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# Windthrow resistance of apple trees grafted in an orchard

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**Abstract** Pull-down tests were conducted for apple trees grafted in an orchard and for support posts in order to discuss the failure mode in windthrow damage, the effect of rootstock types on the uprooting strength, and the reinforcing effect of support posts on young trees. The test samples were ten mature trees (20–23 years old) of three varieties grafted on two types of rootstocks, three young trees (7 years old) grafted on dwarf rootstocks, and nine support posts of larch logs and steel pipes. The failure modes were found to be uprooting for mature trees and rootstock breakage for young trees. The uprooting strength of apple trees was considerably smaller than the uprooting strength of forest trees reported in previous studies. However, the windthrow resistance of the apple trees with respect to the critical wind velocity was estimated to be sufficient despite their low uprooting strength because of their small height. Young trees should be supported with wooden posts for a few years after grafting so that they acquire sufficient windthrow resistance.

**Key words** Windthrow resistance · Critical wind velocity · Uprooting strength · Apple trees · Pull-down test

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## Introduction

In 2004, Japan faced a record number of ten typhoon attacks that resulted in severe windthrow damage to both plantations and park trees. Apple trees planted in orchards in Hokkaido also suffered considerable damage by typhoons 0415 and 0418, and the damaged area extended to 666 ha in Hokkaido.[1] Although most of the damage to apple trees was in the form of fruit drop, uprooting of mature trees and stem break of young trees were also observed.

Yamamoto[2] analyzed the windthrow susceptibility for orchard trees by assuming the tree to be a cantilever beam supported at ground level and on the basis of experimental data for the strength of stems and roots. The drag coefficients for the tree crowns were estimated from a wind tunnel study conducted on small models. Although pull-down tests are necessary to evaluate the uprooting strength of trees, the experimental data have been limited to forest trees heretofore. The pull-down test results for forest trees[3–6] suggest that there are considerable differences among species and among soil conditions. In this study, the windthrow resistance of apple trees is discussed based on pull-down tests. The effects of the rootstock types on which apple scions are grafted and of support posts on young trees are also discussed.

## Materials and methods

### Sample trees

Thirteen apple trees (*Malus domestica*) grafted on two kinds of rootstocks in the Yoichi Orchard of the Field Science Center for Northern Biosphere, Hokkaido University, were sampled. The tested rootstocks were marubakaido (*Malus prunifolia* var. *ringo*) and the dwarf rootstock of M.26.[7] The ages of the sample trees after grafting were 20–23 years for mature trees and 7 years for young trees. The tree height, crown height, crown diameter, breast-height

**Table 1.** Dimensions of sample trees

| No. | Rootstock[a] | Variety[b] | Age (years) | $H$ (m) | $H_C$ (m) | $D_C$ (m) | $D_B$ (cm) | $D_0$ (cm) |
|---|---|---|---|---|---|---|---|---|
| 1 | Marubakaido | S | 21 | 4.6 | 1.6 | 5.90 | 22.0 | 25.8 |
| 2 | Marubakaido | S | 21 | 4.6 | 1.1 | 6.20 | 22.6 | 26.1 |
| 3 | Marubakaido | S | 21 | 4.5 | 1.1 | 5.40 | 25.5 | 36.0 |
| 4 | Marubakaido | S | 21 | 3.9 | 1.6 | 5.25 | 22.6 | 25.5 |
| 5 | Marubakaido | S | 21 | 5.0 | 1.8 | 5.60 | 20.7 | 27.7 |
| 6 | M.26 | GD | 23 | 3.7 | 1.6 | 4.35 | 22.3 | 22.9 |
| 7 | M.26 | GD | 21 | 3.5 | 1.5 | 5.15 | 20.7 | 24.5 |
| 8 | M.26 | GD | 20 | 4.5 | 1.8 | 5.35 | 23.6 | 33.7 |
| 9 | M.26 | RG | 22 | 4.3 | 1.2 | 5.25 | 23.2 | 24.2 |
| 10 | M.26 | RG | 22 | 4.3 | 1.2 | 4.50 | 16.6 | 20.7 |
| 11 | M.26 | F | 7 | 3.4 | 0.5 | 2.30 | 6.0 | 10.2 |
| 12 | M.26 | F | 7 | 3.1 | 0.5 | 2.85 | 5.7 | 11.3 |
| 13 | M.26 | F | 7 | 3.1 | 1.0 | 2.75 | 6.7 | 9.9 |

