Estimation of drag coefficient of trees considering the tree bending or overturning situations

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Abstract: *Drag coefficients of a real tree trunk and the sheltering effects of an upstream trunk on a downstream one in a linear arrangement with different spacings and inclinations were investigated in detail. In addition, for elucidating the change of drag coefficient for an overturned tree, drag force acting on a real tree with roots was also measured in this study. For the measurement of drag force with different inclinations, Terminalia Cattapa and Albizia sp., vegetated in Sri Lanka, were selected in this study. Drag coefficient of inclined tree trunk has the similar tendency in relation to the Reynolds number with that of vertical standing tree investigated in Tanaka et al.(2011). For the vertical tree trunk with rough surface, drag coefficient of rear-side tree trunk was decreased with decreasing L/d (where, L is spacing and d is the diameter of trunk). In addition, as a result of mutual interference experiment of two inclined tree trunk, the drag coefficient of rear-side trunk decreased with the increase of the inclination. Under the influence of the increment of projected area due to existence of roots and shear force acting on tree trunk surface, the drag coefficient of a tree with roots became similar value (1.0-1.2) comparing with that of a vertical standing tree.*

Keywords: *drag coefficient, Reynolds number, bending, overturning, tree roots, sheltering effect*

1. INTRODUCTION

In recent years, forestation in a river becomes a big problem in Japan. The trees in a river increase the drag force to the flow, rise the water level at flood events when they are dense and not broken. When the tree is broken, it produces floating debris and causes a damage to downstream bridges and other structures in a river. Therefore, it is very important to manage trees in a river, and it is also essential to estimate the drag characteristic of trees with high-accuracy for the design and management of river.
Previous studies usually placed smooth circular cylinders (drag coefficient around 1-1.2) on a flume bed in a submerged or emergent condition and investigated the effects on flow (Li and Shen 1973, Petryk and Bosmajian 1975, Baptist et al. 2007). However, the drag coefficient or flow structure of real trees depends on various factors, including velocity (Mayhead 1973, Kouwen and Fathi-Mogfadam 2000, Armanini et al.l 2005), velocity and canopy morphology (Su et al. 2008), flexibility (Schoneboom and Aberle 2009, Wunder et al. 2009), the presence of leaves in emergent or submerged condition (Wunder et al. 2010), and plant density (Nepf 1999, Takemura and Tanaka 2007, Tanaka and Yagisawa 2010). Moreover, Tanaka and Yagisawa (2009) investigated the breakage pattern of trees by field investigation after a large flood event, and classified the unwashed-out breakage pattern as trunk bending or overturning. If a tree is bent, it is important to know the drag coefficient of a bent trunk or branches. When a tree is overturned,

the knowledge of a drag coefficient of uprooted roots is necessary. However, much details/information about the drag coefficient is not available under these situations.

Figure 1 shows the schematic diagram of our study regarding the tree drag characteristics. Tanaka et al.(2011) have already conducted Experiment 1 and Experiment 2 in Figure 1. Therefore, the objectives of this study were to elucidate the drag characteristics of real trees especially paying attention on 1) inclination to the flow (Experiment 3), 2) sheltering effect by frontal trees on rear-side tree (Experiment 4) and 3) overturned condition (Experiment 5). For their objectives, wind tunnel experiments and towing tank experiments were conducted.

