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NUMERICAL SIMULATION ON DEBRIS-FLOW WITH DRIFTWOOD AND ITS CAPTURING DUE TO JAMMING OF DRIFTWOOD ON A GRID DAM

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A two-dimensional numerical model is developed for computing the characteristics of debris flow with driftwood and its capturing process due to jamming of driftwood on a grid dam. Equations of the rotational motion and the translational motion of driftwood are evaluated dynamically in the Lagrangian form. A numerical model is developed with an interacting combination of Eulerian expression of the debris flow and Lagrangian expression of the driftwood, in which the fluctuation components of the position and the rotational angular velocity of the driftwood are dealt with stochastically. The jamming of driftwood on a grid dam is evaluated based on the geometric conditions and probabilistic approaches. The simulated results of outflow discharge and driftwood agree well with the experimental results.

Key Words **:** *Debris flow, driftwood, grid dam, jamming of grid opening, two-dimensional model*

1. INTRODUCTION

In recent years much driftwood has combined with debris flow, due to heavy downpours over mountainous rivers, which result in damage of properties and loss of lives in the lower reaches of rivers. Generally the catchment area of mountainous rivers is covered by forest. In these areas, debris flow flows down along the river with driftwood. Such driftwood clogs narrows in the river course or bridge or culvert sites giving rise to flooding, bridge damage or destruction. Many researchers such as Takahashi *et al.*[1)], Honda and Egashira[2)] and others have proposed numerical models of debris flow as a mixture of sediment and water, but they have not considered the behavior of debris flow with driftwood. On the other hand, some numerical studies to compute the behavior of driftwood only with clear water flow have been carried out by Nakagawa *et al.*[3)], and few others, but they have not focused on computing the behavior of driftwood with debris flow or sediment water mixture flow.

Check dams are one of the effective structural countermeasures for debris flow control[4)]. Many researchers have investigated debris flow capturing by check dams considering sediments of the flow only[4), 5), 6)]. Only very few research works have been carried out on capturing of debris flow and driftwood by check dam[7)]. Furthermore, these studies are limited to experimental study and on closed type check dam only. Debris flow may be captured due to jamming of driftwood on an open type check dam. Therefore, recent attention is required to focus on behavior of debris flow with driftwood and countermeasures against debris flow with driftwood.

In this study, a two-dimensional numerical model is developed for computing the behavior of debris flow with driftwood and its capturing process due to jamming of driftwood on a grid dam. A numerical model is developed with an interacting combination of Eulerian expression of the debris flow and Lagrangian expression of the driftwood. The motion of driftwood is restricted near the flow surface. The simulated results are compared with those obtained from hydraulic model experiments.

2. NUMERICAL MODEL OF MOTION

(1) Basic equations of debris flow motion

The horizontally two-dimensional momentum equations, continuity equations of flow and sediment of debris flow can be expressed as

$$\frac{\partial M}{\partial t}+\beta\frac{\partial(uM)}{\partial x}+\beta\frac{\partial(vM)}{\partial y}=gh\sin\theta_{bx0}$$
$$-gh\cos\theta_{bx0}\frac{\partial(z_b+h)}{\partial x}-\frac{\tau_{bx}}{\rho_T}+\frac{\tau_{sx}}{\rho_T} \qquad (1)$$

$$\frac{\partial N}{\partial t}+\beta\frac{\partial(uN)}{\partial x}+\beta\frac{\partial(vN)}{\partial y}=gh\sin\theta_{by0}$$
$$-gh\cos\theta_{by0}\frac{\partial(z_b+h)}{\partial y}-\frac{\tau_{by}}{\rho_T}+\frac{\tau_{sy}}{\rho_T} \qquad (2)$$

