August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering

Application of Deaves and Harris model for complex heterogeneous terrain

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SUMMARY:
This study performs the BLWT testing for 60 high-complex heterogeneous terrains obtained from real US sites using Terraformer. The mean wind speed profiles for the 60 sites are predicted using the Deaves and Harris model. This study has three main contributions; First, BLWT testing results under 60 sites in the real world are obtained. These data can be used for extensive studies for quantifying the effects of high-complex heterogeneous terrains on boundary layer profiles. Second, the applicability of the Deaves and Harris model for predicting high-complex heterogeneous terrain is confirmed. Third, the minimum patch size in the cross-wind direction is determined for reasonable accuracy of mean wind speed profile prediction based on the parametric study.

Keywords: Boundary Layer Profile, High-complex heterogeneous terrain, Deaves-Harris model

1. INTRODUCTION

The terrain configuration is usually non-homogeneous exposure. Neglecting small-scale roughness change may lead to errors that cannot be ignored in estimating wind load (Schmid and Bünzli, 1995). Thus, many studies have been performed to understand and predict the effect of heterogeneous terrain on the wind speed profile (Cook, 1997, Deaves and Harris, 1978, Kent et al., 2018, Wang and Stathopoulos, 2007, Yu et al., 2021). However, in-depth investigations for the effect of complex heterogeneous terrain on boundary layer profiles are still insufficient.

Recently, the University of Florida equipped the new BLWT with a fully-automated terrain simulator, "Terraformer" (Masters, 2017). This equipment enables us to perform extensive cases of heterogeneous terrain quickly and accurately and accumulate data even with less labor.

The BLWT testing was performed with Terraformer for 60 complex heterogeneous terrains obtained from real US sites. The mean wind speed profiles were predicted using the Deaves and Harris (DH) model (1978). This study has three main contributions; First, BLWT testing results under 60 sites in the real world are obtained. These data can be used for extensive studies for quantifying the effects of complex heterogeneous terrains on boundary layer profiles. Second, the applicability of the DH model for predicting complex heterogeneous terrain is confirmed. Since this model has been applied mainly to simple heterogeneous terrains, additional procedures were developed for application to complex heterogeneous terrains. Third, the optimal patch width in the cross-wind direction is determined based on the parametric study.

2. WIND TUNNEL TESTING UNDER COMPLEX HETEROGENEOUS TERRAIN

2.1. 50 complex heterogeneous terrains

We trained a Convolutional Neural Network (CNN) using 529 sites from 32 US states prone to hurricane events. The input was Landsat 8 images which provide satellite images of the earth's surface with sufficient resolution to show different land cover types. Each image covered an area of 3,840 m × 3,840 m. The National Land Cover Database (NLCD) dataset that labels different land cover types into 20 categories was used to train the network. The CNN achieved an accuracy of 90% after 20 epochs. Each labeled image is divided into four wind tunnel-size images (1,860 m × 540 m). Thus, 529×4 = 2,116 wind tunnel-size labeled images are produced. Next, we converted the land coverage labels to the corresponding roughness length values and plotted all the images into 2D space using the mean and standard deviation. Finally, we used the k-means algorithm to cluster the 2,116 images and select 50 as diverse as possible out of 2,116 images.

2.2. Wind tunnel testing

Terraformer is an 18 × 62 roughness element staggered in the area of 6.1 m × 18.6 m to simulate the real-world upwind terrain. An actuator beneath each roughness element in the Terraformer can independently reconfigure the height and facing surface of elements. Roughness elements have 10 cm × 5 cm plan dimensions, and their height changes from 0 to 16 cm. Figure 1 shows the schematic plan of the BLWT facility containing Terraformer. The length scale is 1:50.

