NUMERICAL SIMULATION OF DEBRIS FLOW WITH DRIFTWOOD IN THE SOZU RIVER, SAKA TOWN, HIROSHIMA PREFECTURE, JAPAN ON JULY 6 2018

NAOKI FUKUOKA
West Japan Engineering Consultants, Inc., Fukuoka City, Japan, fukuoka.river@gmail.com

HIROYUKI NAGANO
National Institute of Technology, Gunma College, Maebashi City, Japan, hr-nagano@cvl.gunma-ct.ac.jp

HARUYUKI HASHIMOTO
Hydrologist (Former Professor of Kyushu University), Fukutsu City, Japan, hashimoto.haruyuki@gmail.com

ABSTRACT

The 2018 debris flow event in the Sozu River resulted in significant deposition of driftwood in the middle reach and sediment in the downstream reach. This paper presents a numerical simulation for examining behavior of driftwood and sediment during the debris flow event. This simulation is based on a flow model which has frontal flow of driftwood only and the following main flow of sediment-water mixture with driftwood in the surface. The simulation results show that the quantity of sediment and driftwood outflow from the mountain area was about 63,000 m^3 and 1,100 m^3, respectively. The former agrees well with the result from laser aerial survey. The latter is of the same order of magnitude as the amount of driftwood deposited in the middle reach. The simulation also reveals that considerable sediment deposition in the downstream reach occurred during the peak rainfall and before the landslide. Immediately after the landslide, a larger amount of driftwood was carried from the landslide location. This caused channel blocking at the two bridges in the middle reach. The simulation method provides satisfactory result in predicting the debris flow event, although the values of all coefficients in the basic equations of the simulation were determined independently of this study.

Keywords: Debris flow, driftwood, woody debris, numerical simulation, Sozu River, Hiroshima prefecture

1. INTRODUCTION

Record heavy rain hit Hiroshima Prefecture from 6th to 7th in July, 2018. This heavy rain triggered many landslides-induced debris flows in the mountain areas of Hiroshima City, Saka Town, Higashi-Hiroshima City and Kure City. In particular Saka Town had the debris flow with woody debris (i.e. driftwood) in the Sozu River. The two bridges in the middle reach trapped a large amount of driftwood and resulted in blocking the river channel in the field area, while the milder slope of the downstream reach caused sediment deposition and flooding along the river channel in the residential area. It is important to know such difference between the behaviors of sediment and driftwood from the viewpoint of the disaster prevention.

The purpose of this study is to investigate the transport and deposition of sediment and driftwood and then understand their behaviors during the debris flow event. This investigation is conducted with a numerical simulation of the 2018 debris flow event.

There are a few previous works on the simulation method of debris flow with driftwood. Nagano et al. (2013) presented a flow model for the numerical simulation of such debris flow. The flow model consists of two parts: the frontal flow part and the following main flow part. The former indicates one layer of accumulated driftwood only, while the latter indicates a structure of two layer, that is sediment-water mixture as the major layer and wood-sediment-water mixture as the surface layer. Fukuoka et al. (2016) applied the flow model to the simulation of the 2014 debris flow event in Hiroshima City and discussed the behavior of sediment and driftwood during the event. Nagano et al. (2018) developed this simulation method for the 2017 debris flow event in Asakura City, which is famous for significant outflow of driftwood.

On the other hand, Fukuoka et al. (2017) performed laboratory experiments on a flow of driftwood-sediment-water mixture as a model of debris flow with driftwood. Through this experiment they verified the accumulation of driftwood at the flow front and found that the flow front seems a bore at steep slope.

The present study is an extension of these previous works. First, we modify the flow model of Nagano et al. (2013) on the basis of the laboratory experiments and then present the numerical simulation method for debris flow with driftwood. Second, we conduct the numerical simulation of the 2018 debris flow event in the Sozu River. Finally, by comparing the simulation result with the field and aerial surveys, we discuss the behavior of sediment and driftwood during the debris flow event.

2. STUDY AREA

Study area is the Sozu River basin in Saka Town (Figure 1). The north and south sides of this town are adjacent to Hiroshima City and Kure City, respectively. On the other hand, the east and west sides of the town are mountain and port areas. Half region of the town is occupied by a mountainous area. The Sozu River basin is located in the northern part of Saka Town. Figure 2 depicts the plan view of the river basin. The Ohban River joins the middle river reach as a tributary. The basin area is 4.2 km^2 and the stream length is about 3 km. Geology and vegetation of the whole region of town is mainly composed of granite and evergreen broad-leaved trees, respectively.

Figure 3 shows the longitudinal profile of the Sozu and Ohban River (National Geographical Survey Institute, 2018). The river bed slope is from 12/100 to 36/100 along the Ohban River, 6.8/100 along the middle reach near the exit of the valley and 1.7/100 along the downstream reach in the open residential area. The Ohban River has a check dam at x'=3,000 m with considerable sediment deposition. Here x' denotes the distance measured from the river mouth.

