

Appropriate shape of boundary transition section of terrain model for mountains-gorge bridge site

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ABSTRACT: To study the appropriate boundary transition section shape of terrain model for mountains-gorge bridge site, a kind of transition curves was derived based on the theory of flow around cylinder with ideal fluid, took an ideal 2D platform terrain as an analysis model to comparatively analyze the flow separation behavior and distribution characteristics of average wind field after airflow flowed along the transition section between curve transition section with equivalent angle of 30° and ramp transition section with included angle of 30° by CFD commercial software FLUENT 6.3, and the total flow transition length of different curve transition sections was also compared. The result shows that when air flows along the curve transition section with equivalent angle of 30° , the distribution characteristics of wind velocity field after airflow flowed along the transition section are much closer to the distribution characteristics of reference wind velocity field than that when airflow flows along the ramp transition section with included angle of 30° , and its total flow transition length is also the relative shortest. The research conclusions could provide some references for the terrain model studies of wind characteristics over the mountains-gorge bridge site.

KEYWORDS: mountains-gorge; terrain model; transition section; bridge site; wind characteristics; CFD

1 INTRODUCTION

When air flow over the mountains-gorge terrain, the air will subject to the blocking, uplifting and separating effects by the mountains, and the air will also subject to the channeling effect and blocking effect by the gorges. For long span bridge in the mountains-gorge terrain, wind characteristics over these bridge sites are very complex, which have a great difference compared with the bridges in the sea or river. There will be a large error if study the wind characteristic of these bridge sites according to the conventional regulation and stipulation (2004). In addition, it is difficult to have experience references from others because the complex of bridge sites terrain and every bridge sites has its own inherent characteristics. With development of the west regions of China, more bridges located in mountains-gorge terrain will be built due to the complex terrain in these regions and the limits of the transport line grade. Therefore, the study on the wind characteristic over bridge site in complex terrain is very urgent and necessary.

The calculation of complex flow over mountains-gorge terrain in practical applications is a difficult task to complete. Theoretical studies are limited by the inherent difficulties to treat real hill or mountains-gorge geometries and boundary conditions and it is also limited by the complexity of the model equations that try to mimic the most important physical phenomena present in the atmospheric boundary layer. Whereas field experimental campaigns are extremely expensive to be carried out and easily affected by environment condition which become a real urgent problem to be solved. A more feasible procedure to analyze the problem is the wind tunnel test method and numerical simulation method, but there is a specific problem in modeling a mountains-gorge terrain model in the wind tunnel test method and numerical simulation method: for the mountains-gorge terrain, it usually has a large elevation

difference everywhere, naturally, there will exist a distance (Δh , as shown in Fig.1) between the terrain model boundary and the wind tunnel floor (or the bottom of the computational domain in numerical simulation method) for the limited terrain area considered in one test, and the air would be separated from the model boundary if there was no transition section from the wind tunnel floor to the terrain model boundary. In order to let the air flow over the terrain “smoothly”, Hu et al. (2006) studied the wind characteristic parameters of a bridge across the V shape valley by terrain model wind tunnel test, and adopted a transitional additional terrain to let the air flow over the terrain model; Chen (2008) also adopted this method in another long span bridge in mountains-gorge terrain. Maurizi (1998) discussed the wind flow over a mountainous area at an altitude of 1000m above sea level, and used a ramp additional terrain with a maximum slope of 10% to let the air flow over the mountainous terrain. Although the transitional additional terrain and the ramp additional terrain have a simple form, the problem is that whether they are valid as a boundary transition section shape to let the air flow over the terrain smoothly.

The undisturbed wind field is usually taken as the reference wind field in wind tunnel tests. In an objective manner, when the inlet air flow over the appropriate boundary transition section, the air should keep the same characteristics as the reference wind field, so the undisturbed wind field will show more representative to act as the reference wind field in further studies. Comprehensive consideration of the boundary transition section in the wind tunnel and the numerical simulation methods, two principles that the appropriate boundary transition section should be satisfied: a) the air should keep the same characteristics as the reference wind field when the air flow over the transition section, and air separation could not occur at the end of the transition section; b) the length of the air flow from the starting point of the transition section to the point that the air get stable is fully short, because a longer transition section will further reduce the model scale factor as the test section of a wind tunnel is limited; besides, for the numerical simulation method a longer transition section also increase calculation region size and computational cost.

