Journal of Wind Engineering & Industrial Aerodynamics 175 (2018) 65–76

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

A hybrid approach for evaluating wind flow over a complex terrain

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ARTICLE INFO

Keywords:
Complex topography
Hybrid approach
WindEEE
Design wind speeds
Building codes

ABSTRACT

Wind speeds over a complex terrain were estimated using a hybrid approach consisting of numerical and large scale wind tunnel simulations. Numerical simulations were performed to identify three critical wind directions out of 12 different wind directions (0°–330° at 30° intervals). These simulations provided the inflow conditions for the wind tunnel tests since the area of topography modeled in the numerical simulation was much larger compared to the wind tunnel test model. Wind tunnel tests were conducted at the state-of-the-art wind testing facility, the Wind Engineering, Energy and Environment (WindEEE) Dome, where the multi-fan (60 fans) inlet facilitated replication of the inflow as determined by the numerical simulations for each of the three critical wind directions. Mean and 3-s gust wind speeds were calculated at 17 different locations on the topography for each of the three critical wind directions. Speed-Up factors at each location were obtained for the most conservative wind speed and then compared with the speed-up factors recommended by the National Building Code of Canada. In general, the building code over-predicted the speed-up factors on the complex topography investigated in the present study.

1. Introduction

Building codes, such as ASCE-7 (ASCE 7-16, 2017), NBCC (NBCC 2015, 2016) or AS/NZS 1170.2 (AS/NZS 1170.2:2011), provide guidelines to estimate wind speed over isolated hills, ridges and escarpments. In nature, an isolated hill in a large terrain with homogeneous roughness is a rare phenomenon and usually a hill is surrounded by other hills in the vicinity. In that respect, Miller and Davenport (1998) studied the wind flow over an array of symmetrical sinusoidal ridges as well as real complex terrain using 2D models in wind tunnel. When compared with building codes, Miller and Davenport (1998) reported that the building codes would lead to conservative results as the codes overpredict the wind speed-up over the hills. Same conclusion as Miller and Davenport (1998) was also drawn by Bitsuamlak et al. (2004). As a result, a number of detailed and comprehensive studies have been conducted to evaluate wind velocities and turbulence intensities in a complex terrain from the perspective of wind energy (Ayotte et al., 2001; Rasouli and Hangan, 2013; Mattuella et al., 2016; Lange et al., 2017), structural loading (Miller and Davenport, 1998; Bitsuamlak et al., 2007; Zhao et al., 2015; Cheynet et al., 2016) and pollutant dispersion (Cermak, 1984; Tong et al., 2005).

Both numerical and experimental approaches have been adopted to study the wind flow over complex terrains. Due to the rapid advancements of computer performance, numerical simulations has been gaining popularity within the wind engineering community (Blocken, 2014). Numerical simulations have the advantages of providing high resolution flow field information and performing parametric analysis at low cost. Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES) based Computational Fluid Dynamics (CFD) modelling approaches are widely used for simulating wind flow over complex topographic terrain.

Kim et al. (2000) performed steady state numerical simulation of wind flow over four different hilly terrains with standard $k-\varepsilon$ and renormalization group (RNG) $k-\varepsilon$ turbulence models. Mean wind speeds and flow separation lengths were compared with the available field data. In general, RNG $k-\varepsilon$ performed better compared to Standard $k-\varepsilon$ turbulence model. Inclusion of neighboring hills in the domain improved the prediction of the three dimensionality of the flow. Loureiro et al. (2008) also carried out steady state numerical simulations to evaluate the performance of six different turbulent models for flow over a steep hill. The turbulence models were standard $k-\varepsilon$, RNG $k-\varepsilon$, standard $k-\omega$, shear stress transport (SST) $k-\omega$, Speziale-Sarker-Gatski Reynolds stress model (SSG-RSM) and baseline $-\omega$ RSM. Out of all these six turbulence models, SST $k-\omega$ gave the best prediction for mean velocity and wall shear stress. Abdi and Bitsuamlak (2014) conducted numerical simulations on idealized and real topographic features using

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https://doi.org/10.1016/j.jweia.2018.01.037
Received 29 September 2017; Received in revised form 22 January 2018; Accepted 24 January 2018

steady state solver with various turbulence models (mixing-length, standard $k-\varepsilon$, RNG $k-\varepsilon$ and realizable $k-\varepsilon$) as well as transient solver with Smagorinsky LES. The study showed that all models predicted the speed-up factors adequately on the upstream side of the hill. However, on downstream side of the hill, the mixing-length model under-predicted the recirculation zone, RNG $k-\varepsilon$ and realizable $k-\varepsilon$ gave better estimates compared to standard $k-\varepsilon$ turbulence model. Model scale LES without wall function performed better compared to full scale LES with wall functions. Although the steady state numerical models are better at predicting mean flow field, they do not provide any transient flow properties which is essential to estimate peak wind loads on structures. On the other hand, one of the major challenges with the transient numerical models such as LES is to generate the time dependent inflow boundary conditions with the appropriate turbulence characteristics (Tutar and Celik, 2007; Tabor and Baba-Ahmadi, 2010; Aboshosha et al., 2015).

