EFFECT OF PHYSICAL TREE CHARACTERISITCS AND SUBSTRATE CONDITION ON MAXIMUM OVERTURNING MOMENT

J. Yagisawa[1], N. Tanaka[2] and M.B. Samarakoon[3]

[1]Assistant professor, Graduate School of Science and Engineering, Saitama University, Saitama, Japan.
[1]E-mail: yagisawa@mail.saitama-u.ac.jp
[1]Telephone;Fax : +81-48-858-3567

[2]Professor, Institute for Environmental Science and Technology, Graduate School of Science and Engineering, Saitama University, Saitama, Japan.
[2]E-mail: tanaka01@mail.saitama-u.ac.jp
[2]Telephone: +81-48-858-3564

[3]Graduate student, Graduate School of Science and Engineering, Saitama University, Saitama, Japan.
[3]E-mail: s08de060@mail.saitama-u.ac.jp

Abstract: Effects of physical tree characteristics and soil shear strength on overturning moment due to flooding were investigated using *Salix babylonica* and *Juglans ailanthifolia*, exotic and invasive plants in Japanese rivers. Tree pulling experiments were conducted, and the resulting damage was examined in order to assess the effects of physical tree characteristics on the maximum overturning moment (M_{max}). In situ soil shear strength tests were conducted in order to measure soil strength parameters. The effects of species differences on the $M_{\max}$ were examined by analysis of the root architecture. *S. babylonica* has a heart-root system that produces a greater overturning moment due to the strong root anchorage and the large amount of substrate that must be mobilized during overturning. *J. ailanthifolia* has a plate-root system that produces a smaller overturning moment. However, trees with the plate-root system may withstand overturning better due to an increased root:shoot ratio. Considering the strategy of *J. ailanthifolia* to increase the root:shoot ratio for anchoring in the substrate, the trunk volume index (height*D_{bh}^2) is a better parameter than D_{bh}^2 because it indirectly involves the difference in belowground volume and surface area. Different soil cohesion values were found at different experimental sites, and the average $M_{\max}$ for overturning each species decreased linearly with increasing soil cohesion.

Keywords: Tree pulling test, Root architecture, Soil shear strength, Maximum overturning moment, *Salix babylonica, Juglans ailanthifoila.*

1 Introduction

Tree damage due to flooding causes serious problems in managed floodplain forests, where trees produce large amounts of debris and sometimes affect on the structures in river, e.g., gates, bridge piers, and weirs. Flood damage also results in a loss of the balance of the floodplain ecosystem. Researchers have investigated direct and indirect effects on floodplain trees due to flooding.

Previous studies of tree-root systems showed that the strength of a tree-root anchorage is governed by several factors, including the root architecture (Dupuy et al. 2005); physical and analytical properties of the soil (Dupuy et al. 2005); depth, shape, and weight of the soil-root plate (Coutts 1986); and location of the rotational axis during overturning (Mickovski and Ennos 2002). Species characteristics, such as the root architecture (Dupuy et al. 2005), are important parameters in determining the overturning moment. Dupuy et al. (2005) studied different root architectures, including the heart-root system, tap-root system, and plate-root system, and found that the heart-root system was the most effective and plate-root system was the least effective against overturning a tree. The Technology Research Center for Riverfront Development (TRCRD) (1994) has developed guidelines for the management of trees in rivers in Japan. The guidelines proposed a model to calculate the maximum resistive bending moment

(M_{max}) of a tree in terms of the square of the breast height diameter. However, they did not elucidate a species difference for the trees in Japanese rivers. Further, researchers have found that the stability of a tree under external forces is mainly governed by physical characteristics such as tree height (H), diameter at breast height (D_{bh}), tree weight, and root-soil plate depth and radius (Peltola et al. 2000). In addition, TRCRD (1994) proposed the overturning moment of a tree as a function of D_{bh}^2. However, this method of calculating the M_{max} neglects several important parameters, such as tree weight and trunk volume.

