NUMERICAL SIMULATION ABOUT IMPULSIVE FORCE ON A HOUSE BY TSUNAMI-DRIVEN WOODY DEBRIS FROM COASTAL FOREST

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Abstract

One of the advantages of coastal forest against tsunami inundation is to reduce fluid force behind forest. However, the coastal forest also has a disadvantage to increase the damage to people and buildings because it produces floating debris when the trees are broken and washed out. The advantage and disadvantage are usually pointed out but have never been compared quantitatively.

The tsunami caused by the Great East Japan Earthquake on 11 March 2011 passed through coastal forest with breaking trees and washing out trees. The coastal forest in Sendai Plains in Miyagi Prefecture could be assumed to reduce the tsunami force behind forest but it also produced much driftwood and could increase the impact force on houses. Therefore, in this research, the numerical simulation model including the judgment of tree breaking and washing out condition, motion of trees after the washout, and collision of houses has been developed and the influence of the driftwoods on houses was analyzed. For the tsunami-driftwood interaction model, two-dimensional non-linear long wave equations and the equation of motion for driftwoods have been combined.

Driftwood's behavior was analyzed by the Lagrangean approach. The collision between the driftwood and houses was supposed to be the completely inelastic collision and the collision force was analyzed by the equation of motion. Numerical simulation was conducted in Miyagino District in Sendai City with the area of 4000m×100m. In the simulation, a collision force on houses by driftwood was analyzed and the magnitude of the collision force was compared with that of the drag force.

The simulation could reproduce well the final location of driftwood. The rate of the collision force of driftwood and the maximum drag force on a house was 0.05 - 0.15. In the case of the collision force on the house which was judged as washout, the largest rate was 0.08. Therefore, the driftwood has been found not to be a main factor for washing out houses. However, it has a possibility to slightly influence the washing out situation of the house where the fluid force was close to the critical value for washing out houses.

Keywords: driftwood, coastal forest, impulsive force

1. Introduction

Since the 1998 Papua New Guinea tsunami, and the 2004 Indian Ocean tsunami, the effectiveness of coastal forest on sand dune or mangrove on reducing fluid force by tsunami has been recognized again and the quantitative research on estimating the effectiveness or limitations of coastal vegetation has been accelerated[1)2)].

The tsunami caused by the Great East Japan Earthquake at 14:46 JST on 11 March 2011, which had a magnitude of 9.0 and epicentre 129 km east of Sendai, broke most of the sea walls (tsunami gates, large embankments) and caused catastrophic damage to people, buildings, and coastal forests in the Tohoku and Kanto districts of Japan. Tanaka et al.[3)] has investigated the effectiveness of the coastal forest in the Japanese tsunami by post tsunami survey and by simulating the reduction of washout region of houses with/without coastal forest and with/without sea embankment. The study indicated that the effect of vegetation was small compared to that of the sea embankment, but it is not negligible as a mitigation countermeasure when a large tsunami comes and overflows the sea embankment.

On the other hand, the coastal forests were destroyed and large amount of driftwood were produced from the forest by the tsunami. Most of the broken trees were bending and not washed out, but some trees vegetated in scoured region by tsunami, i.e. area behind sea embankment or area where liquefaction occurred, were driven to far inland and some of them were subsequently collided with buildings.

Although the coastal forest has a role to reduce the drag force, it also has a possibility to increase the secondary damage by the collision of the driftwood. The advantage and disadvantage of coastal vegetation, namely the "effectiveness of mitigating tsunami fluid force" and "the influence of expanding damage due to producing driftwoods" were pointed out qualitatively in previous research(ex. Shuto(1987)), however, they have never been compared quantitatively.

Most of the formula of impulsive force by the collision of floatings are experience curve by experiments[6)7)]. Research on the numerical simulation about motion of driftwood is a few except for representative researches by Goto et al.[4)] and Nakagawa et al.[5)]. The studies analyzed driftwood's motion by the Lagrangean approach. However, there is no research on analyzing the process of driftwood production from the coastal forest by tsunami, driftwood transportation, and the debris collision that affect the damage situation of a house.

Therefore, the objectives of this study are: 1) to develop numerical simulation model including the judgment of tree breaking and washing out condition (driftwood production process), motion of trees after the washout, and collision to houses (**Fig.1**), and 2) to analyze the influence of the driftwoods on houses at the Japanese tsunami event in Miyagino District, Sendai, Japan.

