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NUMERICAL AND EXPERIMENTAL STUDY ON DEBRIS FLOW WITH DRIFTWOOD FAN DEPOSITION

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Numerical analyses and experimental studies are carried out to investigate the deposition of debris flows with driftwood on the fan. A two-dimensional numerical model is developed for computing the characteristics of debris flow with driftwood, which can simulate all stages of debris flow from initiation, transportation and deposition stages. A numerical model has been developed with an interacting combination of Eulerian expression of the debris flow and Lagrangian expression of the driftwood. A capturing model of debris flow with driftwood by open type check dams is also incorporated into a numerical model. The calculated results of the shapes and thicknesses of a debris flow fan and the positions and rotational angles of deposited driftwood in a debris flow fan are in good agreement with the experimental results. The effects of check dams in the debris flow fan formation are also investigated.

Key Words **:** *Debris flow, driftwood, fan deposition, two-dimensional numerical model, check dams*

1. INTRODUCTION

Debris flow is generally described as gravity flow of a mixture of soil, rocks and water. It is often generated by the erosion of steep debris beds in gullies. When the debris flow reaches a gentle basin from the steep channel, it spreads out, reduces its momentum and then stops after reaching a flatter area. Sediment deposits and leaves mud fluid or clear water flowing downstream. This process gradually creates a debris flow fan[1), 2)]. When debris flow spreads and deposits on the fan, the disastrous damage of property and loss of life may occur[1)].

Many researchers such as Takahashi *et al.*[1)], Tsai[2)], Shieh *et al.*[3)], Ghilardi *et al.*[4)], Rickenmann *et al.*[5)] and others have proposed numerical model to compute the deposition of debris flows on the fan with considering debris flow as sediment water mixture only. However, in recent years debris flow flows with driftwood due to heavy downpours over mountainous rivers[6)]. Based on the observations of past experiences it is clear that the greatest damage has occurred when the debris flow flows with driftwood. Thus, study on deposition of debris flows with driftwood on the fan is very important for the prediction of hazards zone and to establish the soft countermeasures. The study on deposition process of driftwood in a debris flow fan is also necessary. Previous researchers have not focused on computing the deposition of debris flows with driftwood on the fan[1),2),3),4),5)]. On the other hand, few researchers have investigated behavior of driftwood only with clear water flow case[7),8)]. Furthermore, most of the study is focused on assessing specific stages of debris flow. Nevertheless, there is a pressing need for more advanced models that can seamlessly all stages of movement initiation, transportation and deposition of debris flow with driftwood and thereby improve forecasting ability.

In this study, numerical and experimental studies are carried out to investigate the deposition of debris flows with driftwood on the fan. A two-dimensional numerical model is developed for computing the characteristics of debris flow with driftwood, which can simulate all stages of debris flow from initiation, transportation and deposition stages. A model has been developed with an interacting combination of Eulerian expression of the debris flow and Lagrangian expression of the driftwood. The effects of check dams in the debris flow fan formation are also investigated.

2. NUMERICAL MODEL

(1) Basic equations of debris flow

The depth-wise averaged momentum equations of the debris flow and continuity equations of the flow and the sediment particle can be expressed as

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

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

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

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

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 the erosion or deposition thickness measured from the 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 the erosion/deposition velocity used as Takahashi *et al.*[1], C is the sediment concentration in the flow, C_* is the maximum sediment concentration in the bed, β is the 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[9], ρ_T is the 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 described as follows[7]:

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

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

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} are the respective projected areas of the submerged part of the driftwood in x and y directions, C_{Dx} and C_{Dy} are the 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.

