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Examining tree canopy models for CFD prediction of wind environment at pedestrian level

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Abstract

The accuracy of the canopy models for reproducing the aerodynamic effects of trees based on k–ε model was examined for the CFD prediction of wind environment at pedestrian level. After reviewing the previous researches on modeling canopy flows, two types of canopy models were selected. In addition, the model coefficients adopted in the extra term added to the transport equation of turbulence energy k and energy dissipation rate ε, were optimized by comparing numerical results with field measurements.

keywords: Tree canopy model; Aerodynamic effects of trees; Wind environment

1. Introduction

Tree planting is one of the most popular measures to improve outdoor environment, i.e. avoiding strong gust around high-rise buildings, improving outdoor thermal comfort, etc. Thus, an accurate prediction of tree effects is often needed. This study emphasized the modeling of aerodynamic effects of trees, i.e. to decrease the wind velocity but to increase the turbulence. Many tree canopy models proposed for reproducing the aerodynamic effects of trees have been found in literature (Hiraoka, 1993; Green, 1992; Yamada, 1982; Uno et al., 1989; Svensson and Häggkvist, 1990; Liu et al., 1996; Ohashi, 2004; Yoshida

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et al., 2006; Mochida et al., 2004). In the current study, the previous researches involved in using tree canopy models were reviewed and classified. Then, the model coefficients adopted in the tree canopy models were optimized by comparing numerical results with field measurements of wind velocity and turbulent energy k around trees.

2. Modeling for tree canopy

2.1. Modeling of aerodynamic effects of tree canopy

The canopy models were derived based on the k–ε model, in which extra terms were added in the transport equations (cf. Table 1). The extra term "$-F_i$" added in the momentum equation gives the effect of trees on velocity decrease, whilst the extra terms "$+F_k$" and "$+F_\varepsilon$" included in k and ε transport equations simulate the effects of trees on the amount of increase in turbulence and energy dissipation rate, respectively. These extra terms were derived by applying the spatial average to the basic equations (Hiraoka, 1993).

2.2. Classification of the extra terms for incorporating aerodynamic effects of tree canopy

The tree canopy models proposed in the previous researches (Hiraoka, 1993; Green, 1992; Yamada, 1982; Uno et al., 1989; Svensson and Häggkvist, 1990; Liu et al., 1996; Ohashi, 2004; Yoshida et al., 2006; Mochida et al., 2004) can be classified into four types (Types A–D), as shown in Table 1. It can be seen that the same form of "F_i" is used and two different forms of F_k are adopted. The F_k in Types A and B was expressed as follows:

$$F_k = \overline{\langle u_i \rangle} F_i \quad (\langle f \rangle : \text{ensemble-average}, \bar{f} : \text{spatial-average}). \tag{1}$$

This form was analytically derived by Hiraoka (1993).

In Types C and D, F_k was modified to include an additional sink term, i.e.

$$F_k = \text{Production } (P_k) - \text{Dissipation } (D_k). \tag{2}$$

P_k is the production of k within canopy $(= \overline{\langle u_i \rangle} F_i)$; D_k is a sink term to express the turbulence energy loss within canopy (Green, 1992).

In Types A and D, F_ε is modeled by using the length scale "L" within canopy

$$F_\varepsilon \propto \frac{1}{\tau}\left(\frac{k^{3/2}}{L}\right), \quad \text{where } \tau = k/\varepsilon \text{ and } L = 1/a. \tag{3}$$

On the other hand, F_ε in Type B is given by the following relation:

$$F_\varepsilon \propto \frac{1}{\tau} F_k, \quad \text{where } \tau = k/\varepsilon. \tag{4}$$

In Type C, the term corresponding to the sink term in Eq. (2) is added for the expression of F_ε as

$$F_\varepsilon = \text{Production } (P_\varepsilon) - \text{Dissipation } (D_\varepsilon) \quad \left(P_\varepsilon \propto \frac{1}{\tau} P_k,\ D_\varepsilon \propto \frac{1}{\tau} D_k\right). \tag{5}$$