2. Material and Methods

2.1 Detail of the damage by the tsunami in Miyagino District

Field investigation in Sendai Plain including Miyagino District was carried out in 27-29th April in 2011. The tsunami water depth at each site was determined by evidence of collisions, e.g., the height of scars made by debris on tree trunks or by broken branches, and water marks on the walls of damaged buildings, marks on broken roofs, or debris located on roofs (**Fig.2**).

The water depth immediately behind the coastal forest was 3.0-3.6m and the distance from the shoreline was about 800m. The water depth at the front area of the house group was 2.5-4.6m and the distance from the shoreline was about 1200m. The sea embankment was judged as 'washed-out (WE)' in Miyagino District according to the field investigation and the aerial photograph after the tsunami (**Fig.3**). The most of embankment blocks were driven around 50m and the longest distance was over 75m.

The Coastal forest existed along the shoreline in most of the Sendai Plain and Teizan-unga Canal divided the coastal forest in two areas, the offshore side and inland side (**Fig.4-a**). In Miyagino District, the width of the coastal forest was 600-700m excluding the area of the Teizan-unga Canal.

In 2009, Tanaka et al[8)] previously classified tree breaking patterns as trunk-bending (BE), trunk-breaking (BR), overturning including the root anchorage zone (OV), and washing out (W). Similar tree breaking patterns also occurred at this tsunami event. In Miyagino District, the different tree breaking patterns were appeared in the two areas of the coastal forest, the offshore side and inland side (**Fig.4-b**). In the area of the offshore side, trees were broken as trunk-bending (BE) or trunk-breaking (BR), and stayed on the site.

On the other hand, in the area of inland side, trees were broken as overturning including the root anchorage zone (OV) or washing out (W). Most of trees couldn't stay the original location and be washed out. Liquefaction by earthquake loosen the root anchorage and this kind of breaking pattern were assumed to be occurred in inland side. Most of driftwoods accumulated in inland had their roots. So they were considered to be mainly produced from this inland side of the coastal forest (**Fig.5**).

Most of the driftwoods or other debris were accumulated in front of houses (**Fig.6**), so the driftwood's driven motion was considered to be mainly influenced by the push wave rather than the pull wave.

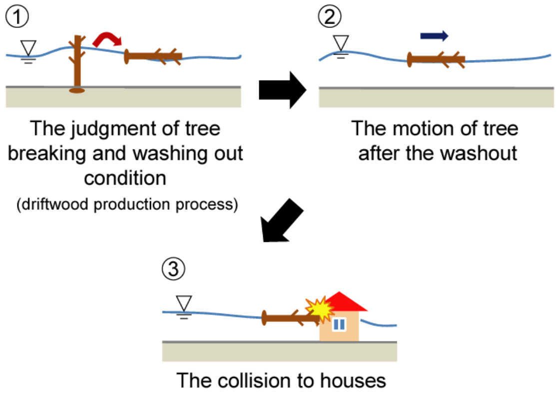

Fig.1 The phenomena of driftwood included in our numerical simulation model.

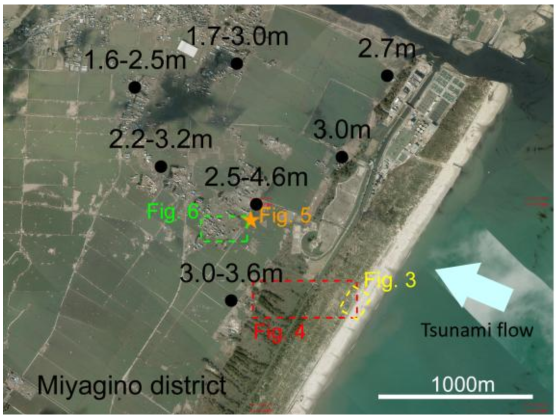

Fig.2 Distribution map of tsunami water depth at Miyagino District.

