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# Numerical Simulation on the Driftwood Behavior in Open-Channel Flows by Using the Distinct Element Method

# NUMERICAL SIMULATION ON THE DRIFTWOOD BEHAVIOR IN OPEN-CHANNEL FLOWS BY USING THE DISTINCT ELEMENT METHOD

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## ABSTRACT

A numerical simulation method has been developed for describing of the behavior of driftwood motion in open-channel flow. The present model has been composed of Eulerian simulation of open-channel flow given by depth-averaged flow analysis and Lagrangian simulation of driftwood motion by using the Distinct Element Method(DEM), which can express the collision and the repulsion of driftwood/driftwood and driftwood/boundaries.

We applied this model to the driftwood motion and its accumulation process by piers and by riparian trees in meandering channels. Calculation results show time series of the driftwood trapping process and the amount of dam-up process by increasing of water level due to jamming of driftwood.

*Keywords*: driftwood, Distinct Element Method, depth-averaged flow analysis

## 1. INTRODUCTION

Due to heavy downpours in mountain basin, much driftwood has combined with debris and sediments, has been washed out and transported downstream, to result in disastrous damage and sometimes considerable loss of life and property in lower reaches of rivers. When the flood flows have been accompanied with much driftwood, it is clear that the serious damage has occurred, which often results in the destruction of bridge and/or embankment by giving rise to flooding due to accumulation of driftwood. And recently in Japan, riparian trees in the course of gravel-bed rivers has been very much increasing. During flood, they can trap floating pieces of driftwood, and sometimes riparian trees could be also washed out by drag force of accumulated driftwood, that is to be source of driftwood in rivers.

In order to clarify the nature of driftwood disasters, the knowledge is necessary to understand the mechanism of driftwoods behavior and accumulation process in front of many obstacles in rivers. Previous studies by many researchers based on hydraulic model experiments about the driftwood behavior have been performed, but a lot of efforts are necessary for setting various experimental conditions, for example, hydraulic conditions, number of obstacles (piers), their shape and location, the number of driftwoods to supply to the channel and so on. On the other hand, a number of simulation studies about the flowing of the driftwood are performed by some researchers. The one of the representative studies is given by Nakagawa et al. (1995), performed the simulation of the driftwood behaviour in a horizontal two-dimensional flow field evaluated dynamically in the Lagrangian form, based on equations of the rotational motion and the translational motion of driftwood. They estimated the time-dependent changes of the driftwood distribution in an inundated area and compared them with hydraulic experiments. The fundamental aspect of the motion of driftwood is probabilistic due to the irregularity of collision at boundary surfaces and inter-driftwood collision. However, they could not deal with effects of collision events in their model. Gotoh et al. (2002) conducted the Lagrangian simulation of the drift-timbers motion induced flood by using moving particle semi-implicit method(MPS) originally proposed by Koshizuka et al.(1995). They can describe damming-up and flooding process due to accumulation of drift-timbers at a small bridge in the vertical 2 dimensional field, by using the MPS method. This study is much interested and brings detailed feature, the fragmentation and coalescence of fluid including water surface waves by the timber-fluid interaction.

In this study, a numerical simulation method has developed which can describe the behavior of driftwood motion in 2D horizontal flow field. The present model has been composed of Eulerian analysis of fluid motion given by depth-averaged flow analysis and composed of Lagrangian analysis of driftwoods motion, because Lagrangian approach is one of the most effective methods for investigation of floating materials in open channel flows. We have analyzed the behaviour of driftwood based on the Distinct Element Method(DEM) originally proposed by Cundall and Strack(1979) which can deal with effects of the irregularity of collision at the driftwood/boundary surfaces and the inter-driftwood.

## 2. SIMULATION MODEL

### 2.1 Model of driftwood

The driftwood is modelled as the stick by connected rigid spherical particle elements with uniform diameter (see Figure 1). Among each particle elements, the spring and dashpot systems are introduced to express the collision and the repulsion of driftwood/driftwood and driftwood/obstacles like piers on the basis of the Distinct Element Method. The translation motion of the element(i) in 2D horizontal calculation domain is governed by the following equations:

