Influence of structural design parameters on seismic performance of shaped single-tower cable-stayed bridges

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Abstract. The geometry and stress state of special-shaped cable-stayed bridges are complicated, so there is no uniform conclusion on their seismic performance and damage mechanisms under random seismic excitation. In light of this, taking a single cable plane curved inclined single tower cable-stayed bridge as the background, this paper establishes a spatial finite element model and conducts structural dynamic characteristics and seismic response analysis. Based on this, taking the bending radius and tilt angle as design parameters, the sensitivity analysis of structural seismic response to design parameters is carried out. The analysis results show that the first 5 vibration modes of the bridge are mainly the lateral vibration of the tower and girder, as well as the vertical vibration of the girder. Besides, the vibration modes are dispersed, and there is no phenomenon where a certain vibration mode dominates.The seismic response of the middle part of the tower is subjected to a large bending moment under the action of seismic force. Sensitivity analysis of structural design parameters indicates that the tower tilt angle and radius of curvature affect the bending moment more than the axial force, and the seismic performance of bridge decreases with the increase of tower tilt angle.

1 Introduction

Cable-stayed bridges are widely used due to their strong crossing ability and beautiful appearance [1~2]. There have been many studies on the seismic performance of conventional cable-stayed bridges, including seismic response analyses considering geometric nonlinearities [3~4], seismic assessment of isolation devices such as friction pendulum bearings and liquid viscous dampers [4-5], analysis of the effect of pile-soil-structure interaction [6], and exploration of the influence of the various design parameters on the seismic performance of structures [7].

In recent years, the shape of cable-stayed bridges has tended to diversify, and a cable-stayed bridge with a unique shape can often serve as a landmark for a region. Using the Nissibi cable-stayed bridge in Turkey as an example, Bayraktar and Mehmet [8] investigated the seismic response of acable-stayed bridges with inverted Y-shaped pylon . Xie et al. [9] used an inverted V-shaped pylon cable-stayed bridge as an example to study the seismic performance of this type of structure through shaking table tests. Kazuhiro Miyachi et al. investigated the torsional effect of S-shaped curved girder cable-stayed bridges and carried out a safety assessment [10]. Unlike conventional cable-stayed bridges, the appearance of "shaped" structures is often asymmetric, which makes the design and construction of cable-stayed bridges more difficult [11]. At the same time, the existing codes are not sufficient to fully support the design of this type of bridge [12].

Based on this, this article takes a curved single tower cable-stayed bridge as an example and uses numerical simulation to explore the influence of main tower design parameters on its seismic response.

2 Overview of the Case Bridge

2.1 Bridge Description

The case bridge is a single cable-stayed heteromorphic inclined single tower hybrid girder cable-stayed bridge with a span arrangement of (84+152) m, in which the tower is curved and shaped like a crescent moon. The bridge layout is shown in Fig. 1.

2.2 Finite Element Model

The software SAP2000 (v20) is used to establish the finite element model of the whole bridge. The establishment of specific nodes and units is depicted in Fig. 2.

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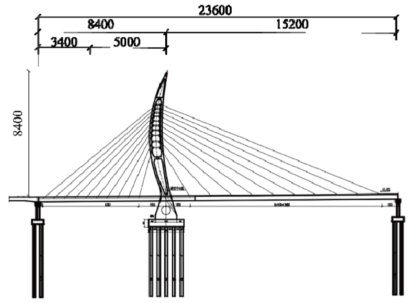

Fig. 1. Arrangement of the main bridge of the case bridge (unit:cm)

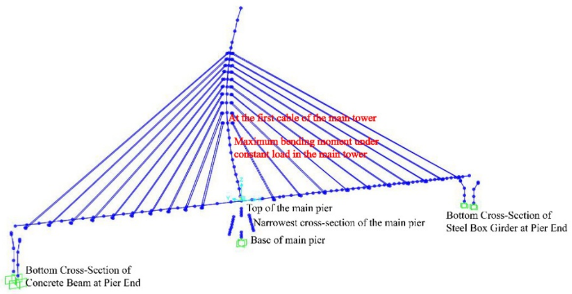

Fig. 2. Schematic of finite element model

The girder is expected to maintain elasticity under earthquake action, so elastic frame elements are used for simulation; Towers and piers may be damaged under earthquake action, so nonlinear frame elements are used to reflect their mechanical behavior under earthquake action; The cable-stayed cable is simulated using truss elements; The bearings are simulated using nonlinear Link elements. It should be noted that the bridge is built on a hard soil layer, the effect of pile-soil interaction on the seismic response of the structure is not considered in the model, and the bottom of the pier and the bottom of the tower are cemented. The boundary conditions of the model are shown in Table 1.

