Journal of Wind Engineering & Industrial Aerodynamics 169 (2017) 168–176

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Aerodynamic roughness parameters in cities: Inclusion of vegetation

Christoph W. Kent[a,*], Sue Grimmond[a], David Gatey[b]

[a] Department of Meteorology, University of Reading, Reading, United Kingdom
[b] Risk Management Solutions, London, United Kingdom

ARTICLE INFO

Keywords:
Aerodynamic roughness length
Drag coefficient for vegetation
Logarithmic wind profile
Morphometric method
Urban
Zero-plane displacement

ABSTRACT

A widely used morphometric method (Macdonald et al. 1998) to calculate the zero-plane displacement (z_d) and aerodynamic roughness length (z_0) for momentum is further developed to include vegetation. The adaptation also applies to the Kanda et al. (2013) morphometric method which considers roughness-element height variability. Roughness-element heights (mean, maximum and standard deviation) of both buildings and vegetation are combined with a porosity corrected plan area and drag formulation. The method captures the influence of vegetation (in addition to buildings), with the magnitude of the effect depending upon whether buildings or vegetation are dominant and the porosity of vegetation (e.g. leaf-on or leaf-off state). Application to five urban areas demonstrates that where vegetation is taller and has larger surface cover, its inclusion in the morphometric methods can be more important than the morphometric method used. Implications for modelling the logarithmic wind profile (to 100 m) are demonstrated. Where vegetation is taller and occupies a greater amount of space, wind speeds may be slowed by up to a factor of three.

1. Introduction

During neutral atmospheric stratification, the mean wind speed ($\overline{U}_z$) at a height z, above a surface can be estimated using the logarithmic wind law (Tennekes, 1973):

$$\overline{U}_z = \frac{u_*}{\kappa} \ln\left(\frac{z - z_d}{z_0}\right) \quad (1)$$

where u_* is the friction velocity, $\kappa \sim 0.40$ (Högström, 1996) is von Karman's constant, z_0 is the aerodynamic roughness length, and z_d is the zero-plane displacement. The aerodynamic roughness parameters (z_d and z_0) can be related to surface geometry using morphometric methods (e.g. Grimmond and Oke, 1999; Kent et al., 2017a).

Uncertainties in wind-speed estimations arise from using idealised wind-speed profile relations, as well as representing the surface using only two roughness parameters (z_d and z_0), which are based upon a simplification of surface geometry. Both observations and physical experiments are therefore critical to assess the most appropriate methods to determine roughness parameters and for wind-speed estimation (e.g. Cheng et al., 2007; Tieleman 2008; Drew et al., 2013). Using the logarithmic wind law (Eq. (1)), Kent et al. (2017a) demonstrate that wind speeds estimated up to 200 m above the canopy in central London (UK) most resemble observations using morphometric methods which account for roughness-element height variability (specifically, the Millward-Hopkins et al., 2011 and Kanda et al., 2013 methods). However, an uncertainty of >2.5 m s^{-1} exists (>25% of the mean wind speed) due to the flow variability throughout the profile (Kent et al., 2017a; their Fig. 7).

Bluff bodies (e.g. buildings) and porous roughness elements (e.g. vegetation) have different influences upon wind flow (Taylor, 1988; Finnigan, 2000; Guan et al., 2000, 2003) which need to be accounted for. Although morphometric methods have been developed for only buildings (examples in Mohammad et al., 2015) or vegetated canopies (e.g. Nakai et al., 2008), existing morphometric methods do not consider both solid and porous bodies (i.e. vegetation) in combination.

With the intention of collectively considering buildings and vegetation to determine z_d and z_0, this work develops the widely-used Macdonald et al. (1998, hereafter *Mac*) morphometric method to include vegetation. The development applies to the more recently proposed Kanda et al. (2013, hereafter *Kan*) development of *Mac* which considers roughness-element height variability. The implications for estimating the logarithmic wind-speed profile (Eq. (1)) up to 100 m above five different urban surfaces are discussed.

* Corresponding author. Room 2U08, Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading, RG6 6BB, United Kingdom.
E-mail addresses: C.W.Kent@pgr.reading.ac.uk, c.s.grimmond@reading.ac.uk (C.W. Kent).

http://dx.doi.org/10.1016/j.jweia.2017.07.016
Received 15 December 2016; Received in revised form 24 July 2017; Accepted 24 July 2017
Available online 4 August 2017

Notation

A^*_f	Unsheltered frontal area of roughness elements
a_0, b_0, c_0, a_1, b_1, c_1	Kanda et al. (2013) method constants
A_f	Frontal area of roughness elements
A_p	Plan area of roughness elements
A_T	Total surface area
C_D	Drag coefficient
F_D	Total drag of roughness elements
H_{av}	Average roughness-element height
$H_{\max}$	Maximum roughness-element height
κ	von Karman's constant = 0.4 (Högström, 1996)
L	Obukhov length $= -\frac{\overline{T}u_*^3}{kg\overline{w'T'}}$
P_{2D}	Two-dimensional porosity
P_{3D}	Three-dimensional or aerodynamic porosity
P_v	ratio of C_{Dv} to C_{Db}
u_*	Friction velocity $= ((\overline{-u'w'})^2 + (\overline{-v'w'})^2)^{0.25} = \sqrt{\tau/\rho}$
U_z	Wind speed at height z
z_0	Aerodynamic roughness length
z_d	Zero-plane displacement
α	z_d correction coefficient (Macdonald et al., 1998)
β	Drag correction coefficient (Macdonald et al., 1998)
λ_f	Frontal area index of roughness elements
$\lambda_{f\text{-}crit}$	Frontal area index for peak z_0
λ_p	Plan area index of roughness elements
ρ	Density of air
σ_H	Standard deviation of roughness-element heights
σ_v	Standard deviation of lateral wind velocity (crosswind)
τ	Surface shear stress

