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COMPUTATIONAL MODELING OF HILL EFFECTS ON TORNADO LIKE VORTEX

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ABSTRACT

Tornado is a complex flow structure, where high swirling flow closer to the ground converges to the center and then moves upward. As a result, it creates a high suction pressure at the ground near the center of the tornado. The main objective of this study is to analyse the impact over flow structure and ground pressure by implementing topographical changes. For the present study a one-celled tornado replicating a real EF-2 scale has been chosen. Previous study suggests that suction ground pressure is highest at the tornado core center, also it changes more sharply near the core center. As a result, the authors decided to raise the surface in the form of a hill at the tornado core center. In this study, two different types of hill based on their slope are implemented for analysing the impact of two different types of topographical changes. It has obtained that as the slope becomes steeper the peak speed up value increases. Also, unlike the synoptic flow case, maximum speed up does not occur at the crest of the hill. Presence of the hill hardly has any impact on the overall pressure distribution at the ground.

Keywords: Computational modeling, Tornado, Hill.

1. INTRODUCTION

Tornado has a very complex flow structure; especially near the ground where most of the engineering structures are present. For years laboratory and numerically scaled models have been used to analyse the impact of tornadic flow-structure due to the vulnerability of gathering actual tornado data. Although some efforts have been made to gather data from actual tornado, still the gathered data are not sufficient enough to analyse the flow structure completely.

In 1972, Ward built a tornado vortex chamber (TVC) with geometric and dynamic similarity to a real scale tornado (Ward, 1972). Following these studies, several laboratories scaled models have been built by various researchers to analyse different aerodynamic properties, such as those developed by Wan and Chang (1972) to analyse the velocity field in a simulated tornado using three dimensional velocity probe for two different swirl ratios. They obtained from their study that, the direction of radial velocity is inward (towards the tornado center) near the boundary, however the direction changes at some distance from the center depending on the swirl ratio values. They also obtained, vertical component of the flow strongly depends on the swirl ratio values. Coincidently, at the same time Davies Jones (1972) found the dependency of core radius over swirl ratio using Ward's tornado simulator. Church et al. (1979) used a tornado simulator similar to the Ward's one and were able to notify the important transition points in a tornadic flow structure. Mitsuta and Monji (1984) used their laboratory scaled model to simulate one and two-celled tornadoes and they found that maximum horizontal velocity occurs near the ground surface and the height of this maximum velocity is insensitive to swirl ratio. Diamond and Wilkins (1984) analysed the impact of translation using modified Ward's tornado simulator and translation causes a local increase in the swirl ratio and also increase the size of the core radii over stationary vortex. Haan et al. (2008, 2010) used their tornado simulator to simulate tornadoes of different swirl ratios, they also compared peak load from the impact of tornadic load on a model low-rise building with those prescribed by the ASCE 7-05 for straight wind over open terrain. Matsui and Tamura (2009) simulated tornadoes of different intensity for different floor roughness conditions and found that floor roughness is more effective for low swirl ratios than higher ones. Zhang and Sarkar (2009) used their ISU (IOWA Tornado Simulator) to analyse the flow structure near the ground and found that the tangential velocity is the dominant component of flow and its peak value is three times higher than radial velocity component. Tari et al. (2010) also simulated tornadoes of different swirl ratios and found the radial and tangential velocity components of flow as well as the core radius increase with the higher swirl ratio values. Refan et al. (2013) used Mini WindEEE Dome to simulate tornadoes of different swirl ration and compared the location of the maximum tangential velocity point with the actual scale tornado to develop a geometric scale factor.

