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Estimation of roughness length at Hong Kong International Airport via different micrometeorological methods

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ABSTRACT

Aerodynamic roughness length scale (z_0) is an essential parameter for the parameterization of momentum flux exchanges at land-atmosphere interface. In this paper, several micrometeorological methods are applied for estimation of z_0 based on wind measurements at Hong Kong International Airport (HKIA). The concepts of source area and internal boundary layer are adopted to better understand the measurement results. The validity and prediction accuracy of the estimation methods for z_0 are examined and discussed. A map of terrain roughness at HKIA is established.

1. Introduction

Surface roughness is an aerodynamic property of the earth, which is related to surface coverage, surrounding obstructions, topographic relief, and so on. It serves continuously as a momentum sink for the atmospheric flow (Wieringa, 1993), and plays an important role in governing wind structures within the atmospheric boundary layer (ABL) (Garratt, 1994). Conventionally, surface roughness can be best indexed by the aerodynamic roughness length z_0 which is regarded as an empirical measure of retarding/disturbing effects that the surface has on near-ground winds. This parameter is essential for the parameterization of momentum flux exchange at land-atmosphere interface, and accurate determination of its value has been identified as a key issue in a wide range of applications in wind engineering, such as determination of design wind loads on structures (Irwin, 2006), estimation of diffusion of pollutant plumes (Wong and Liu, 2013), numerical simulation of environmental problems (Blocken et al., 2007), mathematical modelling of wind field (Meng et al., 1995), assessment of wind energy potential (Emeis, 2014), etc. Surface roughness length is also of great importance to convert wind speeds associated with different terrains, measurement heights or averaging periods, and to better understanding of site-specific measurements of surface wind (Powell and Houston, 1996; Verkaik, 2000; Vickery and Skerlj, 2005; Harper et al., 2010; Masters et al., 2010a, 2010b; Balderrama et al., 2011; Miller et al., 2015; He et al., 2014a, 2016).

Several methods have been developed for the estimation of z_0. These methods can be categorized into three groups: micrometeorological (or anemometric) methods (Verkaik, 2000; Powell et al., 2003; Masters et al., 2010a), classification methods (Davenport, 1960; Wieringa, 1992, 1993), and morphometric (or geometric) methods (Lettau, 1969; Grimmond and Oke, 1999). Since morphometric methods are usually only applicable for built-up terrains, which will not be considered in this study.

Micrometeorological methods are driven by wind measurements. Commonly adopted micrometeorological methods include profile method, variance method and gustiness method. Among these methods, profile method requires mean speed records collected at multiple height levels, while variance and gustiness methods need turbulence measurements recorded at a single level. Details about these methods will be discussed in the following section.

Classification methods rely on existing knowledge of z_0 associated with a group of basic terrain classes. The roughness length for a given terrain can be subjectively assessed using roughness classes and visual estimation. The problem is that roughness length suggested in different literature for the same terrain type may vary distinctly. Wieringa (1992, 1993) reviewed 30 years' roughness data from boundary-layer measurements and compared 5 popular classifications of roughness. It was found that the local-scale classification of Davenport, (1960) is reliable, provided that the lowest two roughness classes are adjusted. Table 1 lists

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Table 1

Davenport classification of effective terrain roughness.

Class		Landscape description	$z_0(m)$
1	Sea	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers	0.0002
2	Smooth	Featureless land surfaces without any noticeable obstacles and with negligible vegetation; e.g., beaches, pack ice without large ridges, marsh, and snow-covered or fallow open country.	0.005
3	Open	Level country with low vegetation (e.g., grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g., grazing land without windbreaks, heather, moor and tundra, runway area of airport. Ice with ridges across-wind.	0.03
4	Roughly open	Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g., low hedges, isolated low buildings or trees) at relative horizontal distances of at least 20 obstacle heights	0.10
5	Rough	Cultivated or natural area with high crops or crops of varying heights, and scattered obstacles at relative distances of 12–15 obstacle heights for porous objects (e.g., shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g., buildings) (analysis may need z_d)	0.25
6	Very rough	Intensively cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bushland, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3–7 building heights and no high trees (analysis requires z_d)	0.5
7	Skimming	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle height; e.g., mature regular forests, densely built-up area without much building height variation (analysis requires z_d)	1.0
8	Chaotic	City centers with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings (analysis by wind tunnel advised)	≥2

the updated version of Davenport's classification (Davenport et al., 2000) that is recommended by World Meteorological Organization (WMO, 2008). One may refer to Stewart and Oke (2012) for further information to better understand the Davenport's classification.