Figure 1. Location of Saka Town.

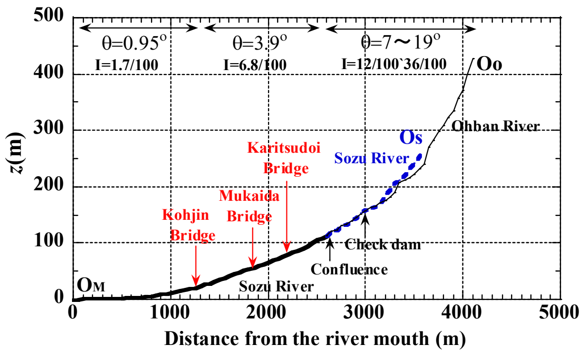

Figure 3. Longitudinal profile of the Sozu and Ohban River.

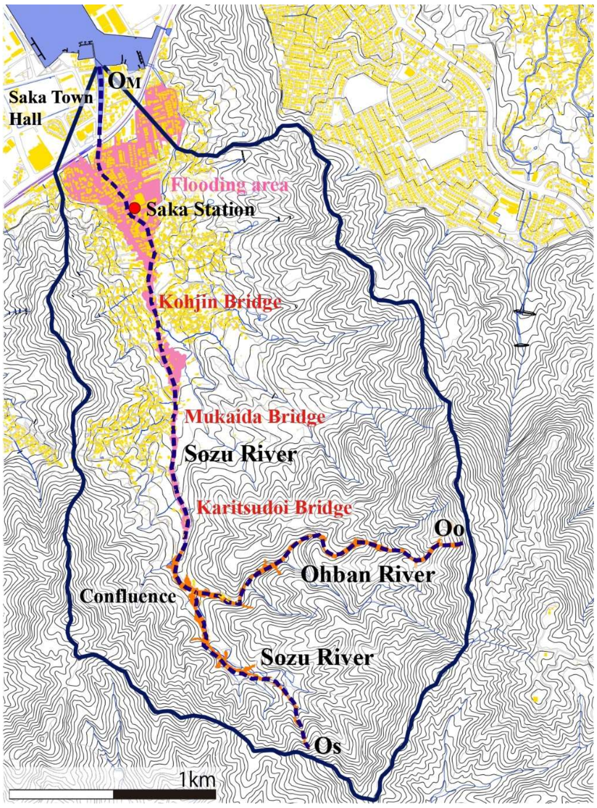

Figure 2. Plan view of the Sozu River basin.

3. OUTLINE OF THE DEBRIS FLOW EVENT

There are two hydrological stations for rainfall measurement in the neighborhood of the Sozu River; one is Saka Station in Saka Town and the other is Tennoh Station in Kure City (Figure 1). Figures 4 and 5 show the rainfall measurements during the debris flow event (Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2018). Rainfall lasted from 8:00 on July 5th to 8:00 on July 7th. Saka Station failed to measure rainfall after 19:00 on July 6th, although Tennoh Station succeeded in the measurement. Saka Station measured the maximum hourly rainfall of 67 mm/hour from 18:00 to 19:00 on July 6th. On the other hand, Tennoh Station measured the maximum hourly rainfall of 55 mm/hour from 19:00 to 20:00 on July 6th and the accumulated rainfall of 388 mm from 8:00 on July 5th to 8:00 on July 7th, respectively. The inhabitants observed that debris flood rapidly increased in river flow level and hit the residential area from 19:00 to 20:00 on July 6th. These observations and the aerial photos after this debris flow event implied that the peak rainfall triggered landslides and debris flows. Figures 6 and 7 depict the situation after the event in the middle and downstream river reach, respectively. Karitsudoi Bridge (x'=2,200 m) and Hata Bridge (x'=2,110 m) trapped a large amount of driftwood and produced woody debris jams, while the downstream river (x'<1,250 m) at mild slope deposited sediment and overflowed the banks. Our measurement showed that the volume of woody debris jams at the bridges was about 1,200 m^3. On the other hand, the laser aerial survey estimated the sediment outflow from the mountain area of the Sozu River basin at about 126,000 m^3.

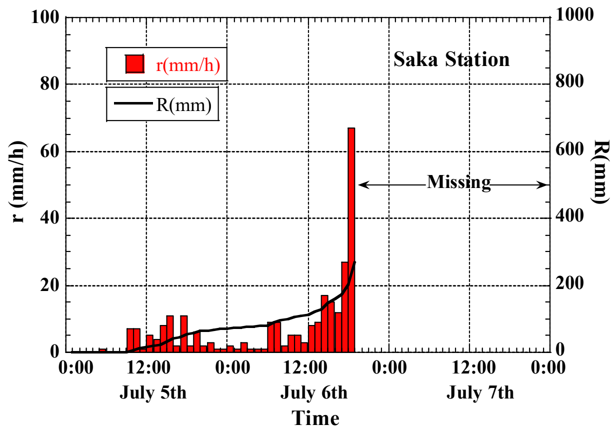

Figure 4. Rainfall situation at Saka Station.

