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DIFFERENCES OF TREE-BREAKING PATTERNS AND BREAKING MOMENT BY FLOODS WITH DIFFERENT TREE AGES AND SUBSTRATE CONDITION UNDER TWO FLOOD DISTURBANCES

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ABSTRACT

For elucidating the tree breakage condition with different breaking mechanisms, i.e. the moment by drag force, the local scour and degradation of the substrate of trees, field investigations on tree damage situation after two flood events (October 2006 and September 2007) were conducted in the Arakawa River and the Tamagawa River, Japan. The moment by the drag acting on the trees was calculated with different tree ages and various flood disturbance values. Comparing the flood period (T_2) with the maximum tree age (T_1), at which tree is broken, three habitats in the Arakawa River can be classified whether it has a tendency to be a forest or not. Tree has mainly two damaged patterns, trunk bending or breakage and overturning or uprooting (washing out). Considering plant regeneration situation of *Salix subfragilis* after 1year of the first flood event (October 2006), no such importance of the trunk bending or breakage pattern can be considered. When severe scouring occurs, the threshold overturning moment can be quite small. The tree overturning and uprooting were restricted to the bank side of the gravel bar, however, some trees, especially *Robinia pseudo-acacia* and *Morus bombycis*, were overturned if the substrate has a thin soil zone on the gravel layer.

Keywords: tree breaking pattern forestation, regeneration, root zone, moment by drag force

1. INTRODUCTION

The vegetation in a river creates a valuable natural environment that maintains the biodiversity. However, forestation in the river sometimes becomes a big problem because it reduces the river flow capacity toward the downstream and adds additional drag force on the bridge pier in the river when it attaches and accumulates around the pier. In addition, the excessive forestation by mono tree species sometimes affects the biodiversity in the river habitat. Therefore, the rehabilitation of the gravel river bed and the removal of the trees have been discussed recently.

Considering the above situation, the breaking condition of the vegetation in the river by the flood should be elucidated. Breaking condition of trees has been investigated for wind damage in forests (Gardiner et al., 2000) and for damage of the coastal vegetation by tsunami (Tanaka et al., 2006, 2007a). The damage mechanism of a tree in the river or in the coast is similar to the mechanism of the wind damage, but more complex, because the relationship between the height of the tree and the water depth is different in both the river flood and tsunami. The effects of the flow pattern around the tree and the drag force on it are changed with the water depth. The drag force also affects the shear stress on the substrate around a tree. Then the damage pattern of the vegetation in the river becomes more complex.

Therefore, the objectives of this study are; 1) to propose the method whether the habitat has a tendency to be a forest or not, 2) to investigate the breaking pattern of the river vegetation by the floods, and 3) to elucidate quantitatively the critical turning or breaking moment needed to uproot or to break the trunk of the trees. For those objectives, the damaged situation of the trees in the river was investigated on a gravel bar or on the floodplain of the Arakawa River after two flood events, October 2006 and September 2007, and on the Tamagawa River after Typhoon nine in September, 2007. Kumagaya Arakawa-ohashi, and Kuge-bashi observation sites are located in the Arakawa River as shown in Figure 1; where, Todoroki, Fuchu-Yotsuya, Hinobashi, Nagatabashi and Inagi observation sites are located in the Tamagawa River. The damaged pattern and the flood water depth trait were investigated in each site.

