STUDY ON BOUNDARY CONDITIONS OF GROUND ANCHORED CABLE STAYED BRIDGE WITH SINGLE INCLINED TOWER

Yajun ZHANG1*, Xiaoshan WANG2 and Yahao LIU1, Ranran LI1
1Master, School of Highway, Chang'an University, Xi'an, China
2Engineer, Liuzhou OVM Engineering Co., Ltd, Liuzhou, China
*Corresponding author email: 2018121044@chd.edu.cn

Abstract. In order to study the influence of boundary conditions at the bottom of the tower on the structural characteristics of a ground anchored cable-stayed bridge with single inclined tower, taking a bridge project as an example, the finite element model is established to study the static, dynamic and overall stability of three structural systems, namely, universal hinge connection, unidirectional hinge connection and consolidation connection, between the bridge tower and the concrete tower base. The results show that: The internal force can be reduced by universal hinge connection between tower bridge and tower base, and structural deformation can be reduced by choosing consolidation method. However, there will be huge torque and transverse bending moment at the bottom of tower, so the consolidation system should not be selected first; the dynamic characteristics of the three systems are different, but the dynamic characteristics of the main girder are basically the same. In terms of stability, the boundary conditions have little effect on the low-order instability modes of the structure, and the stability can be considered as the final factor of the structure selection.

1. Introduction
The mechanical characteristics of ground anchored cable-stayed bridge with single inclined tower are different from those of ordinary cable-stayed bridges. The static and dynamic characteristics of this bridge type have been studied by scholars. Lingling Zhou [1] studied the mechanical performance of the rigid frame system of the ground anchored single tower cable-stayed bridge under various loads, and concluded that the automobile load is the most sensitive to the mechanical performance of the structure. By selecting several key parameters, Xiaoye Luo [2] and Gaosi Wang [3] studied their influence on the stress of the bridge in detail, and then obtained the reasonable parameter values of the whole bridge. According to Pingming Huang [4]'s research, the number of auxiliary piers has little effect on the vibration mode and frequency of single tower cable-stayed bridge under five different boundary conditions. According to Dafeng Gao [5], the dynamic characteristics of cable-stayed bridge with single inclined pylon under the conditions of tower bottom consolidation, pile and changing bridge structural parameters have little difference. However, the above-mentioned researches are all based on the bridge structure with the bridge tower inclined to the bank, and the bridge whose tower inclines to the center of the river is rarely studied, and the bridge studied in this paper belongs to the latter.

In this paper, the internal forces and displacements of three kinds of structural systems, universal hinge connection, unidirectional hinge connection and consolidation between steel tower and tower base, under the action of dead load and moving load, as well as the dynamic characteristics and overall
stability of these three systems are studied, the research results can provide reference for similar bridge structure system selection.

2. Project overview
This structure is a ground anchored single inclined tower special-shaped cable-stayed bridge with a total length of 233m and a span arrangement of \((99.8 + 51.0 + 25.0 + 27.4 + 30.2)\) m. As shown in Figure 1. The bridge tower is a steel inclined tower with an inclination of 60° and a tower height of about 85m. A viewing platform is set at the vertical height of about 50m from the tower bottom. The bridge tower is in the form of variable cross-section. An elevator is designed at the back of the tower to access the viewing platform. Therefore, the back of the tower is designed as a straight line. The main girder is a spatial curved beam with variable cross-section, and the beam width ranges from 6m to 12m. As shown in Figure 2. The stay cables are set as 8 back ground anchor cables, 4 front ground anchor cables and 9 pairs of bridge deck cables. The pier is supported by steel pipe. The bridge tower and main girder are made of Q420 steel, the steel pipe support is made of Q345 steel, steel strand with tensile strength of 1860 MPa is used for back cable, and 1670 MPa parallel steel wire is used for front ground anchor cable and main beam cable.