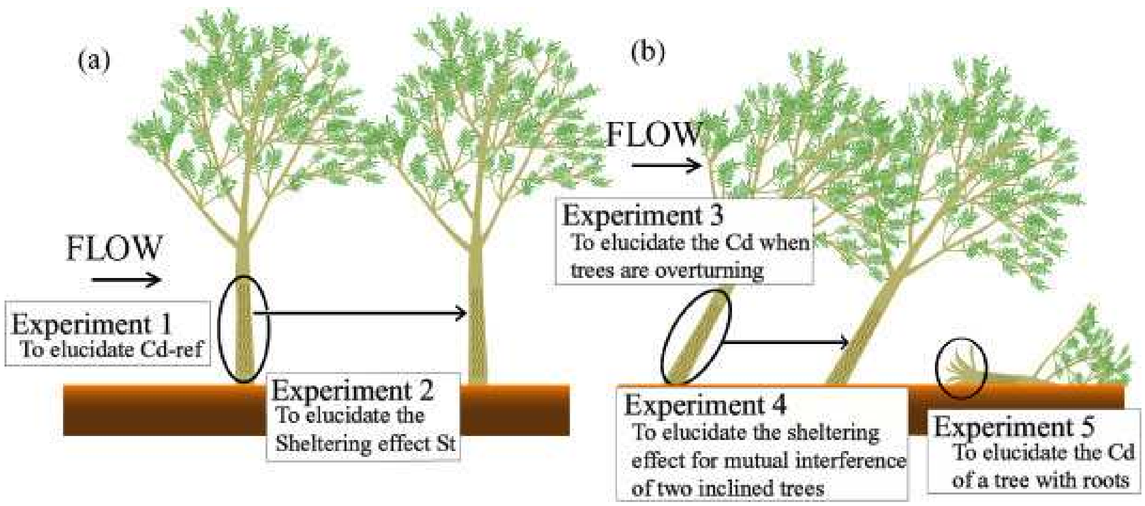


Figure 1 Schematic diagram

(a) Drag characteristic of vertical tree (b) Drag characteristic of inclined tree

2. MEASUREMENT METHOD

In this study, the following three experiments were conducted.

1) Experiment 3: estimation of the drag coefficients of an inclined tree.
2) Experiment 4: the sheltering effect due to mutual interference of two inclined trees
3) Experiment 5: the drag coefficient of trees with roots

However, comparison with results of our study (Experiment 3-5) and that of Tanaka et al.(2011) is needed in section 3(Results and Discussions). Therefore experimental method and results of Tanaka et al.(2011) are also shown in this study.

Experiment 1 and 2 were carried out at an Eiffel type wind tunnel facility with a 0.5 m × 0.5 m cross section at Saitama University (Figure 2). The setup for Experiment 1 is shown in Figure 2b. Figure 3 shows the cross sections and side views of trunk models used in Experiment 1. In this study, *Robinia pseudoacacia* (rough surface; hereafter, Trunk-R), willow(*Salix* sp.; hereafter, Trunk-W), a circular polyvinyl chloride cylinder(smooth surface; hereafter, Cylinder-S) and a different type of circular cylinder (roughness surface; hereafter, Cylinder-R) were used for Experiment 1. Cylinder-R had a different aspect ratio and non-dimensionalized equivalent roughness height as Trunk-R.

First, the drag force acting on Cylinder-S was measured directly, and the drag coefficient was calculated. Then, the relationship between Reynolds number ($R_e = ud/\nu$, where u is the reference velocity, d is a diameter of the tree trunk or the cylinder, and ν is kinematic velocity) and drag coefficient was derived using Trunk-R, Trunk-W, and Cylinder-R to elucidate the effects of different surface roughness conditions on drag characteristic. Trunk-R, Trunk-W, Cylinder-S, and Cylinder-R were 0.35 m in length. Two rods were inserted into the cut ends of the specimen to minimize the effect of three-dimensional separation of the boundary layer (the so-called horse-shoe vortex) at the upper and lower walls. Trunk-R, Trunk-W, Cylinder-S, or Cylinder-R with rods were separately installed at 4.3 m from the inlet of the wind tunnel. Two Load-cell instruments (the product made by AIKOH: RX-10, the measurement maximum load is

100N, the resolving power is 1/1000) were set at the upper and lower ends of each rod attached to the model, and the drag forces acting on the upper (*Fu*) and lower (*Fl*) parts of the model were measured.

