Research on Transverse Restraint System of Cable-stayed Bridge under Ultra High Performance Concrete Deck Pavement

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Abstract. In order to explore the optimal lateral restraint system for long-span cable-stayed bridges under ultra-high performance concrete deck pavement. This paper takes a UHPC deck pavement cable-stayed bridge as an example, selects four different lateral restraint systems, calculates the stress of each key section of the cable-stayed bridge under the action of an earthquake, and then selects the optimal lateral Constraint system. The research results show that when ultra-high performance concrete is used as the bridge deck pavement, the increase in the quality of the bridge deck system will have a greater adverse effect on the seismic performance of the bridge. Compare the internal force response and displacement response at each key section of the bridge under four different lateral restraint systems under earthquake action. Compared with the other three systems, the internal force response and displacement response value of the horizontal cable system is smaller, and the energy dissipation and shock absorption effect is better. For cable-stayed bridges using ultra-high performance concrete as the deck pavement, in the selection of the lateral restraint system, a restraint system of cables is set between the towers and beams, which can better reduce the impact of the increase in the quality of the bridge deck on the seismic performance of the bridge, is the most reasonable horizontal restraint method. Considering the internal force and displacement response of the bridge structure and the safety of the support under the earthquake, the parameter selection of the cable support is $k = 135000$ kN/m and $S = 0.4$ m.

Keywords. Restraint system; UHPC pavement; bridge seismic

1. Introduction

China is located between the two major seismic zones in the world, and is one of the most active earthquake areas in the world. With the rapid development and urbanization of China's economy, a large number of population are concentrated, and people's dependence on the traffic line is becoming stronger and stronger. Once an earthquake causes damage to the traffic line, it may lead to great loss of life, property and other indirect economy.

As the lifeline engineering in the transportation system, the seismic capacity of the bridge directly determines the line fluency of the whole traffic in the earthquake. Therefore, how to ensure the safety performance and normal use function of bridge structure under earthquake action is of great help to earthquake disaster prevention and reconstruction work after earthquake [1-2].

Cable stayed bridge as a long-span bridge with high utilization rate, its seismic performance is an indispensable part of bridge design. The restraint system of cable-stayed bridge is mainly divided into two directions: longitudinal and transverse. For the large-span cable-stayed bridge with unconsolidated main beam and pylon (Pylon Pier), the restraint systems in the two directions are independent. Among them, the longitudinal restraint system has a great impact on the overall structural behavior of the
bridge, which is the main feature of the structural restraint system. While the transverse restraint system has a direct impact on the transverse force of the bridge [3-4]. Looking back on the large-scale bridge accidents in recent years, the transverse overturning accidents of bridges occur frequently. It can be seen that in the normative design of bridge safety, the consideration of longitudinal safety has been relatively perfect, while the transverse safety design of bridges is relatively insufficient.

In the context of refined design requirements, the design of lateral constraint system is more important and indispensable. The main purpose of this paper is to improve the internal force and displacement response of the structure under the action of extreme wind and earthquake, reduce the displacement and dynamic wear of expansion device and support, and increase the safety of bridge under the action of ultimate static and dynamic [5].

Many scholars at home and abroad have made great achievements in the study of the restraint system of long-span cable-stayed bridges. He Luping [6] compared the seismic responses of five restraint systems, namely lateral fixed restraint system, lateral sliding restraint system, bearing failure system, auxiliary Pier damping restraint system and auxiliary pier +transition pier damping restraint system. He found that the restraint system with transverse viscous dampers has the best seismic effect and is more economical. Wang Long [7] studied the asymmetric lateral seismic system of hybrid single tower cable-stayed bridge, and concluded that the lateral restraint system with viscous damper is more reasonable, and the reasonable value of damper parameters is also explored. Jiang Chonghu [8] systematically analyzed the influence of various restraint systems on the lateral seismic resistance of the bridge, and concluded that for the lateral restraint at the bridge tower, under the action of an earthquake, the support plus elastic cable system or the support plus damper system is effective Shock absorption system. The internal force and displacement of the structure are well controlled. Ye Aijun [9] analyzed the influence of lateral restraint system with viscous fluid damper on seismic response of super long-span cable-stayed bridge (SuTong Bridge). The research focuses include the reasonable setting mode of damper and the influence of damper parameters on seismic control effect.