The additional terms illustrated in Table 1 contain five parameters, namely the model coefficients $C_{p\varepsilon 1}$ and $C_{p\varepsilon 2}$, the fraction of the area covered with trees η, the leaf area density a, and the drag coefficient C_f. $C_{p\varepsilon 1}$ and $C_{p\varepsilon 2}$ are regarded as model coefficients in

Table 1
Additional terms for tree canopy model

	F_i	F_k	F_ε	Selected values for numerical coefficients
Type A	$\eta C_f a \overline{\langle u_i \rangle} \sqrt{\overline{\langle u_i \rangle}^2}$	$\overline{\langle u_i \rangle} F_i$	$\eta \frac{\varepsilon}{k} \cdot C_{p\varepsilon l} \frac{k^{\frac{3}{2}}}{L} \quad \left(L = \frac{1}{a}\right)$	Hiraoka (1993): $C_{p\varepsilon 1} = 0.8$–1.2
Type B		$\overline{\langle u_i \rangle} F_i$	$\frac{\varepsilon}{k} \cdot C_{p\varepsilon l} F_k$	Yamada (1982): $C_{p\varepsilon 1} = 1.0$ Uno et al. (1989): $C_{p\varepsilon 1} = 1.5$ Svensson and Häggkvist (1990): $C_{p\varepsilon 1} = 1.95$
Type C		$\overline{\langle u_i \rangle} F_i - 4\eta C_f a \sqrt{\overline{\langle u_j \rangle}^2}$	$\frac{\varepsilon}{k}\left[C_{p\varepsilon 1}(\overline{\langle u_i \rangle} F_i) - C_{p\varepsilon 2}\left(4\eta C_f a \sqrt{\overline{\langle u_j \rangle}^2}\right)\right]$	Green (1992): $C_{p\varepsilon 1} = C_{p\varepsilon 2} = 1.5$ Liu et al. (1996): $C_{p\varepsilon 1} = 1.5$, $C_{p\varepsilon 2} = 0.6$
Type D		$\overline{\langle u_i \rangle} F_i - 4\eta C_f a \sqrt{\overline{\langle u_j \rangle}^2}$	$\eta \frac{\varepsilon}{k} \cdot C_{p\varepsilon l} \frac{k^{\frac{3}{2}}}{L} \quad \left(L = \frac{1}{a}\right)$	Ohashi (2004): $C_{p\varepsilon 1} = 2.5$

F_i: extra term added in the momentum equation.
F_k: extra term added in the transport equation of k.
F_ε : extra term added in the transport equation of ε.
η: fraction of the area covered with trees.
a: leaf area density.
C_f: drag coefficient for canopy.

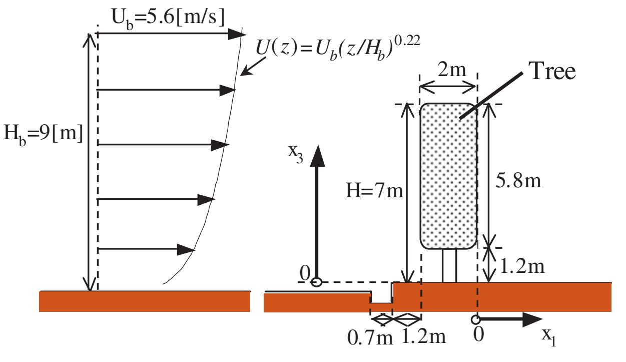

Fig. 1. Configuration of test model and inflow condition. (Computational domain: $100\,\mathrm{m}(x_1) \times 100\,\mathrm{m}(x_3)$).

