# Effects of the coastal forests, sea embankment and sand dune on reducing washout region of houses at the tsunami caused by the Great East Japan Earthquake

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***Abstract:*** *The tsunami caused by the Great East Japan Earthquake on 11 March 2011, broke most of the sea embankment and coastal forests, and caused dreadful damage to people and buildings in Tohoku and Kanto districts of Japan. This study hypothesized that the coastal forest had a tsunami mitigation effect even when the coastal vegetation was bent down, because most of the vegetation was not washed out, hence could acts as a dense roughness element. Therefore, the objective of this study is to evaluate the vegetation effect on reducing the washout region of houses under severe tree breaking phenomenon using numerical simulation and data from field investigation in April and May 2011. Numerical simulations estimated the effects of a 640m-coastal forest, sea embankment around 5.4m in height or sand dune (2m increase) on reducing the washout region of houses by around 100 m, 600m and 600m for 10m height tsunami at coast. It was observed/concluded that although the quantitative effect of coastal forest is smaller than sea embankment, the coastal forest and sand dune is not a negligible component of the mitigation measures when a large tsunami occurs and overflows the sea embankment.*

***Keywords:*** *tsunami, coastal vegetation, inland embankment, critical moment of washout of houses*

## 1. INTRODUCTION

Tsunamis can cause massive destruction to both human life and socioeconomic property both on the coast and in the hinterlands. The importance of further mitigation techniques were recognized to be constructed after the Indian Ocean tsunami. Mitigation techniques are broadly categorized into two types. These include hard solutions utilizing large embankments and tsunami gates, and soft solutions utilizing a natural buffer zone of coastal vegetation, and sand dunes. Research on the effectiveness or limitations of coastal vegetation has accelerated since the 1998 Papua New Guinea tsunami, and the Indian Ocean tsunami on 26 December 2004.

The tsunami caused by the Great Japan Earthquake at 14:46 JST on 11 March 2011, which had a magnitude of 9.0 and epicenter 129km east of Sendai, broke most of the sea walls (tsunami gates, large embankments) and caused dreadful damage to people, buildings, and coastal forests in the Tohoku and Kanto districts of Japan. In particular, the tsunami passed through sand dunes planted with coastal vegetation (mainly pine trees) and completely washed out the houses behind the forests for 0.4–1.6km and partly destroyed them for 1.4–5.2km, especially in the Sendai Plain.

Several of our previous studies (Shuto (1987); Tanaka et al.(2007)). have discussed the effects of vegetation on tsunami mitigation based on numerical simulation results. However, the effect of tree breakage was not considered in most of these studies except for Yanagisawa et al.(2009), Tanaka et al.(2010) and Thuy et al.(2011). Yanagisawa et al. performed field surveys and proposed a fragility function for mangrove trees (*Rhizophora* sp.) to describe the relationship between the probability of damage and the bending stress caused by the maximum bending moment that was based on the field studies. Authors also analyzed how the breaking of trees in a forest affects tsunami disaster mitigation effects using a numerical model based on two-dimensional nonlinear long-wave equations which calculate the breaking condition of sand dune vegetation directly considering the tsunami force and bending moment of trees (Tanaka et al.(2010); Thuy et al.(2011)).

Even though the coastal vegetation was bent down by the Japanese tsunami, most of the vegetation was not washed out, hence could acts as a dense roughness element. Therefore, the objective of this study was to evaluate the effect of vegetation in reducing the damage to houses when severe tree-breaking phenomena occur. To fulfill these objectives, a field investigation was conducted in the coastal zone of the Sendai Plain, Japan, and quantitative information on the effects and limitations of coastal vegetation was evaluated by a numerical simulation.

## 2. SITE LOCATIONS AND MEASUREMENT METHOD

### 2.1. Information of sites

Field investigations were carried out in April and May of 2011 in the tsunami-affected forests in the Tohoku area of Japan (see **Figure.1**). The representative vegetation was mainly *Pinus densiflora* Siebold and Zucc. and *P*. *thunbergii* Parlat. In each location, tsunami water depth, damaged situation of sea embankment, trees (diameter, height and density) and houses were investigated. The tsunami water depth at each site was determined by water mark or evidence of collisions.