According to the research results of cable-stayed bridge restraint system in recent years, it can be seen that the lateral restraint system has been paid more and more attention. Most of the studies think that the transverse restraint system of the bridge is more safe and reasonable, but the cost of the viscous damper is higher and the requirements are more strict, so it is uneconomical to deploy large-scale in the lateral restraint of the bridge. By comparing the seismic responses of four kinds of lateral restraint systems under earthquake action, this paper puts forward a lateral restraint system which is more economical, reasonable and has good anti-seismic performance than transverse damper, which can provide reference for setting lateral restraint system of long-span bridges.

2. Relying on engineering

2.1. Project overview

The span layout of the cable-stayed bridge is 60 m + 140 m + 400 m + 140 m + 60 m. The deck pavement adopts 4cmSMA-13 + 5cm UHPC pavement. The paving form is shown in Fig 1. The density of UHPC pavement is 2800 kg/m³, the design compressive strength is 130 MPa, and the elastic modulus is 40 GPa. The bridge type is steel box girder cable-stayed bridge with double pylons and double cable planes. The basic intensity of the bridge site is grade VIII. The fortification category is class A. The site is class III, and the site soil is of soft soil type. The main tower is 151.4 m high, the bearing platform is rectangular, and the foundation adopts a steel-concrete composite pile group foundation. The transition pier adopts a portal frame structure. In terms of material selection, C55 concrete is used for tower body. C35 underwater concrete is used for pile foundation. C40 concrete is used for bearing platform. C40 concrete is used for pier body of transition pier and auxiliary pier. C50 concrete is used for capping beam of transition pier.
2.2. Establishment of spatial dynamic analysis model

The three-dimensional dynamic finite element model of the cable-stayed bridge is constructed by using the CSI bridge finite element program to analyze the seismic performance. The calculation models are based on the x-axis along the bridge direction, y-axis in the transverse direction and Z-axis in the vertical direction. In the model, the main tower, main girder, transition pier, auxiliary pier and north-south approach bridge of the main bridge are discretized into space beam elements. The main beam of the main bridge adopts a single beam mechanical model, and forms a "fishbone" model with the cable of the cable-stayed bridge through the master-slave constraint. The spatial truss element is used for the stay cable, and the influence of the cable sag effect and the geometric stiffness of the dead load are considered. The m-method is used to simulate the foundation Pile soil effect. The spatial finite element model is shown in Fig. 2.

2.3. Seismic input and bridge dynamic analysis

The bridge is a double pylon cable-stayed bridge with main span of 400 m, belonging to class A bridge. Combined with the structural design of the bridge and in accordance with the detailed rules for seismic design of highway bridges (JTG/T2231-01-2020) [10]. The seismic fortification level of the bridge is determined as follows, the recurrence period of E1 is 475 years, and that of E2 is 1975. The seismic time history curve is shown in the figure 3 and figure 4 below.
In response spectrum seismic response analysis, the first mode of Rayleigh damping is determined as the basic mode of the structure, and the second mode is the mode with the largest effective mass ratio. According to the established spatial dynamic analysis model of the bridge, the dynamic characteristics of the structure are analyzed and studied. The first 10 order dynamic characteristics are listed below as shown in Tab 1.

| Order | Cycle (s) | Frequency (Hz) | Mode characteristics                                      |
|-------|-----------|----------------|-----------------------------------------------------------|
| 1     | 5.479     | 0.183          | First stage longitudinal drift of main beam               |
| 2     | 2.298     | 0.435          | First order vertical bending of main beam                 |
| 3     | 1.788     | 0.559          | First order side bending of main beam                      |
| 4     | 1.642     | 0.609          | First order antisymmetric vertical bending of main girder |
| 5     | 1.553     | 0.644          | First order antisymmetric side bending of main beam       |
| 6     | 1.321     | 0.757          | Secondary bending of main beam                             |
| 7     | 1.306     | 0.766          | Longitudinal vibration of Auxiliary Pier                  |
| 8     | 1.181     | 0.847          | Second order vertical bending of main beam                |
| 9     | 1.173     | 0.852          | Longitudinal vibration of transition pier                 |
| 10    | 1.125     | 0.889          | Longitudinal vibration of Auxiliary Pier                  |
3. Analysis of bridge deck pavement and restraint system

3.1. Comparative analysis of different bridge deck pavement

In this super large bridge, when UHPC is used as the bridge deck pavement, the UHPC pavement volume of the bridge deck system is 1200 m³, and the UHPC density is 2800 kg/m³. Compared with the ordinary asphalt mixture pavement, the weight of the whole bridge deck system increases by about 34%. Under the E2 earthquake, the bending moment and shear force at the bottom of the tower of the bridge structure with UHPC deck pavement are greatly increased, and the displacement responses of the beam end and the top of the tower increase obviously. Therefore, the use of UHPC rigid pavement will bring adverse impact on the seismic performance of bridge structure. In order to make full use of the advantages of rigid pavement, and not bring adverse impact on the seismic performance of the bridge, it is necessary to further optimize the constraint system of the bridge.