(2) Basic equations of driftwood motion

The flow motion of driftwood is restricted near the flow surface. However, when a debris flow debouches from a canyon mouth at which the slope abruptly becomes flat, its competence to transport sediment markedly decreases and its materials are deposited on a debris fan. The flow motion of driftwood becomes contact with bed surface after reducing certain flow depth due to debris flow deposition in a fan area. The driftwood stops due to the friction forces generated between driftwood and bed surface. By introducing these friction forces, the equations of motion of each piece of driftwood, individually labeled by subscript k are expressed as

$$(m_k+mC_M)\frac{du_k}{dt}=-m_k g\frac{\partial H_k}{\partial x}$$
$$-\frac{1}{2}\rho_T C_{Dx}W_k(u_k-U_k)A_{kx}\pm F_{fx} \qquad (7)$$

$$(m_k+mC_M)\frac{dv_k}{dt}=-m_k g\frac{\partial H_k}{\partial y}$$
$$-\frac{1}{2}\rho_T C_{Dy}W_k(v_k-V_k)A_{ky}\pm F_{fy} \qquad (8)$$

$$\frac{dX_k}{dt}=u_k \quad ; \quad \frac{dY_k}{dt}=v_k \qquad (9)$$

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 the virtual mass coefficient, H_k is the flow level at the centroid position of the driftwood, and F_{fx} and F_{fy} are the friction forces in x and y directions, which are opposite in direction to the flow motion of driftwood. These friction forces are described as follows:

$$F_{fx}=\mu_{kx}m_k g\cos(\theta_x)_k \quad ; F_{fy}=\mu_{ky}m_k g\cos(\theta_y)_k \qquad (10)$$

where μ_{kx} and μ_{ky} are the kinetic friction coefficients in x and y directions and $(\theta_x)_k$ and $(\theta_y)_k$ are the bed slope at the position of the centroid of the driftwood in x and y directions.

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[7]

$$Id^2\theta_k/dt^2=\sum N_0 \qquad (11)$$

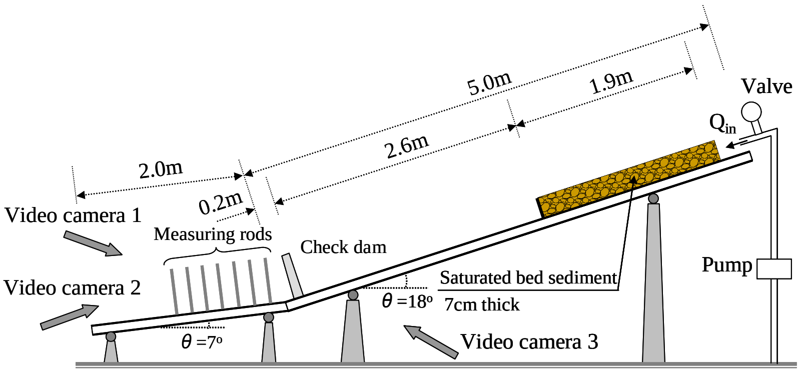


Fig.1 Experimental flume setup.

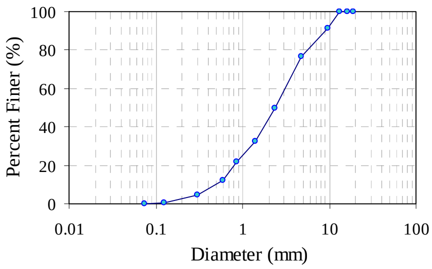


Fig.2 Particle size distribution of sediment bed.

where θ_k is the rotational angle of driftwood piece and I is the moment of inertia around the centroid of the driftwood. The calculation method with formula discretization can be found in Shrestha *et al.*[10].

The position and rotational angle of driftwood can be evaluated deterministically by integrating Eq.(9) and Eq.(11), respectively, but they fluctuate due to the collision of driftwood with boulders and disturbances on the flow surface during the collision of sediment particles. These fluctuation components are considered as method given by Shrestha *et al.*[6].

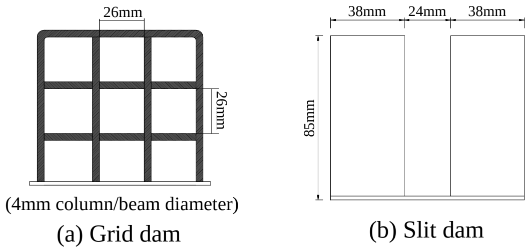


Fig.3 Detail of check dams.