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=i_b \qquad (3)$$

$$\frac{\partial(Ch)}{\partial t}+\frac{\partial(CM)}{\partial x}+\frac{\partial(CN)}{\partial y}=i_bC_* \qquad (4)$$

where $M\ (=uh)$ and $N\ (=vh)$ are the flow discharge per unit width in x and y directions, u and v are the velocity components in x and y directions, h is the flow depth, z_b is erosion or deposition thickness measured from original bed elevation using equation $\partial z_b/\partial t+i_b=0$, θ_{bx0} and θ_{by0} are the x and y components of slope of the original bed surface, i_b is erosion/deposition velocity used as Takahashi *et al.*[1]), C is the sediment concentration in the flow, C_* is maximum sediment concentration in the bed, β is momentum correction factor, g is the acceleration due to gravity, τ_{bx} and τ_{by} are the bottom shear stresses in x and y directions used as Takahashi[8]), ρ_T is mixture density, and τ_{sx} and τ_{sy} are the shear stresses at the flow surface in x and y directions generated as the reaction of the drag force acting on the driftwood as follows;

$$\tau_{sx}=\frac{1}{A}\sum_{k=1}^{N_t}\left\{\frac{1}{2}\rho_T C_{Dx}W_k(u_k-U_k)A_{kx}\right\} \qquad (5)$$

$$\tau_{sy}=\frac{1}{A}\sum_{k=1}^{N_t}\left\{\frac{1}{2}\rho_T C_{Dy}W_k(v_k-V_k)A_{ky}\right\} \qquad (6)$$

where u_k and v_k are the respective driftwood velocity components in x and y directions, U_k and V_k are the respective local velocity components of the fluid in x and y directions at the position of the centroid of the driftwood, $W_k=\sqrt{(u_k-U_k)^2+(v_k-V_k)^2}$, A_{kx} and A_{ky} is the respective projected areas of the submerged part of the driftwood in x and y directions, C_{Dx} and C_{Dy} are drag coefficients in x and y directions, A is the flow surface area, and N_t is the number of total pieces of driftwood in area A.

As the motion of the piece of driftwood is restricted near the flow surface, the surface flow velocity components are calculated as Takahashi[8]).

(2) Basic equations of driftwood motion

It is assumed that the pieces of driftwood are sufficiently dispersed so that collisions between them are infrequent. The equations of motion of each piece of driftwood, individually labeled by subscript k are expressed as

$$\frac{dX_k}{dt}=u_k\ ; \qquad \frac{dY_k}{dt}=v_k \qquad (7)$$

$$(m_k+mC_M)\frac{du_k}{dt}=m(1+C_M)\frac{dU_k}{dt}-m_kg\frac{\partial H_k}{\partial x}$$
$$-\frac{1}{2}\rho_T C_{Dx}W_k(u_k-U_k)A_{kx} \qquad (8)$$

$$(m_k+mC_M)\frac{dv_k}{dt}=m(1+C_M)\frac{dV_k}{dt}-m_kg\frac{\partial H_k}{\partial y}$$
$$-\frac{1}{2}\rho_T C_{Dy}W_k(v_k-V_k)A_{ky} \qquad (9)$$

where X_k and Y_k are the position of the centroid of the driftwood, m_k is the mass of the driftwood, m is the mass of the fluid occupied by volume of a piece of driftwood, C_M is virtual mass coefficient, and H_k is the flow level at centroid position of the driftwood.

The rotational motion around the axis of the centroid of the driftwood is described by evaluating the moment N_0 produced by the hydrodynamic force acting on the driftwood as

$$Id^2\theta_k/dt^2=\sum N_0 \qquad (10)$$

where θ_k is the rotational angle of the piece of driftwood and I is the moment of inertia around the centroid. The rotational motion of driftwood is also supposed to be restricted on the flow surface and the rotation on the vertical plane is not considered.

a) Fluctuation of position of driftwood

Driftwood position can be evaluated by integrating Eq.7 deterministically, but it fluctuates due to the collision of driftwood with boulders and disturbances on the flow surface during the collision of sediment particles. Hence, the fluctuation components of driftwood position ΔX_k and ΔY_k are evaluated as Nakagawa *et al.*[3]).

