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ORIGINAL ARTICLE

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Evaluation of drag coefficients of poplar-tree crowns by a field test method

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Abstract To estimate the wind force that causes windthrow damage to a tree, the drag coefficients of actual-sized trees were evaluated by a field test method. In this method, wind velocity and stem deflection were monitored simultaneously. The wind force acting on a tree crown was calculated from stem deflection; stem stiffness was evaluated by conducting tree-bending tests. The results of tests conducted on three poplar trees showed that drag coefficient decreased with an increase in wind velocity. Although the variation in the drag coefficient was large at low wind velocity because of the vibrating behavior of the stem subjected to variable wind force, the variation at wind velocities above 10 m/s was small. The average drag coefficient at a wind velocity of 30 m/s was estimated by the curve-fitting of a power function to the wind velocity–drag coefficient relationship to be 0.102, which was smaller than that of actual-sized conifers studied in previous wind tunnel experiments. The drag coefficients of these crown areas in the defoliation season were smaller than those measured in the leafy season.

Key words Drag coefficient · Poplar-tree crown · Windthrow resistance · Field test method

Introduction

Windthrow damage to trees in plantation forests and along roadsides in urban districts has caused enormous economic loss and danger to human life.[1] To predict wind damage to trees, such as stem breakage or uprooting, it is essential to quantitatively estimate the wind force acting on a tree crown. The drag coefficient of a tree crown (C_D) defined in Eq. 1, which is necessary to estimate wind force (P_w), has been evaluated from wind tunnel studies:[2–7]

$$P_W = \frac{1}{2} C_D \rho A U^2 \tag{1}$$

where ρ is air density (1.20 kg/m^3), A is the horizontally projected crown area, and U is wind velocity.

Most of the specimens used for the wind tunnel studies were dwarf potted trees or small models because of the wind tunnel size restriction. However, with regard to the wind-force response, it is noteworthy that the similarity rule is not applicable to the relationship between dwarf trees and actual trees. In fact, the drag coefficients of small trees at a wind velocity of 10 m/s were found to be 0.95–1.35,[4] 0.75–0.95,[5] and 1.00,[6] and these values were considerably greater than those of actual-sized trees,[3] i.e., 0.29–0.88. These actual-sized specimens were coniferous species for plantations. Drag coefficients of actual-sized broadleaf species have not yet been obtained. These C_D values are necessary for wind-break assessment for park trees or roadside trees.

The aim of this study was to develop a test method to evaluate the C_D of actual-sized trees in the field, which is a more convenient method compared with wind tunnel experiments. In this article, the drag coefficients of actual-sized poplar trees were evaluated by the proposed field test method, which involved monitoring the wind velocity and stem deflection simultaneously.

Materials and methods

Sample trees

Three trees were sampled from the east–west row of black poplars (*Populus nigra* var. *italica*) planted in 2000 in the Hokkaido University Campus. The south side of the row of trees is an open space without any buildings, and the prevailing wind direction is south. The dimensions of two of the sample trees (trees no. 1 and 2) were measured in

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Table 1. Dimensions of sample trees

No.	H (m)	D_B (cm)	L_C (m)	B_C (m)	A (m^2)	H_W (m)
1	13.1	24.2	9.3	4.4	32.5	8.4
2	12.3	19.3	7.8	3.6	22.0	8.4
3	12.9	24.1	8.9	4.1	29.0	8.5

H, tree height; D_B, breast-height diameter; L_C, crown length; B_C, crown breadth (east-west direction); A, horizontal projected area of crown assuming an ellipsoidal crown (east-west direction); H_W, height of wind pressure center

Table 2. Measurement periods for wind velocity and stem deflections

Tree no.	Leaf condition	Measurement period	Measurement time (h)	Analysis time[a] (h)
1	Leaved	Oct. 2007	232	82
	Defoliated	Apr. 2008	120	59
2	Leaved	Oct. 2007	235	58
	Defoliated	Apr. 2008	117	31
3	Leaved	Oct. 2008	402	115
	Defoliated	Apr. 2008	48	44