In parallel with these experimental efforts several numerical analyses have also been performed such as those by Harlow and Stein (1974) using high speed computers to simulate tornadoes of different intensities and analyse several flow related parameters. Rotunno (1977, 1979) numerically modeled Ward's tornado simulator and obtained that core radius is independent of the Reynolds number. He also analysed the flow structure for different swirl ratio values. Church et al. (1993) also numerically simulated the tornado and obtained that as the swirl ratio increases the altitude of the vortex breakdown decreases until swirl ratio, $S = 0.45$. Nolan and Ferrell (1999) obtained from their simulation that vortex Reynolds number controls the structure and maximum wind speed of the tornado flow. Lewellen and Lewellen (1997, 2007) numerically simulated a three dimensional tornado and analysed the flow structure near the ground. Kuai (2008) et al. replicated the ISU tornado simulator numerically and compared their results with the laboratory model. Hangan and Kim (2008) used their simulation to analyse the dependency of flow dynamics over swirl ratio and also its relation with the Fujita scale. Ishihara et al. (2011) simulated tornadic flow using LES turbulence for two swirl ratios which represented one and two-celled tornadoes and obtained from their study that, for one-celled type vortex peak vertical velocity occurs at the center, however for two-celled vortex it occurs near the radius of the maximum tangential wind. Hangan and Natarajan (2012) used LES simulation to analyse the impact of ground surface roughness and translation and obtained from their study that translation reduces the maximum mean tangential velocity for low swirl ratio, however for high swirl ratio it increases slightly. Again roughness decreases the mean tangential velocity at all swirl ratios.

In the best of our knowledge limited studies have reported in literature on tornado/building interaction using laboratory scale models (Chang, 1971; Mehta et al. 1976; Jichke and Light, 1983; Bienkiewicz and Dudhia, 1993; Wang et al. 2001; Fouts et al. 2003; Mishra et al., 2003; Sarkar et al., 2006; Sengupta et al., 2006; Haan et al., 2010). In accordance with this, several CFD analysis were also performed by several researchers (Selvam and Millet, 2003; Sengupta, 2006; Nasir et al., 2014; Nasir and Bitsuamlak, 2014).

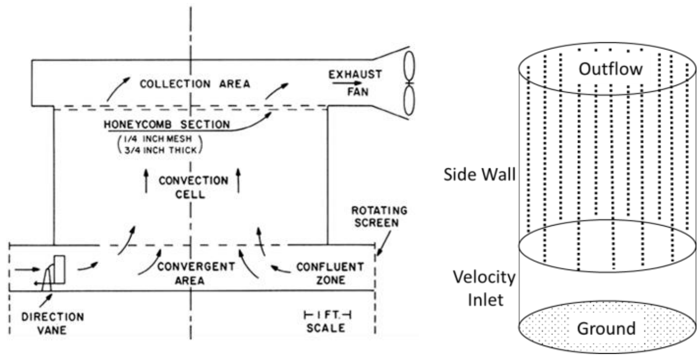
Although most of the research works on tornado flow structure are based on the roughness effect or translational effect, there are no significant analysis have been done on the tornadic flow structure under the influence of topographical changes in the previous. However, some analysis can be found in the literatures regarding the straight wind flow over a complex terrain (Bergeles, 1985; Paterson and Holmes, 1993; Maurizi, 2000; Bitsuamlak, et al., 2003; Lun, et al., 2003 and Chung and Bienkiewicz 2004). In the present study, topographical changes have been implemented on the ground by two different types of hills (based on the slope of the hill). The hills are presented on such manner so that the peak of the hill coincides with the center of the tornado.

2. METHODOLOGY

2.1 Numerical model for tornado simulator and topographical change

For the present study, a numerical model depicting the Purdue tornado simulator is used (see Figure 1a). The actual Purdue tornado simulator is cylindrical in shape, where flow enters into the simulator from the bottom. Guide vanes are provided at the inlet to provide desired angle in the inflow. Once the swirling flow enters inside the simulator through the confluent region it reroutes vertically upward in the convection region. To emphasize this vertical movement of swirling flow, an exhaust fan is installed at the outlet to suck out the air from the simulator. Keeping the main operational mechanism in mind, some modification is made into the simplified numerical model (see Figure 1b)

The simplified numerical model is also cylindrical in shape. Despite of providing with the guide vanes, a computer code has implemented to achieve the desired angle in the inflow. A "shear free" sidewall was provided and at the outlet "outflow" boundary condition has been provided. Purdue tornado simulator is a laboratory scaled simulator which is the modified version of the Ward's tornado simulator. Purdue tornado simulator is around 2m in height and 0.4m in radius. As a result, the original simulator is scaled up in the present numerical analysis keeping the aspect ratio similar to the laboratory scaled model.