$$\rho\left(\frac{\sigma}{\rho}+C_M\right)A_3 d^3\frac{du_{pi}}{dt}=\sum_j\left[-f_n\cos\alpha_{ij}+f_s\sin\alpha_{ij}\right]_j +\frac{1}{2}\rho C_D A_2 d^2\sqrt{\left(u-u_{pi}\right)^2+\left(v-v_{pi}\right)^2}\left(u-u_{pi}\right) \tag{1}$$

$$\rho\left(\frac{\sigma}{\rho}+C_M\right)A_3 d^3\frac{dv_{pi}}{dt}=\sum_j\left[-f_n\sin\alpha_{ij}+f_s\cos\alpha_{ij}\right]_j +\frac{1}{2}\rho C_D A_2 d^2\sqrt{\left(u-u_{pi}\right)^2+\left(v-v_{pi}\right)^2}\left(v-v_{pi}\right) \tag{2}$$

in which t=time; ρ=density of fluid; σ=density of particle element; $C_M$=added-mass coefficient; $A_2$,$A_3$=two- and three-dimensional geometrical coefficients of particle element; d=diameter of particle element; $u_{pi}$,$v_{pi}$=velocity of particle element in longitudinal(x) and lateral(y) directions on horizontal plane; u,v=velocity components of x and y directions; $C_D$=drag coefficient; $\alpha_{ij}$=contacting angle between the i-th and the j-th elements; $f_n$,$f_s$=normal and tangential components of the force acting on the contacting plane between the i-th and the j-th elements on local coordinate system n-s(see Figure 2), given by the spring and dashpot systems based on DEM. In the event of two contacting elements, the springs and dashpots system is introduced in both of the normal and tangential direction on the n-s coordinate. The acting force between the i-th and j-th elements in normal and tangential direction, $f_n$ and $f_s$ can

Figure 1 Model driftwood by constituting particle elements

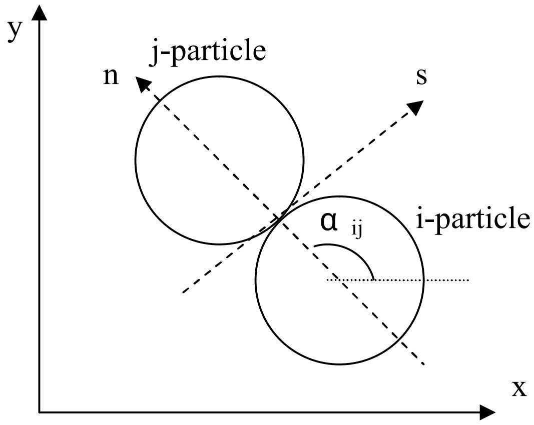


Figure 2 Local coordinate system of contacting particle elements

be written as follows:

$$f_n = e_n^{\ t} + d_n^{\ t} \quad ; \quad f_s = e_s^{\ t} + d_s^{\ t} \tag{3}$$

$$e_n^{\ t} = e_n^{\ t-1} + k_n \Delta L_n \quad ; \quad d_n^{\ t} = \eta_n \cdot \Delta L_n / \Delta t \tag{4}$$

$$e_s^{\ t} = e_s^{\ t-1} + k_s \Delta L_s \quad ; \quad d_s^{\ t} = \eta_s \cdot \Delta L_s / \Delta t \tag{5}$$

in which $e_n, e_s =$ forces working on springs; $d_n, d_s =$ forces working on dashpots; $\Delta L_n, \Delta L_s =$ the displacements of element in normal and tangential direction during the time step $(= \Delta t)$ ; $k_n, k_s =$ spring constants; and $\eta_n, \eta_s =$ damping coefficients in normal and tangential direction. In this simulation, particle elements are also set and fixed at boundaries like piers and riparian trees, making it possible to include the effect of the collision events between the driftwood and the obstacles. These equations of motion are solved explicitly to trace the motion of the individual elements.

The driftwood can be regarded as a stick solid without any deformation. Here the motion of driftwood is tracked by using the model of passively moving solids proposed by Koshizuka et al.(1998). At first procedure of simulation, the motions of each elements constituted by a driftwood are calculated by Eq. 1 and Eq. 2. This means that the conjunction among individual elements is not considered at this step. As a result of this calculation, the driftwood deforms, hence the relative locations of elements are corrected according to Koshizuka et al.(1998). Thus, the following procedure from Eq.6 to Eq.10 is conducted.