$H$, Tree height; $H_C$, crown height; $D_C$, crown diameter; $D_B$, breast-height diameter; $D_0$, stem diameter at ground level
[a] Marubakaido, *Malus prunifolia* var. *ringo*; M.26, dwarf stock
[b] S, Senshu; GD, Golden delicious; RG, Red gold; F, Rakurakufuji

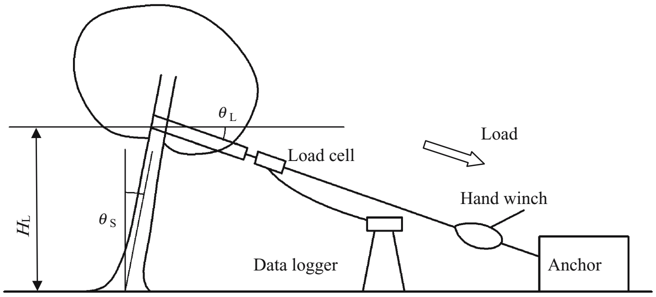


**Fig. 1.** Schematic diagram of the pull-down test

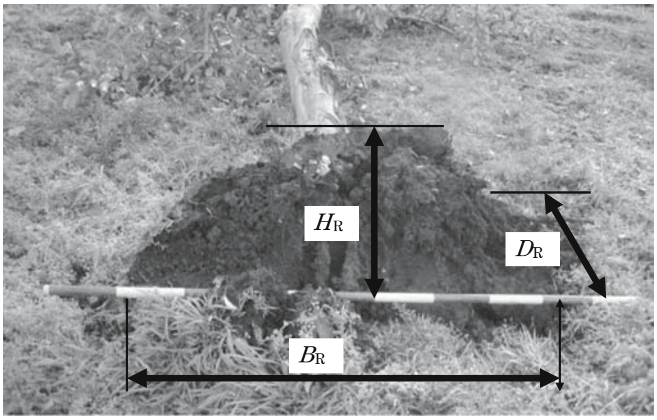


**Fig. 2.** Dimensions of a root plate measured after uprooting. $H_R$, height of root-plate rise; $D_R$, depth of the root plate; $B_R$, breadth of the root plate

diameter, and stem diameter at ground level were measured before the pull-down tests (Table 1).

## Support post specimens

Usually, young apple trees are supported by a single post such as a log or a steel pipe. Six larch logs of approximately 10 cm in diameter (PG post) and three steel pipes with an outer diameter of 35 mm and a pipe wall thickness of 2 mm were used in the pull-down tests. The post specimens were embedded approximately 1 m into the ground before the tests.

## Pull-down test

The pull-down tests were conducted by pulling a load sling strapped to a stem at a low position of the crown with a hand winch (capacity: 29 kN) until the tree failed by uprooting or stem break (Fig. 1). The heights of the load slings were 170 cm for tree nos. 1–10 and 120 cm for tree nos. 11–13. The load slings for the support posts were strapped at a height of 120 cm at which the young trees were bound to the posts. The tensile loads were detected with a load cell connected between the load sling and a wire. The moment at the tree base ($M_R$) was calculated by Eq. 1.

$$M_R = P\cos\theta_L H_L \tag{1}$$

where, $P$ denotes the tensile load; $\theta_L$, the load angle; and $H_L$, the height of the load.

The horizontal displacement of the reference point set on the stem was measured with a transit placed a few meters distance from the sample tree. The heights of the reference points were 140 cm for tree nos. 1–10 and 120 cm for tree nos. 11–13 and the support posts. The rotation angles of the sample trees were calculated from the horizontal displacement, which includes the bending deflection of the stem, assuming the rotation center lies at ground level.