(a) (b)

Figure 1: (a) Laboratory and (b) simplified numerical model of Ward's tornado vortex chamber.

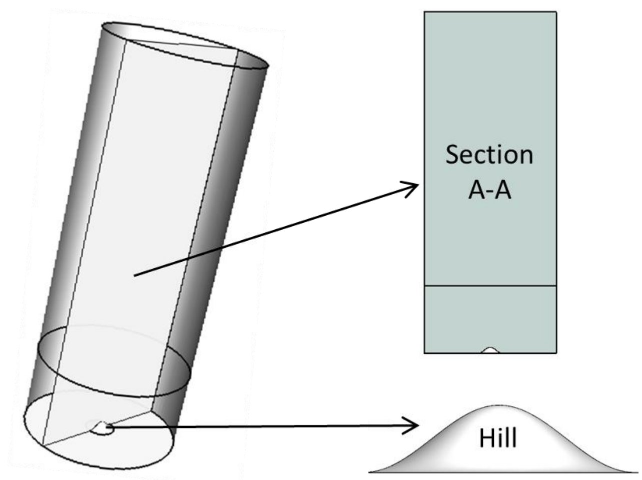


Figure 2: Location of hill in the simulator.

Inside the simulator, ground surface is altered at the center of the simulator in the form of a hill. The reason for such location of the hill is that the crest of the hill coincides with the center of the tornado (see Figure 2).

2.2 Geometric scaling factor for full scale simulation

As already mentioned in the introduction that one of the main features of this current study is the full scale numerical modeling. As a result, a geometric scale factor is required to scale up the Purdue tornado simulator. The scale factor for the tornado simulation is chosen by a matching process developed by Refan et al (2013) based on experiments carried out at the mini WindEEE Dome. First, the maximum tangential velocity of numerically simulated tornadoes is determined for different swirl ratios ranging from one to two-celled tornadoes. Then, the horizontal distance from the tornado center and height above the ground corresponding to the maximum tangential velocities for each simulated tornado are obtained and compared with actual tornado data. Since according to fluid dynamic solution there can be only one length scale, it is expected that both the horizontal distance and height of the maximum tangential velocity will converge to a similar length scale value for a particular swirl ratio. Thus, a specific swirl ratio that represents the target tornado is identified.

For the present study, an Enhanced Fujita scale-2 (EF-2) tornado is chosen that took place in Happy, Texas in 2007. The reason for choosing such an EF-2 scale tornado is that, in nature about 90% tornadoes are EF- 2 scale. CFD simulations for various swirl ratios are carried out and the geometric scaling between the field measurements and CFD is plotted as shown in Figure 3 following the procedure explained earlier.

The core radius and height of the maximum tangential velocity point for the actual tornado and the CFD simulated tornado converged for swirl ratio 0.4 at scale factor of 4222 (see Figure 3) for the target tornado case.

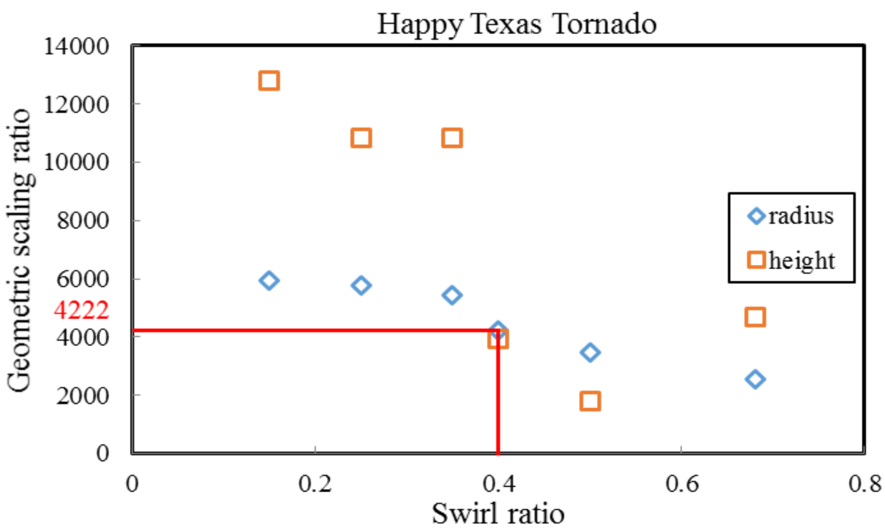
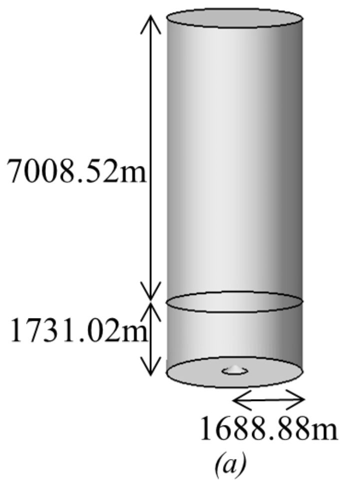
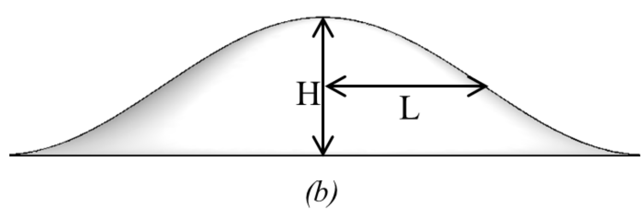