Table 2
Computed test cases

Case	Model	$C_{p\varepsilon 1}$	$C_{p\varepsilon 2}$	Previous works
B-1	Type B	1.0	–	Yamada (1982)
B-2	Type B	1.5	–	Svensson and Häggkvist (1990)
B-3	Type B	1.8	–	
B-4	Type B	2.0	–	
C-1	Type C	1.5	1.5	Green (1992)
C-2	Type C	1.5	0.6	Liu et al. (1996)
C-3	Type C	1.8	0.6	
C-4	Type C	1.8	1.0	
C-5	Type C	1.8	1.1	
C-6	Type C	1.8	1.2	
C-7	Type C	1.8	1.3	
C-8	Type C	1.8	1.4	
C-9	Type C	1.8	1.5	
C-10	Type C	1.8	1.6	
C-11	Type C	1.8	1.7	
C-12	Type C	1.8	1.8	

turbulence modeling for prescribing the time scale of the process of energy dissipation in the canopy layer. Special attention was given to their appropriate values in this study. On the other hand, η, a, and C_f are the parameters required to be determined according to the real conditions of trees. The distributions of η values within the computational domain can be evaluated according to the real conditions. The values of a and C_f can be roughly determined by referring the previous researches in the field of meteorology (Matsushima and Kondo, 1997; Kondo and Watanabe, 1992; Wilson and Shaw, 1977).

3. Optimization of the numerical coefficients

In this study, the models of Types B and C were selected. The values of $C_{p\varepsilon 1}$ and $C_{p\varepsilon 2}$ included in F_ε have significant effects on the prediction accuracy. In view of the overwhelming disagreement between those adopted values in previous studies (Hiraoka, 1993; Green, 1992; Yamada, 1982; Uno et al., 1989; Svensson and Häggkvist, 1990; Liu et al., 1996; Ohashi, 2004; Yoshida et al., 2006; Mochida et al., 2004), $C_{p\varepsilon 1}$ and $C_{p\varepsilon 2}$ were optimized by the present authors through a comparison between numerical results and measurement.

3.1. Outline of CFD analyses

Fig. 1 shows the configuration of the test model and the inflow condition used. The results obtained from Types B and C canopy models were compared with field measurement data recorded in the wake zone behind the pine tree (Kurotani et al., 2002). Two-dimensional calculations were carried out at the central section of the pine tree. The canopy model adopted in this study used a revised k–ε model based on a "mixed time scale" concept (Nagano and Hattori, 2003), with extra terms added into the transport