To study the appropriate boundary transition section shape of terrain model for mountains-gorge bridge site in wind tunnel test and numerical simulation test, in this paper, a kind of transition section curves was derived based on the theory of flow around cylinder with ideal fluid, took an 2D platform terrain as an analysis model to comparative analyze the flow separation behavior and distribution characteristics of wind velocity field after air flowed along the transition section between curve transition section and the ramp transition section by CFD commercial software FLUENT 6.3, and the total flow transition length of different curve transition section shapes were also compared. The research conclusions could provide some references for the terrain model studies of wind characteristics over the mountains-gorge bridge site.

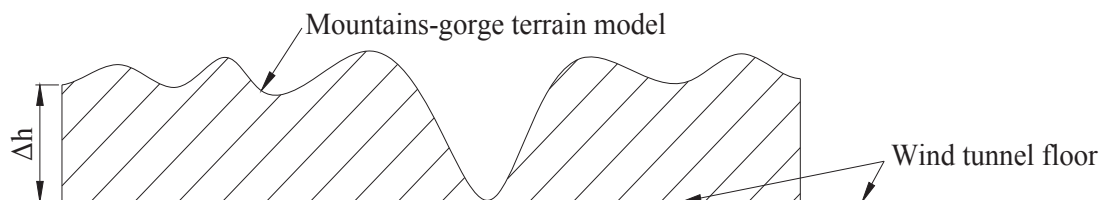


Fig.1 Distance between the terrain model boundary and the wind tunnel floor

2 TRANSITION SECTION CURVES BASED ON IDEAL FLUID AROUND CYLINDER THEORY

The undisturbed reference inlet air can be regarded as a uniform rectilinear flow, and its vertical wind velocity is zero. Therefore, the vertical wind velocity of the flow at the starting and end points of the transition section should also be equal to zero. When the air flow over

the transition section, except for the flow near the wall is subjected to the influence of air viscosity, the airflow could be taken as the potential flow in other large regions. Based on the theory of flow around cylinder with ideal fluid, the stream function and the wind velocities are given as follows:

$$\psi = U_{\infty} y \left(1 - \frac{a^2}{x^2 + y^2} \right) \quad (1)$$

$$u = \frac{\partial \psi}{\partial y} = U_{\infty} \left[1 + a^2 \frac{y^2 - x^2}{(x^2 + y^2)^2} \right] \quad (2)$$

$$v = -\frac{\partial \psi}{\partial x} = -U_{\infty} a^2 \frac{2xy}{(x^2 + y^2)^2} \quad (3)$$

where ψ is the stream function; U_{∞} is the inference wind velocity, a is the radius of the cylinder; u 、 v are the longitudinal velocity and vertical velocity, respectively; x 、 y are the corresponding coordinate of the flow, as shown in Fig.2.

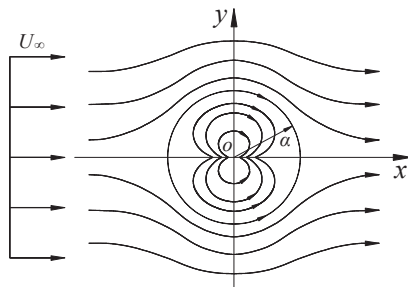


Fig.2 Flow around cylinder with ideal fluid

It can be seen from Eq. (3) that, when $x = 0$ or $x = \pm\infty$, the vertical wind velocity v is equal to zero. According to the nature of stream function, each streamline can be regarded as a wall without influence the initial flow field. Therefore, the streamline can be taken as the shape of transition section, and its starting and end points are just the coordinate points of which vertical wind velocity is zero in Fig.2. Note that, the transition section may have an indefinite length if take the coordinate point $x = \pm\infty$ at the end point of the transition section. Therefore, to satisfy the length requirements of transition section, the Eq. (1) can be rewritten as:

$$\begin{aligned} \psi &= U_{\infty} y \left[1 - \frac{a^2}{y^2} \cdot \frac{1}{1 + (x/y)^2} \right] \\ &= U_{\infty} y \left[1 - \frac{a^2}{y^2} \cdot \sum_{n=0}^{\infty} (-1)^n \left(\frac{x}{y} \right)^{2n} \right] \\ &= U_{\infty} y \left\{ 1 - \frac{a^2}{y^2} \left[1 - \left(\frac{x}{y} \right)^2 + \left(\frac{x}{y} \right)^4 - \left(\frac{x}{y} \right)^6 + \left(\frac{x}{y} \right)^8 - \left(\frac{x}{y} \right)^{10} + \dots \right] \right\} \end{aligned} \quad (4)$$