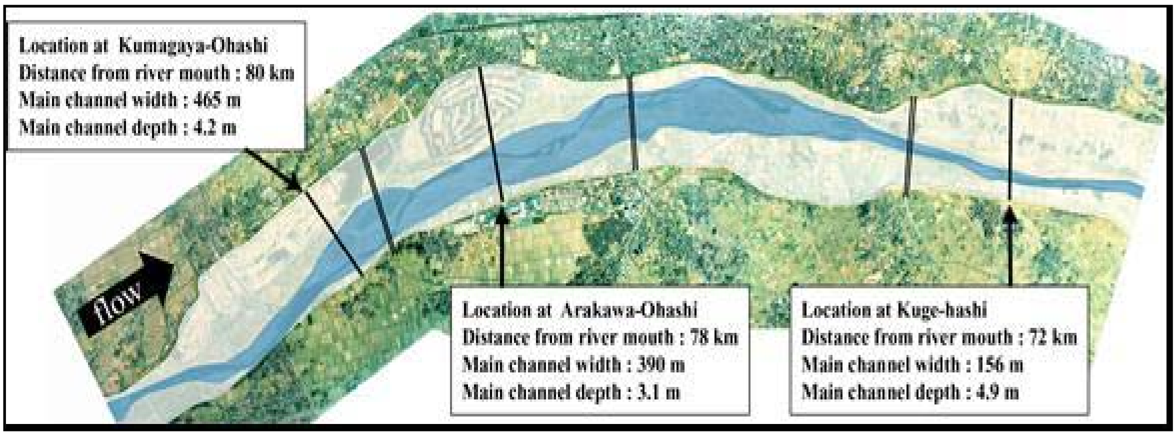

Figure 1 Location of the Arakawa River field observation sites.

2. FIELD INVESTIGATION AND ANALYSIS

2.1 Analysis of tree-breaking threshold considering the breaking pattern

Gardiner at al.(2000) proposed two equation for tree breaking threshold, trunk breakage and overturn. The trunk breakage moment, M_{bc} (kNm), can be calculated as;

$$M_{bc} = \frac{\sigma_{\max} I}{R} \cong kd^3 \quad (1)$$

where, R, d are the radius and diameter of breakage section of a tree trunk (m), respectively, $\sigma_{\max}$ is the critical bending moment of the outer fiber of tree trunk (N/m^2), I is the second moment of the area (m^4).

If $\sigma_{\max}$ can be assumed constant, the breakage condition becomes a function of d^3. In that case, k becomes a constant depending of the tree species. The critical bending moment to overturn, M_{overc}, is proposed as a function of trunk weight (Gardiner at al., 2000) based on tree pulling experiments on almost 2000 trees as:

$$M_{overc} = k_{over} \times (trunk\ weight) \quad (2)$$

Where, k_{over} is a constant.

Similar equation was also proposed by Technology Research Center Riverfront Development (TRCRD) (1994) as:

$$M_{turnc} = 24.5 d_{BH}^{2} \tag{3}$$

Where, M_{turnc}, is the critical overturning moment of a tree in Japanese rivers (Nm), d_{BH} is a breast height diameter of a tree trunk (cm). This corresponds to assume that the trunk weight is proportional to d_{BH}^2 in Eq. 2.

Some experimental loading tests for some trees in the river were conducted in the experimental room, Saitama University, Japan as shown in Figure 2. With these experiments, the constant k in Eq. 1 was estimated.

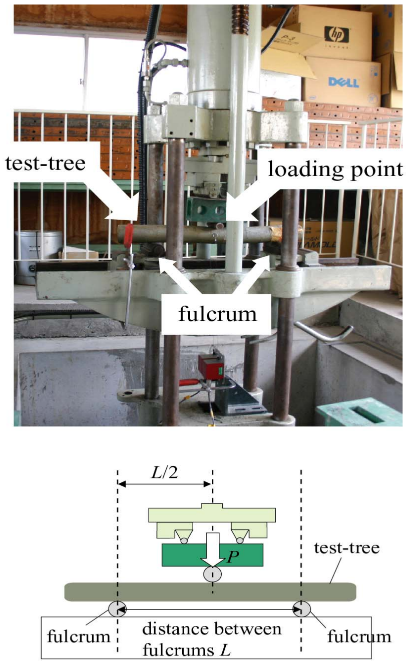

Figure 2 Experimental setup for loading test

One more important mechanism for resisting bending moment is the root tensile strength. As the roots increase the soil shear strength by anchoring the soil layer and by forming the binding network (Tosi, 2007), they increase the threshold moment for the overturning when the soil shear stress exceeds the critical soil shear strength value. Later, this point will be discussed with the results, section no. 3.