The translational velocity vectors( $\mathbf{T_k}$ )and the rotational velocity vectors( $\mathbf{R_k}$ )of k-th elements in a driftwood stick are calculated as follows:

$$\mathbf{T}_k = \frac{1}{N_k} \sum_{i=1}^{N_k} \mathbf{u}_{ki} \tag{6}$$

$$\mathbf{R}_k = \frac{1}{I_k} \sum_{i=1}^{N_k} \left\{ \mathbf{u}_{ki} \times \left( \mathbf{r}_{ki} - \mathbf{r}_{gk} \right) \right\} \tag{7}$$

in which, $N_k$ =number of elements constituting the k –th driftwood. The gravity center $\mathbf{r}_{gk}$ and the moment of inertia $I_k$ of the k-th driftwood are given by

$$\mathbf{r}_{gk} = \frac{1}{N_k}\sum_{i=1}^{N_k}\mathbf{r}_{ki} \tag{8}$$

$$I_k = \frac{1}{N_k}\sum_{i=1}^{N_k}\left|\mathbf{r}_{ki} - \mathbf{r}_{gk}\right|^2 \tag{9}$$

Then, the velocity vectors of the elements constituting driftwood are replaced by eq.(10) to satisfy the motion as a rigid body

$$\mathbf{u}_{ki} = \mathbf{T}_k + \left(\mathbf{r}_{ki} - \mathbf{r}_{gk}\right)\times \mathbf{R}_k \tag{10}$$

## 2.2 Basic equations of fluid motion

To calculate the flow with floating driftwood is given by horizontal two-dimensional momentum equations including the reaction force of the drag force acting on the driftwood produced by the relative velocity between fluid and driftwood. The depth-averaged governing equations are composed of the continuity and the momentum balance equations in the 2D boundary fitted-coordinate system proposed by Nagata et al. (2000) as follows.

$$\frac{\partial}{\partial t}\left(\frac{h}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{Uh}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{Vh}{J}\right) = 0 \tag{11}$$

$$\begin{aligned}
&\frac{\partial}{\partial t}\left(\frac{Q^\xi}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{UQ^\xi}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{VQ^\xi}{J}\right) - \frac{M}{J}\left(U\frac{\partial \xi_x}{\partial \xi} + V\frac{\partial \xi_x}{\partial \eta}\right) - \frac{N}{J}\left(U\frac{\partial \xi_y}{\partial \xi} + V\frac{\partial \xi_y}{\partial \eta}\right)\\
&= -gh\left(\frac{\xi_x^{\ 2} + \xi_y^{\ 2}}{J}\frac{\partial z_s}{\partial \xi} + \frac{\xi_x\eta_x + \xi_y\eta_y}{J}\frac{\partial z_s}{\partial \eta}\right) - \frac{\tau_b^{\ \xi}}{\rho J} - \frac{F^\xi}{\rho J}\\
&+ \frac{\xi_x^{\ 2}}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'^2}h\right) + \frac{\xi_x\eta_x}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'^2}h\right) + \frac{\xi_y^{\ 2}}{J}\frac{\partial}{\partial \xi}\left(-\overline{v'^2}h\right) + \frac{\xi_y\eta_y}{J}\frac{\partial}{\partial \eta}\left(-\overline{v'^2}h\right)\\
&+ \frac{\xi_x\eta_y + \xi_y\eta_x}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'v'h}\right) + \frac{2\xi_x\xi_y}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'v'h}\right)
\end{aligned} \tag{12}$$

$$\begin{aligned}
&\frac{\partial}{\partial t}\left(\frac{Q^\eta}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{UQ^\eta}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{VQ^\eta}{J}\right) - \frac{M}{J}\left(U\frac{\partial \eta_x}{\partial \xi} + V\frac{\partial \eta_x}{\partial \eta}\right) - \frac{N}{J}\left(U\frac{\partial \eta_y}{\partial \xi} + V\frac{\partial \eta_y}{\partial \eta}\right)\\
&= -gh\left(\frac{\xi_x\eta_x + \xi_y\eta_y}{J}\frac{\partial z_s}{\partial \xi} + \frac{\eta_x^{\ 2} + \eta_y^{\ 2}}{J}\frac{\partial z_s}{\partial \eta}\right) - \frac{\tau_b^{\ \eta}}{\rho J} - \frac{F^\eta}{\rho J}\\
&+ \frac{\xi_x\eta_x}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'^2}h\right) + \frac{\eta_x^{\ 2}}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'^2}h\right) + \frac{\xi_y\eta_y}{J}\frac{\partial}{\partial \xi}\left(-\overline{v'^2}h\right) + \frac{\eta_y^{\ 2}}{J}\frac{\partial}{\partial \eta}\left(-\overline{v'^2}h\right)\\
&+ \frac{\xi_x\eta_y + \xi_y\eta_x}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'v'h}\right) + \frac{2\eta_x\eta_y}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'v'h}\right)
\end{aligned} \tag{13}$$