In addition, the stability of a tree is also governed by the shear strength of the soil at the base of the root-soil plate (Peltola et al. 2000). Rahardjo et al. (2009) found that the resistance to overturning is increased by increasing the soil shear strength. Nevertheless, the effects of soil shear strength on the M_{max} for trees in Japanese rivers have not been investigated yet.

Thus, the objectives of this study were to (1) elucidate the effects of species differences on M_{max} by considering the root architecture, (2) develop a model of the relationship between the M_{max} and important tree characteristics to determine the M_{max} for overturning trees, and (3) clarify the effects of shear strength of soil on the M_{max} for overturning. The tree species weeping willow (*Salix babylonica Linn*.) and Japanese walnut (*Juglans ailanthifolia Carr*.) were selected because they had been affected by earlier flooding conditions, and they were widely distributed on the investigation sites.

2 Material and Method

2.1 Site information and tree pulling tests

The tree-pulling experiments were carried out in August 2009 at three sites located on the floodplains (35°49′38.8″ N, 139°39′37.1″ E) of the Arakawa River in the Kanto area of Japan. The three selected sites were located close to each other (sites 1 and 2 were on the same side of the river about 300 m apart, and site 3 was on the opposite side of the river) (Fig. 1). All sites were approximately the same relative height above the normal water level (about 2.0 m) and had the same flood frequencies. There were two severe flooding events from 1995 to 2004 on these floodplains due to typhoons. The condition of soil at each experimental site was investigated by using a softness test. In site 1, the top 1.05 m from the ground surface was fine sand (0.10-0.25 mm), and the next 0.90 m was silt (0.002 -0.05 mm). The top soil layer of site 2 consisted of clayey fine sand (0.05-0.10 mm) up to 1 m deep, and the next 1 m was sand mixed with clayey silt (0.0001-0.001 mm). In site 3, the top 0.65 m from the ground surface was fine sand (0.10-0.25 mm), and the next 1.3 m was sandy silt (0.001-0.002 mm). All the soil diameters are defined according to the USDA soil textural classification system. Stands of *S. babylonica* and *J.ailanthifolia* growing on sandy soils were tested at each site. Tree trunks with apparent defects such as decay, damage, and obvious fungus infection were avoided in order to limit the number of interacting factors that could not be distinguished in the analysis. Trees in the range of D_{bh} ($3 < D_{bh} < 40$ cm) were selected in order to evaluate the effect of D_{bh} on maximum resistive bending moment.

For elucidating the maximum resistive bending moment, the tree pulling tests were carried out using a method previously used and described by many researchers (Peltola et al. 2000). The force required to

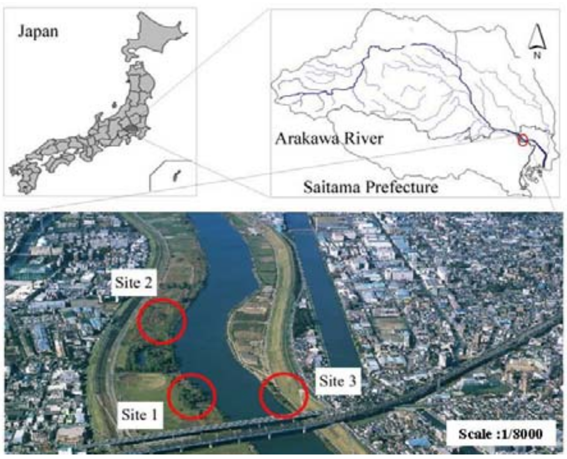

Fig.1 Experimental sites on floodplains of the Arakawa River

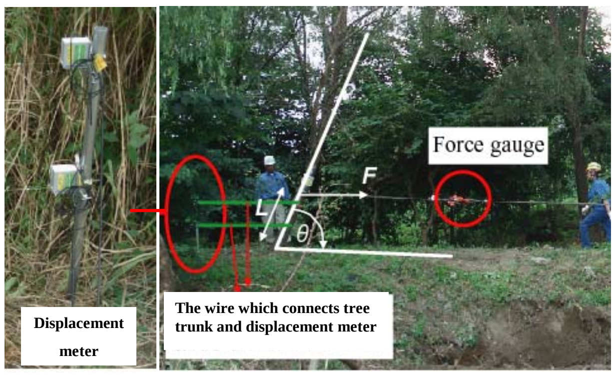

Fig.2 Layout of tree-pulling system
L: The distance from the base to the cable attachment point, F: The force applied via the rope,
θ: The angle of the trunk to the horizontal at the