3.2. Constraint system analysis

The main beam restraint system of the super large bridge is studied. Different restraint systems are set up in the transverse direction of the bridge. The seismic performance of the bridge is analyzed on the basis of each restraint system. The reasonable restraint system is determined by comparing the internal force response and displacement response of the key section of the bridge.

Using the established 3D dynamic analysis model of the super large bridge, the transverse seismic response of the bridge is analyzed by setting lateral restraint, lateral relaxation, transverse cable support [11], and lateral elastic constraint at the joint of tower and beam of the bridge. The E2 leveling seismic wave is selected, and the method of nonlinear time history analysis is used to study the seismic response laws of the main tower bottom and the internal force beam end displacement at the bottom of the platform. Comprehensively consider the influence of structural internal force and displacement, and explore the reasonable lateral structural system of the bridge. The specific working condition settings are shown in Tab 2.

| Working condition | Transverse restraint form at main tower |
|-------------------|---------------------------------------|
| I                 | Lateral restraint system               |
| II                | Lateral relaxation system              |
| III               | Cable support system is set horizontally between tower and beam |
|                  | Elastic restraint system is set between tower and beam(Spring stiffness 2000 kN/m) |

Using the three-dimensional dynamic analysis model mentioned above, the lateral restraint system is selected and the lateral + vertical E2 level seismic wave is input. The linear time history analysis method is adopted. The damping of the structure is calculated by Rayleigh damping formula, and the two-order mode with larger participation coefficient is used for calculation. The internal force response and displacement response of each key section of the main bridge are obtained as follows figure 5 to figure 8.
Figure 5. Axial force of key section under earthquake action

Figure 6. Transverse shear of key section under earthquake action
By comparing the seismic response of this extra-large bridge under different lateral restraint systems, the key sections of the bridge. It can be seen that for the bottoms of the main towers on both sides, when horizontal and vertical seismic waves are input to the bridge, the internal force responses of the tower bottoms of different restraint systems are different. The specific performance is that the axial force at the bottom of the tower is the smallest when the cable support system is installed horizontally between the tower beams, and the axial force at the bottom of the tower is larger for the lateral restraint system and the lateral relaxation system. The shear force at the bottom of the tower with the cable support system installed transversely between the tower beams is the smallest, and the shear force at the bottom of the tower with the transverse restraint system is the largest. The bending moment at the bottom of the tower with a cable support system installed transversely between the tower beams is the smallest, and the bending moment at the bottom of the tower with the lateral
restraint system and the lateral relaxation system is larger.

For the relative displacement between tower and beam, when the lateral + vertical seismic wave is input to the bridge, the relative displacement difference between tower and beam with different restraint system is relatively large. Which is shown as follows, the relative displacement between tower and beam with cable support system and transverse restraint system is small, within 0.5 m range, it can meet the design requirements. The relative displacement between the horizontal relaxation system and the tower beam with the elastic restraint system installed horizontally is relatively large, reaching about 0.8 m.

To sum up, compared with other systems, the restraint system with lateral cable support between tower and beam has more reasonable stress under earthquake action, and the displacement between tower and beam also meets the requirements. Which can significantly improve the seismic performance under seismic conditions, and is the most reasonable seismic system among the four systems.

4. Parameter analysis of cable damping support

The cable damping bearing is mainly composed of basin bearing (or spherical steel bearing), cable and shear bolt. Its action mechanism is that the upper structure will slide at the friction surface to realize the energy dissipation. Under the strong earthquake, the shear bolt in the support is sheared, and the bearing slides. The elastic cable is used to control the relative displacement of the tower and beam, so as to effectively reduce the seismic response of the structure. The bearing is not sensitive to the frequency of input seismic wave and has a wide range of isolation. The specific structure is shown in the figure 9 and figure 10 below.