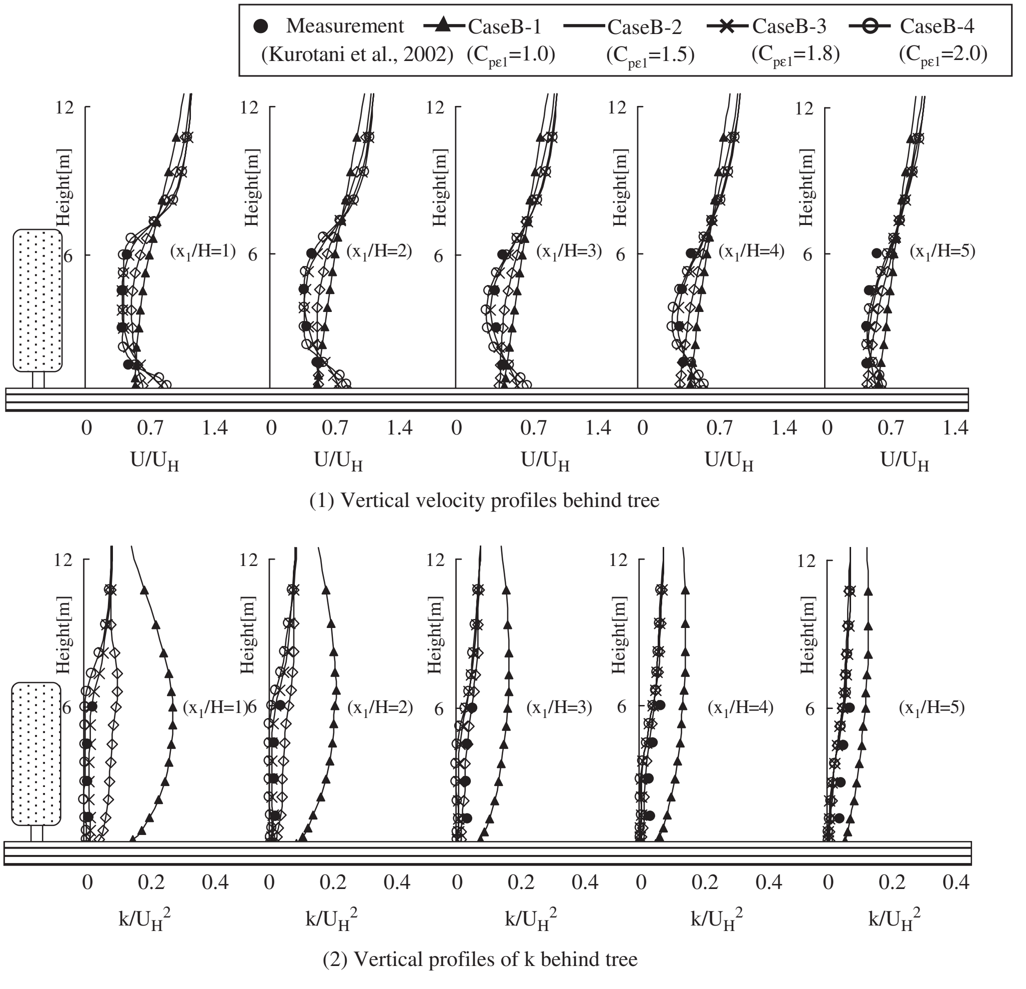

Fig. 2. Comparison of Type B canopy model results with measurement data. (H: a height of tree, U_H: inflow velocity at a height of H).