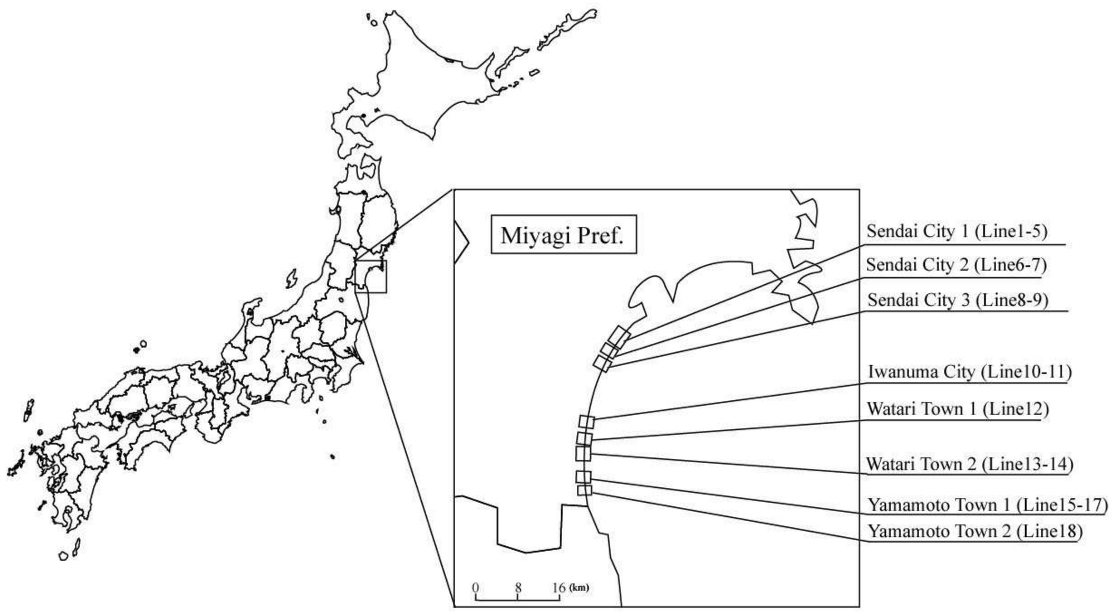



**Figure.1 Location of investigation sites**

For analysing the effect of coastal forest, sea embankment and sand dune, 18 locations were selected (**Table.1**). Damage situation of inland by the Japanese tsunami was very complex, since the sea embankment was breached in some area and coastal forest was mostly broken. Among 18 locations, one location (Wakabayashi District as shown in **Figure.2**) was selected considering that; 1) sea embankment existed and it was not washed out, 2) there were no inland embankment such as road embankment that affects tsunami inundation pattern greatly, and 3) the density of houses were not so large because washed out houses produced large quantity of debris and it affected the energy dissipation process and washout condition of houses. After validating the numerical model using the information of tsunami water depth measured at the post tsunami survey in many locations in this site, the effect of coastal forest, sea embankment and sand dune for reducing the washout region of houses were compared with each other.