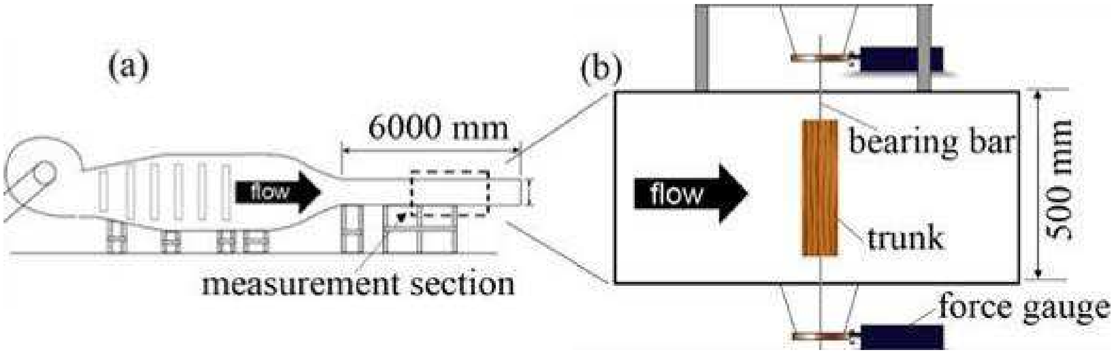


Figure 2 Experimental apparatus, (a) Wind tunnel, (b) set-up for Experiment 1 (Tanaka et al.(2011))

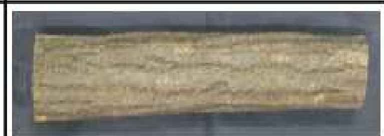
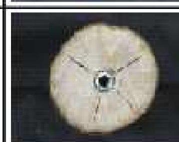
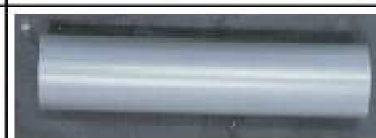
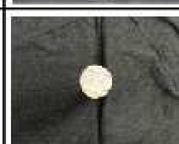
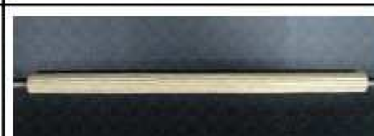
	d (cm)	k_s/d $\times 10^{-3}$	cross section	side view
Trunk-R	7.8	45		
Trunk-W	7.7	11		
Cylinder-S	7.6	–		
Cylinder-R	2.0	45		

Figure 3 Surface roughness characteristics of trunk model.
The cross section and side views of Trunk-R, Trunk-W, Cylinder-S, and Cylinder-R.
The maximum k_s/d (d : trunk diameter, k_s : equivalent roughness height) value of each model is shown in the table (Tanaka et al.(2011))

The drag coefficient Cd of the model by the total drag force F (F = Fu + Fl) was calculated from the following equation.

$$C_d = \frac{2F}{\rho u^2 A} \tag{1}$$

Where, F is the drag force (N), ρ is the density of water (kg/m3), u is velocity (m/s) and A is a project area (m^2).

A towing tank facility in the University of Peradeniya was also used in this study. The towing tank has a carriage which is installed on the channel with the length of 50 m, the width of 2 m, and the depth of 2 m (Figure 4).
In each above-mentioned towing tank experiment, tree models are installed in the rear side of the carriage. Drag force was measured by Load cell as the same one used in Experiment 1 with running the carriage. The drag force (*F*) was calculated by the measured value of *F2* in the experiment and substituted in the drag coefficient equation considering the balance of a moment as bellow:

$$F3 = \frac{F2 \times L}{L + y} \qquad (2)$$

Where, F2 and F3 are the drag at the point of P2 and middle of tree in the figure 4,respectively. *y* is the distance from the point where *F2* acts to the half of water depth (m), *L* is the distance from the point where *F1* acts to the point where *F2* acts (= 1.042 (m) in this study).
The experimental conditions of Experiment 3 are shown in Table 1(a). The inclinations of trees in the experiment were set in two cases as θ = 0 (vertical) and 30 degrees. The range of Reynolds number R_e is from $2.0{\times}10^4$ to $9.0{\times}10^4$. *Terminalia Cattapa* with a mean diameter of 3.5cm was used as the trees model. The reason why this species was chosen as roughness condtion of tree trunk surface is similar to that of *Willow.*

The experimental conditions of Experiment 4 are shown in Table 1b. In Experiment 4, two inclined tree models were arranged in the towing direction. The same *Terminalia Cattapa* as Experiment 3 with 3.5 cm-diameter (*d*) was used for a rear-side tree. The trees model with 4.0cm diameter tree was used for a front side tree. Under the condition, the sheltering effect of drag force by front side tree on rear side tree was measured. The inclination of the trees model were conducted two cases as θ = 0°, and 30°. In addition, non-dimensional length *L/d* (where, *L* is the distance between trees) was set two cases (4 and 10) in each inclination. Then, a total of 6 cases were conducted in Experiments 3 and 4.