[a] Data for wind velocities above 5 m/s were included

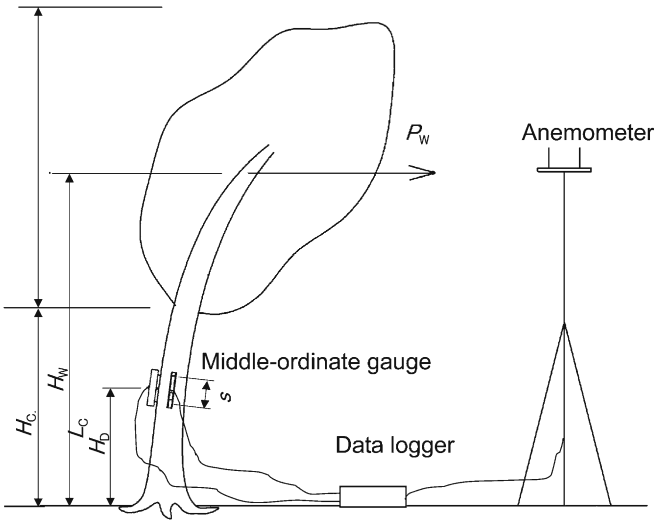

Fig. 1. Field test method for monitoring wind velocity and stem deflections

October 2007 and those of tree no. 3 were measured in October 2008 (Table 1).

Field tests

Wind velocity and stem deflection of the sample trees were monitored simultaneously (Fig. 1). The north–south and east–west components of the wind velocity (U) were monitored using an ultrasonic anemometer (Young; model 85000) by placing it near each sample tree. The height of the anemometer was adjusted with respect to the height of the wind pressure center (H_W) (Eq. 2), which corresponds to the center of gravity of the crown; a crown was considered to be an ellipse whose major and minor axes are the length and breadth of the crown, respectively.

$$H_W = H_C + \frac{1}{2} L_C \tag{2}$$

where H_C is the height of the crown base and L_C is the length of the crown.

Stem deflections were measured using a self-made middle-ordinate gauge,[8] both ends of which were screwed into a stem at a height of 115–165 cm. A deflection sensor (Kyowa Dengyo; DTH-A-5) was set at the center of the gauge span ($s = 500$ mm). The wind velocity and stem deflections (δ) were measured along both the north–south and the east–west orientations and recorded in a data logger at 10-Hz intervals. The measurements were performed on windy days in both leaved and defoliated seasons; the measurement results are listed in Table 2. The measured data were divided into 1-h intervals, and data for 389 h, which included those measured at wind velocities above 5 m/s, were analyzed.

To measure the stiffness of the tree stems, bending tests of the sample trees were conducted once on calm days in each measurement period. A bending moment below the elastic limit was applied by pulling the stem from the north and east directions using a hand winch. The applied force was measured using a load cell connected between the sling, which was tied to the stem, and the hand winch, and it was recorded in the data logger. From the elastic relationship between the moment applied at the middle-ordinate gauge (M_L) and stem deflection (δ), stem stiffness (K) was determined for both the north–south and the east–west orientations.

$$K = \frac{M_L}{\delta} \tag{3}$$

After the bending tests, the natural periods of the sample trees were determined from the free-swaying movements of the stems.

Calculation of C_D

The wind force acting on a crown (P_w) was calculated from Eq. 4.

$$P_W = \frac{K\delta}{(H_W - H_D)} \tag{4}$$

where H_D is the height of the deflection sensor (Fig. 1).

Then, C_D was calculated every second from the ratio of P_W to U^2 using Eq. 1. C_D of the north–south component was analyzed because the east–west component was rather small and might have been affected by the adjacent trees.

Results and discussion

Shapes of tree crowns

The actual areas and heights of the centers of gravity of the sample tree crowns were obtained by binarizing their photographs (Fig. 2). The actual areas of the crowns were found to be smaller than those obtained by assuming an ellipsoidal shape by 19%–27% and greater than those obtained by assuming a triangular shape, as is the case with conifers,[3] by 15%–27%. The heights of the centers of gravity were estimated to be 47%–48% of L_C from the crown base. In this study, the projected frontal area of the crowns was assumed to be an ellipsoid. This assumption was also used for calculating C_D of defoliated crowns.

The effect of the wind force acting on the stem below a crown was neglected because of the small area of the stem as compared to that of the crown, slow wind velocity near the ground level, and short distance between the wind-pressure center of a stem and the height of the middle-ordinate gauge (H_D).