$$\Delta X_k=\sqrt{4K_x(2\Delta t)}erf^{-1}(\alpha)\ ; \quad \Delta Y_k=\sqrt{4K_y(2\Delta t)}erf^{-1}(\beta) \qquad (11)$$

where K_x and K_y are longitudinal and transverse diffusion coefficients; α and β are random variables uniformly distributed in the range (0,1), and erf^{-1} is the inverse of error function, *erf*, given by

$$\left.\begin{aligned} erf(s)&=\{1-\Phi(\sqrt{2}s)\}=\left(1/\sqrt{\pi}\right)\int_s^{\infty}\exp(-\eta^2)d\eta \\ \Phi(s)&=\left(1/\sqrt{2\pi}\right)\int_{-\infty}^{s}\exp(-\eta^2/2)d\eta \end{aligned}\right\} \qquad (12)$$

The driftwood position is estimated by adding the fluctuation value to the value obtained from the equations of motion deterministically as

$$X_k^{n+3}=X_k^{n+1}+u_k^{n+2}(2\Delta t)+\sqrt{4K_x(2\Delta t)}erf^{-1}(\alpha) \qquad (13)$$

$$Y_k^{n+3} = Y_k^{n+1} + v_k^{n+2}(2\Delta t) + \sqrt{4K_y(2\Delta t)}erf^{-1}(\beta) \qquad (14)$$

b) Fluctuation of rotational angle of driftwood

The rotational angle of driftwood is evaluated as

$$d\theta_k / dt = \omega_d + \omega_p \qquad (15)$$

where ω_d is the angular velocity of the piece of driftwood obtained deterministically and ω_p is the fluctuation of the angular velocity of the driftwood evaluated stochastically. Assuming the rotational angular velocity of the fluctuating component of a piece of driftwood follows a normal distribution, its distribution function, Φ, is given by

$$\Phi\left(\frac{\omega_p - \overline{\omega}}{\sigma_w}\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{\omega_p - \overline{\omega}}{\sigma_w}} \exp(-\eta^2/2)d\eta \qquad (16)$$

where $\gamma = (\omega_p - \overline{\omega})/\sigma_w$ is obtained from the inverse function, Φ^{-1}, for uniformly distributed random numbers within (0,1), $\overline{\omega}$ and σ_w are the mean and standard deviation of angular velocity of driftwood.

3. LABORATORY EXPERIMENTS

(1) Determination of diffusion coefficients and rotational angle of driftwood

A rectangular flume of 5m long, 30cm wide and 45cm deep is set at slope of 18^o. To measure the position and rotational angle of the driftwood, 19 pieces measuring rods having the same length as the flume width, are stretched across the flume at intervals of 10cm in the downstream direction along the 1.8m measuring reach from 2.6m downstream from the upstream end (x=0). Sediment (mean size= 1.86mm, maximum size=4.75mm) is supplied with a sediment feeder at 0.8m downstream from the upstream end and water discharge is supplied from the upstream end of the flume. A piece of driftwood is supplied at x=-10cm after supplying designated water and sediment mixture flow discharge. The position and rotational angle of the moving driftwood are measured with a video camera. Such measurement is repeated 30 times for each experiment under the same hydraulic conditions. A 3.5cm long, cylindrical piece of driftwood with a diameter of 3mm and a mass density ρ_d = 0.785g/cm^3 is used. Eight experiments are carried out with different hydraulic conditions.

a) Diffusion coefficient of driftwood

The scattering process of driftwood is described as a diffusion process and the diffusion coefficients might be defined. The frequency distributions of transverse and longitudinal positions of the driftwood are shown in **Fig.1** and **Fig.2a**, in which solid line is calculated from the normal distribution. The longitudinal and transverse diffusion coefficients of the driftwood are evaluated as

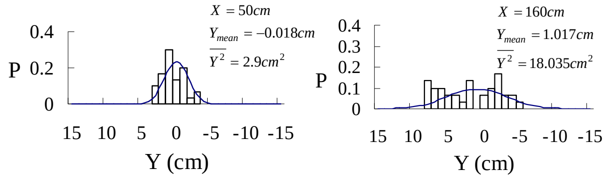


Fig.1 Frequency distribution of the transverse positions of the driftwood, RUN 1.