**Table.1 Information on the field investigation sites**

| Line No | City or town | Location (latitude, longitude) N | E | Length of washout region from coast (m) | Condition of embankment after the tsunami | Washout condition of coastal forest | Existence of houses near sea embankment or on the sand dune region | Existence of large building within the washed out region of houses |
|---|---|---|---|---|---|---|---|---|
| 1 | Sendai | 38°15'20" | 141°0'43" | 2100 | WE | WS | EE | not existed |
| 2 | Sendai | 38°15'15" | 141°0'39" | 1400 | NW | NF | EE | existed |
| 3 | Sendai | 38°14'56" | 141°0'39" | 800 | WE | NS | NH | existed |
| 4 | Sendai | 38°14'33" | 141°0'21" | 1800 | WE | NS | NH | not existed |
| 5 | Sendai | 38°14'8" | 141°0'1" | 1400 | WE | WO | NH | not existed |
| 6 | Sendai | 38°13'2" | 140°59'12" | 1800 | NW | NS | ES | not existed |
| 7 | Sendai | 38°12'50" | 140°59'3" | 2000 | NW | NS | ES | not existed |
| 8 | Sendai | 38°12'24" | 140°58'42" | 1900 | NW | NS | NH | not existed |
| 9 | Sendai | 38°10'51" | 140°57'50" | 1900 | NE | NF | ES | not existed |
| 10 | Iwanuma | 38°4'42" | 140°55'34" | 500 | NW | WS | NH | not existed |
| 11 | Iwanuma | 38°4'22" | 140°55'31" | 800 | NW | WS | NH | not existed |
| 12 | Watari | 38°2'21" | 140°55'19" | 1200 | WE | NT | ES | not existed |
| 13 | Watari | 38°1'3" | 140°55'6" | 900 | NW | WS | NH | not existed |
| 14 | Watari | 38°0'1" | 140°54'59" | 1000 | WE | WS | NH | not existed |
| 15 | Yamamoto | 37°58'17" | 140°54'55" | 600 | NW | WS | NH | not existed |
| 16 | Yamamoto | 37°57'53" | 140°54'58" | 1200 | NW | WS | NH | not existed |
| 17 | Yamamoto | 37°57'32" | 140°54'59" | 1000 | WE | WS | NH | not existed |
| 18 | Yamamoto | 37°65'26" | 140°55'12" | 1600 | WE | WS | NH | not existed |

Note: WE: Washed-out embankment, NW: Broken but not washed-out embankment, NE: No embankment, ES: There was houses in sand dune region, EE: There was houses near the embankment, NH: There were no houses near the embankment and/or on sand dune, NS: Tree existed, but there were no scour region and trees were not wahed out, NF: There was no forest, NT: Scour region was genearted but there were no trees in the scour region, WS: Washed out from the scoured region, WO: Washed out not only by scouring but also by mainly overturning

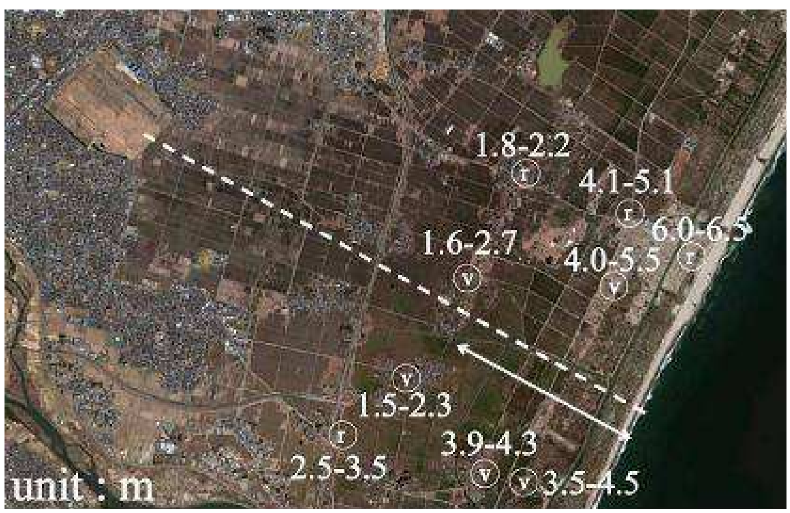



**Figure.2 The location of analyzed area at Wakabayashi District , where numerical values show the observed tsunami water depth, *v* means the data for model validation, *r* means reference data, dotted line shows inundated area, and line with an arrow means the washout region of houses.**

## 2.4. Numerical simulation

To elucidate the mitigating effect of a coastal forest quantitatively, numerical simulations were conducted using the model developed by Thuy et al.(2009) used, 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.

