Analysis on dynamic characteristics and wind-induced buffeting response of Hezhang Large-span Bridge

Jiwei Huang 1*
1 Department of Management Engineering, Sichuan College of Architectural Technology, Deyang, Sichuan, 618000, China
*Corresponding author’s e-mail: cqjtdxhw@126.com

Abstract. Hezhang Large-span Bridge is a concrete continuous rigid frame bridge with super high pier. The highest pier reaches 197m and stands the peak among the similar bridges. In order to study the wind resistance capacity of the bridge, ANSYS, a finite element software, is applied to establish models at the stage of the largest cantilever constructing and completing of the bridge. The dynamic characteristics of the models are solved by subspace iteration method and the fluctuating wind velocity time history was generated by modified Fourier spectrum method. After that, the buffeting load time history is calculated based on the theory of quasi-steady state and the buffeting time history of the stage of the largest cantilever constructing and completing of the bridge is gained respectively by time history analysis.

1. Project profile
Hezhang large span bridge lies in Bijie to Weining section on the express way of Tongren to Weining, Guizhou. It is located in the north area of Wumengshan mountain chain on the Yunnan-Guizhou Plateau with the terrain of higher in the north and lower in the south and is classified as structural erosion river valley physiognomy. The bridge crosses Hezhanghou River, the abutments on both banks is relative high and is unlikely of ponding and there is no perennial surface runoffs and pools. Faults do not exist in the bridge area and the intermediary weathered bed rock is continuous, stable, thick and strong, the site is stable.

The main bridge’s superstructure adopts (96+2×180+96)m pre-stressed concrete continuous frame while the approach bridge on both sides adopts 40m simply supported continuous T beam structure. The two main girders are PC girder cross section and their transverse section is single box single chamber poured by C55 concrete; the girder’s height at the end is 11.5m and 4m at the mid span, varying based on parabola with 1.6 powers. The bottom plate’s thickness at the end is 1.3m and 0.32m at the mid span, arises based on parabola with 1.6 powers. The box girder ceiling is 0.3m thick except 0# block whose thickness is 0.5m, and the web plates are 0.7 m, 0.6 m, 0.45m thick except 0# block whose thickness is 0.9m. Figure 1 shows the elevation of the Hezhang large span bridge.

Main pier 10#, 12# adopts double thin-wall piers, 7.5m wide and 3.0m thick. The wall thickness is 1.0m lateral and 0.6m longitudinal. Solid section is set 4.0m below the pier top and 3.0m above the pier bottom. Figure 2 shows the general structure of 10#, 12# pier.

Main pier 11# is 195m high with box girder cross section, the pier is 17.5m wide lateral and 9.0m wide longitudinal at the top and then vary at the ratio 60:1 to the bottom. The wall width is 1.2m lateral and 0.8m longitudinal, a 0.6m thick stiffening rib is set at the middle longitudinally and two are...
set laterally, 5 diaphragm plates are set vertically. Solid section is set 3.0m below the pier top and above the pier bottom respectively. The pier is poured with C50 concrete.

![Figure1. The bridge elevation](image1)

At present, time domain method has become the develop tendency of buffeting calculation than frequency domain method because it can gain response result of time history with consideration of multi-buffeting coupling effect and is easy to involve effect of kinds of nonlinear factors. Analysis on buffeting time history at the stage of the largest cantilever constructing and completing of the bridge is done through ANSYS to provide a reference for similar bridge.

2. Establishment of finite element model and dynamic characteristic analysis

2.1 Finite element model

ANSYS is a large scale general finite analysis software who combines structural, fluidic, electrical, magnetic and sonic analysis together. The finite model of the Hezhang bridge is established by ANSYS’s parameterized design language. The girder of the bridge is poured with C55 concrete while C50 for the piers, the material properties is listed in Table1.

|                | Project | Strength  | Elastic modulus | Modified volume weight | Poisson’s ratio |
|----------------|---------|-----------|-----------------|------------------------|----------------|
| Main girder    | C55     | 3.55×10^4 MPa | 2772kg/m³       | 0.2                    |
| Pier           | C50     | 3.45×10^4 MPa | 2600kg/m³       | 0.2                    |

Box girder and pier with variable cross-sections are simulated by user defined spatial beam element BEAM188.

The boundary condition is set as follows: The 10#, 12# pier’s bottom is fixed with the top of cap and the pier’s top is fixed with the box girder’s bottom, the both end of the girder are free in the constructing stage. In the complete stage, only the main bridge piers is considered and the piers’ bottom is fixed with the top of cap and the piers’ top is fixed with the box girder’s bottom. The connection pier between main and approach bridge is hinged joint with main bridge vertically and laterally and free longitudinally.

2.2 Dynamic characteristic analysis

Self-vibration property is an important dynamic feature of a structure and it is also the base of obtaining other dynamic response of a structural system.
There are several solving methods for dynamic characteristic analysis such as Rayleigh-Ritz theory, generalized Jacobi method and subspace iteration method. The subspace iteration method is adopted in this paper.