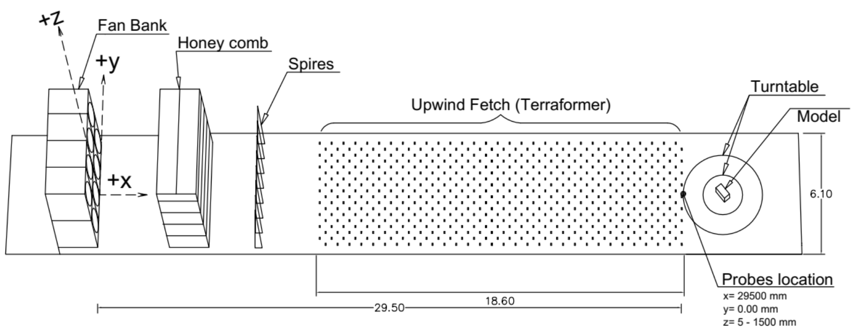

Figure 1. Schematic plan of BLWT facility in the University of Florida

3. MEAN WIND SPEED PROFILE PREDICTION

3.1. Theoretical background

The BLWT testing results are compared with prediction results using the DH model. The DH model for the characteristics of the boundary layer was developed in two stages. First, a model for the boundary layer in equilibrium over flat homogeneous roughness was developed. Second, the model was developed to account for multiple-step changes in surface roughness (Cook, 1997). The detailed procedure is described in Deaves and Harris (1978). The logarithmic wind law (Blackadar and Tennekes, 1968) in Eq. (1) is used for the boundary layer profile in the equilibrium of homogeneous conditions.

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

where $U(z)$ is the mean along-wind speed at height z, κ is von Karman's constant (=0.40), u_* is the friction velocity, z_0 is the aerodynamic roughness length, and d is the zero-plane displacement. These aerodynamic roughness parameters (ARPs), u_*, z_0, and d, were calculated in advance based on the BLWT testing results on uniform terrain while changing block height (H), as shown in Figure 2. The BLWT testing-based ARP calculation method is described by Catarelli et al. (2020).

The fully-automated prediction process is developed for DH model-based mean wind speed profiles under complex heterogeneous terrain. First, H maps of the terrains are transformed to z_0 maps based on the results in Figure 2. Second, the coefficient of variation (COV) of the z_0 maps is calculated. If COV is less than 0.25, the terrain is considered homogeneous. If COV exceeds 0.25, it is additionally checked whether there is an extreme z_0 changepoint in the along-wind direction. For this check, a linear computational cost-based optimal detection algorithm is used (Killick et al., 2012). If there is an extreme changepoint, the terrain is considered to contain a transition. Otherwise, the terrain is considered to be homogeneous terrain as like the terrain whose COV is less than 0.25. Third, the effective z_0s for each patch are calculated using a grid-squared average-based approach (Taylor, 1987). Lastly, the boundary layer profiles are predicted using DH model.

3.2. Prediction results

The results at site 8 are shown as a representative case in Figure 3. The site has a transition point at approximately 700 m, as shown in (a) and (b) of Figure 3. The transition region in the DH model can be calculated using information such as downwind length and effective z_0 values for each patch. The prediction result shows good agreement with the testing result.

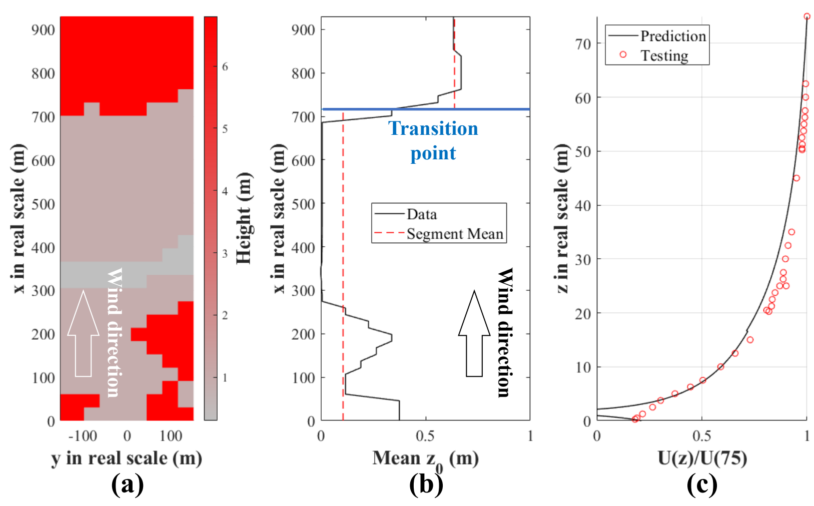

Figure 2. Results for site 8: (a) Terrain morphology; (b) Mean z_0 in x-direction; and (c) Comparison of boundary layer profiles between prediction and testing results

3.3. Parametric study

The cross-wind patch width (y-direction) was reduced, and the prediction results using the reduced patch were compared with the testing results, as shown in Figure 3. The difference is minimized when 20 to 25% of the width in front of the measurement point is used.