To analyze the moment acting on the tree, the drag force F, including the tree stand structure (Tanaka et al., 2007a), is considered as:

$$\begin{aligned} F &= \int_0^h \frac{1}{2} C_d(z) \rho u(z)^2 d(z) dz = \frac{1}{2} \rho C_{d-ref} D_{BH} U^2 \int_0^h \frac{d(z)}{D_{BH}} \frac{C_d(z)}{C_{d-ref}} dz \\ &= \frac{1}{2} \rho C_{d-ref} D_{BH} U^2 \int_0^h \alpha(z) \beta(z) dz \end{aligned} \tag{4}$$

$$\alpha(z) = \frac{d(z)}{D_{BH}} \quad , \quad \beta(z) = \frac{C_d(z)}{C_{d-ref}} \tag{5}$$

$$M = \frac{1}{2}\rho C_{d-ref} D_{BH} U^2 \int_0^h z\alpha(z)\beta(z)dz \tag{6}$$

Where, z = vertical axis from the bottom (m), $C_{d\text{-}ref}$, reference drag coefficient (=1 considering a circular cylinder in this study), $C_d(z)$, $u(z)$, $d(z)$= the drag coefficient, the velocity(m/s) and the cumulative width of the tree trunk and branch (m) at height = z, respectively, ρ = the density of fluid (kg/m^3), h = the tsunami or the flood water depth (m), D_{BH} = the breast height diameter of the tree trunk (m) (=1.3 m from ground), $\alpha(z)$ = additional coefficient for expressing the vertical tree structure, $\beta(z)$ = additional coefficient for representing the effect of leaves (=1.25). In this research, the vertical velocity distribution was not considered, and the sectional average velocity U (m/s) was used for $u(z)$ as shown in Figure 3. For more details, see Tanaka et al. (2007c).

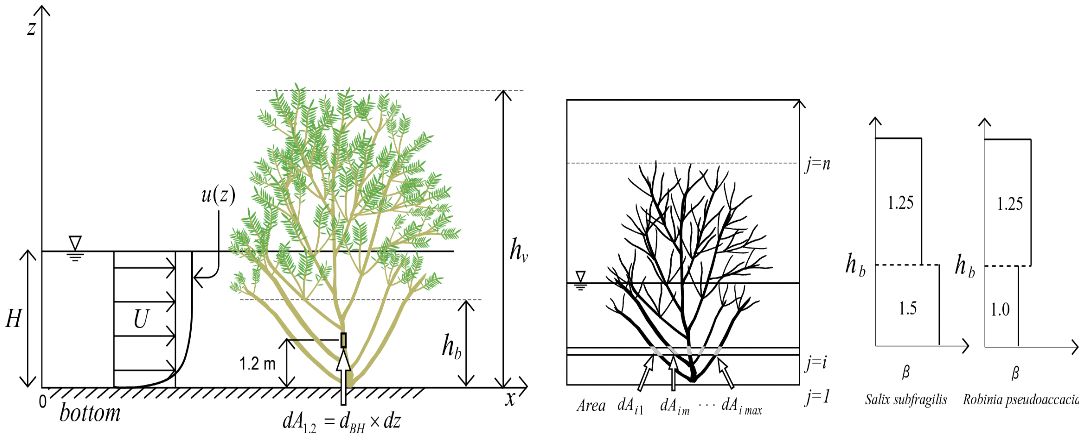

Figure 3 Schematic diagram of the drag force defined in this study

For analyzing the possibility whether the habitat has the tendency to become a forest, the velocities and the water depths were calculated by using both of the one-dimensional momentum equation and the continuity equation. The moment value (M) acting on the trees at the habitat shown in Figure 1 is compared with the threshold value M_{bc}. The diameter at the breast height and the tree height (h_v) was given as a function of the tree age (Tanaka et al., 2007b). The discharges value in each habitat as in Figure 1 are estimated as a function of the return period by using the upstream maximum discharge data of the years from 1955 to 2005 at Yorii discharge station (94.7km from Tokyo Bay) and by analyzing them with Weibul plot method. In addition, the water depth at the three habitats was derived by Manning equation assuming the quasi-normal flow at the flood peak. Manning roughness coefficient and bed slope were given as 0.035 (m$^{-1/3}$s) and 1/375, respectively.

2.2 Field investigation and Local velocity estimation method around trees

Two methods were used for evaluating the flow velocity approaching the trees.