pull down the trees was applied by the arm of an excavator with a system (Fig. 2) comprising a double rope and a load cell (type TLP-108, Tokyo Sokki Kenkyujo Co., Ltd.). The load values measured by load cell were recorded every second by a data logger that was connected to the load cell. The cable attachment point was kept at a constant height of 1.2 m (10-30% of tree height) above the ground because the tree height is usually higher than the flood water depths and the fluid forces of the flood act only on the submerged part. The angle of the trunk to the horizontal at the point of failure was determined from two displacement gauges as shown in Fig. 2. The displacement gauges were connected to the trunk using two parallel ropes. The displacement gauges and data logger were synchronized to each other, and hence the load data could be easily linked with the positions of the tree during the pulling period. The angle of the trunk to the horizontal at maximum load was derived using the information recorded by the data logger and displacement gauges.

The maximum resistive bending moment at the trunk base was calculated from the following equation:

$$M_{\max} = FL\sin\theta \tag{1}$$

where M_{max} is the maximum resistive bending moment at the trunk base (kNm), F is the force applied via the rope (kN), L is the distance from the base to the cable attachment point along the trunk (m), and θ is the angle of the trunk to the horizontal at the time of maximum load (deg). The bending moment due to the weight of the offset trunk and the crown itself was not considered in this study. The maximum applied bending moment was expected to equal the maximum resistive bending moment.

2.2 Measurements of tree characteristics

The following characteristics were measured on all the trees pulled over: trunk diameter at breast height D_{bh} (cm), tree height H (m), root-soil plate depth (R_d), and root-soil plate radius (R_r). The root-soil plates were separated from the trunk after overturning and brought to Saitama University. The R_r was measured by taking the average of four perpendicular measurements parallel to the ground. In every measurement, the radius was measured as the length from the center of the tree trunk to the outer margin of the central mass of roots and soil. In addition, the R_d was measured as the average length of roots in the root-soil plate. Table 1 summarizes the basic characteristics of the trees pulled out.

2.3 In situ soil shear strength analysis

In situ shear tests were conducted after the tree-pulling experiments to measure the soil strength characteristics (cohesion c and angle of internal friction ø) at each site in order to evaluate the effects of soil parameters on overturning moments. Soil samples were tested in dry soil conditions (soil moisture content = 12–15%). The size of the shear box was 24 cm x 24 cm x 15 cm. The shearing force was applied manually perpendicular to one of the edges of the box to avoid the rotation of the specimen that occurs during the application of a shearing force. Because some of the roots tend to be concentrated at great depth, the normal stress on the shear plane is considerably high. Thus, vertical loads on top of the soil specimen were applied in the in situ shear tests conducted at each site.

Table 1 Summary statistics from tree-pulling database for two tree species

Variable	Notation	Unit	Tree species	
			S. babylonica 17[a]	*J. ailanthifolia* 6[a]
Tree Height	H	m	9.5 (2.2)[b]	6.3 (1.7)
Trunk diameter at breast height	D_{bh}	m	23.7 (9.6)	11.0 (5.5)
Crown width	C_w	m	7.0 (2.0)	6.3 (1.6)
Crown depth	C_h	m	7.0 (1.7)	4.5 (1.5)
Lowest branch height	B_h	m	2.5 (0.7)	1.8 (0.5)
Maximum resistive bending moment	M_{max}	kNm	53.0 (41.5)	17.0 (13.9)
Angle of trunk at M_{max}	θ	°	12.7 (8.5)	23.0 (17.2)