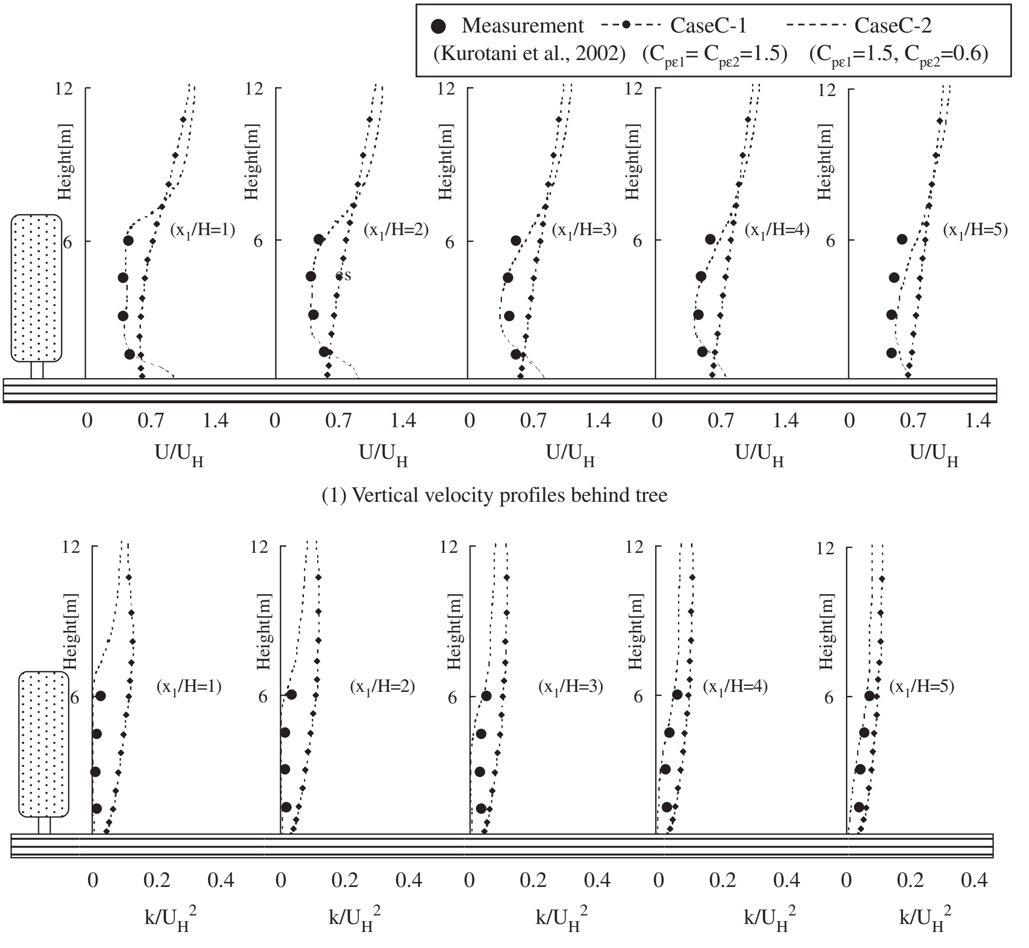

Fig. 3. Comparison of Type C canopy model results with measurement data.

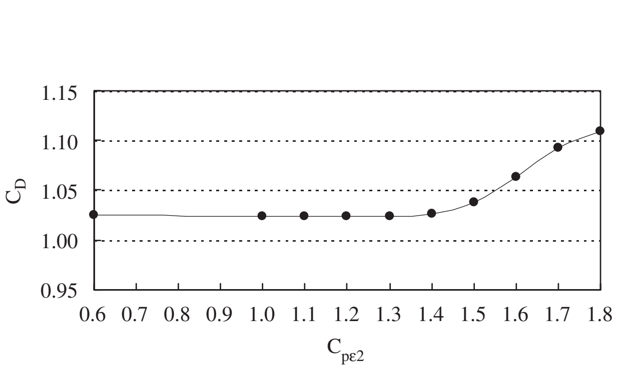

Fig. 4. Comparison of numerically predicted drag coefficient C_D of the tree (Type C: $C_{p\varepsilon1} = 1.8$).

equations. This model was primarily aimed at low Reynolds (*Re*) number modeling. Since the effects of near-wall behaviors proximity to the ground under the tree crown on the entire flow are not so significant, in this study, a log-law type wall function was used as the ground surface boundary condition and only high *Re* number area was solved (Murakami et al., 2003).

3.2. Computed test cases

All the test cases are summarized in Table 2. In Cases B-1–B-4, Type B canopy model was adopted and $C_{p\varepsilon 1}$ was changed from 1.0 to 2.0. In Cases C-1 and C-2, Type C canopy model was employed and $C_{p\varepsilon 2}$ was varied under the condition of $C_{p\varepsilon 1} = 1.5$. In Cases C-3–C-12, $C_{p\varepsilon 1}$ was increased to $1 \cdot 8$ and $C_{p\varepsilon 2}$ was changed from 0.6 (Case C-3) to 1.8 (Case C-12).