Fig. 2. Photographs (*upper panel*) and binarized images (*lower panel*) of crowns of sample trees: *left*, no. 1; *center*; no. 2; *right*, no. 3

Relationship between wind velocity and C_D

Stem deflection showed a positive relationship with wind velocity (Fig. 3). The average C_D calculated from this relationship decreased with an increase in the wind velocity (Fig. 4). This decrease in C_D can be explained by the decrease in the projected area of the crowns because of the swaying movement of leaves and branches, as observed in a wind tunnel study.[3] The variation in C_D was found to be large at a low wind velocity, which could be explained by the vibrating behavior of a stem subjected to a variable wind force; fine fluctuations were observed in stem deflection (see Fig. 3). The variation in C_D was small at wind velocities above 10 m/s. To reduce the effect of vibrations at low wind velocities such as 5 m/s, C_Ds were calculated by generating moving averages from 1 to 10 s; this range includes the natural periods of the sample trees (2.8–3.7 s) (Fig. 5). However, no

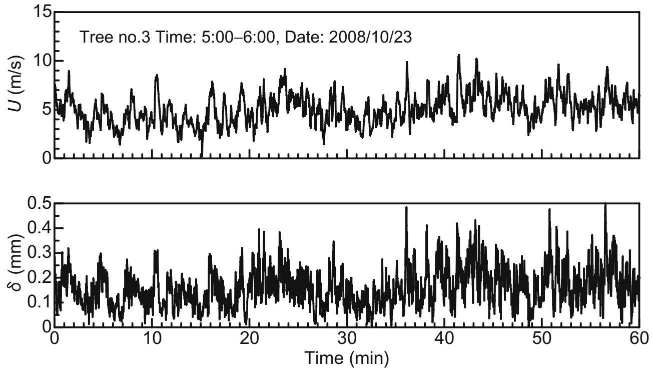

Fig. 3. An example of the time-series fluctuations for wind velocity (U) and stem deflections (δ)

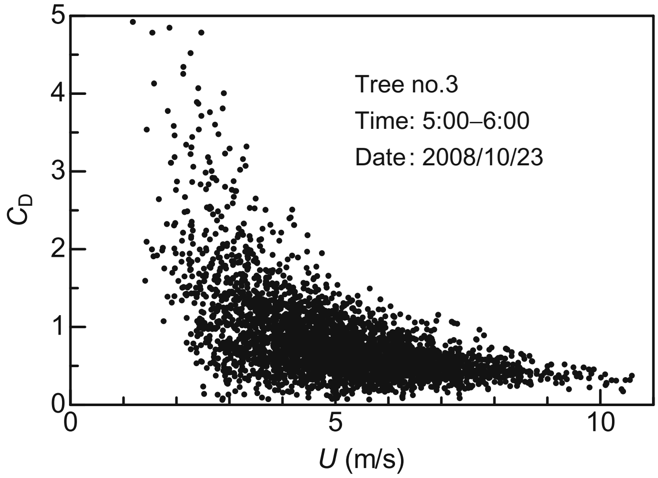

Fig. 4. Relationship between drag coefficient (C_D) and wind velocity (U)

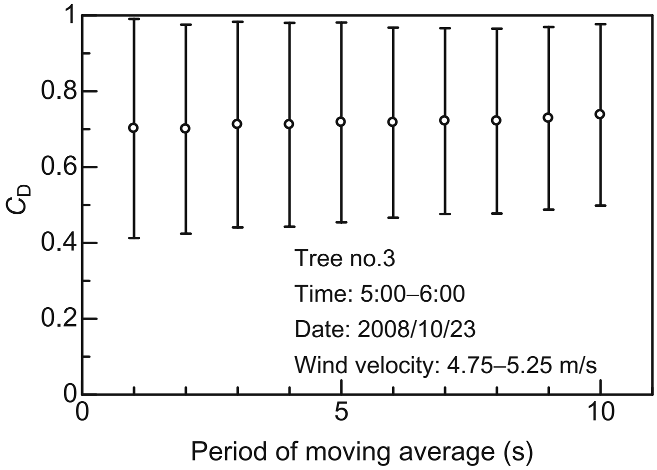

Fig. 5. Average and standard deviations in C_D calculated by generating moving averages from 1 to 10 s