[a] Number of observations relative to each tree species

[b] Means with standard deviations are presented for each variable

3 Results

3.1 Mode of failure

All the trees, i.e., 17 *S. babylonica*, and 6 *J. ailanthifolia*, were uprooted during the pulling experiments. The number of trees of one species selected depended on the availability of such trees within the boundaries of the sites. Uprooting failures were characterized by the lifting of the intact root plate with the tree falling under its own weight. Trunk failures were not observed for any of the trees subjected to the pulling tests. The angle of the trunk to the vertical at M_{max} showed a significant inverse correlation with the tree height for each species. A similar variation was seen among the tree species where the average tree heights of 9.5 m and 6.3 m for *S. babylonica* and *J. ailanthifolia*, respectively, provided the maximum resistance on average when the trunk was deflected by ≈13° and ≈23° to the vertical, in sequence. Two types of root systems were observed on all the trees tested: *S. babylonica* had a heart-root system while *J. ailanthifolia* had a plate-root system (Fig. 3).The more effective root architecture to withstand overturning was the heart-root system (average M_{max}= 52.97 kNm for average root-soil plate depth = 89.4 cm). This root system was composed of lateral, oblique, and vertical roots that originate from the trunk bole. This structure was densely branched, and the secondary lateral roots were oriented randomly between the horizontal and vertical directions. The plate-root system was the less effective (average M_{max}= 16.96 kNm for average root-soil plate depth = 65 cm). This system did not have a tap root but only main lateral roots, which were attached to the stump.

3.2 Variation of Mmax with tree characteristics

The variations of M_{max} against D_{bh} for *S. babylonica* and *J. ailanthifolia* at different experimental sites are shown in Fig. 4(a) and (b), respectively. Fig. 4(a) depicts the variation of M_{max} with D_{bh} for *S. babylonica*, and it indicates that the M_{max} of trees that have nearly same D_{bh} but grow at different sites are not equal. A similar variation could be seen for the case of *J. ailanthifolia* (Fig. 4(b)). Thus, trees belonging to one species, distributed at different sites were not analyzed together. Therefore, the following analyses were done on the *S. babylonica* at study site 1 and *J. ailanthifolia* at study site 3.

Fig.3 Different types of root architectures for (a) hear-root system, (b) plate-root system

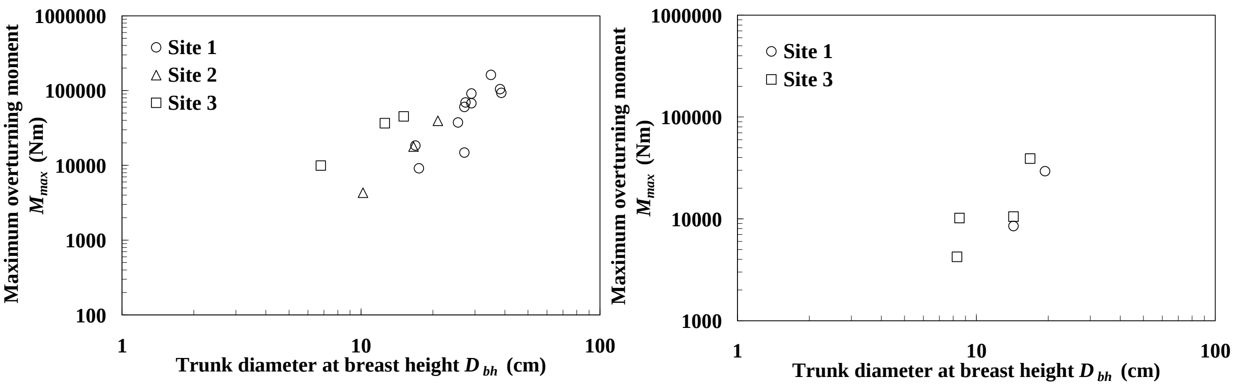

Fig.4 The variation of Mmax against D_{bh} in different experimental sites for
(a) *Salix babylonica*, (b) *Juglans ailanthifolia*

Table 2 Correlation coefficients for relationships between tree characteristics and M_{max} for *S. babylonica*

