J. Wind Eng. Ind. Aerodyn. 121 (2013) 98–105

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Observations of wind speed profiles over Greater London, UK, using a Doppler lidar ☆

Daniel R. Drew *, Janet F. Barlow, Siân E. Lane

Department of Meteorology, University of Reading, UK

ARTICLE INFO

Article history:
Received 21 December 2012
Received in revised form
22 July 2013
Accepted 26 July 2013
Available online 1 September 2013

Keywords:
Wind
Urban
Doppler lidar
Internal boundary layer
Roughness length
Morphology
Deaves
Harris
Wind speed profile

ABSTRACT

To calculate the potential wind loading on a tall building in an urban area, an accurate representation of the wind speed profile is required. However, due to a lack of observations, wind engineers typically estimate the characteristics of the urban boundary layer by translating the measurements from a nearby reference rural site. This study presents wind speed profile data obtained from a Doppler lidar in central London, UK, during an 8 month observation period. Used in conjunction with wind speed data measured at a nearby airport, the data have been used to assess the accuracy of the predictions made by the wind engineering tools currently available.

When applied to multiple changes in surface roughness identified from morphological parameters, the non-equilibrium wind speed profile model developed by Deaves (1981) provides a good representation of the urban wind speed profile. For heights below 500 m, the predicted wind speed remains within the 95% confidence interval of the measured data. However, when the surface roughness is estimated using land use as a proxy, the model tends to overestimate the wind speed, particularly for very high wind speed periods. These results highlight the importance of a detailed assessment of the nature of the surface when estimating the wind speed above an urban surface.

1. Introduction

To design tall buildings in urban areas, wind engineers need to calculate the maximum potential wind loading on the structure. This requires an accurate representation of the characteristics of the urban boundary layer (UBL) in strong wind conditions. Several theoretical and empirical models to describe the vertical distribution of mean wind speed have been proposed, the predictions of which are dependent on the characterisation of the underlying surface. However, at present, due to the lack of both observed wind speeds and surface roughness data, there has been limited validation of the models in urban areas.

For a horizontally homogeneous surface, a number of equilibrium wind speed profile models are available; power law, log law and Deaves and Harris model (Davenport, 1960; Simiu and Scanlan, 1996; Deaves and Harris, 1978). However, in urban areas there may be several changes in the nature of the surface within a few kilometres of the site. A number of studies have developed theoretical models which consider the effects of surface heterogeneity. Panofsky and Dutton (1984) and Elliott (1958) considered the growth of a new inner boundary layer at a step change in surface roughness. Deaves (1981) used this concept to extend the applicability of the Deaves and Harris model to heterogeneous terrain. This was subsequently adapted into the UK wind loading code and the ESDU data items (ESDU, 2006; British Standard, 1995).

A number of studies have investigated the characteristics of the boundary layer in various urban areas. Rotach et al. (2005) and Li et al. (2010) investigated the urban wind speed profile over Basel and Beijing respectively using data obtained at various elevations on meteorological masts. However, these observations are confined to heights relatively close to the surface. To detail the wind characteristics for higher altitudes, ground-based remote sensing techniques, such as Doppler Sodar, have been deployed in a number of urban areas. Emeis (2004) investigated the characteristics of the boundary layer up to a height of 210 m agl over Hannover. While, Barlow et al. (2008) observed the wind speed profile up to a height of 110 m above Salford, UK. In addition, Tamura et al. (2001) used observations from a number of Doppler Sodars located at various sites across Tokyo to consider the impact of variations in terrain roughness of the upstream fetch on wind speed profiles. Due to the increased terrain roughness of the upstream fetch, the mean wind speeds at low altitudes measured at a city centre location were lower than those observed at both a coastal and suburban location.

As part of the ACTUAL project (Advanced Climate Technology: Urban Atmospheric Laboratory, 2011) a pulsed Doppler lidar has been installed at a site on Marylebone Road, Greater London, to

* Tel.: +44 11 837 86 010.
E-mail address: d.r.drew@reading.ac.uk (D.R. Drew).

0167-6105/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jweia.2013.07.019

obtain the characteristics of the urban boundary layer. This study presents the wind speed profiles observed during high wind speed periods for a range of wind directions. The objectives of this paper are twofold: (1) to compare the observed wind speed profiles with the predictions of both the equilibrium and non-equilibrium models and (2) to investigate whether a detailed assessment of the urban surface improves the accuracy of the models.

2. Wind speed profile models

For sites with a long fetch over a homogeneous terrain, the boundary layer can be considered to be in equilibrium with the underlying surface. (i.e the wind speed profile does not change as the fetch of upwind uniform terrain increases). Rao et al. (1974) showed that an equilibrium profile is established for a fetch of the order of 100 times the boundary layer height. In practice there are very few sites, where a sufficiently long upwind fetch of uniform terrain occurs for an equilibrium boundary layer to exist. A number of both equilibrium and non-equilibrium wind speed profile models are available, and are reviewed here.