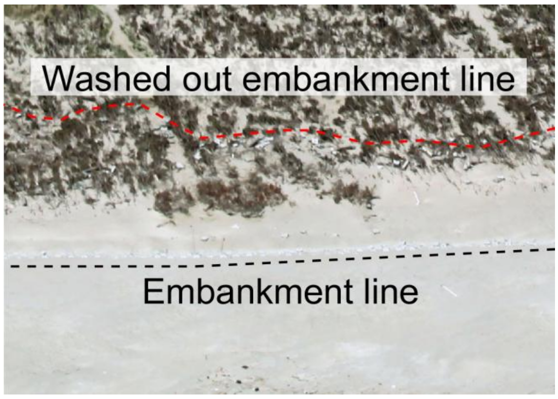

Fig. 3 Original location and post-tsunami location of sea embankments

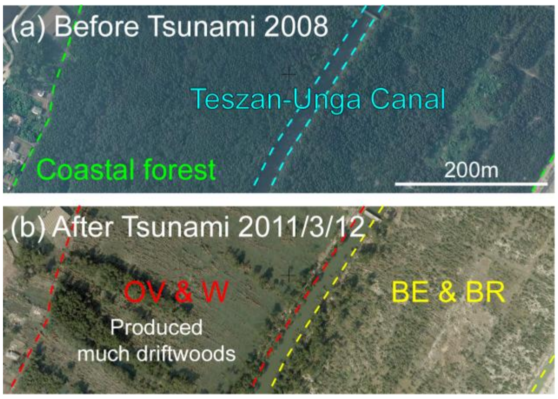

Fig. 4 (a) The Original condition of coastal forest before the tsunami. (b) The Breaking condition after the tsunami. BE:bent, BR:broken, OV:overturned, W:washed out

Fig. 5 The driftwoods with roots that were produced from coastal forest and accumulated in inland

Fig. 6 The driftwoods and other debris that were accumulated in front of houses

2.2 The numerical simulation model of Tsunami

The numerical simulations were conducted using the model of Thuy et al. [9], which is formulated by two-dimensional nonlinear long-wave equations (continuity equation: Eq.(1), momentum equations: Eqs.(2) and (3)), and an sub-depth scale (SDS) turbulence model (Nadaoka and Yagi, 1998)

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (hV_x)}{\partial x}+\frac{\partial (hV_y)}{\partial y}=0 \tag{1}$$

$$\frac{\partial V_x}{\partial t}+V_x\frac{\partial V_x}{\partial x}+V_y\frac{\partial V_x}{\partial y}+g\frac{\partial \zeta}{\partial x}+\frac{\tau_{bx}}{\rho h}+\frac{F_x}{\rho h}-\frac{E_{Vx}}{h}=0 \tag{2}$$

$$\frac{\partial V_y}{\partial t}+V_x\frac{\partial V_y}{\partial x}+V_y\frac{\partial V_y}{\partial y}+g\frac{\partial \zeta}{\partial y}+\frac{\tau_{by}}{\rho h}+\frac{F_y}{\rho h}-\frac{E_{Vy}}{h}=0 \tag{3}$$

$$\left(\tau_{bx},\ \tau_{by}\right)=\frac{\rho g n^2}{h^{1/3}}\times\left(V_x\sqrt{V_x{}^2+V_y{}^2},\ V_y\sqrt{V_x{}^2+V_y{}^2}\right) \tag{4}$$

$$\left(F_x, F_y\right)=\gamma\frac{1}{2}\rho C_{D-all} b_{ref}\, h\times\left(V_x\sqrt{V_x{}^2+V_y{}^2},\ V_y\sqrt{V_x{}^2+V_y{}^2}\right) \tag{5}$$

$$E_{vx}=2\frac{\partial}{\partial x}\left(h\nu_e\frac{\partial V_x}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\nu_e\frac{\partial V_x}{\partial y}+h\nu_e\frac{\partial V_y}{\partial x}\right) \tag{6}$$

$$E_{vy}=2\frac{\partial}{\partial y}\left(h\nu_e\frac{\partial V_y}{\partial y}\right)+\frac{\partial}{\partial x}\left(h\nu_e\frac{\partial V_x}{\partial y}+h\nu_e\frac{\partial V_y}{\partial x}\right) \tag{7}$$

Where x and y are the horizontal coordinates; V_x and V_y are the depth-averaged velocity components in x and y directions, respectively; t is the time; h the total water depth ($h = h_0+\zeta$); h_0 the local still water depth (on land, the negative height of the ground surface); ζ the water surface elevation; n the Manning roughness coefficient; and γ the tree density (number of trees/m^2). $C_{D\text{-}all}$ is the depth-averaged equivalent drag coefficient considering the vertical stand structure of the trees, which was defined by Tanaka et al.[1] as:

$$C_{D-all}(h)=C_{D-ref}\frac{1}{h}\int_0^h \frac{b(z_G)}{b_{ref}}\frac{C_D(z_G)}{C_{D-ref}})dz_G \tag{8}$$

where $b(z_G)$ and $C_D(z_G)$ are the projected width and drag coefficient of a tree at height z_G from the ground surface, and b_{ref} and $C_{D\text{-}ref}$ are the reference projected width and reference drag coefficient, respectively, of the trunk at z_G =1.2 m in principle. The eddy viscosity coefficient ν_e is expressed in the SDS turbulence model[10), 11)].