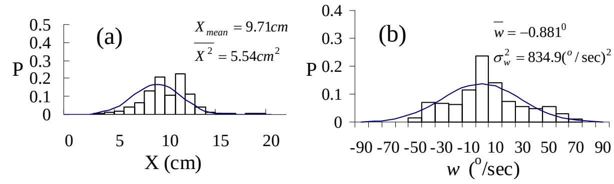


Fig.2 Frequency distribution of (a) longitudinal position, and (b) rotational angular velocities of the driftwood, RUN 1.

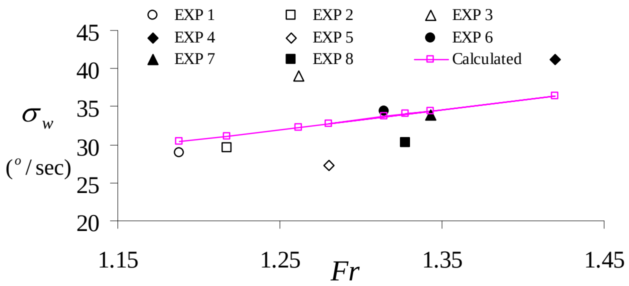


Fig.3 Relation of Froude number, Fr, to standard deviation, σ_w, of the rotational angular velocities of the driftwood.

$$K_x = (1/2)(\overline{dX^2}/dt) \quad ; \quad K_y = (1/2)(\overline{dY^2}/dt) \qquad (17)$$

where $\overline{X^2}$ and $\overline{Y^2}$ are longitudinal and transverse variance. The average value of the non dimensional diffusion coefficients $K_x/u_*h = 0.649$ and $K_y/u_*h = 0.343$ are obtained, in which $u_* = \sqrt{gh\sin\theta}$ is friction velocity.

b) Rotational angle of driftwood

Frequency distribution of the rotational angular velocities of driftwood obtained experimentally is shown in **Fig.2b**, in which solid line is calculated by assuming the normal distribution with values of the parameters determined from the experiments. The mean value of the angular velocities is approximately zero, $\overline{\omega} \approx 0$. The standard deviation appears to be prescribed by the hydraulic parameters, and it is related to the Froude number. The relation between the Froude number, Fr, and the standard deviation of the rotational angular velocity of the driftwood, σ_w, is shown in **Fig.3**, and the relation is obtained as $\sigma_w = 25.61Fr$.

(2) Experiments for debris flow motion with driftwood and its capturing by a grid dam

A rectangular flume of 5m long, 10cm wide and 13cm deep is set at slope of 18^o. A sediment bed of 1.9m long and 7cm deep is positioned 2.8m upstream from the outlet of the flume. Sediment materials with mean diameter d_m = 2.39mm, maximum diameter d_{max} = 11.2mm, C_* = 0.65, $\tan\phi$ =

0.7 (ϕ=angle of repose) and sediment density σ = 2.65g/cm^3 are used. The particle size distribution of sediment mixture is shown in **Fig.4a**. Cylindrical pieces of 38 driftwood pieces (ρ_d =0.785g/cm^3) are positioned on the bed sediment at intervals of 10cm c/c along the downstream direction from 7.5cm downstream from the upstream end of the bed sediment in two columns 2cm apart. Debris flow is produced by supplying a constant water discharge 270cm^3/sec for 10sec from the upstream end of the flume. A grid dam (**Fig.4b)** is set at 20cm upstream from end of the flume. The experiments are carried out for driftwood pieces of diameter 3mm and 4mm with 3.5cm, 4.0cm and 4.5cm in length.