where ξ and η=boundary fitted-coordinates; x and y=Cartesian coordinates; *h*= flow depth; *M* and *N*=x- and y-components of discharge flux; g=gravity acceleration; $z_s$=water surface elevation; $-\overline{u'^2}$, $-\overline{u'v'}$ and $-\overline{v'^2}$ =Cartesian components of depth-average Reynolds stress tensors; $\xi_x$, $\xi_y$, $\eta_x$ and $\eta_y$ =metrics; J=Jacobian defined as $J = 1/\left(x_\xi y_\eta - x_\eta y_\xi\right)$; *U* and *V*=contravariant components of velocity vectors; $Q^\xi$ and $Q^\eta$ =contravariant components of discharge fluxes; $\tau_b{}^\xi$ and $\tau_b{}^\eta$ = contravariant components of bottom shear stress vectors;

$$U = \xi_x u + \xi_y v \quad , \qquad V = \eta_x u + \eta_y v \tag{14}$$

$$Q^\xi = \xi_x M + \xi_y N \quad , \qquad Q^\eta = \eta_x M + \eta_y N \tag{15}$$

$$\tau_b{}^\xi = \xi_x \tau_{bx} + \xi_y \tau_{by} \quad , \qquad \tau_b{}^\eta = \eta_x \tau_{bx} + \eta_y \tau_{by} \tag{16}$$

Where u and v= x- and y-components of velocity vectors; $\tau_{bx}$ and $\tau_{by}$ = x- and y-components of bottom shear stress vectors as follows.

$$\tau_{bx} = \frac{\rho g n^2 u \sqrt{u^2 + v^2}}{h^{1/3}} \quad , \quad \tau_{by} = \frac{\rho g n^2 v \sqrt{u^2 + v^2}}{h^{1/3}} \tag{17}$$

where n= Manning's coefficient; $F^\xi$ and $F^\eta$ = contravariant components of the reaction force of the drag force vectors defined as follows.

$$F^\xi = \xi_x F_x + \xi_y F_y \quad , \qquad F^\eta = \eta_x F_x + \eta_y F_y \tag{18}$$

$$\begin{aligned} F_x = {} & \frac{1}{2}\rho C_D \frac{A_k}{A_f} \sum_k^w \left(u - u_{pk}\right)\sqrt{\left(u - u_{pk}\right)^2 + \left(v - v_{pk}\right)^2} \\ & + \frac{1}{2}\rho C_{Dv} \lambda h u \sqrt{u^2 + v^2} + \frac{1}{2}\rho C_{Db} \frac{A_b}{A_f} u \sqrt{u^2 + v^2} \end{aligned} \tag{19}$$

$$\begin{aligned} F_y = {} & \frac{1}{2}\rho C_D \frac{A_k}{A_f} \sum_k^w \left(v - v_{pk}\right)\sqrt{\left(u - u_{pk}\right)^2 + \left(v - v_{pk}\right)^2} \\ & + \frac{1}{2}\rho C_{Dv} \lambda h v \sqrt{u^2 + v^2} + \frac{1}{2}\rho C_{Db} \frac{A_b}{A_f} v \sqrt{u^2 + v^2} \end{aligned} \tag{20}$$

where $A_f$= numerical grid area; $A_k$= projected area of elements of driftwood; $A_b$= projected area of piers to the flow;λ=the density of riparian trees defined as the projected area of trees to the flow per unit volume of fluid; w= the number of elements; $C_{Dv}$, $C_{Db}$= coefficients of the drag force by riparian trees and piers. The depth-averaged Reynolds stress tensors are evaluated by the following model:

$$-\overline{u_i' u_j'} = D_{ij}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \quad , \qquad D_{ij} = \alpha h u_* \tag{21}$$

where $u_*$=friction velocity; $\delta_{ij}$=Kronecker's; delta, α=proportional constant; $D_{ij}$= kinematic eddy viscosity; k=depth-averaged turbulent kinetic energy derived from integration of the empirical formula proposed by Nezu and Nakagawa(1993) as $k = 2.07u_*^{\ 2}$ ( $u_*$ ; friction velocity) .