The first 20 degrees of dynamic characteristics of the largest cantilever constructing stage and complete stage of the 80m and 195m pier is calculated by ANSYS. It is obvious from table 2 that the higher the degree is, the higher the structure’s frequency. The 80m and 195m pier’s period is about 6.25 at the stage of the largest cantilever constructing and 4.55 at the stage of completing of the bridge. From this, a conclusion could be made that the Hezhang bridge is a sensitive structure to wind and its wind resistant ability is weaker in constructing stage than that in complete stage.

| Working condition Order | 80m pier cantilever constructing stage | 195m pier cantilever constructing stage | Complete stage |
|-------------------------|--------------------------------------|----------------------------------------|----------------|
| 1                       | 0.16                                 | 0.16                                   | 0.22           |
| 2                       | 0.21                                 | 0.19                                   | 0.24           |
| 3                       | 0.26                                 | 0.35                                   | 0.37           |
| 4                       | 0.54                                 | 0.59                                   | 0.42           |
| 5                       | 1.19                                 | 0.94                                   | 0.46           |
| 6                       | 1.28                                 | 0.94                                   | 0.51           |
| 7                       | 2.11                                 | 1.05                                   | 0.76           |
| 8                       | 2.15                                 | 1.18                                   | 0.84           |
| 9                       | 2.95                                 | 1.19                                   | 1.04           |
| 10                      | 3.12                                 | 1.29                                   | 0.22           |

3. Simulation of stochastic process for wind velocity fluctuations

The key of buffeting analysis lies on the simulation of the fluctuant wind loads. So consequent and vertical fluctuant wind velocity are simulated separately and then applied on the structure to form buffeting load.

Fluctuant wind field simulation is composed by MATLAB 7.1 with modified Fourier spectrum method. The bearing points of wind load are node 53 of 11# pier in cantilever constructing stage and node 175 in complete stage. Consequent and vertical wind are applied on main girder while consequent wind only on the pier. Table 3 shows the parameters of Hezhang bridge’s stochastic wind filed simulation.

| Parameters                              | Value (value picking method) |
|-----------------------------------------|------------------------------|
| Sampling number                         | nt=3601                      |
| Fourier transform number                | nfft=4096                    |
| Valley wind effect coefficient          | KKK=1.18                     |
| Time step                               | dt=0.25s                     |
| Number of time step                     | T=3600s                      |
| Time spent                              | t=900s                       |
| Ground roughness coefficient            | Z0= 0.05                     |
| Average wind                            | Average wind velocity V_{10} at 10m high =23.37m/s, The design |
velocity datum height of main girder = 100m. The design datum wind velocity $V_d$ of main girder = 34.12 m/s. Other heights’ velocity is calculated by exponential law.

Target spectrum
- Horizontal fluctuation adopts Kaima spectrum;
- Vertical fluctuation adopts Panofsky spectrum.

Frequency range
- Lowest cut-off frequency $\omega_l = 0$;
- Highest cut-off frequency $\omega_u = 2\pi$.

Limited by the space, only the time-histories simulation result of consequent fluctuating wind velocity is given in figure 3. The calculated value is almost match with the target value in figure 4, which can be accepted.

4. Simulation of stochastic process for wind velocity fluctuations

4.1 Formula of quasi-stationary buffeting load

4.1.1 Fundamental assumption. At present, aerodynamic theory based on quasi-stationary assumption is commonly adopted by codes of countries when considering the aerodynamic effect and calculation of fluctuating wind buffeting response. The theory is based on 3 assumptions below:

First, the rigidity of the structure is high enough, the vibration of the structure is small compared with wind velocity; the size of the structure is medial, not too big nor too tiny, and can be compared with integral length scale of turbulent field.

Second, the aerodynamic coefficient of fluctuating wind is equal to the stationary aerodynamic coefficient of static wind.

Third, the fluctuation of the aerodynamic force is totally determined by the fluctuation of velocity. The relation is fixed and do not change with time. The aerodynamic force’s time-lag effect and memory effect is neglected. The fluctuating velocity and the aerodynamic force’s orthogonal correlation stay the same.

The quasi-stationary aerodynamic theory based on above three assumptions is comprehensively used in structure’s wind analysis. Its precision is acceptable for engineering purpose.

4.1.2 Quasi-stationary formula on main girder. The quasi-stationary formula on main girder expressed by area of nodes domination under the global coordinate system with neglection of self-excitation force is:

\[ F_{xy}(t) = L_y(t) \cos(\alpha_t) + D_y(t) \sin(\alpha_t) \]  

\[ F_{xz}(t) = D_z(t) \cos(\alpha_t) - L_z(t) \sin(\alpha_t) \]  

\[ M_{xh}(t) = M_h(t) \]
Simulated time history of fluctuant wind velocity buffeting force can be obtained by combination of equation (4) and time history of fluctuant wind velocity.