Abbreviations

CC_hv	City centre with high vegetation
CC_lv	City centre with low vegetation
Kan	Kanda et al. (2013) morphometric method
Mac	Macdonald et al. (1998) morphometric method
Pa	Urban park
SB_hv	Suburban area with high vegetation
SB_lv	Suburban area with low vegetation

Additional subscripts

b	Buildings
v	Vegetation
l-on	Leaf-on
l-off	Leaf-off

2. Methodology

2.1. Macdonald et al. and Kanda et al. Morphometric methods

Morphometric methods traditionally characterise roughness elements by their average height (H_{av}), plan area index (λ_p) and frontal area index (λ_f). The λ_p is the ratio of the horizontal area occupied by roughness elements ('roof' or vegetative canopy, A_p) to total area under consideration (A_T), whereas λ_f is the area of windward vertical faces of the roughness elements (A_f) to A_T. By including the standard deviation (σ_H) and maximum ($H_{\max}$) roughness-element heights, newer methods consider height variability (Millward-Hopkins et al., 2011; Kanda et al., 2013).

The *Mac* method is derived from fundamental principles and without assumptions about wake effects and recirculation zones of solid roughness elements (Macdonald et al., 1998), which vary for porous elements (Wolfe and Nickling, 1993; Judd et al., 1996; Sutton and McKenna Neuman, 2008; Suter-Burri et al., 2013). The formulation of z_d and z_0 is (Macdonald et al., 1998):

$$Mac_{z_d} = \left[1 + \alpha^{-\lambda_p}\left(\lambda_p - 1\right)\right]H_{av} \tag{2}$$

$$Mac_{z_0} = \left(\left(1 - \frac{z_d}{H_{av}}\right)\exp\left[-\left\{0.5\beta\frac{C_{Db}}{\kappa^2}\left(1 - \frac{z_d}{H_{av}}\right)\lambda_f\right\}^{-0.5}\right]\right)H_{av} \tag{3}$$

where the constant, α, is used to control the increase in z_d with λ_p, a drag correction coefficient, β, is used to determine z_0 and C_{Db} is the drag coefficient for buildings. Coefficients can be fitted to observations. For example, using Hall et al.'s (1996) wind tunnel data, Macdonald et al. (1998) recommend $C_{Db} = 1.2$ and $\alpha = 4.43$, $\beta = 1.0$ for staggered arrays; and $\alpha = 3.59$, $\beta = 0.55$ for square arrays. The staggered array values and $C_{Db} = 1.2$ are used here.

Using large eddy simulations for real urban districts of Japan, Kanda et al. (2013) argue that the upper limit of z_d is $H_{\max}$ and therefore:

$$Kan_{z_d} = \left[c_o X^2 + \left(a_o\,\lambda_p^{\,b_o} - c_o\right)X\right]H_{max},\quad X = \frac{\sigma_H + H_{av}}{H_{max}} \tag{4}$$

and

$$Kan_{z_0} = \left(b_1 Y^2 + c_1 Y + a_1\right)Mac_{z_0},\quad Y = \frac{\lambda_p\,\sigma_H}{H_{av}} \tag{5}$$

where $0 \le X \le 1$, $0 \le Y$ and a_0, b_0, c_0, a_1, b_1 and c_1 are regressed constants with values: 1.29, 0.36, −0.17, 0.71, 20.21 and −0.77, respectively.

2.2. Considering vegetation

Although, consideration has been given to treatment of vegetation within building-based morphometric methods (e.g. a reduction of height, Holland et al., 2008), the flexibility, structure and porosity of vegetation suggest the effects upon wind flow and aerodynamic roughness are more complex (Finnigan, 2000; Nakai et al., 2008). During the method development proposed here, vegetation porosity is used, as it is the most common descriptor of the internal structure (Heisler and Dewalle, 1988) and relatively easy to determine (Guan et al., 2002; Crow et al., 2007; Yang et al., 2017). Unlike other characteristics (e.g. structure or flexibility), porosity can be generalised across vegetation types or species with values between 0 (completely impermeable) and 1 (completely porous). Optical (P_{2D}) and volumetric/aerodynamic (P_{3D}) porosity can be related to each other: $P_{3D} = P_{2D}^{0.40}$ (Guan et al., 2003), $P_{3D} = P_{2D}^{0.36}$ (Grant and Nickling, 1998).

The drag of vegetation is also considered, which through absorbing momentum from the wind (Finnigan, 2000; Guan et al., 2003; Krayenhoff et al., 2015) can significantly reduce the surface shear stress (τ) (Wolfe and Nickling, 1993), as well as reduce the exchange between in-canopy and above-canopy flow (Gromke and Ruck, 2009; Vos et al., 2013). The drag generated by vegetation (Wyatt and Nickling, 1997; Grant and Nickling, 1998; Gillies et al., 2000, 2002; Guan et al., 2003) and other porous structures (Seginer, 1975; Jacobs, 1985; Taylor, 1988) varies from that of a solid structure with similar geometry. This variation is more complex than can be resolved by a simple reduction of the frontal area (e.g. Taylor, 1988; Guan et al., 2003). Therefore, the changes in drag are directly considered using the drag coefficient.

Typically, morphometric methods use a single drag coefficient for buildings (C_{Db}), whereas here the drag coefficient of vegetation (C_{Dv}) is also used. The nature and type of vegetation (e.g. size, structure,