Terrain numerical simulation based on RANS/LES hybrid turbulence model

Lu Xiegui\textsuperscript{1}, Chen Qiuhua\textsuperscript{2}, Qian Changzhao\textsuperscript{2}, Chen Changping\textsuperscript{1,2,3}
\textsuperscript{1} School of Architecture and Civil Engineering, Xiamen University, Xiamen, China; \textsuperscript{2} Haixi Wind Engineering Research Center, Xiamen University of Technology, Xiamen, China; \textsuperscript{3} Xiamen Ocean Vocational and Technical College, Xiamen, China; E-mail: cpchen@126.com

Abstract. Based on the computational fluid dynamics (CFD) method, the terrain of 2 km near the proposed humanoid landscape bridge in Xiamen is taken as the research object. Firstly, the three-dimensional topographic map is established. Because the selected terrain is relatively flat, the bridge area is adopted in the form of spline curve. The boundary is extended, and the exponential rate of wind speed boundary conditions is applied to the boundary to avoid non-0m/s wind speed from the inflow near wall boundary. The RANS/LES hybrid mode is used to numerically analyze the external flow field of the terrain. The $2-\nu\varepsilon\kappa$ turbulence model of the three equations is used as the RANS part of the RANS/LES hybrid turbulence model. According to the Boussinesq hypothesis and dimension-analysis, the differential form equations of $\nu^2$ are rationally simplified, and the algebraic form of the normal stress equation of $\nu^2$ and the new turbulent viscosity equation are obtained and written into FLUENT in UDF form. By comparing and analyzing the standard $\kappa-\varepsilon$ turbulence model and the $\omega-\kappa$ turbulence model, the wind speed amplification factor and the variation law of wind parameters along the height are studied, and the canyon effect and the reduction effect of the wind field are discussed. The results show that under the same calculation conditions, the mixed turbulence model can accurately reflect the change of airflow in the near-wall wall, and more accurately capture the wind field away from the bridge near the wall.

1. Introduction
In many numerical simulations of terrain, there are often engineering backgrounds of long-span bridges. This makes our focus not only on accurately simulating the near-surface flow characteristics and capturing the flow separation characteristics, but also on the flow field far from the bridge location in a certain height near the ground. Therefore, we attach great importance to the selection of turbulence model. Li Yongle et al\textsuperscript{[1-2]} used the laminar flow model to simulate the 8km\times8km regional terrain wind field in the deep-cut canyon bridge site, and compared the wind speed along the height under different working conditions, and proposed the general classification of the canyon wind field. According to the variation characteristics of the wind speed along the main beam, the joint distribution of average wind speed and wind angle of attack is obtained. Zhang Yue et al\textsuperscript{[3]} studied the wind environment near the site of a cable-stayed bridge in the western mountainous area, and compared the actual measurement with the numerical simulation using the $SST\kappa-\omega$ turbulence model and the Realizable$\kappa-\varepsilon$ turbulence model. Zhang Xiangxu et al\textsuperscript{[4]} analyzed the wind field of a large-span arch bridge in the mountainous area of western China, and used the circular curve and cosine curve to expand the terrain boundary. The $SST\kappa-\omega$ turbulence model was used to simulate the wind field.
Uchida and Ohya[5] used the large eddy simulation method to study the air flow on complex terrain, and discussed two different grid schemes, and obtained the distribution of average wind speed and pulsating wind speed. In the turbulence model, large eddy simulation is a turbulent numerical simulation method between direct numerical simulation (DNS) and RANS[6], which is the most rapidly developing turbulence model in recent years. The main idea is to directly solve the large-scale eddy in the flow field and establish a model for small-scale turbulent pulsation. For complex terrain where the flow field changes more severely, the resolution requirements of the grid are also higher. In order to solve the above-mentioned problem: the near-wall wall capture flow characteristics, the bridge site is concerned with the wind field distribution. This paper adopts the RANS/LES hybrid mode, and the idea is to simplify the use of Reynolds at the near wall to reduce The number of small grids, while large eddy simulation in the far field, captures the flow field characteristics at the bridge site height. Among them, the three-equation $\kappa - \varepsilon - v^2$ turbulence model is chosen as the RANS model in the mixed turbulence model.