Figure 3: Determining scaling factor for small-scale numerical depicting Purdue tornado simulator.

2.3 Computational domain and topographical changes





Type of hill	H	L	H/L
Steep hill	160	160	1
Shallow hill	160	320	0.5

(c)

Figure 4: Dimensions for (a) full computational domain and (b), (c) dimension of the hills

For the present study two different types of hills (slopes are different) are chosen (see Figure 4). Although the dimensions are different but the slope of the hills are kept identical to the previous study by Bitsuamlak et al. (2006) to compare the results between the impact of hill on straight wind and tornado flow.

For the simulation, commercial software STAR-CCM+ is used. The main advantage of this software is the availability of octagon mesh elements which simulates more efficiently cylindrical shape domains. Although, the base mesh size is kept comparatively coarse because of the large domain size, the mesh size near the ground and also around the hills are kept very fine (wall Y-plus < 2) to capture the sharp velocity changes near the solid region (see Figure 5a, b and c).

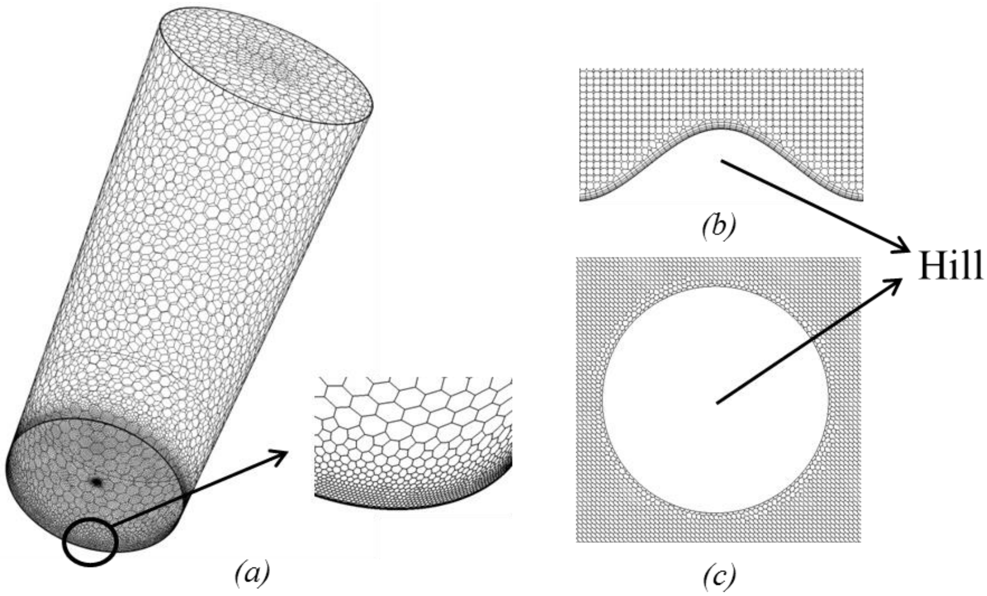


Figure 5: Mesh distribution: Finer mesh close to the ground (a), and around study hill elevation view (b) and plan view (c).