4.1.3 The quasi stationary buffeting force formula of piers. For the application point of buffeting force on pier, equation (5) is available when aerodynamic resistance is neglected.

\[
F_{zA}(t) = \rho U u(t) A_o C_D
\]

The implications of letters are the same as above.

4.1.4 Analysis on response of 195m pier in cantilever constructing stage. The simulated time history data of stochastic fluctuant wind velocity is read through *VREAD, a APDL command in ANSYS, and then the fluctuant wind buffeting force which is later applied to the finite element model is obtained as loads on nodes with the time step at 0.1s and the number of time steps at 2000 from the formula of quasi-stationary buffeting force of main girder and piers. Relative parameters’ picking is referenced to literatures.

The consequent and vertical orientation is set as the axis Z and Y in global coordinate system of the model respectively. The Z axis and Y axis’ time history of buffeting force of a node on main girder is given in figure 5 and 6 respectively.

The buffeting response results at cantilever constructing and complete stage of the 195m pier is given in table 4 and 5 respectively. The response result of static wind can be found in the literature (6). Due to the neglect of non-linear factors, the total response=static wind response+ buffeting response; amplified fluctuant coefficient= total response/static wind response.

| Response mode                        | Static wind response | Buffeting response value | Total response | Amplified fluctuant coefficient |
|--------------------------------------|----------------------|--------------------------|----------------|-------------------------------|
| Lateral displacement of main girder (cm) | 10.43                | 20.96                    | 31.37          | 3.01                          |
| Vertical displacement of main girder (cm) | 0.53                 | 1.22                     | 1.75           | 3.30                          |
| Torsional displacement of main girder (cm) | 0.11                 | 0.25                     | 0.36           | 3.27                          |
Max moment at bottom of 11# pier (kN•m) 114 790.58 279 462.46 384 253.04 3.35

Table 5. The results summary of buffeting response in Hezhang bridge finished stage

| Response mode                                      | Static wind response | Buffeting response value | Total response | Amplified fluctuant coefficient |
|---------------------------------------------------|----------------------|--------------------------|----------------|---------------------------------|
| Lateral displacement of main girder (cm)          | 11.01                | 19.42                    | 30.43          | 2.76                            |
| Vertical displacement of main girder (cm)         | 0.61                 | 1.14                     | 1.75           | 2.87                            |
| Torsional displacement of main girder (cm)        | 0.10                 | 0.19                     | 0.29           | 2.90                            |
| Max moment at bottom of pier (kN•m)               | 173 981.63           | 26 338.82                | 200 320.45     | 3.22                            |

5. Conclusions

Conclusions are made as below after analysis on dynamic characteristic and wind induced buffeting response of 80m and 195m pier at the stage of cantilever constructing and complete of Hezhang large span bridge by ANSYS.

1) The dynamic characteristic analysis shows that: the higher the degree is, the higher the structure frequency is. The 80m and 195m pier’s period is about 6.25 at the stage of the largest cantilever constructing and 4.55 at the stage of completing of the bridge. From this, a conclusion could be made that the Hezhang bridge is a sensitive structure to wind and its wind resistant ability is weaker in constructing stage than that in complete stage.

2) The max wind induced displacement and the max moment at bottom of 195m pier is 31.37cm, 30.43cm and 384 253.04kN•m, 200 320.45kN•m at the stage of the largest cantilever constructing and the stage of completing of the bridge respectively.

3) The amplified fluctuant coefficient of 195m pier at cantilever constructing stage is between 3.01 to 3.35, the average value is 3.18; and that at the complete stage is ranged from 2.76 to 3.22, the average value is 2.99 which is lower, that is, the bridge is more sensitive to wind during its construction than after completion.

References

[1] Huang, J.W., Liu, D. (2011) Nonlinear stability calculation analysis of high pile long-span continuous steel bridge. Western China Communications Science & Technology, 11:43-47.
[2] Xiang, H.F., Chen, A.R. (2003) Recent advances in research on aerodynamics of extra long-span bridges. China Civil Engineering Journal, 04:1-8.
[3] Li, L., Peng, Y.C., Hu, L. (2005) Time domain analysis of wind-induced buffeting of longtan river bridge, Highway, 11:59-62.
[4] Yang, H.B. (2015) Wind-induced buffeting response analysis of the maximum cantilever state of Hezhang Bridge. Transportation Science & Technology, 272:1-4.
[5] Huang, J. W. (2012) Study on wind stability and optimization of continuous rigid frame bridge with long-span and super high piers, Chongqing: Chongqing Jiaotong University.
[6] Qin, S.Q. (2018) Yang, H.B. (2015) Parametric analysis of the dynamic property of a large-scale basket handle arch bridge. Highway Engineering, 43:1-5.