### 2.3 Procedure and conditions of simulation

The fundamental procedure of present simulation is as follows. (a) At first, a flow field is calculated as the initial condition by using eqs.(11) to(21), and pieces of driftwood are supplied into the flow.(b) The motion of driftwood is traced by eqs.(1) and (2) with the judgements to contact between elements. (c) In the numerical mesh with driftwood and/or obstacles (piers, riparian trees), the drag force is produced as the flow resistance given by eq.(18) to(20), and the calculated flow field is revised by these procedures.

## 3. DRIFTWOOD BEHAVIOR IN OPEN-CHANNEL FLOWS

Firstly, the simulation of the flow with four piers in a meandering channel during the passage of driftwood is performed. The driftwood has 10m in length with a diameter of 0.2m and a specific gravity (σ/ρ)=0.7. The span length and width of piers is 10m and 1m respectively. The channel has the bed slope of 1/100, the width of 50m and the constant inflow discharge 200m$^3$/s, supplied 100 pieces of driftwood at the upstream boundary instantaneously.

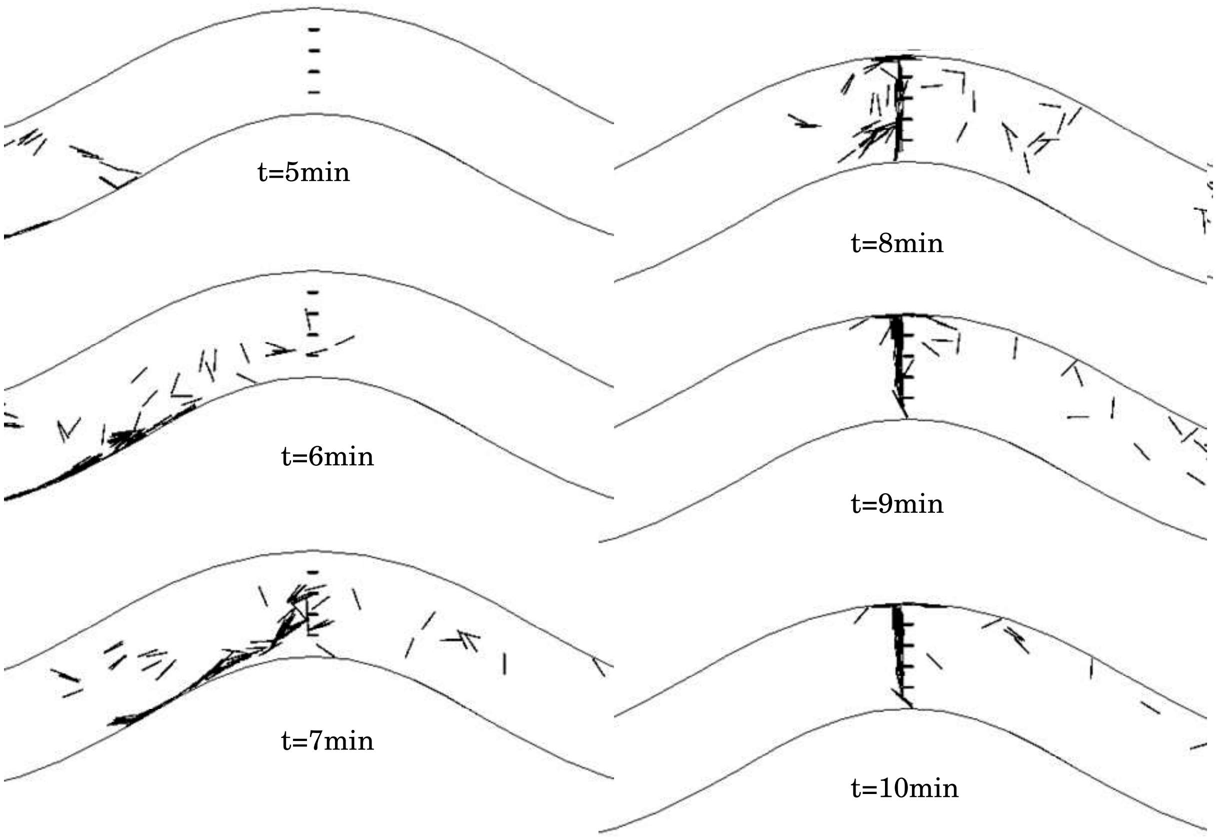


Figure 3 Simulated distribution of driftwood in an open channel flow with piers

Figure 3 shows temporal changes of the flowing process of driftwood in the meandering channel with piers. The driftwood lump is flowing along the inner-bend bank and is caught between and/or in front of piers and the resultant jam occurs due to the accumulation