2. $\kappa - \varepsilon - v^2$ Turbulence model simplification

LAUNDER[7] pointed out that the normal stress of the vertical wall has a great influence on the turbulent kinetic energy and accounts for a large proportion of the eddy viscosity coefficient when studying the low Reynolds number turbulent flow near the wall. In response to this conclusion, Durbin[8] constructed a vertical wall normal stress $v^2$ equation based on the standard $\kappa - \varepsilon$ turbulence model, and closed the RANS equation by using the near-wall elliptic relaxation function equation ($f$) to obtain the $\kappa - \varepsilon - v^2$ turbulence model. And the governing equations for $v^2$ and $f$ are[8]:

$$
\frac{\partial (\rho v^2)}{\partial t} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial v^2}{\partial x_j} \right] + \rho f v^2 - \rho v^2 \frac{\varepsilon}{\kappa}
$$

$$
L^2 \frac{\partial}{\partial x_j} \left( \rho \frac{\partial f}{\partial x_j} \right) = \rho f + \rho c_\varepsilon \left( \frac{2/3 - v^2/\kappa}{T} \right) - c_2 \frac{p_x}{\kappa}
$$

In this equation,

$$
\mu_t = \rho \sigma_{\mu} v^2 T
$$

$$
P_x = \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
$$

$$
T = \max \left( \frac{\kappa}{\varepsilon}, \frac{6}{5} \left( \frac{v^2}{\varepsilon} \right)^{0.5} \right)
$$

$$
L = 0.3 \max \left( \frac{\kappa^{1.5}}{\varepsilon} c_\eta \left( \frac{v^3}{\varepsilon} \right)^{0.25} \right)
$$

And $c_\mu = 0.19$, $c_\eta = 70$, $\sigma_\kappa = 1.0$, $c_1 = 1.4$, $c_2 = 0.3$

The $\kappa - \varepsilon - v^2$ turbulence model does not use the wall function in the near wall area, and the turbulence has anisotropic characteristics, which can more accurately simulate the flow separation phenomenon.

To build a RANS/LES hybrid turbulence model, the $\kappa - \varepsilon - v^2$ turbulence model needs to be simplified. According to the Boussinesq hypothesis[9], the momentum transfer caused by turbulent eddies can be expressed by the eddy viscosity coefficient:

$$
\tau_{ij} = 2 \mu_t S_{ij}^* - \frac{2}{3} \rho k \delta_{ij}
$$
Here $\mu_t$ is called the eddy viscosity coefficient. Let $i = j = 2$, and substitute $v_i = c_\mu v^2T$ in the $\kappa - \varepsilon - v^2$ turbulence model into the eddy viscosity coefficient to get:

$$\frac{v^2}{\kappa} = C_1 \left(1 - C_2 \frac{v^2 \partial y}{\varepsilon \partial y}\right)$$

In this equation, $C_1$ and $C_2$ are constants. Through dimensional analysis, taking $y^* = yk^{1/4} k^{1/2} / v$, and $I^* = \kappa^{3/2} (\partial y)$, the equation can be rewritten as a dimension form\[^{10}\]:

$$\frac{v^2}{\kappa} = C_1 \left(1 - g(y^*, I^*)\right)$$

Where $g(y^*, I^*)$ is the pending function. Assuming that the value tends to infinity, ie away from the wall, the turbulence should be a uniform flow, which exists\[^{10}\]:

$$\frac{v^2}{\kappa} = C_1 \left(1 - g(y^*, I^*)\right) \xrightarrow{y^* \to \infty} C_1$$

When $y^*$ is very infinitely close to 0, the normal kinetic energy tends to 0, and you can get:

$$\frac{v^2}{\kappa} = C_1 \left(1 - g(y^*, I^*)\right) \xrightarrow{y^* \to 0} 0$$

It is assumed that the wall damping effect is only related to the geometry, and the influence of the turbulent vortex scale $I^*$ can be ignored. Using the exponential function instead of $g(y^*, I^*)$, the algebraic form of the normal stress $v^2$ equation can be obtained:

$$\frac{v^2}{\kappa} = A \left(1 - \exp\left(-\frac{y^*}{B}\right)\right)$$

Where $A$ and $B$ are pending coefficients. The $\kappa - \varepsilon - v^2$ turbulent viscosity in the final turbulence model translates into:

$$v_t = c_\mu A \left(1 - \exp\left(-\frac{y^*}{B}\right)\right) \kappa T$$

In order to determine the undetermined coefficients $A$ and $B$, the original $\kappa - \varepsilon - v^2$ turbulence model can be activated by using the TUI command in FLUENT to obtain the velocity variances $v^2$, $y^*$ and the turbulent kinetic energy value $\kappa$ at different monitoring points, and curve fitting is performed, thereby obtaining $A = 0.638$ and $B = 69.71$ in reverse.

