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The effect of surface roughness on the corner flow properties of “tornado-like” vortices

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SUMMARY:
The effect of surface roughness on the target flow properties of tornadoes like the maximum tangential velocity and the core size is widely debated due to the discrepancies in the effects reported by previous studies. This study reports the results of Large Eddy Simulations of “tornado-like” vortices (TLV) with external swirl ratios in the range of 0.22 to 1.00 over five ground roughness. Surface roughness reduces the core radius near the ground, except at the transition swirl ratio where the trend is reversed, and the core enlarges. The transition swirl ratio, however, depends on the roughness level itself and our study supports the widely reported claim that surface roughness has an effect similar to reduction in swirl ratio. The trends in maximum tangential velocity are, however, more height-sensitive due to the competing effects of depleting angular momentum in the surface layer and potential speed-up due to enhanced convergence. The results clearly indicate that the effect of surface roughness on the maximum tangential velocity and core size are strongly dependent on external swirl ratio and not just the roughness level itself.

Keywords: “Tornado-like” vortices, surface roughness, Large Eddy Simulation (LES), Swirl ratio

1. INTRODUCTION

The Davenport wind loading chain (Davenport, 1961) formalized the idea that the response of a structure to wind is an integrated effect of (i) the wind climate as governed by the storm, (ii) the local wind exposure as dictated by the terrain conditions, (iii) the aerodynamic characteristics (shape) of the building and (iv) the dynamic characteristics (structural properties) of the building. This conceptualization has established a systematic framework for conducting wind tunnel tests using scaled models to predict the response of buildings to wind effects, such that the prediction can be only as accurate, or less, as the least accurately modelled link of this chain in the laboratory. Consequently, employing an intricate combination of spires, barriers, and roughness elements to model the terrain conditions and match full-scale velocity profiles is a well-established procedure in the simulation of the atmospheric boundary layer, typical of synoptic wind systems.

Despite recent advances in simulating “tornado-like” flows to study the effect of tornadoes on the built environment (Refan et al., 2014; Tang et al., 2018), the same level of sophistication in modelling the terrain conditions is not often considered in tornado wind loading studies. Most aerodynamic studies on the interaction of tornadoes with buildings consider a smooth floor, presumably corresponding to open terrain conditions (Haan et al., 2010; Kopp and Wu, 2020). This is partly due to lack of good quality full-scale, near-ground velocity measurements to serve as target profiles, and in part due to a lack of consensus on the effects of terrain on the tornado wind-field. Sabareesh et al., 2012 and Sabareesh et al., 2013 are the only studies, to the best of the authors' knowledge, that have considered the effect of terrain roughness on tornado wind loads. These studies indicate that terrain roughness influences both, the peak loads on the building and the aerodynamic signature of the phenomenon itself.

The localized, transient, and unpredictable nature of tornadoes along with the safety concerns associated with such intense storms, make it extremely difficult to obtain good quality field measurements. The radial profiles of tangential velocity at various elevations are considered the most reliably extracted information from field measurements. Of particular interest to the wind engineering community is the maximum mean tangential velocity (denoted by U) and its radial location (defined as the core radius and denoted by R). These quantities dictate the overall size and the dominant velocity magnitude in the flow that serve as target properties used for scaling laboratory vortices (Haan et al., 2008; Refan et al., 2014). Furthermore, the vertical location of the maximum tangential velocity (denoted by Z) above the ground is another important length dimension but is not always available from measurements of tornadoes in nature. Nonetheless, a characteristic vertical dimension in the flow forms an integral part of consistent scaling of laboratory vortices as introduced by Refan et al., 2014 and later reinforced by Baker and Sterling, 2019.

The effect of changing the external swirl ratio, the primary non-dimensional parameter, on U, R and Z over a smooth floor is well studied and documented. Refan et al., 2014 used this to establish a consistent scaling procedure for tornado simulations that relies on one point in the flow, that point being defined by R and Z. It has also been long known that introduction of surface roughness affects U, R and Z. However, a review of the studies on this subject shows that the effect of surface roughness on these primary flow quantities of interest, particularly R, and U, is not well understood. It appears that all permutations of increasing and decreasing trends in the R and U have been reported by these studies. This observation was also pointed out by Wang et al., 2017 and Razavi et al., 2018 and led the authors of those studies to make useful speculations; albeit lacking conclusiveness. It is therefore essential to evaluate how these target flow properties are affected by surface roughness.