Finally, the experimental conditions of Experiment 5 are shown in Table 1-(c). *Albizia* of which trunk diameter is 5.0cm and mean root diameter is 32.0 cm was used in the Experiment 5. The tree model with roots was installed as θ = 90 degrees (horizontal) and roots were set at the front side to the flow considering the overturned situation. Moreover, the range of a Reynolds number R_e was set as the same range with the Experiment 1 ($2.5{\times}10^4$ to $1.2{\times}10^5$) by using 5.0 cm-diameter tree in order to compare with θ = 0 degree case.

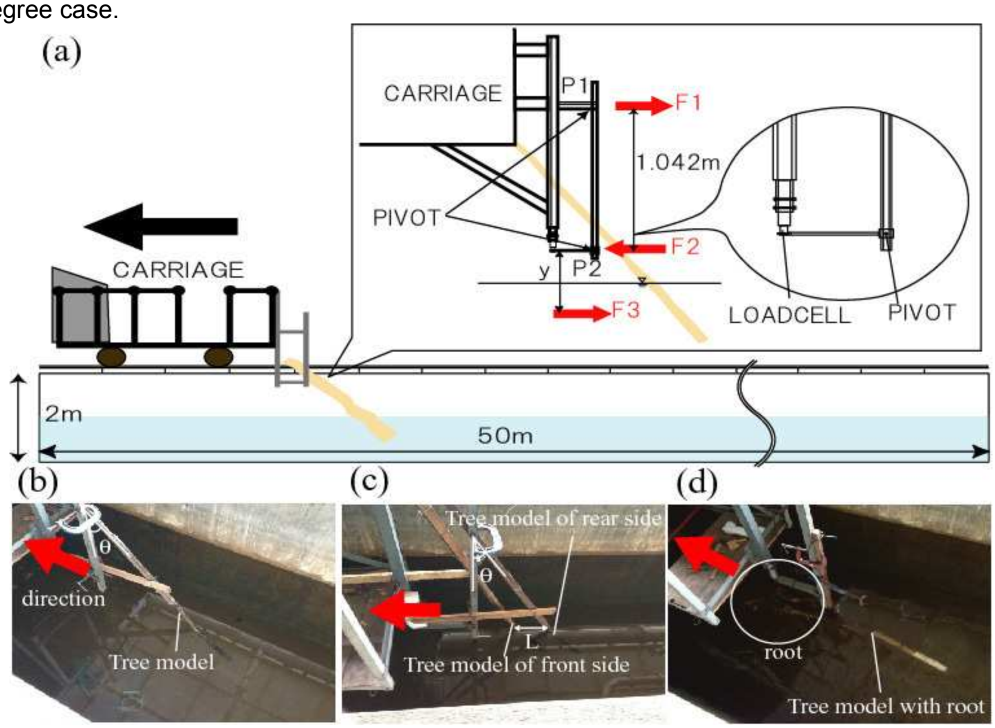


Figure 4 Experimental set up
(a) Towing Tank (b) set up of an inclined tree
(c) set up of two inclined trees (d) set up of a tree with roots

Table 1 Experiment condition and Material.
(a) Experiment 3 (b) Experiment 4 (c) Experiment 5

(a)

Tree Species	diameter d (m)	angle θ (°)	velocity u (m/s)
Terminalia Cattapa	0.035	0	0.50, 0.75, 1.00,1.25, 1.50, 1.75,2.00, 2.25
		30	

(b)

Tree Species	diameter d (m)	angle θ (°)	L/d	velocity u (m/s)
<Front side> *Terminalia Cattapa*	0.04	0	3.7	0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25
			10.6	
<Rear side> *Terminalia Cattapa*	0.035	30	3.6	
			11.4	

(c)

Tree Species	diameter d (m)	angle θ (°)	velocity u (m/s)
Albizia	0.05	90	0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25