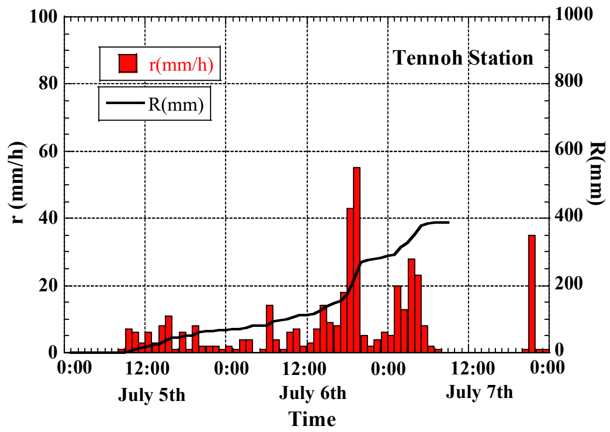

Figure 5. Rainfall situation at Tennoh Station.

Figure 6. Driftwood trapped by Karitsudoi Bridge (Upstream view at *x'*=2,200m on July 22, 2018).

Figure 7. Sediment deposition in the downstream river channel (Downstream view at *x'*=500m on July 21, 2018)

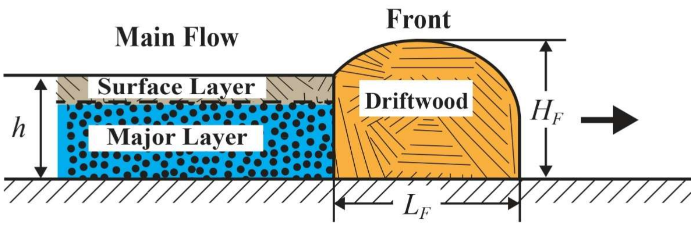

Figure 8. Schematic diagram of the simulation model of a debris flow with driftwood.

The prefecture office estimated the volume of sediment deposited in the downstream river channel and in the residential area at about 24,000 m^3 and 42,000 m^3, respectively.

4. SIMULATION MODEL AND CONDITIONS

A large amount of driftwood and sediment deposited in the middle and downstream reach originated in mountain slopes, river bed and river side banks. Naturally dense trees stood on mountain slopes and river side banks. Erosion of river bed and side, and slope failures at river head resulted in debris flow with driftwood in the surface. Since flow surface velocity is larger than front velocity, driftwood tends to accumulate at the flow front. Such driftwood accumulation at flow front was actually observed during the 2014 debris flow event at Minamikiso Town (Ishikawa, 2018) and the laboratory experiments (Fukuoka et al., 2017). Using these results, we provide a flow model as shown in Figure 8. It is composed of two parts; one is front of the main flow, and the other is the following main flow. The frontal flow is driftwood accumulated, while the main flow is sediment-water mixture with driftwood in the surface. Therefore, the main flow has the structure of two layers; the major one is sediment-water mixture and the surface is driftwood-sediment-water mixture. This model enables us to describe the movement of driftwood and sediment with river bed erosion/ deposition, river side erosion and mountain slope failure.

4.1 The basic equations for the major layer of main flow

The major layer of the main flow is sediment-water mixture. We assume that the cross sections of the river reach are approximately rectangular and then the riversides are eroded in lateral direction with angle of 90º. The mass and momentum conservation laws for such flow yield the following equations:

Momentum equation $$\frac{\partial Q}{\partial t}+\frac{\partial (vQ)}{\partial x}=-gBh\frac{\partial H}{\partial x}-(B+2h)\frac{v^2}{\varphi^2} \tag{1}$$

Continuity equation of sediment-water mixture $$\frac{\partial (Bh)}{\partial t}+\frac{\partial Q}{\partial x}=\varepsilon_z i_s + Bi_b + q_{in} \tag{2}$$

Continuity equation of sediment $$\frac{\partial (CBh)}{\partial t}+\frac{\partial (C_T Q)}{\partial x}=C_*\varepsilon_z i_s + C_* Bi_b + q_{\sin} \tag{3}$$

where t = time; x = distance measured in the downstream direction; Q = flow discharge of sediment-water mixture; v = average velocity; h = flow depth; z = bed level; $H = h+z$ = flow surface level; B = river bed width = flow width; $\varphi = v/u_*$ = non-dimensional average velocity; u_* = friction velocity; ε_z = average depth of side bank failure due to side erosion; i_s = both side erosion rate; i_b = bed erosion rate; C = volumetric concentration of sediment in flow; C_T = flux-averaged sediment concentration; C_* = maximum possible sediment concentration=0.7; q_{in} = lateral inflow rate of sediment-water mixture from the both sides; and q_{sin} = lateral inflow rate of sediment from the both sides. For the 2017 debris flow event in Asakura City, ε_z was found to take a value near 5 m (Nagano et al., 2018).

