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Numerical study on effects of ground surface roughness on wind fields over topography

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SUMMARY:
Since mountainous topography can significantly increase wind speeds compared to the same weather pattern over flat terrain, accurate estimation of these speedup effects is important to ensure the safety of structures in regions with significant topography. Wind tunnel testing has been widely used to evaluate topographic effects; however, the approach has challenges associated with the small scale of the topographic models. In particular, the approach used to represent the roughness of the ground surface in wind tunnel testing can significantly impact the estimation of topographic speedup near the ground. To better understand the effects of surface roughness on flow fields over topography, the current study numerically investigates flow fields over topographic features using different representations for the ground surface, including smooth, rough, and terraced walls. The influence of forest cover on wind flow over topography, which is particularly challenging to model in the wind tunnel, is also investigated numerically. This study provides insights not only on the effects of ground surface roughness on wind flow over topography but also on suitable approaches for representing surface roughness in experimental and numerical simulations.

Keywords: Computational Fluid Dynamics (CFD), ground roughness, topography

1. INTRODUCTION

Structures located on mountainous terrain may experience higher wind loads than those on flat terrain due to acceleration of wind speed over the topography. Accurate estimation of such topographic speedup effects, and the corresponding increases in wind loads, is critical to ensure the safety of structures in regions with significant topography. Topographic speedup effects generally depend not only on the shape and size of the topographic feature but also on the surface roughness of the topographic feature and its surrounding terrain. To investigate the topographic effects on flow fields, many efforts have been made using various approaches: analytical/empirical methods (Taylor and Lee 1984; Lemelin et al. 1988), wind tunnel experiments (Finnigan et al. 1990; Takahashi et al. 2005; Lubitz and White 2007; Rasouli et al. 2009), field measurements (Taylor and Teunissen 1987; Berg et al. 2011) and computational simulations (Shamsoddin and Porté-Agel 2017; Morales Garza et al. 2019; Liu et al. 2020). Among them, wind tunnel testing has been widely used for topographic investigations; however, this method still has significant challenges associated with the small length scales that must be used in modeling of topographic features, typically between 1:500 and 1:5000 (ASCE 2021). The small length scale results in a significant Reynolds number mismatch and introduces multiple challenges, including generation of approach flow profiles at such small scales, measurement of flow velocities very close to the ground surface, and suitable modeling of the ground surface roughness. Given the importance of near-ground flow fields (e.g., for evaluating loads on structures), previous research has considered various methods for modeling the roughness of the ground surface. Recently, the use of a terraced modeling approach (i.e., where the model has a stepped profile with terraces corresponding to elevation contours at a specified contour interval) has been widely adopted in topographic experiments, mainly owing to (i) efficient fabrication of terraced models using computer numeric control (CNC) machines and (ii) realistic representation of local large-scale turbulence near the ground at higher Reynolds numbers (McAuliffe and Larose 2012). To the best of the authors' knowledge, however, no systematic study has been performed to evaluate the alternative approaches for representing ground surface roughness in topographic experiments for wind engineering applications. Therefore, the objective of the current study is to investigate the influence of the ground surface roughness on the flow field over topography by means of numerical methods. We performed computational fluid dynamics (CFD) simulations of flow over two-dimensional ridge and plateau features using numerical wall treatments corresponding to different representations of the surface roughness commonly used in wind tunnel testing, including smooth, rough, and terraced walls. The influence of forest cover on wind flow over topography, which is particularly challenging to model in the wind tunnel, was also investigated numerically, and the resulting flow fields were compared. The results of this study provide insights not only on the effects of ground surface roughness on wind flow over topography but also on suitable approaches for representing surface roughness in experimental and numerical simulations.

2. COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATIONS

The current study conducted Reynolds-Averaged Navier-Stokes (RANS) simulations with an open-source CFD package OpenFOAM v7.0 (OpenFOAM 2020) in two-dimensional settings.

2.1. Topographic models

Figure 1 shows schematics of the two-dimensional ridge and plateau features considered in this study, whose mathematical functions can be respectively described as

$$z_{ridge}(x) = H \cdot cos^2\left(\frac{\pi}{2L}x\right) \qquad \text{for } -L \leq x \leq L \tag{1}$$

and

$$z_{plateau}(x) = \begin{cases} H \cdot cos^2\left(\frac{\pi}{2L_1}\,x\right) & \text{for } -L_1 \leq x \leq 0 \\ H & \text{for } 0 \leq \mathrm{x} \leq \mathrm{L}_2 \\ H \cdot cos^2\left(\frac{\pi}{2L_3}(x - L_2)\right) & \text{for } L_2 \leq x \leq L_3 \end{cases}, \tag{2}$$

where H is the height of the ridge and plateau features, L is the half of the ridge length, and L_1, L_2, and L_3 denote the lengths of the shallow-sloped, flat and steep-sloped regions of the plateau, respectively. Note that the x coordinate direction is consistent with the wind direction.