## Dimensions of root plates

After the pull-down tests, the height of root-plate rise ($H_R$) and the depth ($D_R$) and breadth ($B_R$) of the root plate were measured (see Fig. 2). The area ($A_R$) and volume ($V_R$) of the root plate (assuming the root plate as a hemiellipsoid whose three radii are $B_R/2$, $D_R$, and $H_R$), and the geometrical moment of the uprooted area of an ellipse-shaped root plate ($G_R$) were calculated from Eqs. 2–4 as indices to the moment resistance of the root plates given that the uprooting moment is expected to be positively proportional to the dimensions of the root plate.[8]

$$A_R = \frac{\pi H_R B_R}{2} \quad (2)$$

$$V_R = \frac{\pi H_R B_R D_R}{3} \quad (3)$$

$$G_R = \frac{H_R^2 B_R}{3} \quad (4)$$

The uprooting mechanism has been explained as a shear slip at the boundary surface between the root bowl and the soil in the case of deep-rooted trees and the overturn failure of a thin root plate, which is initiated by the tensile failure of the windward side of the root plate in the case of shallow-rooted trees.[9] In the former case, the uprooting resistance may be proportional to $A_R$ or $V_R$. In the latter case, the amount of tensile stress acting on the windward side of the root plate is proportional to the distance from the rotation center of the root plate. By assuming that the rotation center lies at the ground level along the stem line, the uprooting moment may be proportional to the geometrical moment of area for the windward side of the root plate ($G_R$).[8]

### Density of rootstock wood and strength of stem wood

The specimens for wood density were cut from the horizontal-root ends of tree nos. 1–10, where tensile fracture occurred during uprooting. The density specimens for tree nos. 11–13 were cut from both the rootstock sides and scion sides of the grafted sections and at the breast-height position of each tree.

Thirty-centimeter-long logs were cut from tree nos. 1–10, corresponding to the part 90–120 cm above ground level. Each log was quarter-sawn to obtain 30-mm-thick unedged planks, including piths. Twenty small, clear specimens, each with a cross section measuring 20 × 20 mm and a length of 300 mm, were cut from both the outer sides of the ten air-dried planks and the modulus of elasticity (MOE), bending strength (modulus of rupture; MOR), and compressive strength parallel to the grain (CS) were measured. The average moisture content of the specimens was 12.7%.

### Estimation of critical wind velocity

By assuming the trees to be cantilever beams fixed at ground level, the moment at the ground level ($M_R$) induced by a wind force acting on the crown is expressed by Eq. 5.

$$M_R = \frac{1}{2} C_D \rho v^2 A H_W \quad (5)$$

where $C_D$ denotes the drag coefficient of the tree crown; $\rho$, the air density (1.20 kg/m$^3$); $v$, the wind velocity; $A$, the horizontally projected crown area; and $H_W$, the height of the wind pressure center.

By assuming the horizontally projected shape of the crown to be an ellipse, the height of the wind pressure center is half the crown length above the crown height. Subsequently, the critical wind velocity ($v_c$) that causes uprooting or stem break at ground level is calculated by Eq. 6 as follows:

$$v_c = 4\sqrt{\frac{M_{max}}{C_D \rho \pi D_C (H^2 - H_C^2)}} \quad (6)$$

where $M_{max}$ denotes the maximum moment at the tree base observed in the pull-down tests; $D_C$, the crown diameter; $H$, the tree height; and $H_C$, the crown height.

## Results and discussion

The failure modes observed in the pull-down tests were classified into two modes: uprooting for mature trees (nos. 1–10) and bending failure at ground level for young trees (nos. 11–13).

### Uprooting failure for mature trees

The moment–rotation angle relationships were almost linear at low stress levels. Furthermore, the root systems gradually yielded as the load increased and reached the maximum load when the horizontal roots at the edge of the tension side of the root plates fractured with a snapping sound (Figs. 3, 4). The uprooting moment of the marubakaido rootstock was greater than those of M.26 at the significance level of 5% (Fig. 5). Although the correlations between the root-plate dimensions ($A_R$, $V_R$, and $G_R$) and the maximum moment ($M_{max}$) were not strong, the root-plate dimensions of marubakaido were greater than those of M.26 (Fig. 6). The results suggested that the apple trees grafted on M.26 were susceptible to uprooting damage because of their less-developed root plate.

The power function of the breast-height diameter ($D_B$) curve-fitted to the $M_{max}$–$D_B$ relationship was compared with the power functions reported in previous studies (Fig. 7).