Table 1. Model boundary conditions

Position	x	y	z	R_x	R_y	R_z
Tower and Beam	1	1	1	1	1	1
Bidirectional bearing with beam	0	0	1	1	0	1
Unidirectional bearing and beam	0	1	1	1	0	1

Note: x, y, and z are longitudinal, transverse, and vertical translational degrees of freedom, respectively; Rx, Ry, and Rz are longitudinal, transverse, and vertical rotational degrees of freedom, respectively; 0 means free; 1 means with (master-slave) constraints.

2.3 Modal analysis

The results of the modal analysis are listed in Table 2. Due to the tower-girer-pier-consolidated system, the stiffness of this bridge is large, and the self-oscillation period is small, its first-order self-oscillation period is 2.44s, and the vibration pattern is characterized by the side pendulum of the main tower. The first 5 order are mainly dominated by the transverse swing of the tower and the vertical bending of the girder. The consolidated pier system and the large main pier section make the vibration mode of the tower girder bridge not appear the longitudinal drift mode like the traditional cable-stayed bridge.

Table 2. Structural dynamic characteristics

Mode Order	Self-oscillation period	Frequ-ency	Characteristics of vibration pattern
	Sec	Cyc/sec	
1	2.44	0.41	Tower lateral Swing
2	1.05	0.95	First-order antisymmetric vertical bending of the main beam
3	0.64	1.57	First-order symmetrical vertical bending of the main beam
4	0.47	2.12	Tower second-order side pendulum
5	0.44	2.25	Second-order antisymmetric vertical bending of the main beam

3 Seismic Response Analysis

3.1 Seismic Wave Input

According to the requirements of Seismic Design Code for Urban Bridges [13], the E2 level (the design acceleration response spectrum with a 50-year exceedance probability of 2%) design response spectrum is generated, and 7 matching artificial seismic waves are selected as the excitation input. The comparison between the response spectra corresponding to the seven artificial seismic waves and the designed response spectra is drawn in Fig. 3

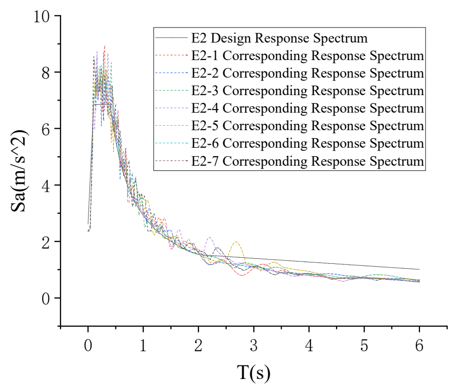

Fig. 3. Comparison of the design response spectrum and target time-history response spectrum

In this paper, the ground vibration inputs use longitudinal plus vertical combination (X+Z) as well as transverse plus vertical combination (Y+Z), and according to the Code for Seismic Design of Urban Bridges, the vertical ground vibration is obtained by multiplying the horizontal ground vibration by 0.65 [13]. The seismic response takes the average value of the calculated results of 7 seismic waves.

3.2 Seismic Response Patterns

Regardless of the input of ground vibration in the direction of (X+Z) or (Y+Z), the axial force caused by seismic force is in an overall decreasing trend throughout the tower from bottom to top. The bending moment of the upper tower is distributed in a fluctuating state, and the bending moment in the middle of the upter tower is the largest.

Under (Y+Z) seismic input, the axial force of the pier under the tower is 1.6 times the sum of the remaining piers, while the bending moment of that of is 7.4 times the sum of the remaining piers; Under (X+Z) seismic input, the axial force of the pier under the tower is 2.2 times the sum of the remaining piers, while the bending moment of that of reaches 33.9 times the sum of the remaining piers.

In conclusion, the lowermost cross section of the main tower where the tension cable exists, the cross section of the part with the largest bending moment under self-weight and the cross section of each pier are chosen to consider the sensitivity of the parameters under seismic action.

4 Parametric Sensitivity Analysis

Considering the influence of the shape of the tower on the structural seismic performance, the two parameters that have a greater influence on the shape of the tower are selected for sensitivity analysis.