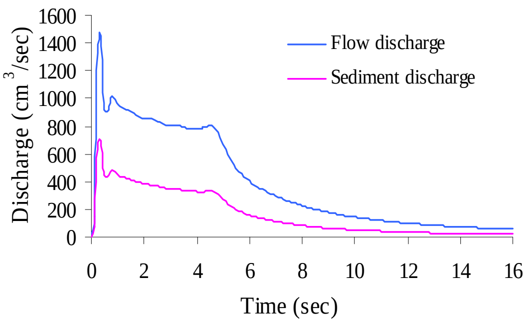


Fig.4 Simulated discharge at 10cm upstream from debouching point, driftwood D_d=3mm, L_d=3.5cm, without check dam.

3. EXPERIMENTS AND METHOD

A flume channel of 2m long, 60cm wide and 20cm deep is connected to the downstream end of 5m long, 10cm wide and 13cm deep flume as shown in **Fig.1**. The slopes of the upstream channel and downstream channel are 18 degrees and 7 degrees, respectively. A sediment bed of 1.9m long and 7cm deep is positioned from 2.8m to 4.7m upstream measured from the debouching point and soaked by the seepage flow. Sediment materials with mean diameter d_m = 2.39mm, maximum diameter $d_{\max}$ = 11.2mm, $\tan\phi = 0.7, C_* = 0.65$ and sediment density σ =2.65g/cm^3 are used. The particle size distribution of the sediment bed is shown in **Fig.2**. Cylindrical pieces of 38 driftwood pieces are positioned on the sediment bed at intervals of 10cm c/c along the downstream direction from 7.5cm downstream from the upstream end of the sediment bed in two columns 2cm apart. To investigate the effectiveness of check dams on the debris flow fan deposition, grid or slit type check dams (**Fig.3**) are set at 20cm upstream from the debouching point.

Debris flow is produced by supplying a constant water discharge 270cm^3/sec for 10sec from the upstream end of the flume. The variations of the shape and thickness of the debris flow fan deposition are measured by two video cameras. The positions and rotational angle of deposited driftwood are also determined by video cameras.

4. RESULTS AND DISCUSSIONS

The numerical simulations and experiments are performed to investigate the deposition of debris flows with driftwood on the fan. The parameters of the simulation are as follows; $\Delta x = 5$cm, $\Delta y = 1$cm, Δt = 0.001sec, C_{Dx} = 1.0, C_{Dy} = 1.0, C_M = 1.0, $\mu_{kx} = 0.3$ and $\mu_{ky} = 0.11$. By using the same values of friction coefficients in x and y directions, it is difficult to get the same results as experimental. Thus, the different values of friction coefficients in x and y directions are used to get good results with compared to the experimental results.

Fig.4 shows the simulated flow and sediment discharge at 10cm upstream from a debouching point of the flume with driftwood diameter D_d=3mm and length L_d=3.5cm case (density of driftwood ρ_d =0.785g/cm^3). Driftwood as floating objects is considered and the initial movement of driftwood is evaluated with the flow depth and the respective velocity components of the fluid. **Fig.5** and **Fig.6** show the simulated and experimental results of the

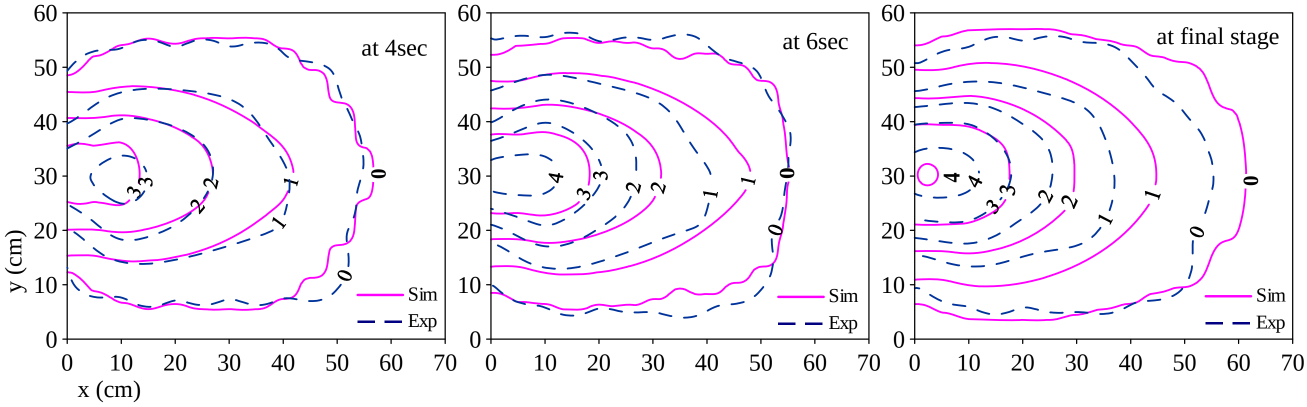


Fig.5 Temporal changes of shapes and thicknesses of a debris flow fan, with driftwood D_d=3mm and L_d =3.5cm, without check dam.