	M_{max}	D_{bh}	D_{bh}^2	H	$H*D_{bh}^2$	R_d	R_r
M_{max}	**1**	-	-	-	-	-	-
D_{bh}	**0.70**	**1**	-	-	-	-	-
D_{bh}^2	**0.70**	**1**	**1**	-	-	-	-
H	**0.61**	**0.29**	**0.29**	**1**	-	-	-
$H*D_{bh}^2$	**0.83**	**0.94**	**0.94**	**0.54**	**1**	-	-
R_d	**0.06**	**0.01**	**0.01**	**0.39**	**0.07**	**1**	-
R_r	**0.51**	**0.88**	**0.88**	**0.17**	**0.78**	**0.002**	**1**

Table 3 Correlation coefficients for relationships between tree characteristics and M_{max} for *J. ailanthifolia*

	M_{max}	D_{bh}	D_{bh}^2	H	$H*D_{bh}^2$	R_d	R_r
M_{max}	**1**	-	-	-	-	-	-
D_{bh}	**0.66**	**1**	-	-	-	-	-
D_{bh}^2	**0.66**	**1**	**1**	-	-	-	-
H	**0.83**	**0.8**	**0.8**	**1**	-	-	-
$H*D_{bh}^2$	**0.84**	**0.99**	**0.99**	**0.86**	**1**	-	-
R_d	**0.71**	**0.89**	**0.89**	**0.62**	**0.86**	**1**	-
R_r	**0.24**	**0.001**	**0.001**	**0.22**	**0.01**	**0.003**	**1**

There were significant correlations between the M_{max} and various tree characteristics, such as the tree height, D_{bh}, D_{bh}^2, $H*D_{bh}^2$, and root-soil plate depth and radius ($p<0.05$), with $H*D_{bh}^2$ explaining the greatest proportion of the variation in M_{max} for all trees tested. However, D_{bh}^2 also had a good correlation with M_{max}. Tree height showed rather weak correlations with M_{max} and other tree characteristics, especially for *S. babylonica*. The correlation between M_{max} and root-soil plate depth for *S. babylonica* was significant, whereas the correlation coefficient was very weak (R^2=0.06). On the other hand, while the correlation between M_{max} and root-soil plate radius for *J. ailanthifolia* was significant, the correlation coefficient was quite law (R^2=0.24). The best regressions also show that the M_{max} required to uproot a tree increases with increasing height multiplied by the second power of D_{bh} for a fixed height and D_{bh}. Similarly, the M_{max} required for uprooting a tree increased with increasing tree height for a fixed taper or with increasing D_{bh} for a fixed tree height. The correlation coefficients of relationships between M_{max} and tree characteristics and tree characteristics themselves for *S. babylonica* and *J. ailanthifolia* are presented in Table 2 and Table 3, respectively. The correlations between tree characteristics themselves were strong except in the cases of soil-root plate depth for *S. babylonica* and soil-root plate radius for *J. ailanthifolia*.

The data showed that tree height multiplied by the square of D_{bh} explained the greatest proportion of the variation in M_{max} for all the trees tested. Hence, M_{max} could be written in terms of D_{bh} and tree height. The following equations show the corresponding relationships.

$$M_{\max} = 0.81(H * D_{bh}^{\ 2})^{1.23} \qquad S.\ babylonica \qquad (2)$$

$$M_{\max} = 44.49(H * D_{bh}^{\ 2})^{0.79} \qquad J.\ ailanthifolia \qquad (3)$$

where M_{max} is in Nm, H is in m, and D_{bh} is in cm. However, the Technology Research Center for Riverfront Development (TRCRD) of Japan proposed the overturning moment of a tree as a function of D_{bh}^2 (TRCRD, 1994) as follows.

$$M_{turnc} = 78.8 d_{BH}^{\ 2} \qquad (4)$$

where M_{turnc} is the critical overturning moment of a tree in rivers (Nm), and d_{BH} is the diameter of a tree trunk at breast height (cm). Hence, the following models were also developed between M_{max} and D_{bh}^2 to compare the equation of overturning moment with that by TRCRD (1994).

$$M_{\max} = 87.59 D_{bh}^{\ 2} \qquad S.\ babylonica \qquad (5)$$

$$M_{\max} = 85.61 D_{bh}^{\ 2} \qquad J.\ ailanthifolia \qquad (6)$$

where M_{max} is in Nm and D_{bh} is in cm. The models (Eq (5) and (6)) were validated for all the trees pulled down at experimental sites 1, 2, and 3. It can be seen that the correlations coefficients are fairly strong (0.43-0.97), and thus the models are applicable to determine the M_{max} of both tree species before overturning due to a severe flooding condition.