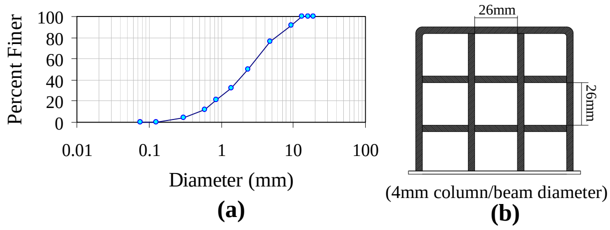


Fig.4 (a) Particle size distribution of bed sediment, (b) Grid dam.

4. DRIFTWOOD JAMMING AND DEBRIS FLOW DEPOSITION

(1) Driftwood jamming on a grid dam

The jamming of driftwood on a grid dam is evaluated with the geometric conditions and probabilistic approaches. Four cases are considered as conditions under which driftwood is jammed on open spaces of a grid dam: (1) a piece of driftwood with a large rotational angle (**Fig.5a**). On the basis of the experimental results, it is considered the rotational angle of the driftwood to be in the range $70^o \le \theta_k \le 90^o$. (2) A piece of driftwood will be jammed on a grid dam due to geometric conditions as $y_{d1} < y_{g1}$ and $y_{d2} > y_{g2}$ (**Fig.5b**). (3) A piece of driftwood coming from the rear also will be jammed by the pieces of driftwood already jammed on a grid dam (**Fig.5c**). It is considered that when more than five pieces of driftwood already jammed at previous time level of calculation, all pieces of driftwood coming from the rear are also considered to be jammed on a grid dam. (4) The pieces of driftwood will be jammed when the number of pieces of driftwood arrival at grid opening at a same time (**Fig.5d**). In this case, the probability of a piece of driftwood jamming depends on the number of driftwood arrival at grid opening at same time. This probability, $p(n)$, can be assessed in hydraulic experiments with assuming the functions of length (L_d) and diameter (D_d) of driftwood, clear spacing between two columns of grid dam (L_g) and number of driftwood (n) arrival at same time. The following relation is obtained from the experimental values as

$$p(n) = 0.32\left(\frac{L_d}{L_g - D_d}\right)^{0.63} n^{0.3} \qquad (18)$$

This equation is represented in **Fig.6** with experimental values. To determine which pieces of driftwood will be jammed, the random variable, q, uniformly distributed in the range (0,1), is generated for each piece of driftwood flowing down the flume. The driftwood is considered to be jammed when the condition $p(n) > q$ is satisfied.

(2) Debris flow deposition due to jamming of driftwood on a grid dam

Due to the jamming of driftwood on a grid dam, sediment is deposited behind the grid dam. The effects of the driftwood jamming on debris flow deposition at grid dam is evaluated based on the projected horizontal length of driftwood piece in y direction with its rotational angle and clear spacing of column of grid dam, and the sediment passing rate, P_s, through a grid dam is determined as $P_s = L_o / L_g$ (**Fig.7**). The deposition velocity, i_{dep}, is derived under the mass conservation law of sediment discharge per unit width (Q_{sed}) and sediment deposition as

$$\left.\begin{aligned} C_*\Delta x \Delta z &= (1-P_s)Q_{sed}\Delta t \\ i_{dep} &= -\Delta z/\Delta t = -(1-P_s)Q_{sed}/(C_*\Delta x) \end{aligned}\right\} \qquad (19)$$

where Δx is the distance increment of calculating point and Δz is the thickness of the deposition.