Method-1: Most of the grasses were broken around the trees in the investigated site after 2007 flood. Tanaka et al.(2004) investigated the breaking moment of *Phragmites australis* and *Miscanthus sacchariflorus*, perennial grasses in the river habitat, and found them to be 0.62 Nm and 1.25 Nm, respectively, in case of 3-4 mm diameter classes. If the grasses are broken, the moment can be assumed larger than the critical value. According to this, we can assume and guess the minimum velocity at the trees habitat. In the wake of the tree, *M. sacchariflorus* trees were sometimes not broken (Figure 4). According to Takemura and Tanaka (2007), the wake flow velocity, u_{wake}, can be assumed as:

$$u_{wake} = \gamma U \tag{7}$$

Where, U is the approach velocity of the colony-type trees, γ is a constant depending on G/D, where G is the cross-stream gap between the trees and D is the reference diameter of the trees. From the field investigation, $G/D = 1$ and 2 for *Robinia pseudo-acacia* and *Salix subfragilis*, respectively and it corresponds to $\gamma = 0.70$, 0.65, respectively. When *M. sacchariflorus* were not broken, we can assume the maximum value of u_{wake} from the threshold breaking moment of the plant by solving u_{wake} (U in eq.(6)) under M = 1.25Nm, critical value of the *M. sacchariflorus*. From u_{wake}, maximum value of U in eq.(7) can be assumed.

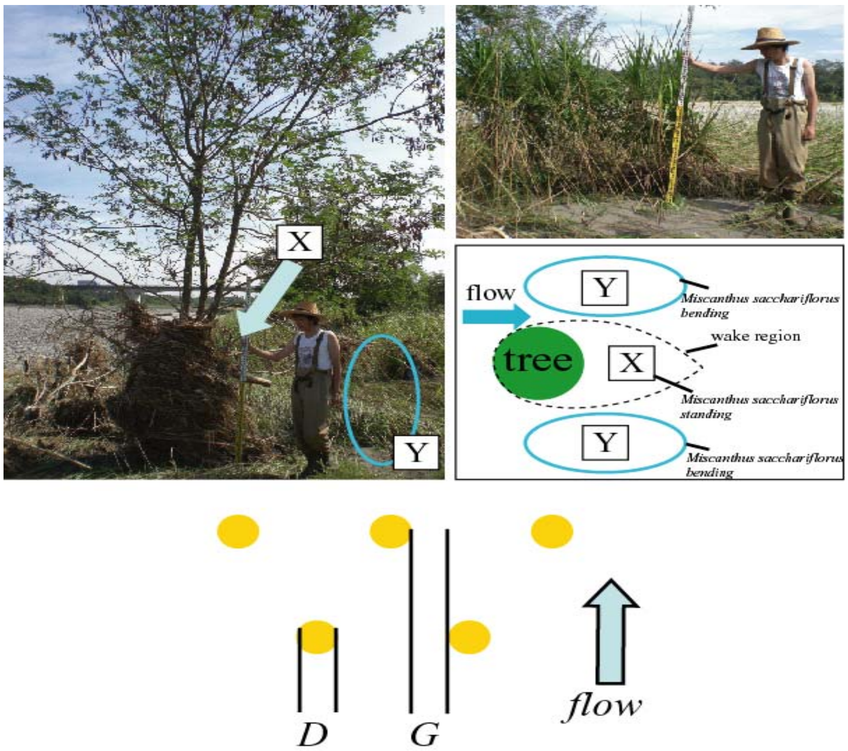

Figure 4 Flood trait around a tree at Kumagaya. (a) bending *Miscanthus sacchariflorus* (Y), (b) standing *Miscanthus sacchariflorus* (X), (c) definition of trunk width (D) and gap (G).

Method-2: the water surface gradient from Kumagaya Station to Uematsubashi Station, upstream and downstream of the observed gravel bar, was ranged from 1/344 to 1/359 which is similar to the bed gradient. Then, the quasi-normal flow was assumed to evaluate the velocity at the damaged trees on the gravel bar. Manning equation and Manning roughness coefficient $\boldsymbol{n_w}$, which includes the surface roughness and the resistance by grasses, are used for evaluating the flow velocity in each habitat. Manning roughness coefficient can be given as:

$$n_w = \sqrt{{n_b}^2 + \frac{C_d}{2g} a_w h_w^{\frac{4}{3}}} \tag{8}$$

Where, n_b is the surface roughness ($m^{-1/3}s$), a_w is the projected area of plants in the unit volume (m^2/m^3), h_w is the vegetation height (m), g is the gravitational acceleration (m/s^2).