Table 4 Peak strength characteristics of soil obtained by in situ shear test and average M_{max} of two tree species in different site

Parameter	species	Notation	Unit	Site location		
				Site 1	Site 2	Site 3
Cohesion	—	c	kN/m^2	1.3	3.2	2.7
Angle of internal friction	—	φ	°	60.9	35.0	39.6
Average maximum overtuning moment	*S. babylonica*	M_{max}	kNm	66.1	20.5	30.5
	J. ailanthifolia			18.9	—	16.0
Average root-soil plate depth	*S. babylonica*	R_d	m	99.4	71.7	74.0
	J. ailanthifolia			68.0	—	63.5

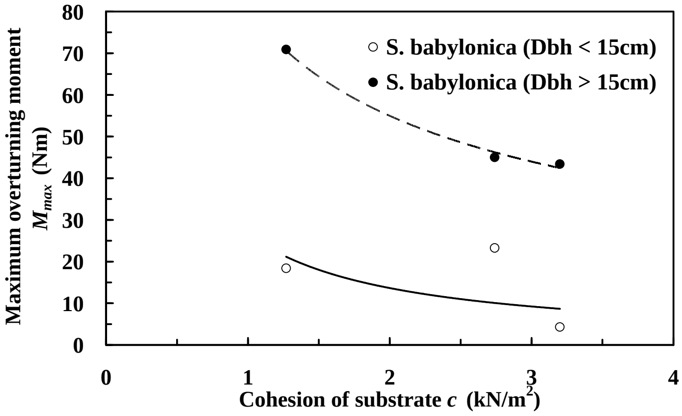

Fig.5 Variation of M_{max} against soil cohesion at each experimental site

The models developed in this study take a pattern similar to equation (4), although the coefficients are different. The reason why the coefficients of equations (5) and (6) have similar values, even though the two tree species have different root architectures, will be explained in the Discussion.

3.3 Effects of soil shear strength on M_{max}

Soil shear strength is one of the key factors that govern the strength of the tree-root anchorage. The shear strength of a soil is governed by effective cohesion and the effective angle of internal friction as given by the Mohr-Coulomb equation. Therefore, in situ shear tests were conducted after the tree-pulling experiments at each site in order to determine the soil shear strength parameters. The peak strength characteristics of soil obtained through in situ shear tests in dry conditions (soil moisture content = 12–15%), the average root-soil plate depth of each tree species at each site, and the average M_{max} of tree species at different sites are shown in Table 4. The effects of soil cohesion on the size of the root-soil plate and M_{max} for overturning were examined among the trees of the same species at different sites. The depth of the root-soil plate decreased with increasing soil cohesion for both tree species. Fig.5 shows the variation of average M_{max} against soil cohesion. The corresponding equations are as follows.

$$M_{\max} = 26.7c^{-0.97} \qquad S.\ babylonica, \quad D_{bh} < 15 \text{ cm} \qquad (7)$$

$$M_{\max} = 80.5c^{-0.55} \qquad S.\ babylonica, \quad D_{bh} > 15 \text{ cm} \qquad (8)$$

where c is soil cohesion (kN/m^2). Fig.5 and comparison of the coefficients of the above equations demonstrate that the average M_{max} decreased linearly with increasing soil cohesion for both tree species.