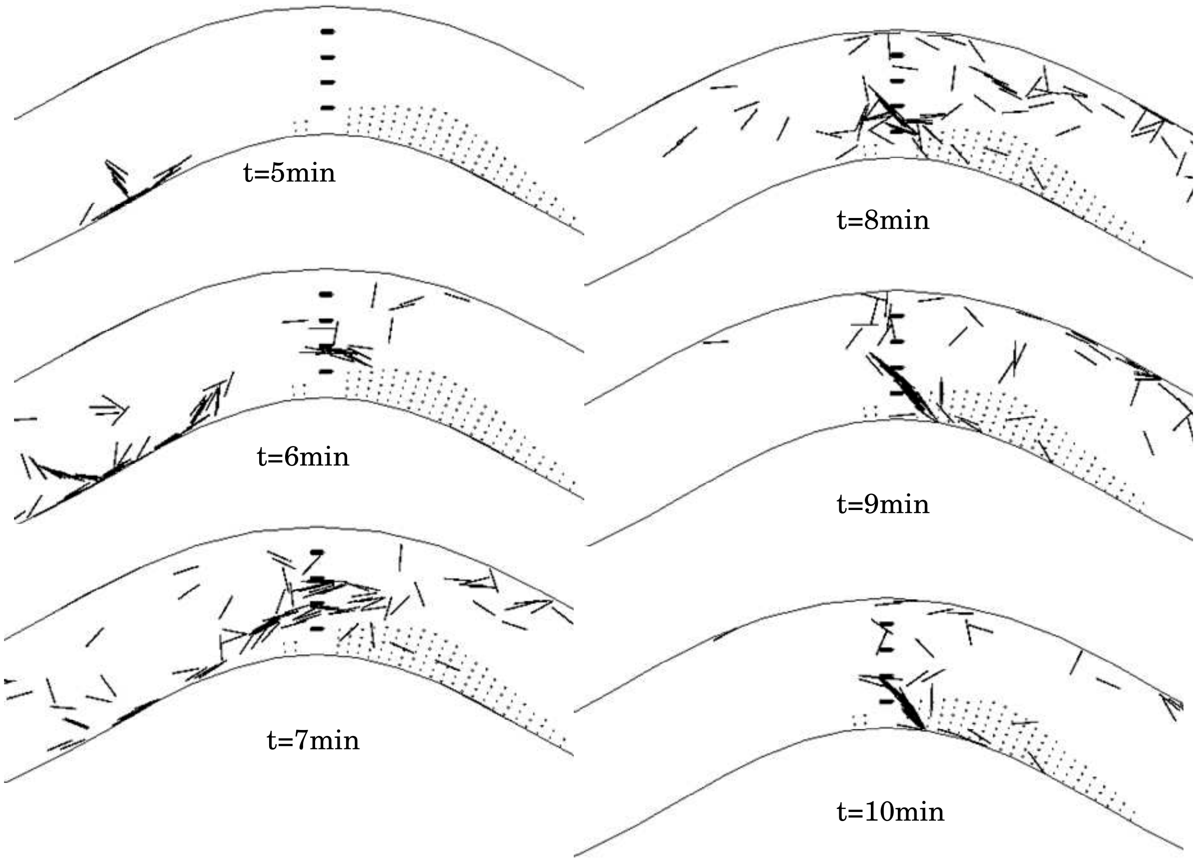


Figure 4 Simulated distribution of driftwood in the flow with the bar with riparian trees