From the perspectives of practical applications and further researches, retaining only the first five terms in Eq.(4), and the corresponding stream function and the vertical wind velocities as given as:

$$\psi_5 = U_\infty y - a^2 U_\infty \frac{1}{y} + a^2 U_\infty \frac{x^2}{y^3} - a^2 U_\infty \frac{x^4}{y^5} + a^2 U_\infty \frac{x^6}{y^7} - a^2 U_\infty \frac{x^8}{y^9} \quad (5)$$

$$v_5 = -\frac{\partial \psi_5}{\partial x} = -2a^2 U_\infty \frac{x}{y^3} + 4a^2 U_\infty \frac{x^3}{y^5} - 6a^2 U_\infty \frac{x^5}{y^7} + 8a^2 U_\infty \frac{x^7}{y^9} \quad (6)$$

Let the vertical wind velocity in Eq. (6) equal to be zero, and then it leads to:

$$\begin{cases} x_1 = 0.778y \\ x_2 = 0 \end{cases} \quad (7)$$

where x_1 、 x_2 can be taken as the x-coordinate value of starting and end points of the transition section, respectively. Substituting Eq. (7) into Eq. (5) yields:

$$\begin{cases} y_1 - \frac{0.673a^2}{y_1} = \frac{\psi_5}{U_\infty} \\ y_2 - \frac{a^2}{y_2} = \frac{\psi_5}{U_\infty} \end{cases} \quad (8)$$

where y_1 、 y_2 are the corresponding y-coordinate value of starting and end points of the transition section, respectively, and the value of y_1 、 y_2 can be obtained from Eq.(8):

$$\begin{cases} y_1 = \frac{m + \sqrt{m^2 + 2.692a^2}}{2} \\ y_2 = \frac{m + \sqrt{m^2 + 4a^2}}{2} \end{cases} \quad (9)$$

where $m = \psi_5 / U_\infty$.

Hence, the starting coordinate point (x_1, y_1) and end coordinate point (x_2, y_2) are all determined via Eqs. (7) and (9). Since the length of the air flow from the starting point of the transition section to the point that the air get stable must be fully short. Therefore, the length of transition section also should be fully short. For the shortest transition section (refer to the projected length), in other words, its equivalent slope k_0 (shown in Fig.3), which can be expressed as Eq. (10), must be maximum.

$$k_0 = \frac{y_2 - y_1}{x_2 - x_1} = \frac{y_2 - y_1}{0.778y_1} \quad (10)$$

Substituting Eq. (9) into Eq. (10) yields:

$$k_0 = 1.285 \left(\frac{\sqrt{m^2 + 4a^2} - \sqrt{m^2 + 2.692a^2}}{m + \sqrt{m^2 + 2.692a^2}} \right) \quad (11)$$

And when $m \rightarrow -\infty$, the maximum k_0 , denoting by $k_{0\max} = 0.624$, which is independent of the value of a . Usually, the height of transition section is approximately equal to the height of the terrain model boundary, denoted by h_0 , thus, $h_0 = y_2 - y_1$, according to the Eqs. (9) and (11), the relation between a and m can be obtained as follows:

$$\begin{cases} \frac{m + \sqrt{m^2 + 4a^2}}{2} - \frac{m + \sqrt{m^2 + 2.692a^2}}{2} = h_0 \\ 1.285 \left(\frac{\sqrt{m^2 + 4a^2} - \sqrt{m^2 + 2.692a^2}}{m + \sqrt{m^2 + 2.692a^2}} \right) = k_0 \end{cases} \quad (12)$$