2.3 Breaking and washout condition of trees

To clarify tree breaking, the models of Tanaka et al.[11] and Thuy et al.[12], which consider the breaking conditions of tropical sand dune vegetation, were adapted to pine trees. The moment acting on the tree trunk at ground height (Eq.(9)) and the critical bending moment of trees (Eq.(10)) were used for judging tree trunk bending as shown below.

$$M = F \times \frac{h}{2} = \frac{1}{2} C_{D-all} \rho u^2 h d_{BH} \frac{h}{2} = \frac{1}{4} C_{D-all} \rho u^2 h^2 d_{BH} \tag{9}$$

$$M_{bcri} = k D_{BH}{}^3 \tag{10}$$

where u (m/s) ($= \sqrt{V_x{}^2 + V_y{}^2}$) is the velocity; $C_{D\text{-}all}$ drag coefficient (=1 before breaking, because the pine trees at the site did not have many branches); ρ (kg/m^3) density of fluid; h (m) tsunami water depth; d_{BH} and D_{BH} (=100 d_{BH}) tree trunk diameter at breast height in m and cm units, respectively; k dimensional constant (=2 or 3 for hard trunk and elastic trees, respectively[8]).

When M was larger than M_{bcri}, the tree was judged to be bent, and the drag coefficient was changed from 1.0 to 0.2. The fluid force index (u^2h) and the moment index (u^2h^2) were defined considering the fluid force (F) and moment by drag force (M). At the near-shore side of coastal forest in Miyagino District, pine trees 15 cm in diameter and 9.6 in height were mostly bent. The threshold momentum index is around 180 m^4/s^2.

At the inland side of coastal forest in Miyagino District, both tree overturning and washout were observed. The diameter and tree height of pine trees were 26cm and 11.0m., respectively. Overturning is related to the aboveground weight and usually expressed as a function of $D_{BH}{}^2$ (Samarakoon et al., 2011; Tanaka et al., 2011). The ground height of the coastal forest was low, and some possibility of liquefaction of the substrate in the forest was reported. Tanaka et al.[15] reported that the smallest value of overturning was around $M_{ocri} = 5\ D_{BH}{}^2$ in the case of a river flood they investigated. In this study, the equation was applied to judge overturning. When a tree was judged overturned in the survey, the $C_{D\text{-}all}$ value was changed from 1.0 to 0.0.

2.4 The numerical simulation model of driftwood's behavior

The numerical simulation model of driftwood's behavior is considered a system of particles therefore the rotational motion is neglected. In addition, mutual interaction of driftwoods, i.e. sheltering or collision, is not considered because the timing of the driftwood generation is not the same and the tree density (trees/m^2) is not so high. The material density of driftwood (ρ_d) is smaller than the density of water (ρ), and driftwood is assumed to float on the water surface all time when it is moving. As the drag force and inertia force are acted on a driftwood, the momentum equation of driftwood becomes;

$$m\frac{dV_x}{dt} = \rho vol\frac{Du_x}{Dt} + \rho C_M vol\left(\frac{Du_x}{Dt} - \frac{dV_x}{dt}\right) + \frac{1}{2}\rho C_{Dx} A_{Dx}\sqrt{(u_x - V_x)^2 + (u_y - V_y)^2}\,(u_x - V_x) \tag{11}$$

$$m\frac{dV_y}{dt} = \rho vol\frac{Du_y}{Dt} + \rho C_M vol\left(\frac{Du_y}{Dt} - \frac{dV_y}{dt}\right) + \frac{1}{2}\rho C_{Dy} A_{Dy}\sqrt{(u_x - V_x)^2 + (u_y - V_y)^2}\,(u_y - V_y) \tag{12}$$

Where m is the mass of driftwood, *vol* the volume of driftwood, Vx, Vx the driftwood velocity, u_x, u_y the current velocity (flow velocity), A_{Dx}, A_{Dy} the drag area, C_{Dx}, C_{Dy} the coefficient of drag, C_M the coefficient of added mass or virtual mass and Du_x/Dt, Du_y/Dt the total horizontal acceleration of water near the driftwood, which can be explained as follows in two dimensions (Eq.(13)).