2.4 Boundary condition for tornado simulator and building

The following boundary conditions for tornadic flow are used: an exhaust fan at the outlet of the laboratory model is replaced by the outflow boundary condition in the numerical model and at the inlet the flow velocity has two components (radial and tangential) in order to produce the swirling flow field. The equation for the radial and tangential velocity components are as follows:

$$V_r = V_1 \times \left(\frac{z}{z_1}\right)^{1/7} \quad [1]$$

$$V_t = \frac{2H_o}{R_o} \times S \times V_r \quad [2]$$

where, V_r and V_t are the radial and tangential component of velocity at 'z' height from ground surface respectively. 'S' is the swirl ratio which actually determines the intensity of model scale tornado. Here, S = tanθ/2a; θ is the inflow angle at the inlet and 'a' is the aspect ratio. H_o and R_o are the inlet height and radius of inlet respectively. V_1 and z_1 are the reference velocity and height respectively. For the current full-scale numerical model, reference velocity, V_1 and height, z_1 of 10m/s and 106m are chosen respectively based on the actual data obtained from the tornadic event that took place in Happy, Texas in 2007.

2.5 Turbulence model used for simulation

The present analysis is limited to the steady condition of the flow, as a result Reynolds Average Navier-Stokes (RANS) equations are used together with the Reynolds Stress Model (RSM). RSM turbulence model is chosen over k-epsilon and other two equation models because of its better accuracy for rotating flows. The two equation models are based on the Boussinesq assumption which postulates that, the Reynolds stress tensor must be proportional to the strain rate tensor. However, for complex flows, such as tornadic flow, this particular assumption does not work because of the curvature effect. Again Large Eddy Simulation (LES) turbulence model is not considered because of the nature of the simulations which makes it computationally costly.

3. RESULTS AND DISCUSSION

To analyse the effect of hill at the center of the tornado, Fractional Speed-Up Ratio (FSUR) is calculated for both steep and shallow hill. For synoptic flow-field FSUR is defined in terms of $U(z)/U_o(z)$, where $U(z)$ is the velocity at height 'z' above the hill surface and $U_o(z)$ is the upstream velocity at the same height (see Figure 6).

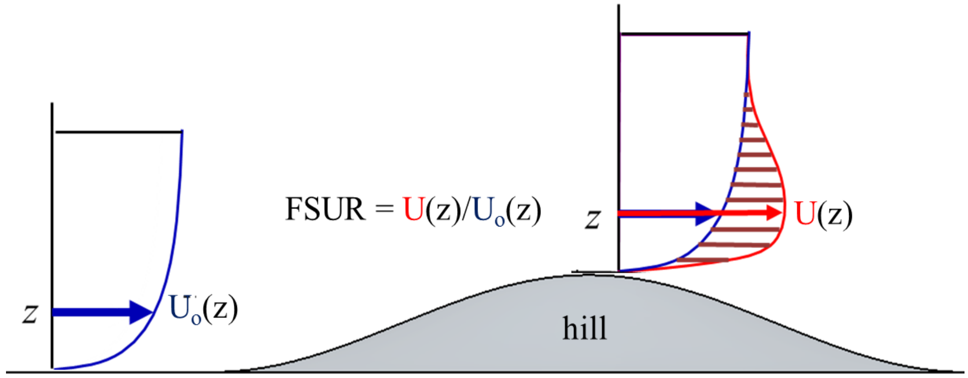


Figure 6: FSUR calculation for synoptic flow

Unlike synoptic flow, tornado has a very complex flow structure where the flow characteristics change with the locations inside the tornado. As a result, FSUR value is calculated in a slightly different manner. For tornado, FSUR is obtained by $U^{'}(z)/U_o^{'}(z)$, where $U^{'}(z)$ is the velocity at height 'z' above the hill surface and $U_o^{'}(z)$ is the velocity at the same height at the same location inside the tornado but with the absence of the hill.