The open spaces of grid dam may be also blockaded by large boulders, and growing rate formula developed by Satofuka and Mizuyama[6] is

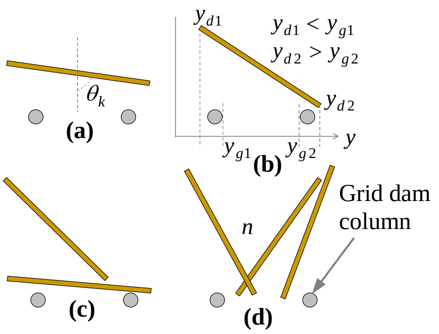


Fig.5 Driftwood position and jamming process.

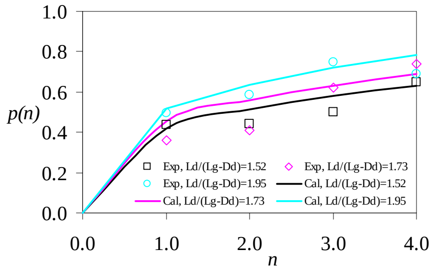


Fig.6 Plot of jamming probability as Eq.18 with experimental data.

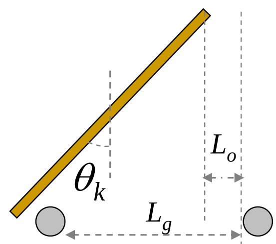
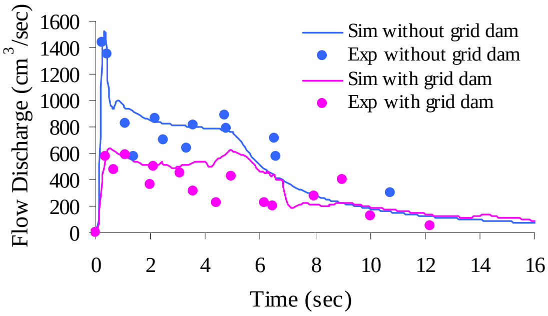
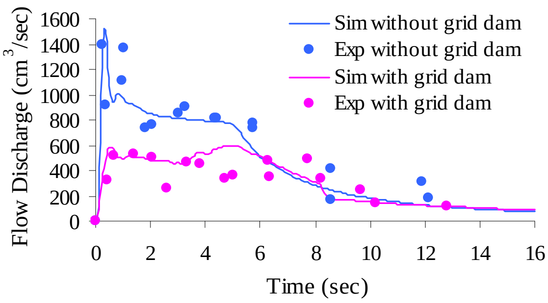


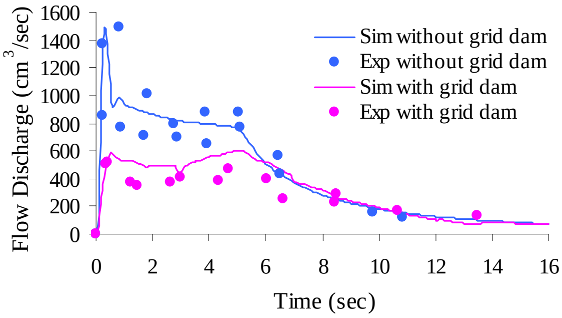
Fig.7 Schematic diagram for sediment passing rate through grid dam.



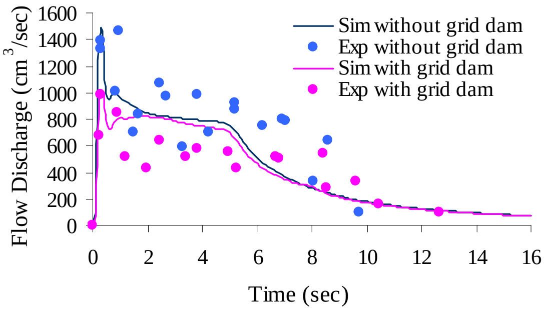
(a) Case with driftwood D_d=3mm and L_d =3.5cm