$$\frac{Du_x}{Dt} = \frac{\partial u_x}{\partial t} + u_x\frac{\partial u_x}{\partial x} + u_y\frac{\partial u_x}{\partial y},\ \frac{Du_x}{Dt} = \frac{\partial u_x}{\partial t} + u_x\frac{\partial u_x}{\partial x} + u_y\frac{\partial u_x}{\partial y} \tag{13}$$

Driftwood's behavior was analyzed by the Lagrangean approach (Eq.(14)).

$$\frac{dX}{dt} = V_x,\ \frac{dY}{dt} = V_y \tag{14}$$

2.5 The numerical simulation model of collision

The collision models are based on the impulse momentum concept, in which the impulse of the resultant force (F_{cx}, F_{cy}) acting for an infinitesimal time (Δt) is equal to the change in linear momentum;

$$I_{cx} = 0 - mV_{Cx} = \int_{t_C}^{t_C+\Delta t} F_{Cx}\,dt,\ I_{cy} = 0 - mV_{Cy} = \int_{t_C}^{t_C+\Delta t} F_{Cy}\,dt \tag{15}$$

Where I_{cx}, I_{cy} is the impulse in x, y directions respectively, V_{Cx}, V_{Cy} the velocity of the driftwood in x, y directions, respectively, at just colliding and t_c the instantaneous colliding time.

As it is rather difficult to estimate Δt accurately, the Δt was estimated roughly according to the damage (deformation) of houses at the tsunami affected site and the some movies about the tsunami inundation. According to the field investigation in Miyagino District, the walls of houses were deformed by the driftwood and the sticking length was about driftwood's diameter. The diameter was about 0.20m therefore the distance that driftwood moved during Δt was assumed around 0.20m. According to analysis of the movie on tsunami inundation, the flow velocity estimated by floatings near houses was about 4m/s. Assuming that the V_{Cx}, V_{Cy} was equal to the flow velocity, Δt can be estimated around 0.1s.

2.6 The condition of numerical simulation

A set of the model equations was solved by the finite-difference method of a staggered leap-frog scheme, which is used widely in numerical simulations of tsunamis[12)]. A sinusoidal incident tsunami was given as a time-dependent boundary condition at the most offshore side of the computational domain. The initial conditions were given for a wave-less state in whole computational domain. In the numerical simulation, a uniform grid size of 10 m was applied. The Manning roughness coefficient n was set as 0.025 s/m$^{1/3}$ for a relatively bare rough ground. Forest length and tree density was set as the condition of the site being evaluated.

A uniform coastal topography with a cross-shore section perpendicular (x-axis) to a straight shoreline, as shown in **Fig. 7**, was the model case in Miyagino District. The density of houses here was low compared with other districts, so the effect of impact force by floating debris from houses could be considered small in this area. The offshore water depth at an additional wave-generation zone with a horizontal bottom was 200 m below the datum level of z = 0. The direction of the incident tsunami was perpendicular to the shoreline. In the present paper, the run-up of only the first wave is discussed. The maximum tsunami water depth at the shoreline was set at 10 m, which is the average value in this area.

In order to modelling the washout of the sea embankment, its height was lowered to ground surface when it passed 3400 s from the occurrence of tsunami considering the analysis by Tanaka et al. (2012). The width of the coastal forest was 610 m, and it started at x = 140 m from the shoreline. The forest was assumed to extend finitely in the direction of the shoreline (y-axis). The width of coastal forest at near-shore side and inland side were 300 m and 310 m, respectively.

When a tree was judged as ‘washout’ in the area of inland side, driftwood was assumed to be produced. Driftwood was assumed to move only when the water depth was above the diameter of root clump of driftwood.

