Wind velocity profile observations for roughness parameterization of real urban surfaces

Jongyeon Lim[1], Ryozo Ooka[2], Hideki Kikumoto[3]
[1] *Institute of Industrial Science, The University of Tokyo, Japan, jylim@iis.u-tokyo.ac.jp*
[2] *Institute of Industrial Science, The University of Tokyo, Japan, ooka@iis.u-tokyo.ac.jp*
[3] *Institute of Industrial Science, The University of Tokyo, Japan, kkmt@iis.u-tokyo.ac.jp*

dated : 29 June 2015

1. Introduction

The wind velocity u with height in purely mechanical turbulence can be derived from the logarithmic law described in Eq. (1), allowing estimation of two major roughness parameters, which are the aerodynamic roughness length z_0 and displacement height d.

$$u = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right) \qquad (1)$$

where u is the observed mean wind velocity, u_* is the friction velocity, z is the observation height, and κ is the von Karman constant.

Conventional roughness parameterizations for urban surfaces, e.g. Macdonald et al. (1998) and Kanda et al. (2013), have typically used urban morphological parameters such as the building plan area fraction (i.e., the ratio of the plan area occupied by buildings to the total surface area), the frontal area index (i.e., the total area of buildings projected into the plane normal to the approaching wind direction), and the building height information. Particularly, Theurer (quoted in Macdonald et al., 1998) noted z_0 is related primarily to the frontal area index, while d is mainly a function of the building plan area fraction. The value of this urban morphological parameters for a real urban area appears to be various, implying that there is potential for the roughness parameters to vary with the wind direction. However, few have attempted to consider real urban areas, fewer still have considered the role of wind direction.

In the present study, we conducted observation of the wind profile for seven months above a high-density area in Tokyo, Japan, using a Doppler LIDAR system (DLS). The observation results provide a database of the wind velocity for 24 altitude, from which we estimated roughness parameters for each wind direction. This paper shows the difference of roughness parameters according to wind direction, which described by different urban morphological characteristics.

2. Observation of wind velocity profile using Doppler LIDAR system

The wind velocity profile data used here were collected from a DLS (WindCube8, manufactured by LEOSPHIERE) that was setup on the rooftop of the Institute of Industrial Science of the University of Tokyo, Japan (35°39'46"N, 139°40'41"E, 27.5 m altitude). The field of about 1-km radius surrounding the DLS is comparatively flat for building morphology, and is mainly occupied by residential housing with varying heights of 3–9 m (73.8%), and a few buildings with heights over 30 m (0.5%). The mean height of the roughness elements is about 7 m, and the standard deviation of the heights of the roughness elements is about 4 m. By comparison, the topographic elevation difference within the field of about 1-km radius surrounding the DLS reaches 30 m (high in northwest and low in southeast).

The observations were conducted from September 2013 to December 2013, and from April 2014 to June 2014. The DLS used in this observation transmits a pulsed laser with a wavelength of 1.54 μm, receives the light backscattered by aerosols such as dust and other particles in the air, and measures the line-of

-sight component of wind velocity using the Doppler frequency shift of the backscattered light. The orientation of transmission changes in the four cardinal directions, so that three components of wind velocity can be calculated. Using this DLS, the wind velocity data from 67.5 m to 527.5 m (20 m apart, 24 altitudes) were obtained with a temporal resolution of about 30 seconds.

The vertical component of measured wind velocity is one or more orders of magnitude smaller than the horizontal components. Hence, this analysis applies only to the horizontal components. We use wind velocity in this paper to refer to the scalar quantity of the horizontal velocity components. Additionally, when the wind speed is small, the wind direction fluctuates significantly and the statistics becomes unsteady (Liu et al., 2009); thus data for wind velocity < 5m/s are not used.

3. Atmospheric neutrality

The logarithmic wind profile is often called the neutral wind profile, because when convection is negligible, the lapse rate is nearly adiabatic, and the stratification is nearly hydrostatically neutral (Panofsky and Dutton, 1984). In this paper, the data for neutral atmospheric condition was filtered from the entire DLS observation data using atmospheric stability statistics which were obtained from eddy covariance method (ECM). National Defense Academy of Japan (Prof. Hirofumi Sugawara) provided the ECM observation data used in this analysis. The data contains the wind velocity, momentum flux, and heat flux collected from the ultrasonic anemometer at the 52 m level of the broadcast tower, which is located about 600 m east-northeast direction of DLS. We used the value of $1/L$ as a parameter which represents atmospheric stability, where L is the Monin−Obukhov length.