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

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

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

where

$$\vec{\tau}_b=\frac{\rho g n^2}{h^{1/3}}\vec{V}\left|\vec{V}\right| \tag{4}$$

$$\vec{F}=\gamma\frac{1}{2}\rho C_{D-all}b_{ref}\vec{V}\left|\vec{V}\right|h \tag{5}$$

$$E_{vx}=2\frac{\partial}{\partial x}\left(h\nu_e\frac{\partial V_x}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\nu_e\frac{\partial V_x}{\partial y}+h\nu_e\frac{\partial V_y}{\partial x}\right) \tag{5}$$

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

$x$ 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); $\zeta$ the water surface elevation; $n$ the Manning roughness coefficient; and $\gamma$ the tree density (number of trees/m$^2$). $C_{D-all}$ is the depth-averaged equivalent drag coefficient considering the vertical stand structure of the trees, which was defined by Tanaka et al.(2007) as:

$$C_{D-all}(h)=C_{D-ref}\frac{1}{h}\int_0^h\frac{b(z_G)}{b_{ref}}\frac{C_D(z_G)}{C_{D-ref}})dz_G \tag{7}$$

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 $C_{D-ref}$ are the reference projected width and reference drag coefficient, respectively, of the trunk at $z_G$ =1.2m in principle. The eddy viscosity coefficient $v_e$ is expressed in the SDS turbulence model.

To clarify tree breaking, the models of Tanaka et al.(2010) and Thuy et al.(2011), which consider the breaking condition of tropical sand dune vegetation, were adapted to pine trees. Moment acting on the tree trunk at ground height (Eq.(8)) and critical bending moment of trees (Eq.(9)) are used for judging tree trunk bending as below.

$$M=F\times\frac{h}{2}=\frac{1}{2}C_{D-all}\rho u^2 h d_{BH}\frac{h}{2}=\frac{1}{4}C_{D-all}\rho u^2 h^2 d_{BH} \tag{8}$$

$$M_{bcri}=kD_{BH}{}^3 \tag{9}$$

where $u$ (m/s) ($=\sqrt{V_x{}^2+V_y{}^2}$) is the velocity; $C_{D-all}$ drag coefficient (=1 before breaking, because the pine trees at the site doesn't have many branches); $\rho$ (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 unit, respectively; $k$ dimensional constant (=2 or 3 for hard trunk and elastic trees, respectively (Tanaka & Yagisawa, 2009). When $M$ is larger than $M_{bcri}$, the tree is judged to be bent down and the drag coefficient is changed from 1.0 to 0.2. Considering fluid force ($F$) and moment by drag force ($M$), the fluid force index ($u^2h$), and the moment index ($u^2h^2$) were defined. At Wakabayashi district, pine trees with 15cm in diameter and 9.6m in height were mostly bending. The threshold momentum index is around 180m$^4$/s$^2$.

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. A sinusoidal incident tsunami was given as a time-dependent boundary condition at the most offshore side of the wave-generation zone. The initial conditions were given for a waveless state in the computational domain including the wave-generation zone. In the numerical simulation, a uniform grid size of 10m was applied considering available elevation data and CPU time. The Manning roughness coefficient $n$ was set as 0.025s/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 **Figure.3**, was selected as a model case. The density of houses here was low compared with other districts, so the effect of impact force by floating debris could be considered small in this area. The offshore water depth at an additional wave-generation zone with a horizontal bottom was 200m 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 width of the coastal forest was 640m, and it started at $x$ = 80m from the shoreline. The forest was assumed to extend finitely in the direction of the shoreline ($y$-axis). The maximum tsunami water depth at the shoreline was set at 10m, which is the average value in this area.