Assuming sediment concentration profile uniform, we obtain the relation of $C_T = C$.

River bed erosion rate i_b and both side erosion rate i_s are defined as

$$i_b = -\partial z/\partial t \tag{4a}$$

$$i_s = \partial B/\partial t \tag{5a}$$

Q, h, z, B and C_T are unknowns in Eqs. (1), (2) and (3). Solving these equations requires two more equations. From laboratory experiments Takaoka et al. (2005) derived two erosion rate equations of channel bed and side in a steep erodible channel:

River bed erosion rate equation $$i_b = k_b (C_{T\infty} - C_T)^p v \quad \text{for } C_{T\infty} > C_T \tag{4b}$$

$$i_b = -k_b (C_T - C_{T\infty})^p v \quad \text{for } C_{T\infty} < C_T \tag{4c}$$

River side erosion rate equation $$i_s = k_s v \tag{5b}$$

where $C_{T\infty}$ = equilibrium sediment concentration; k_b and p= coefficients regarding bed erosion rate; and k_s = coefficient for both side erosion rate. Eq.(5b) overestimates side erosion because of its neglecting the critical condition of erosion. In the present study, we use the following modified equation to consider the critical condition of both side erosion:

Modified river side erosion rate equation $$i_s = k_s (v - \kappa_c v_c) \tag{5c}$$

where v_c = critical velocity of side erosion; and κ_c = correction factor for critical velocity of side erosion.

Takaoka et al. (2005) found the coefficients to take values of k_b = 0.01 and p = 0.7 in Eqs. (4b) and (4c) from the laboratory experiments. On the other hand, Nagano et al. (2018) found appropriate values of k_s = 0.002 and κ_c = 10 in Eq. (5c) from the application of this simulation method to the 2017 Asakura debris flow event.

Critical velocity of river side erosion can be given by

$$v_c = \varphi u_{*c} = \varphi\sqrt{sgd\tau_{*c}} \tag{5d}$$

where u_{*c} = critical friction velocity; $s = (\sigma - \rho)/\rho$; d = sediment grain diameter; and τ_{*c} = critical non-dimensional shear stress. Denoting equilibrium sediment discharge per unit width by $q_{s\infty}$, we can express the equilibrium sediment concentration as

$$C_{T\infty} = \frac{Bq_{s\infty}}{Q} \tag{6}$$

The equilibrium sediment discharge $q_{s\infty}$ can be evaluated by the formula of Hashimoto et al. (2003 & 2004); this is found appropriate for various modes of sediment transport in a steep open channel:

$$\frac{q_{s\infty}}{\sqrt{sgd^3}} = 4.7\tau^{3/2}\left(1-\frac{\tau_{*c}}{\tau_*}\right)\frac{1}{(\alpha - I_f)\cos\theta}G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) \tag{7a}$$

where τ_* = non-dimensional shear stress; θ = bed slope angle; I_f = friction slope; and w_0 = fall velocity of a sediment grain in water; α = 0.875. G is a function of I_f, h/d and w_0/u_*. According to Hashimoto et al. (2003 & 2004), G can be approximated by

$$G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) = 1 + 0.1\left(\ln\left(\frac{h}{d}\right)\right)^2 (I_f)^{-0.8} \exp\left\{-2.5\left(\frac{w_0}{u_*}\right)^{0.5}\right\} \tag{7b}$$

4.2 The basic equation for surface layer of main flow

The surface layer is composed of driftwood-sediment-water mixture, the velocity of which is same as the surface velocity of the major part of main flow. Driftwood in the surface layer is produced through the erosion of river side and the transport from the upstream area. Therefore, we can obtain the following equation:

Continuity equation of driftwood
$$\frac{\partial V_d}{\partial t} + \frac{\partial Q_d}{\partial x} = n_0 i_s \frac{\pi}{4} d_d^2 l_d \tag{8}$$

where V_d = volume of driftwood on unit length of river bed in the x-direction; Q_d = volume of driftwood transported per unit time (i.e. driftwood discharge); n_0 = number of trees standing on unit area of river side bank; d_d = diameter of a tree; and l_d = length of a tree. Indicating number density of driftwood on river bed by n_d, we can express V_d as

$$V_d = Bn_d \frac{\pi}{4} d_d^2 l_d \tag{9}$$

Denoting velocity of driftwood by v_d yields driftwood discharge Q_d and driftwood number flux N_d:

$$Q_d = V_d v_d \tag{10}$$

$$N_d = Bn_d v_d \tag{11}$$

For convenience we assume the relationship between driftwood velocity v_d and average velocity v:

$$v_d = a_s v \tag{12}$$

where a_s represents the ratio of surface velocity to average velocity and is found to take a value near 1.25 from the equation of Hashimoto and Hirano (1996, 1997) and Hashimoto (2010).