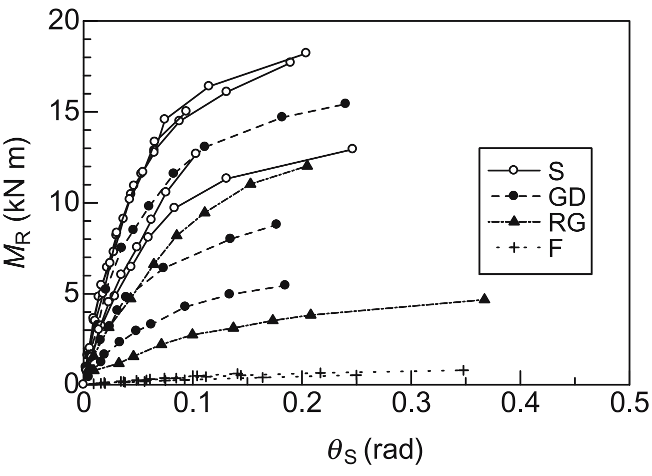


**Fig. 3.** Relationships between moment ($M_R$) and rotation angle ($\theta_S$) for all sample trees. *S*, Senshu; *GD*, Golden delicious; *RG*, Red gold; *F*, Rakurakufuji

**Fig. 4.** Uprooting failure initiated by tensile fracture of horizontal roots (tree no. 6)

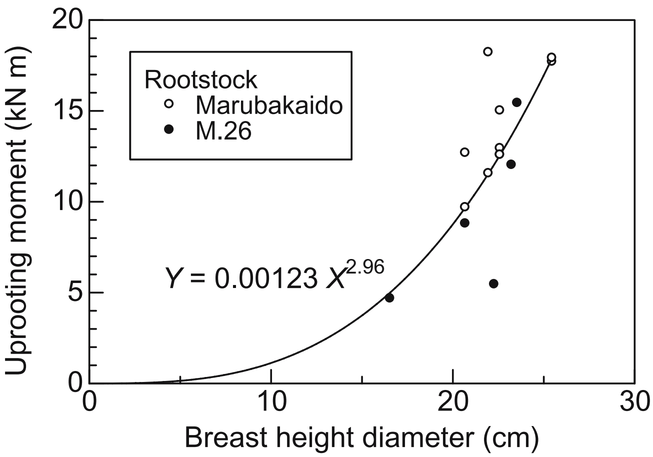


**Fig. 5.** Uprooting moment as a function of breast-height diameter

The thick lines and filled circle (sites b, d, h, and i) are the results for broad-leaved species. The thin broken line (site e) represents coniferous plantations on soils of volcanic origin.[5] Although the trends show that the uprooting moments of broad-leaved trees are greater than those of conifers for identical sites, the uprooting moments vary considerably among the sites and species. The uprooting moments of the apple trees (site i) are considerably smaller than those for other sites and species. This might be attributed to the poorly developed root plates and the cultivation treatment.

An adequate correlation was observed between the initial stiffness and the uprooting moment, where the initial stiffness was defined as the slope of a regression line fitted to the moment–deflection angle data shown in Fig. 3 in the range from $0.1\,M_{max}$ to $0.4\,M_{max}$ (Fig. 8). Although the component of bending deflection of the trunk is not subtracted from the observed horizontal displacement, the uprooting moment could be estimated nondestructively from the tree