It should be noted that, the above equations are all derived based on the potential flow theory, therefore, in the actual viscous fluid, the value of k_0 need to adjusted, but the value of k_0 must smaller than $k_{0\max} = 0.624$. When the values of h_0 and k_0 are determined, then the values of a and m can be obtained by solving the Eq.(12), next substituting h_0 and k_0 into the Eq. (5) yields the following form of transition section curve:

$$y - \frac{a^2}{y} + \frac{a^2 x^2}{y^3} - \frac{a^2 x^4}{y^5} + \frac{a^2 x^6}{y^7} - \frac{a^2 x^8}{y^9} - m = 0 \quad (13)$$

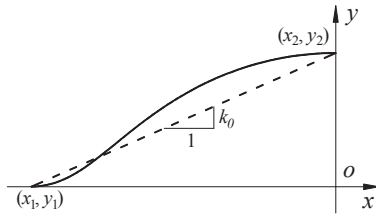


Fig.3 Equivalent slope of curve transition

3 WIND CHARACTERISTICS BETWEEN CURVE TRANSITION SECTION AND RAMP TRANSITION SHAPES

The references (Hu et al. 2006; Chen et al. 2008) both adopted the ramp transition section, but the applicability of the ramp transition section to the boundary transition section for the mountains-gorge bridge site terrain model needs to be validated. Therefore, the flow separation behavior and distribution characteristics of wind velocity field between the curve transition section and the ramp transition section are compared in the next.

3.1 Numerical model

In order to focus on the flow characteristics of different transition sections, the terrain model was simplified to a 2D platform terrain with the height of 0.385m, and the same two transition sections are set at the two ends of the platform terrain. The total length of transition sections and the platform terrain is 18.0m. Since the ramp transition section with a angle of 30° could satisfy the practical engineering (Hu et al. 2006), so the curve transition section with the equivalent slope of 0.58 (corresponding equivalent angle is 30°) are chosen to be compared. Using the parameters of $h_0 = 0.385\text{m}$ and $k_0 = 0.58$, the specific form of curve transition section can be obtained by Eqs.(12) and (13), and it is given as Eq.(14). Besides, an empty domain model with no transition sections is also presented to serve as a basic reference model, it could judge which transition section is better when the air flow over the transition section. The 2D platform terrain model and different transition sections are shown in Fig.4.

$$y - \frac{21.298}{y} + \frac{21.298x^2}{y^3} - \frac{21.298x^4}{y^5} + \frac{21.298x^6}{y^7} - \frac{21.298x^8}{y^9} + 15.968 = 0, \quad (0.664 \leq x \leq 0) \quad (14)$$

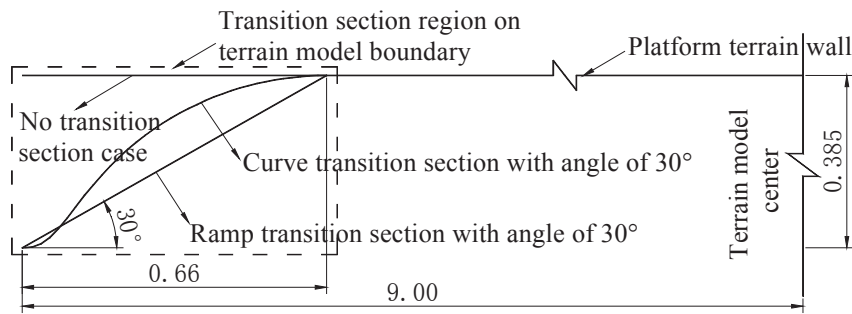


Fig.4 Terrain model and different transition section shapes (dimensions are given in m)

3.2 Boundary conditions and analysis parameters

The length from the center of terrain model to the inlet and outlet boundaries are 35.0m and 55.0m, and the height of the domain is 15.0m, satisfying the requirement of blocking ration smaller than 3% (Bekele and Hangan 2002). The domain is discretized by structured meshes and the height from the center of the wall-adjacent cell to the bottom wall is 0.0005m. As a result, the total number of meshes is 700,000. The boundaries are shown in Fig.5, in which the inlet velocity is 10.0/s and the turbulence intensity is 0.5%. In this investigation, the CFD commercial software FLUENT 6.3 is employed, and the flow is supposed to be incompressible and steady. When choosing the discretization schemes for the governing equations, the SIMPLEC algorithm is applied to the pressure-velocity coupling, the second order interpolation scheme is used for pressure, and the second order upwind scheme is adopted for moment and turbulence properties. The values set for the inlet boundary are used to initialize the flow field, and the scaled residuals for all variables are set to be 10^{-6} . For the no transition section case, the height of the domain is 14.615m ($=15\text{m}-0.385\text{m}$), and the corresponding inlet velocity is set to 10.263m/s ($=10 \times 15 / 14.615\text{m/s}$).