3. RESULTS AND DISCUSSION

3.1. Effect of surface roughness of tree trunk and roots on drag coefficient (Experiment 1 and 5)

Figure 5 shows the variation of drag coefficient with Reynolds number (R_e) for the real tree trunk (Trunk-R, Trunk-W), circular cylinders (Cylinder-S, Cylinder-R) and tree with roots. Although the drag characteristics of real trunks have been investigated in wind tunnel experiments, the characteristics can also be applied to the vegetative drag of trees in water flow. The Mach number (M_a = U/a, U is the relative velocity of fluid, a is the acoustic velocity) in this study was around 0.02‐0.07 and was less than 0.3, which is often used as a maximum Mach number for incompressible gas flow (Schlichting 1979, Potter and Foss 1982) The drag coefficients of Trunk-R, Trunk-W, and Cylinder-S were smaller than those obtained in previous research (1.0‐1.2) (Wieselsberger 1921). The aspect ratio is supposed to affect the drag coefficient. It is well known that the drag coefficient of a circular cylinder with a smooth surface decreases with decreasing aspect ratio (Okamoto and Yagita 1973, Uematsu and Yamada 1995). The aspect ratio of Trunk-R, Trunk-W, and Cylinder-S was about 4.5, and the aspect ratio was supposed to greatly affect the drag coefficients because the effect of the detour flow from the gaps at the top and bottom of the cylinder became large.

A different tendency can be seen between the drag coefficient of Trunk-R and Trunk-W. The percentage of the standard deviation of the drag force on Trunk-W, which has small roughness, and the average drag force on it was around 2-8 %. In contrast, the percentage for Trunk-R, which has large surface roughness, was around 5-20 %. In the case of Trunk-R, the boundary layer of the trunk surface may become turbulent because Trunk-R had a large k_s/d than that of Achenbach (1971). Therefore, the flow had already become supercritical, and the drag coefficient of Trunk-R showed a constant value without depending on R_e. In contrast, the drag coefficient of Trunk-W decreased gradually with increasing R_e. In the case of Trunk-W, the boundary layer of the trunk surface may range within a transition region from laminar to turbulent because the k_s/d of trunk-W was similar to the condition of k_s/d =1×10^{-3}-9×10^{-3} in Achenbach(1971). The results of the trunk experiments in this study did not show a large change of drag coefficient with changing R_e as shown in previous research (Wieselsberger 1921, Achenbach 1971) because the surface roughness of real tree trunks is irregular.

On the other hand, the drag coefficient of Cylinder-R with a large aspect ratio was evaluated to be around 1.0. This value is similar to that of the smooth cylinder with the same aspect ratio. In addition, the drag coefficient of a tree with roots was almost same value for Cylinder-R at low Reynolds number (R_e) and for Trunk-R, Trunk-W and Cylinder-S at high Reynolds number (R_e). In case of a tree with roots (model for overturned tree), the projected area was decreased in comparison with vertical standing tree. However, drag coefficient of a tree with roots is similar (1.0-1.2) to that of a vertical standing tree.