With regards to estimating peak wind loads, wind tunnel experiments are more reliable compared to the numerical simulations. Building codes (e.g., ASCE 7-16, 2017) also recommends using wind tunnel test for estimating wind loads where the provisions in the code is inadequate. From the structural loading perspective, simulating the time dependent inflow condition is of utmost importance to estimate the peak wind loads. Both point (Miller and Davenport, 1998; Mattuella et al., 2016) and area measurements (Rasouli et al., 2009; Lange et al., 2017) were performed to estimate wind speeds over complex topographic terrains in wind tunnels. Miller and Davenport (1998) performed wind tunnel experiment to calculate wind speed-up over several two dimensional complex terrains. Two different incoming wind profiles with aerodynamic roughness length (z_0) of 1.6×10^{-1} mm and 3.5×10^{-2} mm were employed. The study clearly pointed out that the speed-ups in complex terrain were reduced when compared with those for isolated hills or ridges. Mattuella et al. (2016) also carried out wind tunnel experiments with point velocity measurements over a complex terrain in Espirito Santo, Brazil. Two different incoming profiles with power law exponent of 0.11 (sea and lakes) and 0.23 (city center) were employed. Velocities at different locations over the terrain were measured using a hot wire anemometer for wind turbines micrositing.

For measurements over a large area for overall flow structures and continuous wind information, Particle Image Velocimetry (PIV) is sometimes employed. Rasouli et al. (2009) performed PIV experiment in a boundary layer wind tunnel for three horizontal planes and one vertical plane over a terrain in Hong Kong. Inflow velocity profiles were not reported in the study. Lange et al. (2017) also used PIV in a vertical plane over a scaled model of Bolund peninsula in Denmark. The testing was conducted at the WindEEE Dome with inflow profiles matched with onsite full scale measurements. It was concluded that the flow characteristics over the terrain were extremely sensitive to topographic features on the terrain. Although PIV is a great tool to investigate flow features in detail, the cost associated with PIV is significantly higher compared to point measurement techniques. Also, for estimating wind loads on structures or wind energy over a complex terrain, point measurements are sufficient in most of the cases.

From the discussion in the preceding two paragraphs, it can be said the wind tunnel studies mostly use typical atmospheric boundary layer (ABL) profiles as the inflow. Study by Lange et al. (2017) is one of the fewer studies where the inflow profile was replicated from full scale field measurements. Unless the terrain of interest is sited adjacent to a homogeneous roughness terrain for which the ABL profile is available in the literature, assuming standard inflow profiles might not be sufficient to accurately estimate wind flow over a complex terrain.

In this study, a combination of numerical and experimental techniques have been used to estimate wind speeds over a complex topography. Numerical simulations were performed for a much larger area compared to the experimental model to estimate inflow velocity and turbulence intensity profiles for the experiment. Aside from getting wind profiles at the leading edge of the experimental model, numerical simulations were performed also to identify the critical wind directions for some specific locations on the topography and to analyze the wind flow structures around the same locations. The mean velocity and turbulence intensity profiles obtained from the numerical simulations were then replicated in the WindEEE Dome at Western University in order to obtain realistic wind speeds over the topography. WindEEE Dome has 60 fans on one wall of test chamber arranged in 4 rows and 15 columns. Fan speeds between the rows were varied to generate the desired mean velocity and turbulence intensity profiles at the leading edge of the model from the numerical simulations. The novelty of this study is to recreate inflow profiles at large scale by manipulating the inflow conditions that are more realistic for complex terrains compared to standard ABL profiles. Details of the WindEEE Dome are given in Section 4 of this article. In addition to the testing with the profiles generated through CFD, uniform velocity was also employed. A comparison is thus made between the results from testing with boundary layer profiles and uniform flow to predict the most conservative design approach for structures on complex topography. Finally, the speed-up factors calculated based on the present study are compared with the National Building Code of Canada (NBCC 2015, 2016).

The organization of the article is as follows. Section 2, subsequent to the Introduction in Section 1, gives some basic information of the topography. Details of the test model as well as the testing facility are provided in Section 3 and 4 respectively. Section 5 contains the description of the numerical simulations performed in the study, from CAD model to simulation results. Details of the experimental setup, measurement techniques, results along with discussion and comparison of results with building codes are presented in Section 6. A brief summary of the findings from the present study is given in the Conclusions in Section 7.

2. The topography

The topography investigated herein is located in British Columbia, Canada. A Google Earth® view of the area is shown in Fig. 1 along with the measurement locations for this study. For the wind tunnel tests, wind speeds were measured at a total of 17 locations on the topography (Fig. 1). The elevation of the locations are given in Table 1. Among these 17 locations, Location 9 sits at the highest elevation (1485.8 m) whereas Location 1 is at the lowest elevation (504.8 m). These 17 locations are the positions of 17 towers for a proposed transmission line traversing over the topographic ridge.

3. Test model

For the wind tunnel testing at the WindEEE Dome, a 1:1500 scale model was made from Expanded Polystyrene (EPS) foam. 3D CNC foam router by FROGMILL™ was used to make the model. The size of the test model was about 7 m (L) by 5 m (W) with maximum height of 1.3 m. The model covered an area of about 80 square km in full scale. The size and scale of the test model were dictated by the blockage ratio and measurement resolution on the model. Blockage ratio ranged from, depending on the orientation of the model, about 10–17% based on the contraction outlet area and 2–3% based on the cross sectional area of the chamber at the test section. According to Aly et al. (2011), the maximum allowable blockage ratio of 5% (Holmes, 2001) can be relaxed for open jet tests. In their study, pressure measurements on a cube with 16% blockage ratio based on the jet outlet provided reasonable estimates when compared with the values reported in the literature. Therefore, no blockage corrections were made in this study. Masonite sheets (3.2 mm thick) were used to smoothen the height transition from the test chamber floor to model height in the front and at the sides. The model inside the WindEEE Dome is shown in Fig. 2.