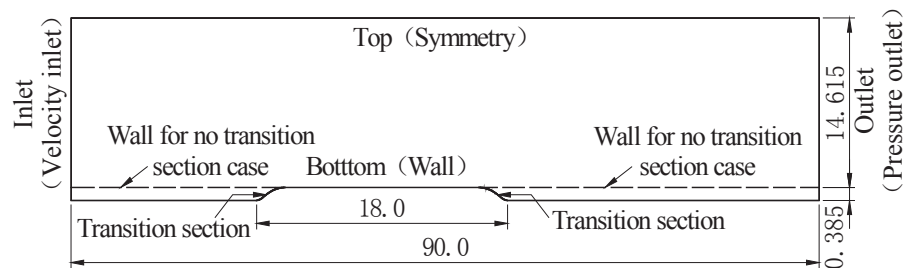


Fig.5 Schematic diagram of computational domain and boundary conditions (unit: m)

3.3 Comparison of flow separation behavior

Flow separation can lead to a thicker boundary layer or a more unstable flow; therefore, an appropriate boundary transition section should avoid the flow separation. Fig.6 compares the wall shear stress between the curve transition section with equivalent angle of 30° and the ramp transition section with an angle of 30° . It can be seen from the figure that the wall shear stress of curve transition section and the ramp transition section are all smaller than zero at the starting point ($x=-9.0\text{m}$), which indicates that the flow separation is occurred. Furthermore, at the end point ($x=-8.34\text{m}$) of the transition section, only the wall shear stress of the ramp transition section is also smaller than zero, so flow separation is also occurred at this position for the ramp transition section. Fig.6 also shows the wall shear stress of no transition section case, the wall shear stresses of curve transition section are closer to those of

no transition section case, which implies that the flow characteristics near the wall for the curve transition section are more close to those of no transition section.

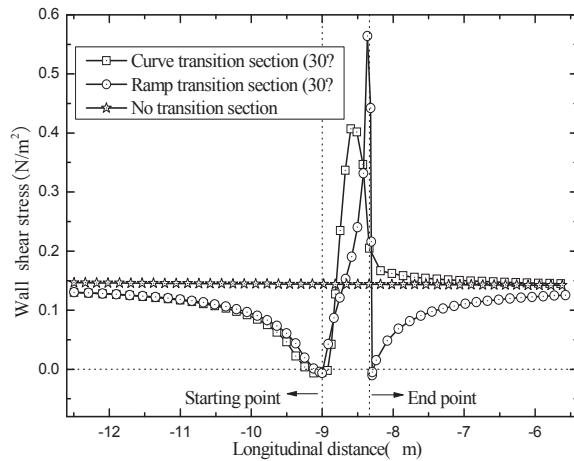


Fig.6 Distributions of wall shear stress

3.4 Distribution characteristics of wind field after air flowed over the transition section

When air flows over the transition section, the characteristics of the air, such as the velocity and wind attack angle, will inevitably change. For different transition sections, the distribution characteristics of wind field will have great differences. A reasonable treatment is to adopt the normalization value. The normalized wind velocity profiles at the end point of the two transition sections and the middle of the platform terrain are shown in Figs.7 and 8, the wind velocity at the end point of the ramp transition section accelerate greatly, which has a great difference from that of no transition section case. However, the wind profile of the curve transition section is more close to that of the no transition section case. In Fig.8, the wind profile of the curve transition section is also more close to that of the no transition section case than the ramp transition section, which indicates that the distribution characteristics of wind field after the air flowed over the transition section is more similar to those of the no transition section case.