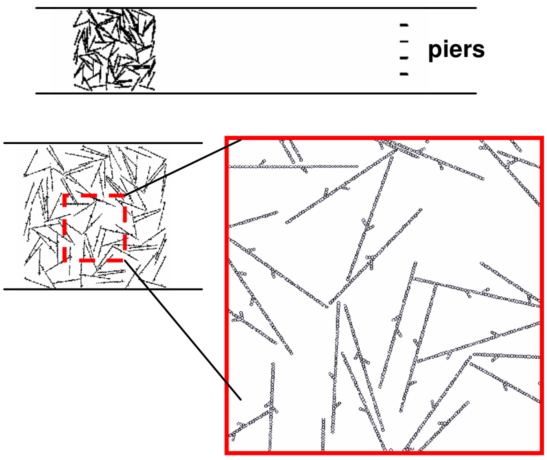


Figure 5 the driftwood having two branches in the straight channel with piers

of driftwood. Figure 4 shows the flow pattern under the influence of these piers and the inner-bank bar with riparian trees. Riparian trees trap the lumps of driftwood along their boundary, especially at the upper side of the forested bar. Such situations often can be seen in the field investigation, e.g., Suzuki and Watanabe (2004) pointed out by an onsite survey after the typhoon in 2003, that the distribution of driftwood beached in river channel is mainly the flood plain at the inner bend with vegetated zones.

When branches remain in individual driftwood, the way of the accumulation is complicated very much. Here, a piece of driftwood is assumed to have two branches as shown

