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LES MODELING OF THE EFFECTS OF GROUND ROUGHNESS AND TRANSLATION ON TORNADO-LIKE VORTICES

Zhenqing Liu[1], Takeshi Ishihara[2]

[1]*Doctor of Civil Engineering, The University of Tokyo, Tokyo, Japan, liu@bridge.t.u-tokyo.ac.jp*
[2]*Professor of Civil Engineering, The University of Tokyo, Tokyo, Japan, ishihara@bridge.t.u-tokyo.ac.jp*

ABSTRACT

The numerical simulation by using LES turbulent model for the tornadoes over roughness and those with a translation speed was carried out in a Ward type simulator. The ground roughness was simulated through adding an additional momentum source in the Navier-Stokes equation and the tornado translation was modeled by providing a relative motion on the ground. The effects of ground roughness and the translation of tornado on the flow fields of two typical tornado-like vortices, vortex breakdown and multi-vortex, were investigated. It was found that, at the high elevation, V_c and r_c shows the same trend versus the external swirl ratio no matter the translation of tornado is introduced. However, if the ground is rough, the core radius at high elevation changes greatly. The ground roughness will expand the size of the core. But for the very small and very high swirl ratio cases, the ground roughness shows the effect of reducing the core size.

Keywords: Tornado-like vortex, LES, ground roughness, translation, swirl ratio, Fujita scale

1. Introduction

The occurrence of tornado increases as global warming intensifies around the world. Therefore the researchers pay much attention to studying the flow structures, dynamics as well as the similarity of the tornado-like vortex experimentally or numerically in the past decades. Many important findings have been obtained, i.e. the dominant parameters determining the flow structure, the organized swirl motion in tornadoes and the similarity between simulated tornadoes and those in nature. These studies mostly focus on the stationary tornadoes over smooth ground, however, tornadoes are always observed with translation speed, ranging from 10m/s to 30m/s, which will absolutely distort the flow fields near the ground. On the other hand the tornadoes can also happen in urban area, e.g. the tornado occurring in Joplin, Missouri, the US in 2011, killing 158 people (2012). Therefore it will make sense to study the effects of ground roughness to the flow structures close to the ground. However, due to the difficulties along with the investigations of the effects from ground roughness and tornado translation, these effects have not been subjected too much examination. Following we will outline some findings from previous studies.

Dessens (1972) examined the influence of ground roughness on tornadoes by a laboratory simulation. This study has shown that passing over forests or towns will greatly affect tornadoes, increasing the core diameter and mean updraft, while suddenly decreasing the wind speeds. However, different with the study by Dessens, the core diameter was found to be decreased by introduction of ground roughness in the study of Diamond et al. (1984). Leslie (1977) studied the roughness effects on suction vortex formation experimentally and they proposed that over a rough surface more swirl is necessary to initiate the transition to a greater number of vortices than over a smooth surface and the flow becomes more turbulent which will cause greater eddy exchange of momentum. Monji and Wang(1989) performed laboratory simulations of tornadoes over three different roughness. They concluded that due to roughness the height of the maximum wind speed moves upward and the core diameter increases at low swirl ratio while less pronounced changes were found at high swirl ratio. In order to prevent the disturbance of flow fields in the boundary layer from intrusive probes, W.Zhang and Sarkar(2008) applied PIV technique to do the measurement and studied the effects of ground roughness on tornado-like vortex. This study shows the roughness will transform high-swirl flow to low-swirl flow and reduce the magnitude of tangential velocity. It was argued that the core diameter to be reduced with increasing the surface roughness. Most recently a large eddy simulation about the roughness effects on tornado-like vortices was carried out by Natarajan and Hangan(2012), same with the conclusion by Monji et al.(1989), the introduction of surface roughness was found to result in increasing core radius at low swirl ratio and the effect become unobvious at high swirl ratio. They also concluded that the roughness causes an effect similar to reduce the swirl ratio. From the review of the previous experimental tests and numerical simulations we can see the researchers are not completely in agreement on how the roughness affects the flow fields near the ground.

The translation of a vortex over ground must have some effects on the flow field structure and dynamics. An experimental study was carried out by Diamond and Wilkins(1984) and the translation of tornado was simulated by using a modified Ward type simulator with installing a movable ground plate. It was found that secondary vortexes are to be generated by the translation. In the numerical study by Lewellen(2000) the translation effects were examined and they found that the added surface shear stress provides a torque that tends to enhance the angular momentum on the side of vortex where the swirl velocity and surface motion are aligned. On the opposite side it will reduce the angular momentum. They also found in the translating case there will be generally fewer secondary vortices than the case without translation. However this study only examined the effect of translation for the tornado with high swirl ratio. Natarajan and Hangan(2012) numerically simulated the effect of tornado translation for the tornado in a larger range of swirl and they proposed that the effect is not uniform across the swirl ratios. The tangential velocity was reduced due to translation for low swirl ratios while the translation causes a slight increase in the maximum mean tangential velocity for high swirl ratio cases. However, a systematic research about the effects of tornado translation is still necessary.