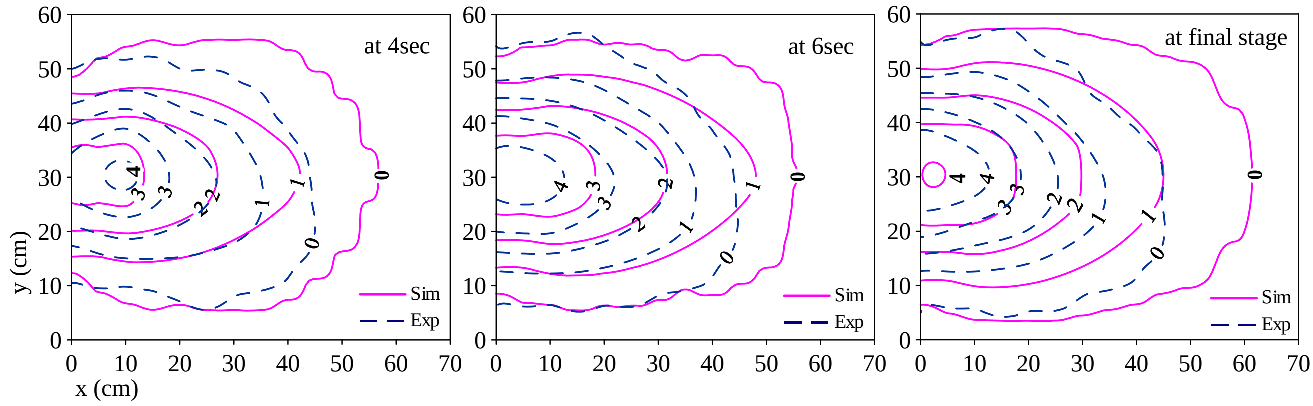


Fig.6 Temporal changes of shapes and thicknesses of a debris flow fan, with driftwood D_d=3mm and L_d =4.5cm, without check dam.

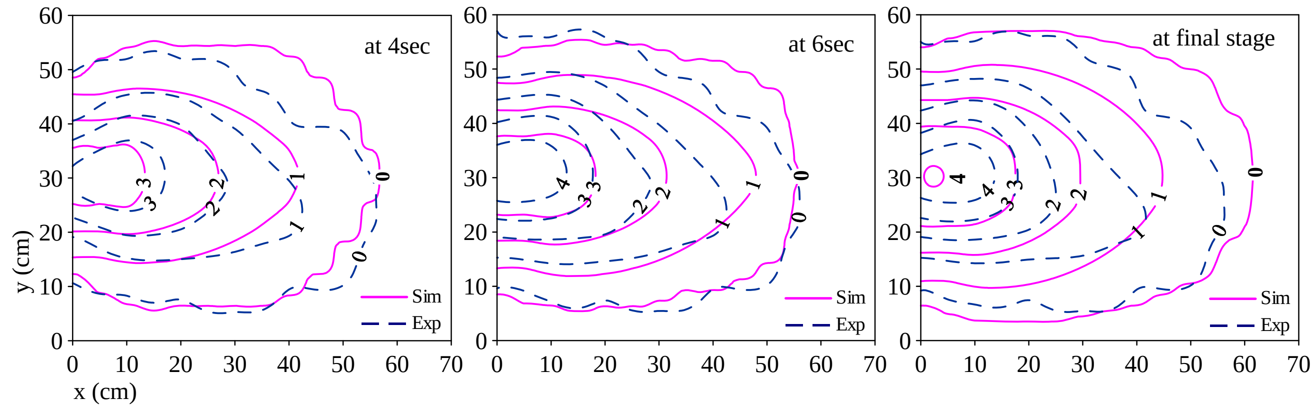
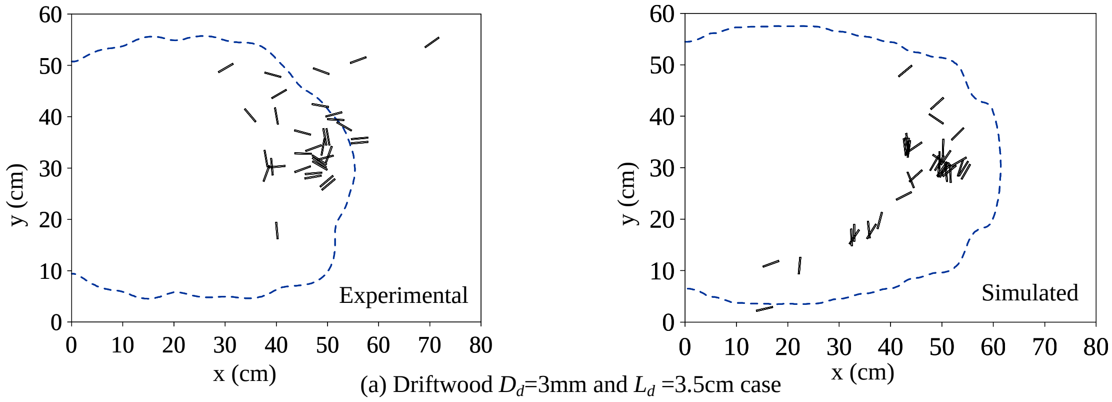