As shown in Fig. 4, the tower profile is controlled by radius A, radius B, and radius C. Given the limited influence of radius C, radius A, and radius B are considered as the first control parameters. In addition, Figure 4 shows that the axis of the tower and the axis of the girder are not perpendicular to each other, there is a certain inclination angle, considering the inclination angle as the second control parameter. As shown in Fig. 5, the angle of inclination toward the steel box girder side is taken as the angle of inclination A, and the angle of inclination toward the concrete box girder side is taken as the angle of inclination B.

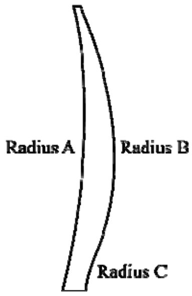

Fig. 4. Schematic diagram of the tower profile

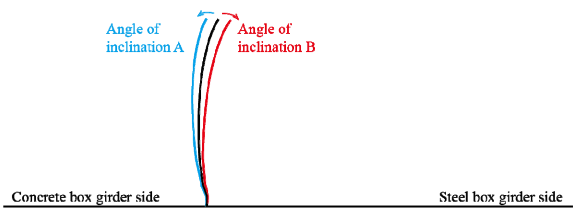

Fig. 5. Schematic diagram of the inclination angle of the tower

To ensure that the cable can still be anchored to the tower after the parameter transformation of the main tower structure, the two control parameters can only be changed in a small range. The adjustment range of design parameters is listed in Table 3.

Table 3 Control parameter values

Position	Original value	Change value 1	Change value 2
Radius A	182m	152m	\
Radius B	84m	95m	100m
Inclined angle A	\	0.5°	1°
Inclined angle B	\	1.5°	3.5°

The above studies are numerically simulated by the finite element software SAP2000 to find the seismic response, using the original model as the base model. To study the effect of each control parameter on the seismic response of the structure. Select the section bending moment and axial force of each key component as the engineering demand parameters, and the selection of specific cross sections is shown in Fig. 3, which are mainly located in the middle of the main tower, the main pier, and the split piers. Use the response rate to reflect the degree of influence caused by parameter changes, and the calculation formula for the rate of change in seismic response is as follows:

$$\text{Rate of change} = \frac{\text{original data} - \text{changed data}}{\text{original data}} \tag{1}$$

From the formula, a positive rate of change represents a decrease and a negative rate of change represents an increase.

The selection of specific cross sections is shown in Fig. 3, which are mainly located in the middle of the main tower, the main pier, and the split piers.

The following sections will be named as follows. The main tower at the first cable: A1; Maximum bending moment under constant load in the main tower: B1; Top of the main pier: C1; Narrowest cross-section of the main pier: D1; Base of the main pier: E1; Bottom Cross-Section of Concrete Beam at Pier End: F1; Bottom Cross-Section of Steel Box Girder at Pier End: G1.

4.1 Effects of Curvature radius

The calculated rate of change of axial force and bending moment with radius of curvature is shown in Fig. 6 and Fig. 7, respectively. The rates of change in the graphs are compared to actual engineering parameters; solid lines are (X+Z) inputs and dashed lines are (Y+Z) inputs. Fig. 6 and 7 have been divided into left and right parts, with the right side reflecting the variation of radius A and the left side reflecting the variation of radius B, where the actual engineering parameters are 84 m for radius A and 182 m for radius B.

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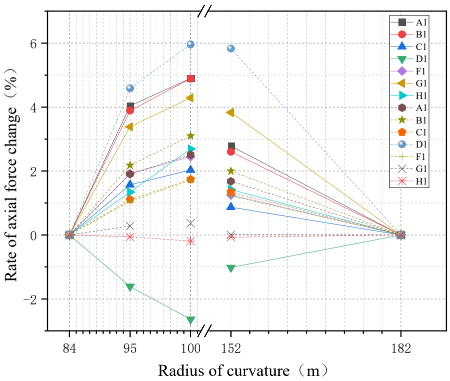

Fig. 6. The variation of cross-sectional axial force with the tower curvature.