(b) Case with driftwood D_d=3mm and L_d =4.5cm



(c) Case with driftwood D_d=4mm and L_d =4.5cm



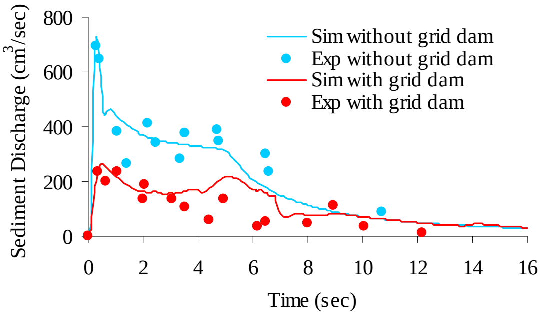
(d) Flow without driftwood case

Fig.8 Flow discharge at downstream end of flume and discharge reduction by grid dam due to driftwood jamming.

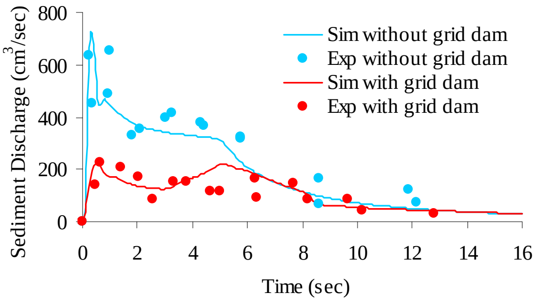
also considered. The deposition velocity equation upstream of a check dam developed by Shrestha *et al.*[4] is also employed to calculate debris flow deposition in the upstream area of check dam.

5. RESULTS AND DISCUSSIONS

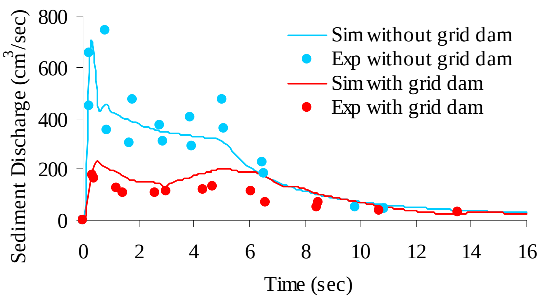
The numerical simulations and experiments are carried out to compute the characteristics of debris flow with driftwood and its capturing process due to jamming of driftwood on a grid dam. The driftwood behavior of scattering in the flow field has been treated as the diffusion process. **Fig.8a** shows the flow discharge at downstream end of the flume and reduction of flow discharge by grid dam with debris flow capturing due to jamming of driftwood on a grid dam, in case of driftwood D_d=3mm, L_d=3.5cm. Debris flow is captured effectively by a grid dam due to the driftwood jamming. The simulated results of flow discharge passed through a grid dam and flow discharge without dam are quite close to the experimental results. The results of out flow discharge for the cases with driftwood D_d=3mm, L_d=4.5cm; and driftwood D_d=4mm, L_d=4.5cm are shown in **Fig.8b** and **Fig.8c**, respectively. **Fig.8d** shows the flow discharge without driftwood case, in which flow discharge is not reduced effectively by a grid dam compared to flow discharge with driftwood cases. Thus from the results, outflow discharge from a grid dam is reduced by a grid dam more effectively in the cases with driftwood due to jamming of driftwood on a grid dam. The results of sediment discharge at downstream end of the flume