2. METHODOLOGY AND TEST CASES

To replicate the effect of terrain roughness on tornadoes, Large Eddy Simulations (LES) of stationary "tornado-like" vortices over different ground roughness scenarios were conducted and the three-dimensional mean and turbulent flow-fields were generated. Five ground roughness scenarios were included in this study. An idealized slip-wall simulation with no ground induced shear was considered to examine the flow-structure in the absence of any ground induced perturbations. A second case of a no-slip wall was simulated to analyse the flow structure over the widely reported smooth wall. Finally, three cases of increasing roughness were simulated by explicitly modelling the roughness blocks of varying heights and fixed spacing. Three roughness heights of 0.5 cm, 1 cm and 2 cm in model-scale, labelled as "Rough I", "Rough II" and "Rough III", respectively, were selected to be in the range of roughness that have been modelled at WindEEE Dome. A logarithmic profile was fit to the mean tangential velocity in the surface layer along the fetch at various radial distances from the inlet up to the core radius to obtain the aerodynamic roughness lengths $(z_0)$of $0.02\,m, 0.075\,m$ and $0.5\,m$ for Rough I, Rough II and Rough III, respectively. The roughness length estimates presented herein illustrate that the roughness cases considered in this study represent at best, low to moderate roughness in nature; the type encountered over farmlands and sparsely scattered vegetation and forests, and not representative of highly urbanized city centres.

3. RESULTS AND DISCUSSION

Error! Reference source not found. shows a comparison between the variation in core radius with height for five roughness cases. The introduction of ground surface roughness, when comparing the no-slip wall case with the slip wall case, reduces the size of the core radius near the ground for all swirl ratios, except for S=0.70 (and 0.75). At this swirl ratio, the trend is seen to reverse such that the introduction of roughness increases the vortex size. S=0.70-0.75 in our simulations corresponds to a phenomenon analogous to the drowned vortex jump where the flow transitions from the sub-critical to a post sub-critical stage. A swirl ratio of 0.70-0.75 for this transition falls in the range of commonly reported values in the literature as well (Tang et al., 2018; Karami et al., 2020). In general, the introduction of roughness is seen to decrease the core size, except at the transition swirl ratio, where the core is observed to expand. Further, this transition swirl ratio is seen to shift to a higher value with the introduction of surface roughness. This means swirl ratio at which the trends in core size reverse changes with the introduction of roughness. Furthermore, the trends in the maximum tangential velocity are found to be less trivial to generalize due to their sensitivity to height. The maximum tangential velocity is dictated by two competing effects; the depletion of momentum in the surface layer and flow acceleration accompanied by enhanced convergence with the introduction of surface roughness.

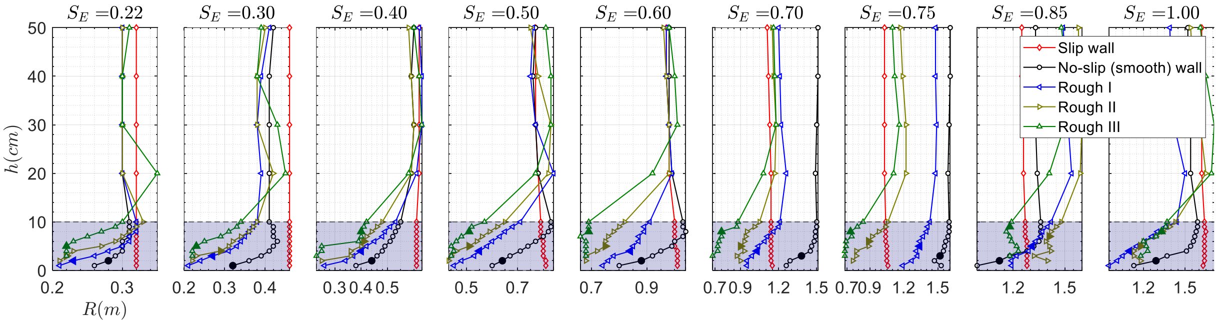

Figure 1: Variation in core radius with height (location of overall maximum tangential velocity marked in solid marker).

4. CONCLUSIONS

The effect of surface roughness on the maximum tangential velocity and core size are strongly dependent on the external swirl ratio, and not just the roughness level itself. The trends in the effect of roughness, particularly the core radius, reverse at the transition swirl ratio. Further, the transition swirl ratio shifts to a higher value with the introduction of roughness. The study indicates that the discrepancies in the results reported in literature are primarily due to the limited range of swirl ratios and surface roughness considered in those studies; such that the former causes to overlook the trend reversal (in core size) at transition swirl ratios and the latter causes overlooking the loss of speed-up (in the tangential velocity) in the surface layer beyond a threshold roughness.

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