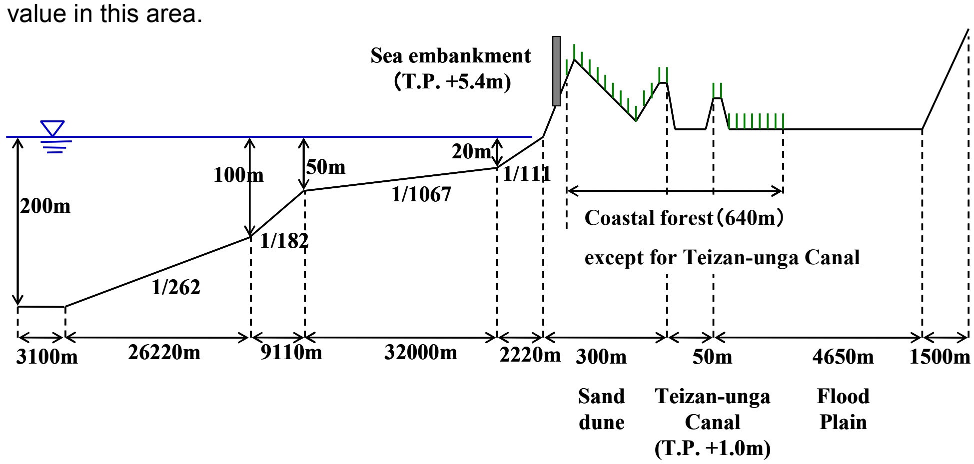



**Figure.3 Schematic of topography for numerical simulation area**

## 3. RESULTS AND DISCUSSION

### 3.1. Verification of numerical simulation including vegetation breaking model

The Japanese tsunami broke coastal forest for long distance, so the validation of not only tsunami water depth but also the breaking length of the coastal forest by the tsunami is also required. Vegetation can reduce the velocity, water depth inside a forest, and timing of the tsunami front arrival.

**Figure.4** shows a comparison of the numerical simulation data with the observed tsunami characteristic (maximum water depth). In this figure, three simulation results are shown; using a non-breaking model in which $C_d$ is set at the before-the-tsunami condition of 1.0), a non-breaking model (in which $C_d$ is estimated in the after-the-tsunami condition by the ratio of broken trees to all trees of 0.24), and a breaking model (in which $C_d$ is changed with time: when a tree is judged ‘broken’, the value is reduced from 1.0 to 0.2). From the results, the breaking model can be seen to reflect the tsunami water marks well. The breaking length of coastal forest by the simulation was 420m and it was a similar value with the actual length. Thus, the effectiveness of our model was validated for this actual tsunami.