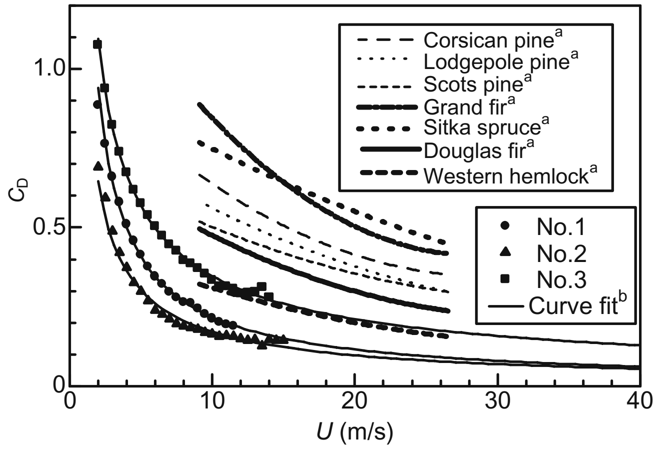

Fig. 6. Comparison between C_D values of poplars and conifers obtained from a wind tunnel study. [a]Reported by Mayhead.[3] [b]Tree no. 1, $Y = 1.77\ X^{-0.911}$; tree no. 2, $Y = 1.14\ X^{-0.824}$; tree no. 3, $Y = 1.79\ X^{-0.714}$

significant change was found in standard deviations as well as the average C_D.

The average C_D was calculated at wind velocity intervals of 0.5 m/s using all data for each measurement period (Fig. 6). C_D decreased with the wind velocity, as already discussed. The average C_D of the leaved crowns at a wind velocity of 10 m/s was 0.250.

Comparison between C_D values of poplars and conifers

Because wind velocity above 30 m/s is assumed as a maximum possible velocity and is considered as such in building design in urban areas, critical wind velocity could also be assumed as 30 m/s concerning the wind resistance of roadside trees.[6] To estimate C_D at the wind velocity of 30 m/s, C_D as a function of U was curve-fitted with a power function (see Fig. 6). The curves for seven conifers studied previously in a wind tunnel experiment[3] are shown in Fig. 6. The average C_D of poplar crowns was found to be smaller than that of western hemlock, which had the smallest value among those for conifers. The results suggested that the wind permeability of poplar crowns is larger than conifer crowns because of the difference in the flexibility of the leaves. The average extrapolated value of C_D at 30 m/s was 0.102; this value can be used for estimating wind velocity that induces wind damage to poplar trees.

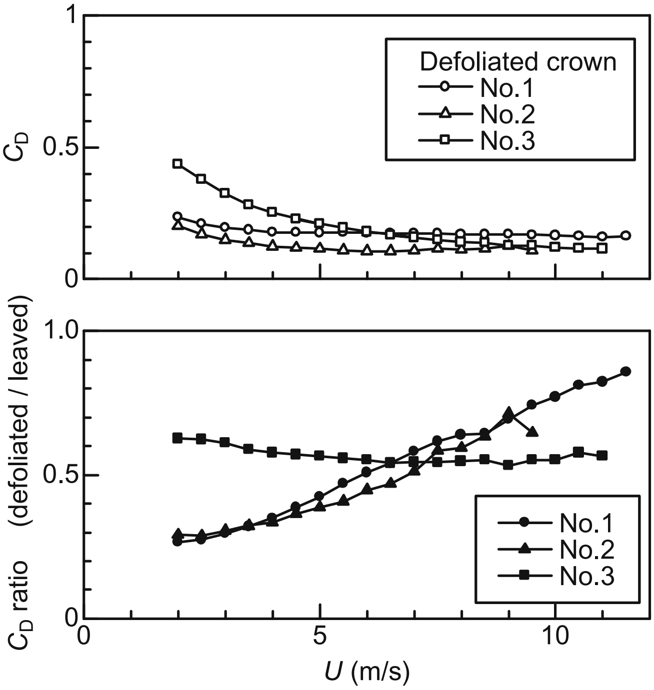

Fig. 7. Relationship between wind velocity (U) and drag coefficient (C_D) for defoliated crowns and C_D ratio (defoliated/leaved)

Effect of leaves on C_D

C_D in the defoliation season was smaller than that in the leaved season, because the same crown areas were used for the calculation. The average C_D of defoliated crowns at 10 m/s was 0.133 (Fig. 7). The change in the crown area with wind velocity variation would be small in the defoliated season because the swaying movement of the defoliated branches would be small. In fact, decrease in C_D with increase in wind velocity was small for trees no. 1 and 2 (Fig. 7). The ratio of C_D of defoliated crowns to that of leaved crowns increased with wind velocity. The ratio at a wind velocity of 10 m/s was in the range of 0.553 to 0.770.

Conclusions

1. Drag coefficients of poplar crowns were successfully evaluated by a field test method in which wind velocity and stem deflection were monitored simultaneously.
2. The drag coefficient decreased with an increase in wind velocity.

3. The drag coefficient of poplar crowns was smaller than that of conifers studied in previous wind tunnel experiments.
4. The drag coefficient of defoliated crowns was smaller than that of leaved crowns.

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