![Figure 9. Cable bearing of Chaoyang Bridge in Nanchang](image)

![Figure 10. Schematic diagram of cable bearing](image)

The restoring force model of cable bearing in figure 11 is mainly composed of basin bearing and restoring force curve of cable. As shown in the figure below. Among them, \( K_1 \) is the initial stiffness of the pot support, \( K_2 \) is the tensile stiffness of the cable, and \( U_0 \) is the free stroke of the cable damping support.
Compared with the ordinary friction bearing, the cable damping bearing has the third linear segment. In this stage, the support provides the restoring force through the tension of the cable. By adjusting the length and thickness of the cable, the values of $U_0$ and $K_2$ can be controlled to realize the control of "force and displacement". For different bridges, the reasonable selection of the parameters of cable damping support can affect the overall seismic performance of the bridge, which also shows that the cable damping bearing has the adaptability to different bridges.

In order to determine the reasonable parameters of the cable support, the stiffness $K$ and free stroke $S$ of the cable support are optimized respectively. The setting of parameter combination condition is as follows Table 3.

| Cable stiffness $K$ (kN/m) | 115000 | 125000 | 135000 | 145000 |
|---------------------------|--------|--------|--------|--------|
| Free travel $S$(m)        | 0.35   | 0.35   | 0.35   | 0.35   |
|                           | 0.4    | 0.4    | 0.4    | 0.4    |
|                           | 0.45   | 0.45   | 0.45   | 0.45   |

The force analysis of different cable support parameters under earthquake action is carried out. By comparing the seismic response of the key positions of the bridge, the optimal cable support parameters of the cable-stayed bridge under the earthquake action are obtained. The calculation results of the bending moment at the bottom of the tower, the moment at the top of the pile and the relative displacement of the tower and beam are as follows Figure 12 to Figure 14.
Figure 13. Relationship between different parameters of cable support and bending moment of pile top

It can be seen from Fig 12 that the bending moment at the bottom of the tower increases with the increase of free stroke \( S \), and the cable stiffness \( K \) has little effect on it.

It can be seen from Fig 13 that the free travel \( s \) and the cable stiffness \( K \) have little effect on the bending moment at the top of the pile, and the bending moment at the top of the pile increases only slightly with the increase of the free travel \( S \).

It can be seen from Fig 14 that the relative displacement between tower and girder decreases with the increase of cable stiffness \( K \) and increases with the increase of free travel \( s \). When the free travel \( S \) is 0.4 m, and the cable stiffness \( K \) is 135000 kN / m and 145000 kN / m, the relative displacement between tower and beam can be controlled within 0.5 m.

The relative displacement between tower and girder is not more than 0.5 m, considering the manufacturing technology of cable damping support, the performance of cable itself and the damping effect on the structure. At the same time, considering that the maximum stress in the cable should not exceed the breaking stress of the wire rope, in order to prevent the cable from being broken, it is suggested that the value of free travel should not be too small, and \( S = 0.4 \) m is the most appropriate value.

To sum up, it is suggested that the parameters of the cable damping support of the bridge are, cable stiffness 135000 kN / m, free travel 0.4 m.

5. Conclusion

In this paper, the seismic performance of long-span cable-stayed bridge with ultra-high strength concrete as deck pavement is analyzed, and the transverse restraint system of its main girder is studied
in depth. The spatial dynamic calculation model is established. The nonlinear time history analysis method is used to analyze and study the four lateral restraint systems of the super large bridge. Including transverse restraint system, transverse relaxation system, cable support system between tower and beam, and elastic restraint system between tower and beam. Considering the internal force of the main tower, the internal force of the pile foundation, the displacement of the beam end and the relative displacement between the tower and beam, the reasonable transverse restraint system of the main girder of the bridge is obtained. The main conclusions are as follows.

A. When UHPC is used as bridge deck pavement, it can effectively improve the stress condition of bridge deck pavement and reduce the fatigue cracking of bridge deck. At the same time, a large area of high-quality deck pavement will also increase the weight of the bridge deck system, which is not conducive to the lateral force of the bridge structure and seismic fortification design.

B. Through the analysis of the lateral restraint system of the main girder of the super bridge, it can be known. Under the lateral and vertical seismic input, the seismic response of the main tower and pile foundation is lower than that of other restraint systems. The relative displacement between tower and beam can be controlled within the safe range of 0.5 m, which is the most favorable for the seismic performance of bridge structure.

C. The parameter sensitivity analysis of the cable damping support is carried out. By selecting different parameter combination conditions, the seismic response of bridge structure under different working conditions is compared. Considering the internal force response and displacement response of the bridge structure and the safety of the support, the cable stiffness of 135000 kN / m and the free travel of 0.4 m are selected as the recommended values of cable support parameters for the actual bridge in this paper.

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