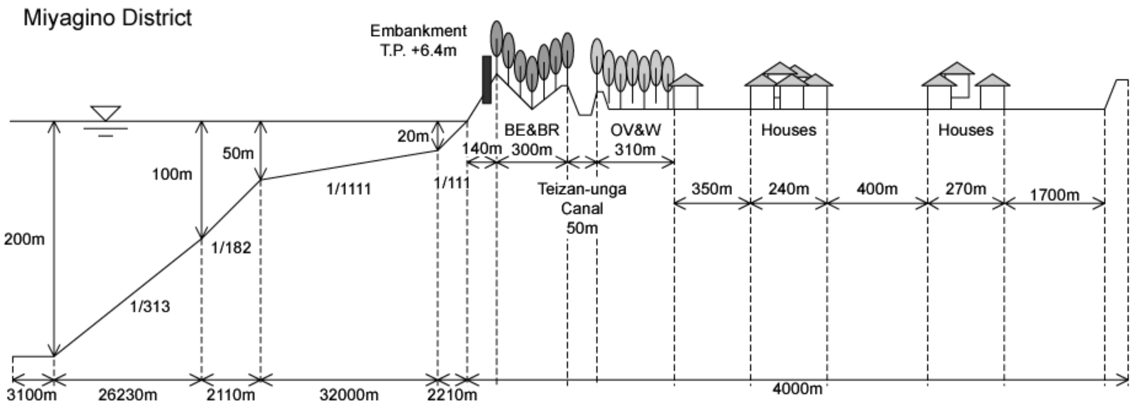

Fig. 7 Schematic of topography for numerical simulation.

3. Result and Discussion

3.1 Time series of driftwood's location

In the numerical simulation, each driftwood motions could be calculated. **Fig.8** shows the locations of driftwoods in time series on two dimensions. Fig.8-A shows the initial condition before the generation of tsunami (t = 0.0 s). At t = 3229.1 s, all trees in the area of inland side had been judged as 'washout' and began to move as driftwoods (Fig.8-B). At t = 3370.3 s, most driftwoods had just collided with the first group of houses and stopped (Fig.8-C). At t = 3751.8 s, the other driftwoods had just collided with the second group of houses and stopped (Fig.8-D). These simulated locations of accumulated debris were close to the actual situation in Miyagino District.