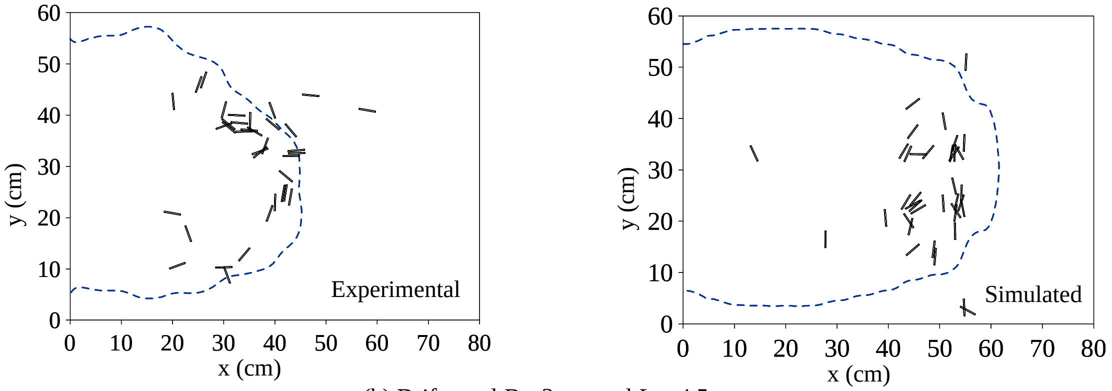
Fig.7 Temporal changes of shapes and thicknesses of a debris flow fan, without driftwood and check dam.

temporal variations of the shapes and thicknesses (i.e., the flow depth plus the deposit thickness) in the process of a debris flow fan formation with driftwood D_d=3mm, L_d=3.5cm and D_d=3mm, L_d=4.5cm cases, respectively. The numbers on the contour lines indicate the thickness in centimeters measured from the surface of the downstream deposition channel. The simulated results are in good agreement with the experimental results. The results of the temporal variations of the shapes and thicknesses of a debris flow fan without driftwood case are shown in **Fig.7**. By comparing the simulated results of the deposition of debris flow on the fan with and without driftwood cases, it is found that the effect of driftwood in the deposition of debris flow on the fan is small, but the position and travel distance of the driftwood on the fan are very important for evaluation of the risks of the hazards.