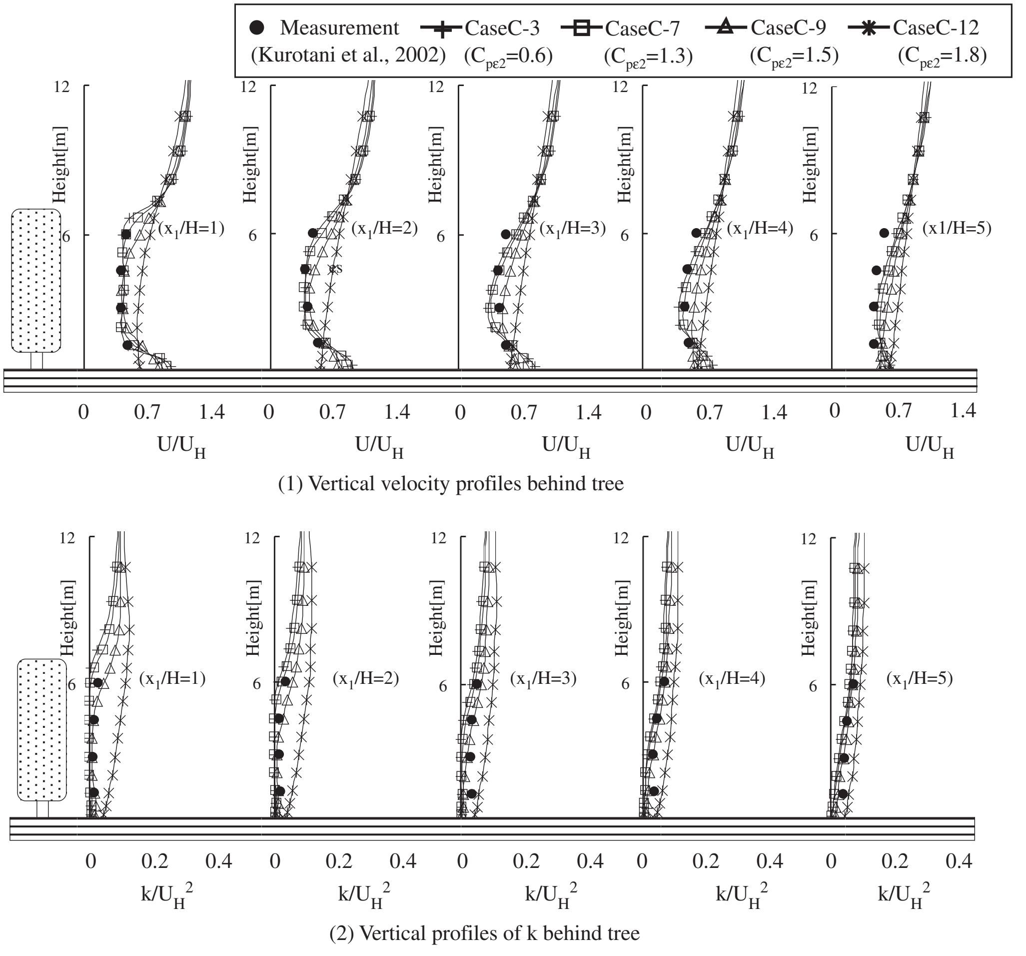

Fig. 5. Comparison of optimized Type C canopy model results with measurement data.

3.3. Results

3.3.1. Results of Type B

Fig. 2 shows the comparison of Type B canopy model results with measurements. Predicted results of $C_{p\varepsilon 1}$ in the range from 1.8 to 2.0 agreed well with the measurement results. The results with $C_{p\varepsilon 1} = 1.8$ (Case B-3) showed the best agreement with measurement data. However, the turbulence energy k tended to be slightly under-predicted in the wake region of the tree in this case.

3.3.2. Results of Type C

3.3.2.1. Case C-1 (Green, 1992) and Case C-2 (Liu et al., 1996). Fig. 3 gives the comparison of Type C canopy model results with measurement data. In Case C-1 ($C_{p\varepsilon 1} = C_{p\varepsilon 2} = 1.5$ (Green, 1992)), both wind velocity and k differed greatly from measurement values. In Case C-2 ($C_{p\varepsilon 1} = 1.5$, $C_{p\varepsilon 2} = 0.6$ (Liu et al., 1996)), the predicted