3. RESULTS AND DISCUSSIONS

3.1 Breaking condition of the trees and the possibility of the forestation

Figure 5 shows the relationship between d_{BH} and the moment by the drag force (M) acting on the trees at the flood event for *Salix subfragilis* and *Robinia pseudo-acacia*. Dotted lines show the threshold moments for trunk breakage. The trend shows that the M_{bc} has a cubic function of d_{BH} as indicated in Eq. 1 and k in Eq. 1 is evaluated as 2.0 and 3.0 for *Robinia pseudo-acacia* and *Salix subfragilis*, respectively by the loading test on the tree trunk. The threshold trunk breakage moment of *Robinia pseudo-acacia* is smaller than that of *Salix subfragilis*, because bending stiffness (*EI*) of *R. pseudo-acacia* is smaller and easily broken compared with that of *S. subfragilis*. Figure 5 also includes the threshold overturning moment equation Eq. 3. Comparing the equation for the trunk breakage, the trunk breakage should be occurred under the diameter 9.0 cm and 12.0 cm for *S. subfragilis* and *R. pseudo-acacia*, respectively. The calculated moment acting at 2006 flood event indicates that, the overturning should be occurred at a larger value than the value calculated from Eq. 3, because the tree (plot A) was broken not by the overturning but by the trunk breakage. If we decide a new coefficient using the plot A, the equation becomes as $M_{turnc} = 80{d_{BH}}^2$ at the habitat and the threshold for the trunk breakage and the tree overturning becomes 25.0 cm in diameter.

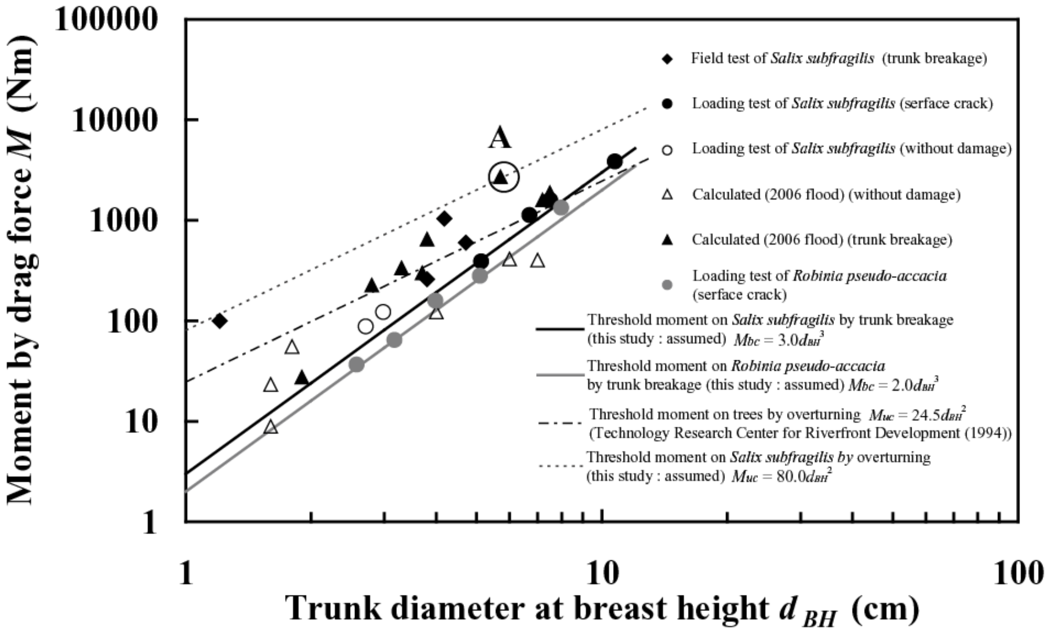

Figure 5 Relationship between d_{BH} and moment by drag force (M) acting on the tree at the flood event for *Salix subfragilis* and *Robinia pseudo-acacia*. Line and dotted lines show the threshold moment for tree overturning. M_{bc}: threshold trunk breakage moment, M_{uc}: threshold overturning moment,

The results indicate that the trunk breakage depends on the tree-trunk material, but the tree overturning threshold could be changed according to the substrate condition. In addition, the trunk diameter at the crossing point for the two equations is important to understand the tree damage mechanism.