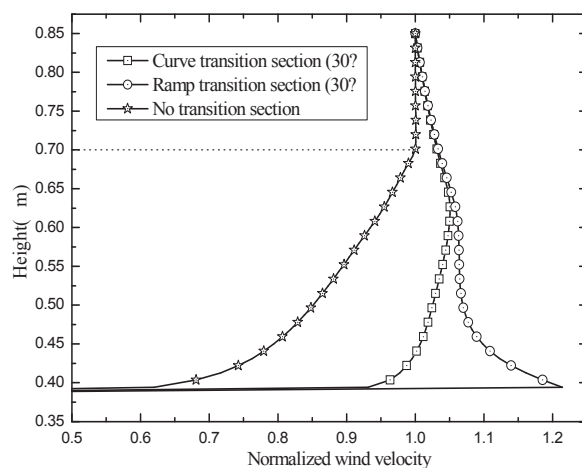


Fig.7 Normalized wind velocity profiles at the end of transition section

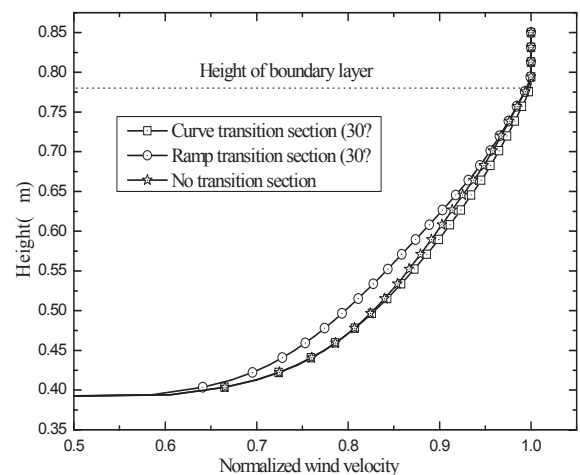


Fig.8 Normalized wind velocity profiles at the middle of terrain model

In order to investigate the normalized wind velocity from the end point of the transition section to the middle of the platform terrain, a term of “relative normalized wind velocity difference (denoted by γ)” is introduced:

$$\gamma = \sum_{h=0.385}^{h=H} \frac{|v_h/v_H - v_{0h}/v_{0H}|}{v_{0h}/v_{0H} \cdot N} \quad (15)$$

where H is the height of the boundary layer; v_h is the velocity at the height of h from the wall; v_{0h} is the velocity at the height of h from the wall for the no transition section case, v_H is the velocity at the boundary layer, v_{0H} is the velocity at the boundary layer for the no transition section case, and N is the numbers of the points from the wall to the boundary layer. Therefore, the relative normalized wind velocity difference γ along the terrain with different transition sections are shown in Fig.9, with the position near the middle of the platform, the value of γ are all close to that of no transition section case, however, the curve transition section is more closer to the no transition section case than the ramp transition section in the value of γ .

In order to investigate the wind attack angle from the end point of the transition section to the middle of the platform terrain, similarly, the wind attack angle at different transition sections are shown in Fig.10. It can be seen from the figure that the change law of wind attack angle is similar to the relative normalized wind velocity difference γ . Furthermore, the normalized wind velocity difference and the wind attack angle of curve transition section in Figs. (9) and (10) are faster to be stable as the no transition case. Therefore, the total flow transition length of the curve transition section is shorter than that of the ramp transition sections.

As discussed above, the normalized wind velocity difference and the wind attack angle of curve transition section is closer to the no transition section case than those of the ramp transition section, which indicates that the curve transition section is more suitable to be a boundary transition section in the complex terrain.

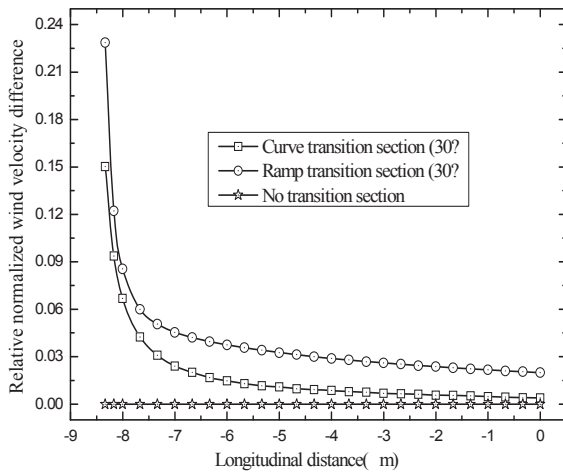


Fig.9 Distributions of average relative normalized wind velocity difference after airflow flowed along the transition section

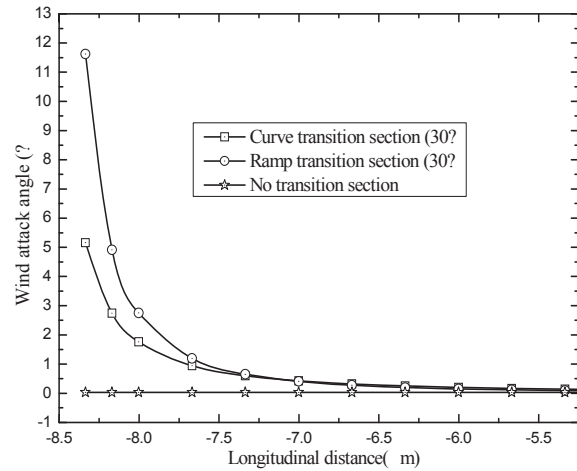


Fig.10 Distributions of average wind attack angle

4 WIND CHARACTERISTICS AMONG DIFFERENT CURVE TRANSITION SECTION SHAPES

In order to consider the different curve transition section shapes, the two other curve transition sections with equivalent angle of 20° and 10° are added in this study case, the different curve transition sections are shown in Fig.11.

Fig.12 shows the wind velocity profiles at the middle of the terrain for different curve transition sections, the different wind velocity profiles all have high concordance with each other. Since the wind velocity along the vertical direction for different curve transition

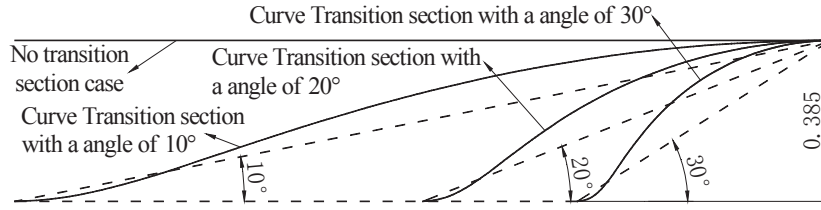


Fig.11 Different curve transition section shapes (dimensions are given in m)

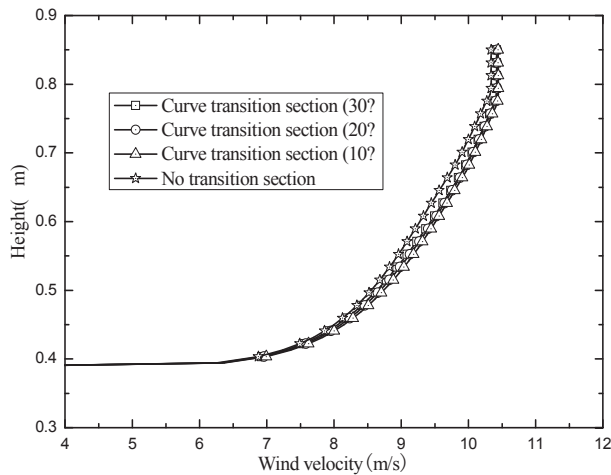


Fig.12 Wind velocity profiles at the middle of terrain model

sections can be probably different. Therefore, a term of “relative wind velocity difference (denoted by α)” is introduced:

$$\alpha = \frac{|v_h - \eta v_{0h}|}{\eta v_{0h}}, \quad \eta = \frac{14.615}{15 - y} \quad (16)$$

where y is the height from the bottom of the domain, η is the velocity ration factor, which is introduced to consider the different domain height between the model with transition sections and the model with no transition section (shown in Fig.5). The relative wind velocity difference α and the wind attack angle along the transition section and the platform terrain at the height $h=0.05\text{m}$ are shown in Fig.13 and 14. It can be seen from the figures that the values of relative wind velocity difference α for different curve transition sections are all decrease first, then increase and then decrease again, but with the position near the middle of the platform, these values are all consistent with the no transition section case. However, it should be noted that the curve transition section with equivalent angle of 30° is faster to be stable as the no transition case. Similarly, the change law of wind attack angle is similar to that of the relative wind velocity difference, as shown in Fig.14. Through the analysis of change laws of relative wind velocity difference and the wind attack angle, it could be concluded that the total flow transition length of curve transition section with equivalent angle of 30° is shorter than those of the other curve transition sections with equivalent angle of 20° and 10° .

5 CONCLUSIONS

To study the appropriate boundary transition section shape of terrain model for mountains-gorge bridge site, a kind of transition section curves were derived based on the theory of flow around cylinder with ideal fluid. Through the analysis of different transition

sections including the curve transition sections and ramp transition section, some main conclusions are given as follows:

(1) Air separation occurs when the air flow along the ramp transition section, while it does not occur when the air flow along the curve transition section.

(2) The relatively normalized velocity profile and the wind attack angle of air flow along curve transition section are closer to those of no transition section case than air flow along the ramp transition section.

(3) The total flow transition length of the curve transition section with equivalent angle of 30° is shorter than the other curve transition sections with equivalent angle of 20° and 10° .

(4) The curve transition section with equivalent angle of 30° could be applied to the boundary transition section shape of the mountains-gorge terrain model in wind tunnel test and numerical simulation test.

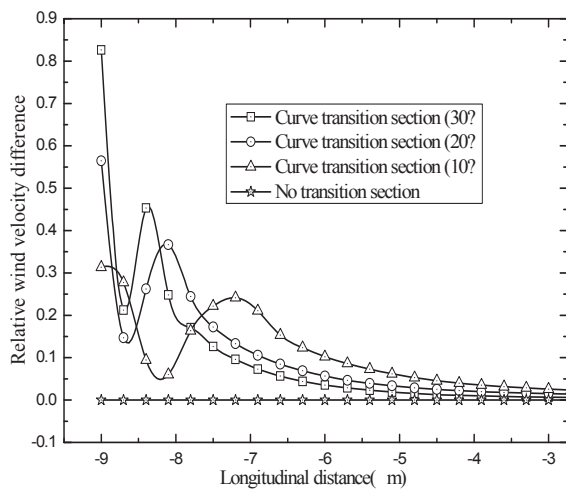


Fig.13 Distributions of relative wind velocity difference with 0.05m high above the wall

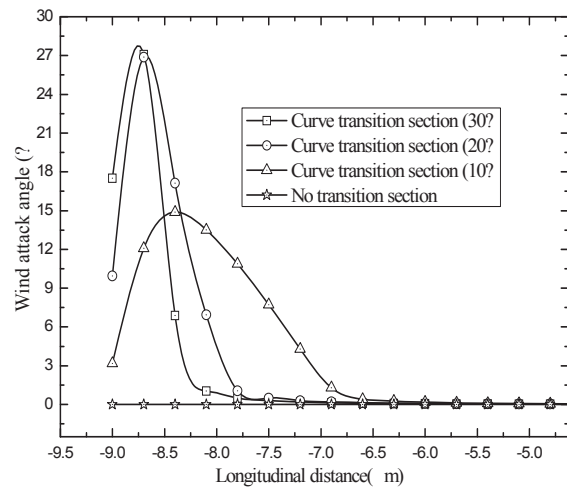


Fig.14 Distributions of wind attack angle with 0.05m high above the wall

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7 REFERENCES

- 1 Wind-resistant Design Specification for Highway Bridges, China Communications Press, Beijing, 2004.
- 2 F. Q. Hu, A. R. Chen and D. L. Wang. Experimental study of wind field in bridge site located in mountainous area, *Journal of Tongji University: Natural Science*, 2006, 34(6): 721-725.
- 3 Z. Q. Chen, C. G. Li, Z. T. Zhang and J. H. Liao. Model test of wind field characteristics of long-span bridge site in mountainous valley terrain, *Journal of Experiments in Fluid Mechanics*, 2008, 22(3): 54-59.
- 4 A. Maurizi, J. M. L. M. Palma and F. A. Castro. Numerical simulation of the atmospheric flow in a mountainous region of the North of Portugal, *Journal of Wind Engineering and Industrial Aerodynamics*, 1998, 74-76: 219-228.
- 5 S. A. Bekele and H. Hangan. A comparative investigation of the TTU pressure envelop. Numerical versus laboratory and full scale results, *Wind and Structures*, 2002, 5(2-4): 337-346.

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