In the present research the details of the model are introduced in section 2 to describe its dimension, grid distribution, boundary conditions, as well as the method simulating the roughness and translation. In section 3 the flow fields of tornado-like vortices are examined in detail and the effects of roughness and translation are clarified.

2. Numerical model

The governing equations, boundary conditions as well as the solution schemes are introduced in Section 2.1 and Section 2.2. Section 2.3 will provide the detailed information of the configurations for the numerical tornado simulator. The method simulating surface roughness and tornado translation will be introduced in Section 2.4 and Section 2.5 respectively.

2.1 Governing equations

In respect that momentum and mass are mostly transported by large eddies, and considering the current computing capability, large eddy simulation (LES) is adopted to simulate the tornado-like vortex. In LES, large eddies are computed directly, while the influence of eddies smaller than grid spacing are modeled. Despite that LES is computationally expensive, it can provide detailed and accurate information. Boussinesq hypothesis is employed and standard Smagorinsky-Lilly model is used to calculate the subgrid-scale (SGS) stresses.

The governing equations are obtained by filtering the time-dependent Navier-Stokes equations in Cartesian coordinates (x, y, z) and expressed in the form of tensor as follows:

$$\frac{\partial \rho \widetilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial \widetilde{u}_i}{\partial t} + \rho \frac{\partial \widetilde{u}_i \widetilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \widetilde{u}_i}{\partial x_j}\right) - \frac{\partial \widetilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where $\widetilde{u}_i$ and $\widetilde{p}$ are filtered velocities and pressure respectively, μ is viscosity, ρ is density, τ_{ij} is SGS stress and is modeled as follows:

$$\tau_{ij} = -2\mu_t \widetilde{S}_{ij} + \frac{1}{3}\tau_{kk}\delta_{ij}; \qquad \widetilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i}\right) \tag{3}$$

where, μ_t denotes SGS turbulent viscosity, and $\widetilde{S}_{ij}$ is the rate-of-strain tensor for the resolved scale, δ_{ij} is the Kronecker delta. Smagorinsky-Lilly model is used for the SGS turbulent viscosity:

$$\mu_t = \rho L_s^2 |\widetilde{S}| = \rho L_s \sqrt{2\widetilde{S}_{ij}\widetilde{S}_{ij}}; \qquad L_s = \min(\kappa d, C_s V^{\frac{1}{3}}) \tag{4}$$

in which, L_s denotes the mixing length for subgrid-scales, κ is the von Kármán constant, 0.42, d is the distance to the closest wall and V is the volume of a computational cell. In this study, C_s is Smagorinsky constant and is determined as 0.032 based on Oka and Ishihara (2009).

2.2 Boundary condition and solution scheme

For the wall-adjacent cells, when they are in the laminar sublayer, the wall shear stresses are obtained from the laminar stress-strain relationship:

$$\frac{\widetilde{u}}{u_\tau} = \frac{\rho u_\tau y}{\mu} \tag{5}$$

If the mesh cannot resolve the laminar sublayer, it is assumed that the centroid of the wall-adjacent cells falls within the logarithmic region of the boundary layer, and the law-of-the-wall is employed as follows:

$$\frac{\widetilde{u}}{u_\tau} = \frac{1}{\kappa}\ln E\left(\frac{\rho u_\tau y}{\mu}\right) \tag{6}$$

where $\widetilde{u}$ is the filtered velocity tangential to wall, y is the distance between the center of the cell and the wall, u_τ is the friction velocity, and the constant E is 9.793. The velocity profiles at the inlet are specified as below:

$$\begin{cases} U_{r_s} = U_1 \frac{z}{z_1}^{\frac{1}{n}} \\ V_{r_s} = -U_{r_s}\tan(\theta) \end{cases} \tag{7}$$

where, U_{r_s} and V_{r_s} are radial velocities and the tangential velocities at inlet, n equals to 7, the reference velocity U_1 and the reference height z_1 are set to 0.24m/s and 0.01m respectively.

Finite volume method is used for the present simulations. The second order central difference scheme is used for the convective and viscosity term, and the second order implicit scheme for the unsteady term. SIMPLE (semi-implicit pressure linked equations) algorithm is employed for solving the discretized equations (Ferziger and Peric, 2002).

The numerical solution was carried out to 30s and the first 10s data were removed to eliminate the transit results. The data from 10s to 30s were applied to obtain the statistical information of the flow fields in the tornado-like vortex. The relative errors decrease with increasing in time period. For 20s, the relative error of the maximum mean tangential velocity in the cyclostrophic balance region becomes less than 1%.

2.3 Configurations of the numerical tornado simulator

In this study, a Ward-type simulator is chosen and numerically simulated. The configurations of the numerical model are shown in Fig.1. Two significant geometry parameters are the height of the inlet layer, h, and the radius of the updraft hole, r_0, which are 200mm and 150mm respectively. The flow rate is calculated by $Q = \pi r_t^2 W_0$, where r_t is the radius of the exhaust outlet and W_0 is the velocity at the outlet. The Reynolds number is expressed as $Re = 2r_0 W_0/\nu$. Swirl ratio S_E is defined as $\tan\theta/2a$, where $a = h/r_0$. Table 1 summarizes the parameters used in this study.