Figure 6 shows the relationship between flood return period (T_1) and the maximum age of the trees broken by the flood (T_2) for both *Salix subfragilis* and *Robinia pseudo-acacia*. If T_1 is larger than T_2, the trees are easily washed out by the floods. The results for Arakawa-ohashi indicate that it has a tendency to be a forest, but it could be removed by the big floods. The forestation can be occurred more easily in Kumagaya-ohashi site. Kugebashi cannot be a forest because the flood with 4-5 years return period can easily break the trees with 15 years old. *R. pseudo-acacia* can maintain their habitat at Kumagaya and Arakawa-ohashi than *S. subfragilis* can do. These calculated results are corresponding to the forestation situation at the three sites, so this method can be a bulk method for analysing the habitat whether it has the tendency to be a forest or not.

3.2 Regeneration of *Salix subfragilis* after 1 year of 2006's flood

Figure 7 shows the regeneration characteristics of *Salix subfragilis* As Figures 7a and 7b show the relationship between the tree age and the diameter at the breast height d_{BH} and *between* d_{BH} and the tree height, respectively. A Line in Figure 7a shows the representative relationship between the tree age and the tree height (Ikeuchi et al., 1998). Even though the tree was damaged in 2006 where tree age = 6.8 years, it regenerated new branches. The main branch diameter is corresponds to an age of 5.7 years of *Salix*. If the tree didn't receive flood damage, the age should be 7.8, and then it means that the flood has a role to decrease only 2.1 years of the tree age in this case. From Figure 7b we can conclude that the bending damage can be recovered more easily than the trunk breakage damage and the height was completely recovered to the level before 2006's flood.

3.3 Breaking, bending and overturning moment of the river vegetation

The velocities calculated by using Method-1 were 1.52-2.17 m/s for Nagatabashi and 0.59-0.90 m/s for Kumagaya, respectively. These values were similar to those ones estimated by Method-2, which were 1.10 - 2.53 m/s for Nagatabashi and 0.51 m/s for Kumagaya, respectively. Therefore, we can use the velocity values calculated by using Method-1 if we have the data essential to us it; otherwise, the velocity values using Method-2 can be used confidently to calculate the moment values at any flood event.

Figure 8 shows the relationship between the breast height diameter and the moment acting on the trunk base and can be used to distinguish the data whether the trees was broken or not. If the tree, *Robinia pseudo-acacia* (at Inagi) or *Morus bombycis* (at Nagatabashi), grows on the floodplain and the root zone is restricted within the zone, the threshold moment for the overturning is low compared with the curve calculated by Eq. 3. However, if the tree, *Salix* spp. (at Hinobashi), grows on the gravel bar and the root is anchored in the substrate, the limitation is relatively larger than its value calculated by Eq. 3.

In case of the river flood, the trunk breakage was seldom occurred at the investigated flood but bending pattern was dominant. Most of the locations where the tree overturning was occurred were restricted to the bank side of the gravel bar or to the flood plain that has thin soil layer on the gravel bed bar in the case of the river flood. The most important point is that, the substrate condition affects the threshold clearly in case of the river flood. Most trees overturning occurred at the habitat which has a thin gravel soil layer and has a small sediment grain size around the tree. Most of *Salix* spp. did not overturn where *Robinia pseudo-acacia* and *Morus bombycis* on the thin floodplain did. This indicates that the timing of the colonization of the tree species is also an important factor.

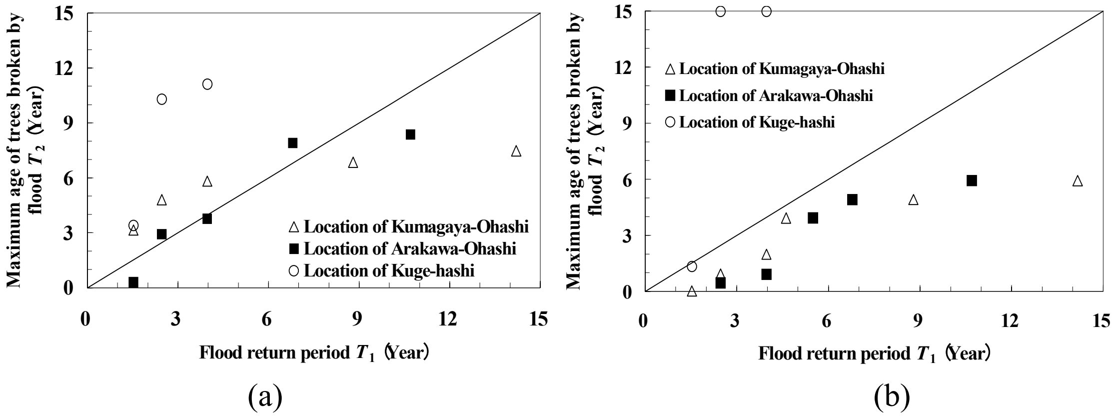

Figure 6 Relationship between the flood return period (T_1) and the maximum age of the trees broken by the flood (T_2) for; (a) *Salix subfragilis*, (b) *Robinia pseudo-acacia*

