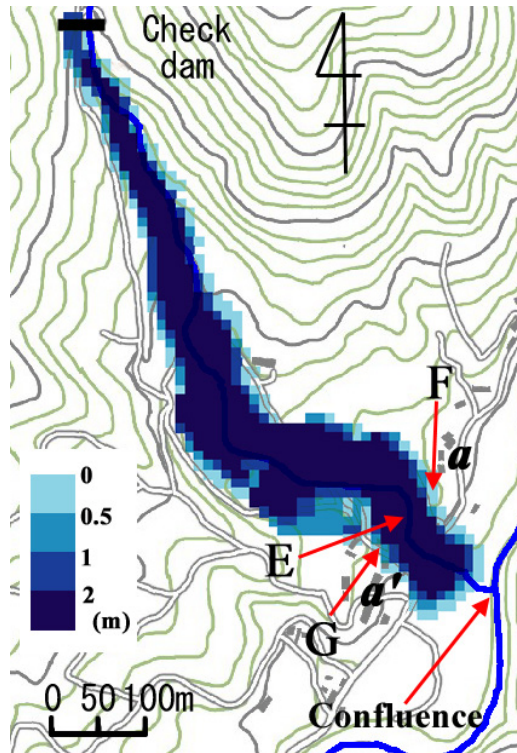


Figure 8: Flow depth calculated at $t = 90$ sec.

5 Conclusions

The results obtained in this study are as follows:

- (1) The transformation of landslide into debris flow is expressed by some response functions. Landslide sediment volume can be regarded as the input of the system and sediment discharge as the output.
- (2) Using the transformation model, we have predicted the debris outflow hydrograph from the middle river reach. The peak discharge of the debris outflow is found about $2,000 \text{ m}^3/\text{s}$.
- (3) In the cases of same landslide duration, the peak discharge is almost same with different response functions. The peak discharge of debris flow depends on the duration of the landslide

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