2.1. Power law

The power-law model is an empirical formula for the mean velocity profile, which is based on finding the magnitude of the exponent, α, which provides the best fit of wind speed observations between two heights:

$$U(z_1) = U(z_2)\left(\frac{z_1}{z_2}\right)^{\propto} \tag{1}$$

where $U(z_1)$ and $U(z_2)$ are the wind mean wind speeds at a height of z_1 and z_2 respectively.

Eq. (1) is based on the assumption that the magnitude of the exponent is a constant between the two heights and is only dependent on the roughness of the underlying terrain. In reality however, α varies with wind speed, stability and the height range of the fit. In addition, the power law does not meet the lower or upper boundary conditions. Consequently the model fits best over the range of moderate heights $30 < z < 300$ m Cook (1997).

2.2. Log law

Asymptotic similarity considerations for a neutral boundary layer show that by matching the law of the wall with the velocity defect law in the region where both laws apply (known as the inertial sublayer), the wind speed profile is given by

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where u_* is the surface friction velocity, k is von Karman's constant and z_0 is the surface roughness length. For regions with densely packed surface obstacles, such as vegetation and buildings, the mean flow does not penetrate to the surface; therefore the wind profile is displaced vertically:

$$U(z) = \frac{u_*}{k}\ln\frac{(z-d)}{z_0} \tag{3}$$

where d is the zero plane displacement. Despite being applied to the whole boundary layer, the log wind profile is only valid in the inertial sublayer (ISL). The ISL typically extends from a height of 4–6 times the mean building height to approximately 10% of the boundary layer depth (Ricciardelli and Polimeno, 2006). Tieleman (2008) and Li et al. (2010) showed that the log law does not provide a good representation of the wind speed profile above heights of approximately 200 m.

2.3. Deaves and Harris model

The Deaves and Harris model (DH) meets both the upper and lower boundary conditions and is therefore applicable to the entire boundary layer, not just the surface layer (Deaves and Harris, 1978). The DH wind speed profile is given by

$$U(z) = \frac{u_*}{k}\left[ln\left(\frac{z}{z_0}\right) + 5.75\left(\frac{z}{h}\right) - 1.88\left(\frac{z}{h}\right)^2 - 1.33\left(\frac{z}{h}\right)^3 + 0.25\left(\frac{z}{h}\right)^4\right] \tag{4}$$

where h is the height of the neutral boundary layer

$$h = \frac{u_*}{Bf} \tag{5}$$

where f is the Coriolis parameter and B is an empirical constant estimated to have a magnitude of 6 from observed wind profiles (Tieleman, 2008).

2.4. Roughness change models

Several theoretical methods have been developed to deal with the effects of a heterogeneous surface (Elliott, 1958; Panofsky and Dutton, 1984; Deaves, 1981). When flow encounters a change in surface roughness, a new inner layer develops (known as an internal boundary layer), which propagates upwards through the upstream layer as the downstream distance increases. Such growth was observed using Doppler Sodars in Tokyo (Tamura et al., 2001). Elliott (1958) showed that the depth of the IBL, δ, can be derived from

$$\delta(x) = 0.28 z_{02}\left[\frac{x}{z_{02}}\right]^{0.8} \tag{6}$$

where x is the distance from the roughness change boundary and z_{02} is the roughness length of the downstream surface. Above δ, the wind speed is independent of x and equal to the value given by the equilibrium profile (at the same height) just upwind of the roughness change.

Mertens (2003) and Heath et al. (2007) assumed that within the IBL, there is an equilibrium log law wind profile, governed by the nature of the new surface. By equating the upstream and downstream wind speed at δ, the wind speed, U at a height of z above the downstream surface can be expressed as

$$U(z) = \frac{\left(\ln\left[\frac{\delta-d_1}{z_{01}}\right]\ln\left[\frac{z-d_2}{z_{02}}\right]\right)}{\left(\ln\left[\frac{z_A-d_1}{z_{01}}\right]\ln\left[\frac{\delta-d_2}{z_{02}}\right]\right)}U_A(z_A) \tag{7}$$

where z_{01} and z_{02} are the roughness lengths and d_1 and d_2 are the displacement heights of the upwind and downwind surfaces respectively and U_A is a reference upwind rural wind speed U_A, (measured at a height z_A).

Deaves (1981) developed a method to deal with the non-equilibrium effects based on a solution of the full elliptic form of the Navier–Stokes equations, which is obtained using a simple eddy-viscosity closure assumption. This solution is consistent with the Deaves and Harris equilibrium wind speed profile (Eq. (4)) when $x \to \infty$. Deaves (1981) applied the method to a wide range of surface roughness changes and collapsed the results onto a series of curves. These curves were fitted with simple equations which are used in the ESDU 82026 to directly estimate the boundary layer velocity profile for a distance x from a roughness change.

Both the equilibrium internal boundary layer method (Eq. (7)) and the Deaves (1981) model enable the wind speed profile downstream of a step change in roughness to be estimated from a wind speed measured at a single height above the upwind surface. However, several changes in roughness typically occur upwind of an urban site. By assuming the growth of a new internal