4.3 The basic equation for the front of main flow

The laboratory experiments on mixture of driftwood, sediment and water showed that the mixture flow had driftwood pieces accumulated at the front like a bore in a steep open channel (Fukuoka et al, 2017). Indicating net volume of whole driftwood pieces accumulated at the front by V_F yields the following equation:

Continuity equation of driftwood
$$\frac{\partial V_F}{\partial t} = (v_d - v)V_d = \frac{a_s - 1}{a_s} Q_d \tag{13}$$

Here the values of v, v_d, V_d and Q_d represent those at the front of main flow. Expressing scales representative of the front in the flow and vertical directions as L_F and H_F, we can have

$$V_F = Bk_F H_F L_F \lambda_d \tag{14}$$

where k_F = correction factor for volume of front; and λ_d = 0.2=volumetric concentration of driftwood pieces at the front. Assuming the front form semicircle, we obtain the coefficient $k_F = \pi/4$ and the relation $L_F = 2H_F$.

4.4 Boundary and initial conditions

We numerically simulate the debris flow event from 16:00 to 21:00 on July 6th. This simulation is made along the Ohban and Sozu River from stations O_o to O_M (Figure 2). Stations O_o and O_M represent the position downstream immediately from the landslide location and the river mouth downstream immediately from Shimosozu Bridge (x'=250 m), respectively.

4.4.1 The boundary condition at the upstream end

We consider two different boundary conditions during the landslide time and the other time. The boundary condition during the landslide time can be given by

$$Q = Q_{w0} + Q_0 \text{ , } h = h_\infty \text{ , } C_T = C_0 \text{ and } Q_d = Q_{d0} \quad \text{for } t_L \le t \le t_L + T \tag{15a}$$

where Q_{w0} = water discharge due to rain; Q_0 = debris flow discharge due to landslide; h_∞ = normal depth; C_0 = sediment concentration; Q_{d0} = driftwood discharge due to landslide; t_L = initiation time of landslide; and T = landslide duration. Occurrence of landslide-induced debris flow can be interpreted as transformation of stationary sediment slope of volume V_s into debris flow of discharge Q_o by landslide (Takaoka et al., 2007). From the concept of response function for the transformation and the mass conservation law for the sediment, Takaoka et al. (2007) obtained the relationship between slope (i.e. landslide) sediment volume and debris flow discharge. We can also derive driftwood discharge from the same discussion as the above one. Assuming the response function 1/ T, we can express debris flow and driftwood discharge as

$$Q_0 = C_* V_s /(TC_0) \text{ and } Q_{d0} = A_s n_0 \frac{\pi}{4} d_d^2 l_d /(T) \quad \text{for } t_L \le t \le t_L + T \tag{15b}$$

On the other hand, the boundary condition during the other time can be given by

$$Q = Q_{w0} \text{ , } h = h_\infty \text{ , } C_T = C_{T\infty} \text{ and } Q_d = 0 \quad \text{for } 0 \le t < t_L \text{ or } t_L + T < t \tag{16}$$

We can estimate Q_{w0} using rational equation at the upstream end with runoff coefficient $f = 0.9$. From the aerial photos of National Geographical Survey Institute (2018) and the observation of the inhabitants we assume the landslide conditions as shown in Table 1.

4.4.2 The boundary condition at the downstream end

The boundary condition at the downstream end can be given by

$$C_T = C_{T\infty} \tag{17}$$

4.4.3 The initial condition

The simulation needs the initial condition of river bed elevation and river bed width. The initial river bed elevation can be determined by topographic map (National Geographical Survey Institute, 2018). The initial river bed width can be determined by the aerial photos before the debris flow event and the empirical relation between river bed width B and river basin area A: $B = 5.36A^{0.37}$ (Park and Hashimoto, 2003).

We assume that river bed was composed of cohesionless sediment 10 m deep. Therefore, erosion of river bed deeper than 10 m is impossible.

4.5 The other conditions

Tables 2 and 3 show the other simulation conditions. Although the rainfall lasted for three days from July 5th to July 7th, the debris flow event occurred during the heavy rain on July 6th. Therefore, we focus the simulation on the period of heavy rain; it is from 16:00 to 21:00 on July 6th. However, Saka Station close to the study river failed the rainfall measurements after 19:00 on July 6th. Therefore, we use the rainfall measurements at Saka Station from 16:00 to 19:00 and Tennoh Station from 19:00 to 21:00 (Figures 4 and 5). The conditions of trees (Table 3) is based on our field observations after the debris flow event. The values of the coefficients in the basic equations have been determined in the previous works (Takaoka et al., 2005; Nagano et al., 2018) independently of the present study. Non-dimensional average velocity φ of debris flow depends on the parameter N_h; this parameter is found to represent sediment-water mixture flow such as Reynolds Number for clear water flow (Hashimoto and Hirano, 1996, 1997; Hashimoto, 2010). On the basis of this parameter we use the values of $\varphi = 8$ for mountain torrent and $\varphi = 10$ for mild river channel.