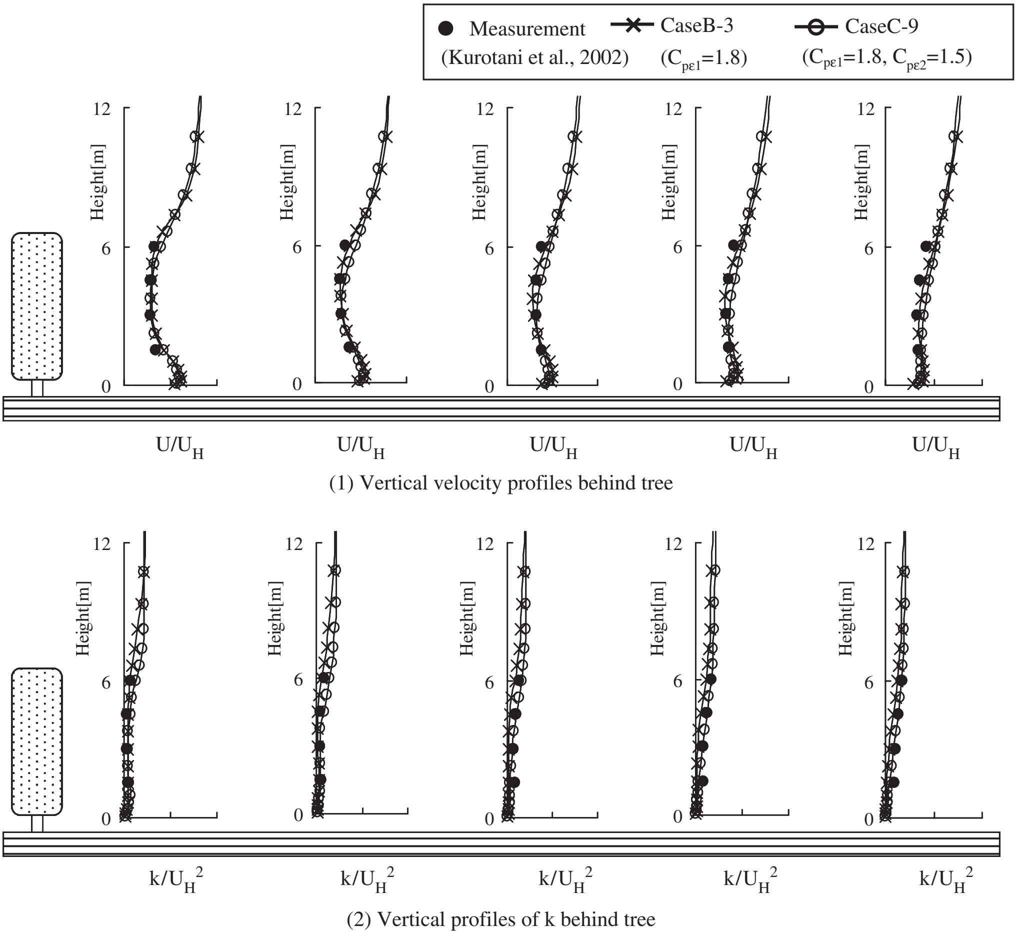

Fig. 6. Comparison between results of Case B-3 and Case C-9.

wind velocity showed good agreement with measurement data, but k was under-estimated in the wake region.

3.3.2.2. Optimization of model coefficient $C_{p\varepsilon 2}$. The model coefficient $C_{p\varepsilon 2}$ was changed gradually in line with the condition of $C_{p\varepsilon 1} = 1.8$. Fig. 4 shows the comparison of predicted drag coefficient C_D of the tree. The C_D values were almost constant when $C_{p\varepsilon 2}$ ranged from 0.6 to 1.4, but an increasing trend of C_D occurred around $C_{p\varepsilon 2} = 1.5$.

Fig. 5 shows the comparison of vertical profiles of wind velocity and k obtained by Type C canopy model, respectively. Computed results corresponded well with the measured value of wind velocity in the range $C_{p\varepsilon 2} = 0.6$–1.5. In the case of $C_{p\varepsilon 2} = 1.5$, the result of the turbulence energy k showed the best agreement with the measurement data among all Type C cases. Judging from the agreement of both the wind velocity and k with the measured data, Case C-9 ($C_{p\varepsilon 1} = 1.8$ and $C_{p\varepsilon 2} = 1.5$) was selected as the best case for Type C canopy model.

3.3.3. Comparison of Type B and Type C models

Fig. 6 compares the results of the best cases of Type B and Type C models, i.e. Case B-3 ($C_{p\varepsilon 1} = 1.8$) and Case C-9 ($C_{p\varepsilon 1} = 1.8$ and $C_{p\varepsilon 2} = 1.5$). As mentioned in Section 3.3.2, Case C-9 accurately reproduced the distributions of k, and the k values in Case C-9 also showed better agreement with the measured data compared to those of Case B-3 (Fig. 6). However, concerning the velocity profiles behind the tree, the result of Case B-3 gives slightly better agreement with the measured data (Fig. 6). Thus, Type B model with $C_{p\varepsilon 1} = 1.8$ was selected as an appropriate model for practical applications, where the effect of tree on the mean velocity field is of most interest. The performance of Type B model has been tested for various situations. One example of comparison between the result of Type B and those obtained by field measurement is given in the next section.