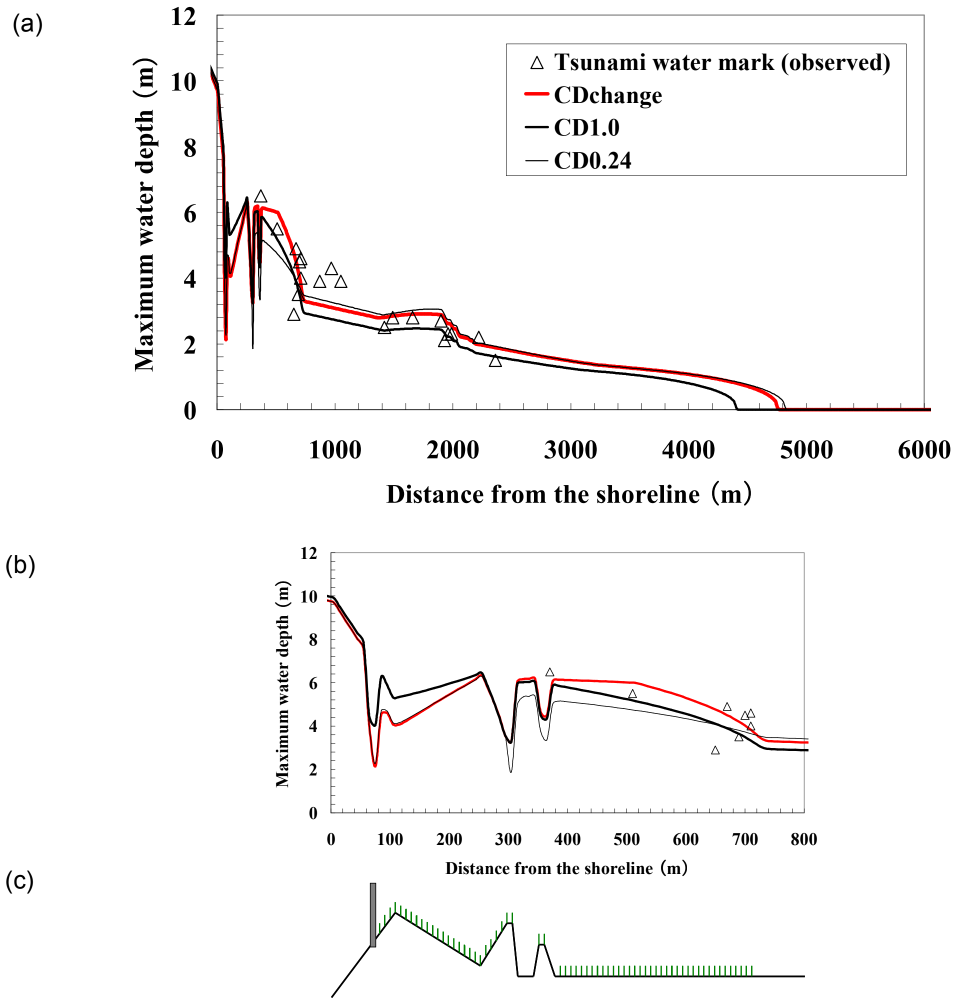
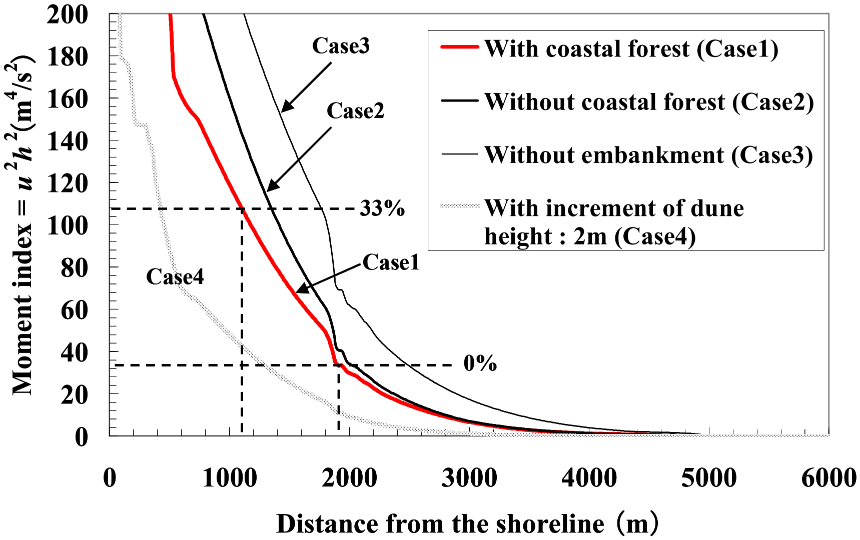



**Figure.4 Comparison with calculated maximum water depth and observed values (a) Validation of maximum water depth for three models. CD change: with breaking model, CD1.0: $C_{D\text{-}all}$ is a constant of 1.0 (before the tsunami), CD0.24: $C_{D\text{-}all}$ is a constant of 0.24 (after the tsunami), (b) the graph which enlarged the range of 0-800 m in Figure.4(a), (c) topographical shape corresponding to the range of Figure.4 (b).**