Considering the axisymmetry of tornado-like vortex, a novel axisymmetric topology method is adopted. With an intent to investigate the turbulent features quantitatively in the vicinity of the center and the region near the ground, a very fine mesh is considered in the domain of the convergence region, where 86 nodes in the radial direction and 45 nodes in the vertical direction are used, and the minimum size of the mesh are about 1mm in the radial direction and 0.1mm in the vertical direction. The spacing ratios in the two directions are less than 1.2 in order to avoid a sudden change of the grid size. The total mesh number is about 7.8×10^5.

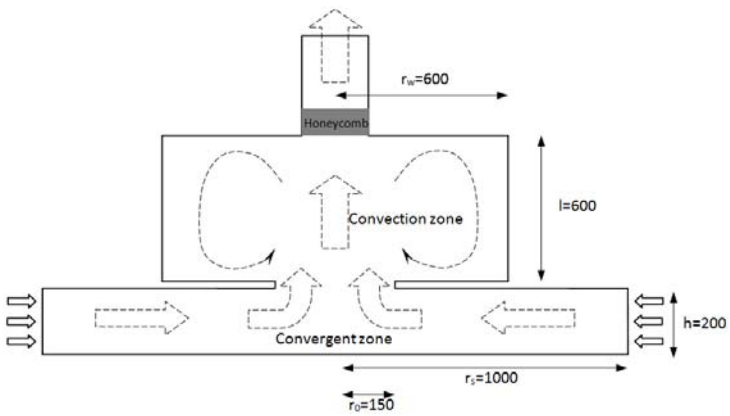


Fig. 1 The geometry of the model, (mm).

Table 1 The parameters used in this study

Height of the inlet layer: h	200mm	Reynolds number: $Re = 2r_0W_0/\nu$	1.60×10^5
Radius of the updraft hole: r_0	150mm	Non-dimensional time step : $\Delta tW_0/2r_0$	0.032
Internal aspect ratio: $a = h/r_0$	1.33	Mesh size in the radial direction	1.0～25.0mm
Radius of the exhaust outlet: r_t	200mm	Mesh size in the vertical direction	0.1～5.0mm
Radius of the convergence region: r_s	1000mm	Mesh number	784200
Velocity at the outlet: W_0	9.55m/s		
Total outflow rate: $Q = \pi r_t^2 W_0$	$0.3m^3/s$		

2.4 Modeling roughness

In the experimental studies considering the effect of ground roughness the roughness blocks are used and the roughness was changed through modifying the areal density of the blocks. Following this idea, in the numerical study by Natarajan and Hangan(2012), the surface roughness was simulated physically by adding some conical pegs on the surface of the ground. However, using this idea will bring much difficulty generating the mesh. Enoki and

Ishihara (2012) developed a method to simulate the ground roughness numerically by adding an appropriate momentum source term in the Navier-Stokes equations, as show in eq(8).

$$\rho\frac{\partial\widetilde{u}_i}{\partial t}+\rho\frac{\partial\widetilde{u}_i\widetilde{u}_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\mu\frac{\partial\widetilde{u}_i}{\partial x_j}\right)-\frac{\partial\widetilde{p}}{\partial x_i}-\frac{\partial\tau_{ij}}{\partial x_j}+f_{\widetilde{u},i} \quad (8)$$

where $f_{\widetilde{u},i}$ is the source term for the ith momentum equation and $f_{\widetilde{u},i}$ can be calculated as:

$$f_{\widetilde{u},i}=-\frac{1}{2}\rho C_{D,\widetilde{u}_i}a_{\widetilde{u}}\widetilde{u}_{mag}\widetilde{u}_i \quad (9)$$

in which $C_{D,\widetilde{u}_i}$ is the drag coefficient of the roughness and can be determined by $\min\left(\frac{1.53}{1-\gamma_u},2.75(1-\gamma_u)\right)$, γ_u is the ratio of the volume occupied by the building to that by the grid in the roughness region; the frontal area density $a_{\widetilde{u}}$ is defined as the ratio of x_i directional surface area to the fluid volume within the roughness; $\widetilde{u}_{mag}$ is the velocity magnitude. In this study we will apply this method to examine the roughness effects on the tornado.