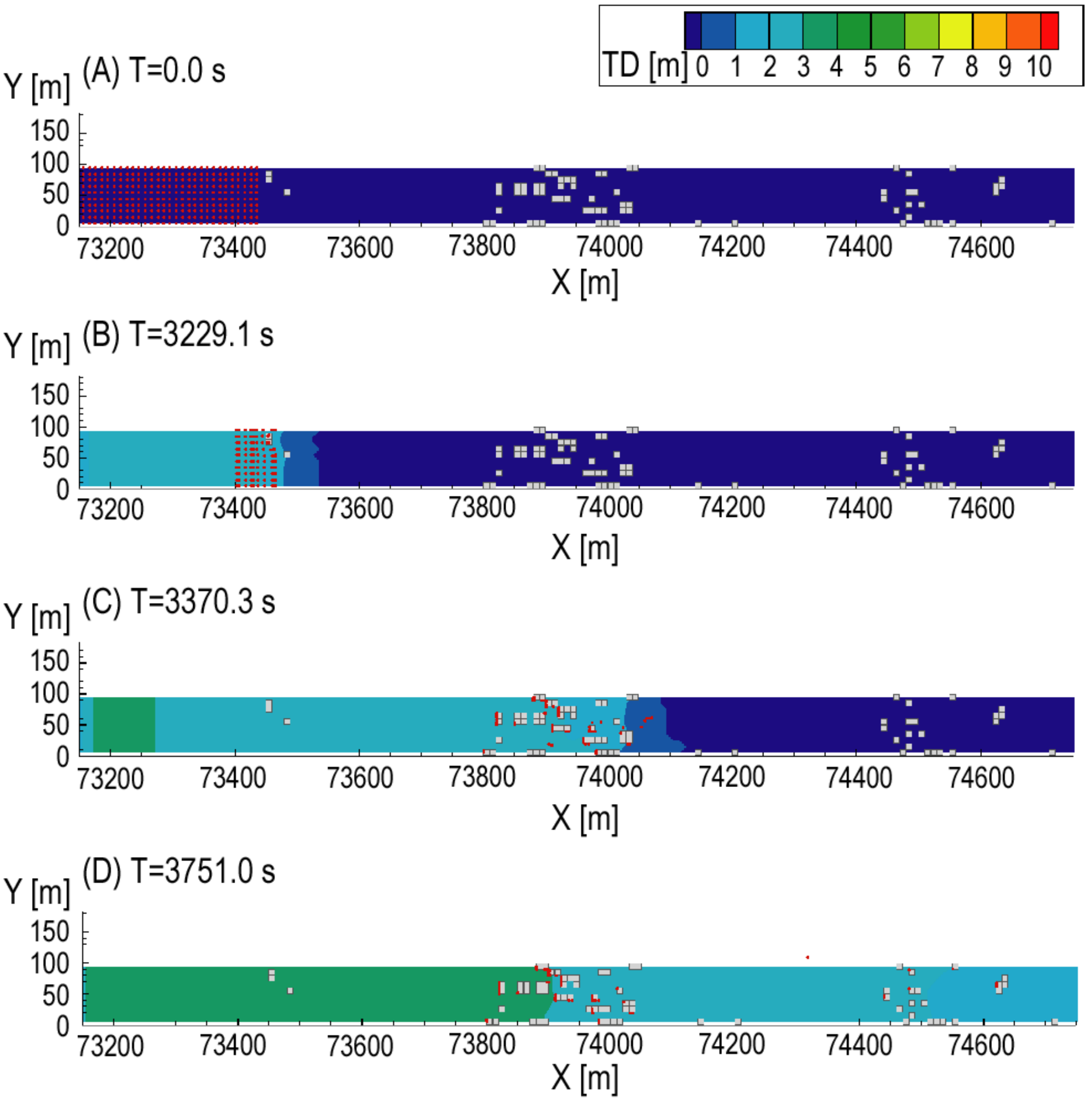

Fig. 8 Time series of driftwood's location. red circle and gray square: location of driftwood, and house, respectively, *TD*: total depth.

3.2 The influence of the driftwoods on houses

Fig.9 shows collision force of each driftwood and the maximum drag force on each house in relation to the distance from the shoreline. Maximum drag force on houses became smaller with increasing the distance from the shoreline, but the collision force of driftwood were not much changed, 0 - 20 kN regardless of the distance. The rate of the collision force of driftwood to the maximum drag force on house was small, 0.05-0.15. Furthermore, when a house was judged as 'washout', the rate was only 0.08 even in the largest case. In this area, a lot of driftwoods were produced from the lower land elevation area behind sand dune, but most trees on sand dune remained although the trees were broken as trunk-bending. Fluid force reduction was also existed even when trees were bent (Tanaka [3)]). Therefore, the driftwood has been found not to be a main factor for washing out houses.

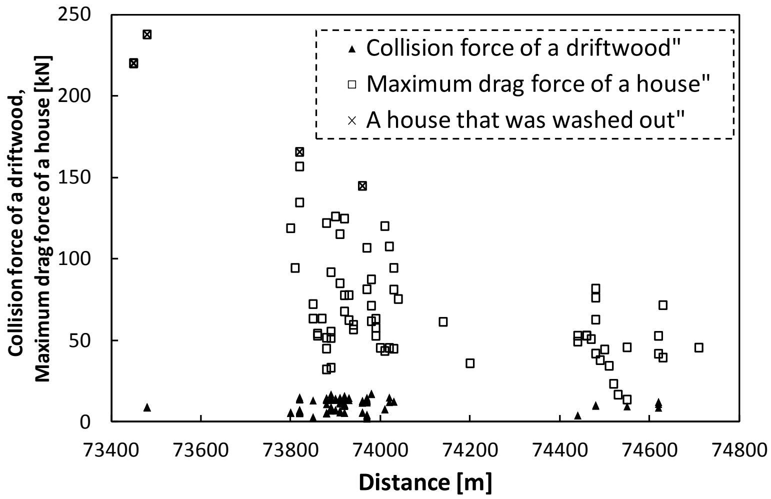

Fig. 9 Collision force of each driftwood and the maximum drag force on each house in relation to the distance from the shoreline.

4. Conclusion

A numerical simulation model including the judgment of tree breaking and washing out condition, motion of trees after the washout, and collision of houses has been developed and the influence of the driftwoods on houses was analyzed. Numerical simulation was conducted in Miyagino District in Sendai City with the area of 4000m×100m. In the simulation, a collision force on houses by driftwood was analyzed and the magnitude of the collision force was compared with that of the drag force. The simulation could reproduce well the final location of driftwood. The rate of the collision force of driftwood and the maximum drag force on a house was 0.05 - 0.15. In the case of the house which was judged as washout, the largest rate was 0.08. Therefore, the driftwood has been found not to be a main factor for washing out houses. However, it has a possibility to slightly influence the washing out situation of the house where the fluid force was close to the critical value for washing out houses. So the appropriate location and arrangement of trees where trees are not washed out is needed in future design.

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