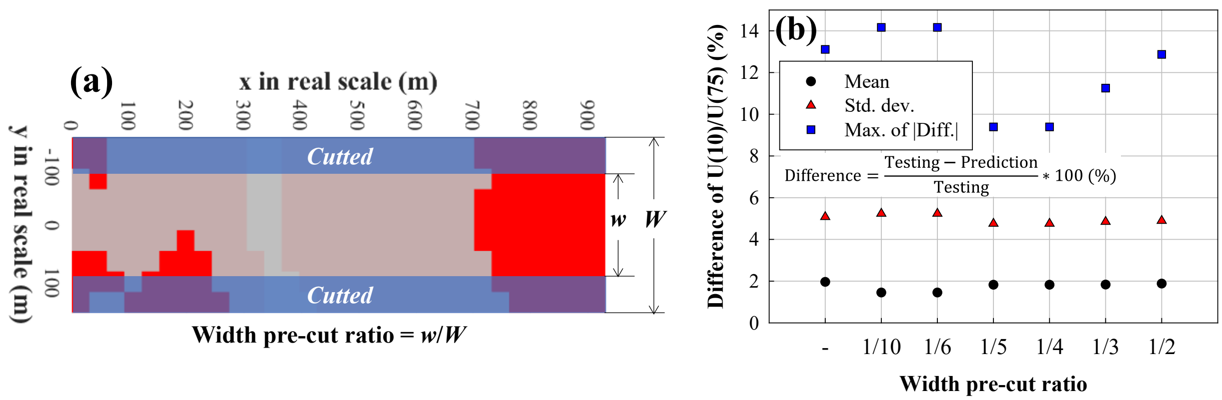

Figure 3. Parametric study: (a) Definition of width pre-cut ratio; and (b) Results

4. CONCLUSIONS

BLWT testing results under 60 sites in the US were obtained. Also, the applicability of the DH model for predicting complex heterogeneous terrain was confirmed. The procedure was developed to apply the DH model to complex heterogeneous terrains. As the results of parametric study, the optimal patch width in the cross-wind direction is determined as 20-25 %.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1856205. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Blackadar, A. K. and H. Tennekes. 1968. Asymptotic similarity in neutral barotropic planetary boundary layers. Journal of the Atmospheric Sciences 25(6), 1015-1020.

Catarelli, R., P. Fernández-Cabán, F. Masters, J. Bridge, K. Gurley and C. Matyas. 2020. Automated terrain generation for precise atmospheric boundary layer simulation in the wind tunnel. Journal of Wind Engineering and Industrial Aerodynamics 207, 104276.

Cook, N. J. 1997. The Deaves and Harris ABL model applied to heterogeneous terrain. Journal of wind engineering and industrial aerodynamics 66(3), 197-214.

Deaves, D. M. and R. I. Harris. 1978. A mathematical model of the structure of atrong winds. CIRIA Report 76, Const Ind. Research and Inf. Assoc.

Kent, C. W., C. S. B. Grimmond, D. Gatey and J. F. Barlow. 2018. Assessing methods to extrapolate the vertical wind-speed profile from surface observations in a city centre during strong winds. Journal of Wind Engineering and Industrial Aerodynamics 173, 100-111.

Killick, R., P. Fearnhead and I. A. Eckley. 2012. Optimal detection of changepoints with a linear computational cost. Journal of the American Statistical Association 107(500), 1590-1598.

Masters, F. J., 2017. Boundary Layer Wind Tunnel, Basic Operations Manual. Gainesville, FL, University of Florida.

Schmid, H. and B. Bünzli. 1995. The influence of surface texture on the effective roughness length. Quarterly Journal of the Royal Meteorological Society 121(521), 1-21.

Taylor, P. A. 1987. Comments and further analysis on effective roughness lengths for use in numerical three-dimensional models. Boundary-layer meteorology 39(4), 403-418.

Wang, K. and T. Stathopoulos. 2007. Exposure model for wind loading of buildings. Journal of Wind Engineering and Industrial Aerodynamics 95(9-11), 1511-1525.

Yu, J., M. Li, T. Stathopoulos, Q. Zhou and X. Yu. 2021. Urban exposure upstream fetch and its influence on the formulation of wind load provisions. Building and Environment 203, 108072.