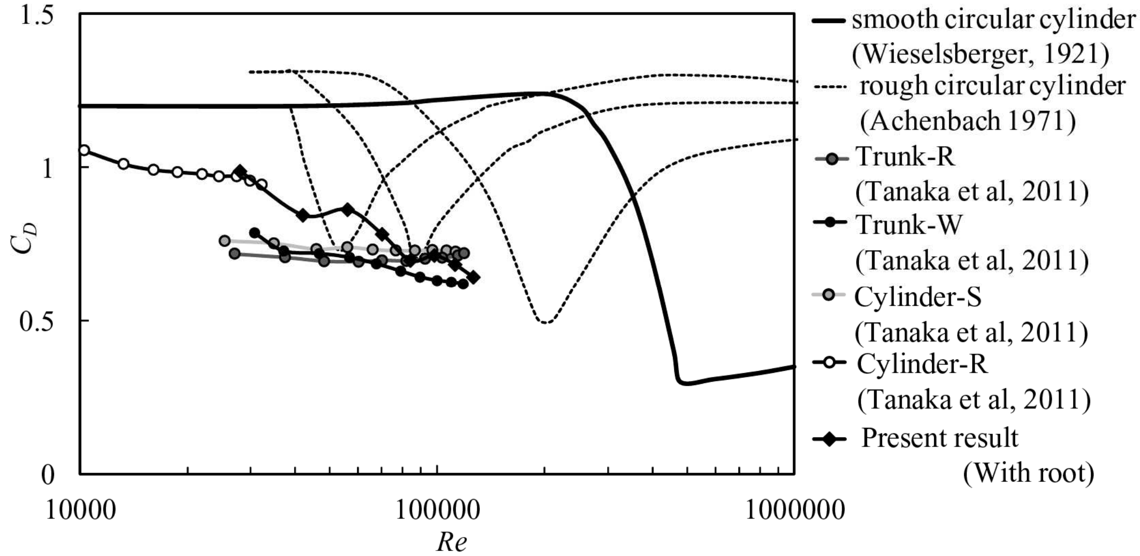


Figure 5 Variations of drag coefficient (C_D) of a tree with roots

3.2. Influence of mutual interference of two trunks and an inclined tree and two inclined tree on drag coefficient (Experiment 2, 3 and 4)

Using two trunk models, the variation of drag coefficient was measured by changing R_e and L/d. The drag coefficient of rear-side model was decreased with decreasing L/d for both surface conditions of the trunk models (Trunk-R and Trunk-W). However, it shows quite different tendency with Reynolds number because the drag force decrement for the frontal trunk at high R_e depends on the surface condition, as shown in Figure 6. In case of Trunk-W, boundary layer of the trunk surface may be ranged within transition region from laminar to turbulent as mentioned in 3.1. Therefore, the wake region becomes narrower with increasing R_e in comparison with laminar or turbulent boundary layer, and approach velocity is supposed to be larger with increasing Reynolds number. The drag force and coefficient of Trunk-W was then increased with increasing Reynolds number.

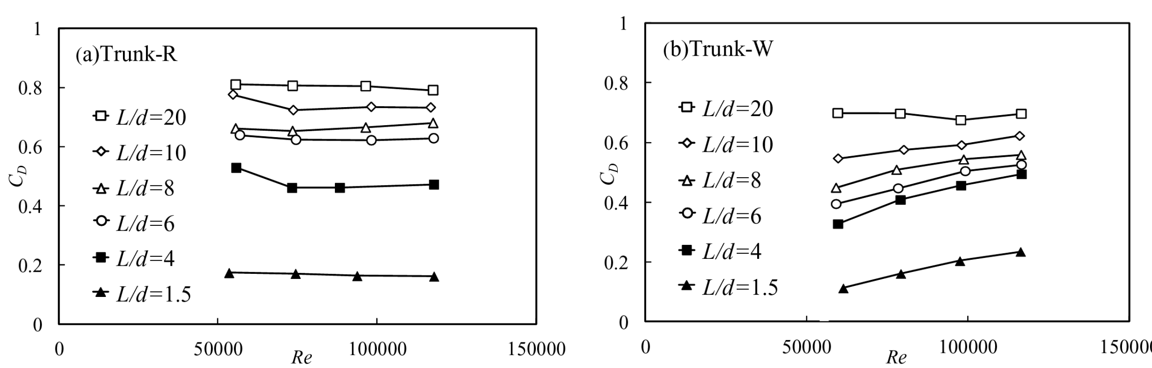


Figure 6 Variations of drag coefficient (C_D) of rear-side models with Reynolds number (a) Trunk-R, (b) Trunk-W (*L* is the distance between two trunk models, *d* is the diameter of trunk model) (Tanaka et al.(2011))

In case of Trunk-R, boundary layer of the trunk surface may be shifted to turbulent enough, and wake region suppose to be not changed with increasing R_e. Therefore, the drag coefficient of Trunk-R becomes almost constant for the investigated R_e. The results for Trunk-R and Trunk-W with different surface roughness shows different tendency. However the trunk surface of both tree species become like Trunk-R when the trunk diameter becomes large with aging. Therefore, when the drag coefficient of real trunk is applied, it is better to apply the drag coefficient of Trunk-R than that of Trunk-W.