The upstream reach, namely the Ohban River, is a natural mountain torrent, whereas the middle and downstream reach of the Sozu River is artificial channel with the both sides fixed. Therefore, this simulation neglects erosion of the both sides of the river channel of $x' \leqq 2{,}400$ m. Furthermore, this simulation neglects debris flood overflow from the channel side banks in the downstream reach ($x' <$ 1,250 m).

5. RESULTS AND DISCUSSION

The simulation results are shown in Figures 9 to 14.

Table 1. Conditions of the landslide.

Initiation time of landslide	t_L=19:00 on July 6th
Duration of landslide	T=60 sec
Volume of landslide sediment	V_s=2,000 m^3
Area of landslide slope	A_s=2,000 m^2
Sediment concentration in the debris flow at the upstream end (landslide location)	C_o=0.4
Sediment grain diameter	d=5 mm
Depth of sediment bed	D=10 m

Table 2. Conditions of the numerical simulation.

Calculation time	5 hours from 16:00 to 21:00 on July 6th
Time step	Δt=0.05 sec
Distance step	Δx= 50 m

Table 3. Conditions of trees on river side banks and mountain slopes.

Number density of trees	n_0 = 0.60 /m^2
Diameter of a tree	d_d = 0.141 m
Length of a tree	l_d = 9.45 m

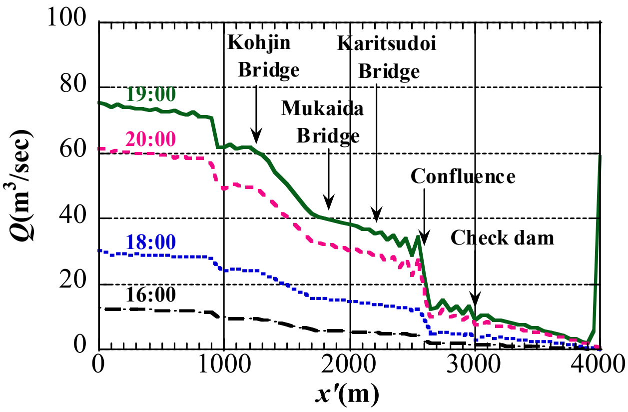

Figure 9. Longitudinal variation in flow discharge.

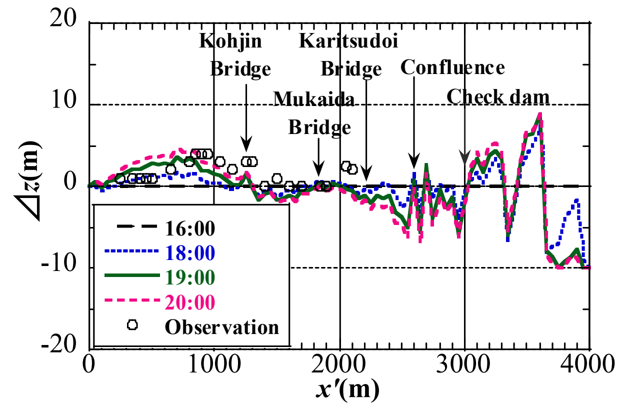

Figure 10. Longitudinal variation in bed elevation change.

First, Figures 9 and 10 indicate longitudinal variation in flow discharge Q and river bed elevation change Δz, respectively. Flow discharge increased gradually with distance downstream and rapidly at the confluence of the Sozu and Ohban River (x'=2,600 m). A sudden increase in flow discharge at the upstream end was due to the occurrence of landslide at 19:00.

Significant erosion of river bed and side bank occurred in the most upstream reach (3,600m <x') of the Ohban River. Considerable deposition of sediment resulted beyond the check dam (x'=3,000 m) because of sudden increase in river bed width. River bed was eroded slightly in the middle reach (1,250 m <x'< 2,200 m). This corresponds to the channel bed situation observed after the event. On the other hand, considerable sediment deposition arose in the downstream reach (x'< 1,250 m). This was ascribed to the milder bed slope. These simulation results of river bed erosion in the upstream and middle reach and sediment deposition in the downstream reach agree reasonably well with the observations.

The volume of sediment outflow from the river basin at the Karitsudoi Bridge is estimated at 63,000 m^3. The volume of sediment deposition in the downstream reach is also found 31,000m^3. These are in good agreement with the laser aerial survey and our measurement. On the other hand, the volume of driftwood outflow from the river basin is estimated at 1,100 m^3. This value can be compared with the measured volume of woody debris jams at the bridges, if the whole outflow of driftwood was trapped by the bridges. These agree well with each other. Here the porosity of woody debris jams is assumed equal to 0.8 from the field survey of the 2013 flood event in the Nayoshi River, Shimane Prefecture (Rusyda et al., 2014).