Given the important role of z_0 in governing the ABL and the diversity of estimation methods for z_0, there is a need to assess the prediction performance of different approaches. However, such works especially those concerning varied micrometeorological methods are limited, as wind measurements required for such comparisons are rarely available. Among few related studies, Barthelmie et al. (1993) compared the prediction results by using classification method, profile method, gustiness method and speed-variance method. Considerable method-related variations in z_0 were reported, with estimations in the same azimuth sector varying by a factor of as much as 20. Verkaik and Holtslag (2007) analyzed the roughness length using three micrometeorological methods. It was reported that under inhomogeneous conditions, the profile method might be invalid and estimation results of z_0 via different wind-turbulence based methods differed evidently. It is further noteworthy that most estimation methods for z_0 may suffer from significant uncertainty. Verkaik (2000) evaluated the performance of two gustiness methods and found that different parametric settings in the models could result in great discrepancy of estimation results.

The motivation of this study is twofold: First, to assess the performance of several roughness estimation methods through cross comparison analysis of the results from these methods; Second, to explore the characteristics of surface wind at Hong Kong International Airport (HKIA) and determine associated roughness length so as to advance wind shear alerting for aircraft operation at the airport.

The remainder of this paper is organized as follows. Section 2 introduces the estimation methods considered in this paper. Section 3 describes the observation sites and datasets of wind measurements. The estimation results are presented in Section 4. Conclusions and main findings of this study are summarized in Section 5.

2. Introduction of estimation methods

2.1. Source area and internal boundary layer

Due to adoption of wind measurements, z_0 derived via micrometeorological methods depends on both surface covers and arrangement of measurement systems. It is stressed that a device placed above a site explores only a portion of its surroundings. Meteorologically, the portion of upstream surface that contains the effective sources contributing to the flux exchanges at the concerned site is termed as the source area (or footprint). A large source area accounts for a large-scale average of surface properties. The source area is a function of observation height, stability condition, and surface roughness (Schmid and Oke, 1990). For wind measurement, it is elliptical in shape and is aligned in the upwind direction (~30° in width) from the concerned site (WMO, 2008). Under neutral condition the area with significant contribution to measurements atop a typical mast lies upwind at a distance of several kilometers, while increasing instability reduces the source area to a region closer to the concerned site.

In principle, terrain classifications are established for uniform terrains. In reality, however, it is not uncommon to encounter terrain changes in an area at a scale larger than several hundreds of meters. Under such heterogeneous conditions, wind structures are dominated by both local (or new) surface and upwind (initial) exposure. Internal boundary layer (IBL) will be formed at the interacting area where atmospheres gradually adapt to the new surface (Garratt, 1990). The IBL depth h_I varies with the distance downwind of fetch change x (Powell and Houston, 1996):

$$h_I = cz_{0R}(x/z_{0R})^{0.8} \tag{1}$$

where c (0.28–0.75) is a constant that depends on stability status ($c \approx 0.3$ under neutral condition), z_{0R} is the larger value of roughness length of new and initial fetches. Wind structures above h_I are governed by upwind surface cover, while those below $0.1h_I$ are completely adjusted to the new terrain. Wind flows in the middle region demonstrate a blended feature that is influenced by both initial and new terrains: while small eddies are dominated by the immediate action of local obstructions, large eddies exist in accordance with large-scale terrain setups.

For an area with evident variation of terrain setups, the effective roughness length, i.e., the roughness length producing a representative momentum flux for the concerned area (Fielder and Panofsky, 1972), may be estimated by analyzing wind measurements recorded at the blending height, i.e., the height at which the flow is approximately in equilibrium with the local surface and also independent of horizontal position (Mason, 1988). Alternatively, it may be estimated by averaging $\ln(z_{0i})$ (called the $\ln(z_0)$ avearage method hereafter), z_{0i} being the roughness length of each small-scale homogeneous patch (WMO, 2008). But the effective roughness length tends to be larger than the average of z_0 values of all patches, due to the fact that it is easier to charge the atmosphere with turbulence than to discharge it by dissipation (Wieringa, 1993). Thus, the values of z_0 listed in Table 1 constitute a lower limit of effective roughness that can occur in terrain situations where such surface cover is dominant.

2.2. Wind profile based method

Within the surface layer of neutrally stratified atmosphere, vertical profiles of horizontal mean wind speed can be depicted by the logarithmic law: