CFD-Based Wind Field Correction Method for Terrain Wind Tunnel Tests

Qi Zhou1, *, Yuxiang Zhu2, Yu Wang3, Jiceng Han4

1 Department of Civil Engineering, Shantou University, Guangdong Shantou, China
2 Department of Construction, State Grid Zhejiang Electric Power Co. LTD, Zhejiang Hangzhou, China
3 Wenzhou Company, State Grid Zhejiang Electric Power Co. LTD, Zhejiang Wenzhou, China
4 Electric Power Research Institute, State Grid Fujian Electric Power Co. LTD, Fujian Fuzhou, China

*Corresponding author e-mail: zhouqi@stu.edu.cn

Abstract. At present, the wind tunnel test results will have certain deviation and distortion when the wind tunnel test is conducted on certain mountainous terrain with complex local terrain and large variation of wind field characteristics due to the accuracy range of the measuring instruments used in wind tunnel test. In order to correct and obtain correct wind tunnel test results, the wind tunnel tests and numerical simulations were conducted on a super-large bridge in the mountainous area of Southwest China, and the wind parameters of the wind field at the bridge site were obtained. The CFD results were compared with the wind tunnel test results to confirm the credibility of the CFD results; a method was proposed to correct the deviated wind tunnel test data based on the CFD simulation results; the deviated wind tunnel test data were corrected and predicted with the above method, and a more satisfactory correction result was obtained.

Keywords: Canyon wind field; wind field at bridge site; wind tunnel test; CFD simulation; correction method.

1. Introduction
In recent years, China has been paying more and more attention to the construction of the transportation system in Western China, and there are more and more large-span bridges across the mountainous areas. Unlike the plains or coastal mountainous areas, the wind field often has complex 3D characteristics at the large-span bridges’ site in mountainous areas. At present, many results have been achieved in the study of wind field characteristics in such mountainous terrain, but the wind field data collected from the terrain wind tunnel tests are still subject to certain deviations and distortions due to the accuracy of the measuring instruments currently used, which have a great impact on the subsequent engineering practical application. Therefore, it is necessary to find a simple and easy method to correct the wind field results of terrain wind tunnel tests based on CFD simulation results.
At present, the results achieved in the study of wind field characteristics of mountainous terrain from the field measurements and wind tunnel tests are as follows: Chen Qixin [1] found that the airflow in mountainous canyons has a strong “funnelling effect” according to field wind velocity observations; Chen Zhengqing [2] took the terrain of Ai Village Bridge site across Dehang Grand Canyon as the study object and found that the distribution of the mean wind velocity profile along the bridge span direction in the canyon could not be expressed in the form of a uniform profile; DeBray [3] studied the flow of individual steep hills and slopes through the wind tunnel tests, giving wind velocity models for different height positions for both upstream and downstream of the slopes. On the other hand, the application of CFD numerical simulation methods in the study of wind characteristics of wind fields in mountainous terrain is also rapidly developing: Yamaguchi et al [4] studied the wind field characteristics in complex canyon terrain through the wind tunnel tests and numerical simulations; Uchida [5] obtained the wind acceleration effect and flow separation phenomenon in a real complex terrain of 9.5km × 5km by numerical simulations; Hu Fengqiang et al [6, 7] used the RNG k-ε turbulence model to completed the numerical simulation of the terrain of the Beipanjiang Bridge site; Zhou Zhiyong [8] completed the grid modeling of a large complex terrain of 23km×27km, and analyzed the wind profile, pressure field, and velocity field etc. at the monitoring site of this area; Li Yongle et al [9] selected the complex terrain of 8km×8km in the area where the large-span suspension bridge is located for numerical simulation analysis under multiple conditions, and gave the distribution characteristics of the spatial wind field in the bridge site area with complex terrain; Xu Hongtao et al [10] used software to numerically simulate the wind environment at the site of super-large bridge across Xiangling River, and introduced the wind velocity amplification factor to characterize the relationship between the inspection point and the inlet wind velocity. In general, there are few studies by combining CFD results with wind tunnel tests or field measurements for terrain wind field analysis, and few studies using CFD results for wind field correction.

In this paper, the terrain near a bridge site is used as the study background, and the wind field characteristics of terrain model are studied by numerical simulation and wind tunnel test methods, the terrain model is established and the structured mesh is divided. Finally, the results of numerical simulation and wind tunnel test are combined to correct the distorted data caused by the angle of the flow line, and a simple and applicable correction method is derived therefrom.

2. Wind Tunnel Test of Terrain Model
The wind tunnel test terrain model was established for the terrain that is selected in a 10km diameter range with the main span of a super-large bridge as the center. The geometric scaling ratio of the model was 1:2200 and the diameter was about 5.5m. The wind tunnel blockage ratio of the terrain model was 9.87%, which meets the wind tunnel test’s requirements. In the test, the terrain model was fixed on a large turntable with a diameter of 6.7m in the TJ-3 wind tunnel in order to test the wind parameters of the terrain model under the effect of incoming flow with different wind angles, as shown in Figure 1. The setting of different wind angle conditions and measurement points of the terrain wind tunnel test are shown in Figure 2.

Figure 1. Wind tunnel terrain model
Figure 2. Schematic diagram of test conditions
3. Numerical Simulation of Terrain

3.1. Geometric Model and Computational Domain
During the geometric modeling, the same modeling area as the wind tunnel test terrain model was selected to derive a smooth 3D terrain surface model, as shown in Figure 3. The dimension of the computational domain was also established according to the actual dimension of the wind tunnel, where the width of the computational domain was taken as 15m, the height of the computational domain is taken as 2m in order to make the flow fully developed, and the computational domain is taken as 10 times the model diameter in the length direction. The dimensions of the computational domain and the boundary conditions are shown in Figure 4.

![Figure 3. 3D terrain surface model](image1)

![Figure 4. Computational domain of model](image2)

3.2. Meshing Method
The overall mesh generation method was selected as the hexahedral structured mesh and the mesh was densified in the core area near the mountain massif, where the minimum mesh scale of the densified area was set to 10m. Meanwhile, the mesh of boundary layer is set in the height direction, and the mesh height of the first boundary layer was calculated to be 0.00045m on the basis of \( y^+ = 1 \) required by the LES model, and the final total computational cells of the whole domain is about 10 million. Figure 5-7 shows the schematic diagram of the overall mesh of the computational domain, the locally densified mesh in the canyon area and the ground boundary layer mesh.

![Fig. 5 Overall mesh of model](image3)

![Fig. 6 Locally densified mesh](image4)

![Fig. 7 Boundary layer mesh](image5)

3.3. Turbulence Model and Boundary Conditions
In this paper, the standard \( k-\varepsilon \) turbulence model was first used for steady computation whose results were initialized as the initial flow field for transient computation, and then the turbulence model was changed to large eddy simulation (LES) for following computation, the standard Smagorinsky model was used as the wall model, the SIMPLEC algorithm was used for the solution of the control equations, the discrete format of the flow convective term, momentum and dissipation rate equations were of second order upwind, and the time step of LES was taken as 0.001s. The boundary conditions of the computational domain were set as follows: The upstream inlet boundary on the left side of the computational domain was the velocity inlet, and the incoming wind velocity and direction were given as: \( u = 12.5m/s, v = 0, w = 0 \).
4. Wind Tunnel Test Results and Correction Methods

4.1. Comparison of Results

Figure 8 shows the comparison between the numerical simulation and the wind tunnel test results of the mean wind velocity profile at the A-side bridge tower, B-side bridge tower and the mid-span measurement point. It can be seen that the numerical simulation results of the mean wind velocity profile trends and the wind tunnel test trends are basically the same, but the numerical simulation results on both sides of the bridge towers produce deviations from the test results, and the growth trend differs significantly from the exponential law.