## 3.2. Effectiveness of coastal vegetation in reducing fluid force.

**Figure.5a** and **b** show the fluid force index ($u^2h$, where $u$ and $h$ are the tsunami velocity and water depth, respectively) and the momentum index ($u^2h^2$) for the present case (with vegetation and an embankment: Case 1), without vegetation (Case 2), without an embankment (Case 3), and with higher sand dune (in this case sand dune height is increased 2m: Case 4). The critical value of the moment index ($M_{cr}$) was around 76m$^4$/s$^2$ according to a real-scale experiment (Takahashi et al.(1985) ). For the fluid force index ($F_{cr}$), the study by Hatori (1985) showed that most houses were washed out when $F_{cr}$ exceeded 100m$^3$/s$^2$, and one-third of houses were lost when $F_{cr}$ was around 15m$^3$/s$^2$. Based on the washout situation observed at the present study site and the simulation result, the $M_{cr}$ values for 33% and 0% washout were 109m$^4$/s$^2$ and 34m$^4$/s$^2$, respectively. This is similar to the value that Takahashi et al. reported in 1985. Moreover, $F_{cr}$ values for 33% and 0% washout values were 41m$^3$/s$^2$ and 18 m$^3$/s$^2$, respectively, which is slightly larger than the figures of Hatori (1985). Based on a comparison of Cases 1 and 2, the vegetation could be assumed to decrease the washout region by around 110m. On the other hand, an embankment could reduce the washout region by 590m. In addition, the comparison of Cases 1 and 4 shows that the sand dune (2m height increment) could be assumed to decrease the washout region of forest around 420m and thus decreased the washout region of houses by around 590m. From the results, the vegetation effect is not large in comparison with the effect of the embankment or sand dune, but it is not negligible either.

(a)




(b)

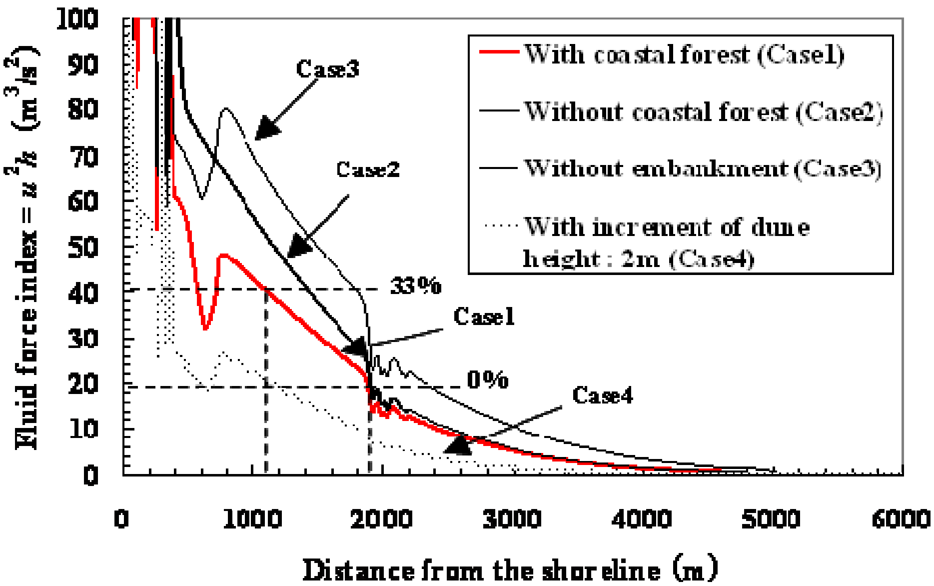



**Figure 5. Differences between cases with/without coastal forest and embankment, and sand dune height (Case 1: with forest (present case), Case 2: without vegetation, Case 3: without an embankment, Case 4: with higher sand dune (in this case sand dune height is increased 2m): (a) moment index. 0% and 33% mean percentage of houses washed out at the location. Figure.5 (b) fluid force index.**

## 4. CONCLUSION

Tree damage is directly related to the tsunami force, but the effects of tree breaking on numerical simulation results were not directly discussed in previous studies except for a study we published recently. We validated our numerical model with field measurement data on the threshold water depth for tree breaking, then breaking length, and finally reduction of water depth. This study demonstrated that the breaking phenomenon decreases the effect of vegetation, but it also has some role in reducing the fluid

force and moment by drag force when trees are not washed out. Therefore, construction of a bioshield in an appropriate area (a region that will not be scoured) is very useful for mitigating the disaster caused by an extremely large tsunami that overflows or destroys an embankment.
A numerical simulation estimated the effects of a coastal forest and embankment on reducing the washout region of houses by around 100m and 600m, respectively. The effect of vegetation is small compared to that of the embankment, but it is not negligible in the mitigation when a large tsunami arrives and the sea embankment overflows.

## 5. ACKNOWLEDGMENTS

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