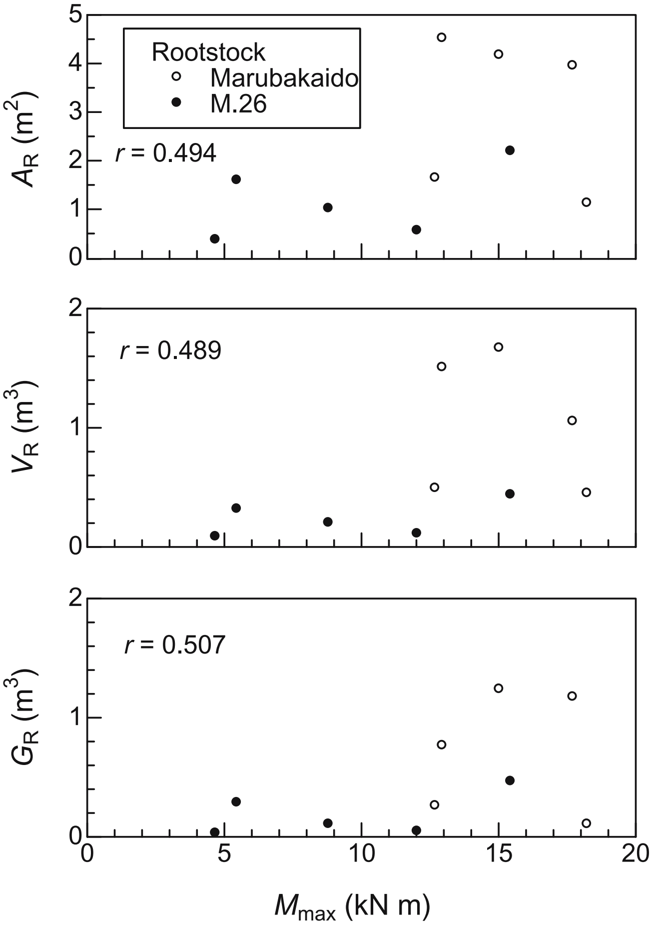


**Fig. 6.** Relationships between dimensions of root plate and uprooting moment ($M_{max}$)

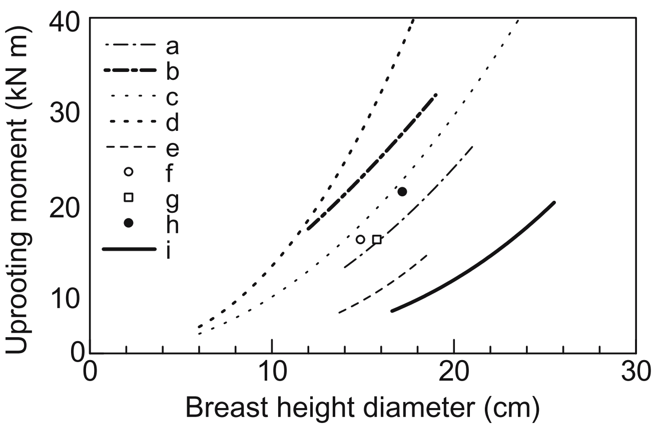


**Fig. 7.** Comparison of relationship between breast-height diameter and uprooting moment observed for various species and sites. *a*, Sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*) ($n = 7$);[4] *b*, arakashi (*Quercus glauca*) and kuri (*Castanea crenata*) ($n = 4$);[4] *c*, sugi ($n = 19$);[3] d, mizunara (*Quercus crispula*) and buna (*Fagus crenata*) ($n = 38$);[3] *e*, todomatsu (*Abies sachalinensis*), ezomatsu (*Picea jezoensis*), akaezomatsu (*Picea glehnii*), and karamatsu (*Larix kaempferi*) ($n = 12$);[5] *f*, Scots pine (*Pinus sylvestris*) ($n = 44$);[6] *g*, Norway spruce (*Picea abies*) ($n = 26$);[6] *h*, birch (*Betula* spp.) ($n = 8$);[6] *i*, this study ($n = 10$)