The wind direction is defined as the clockwise azimuth from due north and the wind directions are divided into 16 sectors with an interval of 22.5°, which are numbered 1 (N), 2 (NNE), 3 (NE), ..., and 16 (NNW) in turn. $1/L$ was divided into data bins with an increment of 0.00125. We estimated roughness parameters z_0 and d from the mean wind velocity profiles within each data bin. Estimation method is the conventional two-parameter fitting of z_0 and d using the least-squares method with the von Karman constant of 0.4. Although the logarithmic fitting region varies according to the surface geometry, all fitting in this study were performed for the level between 67.5 m and 147.5 m. Furthermore, we calculated the root-mean-square error of parameter fitting as defined in Eq. (2),

$$RMSE = \sqrt{\frac{1}{N_z}\sum_{k=1}^{N_z}\left(\langle u(z_k)\rangle - \frac{u_*}{\kappa}\ln\left(\frac{z_k - d}{z_0}\right)\right)^2} \quad (2)$$

and then, we estimated the fitting accuracy of the logarithmic wind profile using *RMSE* normalized with the wind velocity at 67.5 m, hereafter called E_n.

$$E_n = \frac{RMSE}{u_{67.5}} \quad (3)$$

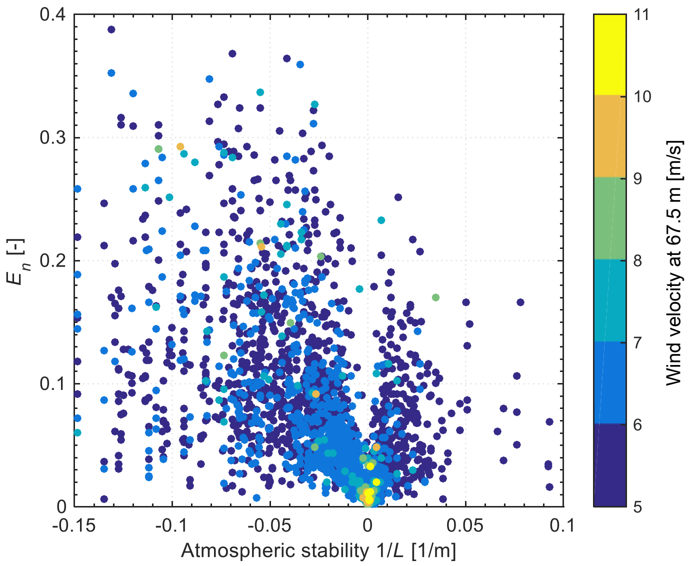


Fig. 1. The relation between the fitting accuracy of the logarithmic wind profile (E_n) and atmospheric stability (1/L).

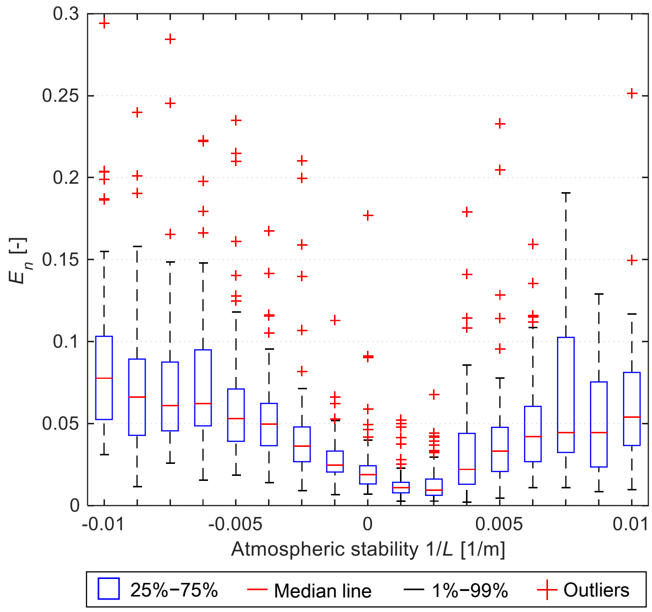
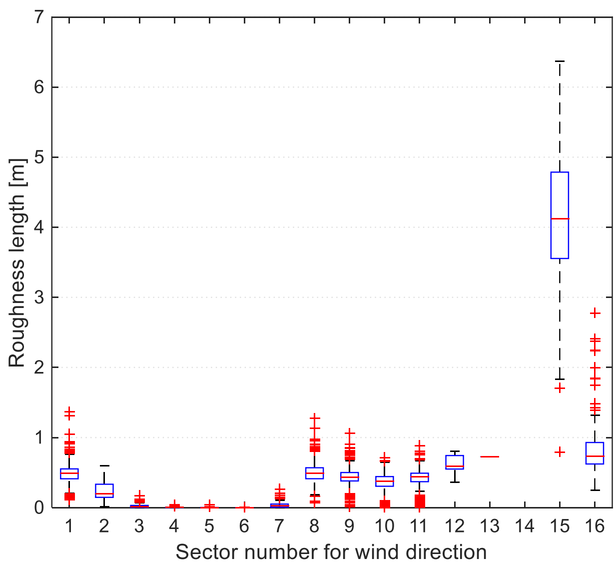