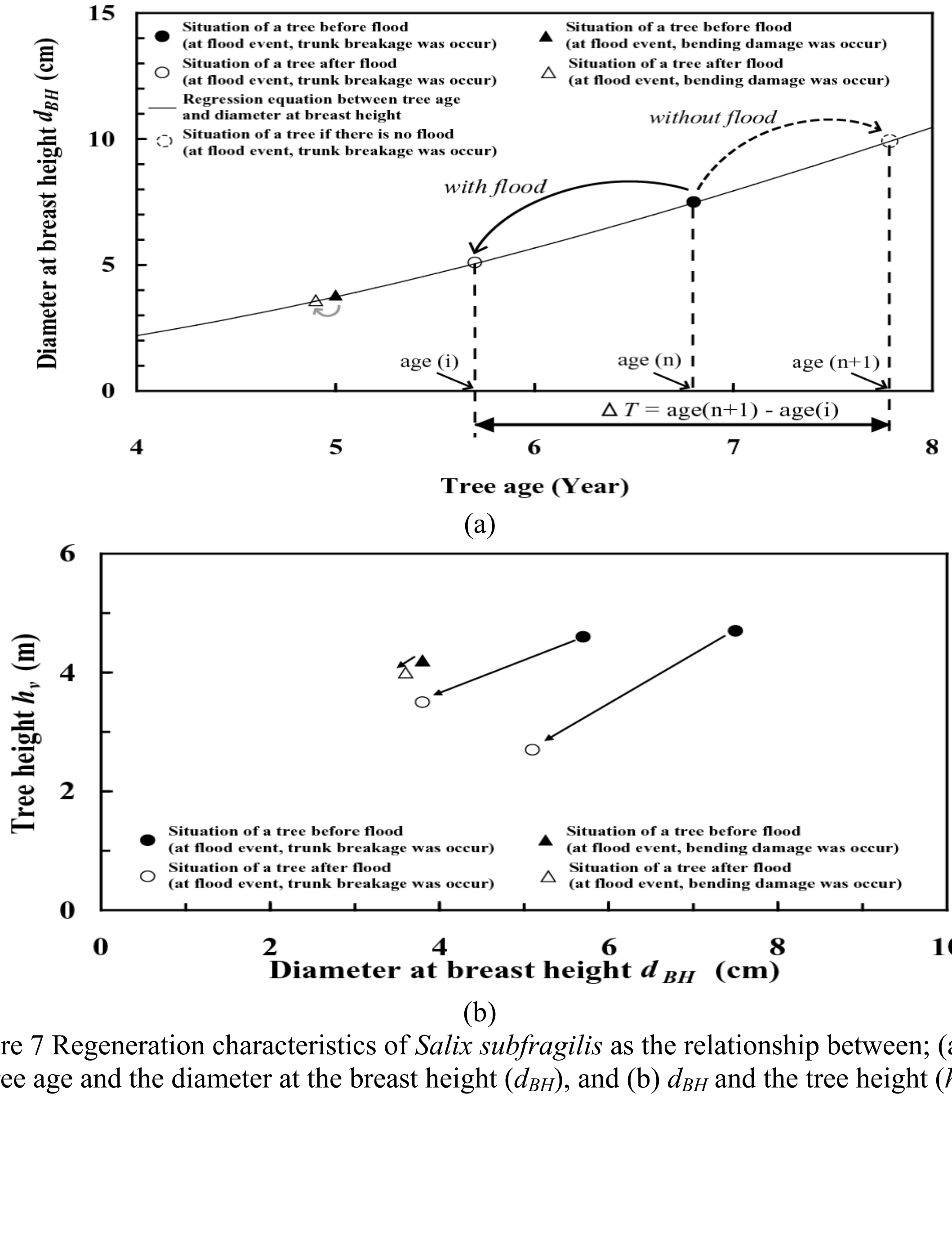

Figure 7 Regeneration characteristics of *Salix subfragilis* as the relationship between; (a) the tree age and the diameter at the breast height (d_{BH}), and (b) d_{BH} and the tree height (h_v)