(a) With driftwood, D_d=3mm, L_d =3.5cm

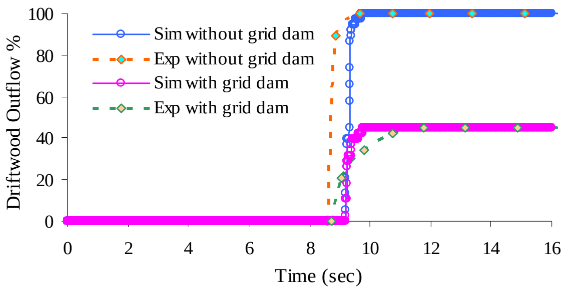


(b) With driftwood, D_d=3mm, L_d =4.5cm

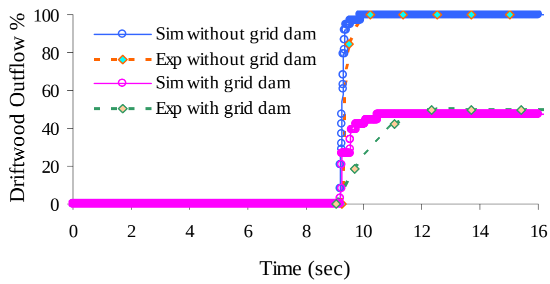


(c) With driftwood, D_d=4mm, L_d =4.5cm

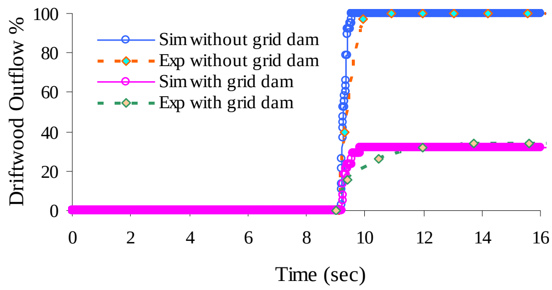
Fig.9 Sediment discharge at downstream end and discharge reduction by grid dam due to driftwood jamming.



(a) Driftwood, D_d=3mm, L_d =3.5cm case



(b) Driftwood, D_d=3mm, L_d =4.5cm case



(c) Driftwood, D_d=4mm, L_d =4.5cm case

Fig.10 Accumulated driftwood outflow at outlet of the flume.

with different sizes of driftwood are shown in **Fig.9**. The sediment discharge is reduced by sediment deposition behind a grid dam due to driftwood jamming on a grid dam. The simulated results of outflow sediment discharge from a grid dam are also agreeable with the experimental results. The effect of driftwood jamming on sediment deposition behind a dam using developed deposition equation is well explained in the simulations.

The results of percentage of temporal driftwood outflow at the downstream end of the flume for different sizes of driftwood cases are shown in **Fig.10**. The percentage of driftwood outflow is the ratio of the number of pieces of driftwood outflow at downstream end to the total amount of driftwood supplied at the inflow boundary. The driftwood passed through a grid dam is reduced due to the driftwood jamming on grid dam. The number of pieces of the driftwood outflows from a grid dam based on the developed driftwood jamming model under the geometric conditions and probabilistic approaches are well explained in the numerical simulations. The simulated results of driftwood outflow time at the downstream end of the flume is also close to the results obtained from the

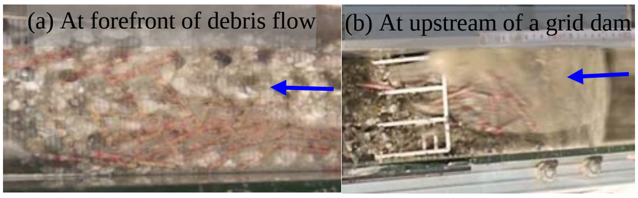


Fig.11 Flow motion of driftwood in debris flow in the flume.

experiments, thus the positions and rotational angle of the driftwood dealt with deterministically and stochastically are well explained in the simulations. **Fig.11** shows the flow behavior of driftwood.

6. CONCLUSIONS

A numerical model is developed for computing the behavior of debris flow with driftwood and its capturing due to jamming of driftwood on a grid dam, and the simulated results are experimentally verified. The process of debris flow captured by grid dam due to jamming of driftwood on a grid dam is investigated. The jamming of driftwood on a grid dam is evaluated based on the geometric conditions and probabilistic approaches. A model is also developed to calculate debris flow deposition due to driftwood jamming on a grid dam. The flow and sediment discharge passing through a grid dam are reduced due to driftwood jamming on a grid dam.

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