4 Discussion

4.1 Variation of M_{max} with root architecture

In this study, we have observed two types of root systems: a heart-root system and a plate-root system. Many previous investigations have reported that the heart-root system generally afforded the most efficient anchorage (Stokes et al. 2005). These root systems possess large lateral roots originating from the centre of the bole, which then rapidly branch into smaller roots. Wu et al. (1988) reported that the heart-root architecture improves soil shear resistance by combining stiffness close to the trunk and

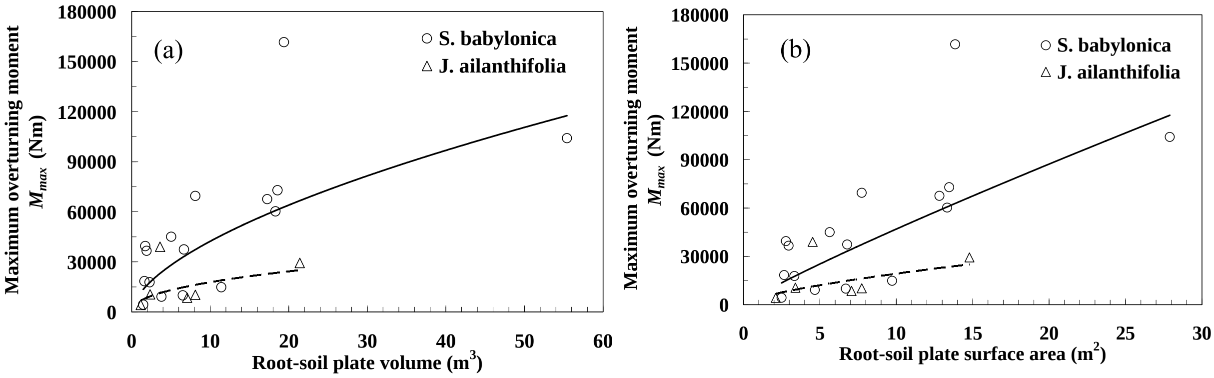

Fig.6 Variation of M_{max} against root-soil plate dimensions for
(a) root-soil plate volume, (b) root-soil plate surface area

dense fibrous networks further away. When forked roots are lifted up out of the soil, they also carry soil upwards with them in the crux of the fork, the weight of which helps to increase overturning resistance.

In the case of a plate-root system, many roots have penetrated only the top soil layer, and thus, a small amount of soil is mobilized during uprooting. The soil/root cohesion will be decreased and anchorage strength reduced when few vertical roots are embedded in the soil. Therefore, when a plate-root system is overturned, the entire root-soil plate is lifted upwards.

Nevertheless, the coefficients in the equations (5) and (6) are not very different. The equations gave relatively identical M_{max} values for both species with similar D_{bh}. However, we have observed that *S. babylonica* and *J. ailanthifolia* have different root systems, which gave different M_{max} values even for the trees with similar D_{bh}. The root:shoot ratio of *J. ailanthifolia* was found to be greater than that of *S. babylonica* for approximately identical D_{bh} (the root:shoot ratios of both *J. ailanthifolia* and *S. babylonica* were 0.19 and 0.05 for trees with D_{bh} of 10.3 and 10.2 cm, respectively). Thus, D_{bh} itself does not explain the overturning moment of *S. babylonica* and *J. ailanthifolia*. The effect of different root systems is also significant in determining the overturning moment. To verify this, the relationships between M_{max} and root-soil plate volume and surface area were analyzed. Figure 6(a) and (b) show the variation of M_{max} with root-soil plate volume and surface area. The figures demonstrate that for a certain value of both volume and surface area of the root-soil plate, the moment required for overturning *S. babylonica* was considerably greater than that for overturning *J. ailanthifolia*. Further, the difference increased with increasing root-soil plate volume and surface area. This indicates a similar conclusion that a heart-root system is stronger than a plate-root system. It also implies why equations (2) and (3) explain the difference of root volume or surface area indirectly because they are functions of the aboveground part, but equations (5) and (6), which are only functions of trunk area, do not.

4.2 Effects of soil shear strength on M_{max}

The failure mode of trees is closely linked to soil type. All the trees tested were overturned with an intact root-soil plate. The trees grew on periodically flooded river floodplains consisting of sandy soils in the top layer of the ground (about 1 m). Normally, the distribution and anchoring ability of tree roots are affected by soil texture and consistency (Mergen 1954). The factors determining the consistency are cohesive and adhesive strength and the angle of internal friction. A cohesive soil is described as one where the particles adhere after wetting and subsequent drying and which requires significant force to crumble the soil (Craig 1990). Usually, the cohesion of sandy soils is rather low. Therefore, the trees grown in less cohesive sandy soils are more likely to be overturned when external forces are applied.