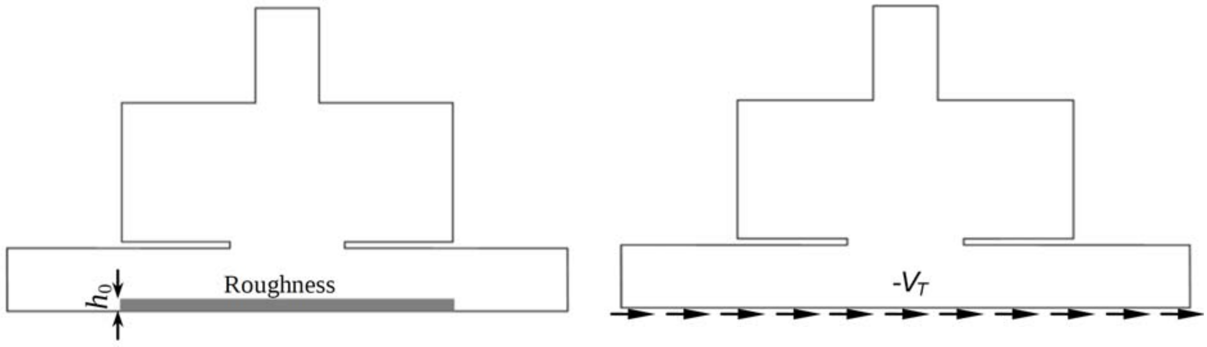
In this study we would like to examine the extreme situation, the very center of the city, therefore, 50m was chosen as the height of the roughness region, h_0 , and the roughness volume density γ_0 is supposed to be 0.25. The identical simulator as the research by Liu and Ishihara (2012) is adopted, in which the length scale was calculated as 1/1900, therefore the same value will be applied to scale the height of roughness region, as a result h_0 is determined as 0.026m. The drag force coefficients are estimated as $C_{D,\widetilde{u}_x}=2.1$, $C_{D,\widetilde{u}_y}=2.1$ and $C_{D,\widetilde{u}_z}=0.0$ by the equation proposed in the study of Enoki and Ishihara (2012). In order to let the flow develop somehow the roughness region begins from the location with some distance from the inlet, as show in Fig.2(a).

2.5 Modeling translation

Tornado translation is difficult to be simulated experimentally by using Ward type tornado simulator, since the apparatus is mounted on the ground and it is impossible to move the simulator. Diamond (1984) installed a movable ground plate in the Ward type simulator which could be propelled across the floor. The simulator is actually stationary what moving is the ground. Using the “top-down” approach, Sarkar (2008) developed a new type simulator which was supported by a crane and suspended above the ground. There is a clear region in between the simulator and the plane and the crane can translate the simulator at a speed up to 0.61m/s. Simulating the tornado translation by using Sarkar’s design is perhaps much closer to the real situation, however considering the computational convenience and that the region near the surface is of interest from the engineering point of view, we decided to model the translating effect following the Diamond’s idea, keeping the simulator stationary while moving the ground surface instead to provide an equivalent relative motion, as shown in Fig.2(b). Only a translation speed is introduced on the ground surface. In the research by Liu and Ishihara (2012) the velocity scale was calculated as 1:3.05, and with the consideration that the tornado translation speed, V_T, are found to be about 10-30m/s in nature we specify 3.3m/s in x direction on the ground surface which corresponds to the scaled speed 10m/s.

3. Results

In the following discussion, the characteristics of the tornado over rough ground will be examined firstly, and then the tornado with a translating speed will be discussed.



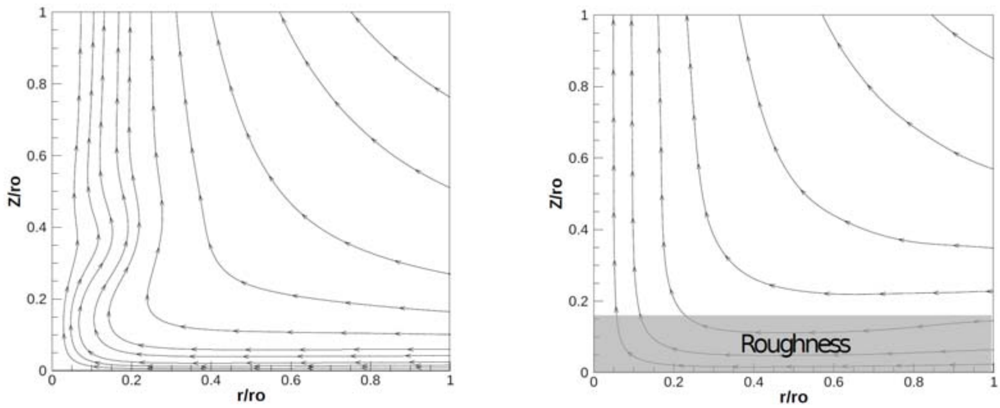
a. b.

Fig.2 Sketch map of the model (a) simulating ground roughness, (b) simulating tornado translation.

3.1 Tornado over ground roughness

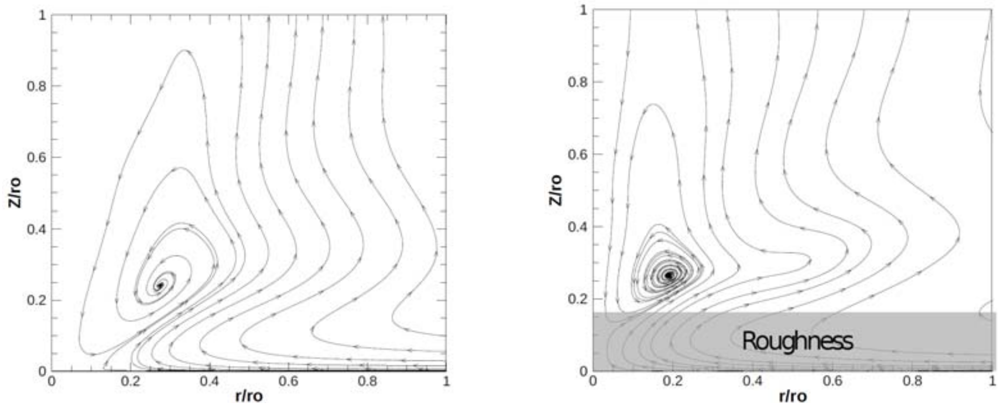
Introduction of the roughness on the ground will strongly affect the flow fields of the tornado-like vortices. Even though several studies have been conducted to examine the roughness effects, the conclusions are not consistent. The study by Natarajan (2012) covers a wide range of swirl ratios; however, the examined cases are very limited. In the present study, we systematically vary the inflow angle θ and 9 cases are studied. In the following discussion, only the flow fields of vortex breakdown and multi-vortex will be examined in detail. Vortex breakdown is the transition status therefore it should be the most sensitive to the change of the boundary conditions, and for the multi-vortex status the similarity law was found by Liu and Ishihara (2012).