Second, Figures 11 and 12 show time-variation in flow discharge Q and driftwood discharge Q_d at Karitsudoi Bridge (x'=2,200 m), respectively. In Figure 12, driftwood discharge Q_d is defined as the volume of driftwood transported per unit time. In fact, this bridge trapped a large amount of driftwood during the debris flow event. Flow discharge Q increased rapidly past 18:00 corresponding to the sudden increase in rainfall at 18:00. Sediment transport was active and sediment concentration became around 10 %. At the same time, driftwood began to appear in the flow (Figure 12). However, driftwood transport was not active yet so as to block the river channel. At this time, it was possible that some pieces of driftwood move through the bridge to the downstream reach.

Third, Figure 13 expresses time-variation in flow surface H and bed elevation z at x'=500 m in the downstream reach. Here the numerical calculations of H and z are independent of the driftwood calculation. We can deduce that rapid increase in flow surface occurred with significant sediment deposition from 18:00 and inundation of this area began around 19:00. At this time, less driftwood transport occurred but significant sediment transport arose.

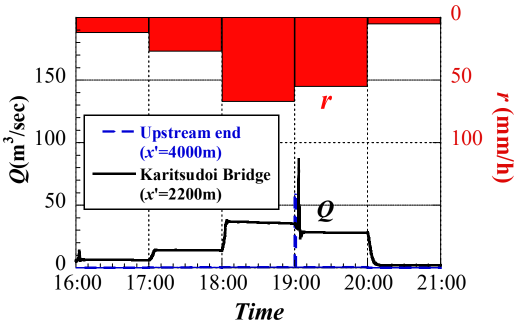

Figure 11. Hydrograph of flow discharge at Karitsudoi Bridge (x'=2,200 m).

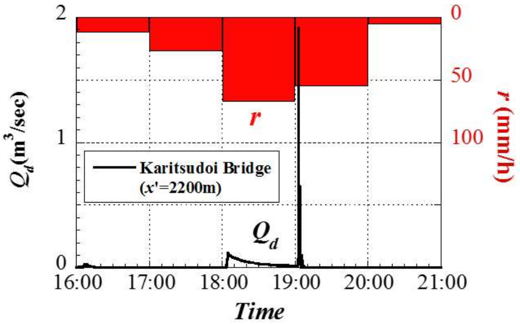

Figure 12. Hydrograph of driftwood discharge at Karitsudoi Bridge (x'=2,200 m).

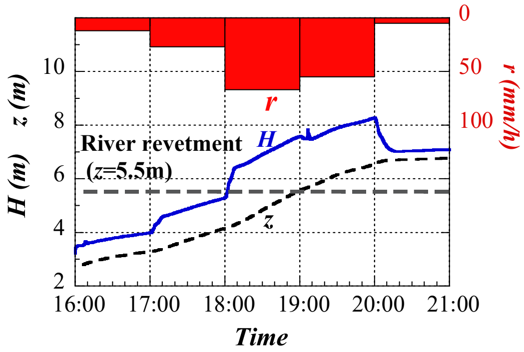

Figure 13. Time-variation in river bed elevation and flow surface at x'=500m in the downstream reach.

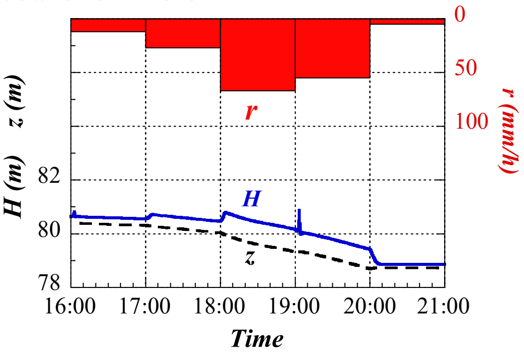

Figure 14. Time-variation in river bed elevation and flow surface at Karitsudoi Bridge (x'=2,200 m).

We assume the occurrence of landslide at 19:00 at Station O_o (Figure 2). The occurrence of landslide on the steep mountain slope resulted in debris flow with a bore. This debris flow arrived at Karitsudoi Bridge (x'=2,200 m) in about 200 second and at Shimososu Bridge (x'=250 m) in about 430 second. The peak flow discharge was Q=89 m^3/sec at Karitsudoi Bridge and Q=81 m^3/sec at Shimososu Bridge. Following this time yielded an instantaneous increase in transport of sediment and driftwood. As a result, flow front of driftwood pieces was 3.2 m deep. On the other hand, the field survey after the event found the bridge girder 2.7m high from the riverbed. This reveals the possibility of channel blocking due to driftwood at Karitsudoi Bridge (Figure 14).

We conclude that this simulation method provides satisfactory result in predicting the debris flow event, although the values of all coefficients in the basic equations were determined independently of this study.