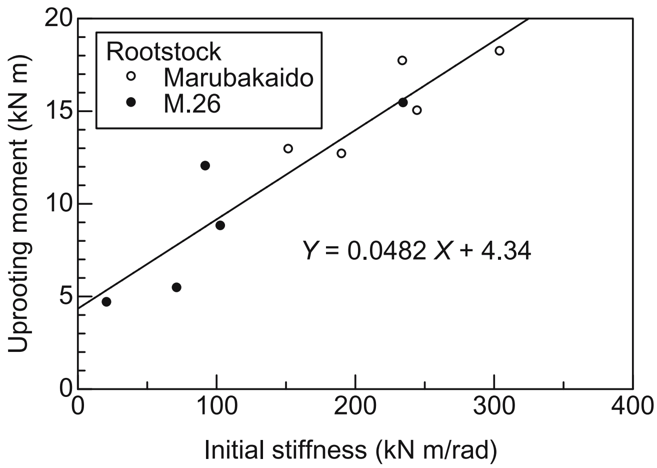


**Fig. 8.** Correlation between initial stiffness and uprooting moment

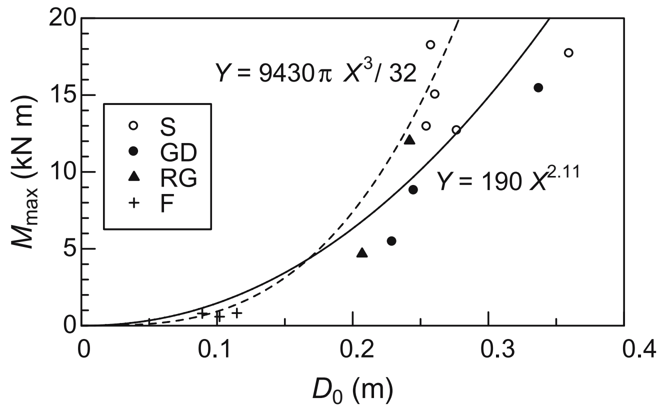


**Fig. 9.** Maximum moment at tree base ($M_{max}$) as a function of the diameter at ground level ($D_0$). The *broken line* was calculated by assuming bending failure at ground level and the solid line is the regression curve for uprooted mature trees

**Table 2.** Mechanical properties of small clear specimens sampled at the breast height of mature trees

| Variety | Specific gravity | MOE (GPa) | MOR (MPa) | CS (MPa) |
|---|---|---|---|---|
| S | 0.729 | 6.18 | 71.5 | 38.1 |
| GD | 0.728 | 8.12 | 77.2 | 43.3 |
| RG | 0.679 | 8.12 | 84.8 | 42.0 |
| Overall | 0.711 | 7.34 | 77.6 | 40.7 |

Data given are mean values for the variety
MOE, Modulus of elasticity; MOR, modulus of rupture; CS, compressive strength parallel to the grain

bending tests, provided the tests were conducted for trees of similar age and from the same orchard.

## Breakage of rootstock for young trees

All trees with an age of 7 years after grafting (nos. 11–13) broke at the rootstock side of the grafted section of the stems. The failure mode was brittle fracture caused by the bending moment. The average MOR at the broken positions was calculated as 9.43 MPa. The average MOR for small, clear specimens cut from the breast-height section of the trunks was 77.5 MPa for air-dry conditions (Table 2). The average bulk density (oven-dry weight/green volume) for the M.26 rootstock of tree nos. 11–13 was 689 kg/m$^3$, which is greater than the average bulk densities of stem wood near the grafted position (656 kg/m$^3$) and of stem wood at the breast-height position (542 kg/m$^3$). The reason why the MOR of rootstock was considerably less than that of trunk wood could be o the anatomical characteristics of the root tissue, such as fiber length. The insufficient radial growth of rootstock a few years after grafting might lead to the breakage of the rootstock.

The maximum moment at the ground level ($M_{max}$, unit: kNm) for young trees can be expressed by Eq. 7, assuming the MOR to be 9.43 MPa.

$$M_{max} = \frac{9430\pi D_0^3}{32} \qquad (7)$$

where $D_0$ denotes the xylem diameter in meters at ground level.

By comparing the function in Eq. 7 with the regression function of $D_0$ for the uprooting strength of mature trees, it is expected that the failure mode for grafted trees changes from rootstock breakage to uprooting as $D_0$ increases (Fig. 9).

Apple trees are supported by wooden or steel pipe posts for several years after grafting. In the pull-down tests, it was observed that the larch wood posts broke at ground level due to an average bending moment of 2.77 kNm. Consequently, the average MOR of larch logs was calculated as 32.4 MPa. On the other hand, the steel pipe post yielded at ground level due to a bending moment of 737 Nm, which was considerably less than that for larch wood posts. By superimposing the moment–deflection curves on those for tree nos. 11–13, the average reinforcing effects of wooden posts and steel pipes for tree nos. 11–13 were estimated as 447% and 198%, respectively (Fig. 10).

## Critical wind velocity

The critical wind velocities ($v_c$) for the tested trees were estimated from Eq. 6, assuming $C_D$ to be 0.2, which corresponds to that for western hemlock (*Tsuga heterophylla*) at a wind velocity of 30 m/s evaluated from a study with an actual-size wind tunnel.[10] Although $C_D$ at a wind velocity of 30 m/s, evaluated in the study by considering seven coniferous species, ranged from 0.2 to 0.6, the smallest value was chosen by considering the thin crown of apple trees and the dense crown of coniferous species.

The estimated $v_c$ for mature trees, which had a breast-height diameter of 20 cm or more, exceeded 40 m/s and showed sufficient resistance to wind force (Fig. 11). The reason for high $v_c$ despite a low uprooting strength was the tree form of low crowns. Although the trees grafted on dwarf stocks (M.26) showed lower uprooting strength than those grafted on marubakaido stocks, no difference in $v_c$ was observed.