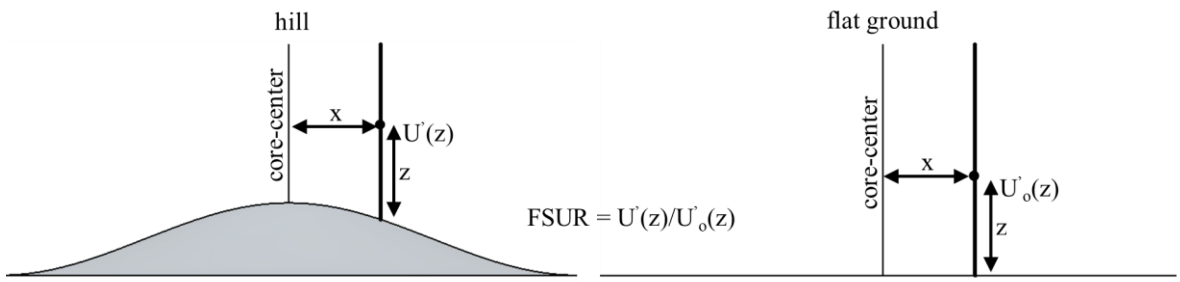


Figure 7: FSUR calculation for hill at the tornado core center

For the present study, line-probes are provided at 50m interval from the crest of the hill surface up to 500m from the center of the hill as well the center of the tornado core. Each line probe is 500m in height so as to cover sufficient space within which most of the engineering structure falls (see Figure 8). Line-probe has not provided at the crest of the hill because coincidently that is the core center where near the ground flow velocity is almost zero for flat ground case. As a result, a slight increase in the flow velocity due to the presence of the hill increases the FSUR values a lot (sometimes > 1000) which makes the analysis impracticable.

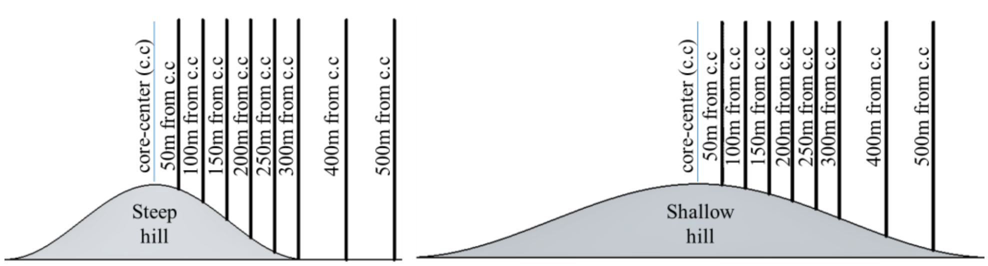


Figure 7: Location of line-probes for steep and shallow hill

3.1 Comparison of FSUR between steep and shallow hill

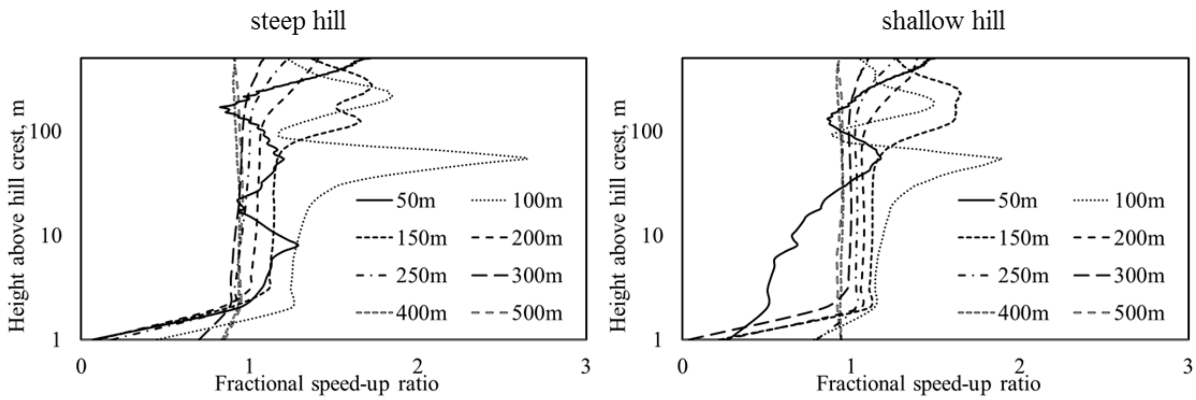


Figure 8: Comparison of FSUR values between steep and shallow hill

From the figure it can be obtained that, closer to the crest of the hill FSUR values are greater than 1, however closer to the feet of the hill FSUR values are almost 1. This indicates that the raised surface of the hill speeds up the flow and this speed up started to decrease and at ultimately diminishes as the raised surface blends with the ground surface. Another important finding is that, the effect of the presence of the hill is very much localized within its location. It hardly impacts the overall tornado flow structure (see Figure 8), because the size of the hills is comparatively much smaller than the size of the entire tornado simulator.