Fig.3 and Fig.4 show the streamlines of the averaged flow fields in order to identify how the flow pattern changes after the introduction of the roughness. The translucency grey block indicates the region of roughness and the arrows shows the direction of the flow. It is clearly shown in Fig.3(a) that at stage of vortex breakdown, the boundary layer inflow penetrates to the center and turns upward, but the vertical flow breaks away from the vertical axis forming an expanded bubble. However, the introduction of roughness on the ground dismisses this expanded bubble which makes the flow fields much similar to those at the single vortex status, see Fig.3(b). Therefore, at the vortex breakdown stage we can safely conclude that the introduction of roughness has the effects of reducing the swirl ratio, as have been proposed by Natarajan (2012). But what needed to be stressed here is that whether roughness could reduce the swirl for all status is still should be examined. In the later we will provide a systematic analysis to answer this question and we will find that the effects of the introduction of roughness are not the simple reduction of swirl. It is more complicated than what have been realized. Increasing the swirl ratio to the status of the multi-vortex the radial jet can not penetrate to the center but moves upward and outward at a stagnation ring as shown in Fig.4(a). The introduction of the roughness disturbs the flow fields especially for the region very close to the ground, see Fig.4(b). The roughness makes the inner downward flow difficult to touch the ground. Actually the inner downward flow is stopped just above the roughness region. However, at high elevation, the size of core is almost same with that in the smooth ground situation which is the indication that the effects of the roughness to the flow fields in the cyclostrophic region become unobvious. Another important finding is that the height at which the maximum tangential velocity appears is not affected by the roughness, still holding as almost a constant 0.01m.



a. **b.**

Fig.3 Comparison of streamlines between tornado over smooth ground (a) and that over rough ground (b) when S_E=0.6. The gray shaded area indicates the region of ground roughness. The arrows show the direction of the fluid's motion.

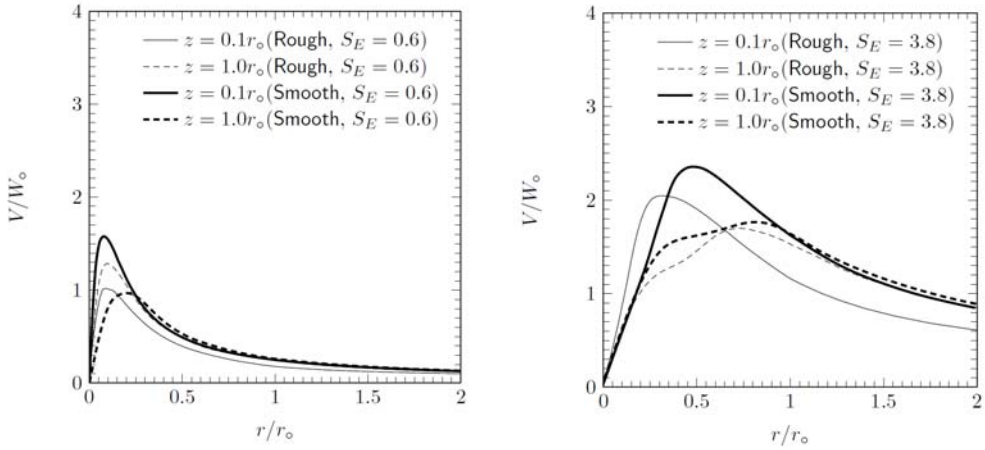


a. **b.**

Fig.4 Comparison of streamlines between tornado over smooth ground (a) and that over rough ground (b) when S_E=3.8. The gray shaded area indicates the region of ground roughness. The arrows show the direction of the fluid's motion.