The friction forces generated between the driftwood and bed surface in Eq.(7) and Eq.(8) are considered only in downstream channel to calculate the driftwood deposition in a debris flow fan. Based on the experimental investigations and numerical analyses, these friction forces are considered when the flow depth is less or equal to the sum of the depth of the submerged part of the driftwood and sediment particle diameter. The depth of the submerged part of the driftwood is calculated by equating the weight of the driftwood piece and the weight of fluid occupied by the volume of a piece of



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



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

Fig.8 Positions and rotational angles of deposited driftwood in a debris flow fan, with driftwood cases (a) D_d=3mm and L_d =3.5cm, (b) D_d=3mm and L_d =4.5cm, without check dam.

driftwood. The comparisons between the simulated and experimental positions and rotational angles of deposited driftwood in a debris flow fan are shown in **Fig.8**. The dashed line in the figures indicates the debris flow fan area. The positions and the rotational angles of the pieces of driftwood in a group found experimentally are fairly well explained by the numerical simulation.

The effectiveness of check dams in a debris flow fan is also investigated through numerical model and hydraulic experiments. The capturing process of debris flow and driftwood by check dam is used as Shrestha *et al.*[6]. **Fig.9** compares the final stage longitudinal bed profile along the center axis of a debris flow fan without check dam and with grid dam, in the case of driftwood D_d=3mm, L_d=3.5cm. **Fig.10** and **Fig.11** show the temporal variations of the shapes and thicknesses of a debris flow fan with grid dam and slit dam, respectively in the case of driftwood D_d=3mm, L_d=3.5cm. The simulated results of the temporal variations of the shapes and thicknesses of the deposition of debris flow on the fan agree with the experimental results. From the results, it is clear that the deposition areas and thicknesses in the cases of check dams are smaller than without check dam case. In check dam cases, the simulated results of the shapes and thicknesses are somewhat larger and higher than experimental

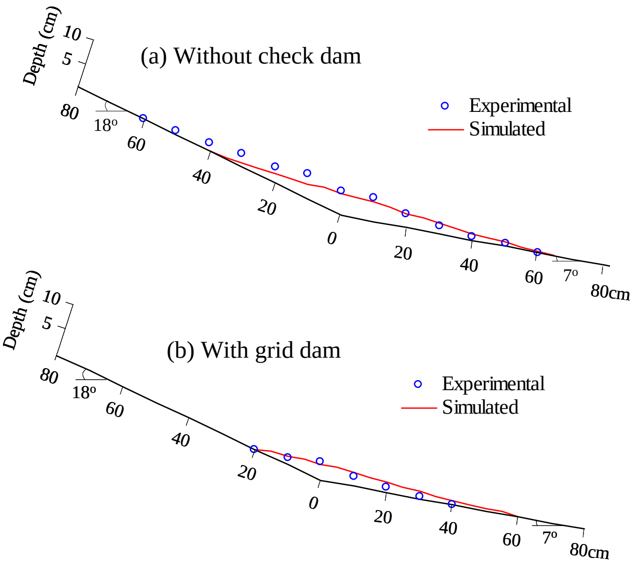


Fig.9 The final stage longitudinal bed profile along center axis of debris flow fan, driftwood D_d=3mm, L_d =3.5cm case.

results, which may be due to the excessive energy loss of flow in the experiments when debris flow collides with the check dam. The positions and rotational angles of deposited driftwood in a debris flow fan with check dam cases are shown in **Fig.12**.

5. CONCLUSIONS

The deposition of debris flows with driftwood on the fan is investigated. The calculated results of the