Now irrespective of the hill type, maximum speed up value occurs for the location where the line-probe is 100m away from the tornado core center or the crest of the hill. This indicates that flow velocity speeds up at some location just away from the core center and very close to the crest of the hill.

Although the location of the maximum speed up is identical for steep and shallow hill, but the FSUR value is higher for steep hill than shallow (see Figure 9).

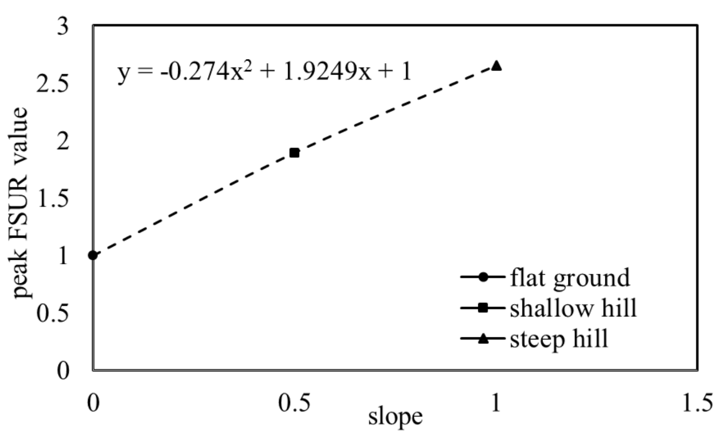


Figure 9: Peak FSUR value comparison

3.2 Comparison of Cp

Pressure coefficient, Cp on the ground is obtained using following equation,

[3] $$C_p = \frac{p - p_o}{\frac{1}{2}\rho {u_o}^2}$$

Here, ‘p_o’ is the maximum pressure at the ground, ‘ρ’ is the density of air and ‘u_o’ is the reference velocity which in this case is the maximum tangential velocity at the crest height of the hill in the absence of the hill.