Further observation of the incoming wind angle near the bridge deck shows that the angle of the incoming flow at the towers on both sides is not completely perpendicular to the main span of the bridge, and there is a large deviation angle, as shown in Figure 9. It can be found that the deviation angle of incoming wind directly leads to a large difference between the wind tunnel test results and the numerical simulation results at the A-side and B-side bridge towers, which the altitude by the terrain ranges about 2,200-3,200m above sea level. Since the wind tunnel test results are no longer credible due to the above phenomenon, it is necessary to find a simple and effective correction method to correct the wind tunnel test results at the bridge towers on both sides and make the corrected data results more credible. To this end, the following correction method is proposed.

4.2. Correction Method Based on Credible CFD Results

In order to correct the wind tunnel test results that are deviated by the angle of the incoming flow line, the existing numerical simulation results are considered for processing. First of all, the credibility of the numerical simulation results should be verified by the following method: Since the incoming wind direction at the mid-span measurement point is basically perpendicular to the direction of the main span of the bridge, the wind tunnel test results at this point can be assumed to be relatively credible, and the difference between the two results at the mid-span measurement points was found through comparison to be less than 5% at the corresponding heights, which proves that the CFD results are credible at the
mid-span. Further, based on the credible CFD results at the mid-span, the wind tunnel test results at other measurement points due to the incoming flow angle are corrected as follows: With the CFD results at the mid-span as the reference value, calculating the ratio of the reference value and the measurement points of the bridge towers on both sides; then with the wind tunnel test results at the mid-span as the reference, using the mentioned ratio as the correction factor, the wind tunnel test results at the measurement points of the bridge towers on both sides are corrected according to the following equation:

$$ U_z = U_1 \times \frac{V}{V_2} $$

wherein: $V_1$ refers to the CFD simulation result at the reference point; $V_2$ refers the CFD simulation result at the point to be corrected; $U_1$ refers the wind tunnel test result at the reference point; $U_2$ refers the corrected wind tunnel test results.

4.3. Comparison of Corrected Results

After corrected by the above method, the comparison of the wind tunnel test results and the CFD results at the measurement points of the bridge towers on both sides is shown in Figure 10.

It can be seen that the corrected test data is in good agreement with the CFD data, and its deviation is greatly reduced compared with the uncorrected test data, and it better reflects the trend of the mean wind profile at both sides of the bridge towers, which is in good agreement with the exponential law. With this correction method, the deviation of the data due to the incoming wind angle not being perfectly perpendicular to the main span orientation is successfully eliminated.

4.4. Correction of Turbulence Intensity

The wind tunnel test results of the mean wind profile with deviations due to the large incoming wind angle were analyzed and corrected in the preceding text; furthermore, the turbulence intensity profiles obtained from the wind tunnel test were checked, and it was found that the wind tunnel test results of the turbulence intensity profiles at the same wind angle had similar problems: Namely, the CFD data did not differ much from the test data at the mid-span measurement point, and basically conformed to the trend of exponential law; however, at the measurement points of the bridge towers on both sides, the wind tunnel test data had the same problem: Namely, there was a large deviation from the CFD data in the altitude range of 2,200-3,200m, and its change trend was no longer smooth, as shown in Figure 11.
5. Conclusion

In this paper, the wind tunnel tests and numerical simulations were conducted on the terrain model of a bridge site, and wind parameters such as mean wind velocity and turbulence intensity of the wind field on the bridge site area were compared and analyzed; a wind tunnel test results’ correction method based on the numerical simulation results was proposed; the deviated wind tunnel test results due to the complex incoming wind at a specific angle of wind direction were corrected. The main conclusions obtained are as follows:

(1) From the wind tunnel test results, it can be obtained that the near-ground wind was influenced by the terrain showing some typical flow characteristics and the wind parameters in the altitude range of 2,200-3,200m were influenced by the terrain at certain angle of wind directions, and the wind tunnel test data produced certain errors.

(2) The credibility of the numerical simulation results was verified, and a correction method for the wind tunnel test results was established based on the comparison of the numerical simulation results with the wind tunnel test results.

(3) The mean wind velocity data and turbulence intensity data obtained from the wind tunnel test were corrected with the above method and the data before and after the correction were compared. The corrected wind tunnel test data had better regularity and were closer to the numerical simulation results, which could be used for further study and analysis.
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