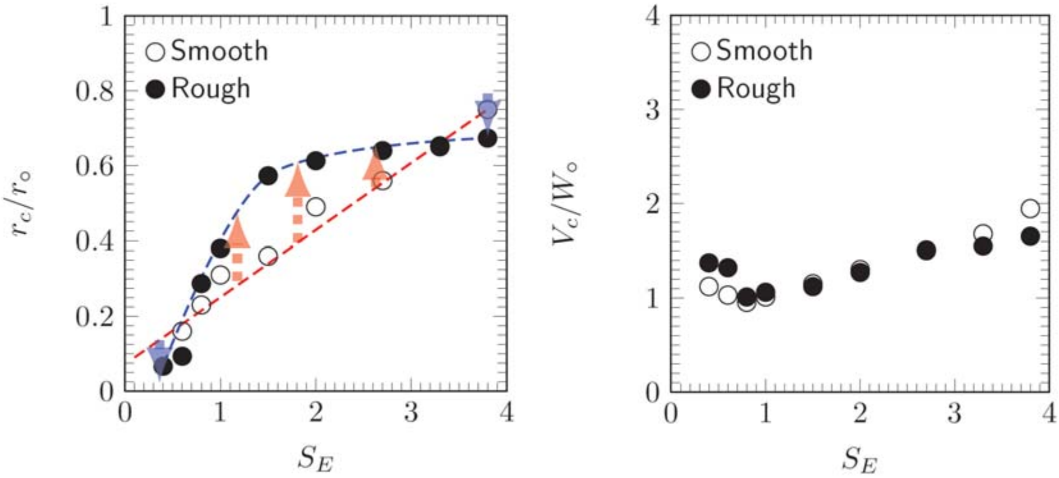
As have been explained in the front discussion, we will only examine the profiles when S_E=0.6 and S_E=3.8. The radial profiles of normalized tangential velocity for S_E=0.6 and S_E=3.8 cases are shown in Fig.5 (a) and (b) respectively and the corresponding thick lines are the profiles when the ground is smooth. It is clear that when S_E=0.6 the near ground overshoot disappeares after the introduction of the roughness and the peak of the tangential velocity at low elevation become smaller than that at high elevation, indicating the flow pattern changes to single vortex which agrees with the discussions about the streamlines before. For S_E=3.8, the maximum value at $z = 0.1r_\circ$ is smaller compared with that in the smooth ground situation and the location of this maximum tangential velocity becomes closer to the center. At high elevation the tangential velocity decreases after the introduction of roughness and the peak moves inward a little.

Several researches have been conducted to clarify how the tornado translation or the ground roughness affects the core of the tornado (r_c) and the maximum tangential velocity (V_c) at high level. In those studies, the angle of inflow was kept as a constant and the researchers examined how r_c and V_c change after the introduction of the ground roughness or tornado translation. Therefore, the same approach will be applied to do the examination in this study.



a. **b.**

Fig.5 Comparison of radial profiles of the normalized tangential velocity between tornado over rough ground and that over smooth ground when (a) S_E=0.6 and (b) S_E=3.8.



a. **b.**

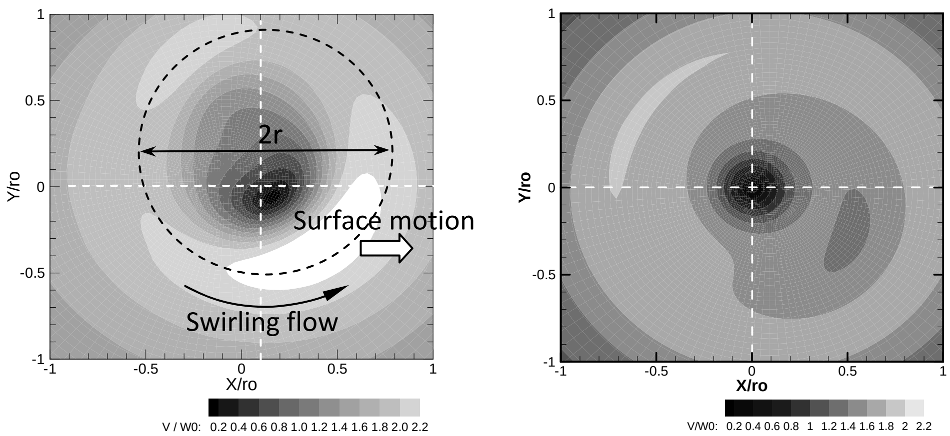
Fig.6 Comparison of normalized (a) r_c and (b) V_c versus S_E between tornado over rough ground and that over smooth ground. Blue arrow indicates decreasing and the red arrow indicates increasing.

The introduction of the ground roughness disturbs the core strongly as shown in Fig.6(a). For the external swirl ratio in between 1 and 3.5, the ground roughness will expand the size of the tornado showing the largest expansion at the stage just after vortex touching down. But for the very high swirl ratio cases, the ground roughness show the effect reducing the core size. Because of the limited cases in the previous studies, the range of swirl ratio is not as wide as that in this study. This may be the reason why some researchers argued that the roughness will enlarge the core whereas some others decrease. The normalized V_c versus S_E is plotted in Fig.6(b). The introduction of the ground roughness will introduce some discrepancies for V_c. When the external swirl ratio is very small the ground roughness will increase V_c, however, with increasing the swirl this effect will reverse. Comparing with the effect to the tornado core size, we can find the effect to V_c due to ground roughness is not so much and it is satisfactory to conclude that V_c can be determined only by the inflow angle.

3.2 Translating tornado

In this simulation, the translating tornado vortex is seen as reference frame; therefore the ground surface was set to move in the opposite direction. Superposing a translation velocity will disturb and break the axisymmetry of the flow fields as shown in Fig.7.