Write a UDF (User Define Function) to write the new turbulent viscosity to the definition of the turbulent viscosity of the RANS/LES hybrid model.

3. CFD numerical simulation model

Figure 1. Bridge floor plan  
Figure 2. Bridge renderings
3.1. Geometric Modeling and Meshing
This paper takes the site selection of a proposed pedestrian walkway in Xiamen as the research object. The long-span humanoid bridge has high flexibility, is more sensitive to incoming wind, and is more prone to bridge flutter and vortex vibration. Therefore, it is of certain importance to study the wind environment of bridges in this area, as shown in Figure 1, Figure 2.

In this paper, we use GoogleEarth combined SketchUp to obtain 2km*2.5km geographic data of the bridge site and establish a three-dimensional geometric model. The location area of the bridge is located in the urban area, and the overall terrain is relatively flat. In order to avoid the assumption that the near-surface boundary conditions do not satisfy the non-slip wall surface, the near-surface wall at the inlet is guaranteed to have a wind speed of 0 m/s. The spline is used to widen the terrain to a certain extent[4], so that the terrain data is at the same elevation at the boundary entrance, as shown in Figure 3.

Figure 3. Bridge topography extension

Figure 4. Structured grid generation

Use the ICEM in Ansys to divide the terrain into a three-dimensional structured grid, as shown in Figure 4. The maximum resolution of the grid is 4×4m, the height of the first layer grid is 0.3m, the expansion ratio between two consecutive cells was limited to 1.2, and finally 6.23 million hexahedral meshes are obtained. Grid quality is higher than 0.7.

3.2. Basic calculation of wind speed and wind direction
The basic wind speed is in accordance with the maximum wind speed in Xiamen City in one hundred years. The maximum wind speed at the height of 10 meters is 39.7m/s. According to the B type landform, the ground roughness coefficient is \( \alpha = 0.16 \), and the wind profile is distributed according to the exponential rate. The expression is as follows:

\[
U(z) = 39.7 \times \left( \frac{Z}{10} \right)^{0.16}, \]

the inflow profile wind is realized by editing the UDF file. The wind speed at the speed entrance is as follows (where \( h_0 \) is the lowest point elevation of the wind speed entrance):

When elevation \( H \geq h_0 + 350m \), \( V_\infty = 70.12m/s \)

When elevation \( H \leq h_0 \), \( V_\infty = 0m/s \)

When the elevation \( h_0 \leq H \leq h_0 + 350m \), \( V_\infty = 39.7 \times \left( \frac{Z}{10} \right)^{0.16} \)

In this expression, \( Z \) is the point position elevation (unit: m) at the entrance boundary; \( V_\infty \) is the velocity inlet flow velocity (unit: m/s).

Statistical analysis of meteorological data in Xiamen for nearly 30 years, using the Origin Pro software to draw a typical wind rose map of Xiamen, as shown in Figure 5. The figure shows the wind speed combined wind frequency distribution in 16 directions in Xiamen. It can be seen from the figure that the dominant wind direction in Xiamen is the E direction.
3.3. Boundary conditions and turbulence models
The numerical simulation uses Fluent calculation software, which uses SSTk-ω model, standard k-ε turbulence model and RANS/LES mixed turbulence model for comparison. Turbulence intensity is 1%, turbulent viscosity ratio is 2, time dispersion is second-order implicit. Gradient calculation by default Least-Squares-Cell-Based, the pressure interpolation method and other spatial discretises are second-order formats, and the SIMPLE algorithm deals with the coupling of pressure and velocity.