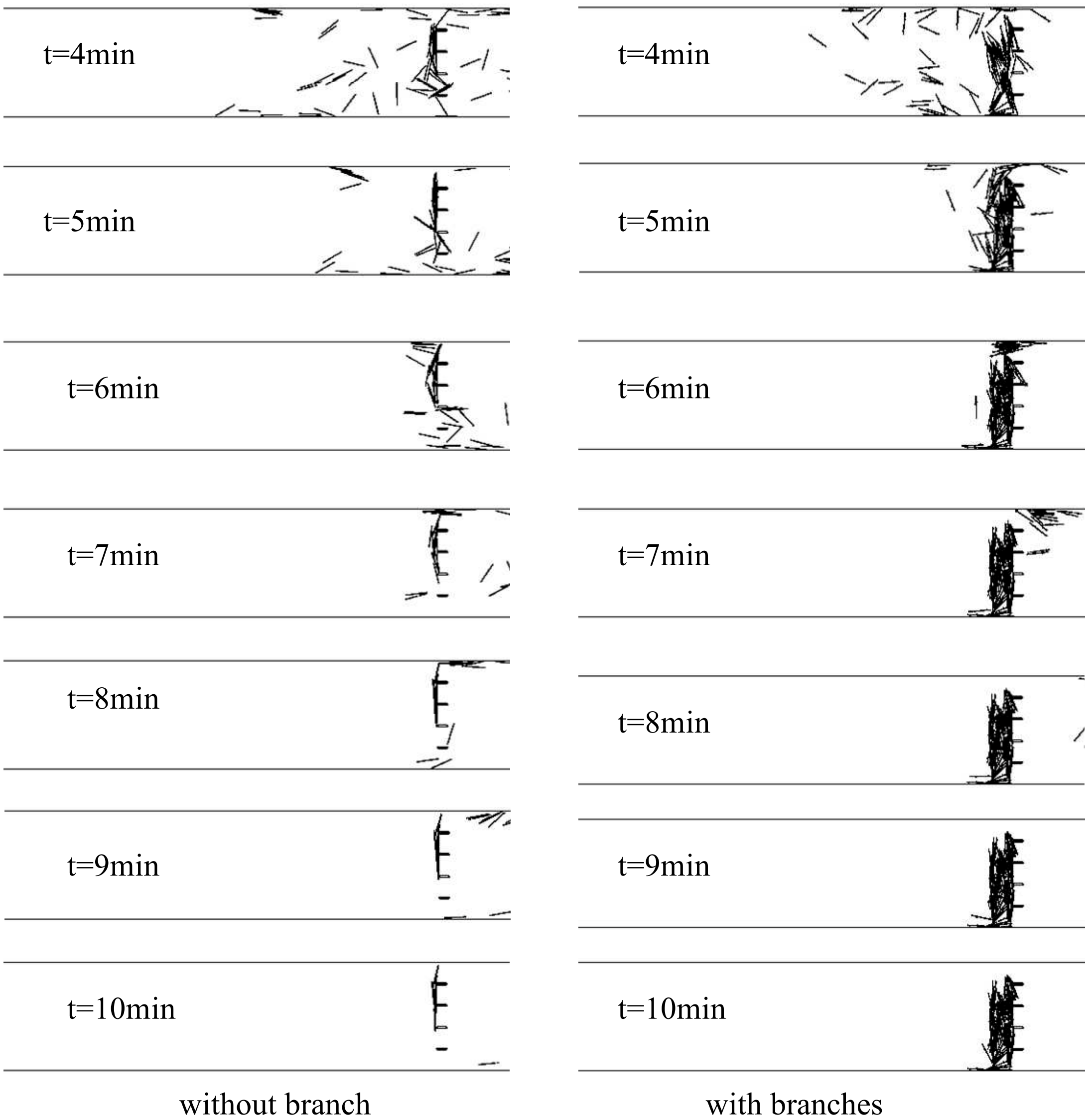


Figure 6 Comparison of the distribution of the driftwood with branches and that without branches

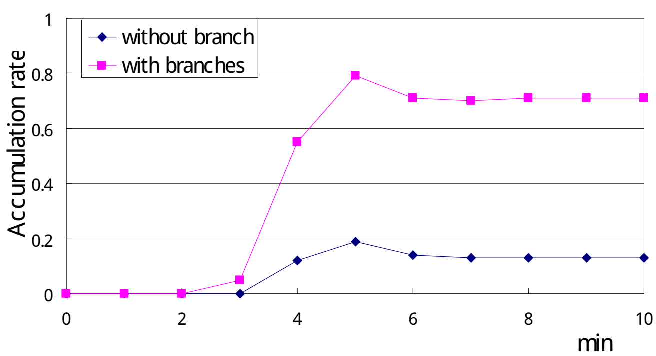


Figure 7 Comparison of the accumulation rate of the driftwood with branches and that without branches

in Figure 5. To consider the geometrical effect of the driftwood on the trapping by piers, simulations of flow with four piers in the straight channel in the case with branch and without

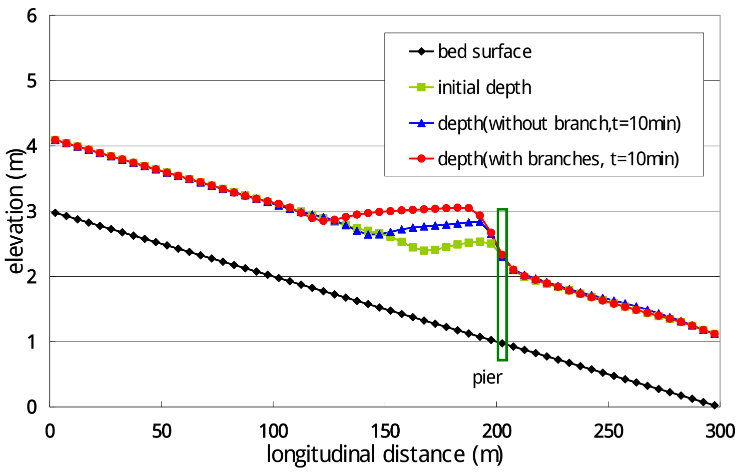


Figure 8 Comparison of backwater effects of the driftwood with branches and that without branches

branches are performed as shown in Figure 6. In the case of driftwood having branches, it is easy to form lumps and to be trapped by obstacles. The accumulation rate is defined as the number of trapping driftwood divided by the total number of supplying driftwood. Figure 7 shows the comparison of the calculated accumulation rate, and about 4 times are higher in the rate in the case of having branches than that of having no branch. The blocking of the part of the cross section brings about an increase of the water depth in the upstream section, as shown in Figure 8. The dammed up water level has risen markedly because the relative velocity of the fluid as compared to the driftwood has become large in front of the piers. The backwater effect of driftwood also can be explained by the present numerical model.

## 4. CONCLUSIONS

In this paper, a numerical simulation of the behavior of driftwood motion is performed on the basis of the DEM with a focus on the collision of driftwood/driftwood and driftwood/other-obstacles. The temporal changes of distribution of driftwood are simulated in channel flows with piers and the bar covered with riparian trees. Furthermore, the backwater profiles due to the accumulation of driftwood are also calculated by the present model. For further development to clarify the nature of the driftwood behaviour, the quantitative evaluation in comparison to refined hydraulic experiments should be required.

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