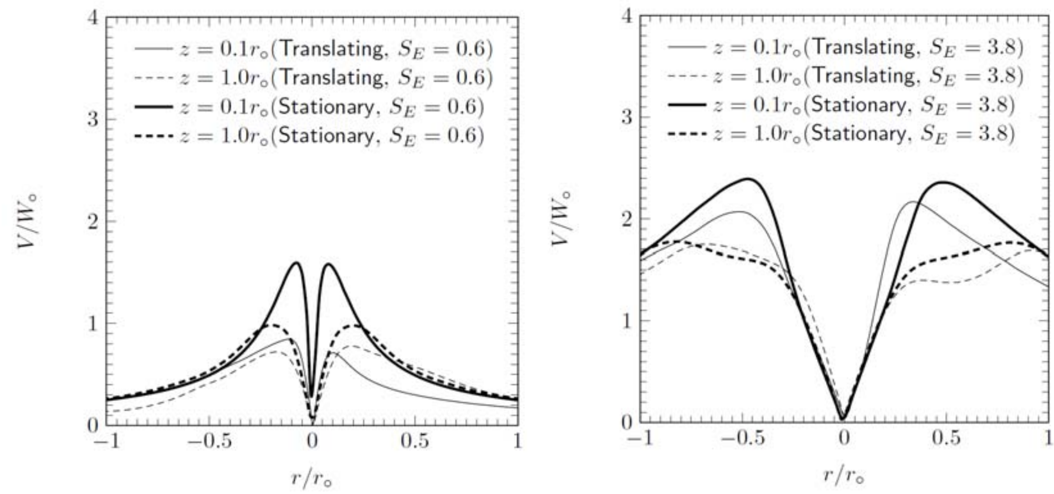
The disturbance of the axisymmetry of the tornado like vortex due to translation brings much difficulty to identify the radius of the tornado core; therefore it is meaningful to give a brief introduction of the way to determine this parameter. We take one horizontal slice for example, as shown in Fig.7(a), where the mean tangential velocity is plotted. This slice is extracted from the case S_E = 3.8 with height of $0.1r_0$. The large hollow arrow indicates the direction of the added velocity on the ground, and the black arrow illustrates the tornado rotation direction. The boundary of the core is identified by fitting the ridge of mean tangential velocity contour shown in dashed black line. And the white dashed lines are the axis with x= 0 as well as y= 0 in order to clearly show the position of the tornado. At low elevation the flow fields are obviously asymmetric but at very high elevation the flow fields become symmetric again, since the center of the tornado coincides the center of the simulator. The legends of the contour shown at the bottom of the two figures have the same scale in order to provide some information about the evolution of the wind speed with height.



a. **b.**

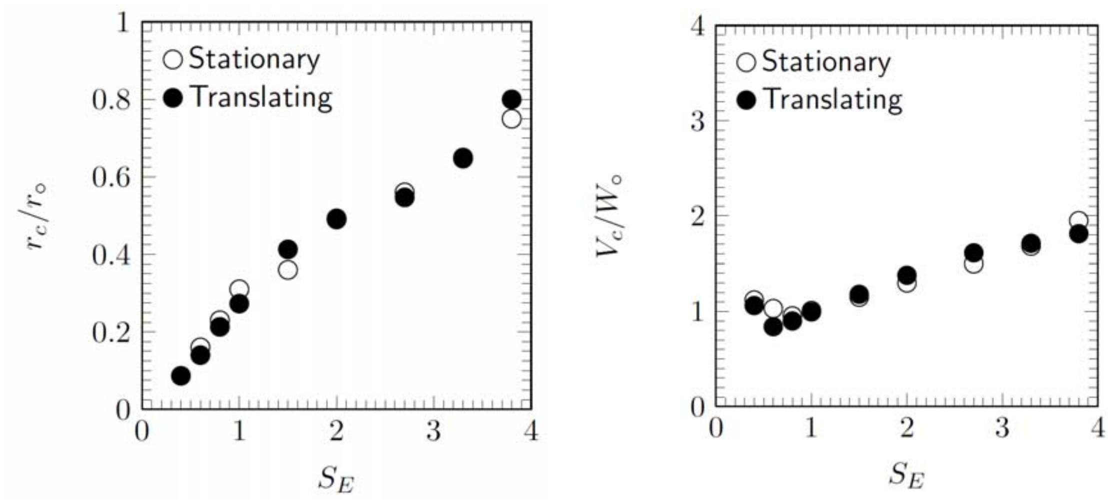
Fig.7 Contour of tangential velocity when the tornado is translating and over smooth ground for S_E = 3.8 at (a) $z = 0.1r_\circ$ and (b) $z = 1.0r_\circ$.