Fig. 2. Variations of E_n for the range of 1/L from −0.01 to 0.01.

Estimation of roughness parameters in next section were performed for 1/L between −0.0025 and 0.005, where 25−75% of E_n < 0.05. In other words, we provided that that range is under neutral atmospheric condition, and which shows good agreement with Golder (1972).

4. Results: estimation of roughness parameters

Data under neutral atmospheric condition were re-classified with the wind directions. We estimated roughness parameters z_0 and *d* from a 30−min ensemble average profiles of each data bin. Estimation results of roughness parameters shows the variations of z_0 and *d* are different when the flow is from different wind directions as shown in Fig. 3. z_0 and *d* is relatively small in sectors 3–7. In sectors 8–11, z_0 is 0.37–0.49 m whilst it is < 0.03 in sectors 3–7. This may be due to the fact that the morphological characteristics are different in different sectors. We have not investigated sectors 12–15 because of lack of data (see Fig. 4)



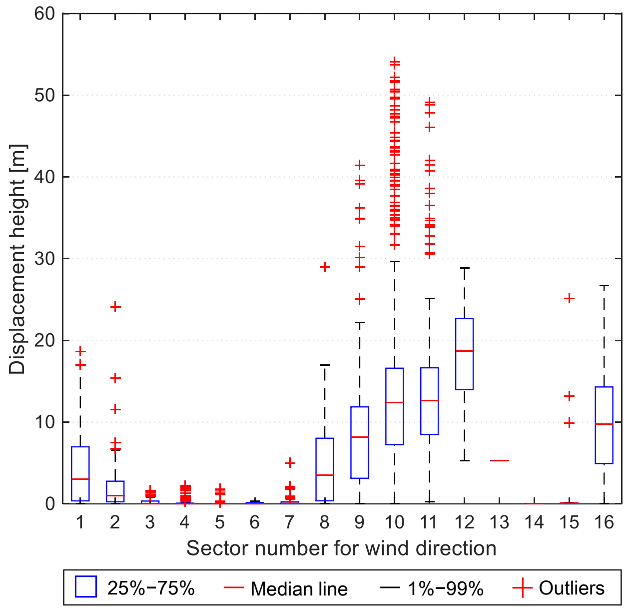


Fig. 3. Variation of the roughness length and displacement height for different sectors of wind direction.

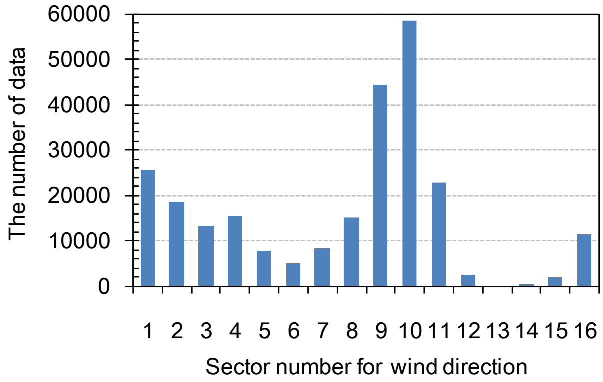


Fig. 4. The number of data under neutral atmospheric condition for each sector

Fig. 5 shows aerial photograph of the study area. The centre of the circle is the location of DLS. The radius of the circle is 2 km. In sectors 3–7, the campus of the university of Tokyo is sited in 1 km (A in Fig. 5), which results in low building plan area as presented in Fig. 6. However, since the campus is sited in sectors 5–7, this does not seem to be sufficient to explain a low level of z_0 and d in sector 3–4. If we widen the roughness source area to 2–3 km, large open space is sited in sectors 3–4 (B in Fig. 5). This fact results in low level of building plan areas and frontal areas in sectors 3–7, and may have influence on low level of roughness parameters in sectors 3–7. However, in sector 5–6, although high rise buildings is located in 2 km (C in Fig. 5), it seems to have no significant influence on roughness parameters in sector 3–7. We think the definition of the roughness 'source area' significantly impacts on roughness parameterizations for urban surfaces which used urban morphological parameters.