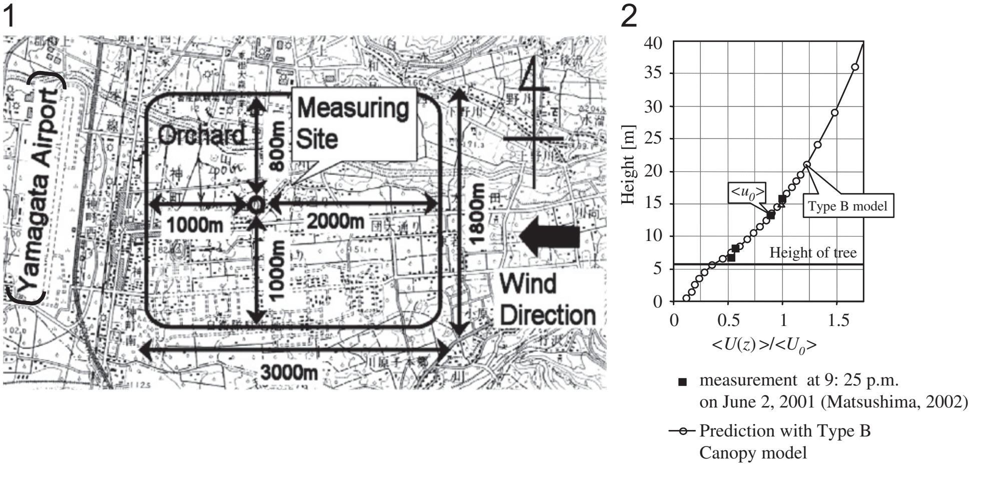

Fig. 7. Comparison of vertical velocity profiles above tree canopy (Higashine, Yamagata). (1) Computational domain (3000 m × 1800 m × 200 m), (2) Vertical profiles of mean streamwise velocity above trees normalized by the mean velocity at 16 m height U_0.

4. Examining the accuracy of Type B model for flow over an apple and cherry orchard

An apple and cherry orchard located in Higashine of Yamagata Prefecture, Japan, was chosen as the target domain for examining the performance of Type B model. Observation data were captured by means of placing a measuring site within this orchard, and was done by Matsushima (2002). The measuring site was surrounded by apple and cherry trees, with average height of 5 m, in four directions i.e. 2 km to the east, 1 km to the south, 1 km to the west and 0.8 km to the north. The computational domain of the orchard covers an area of 3 km (west to east) $\times$ 1.8 km (north to south) $\times$ 0.2 km (vertical). Fig. 7 shows a top view of this orchard. Numerical prediction obtained from Type B model was compared with the observations. In this calculation, $C_f = 0.2$ and $a = 0.83$ were adopted (Kondo and Watanabe, 1992; Wilson and Shaw, 1977). Considering the real conditions of the measuring site, η was taken as 0.4. Fig. 7 shows a comparison of the vertical profiles of the easterly wind between the measurement and predictions. It can be seen that the prediction obtained by Type B canopy model agrees very well with the measurement results.

5. Conclusions

(1) In this study, the previous researches of tree canopy models were reviewed and classified. The model coefficients adopted in the tree canopy models were optimized by comparing numerical results with field measurements of wind velocity and turbulent energy k around trees.
(2) The results of wind velocity distributions behind tree canopies obtained from Type B model with $C_{p\varepsilon 1}$ between 1.5 and 2.0 corresponded well with the measurements, and the result with $C_{p\varepsilon 1} = 1.8$ showed the best agreement with measured data.
(3) The model that considered the effect of energy loss within canopy (Type C) was also examined. Results with the combination of $C_{p\varepsilon 1} = 1.8$ and $C_{p\varepsilon 2} = 1.5$ for Type C model showed the best agreement with measurements among all Type C cases.

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