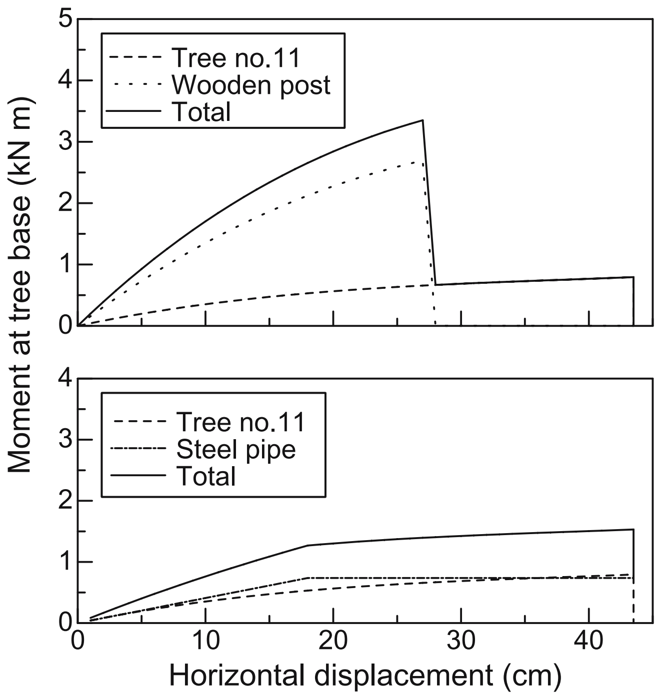


**Fig. 10.** Relationship between moment at tree base and horizontal displacement at a height of 120 cm for tree no. 11 with supports of larch wood posts (*top*) and steel pipes (*bottom*)

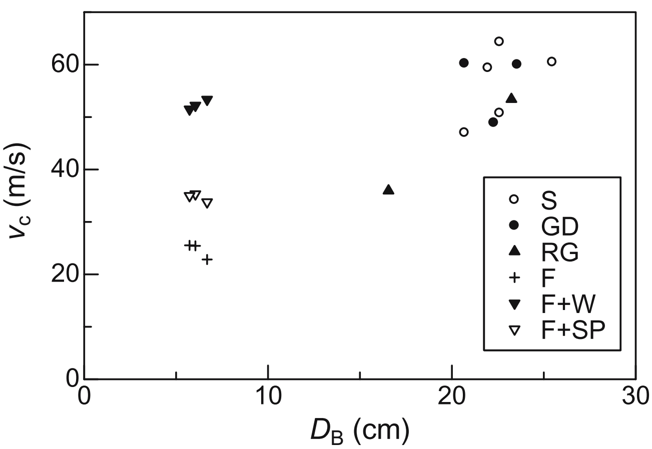


**Fig. 11.** Relationships between estimated $v_c$ and $D_B$ for the different varieties. *F + W*, Rakurakufuji with a wooden post for support; *F + SP*, Rakurakufuji with a steel pipe for support

The estimated values of $v_c$ for young trees (nos. 11–13) were as low as 20–30 m/s. The windthrow resistance of tree nos. 11–13 could be improved by support posts. The estimated $v_c$ values for the trees supported with a larch wood post were 50 m/s, which were equivalent to those for mature trees.

## Conclusions

The windthrow resistance of grafted apple trees was investigated based on pull-down tests. The conclusions obtained are as follows:

1. The windthrow failure for grafted apple trees was classified into two modes: uprooting for mature trees and rootstock breakage at the tree base for young trees. The failure mode was expected to change from rootstock breakage mode to the uprooting mode with an increase in the tree-base diameter.
2. The uprooting strength of apple trees, particularly for those grafted on dwarf rootstocks (M.26), was considerably smaller than the uprooting strengths for other tree species reported in previous studies, due to their poorly developed root system.
3. The windthrow resistance with respect to the critical wind velocity for mature apple trees was considered to be sufficient despite a low uprooting strength. This may be attributed to low tree form. No difference was observed in the critical wind velocities between M.26 and the marubakaido rootstocks.
4. Young trees broke at the tree base a few years after grafting due to the insufficient radial growth of rootstocks. The windthrow resistance of these trees could be increased to that of mature trees by supporting them with wooden posts.

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