In this study the average M_{max} for overturning trees of the same species decreased with increasing soil cohesion. The ability of roots to grow in a soil is an important factor that determines the rate of tree growth. The rate of roots growth is determined by the mechanical impedance that roots experience when they elongate through soil. As soil shear strength increases, the root elongation rate decreases due to the increasing resistance of the soil particles to displacement. Thus, roots easily penetrate the soil more deeply when the shear strength is smaller. Further studies are needed to explain the relationship between the overturning moment of a tree and the shear strength of the soil.

5 Conclusions

Threshold overturning moments were investigated for two tree species with two types of root architectures: the heart-root and plate-root systems. The heart-root system (*S. babylonica*) had a greater M_{max} than the plate-root system (*J. ailanthifolia*) with the same below-ground volume or surface area because the heart-root system affords a stronger anchorage and a large amount of substrate must be mobilized during overturning. However, the plate-root system can withstand overturning by improving the root:shoot ratio. The results of the study show that the M_{max} for overturning a tree has close correlations with the tree's physical characteristics. The trunk volume index explained the greatest proportion of the variation in M_{max} for all trees tested. The trunk volume index explained the above-ground volume of a tree that is related to the root:shoot ratio. Thus, the correlation between the M_{max} and trunk volume index is an indirect method of describing the correlation between the M_{max} and root:shoot ratio. In addition, the overturning moment of a tree is largely affected by the cohesion of the soil. The study found that the average M_{max} for overturning of *S. babylonica* decreased with increasing cohesion of soil.

References

1. Coutts, M.P. "Components of tree stability in Sitka spruce on peaty gley soil" *Forestry*, 59, 1986, pp.173-197.
2. Craig, R.F. "Soil Mechanics", 4th edn. Chapman and Hall, London,1990.
3. Dupuy, L., Fourcaud, T., Stokes, A. "A numerical investigation into the influence of soil type and root architecture on tree anchorage", *Plant Soil*, 278, 2005, pp.119-134.
4. Mergen, F., "Mechanical aspects of wind-breakage and wind firmness", *J Forest*, 52, 1954, pp.119-125.
5. Mickovski, S. B., Ennos, A. R., "A morphological and mechanical study of the root systems of suppressed crown Scots pine *Pinus sylvetris*", *Trees,* 16, 2002, pp.274-280.
6. Peltola, H., Kellomäki, S., Hassinen, A., Granander, M., "Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland", *For Ecol Manage* 135, 2000, pp.143-153.
7. Rahardjo, H., Harnas, F. R., Leong, E. C., Tan, P. Y., Fong, Y. K., Sim, E. K., "Tree stability in an improved soil to withstand wind loading", *Urban Forestry & Urban Greening*, 8, 2009, pp.237-247
8. Stokes, A., Salin, F., Kokutse, A. D., Berthier, S., Jeannin, H., Mochan, S., Kokutse, N., Dorren, L., Ghani, M. A., Fourcaud, T., "Mechanical resistance of different tree species to rockfall in the French Alps", *Plant Soil*, 278, 2005, pp.107-117
9. Technology Research Center for Riverfront Development (TRCRD), "Guideline for Tree Management in Rivers (in Japanese)", Sankaidou, 1994, pp 154-160.
10. Wu, T. H., McOmber, R. M., Erb, R. T., Beal, P. E., "Study of soil-root interaction", *J Geotech Eng-ASCE*, 114, 1988, pp.1351-1375.

Acknowledgements

This study was supported in part by JSPS AA Science Platform Program. This study was partly funded by JSPS Grant in Aid for Scientific Research (ID No. P 09081 and ID No. 21860013). The experiments were conducted jointly with the Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan, and the ECOH Corporation. Prof. Yasushi Sasaki, Saitama University, is acknowledged for his useful suggestions.