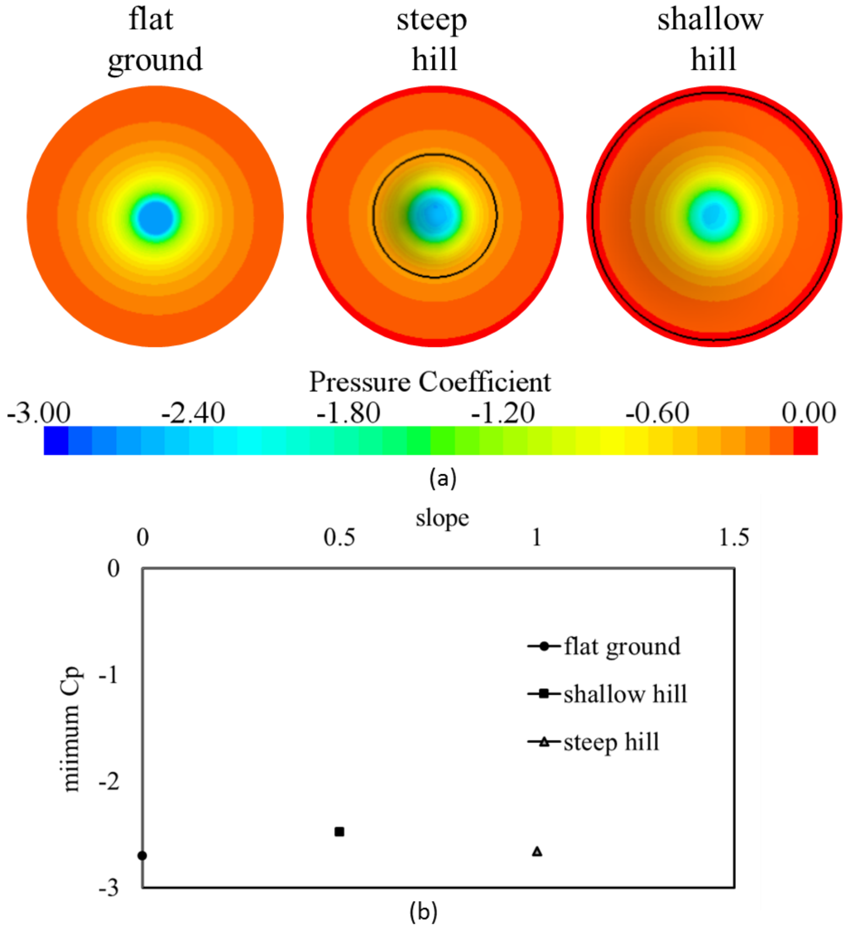


Figure 10: (a) Pressure distribution and (b) minimum Cp on the ground

In Figure 10(a), for all the cases the plots are cropped to the size of the radius of the shallow hill to facilitate the comparison. For all the cases, the pressure distribution is similar where maximum suction (minimum Cp) occurs at the center of the tornado and decreases as it moves away from the center (see Figure 10(a)). This indicates, presence of the hill does not disrupt the general pressure distribution of Cp on the ground (Nasir et al., 2014). Also, maximum suction on the ground for flat case is slightly higher than the shallow hill case and more or less equal to the steep hill case.

3.3 Comparison with synoptic flow

For synoptic flow over a hill FSUR is calculated at the peak of the hill surface because maximum speed up occurs at this location (Bitsuamlak et al., 2006). However, for tornado maximum speed up occurs at a location 100m away from the core center. The main reason for this discrepancy is due to the complexity of the tornadic flow.

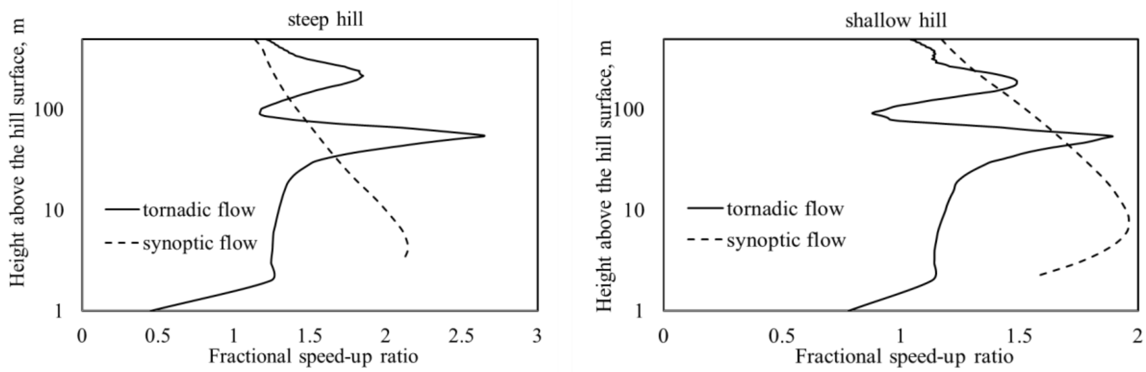


Figure 10: Comparison of FSUR values

Irrespective of the types of the hill, for synoptic flow maximum speed up occurs near the ground (<10m from the ground). However, for tornadic flow it occurs at higher distance from the ground (>50m from the ground). Now for steep hill case maximum FSUR value is higher for tornadic flow than synoptic flow. Unlike this, for shallow hill maximum FSUR is higher for synoptic flow than tornadic flow.

4. CONCLUSION

Some concluding remarks can be obtained from the present study which are as following,

The impact of the hill over the flow-structure is very much localized within the vicinity of the hill. It does not disrupt the overall flow structure. Unlike synoptic flow case, maximum speed up does not occur at the crest of the hill. It occurs slightly away from the crest of the hill. Speed up increases with the increase in the slope of the hill. Overall pressure distribution on the ground does not disrupt by the presence of the either types of the hill.

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