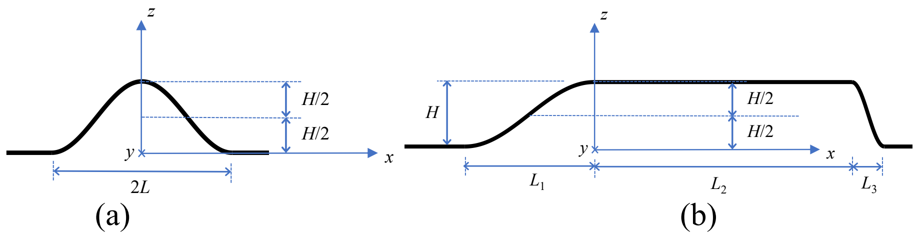

Figure 1. Configurations of the 2D topographic features: (a) ridge and (b) plateau

2.2. Simulation details

Two-dimensional RANS simulations were performed with the *k*-*ω* SST turbulence model (Menter 1993). Depending on the ground roughness treatments of the topographic models used in the study, two types of meshes were generated as shown in Fig. 2. The grid on the left was used for simulations with smooth, rough, and forested ground, while the one on the right was adopted for simulations using the terraced ground on the slopes of the topographic models.

The approach flow for the topographic simulations is the boundary-layer wind in open terrain whose typical roughness length z_0 is 0.03 m in full scale (ASCE 2022). For all flow quantities, zero-gradient conditions were set at the outlet boundary and slip conditions were specified at the top boundary. No-slip condition for velocity and various wall treatments for other variables were applied to the surfaces of the topographic models. The inlet, outlet and top boundaries were located far enough from the models in order not to affect the flow field of interest.

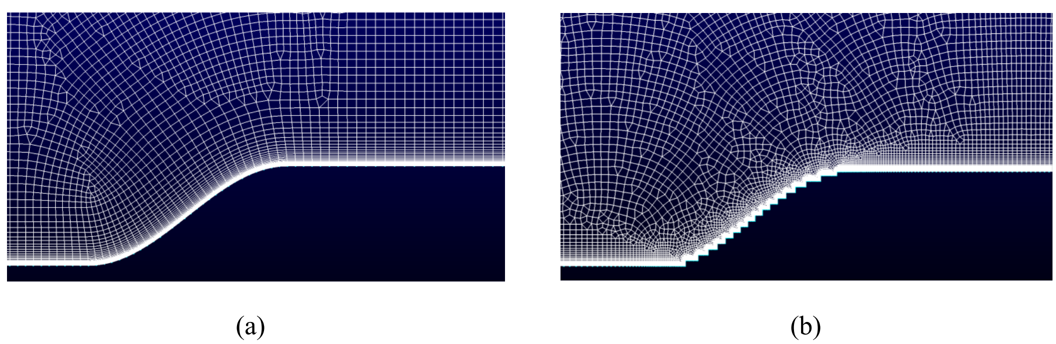

Figure 2. Two types of grids (zoom-in view of mesh around the plateau):
(a) smooth/rough wall and (b) terraced wall

3. RESULTS

Figure 3 presents the preliminary simulation result in the case of a smooth wall surface. In comparison with the velocity above the flat terrain upstream of the topographic features, the streamwise velocity (*U*) significantly increases near the top of the ridge. In contrast, the velocity near the leading edge of the plateau is not as high as that near the top of the ridge because the plateau is located in the wake region of the ridge. This observation confirms that the flow field over topography is significantly affected by a neighboring topographic feature as well as the shape of topography.

The simulation results from smooth, rough, forest, and terraced wall cases are compared to investigate the effects of the ground roughness on topographic flow field, particularly near the ground surface. Also, various configurations in terms of relative locations and distances of the topographic models were used in the study. Simulations and analysis are still in progress. Comprehensive analysis of the simulation results will be provided in the final paper.

Figure 3. Streamwise velocity (U) relative to reference upstream velocity (U_{ref}) in the smooth wall case.

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