The boundary condition at the entrance is Inlet, and the boundary condition at the exit is the Pressure-Outlet. The terrain is a non-slip wall boundary condition, and the surrounding and top surfaces are symmetric boundary conditions (Symmetry). In the mixed turbulence model, the time step is 0.002 s. For this study the convergence criterion for all residuals was fixed at 10e-5.

3.4. Wind speed amplification factor
In the numerical simulation of terrain, the wind speed amplification factor under different wind direction conditions is usually used to judge whether the terrain has the effect of amplifying or reducing the wind speed for the incoming flow. It is generally considered that the ratio of the actual wind speed at the bridge location in the canyon to the wind speed at the inlet boundary condition at the same height is defined as the wind speed amplification factor[11]. The wind speed amplification factor is defined in the following equation:

\[ C_u = \frac{v_i}{v_0} \]

In this expression: \( v_i \) is the monitored wind speed at the bridge point, and \( v_0 \) is the inlet boundary wind speed at the same height.

4. Numerical simulation results analysis
4.1. Influence of three turbulence models on profile wind
Taking the E direction of the maximum probability wind direction as the inflow direction, the relative position of the bridge is selected as the west bridge tower, the bridge 1/4 span, the middle bridge span, the bridge 3/4 span and the east bridge tower as the monitoring points. The wind profile of three
turbulence models and the wind speed amplification factor of mixed turbulence model at eight angles of attack are plotted, as shown in Fig. 6.

As can be seen from the figures (a), (b), (c), there are some differences in the wind profiles presented by the three turbulence models. The wind speed of the \( \kappa - \varepsilon - v^2 / LES \) turbulence model varies smoothly along the elevation, while that of the \( \kappa - \varepsilon - v^2 / LES \) turbulence model varies sharply along the elevation. From the figure (c), it can be seen that there is a wind speed close to 50 m/s in the 10 m elevation range, which is different from the other two turbulence models at the same altitude as the assumption of the inflow profile wind. The magnification effect of terrain on the wind speed is highly evaluated. It can be seen from figure (d) that the maximum wind speed amplification factor is 1.18 and the minimum reduced wind speed factor is 0.845 for the mixed turbulence model at eight angles of attack. It can also be seen from the figure that the annual wind direction E wind speed amplification factor is 1.08.

4.2. Velocity nephograms of three turbulence models at different contours
The height of 0.5m, 1m, 10m to 200m (10m interval) near the ground is taken as the observation object. We can see the velocity nephogram of the whole topographic field of three turbulence models in different contour ranges as shown in Fig. 7.
From Fig. 7 (a), (b), (c), it can be seen that the three turbulence models are in a lower range of relative wind speed at the location of bridge, i.e. A1, A2 and A3 in the figure, and there is no Canyon effect of rapidly increasing wind speed. It can be seen from A4 in figure (d) that the dynamic pressure varies greatly and the wind speed distribution is not uniform at this position. By comparing B1, B2 and B3, it can be seen that the standard $\kappa - \epsilon$ turbulence model and $\omega - \kappa$ SST turbulence model have poor wind capture characteristics at position B, and do not really reflect the real situation of wind speed change at that location. However, the $\kappa - \epsilon - v^2 / LES$ turbulence model can better reflect the real situation of wind field change at that location.

5. Conclusion
1) The numerical results show that compared with the other two turbulence models, the $\kappa - \epsilon - v^2 / LES$ mixing turbulence model is better in evaluating the wind speed in the wind profile. The reason is that the $\kappa - \epsilon - v^2$ turbulence model used in the RANS term of the mixing turbulence model, which takes into account the anisotropic characteristics of the turbulence near the wall.
2) $\kappa - \epsilon - v^2 / LES$ mixed turbulence model performs well in numerical simulation of complex terrain, and can accurately reflect the actual appearance of terrain wind field. The reason is that the mixed turbulence model uses large eddy simulation at the far end of the wall. This simulation method is more accurate than other models in capturing the flow changes of space flow field.
3) It can be seen from the numerical simulation that there is no obvious Canyon effect in the location of the bridge under the condition of the topographic location. Under the condition of perennial wind direction, the wind speed amplification factor is 1.08, which is acceptable in practice.

6. References

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Acknowledgments

The authors would like to acknowledge with great gratitude for the supports of the national science foundation of China (grant no: 51778551), the science and technology plan project of Xiamen (grant No: 3502Z20161016).