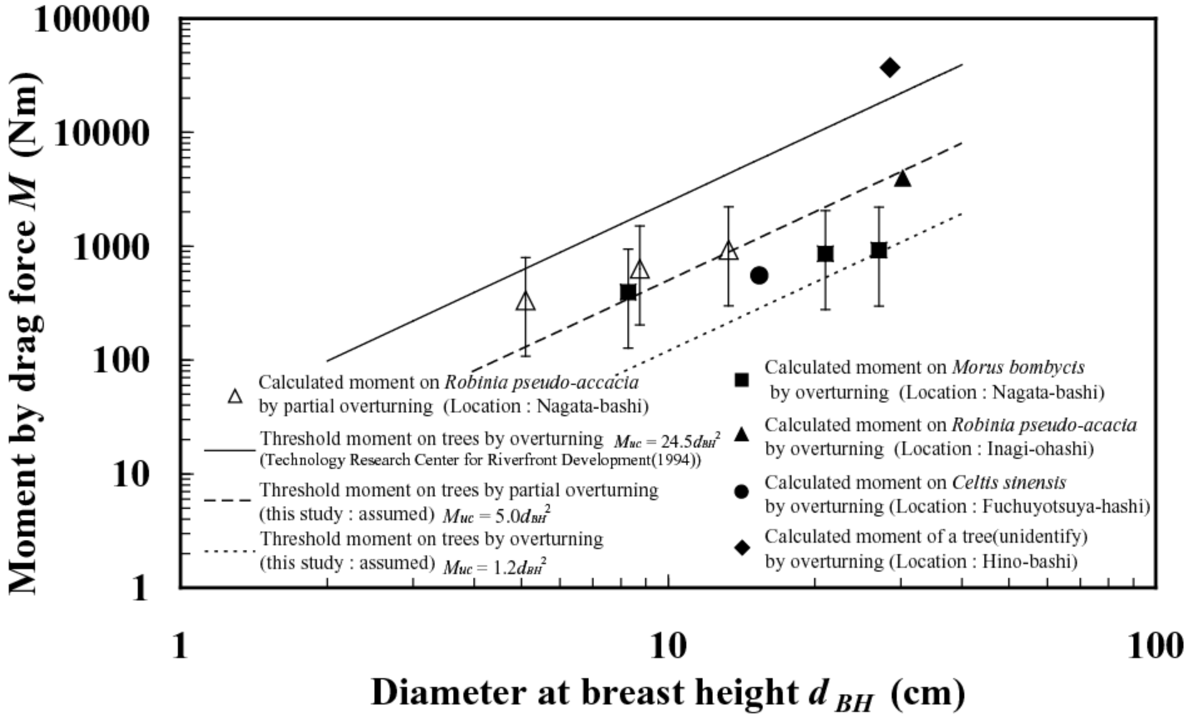

Figure 8 Relationship between d_{BH} and the moment by the drag force (M) acting on the tree at the flood event. Breaking pattern was overturning (tree species: *Morus bombycis* at Nagata, *Celtis sinensis* at Fuchuyotsuya, *Robinia pseudo-acacia* at Inagi, a tree (unknown) at Hinobashi). Continues and dotted lines show the threshold moment for the tree overturning. The bars show the maximum and minimum value explained with Method -1.

The threshold moment has the possibility to be expressed as a function of the substrate condition in case of the river flood. Scouring effect is sometimes more severe in case of the river flood. In addition to the moment acting on the tree, the shear stress condition and the duration of the flood should be analyzed for a further study.

CONCLUSION

The tree has mainly two damaged pattern, trunk bending or breakage and overturning or uprooting (washing out). Considering the plant regeneration situation, the trunk bending or the breakage pattern is not so important and can be neglected. The tree overturning or the uprooting was restricted to the bank side of the gravel bar, however, some trees, especially *Robinia pseudo-acacia* and *Morus bombycis*, overturne if the substrate has thin soil zone on the gravel layer where the root zone is restricted in this case.

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