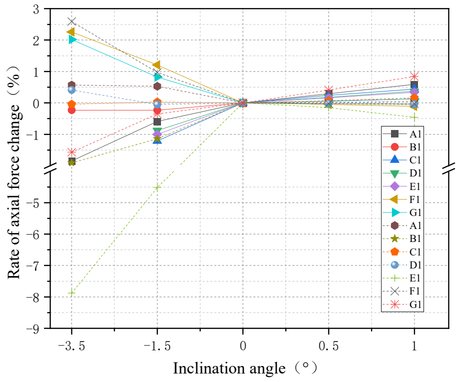

Fig. 8. The variation of cross-sectional axial force with the tower inclination angle

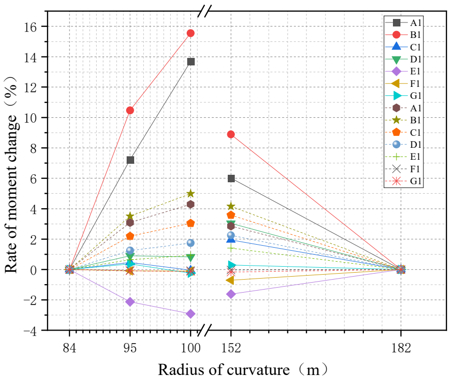

Fig. 7. The variation of cross-sectional bending moment with the tower curvature

Changes in radius A (182m→152m) and radius B (84m→95m→100m) generally have a greater effect on bending moments than on axial forces; Changes in radius A and radius B have a greater effect on the (X+Z) direction than on the (Y+Z) direction; The farther away from the main tower, the smaller the effect of the radius change, the selected cross-section with the greatest impact of the main tower at the first cable cross-section and the main tower under the load of the largest bending moment; The decrease in radius A and the increase in radius B result in a basic decrease in bending moments and axial forces in all sections, implying an increase in the seismic performance of the structure.

4.2 Effects of Tilt angle

The calculated rate of change of axial force with tilt angle is shown in Fig. 8 and the rate of change of bending moment with tilt angle is shown in Fig. 9. The rates of change in the graphs are all compared with actual engineering parameters; solid lines are longitudinal + vertical inputs and dashed lines are transverse + vertical inputs.

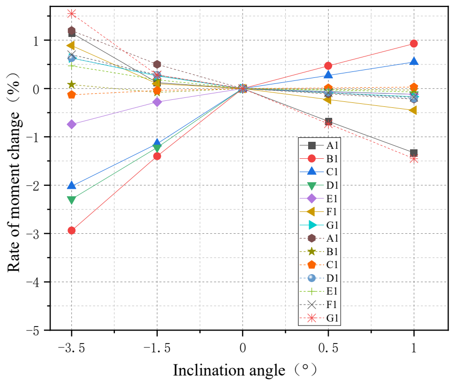

Fig. 9. The variation of cross-sectional bending moment with the tower inclination angle

The effect of tilt angle A (0°→0.5°→1°) on the seismic response of the structure is generally within 1.5%, and the effect of tilt angle B (0°→1.5°→3.5°) on the seismic response of the structure under longitudinal + vertical seismicity is generally within 3.5%; The farther the cross-section is from the main tower, the smaller the effects caused by tilt angle A and tilt angle B. Under lateral + vertical seismicity, the increase in tilt angle B has a larger effect at the narrowest cross-section of the main pier, with a response increase of up to 8%; The increase in the angle of inclination A resulted in a decrease in the axial force and an increase in the bending moment of each section, but the rate of change was small and was considered to have a negligible effect on the seismic performance of the structure within that range; The increase in tilt angle B increases the seismic response of the structure significantly and is considered to reduce the seismic performance of the structure.

5 Conclusions

This article discusses the influence of structural design parameters on the seismic response of a single cable-stayed anisotropic single-tower cable-stayed bridge, and obtains the following conclusions:

(1) The vibration form of the case shaped single-tower cable-stayed bridges is different from that of a

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conventional cable-stayed bridge, and the first 5 vibration modes of the bridge are mainly the lateral vibration of the tower and girder, as well as the vertical vibration of the girder.

(2) By appropriately reducing radius A or moderately increasing radius B of the tower, the maximum values of bending moment and axial force reduced, indicating that reducing radius A or increasing radius B is favourable to improving the seismic level of shaped single-tower cable-stayed bridges.

(3) The relative inclination of the tower and the girder has a variable effect on the seismic performance. An appropriate increase in the angle of inclination A only slightly affected the structural response. However, increasing the tilt angle B significantly increases the dynamic response under seismic action and is not favourable for seismic resistance. Therefore tilt angle B needs to be designed carefully.

This paper only carries out parameter sensitivity analysis for the tower, the impact of changes in girder or other design parameters on seismic response will be further explored in future research

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