6. CONCLUSIONS

The numerical simulation presented in this paper find that flooding occurred on the residential area after the peak rainfall and channel blocking arose at Karitsudoi Bridge immediately after the landslide. The detailed results obtained in this study are as follows:

1. Regarding flow front of driftwood pieces only as a bore yields a flow model shown in Figure 8 for the numerical simulation.
2. Less driftwood transport occurred but significant sediment transport arose during the peak rainfall. In the downstream reach, considerable sediment deposition occurred and then resulted in higher flow surface during the peak rainfall and before the landslide.
3. Considerable driftwood transport arose immediately after the landslide. As a result, flow front of driftwood pieces was higher than the bridge girder. This caused channel blocking at Karitsudoi Bridge in the middle reach.
4. The volume of sediment outflow from the upstream river basin is estimated at 63,000 m^3. The volume of sediment deposition in the downstream river reach is also found 31,000m^3. The volume of driftwood outflow from the upstream river basin is also estimated at 1,100 m^3.
5. The proposed simulation method provides satisfactory result in predicting the debris flow event, although all coefficients in the basic equations of the simulation were determined independently of this study.

REFERENCES

Fukuoka, N., Takaoka, H., Nagano, H., and Hashimoto, H. (2016). An investigation into the 2014 debris flow event with driftwood in Hiroshima City, Japan. *Proceedings of the 20th Congress of the IAHR-APD*, August - 28, 29, 30, 31. Colombo, Sri Lanka. CD-ROM.

Fukuoka, N., Yamamoto, T., Nagano, H., Ikematsu, S., and Hashimoto, H. (2017). Experiments on resistance to debris flow with driftwood in steep open channel. *Proceedings of the 66th annual conference of JSEC*: 94-95 (in Japanese).

Hashimoto, H., and Hirano, M. (1996). The structure of turbulent hyperconcentrated flows and their resistance in an open channel. *Journal of Hydroscience and Hydraulic Engineering*, Vol.14, No.2: 9-17.

Hashimoto, H., and Hirano, M. (1997). A flow model of hyper-concentrated sand-water mixtures. *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings of First International Conference. San Francisco, California, August 7-9*: 464-473.

Hashimoto, H., Park, K., Ikematsu, S., and Tasaki, N. (2003). A sediment discharge formula for various types of sediment transport in a steep open channel. *Annual Journal of Hydraulic Engineering*, JSCE 47: 571-576 (in Japanese).

Hashimoto, H., Takaoka, H., and Park, K. (2004). Sediment discharge formula for steep open channel. *Proceedings of the 9th International Symposium on River Sedimentation*, Yichang, China, October 18-21: 1453-1461.

Hashimoto, H. (2010). Mechanics of sediment transport by open-channel flow. *NAGARE*. The Japan Society of Fluid Mechanics. Vol.29. No.3: 193-202 (in Japanese).

Ishikawa, Y. (2018). Characteristics of recent woody debris disasters and countermeasure. *Proceedings of the 9th Symposium on Sediment-Related Disasters*, JSCE-west: 61-66 (in Japanese).

Japanese Ministry of Land, Infrastructure, Transport and Tourism, (2018). River flood information. http://www.river.go.jp/ (in Japanese).

Nagano, H., Hashimoto, H. and Miyoshi, T. (2013). One-dimensional model of landslide-induced debris flow with woody debris. *Proceedings of the 35th IAHR World Congress*. CD-ROM.

Nagano, H., Fukuoka, N., and Hashimoto, H. (2018). Flow characteristics of wood-sediment-water mixture in the Shirakidani River, Asakura City, Japan in 2017. *Advances in River Engineering*, JSCE, Vol.24: 487-492 (in Japanese).

National Geographical Survey Institute (2018). https://fgd.gsi.go.jp/download/menu.php.

Park, K., and Hashimoto, H. (2003). Runoff analysis of debris flows at Mt. Unzendake Volcano, Japan. *Proceedings of the 3rd International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, D. Rickenmann & C.L. Chen (eds.), *Davos, Switzerland, September 10-12*: 695-704.

Rusyda, M.I., Kusukubo, M., Maricar M. F., Ikematsu, S. and Hashimoto, H (2014). Woody debris accumulation during the flood event in the Nayoshi River, Tsuwano Town, Japan. *Proceedings of the 19th IAHR-APD Congress, Hanoi, Vietnam.* CD-ROM.

Takaoka, H., Hashimoto, H., Park, K. and Hisaoka, N. (2005). Bed and bank erosion rate equations for a steep mountain river. *Proceedings of the 31th IAHR World CONGRESS.* Seoul, Korea, September 11-16: 3131-3143.

Takaoka, H., Hashimoto, H., and Hikida, M. (2007). Simulation of landslide-induced debris flow- The Atsumari debris flow disaster in Minamata City, Japan, *Proceedings of 4th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, Cheng-lung Chen & John J. Major (ed.): 353-363.