The velocity components are extracted to draw the profile; however, the data plotted here does not on the line passing through the center of the simulator, since the center of the tornado now does not coincide with that of the simulator. Therefore, for plotting profiles, we firstly find the location where the horizontal velocity shows zero value. This location is considered as the center of the tornado at this height. Then the data on the line crossing the tornado center and aligning with x axis were extracted. Drawing the profile in this direction is out the consideration that x is the direction of the ground motion and in this direction the profile of the parameters may show the asymmetry most obviously. For S_E=0.6, at the height of $0.1r_\circ$, the center of the tornado locates at $x = 0.3r_\circ$ and $y = 0.01r_\circ$; at the height of $1.0r_\circ$, the center of tornado locates at $x = 0.01r_\circ$ and $y = 0.01r_\circ$. For S_E=3.8, at the height of $0.1r_\circ$, the center of the tornado locates at $x = 0.1r_\circ$ and $y = 0.1r_\circ$; at the height of $1.0r_\circ$, the center of tornado locates at $x = 0.03r_\circ$ and $y = 0.02r_\circ$. Another thing needed to be pointed out is that the profile drawn here have been transmitted to the center of tornado, which means the x axis in the plotting shows the location relative to the tornado center instead of that of the simulator in order to clearly show comparison with the stationary cases.



a. **b.**

Fig.8 Comparison of radial profiles of the normalized tangential velocity between stationary tornado and that with a translating speed when (a) S_E=0.6 and (b) S_E=3.8.



a. **b.**

Fig.9 Comparison of normalized (a) r_c and (b) V_c versus S_E between stationary tornado and that with a translating speed.

The radial distribution of the tangential velocity for both the stationary cases and the translating cases are show in Fig.8. In order to do the discussion conveniently we define the positive x region as the back side and the minus one as the front side. When the external swirl ratio equates to 0.6, it can be found that the tangential velocity decreases with the introduction of the translation, and at the back side the tangential velocity at high elevation becomes larger than that near the ground which is just opposite for the front side. For the very large swirl case the maximum tangential velocity decreases when the tornado translates, and the diameter of the tornado core at both the low and high elevations do not show obvious change. Because of the tilt, the slope of the profile near the center becomes sharp at the back side and smooth in the front.

The core radius r_c and the maximum tangential velocity at high elevation V_c are also plotted versus S_E to examine whether the translation of tornado will affect them, as shown in Fig.9. It can be found that r_c as well as V_c does not change very much, therefore we can argue that the core radius and the maximum tangential velocity at high elevation can be determined only by the external swirl ratio no matter the tornado is stationary or translating.

4. Conclusions

1. The introduction of the ground roughness stopped the inner downward flow at the height of the roughness region. In the roughness region the vertical velocity is upward. And the height of the maximum tangential velocity is not affected by the ground roughness, still locates at about 0.01m.
2. The translation disturbs the symmetry of the tornado, making the flow fields much more complicate. Because of the added shear stress on the ground surface, the contour of mean tangential velocity does not show concentric circles anymore. On the side of vortex where the motion of the ground is aligned with the motion of the fluid the angular momentum is enhanced and on the opposite side reduced.
3. At the high elevation, V_c and r_c shows the same trend versus the external swirl ratio no matter the translation of tornado is introduced. However, if the ground is rough, the core radius at high elevation changes dramatically. The ground roughness will expand the size of the tornado core. But for the very small and very high swirl cases, the ground roughness show the effect reducing the tornado core size.

References

Dessens, Jean, Jr., (1972). "Influence of ground roughness on tornadoes: A Laboratory Simulation", Journal of Applied Meteorology 11, 72-75.

Diamond, Chris J.; Wilkins, Eugene M., (1984). "Translation effects on simulated tornadoes", Journal of Atmospheric Seiences 41, 2574-2580.

D. Natarajan and H. Hangan, (2012). "Large eddy simulation of translation and surface roughness effects on torando-like vortices", Journal of Wind Engineering and Industrial Aerodynamics 104-106, 577-584.

Ferziger, J. and Peric, M, (2002). "Computational method for fluid dynamics", 3rd Edition, Springer.

Haan, F.L., Sarkar, P.P., (2008). Gallus, W.A., "Design, construction and performance of a large tornado simulator for wind engineering applications", Engineering Structures, 30, 1146-1159.

Enoki, K. and Ishihara, T., (2012). "A generalized canopy model and its application to the prediction of urban wind climate", Journal of Japan Society of Civil Engineering A1 68, 28-47. (in Japanese)

Lewellen, D.C., Lewellen, W.S. and Xia. J, (2000). "The influence of a local swirl ratio on tornado intensification near the surface", Journal of the Atmospheric Sciences 57,527-544.

Leslie, Fred W., (1977). "Surface Roughness Effects on Suction Vortex Formation: A Laboratory Simulation", Journal of Atmospheric Sciences 34, 1022-1027.

Liu, Z. & Ishihara, T., (2012). "Effects of the Swirl Ratio on the Turbulent FlowFields of Tornado-like Vortices by using LES Turbulent Model". 7th International Colloquium on Bluff Body Aerodynamics and Applications, Shanghai, China.

Monji Nobutaka and Wang Yunkuan, (1989). "A laboratory investigation of characteristics of tornado-like vortices over various rough surfaces", ACTA Meteorologica Sinica 47, 34-42.

Oka,S. and Ishihara,T., (2009). "Numerical study of aerodynamic characteristics of a square prism in a uniform flow. Journal of Wind Engineering and Industrial Aerodynamics", 97, 548–559.

Wei Zhang and Partha. P. Srakar, (2008). "Effects of ground roughness on tornado-like vorte using PIV", AAWE workshop, Vail, Colorado.