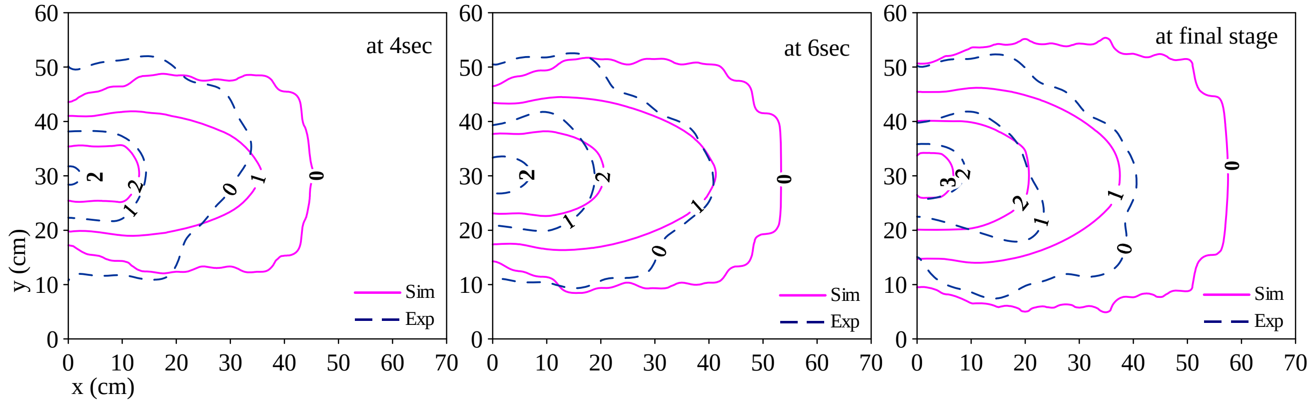


Fig.10 Temporal changes of shapes and thicknesses of a debris flow fan, with driftwood D_d=3mm and L_d =3.5cm, and grid dam case.

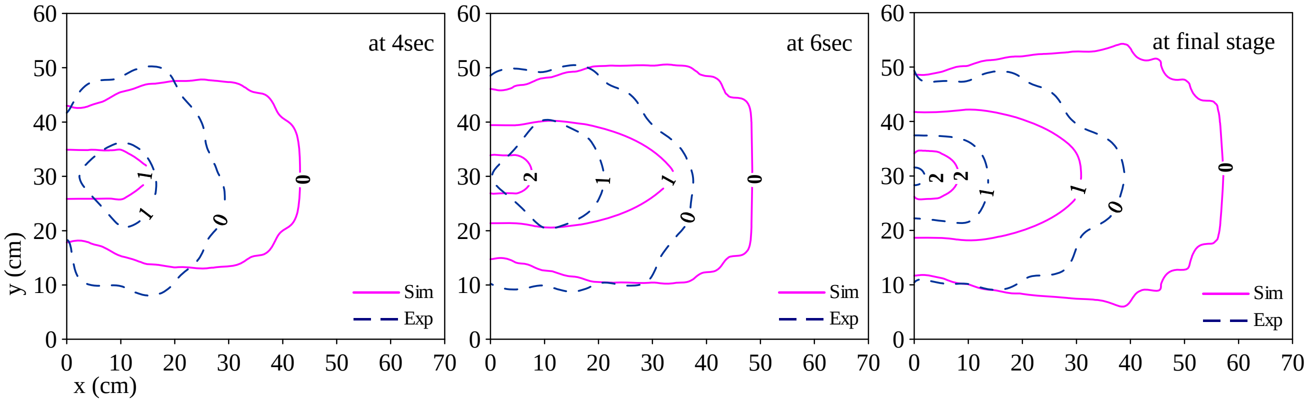


Fig.11 Temporal changes of shapes and thicknesses of a debris flow fan, with driftwood D_d=3mm and L_d =3.5cm, and slit dam case.

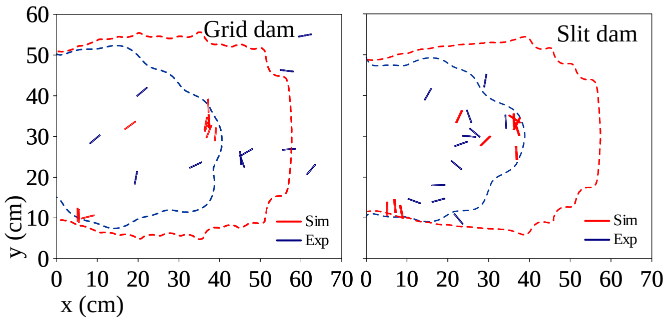


Fig.12 The positions and rotational angles of deposited driftwood in the debris flow fan with check dams, driftwood D_d=3mm, L_d =3.5cm case.

shapes and thicknesses of a debris flow fan and the positions and rotational angles of deposited driftwood in a debris flow fan are in good agreement with the experimental results. The driftwood deposition in a debris flow fan is calculated by considering the friction forces generated between driftwood and bed surface. The effects of check dams in the debris flow fan formation are also investigated. The proposed model can be used to investigate the preventive measures of debris flow disasters with driftwood.

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