On the other hand, Figure 7 shows the drag coefficient of an inclined tree and two inclined trees. The drag coefficients of a single tree of θ = 0° and 30° was 0.86 and 0.68, respectively. In addition, *d/H* of an inclined tree of θ = 0° or 30° was 0.1 or 0.08, respectively. The drag coefficient of an inclined tree of θ = 0° was similar to the approximated line for Uematsu and Yamada (1995). Therefore, the method of measuring drag force used in this study was judged to be appropriate. The result for an inclined tree of θ = 30° was smaller than those of θ = 0° by 20 percents. Since the value of *d/H* was almost the same, the difference was supposed to be caused by the inclination of a tree.

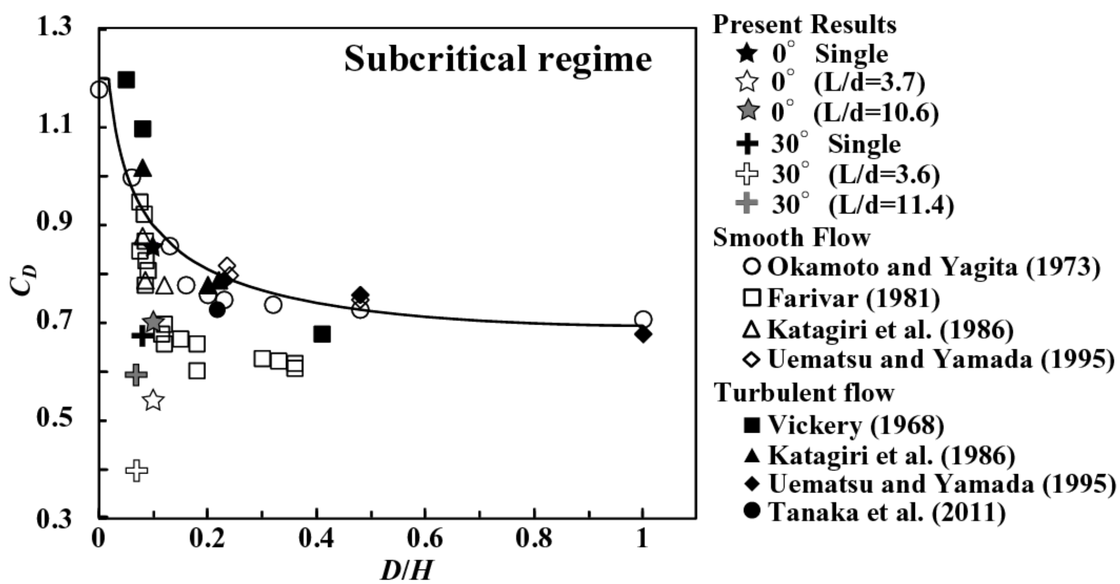


Figure 7 The relationship between aspect ratio (*d/H*) and drag coefficient (C_D) under the subcritical regimes. (This figure is modified from Uematsu and Yamada (1995)).

In case of two inclined trees experiments, drag coefficient of the rear-side tree trunk was decreased with decreasing *L*/d**.** Similar tendency can be confirmed in case of the vertical standing tree (Tanaka et al. (2011)). In addition, drag coefficient of the rear-side tree trunk was decreased with increasing inclination. In case of single trunk, drag coefficient of vertical (θ=0°) and inclined (θ=30°) tree trunks were 0.85 and 0.68, respectively. On the other hand, in case of two trunks (*L/d*=3.7), drag coefficient of vertical tree trunk (θ=0°) and inclined one (θ=30°) was 0.54 and 0.41, respectively. These results indicate that the influence of *L/d* on reduction of C_d value is larger than that of inclination.

4. CONCLUSIONS

The following conclusions were obtained in this study:
1) When tree is inclined, the drag coefficient was decreased about 20% for both of an inclined tree and two inclined trees.
2) The drag coefficient of a tree with roots is almost the same value to Trunk-R and Trunk-W. Therefore, the value of C_d=1.0-1.2 can be given as using projected area of roots when a tree is overturning in a flood event. So the estimation of a projected area of root zone is important.

5. ACKNOWLEDGMENTS

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