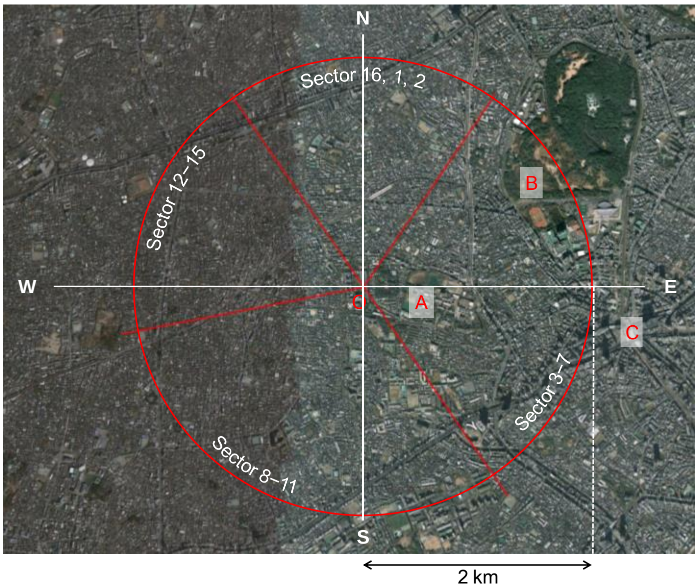


Fig. 5. Aerial photograph of the study area.(From Google Earth)

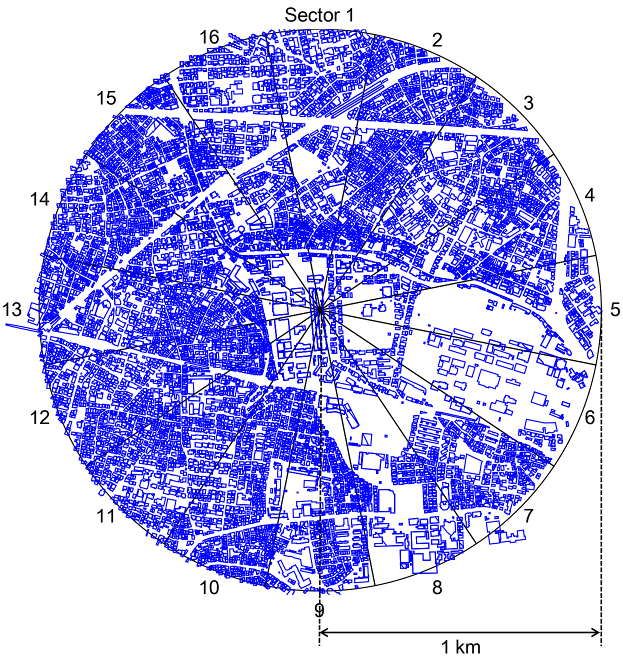


Fig. 6. Building foot prints in the study area.

Acknowledgment

A part of this study was supported by JSPS KAKENHI Grant Number 25-03368, 24226013, and 26709041. This financial contribution is highly appreciated. The authors also acknowledge Prof. Hirofumi Sugawara of National Defense Academy of Japan, for making the observation data available.

References

Golder D., 1972: Relations among stability parameters in the surface layer. *Boundary-Layer Meteorology*, **3**, 47–58

Kanda M., Inagaki , A., Miyamoto T., Gryschka M., Raasch S., 2013: A New Aerodynamic Parametrization for Real Urban Surfaces. *Boundary-Layer Meteorology*, **148**, 357–377

Liu G., Sun J., Jiang W., 2009: Observational verification of urban surface roughness parameters derived from morphological models. *Meteorological Applications*, **16**, 205–213

Macdonald R., Griffiths R., Hall D., 1998: An improved method for the estimation of surface roughness of obstacle arrays. *Atmospheric Environment*, **32**, 1857–1864

Panofsky H., Dutton J., 1984: Atmospheric turbulence: models and methods for engineering applications. *John Wiley & Sons*.