3. Finite element model
According to the structural form and mechanical characteristics of the bridge, the Midas structure finite element model is established. The bridge tower, main beam and steel pipe support are simulated by space beam element, the stay cable is simulated by cable element, and the tower bottom is restrained by general support. The constraint parameters are shown in Table 1. Therefore, the crowd load concentration on the viewing platform is calculated as 0.8kPa full load, and the crowd load concentration on the main beam is calculated as 2.4kPa full load.

| Structural system          | DX | DY | DZ | RX | RY | RZ |
|----------------------------|----|----|----|----|----|----|
| Universal hinge system     | √  | √  |    | √  |    |    |
| Unidirectional hinge system| √  | √  | √  | √  | √  |    |
4. Internal force analysis of bridge tower
The bridge tower is steel tower and tower base is reinforced concrete, so the connection between bridge tower and tower base is the difficulty of this structure, so the internal force of tower bottom should be paid special attention to.

4.1. Internal force of structure under dead load
It can be seen from Table 2 that the universal hinge is set at the bottom of the tower, which releases the bending moment in all directions. Therefore, the longitudinal bending moment, transverse bending moment and torque of the tower bottom are zero. The unidirectional hinge at the bottom of the tower releases the bending moment along the bridge direction, so the longitudinal bending moment is zero under the dead load. However, because the transverse structure of the structure is asymmetric, the lateral deformation and torsional deformation of the tower can’t be completely eliminated by adjusting the cable force. Therefore, this system will produce transverse bending moment and torque at the tower bottom. The bending moment difference between the universal hinge system and the unidirectional hinge system in the middle of the tower is different not big. When the bridge tower is connected with the tower base by consolidation, the root of the tower will produce a large negative bending moment, but the peak bending moment in the middle of the tower will be reduced by about 30% compared with the first two systems. The transverse bending moment and torque of the tower root are almost the same as those of the unidirectional hinge system.

From the perspective of axial force, the bearing capacity of the three systems should be considered.

| Internal force          | Location       | Universal hinge | Unidirectional hinge | Consolidation |
|-------------------------|----------------|-----------------|----------------------|--------------|
| Longitudinal bending moment (kN*m) | Tower bottom | 0               | 0                    | -12736       |
| Transverse bending moment (kN*m) | About 0.4L | 19836           | 19699                | 13163        |
| Axial force (kN)        | Tower bottom  | 51544           | 51540                | 51670        |
| Torque (kN*m)           | Tower bottom  | 0               | 185                  | 200          |

4.2. Internal force of structure under moving load
As the main beam of bridge structure is spatial curved beam, the structure will have obvious displacement in longitudinal and transverse direction under moving load. Therefore, the internal forces in all directions of bridge tower of three systems under moving load should be paid attention to. The results are shown in Table 3.

| Internal force          | Location       | Universal hinge | Unidirectional hinge | Consolidation |
|-------------------------|----------------|-----------------|----------------------|--------------|
| Longitudinal bending moment (kN*m) | Tower bottom | 0               | 0                    | -4439       |
| About 0.65L            | 3802           | 4041            | 3651                 |
| Transverse bending moment (kN*m) | Tower bottom | 0               | -808                 | -764       |
| About 0.65L            | 468            | 421             | 390                  |
| Axial force (kN)       | Tower bottom  | 2215            | 2215                 | 2162        |
| Torque (kN*m)          | Tower bottom  | 0               | 583                  | 572         |

It can be seen from Table 3 that under the action of moving load, the universal hinge support is set at the bottom of the tower, the bending moment along the bridge, the bending moment in the transverse
direction and the torque at the tower bottom are all zero, the peak value of the longitudinal bending moment of the tower body is between the unidirectional hinge system and the consolidation system, and the bending moment near the transverse anchorage zone of the tower body (about 0.65L) is the largest among the three systems. The bending moment of unidirectional hinge system near the cable anchorage zone (about 0.65L) is the largest among the three systems, and the transverse bending moment and torque generated at the root of the bridge tower are also the largest among the three systems. For the consolidated system, a larger negative bending moment will be produced at the root of the tower, which weakens the positive bending moment of the tower body (about 0.65L), and the torque generated is close to that of the unidirectional hinge system. For the axial force at the bottom of the tower, the difference between the three systems under moving load is small.

5. Displacement of bridge tower

5.1. Displacement of bridge tower under dead load

As a landscape bridge, the landscape effect plays an important role. In the finished state, the structural alignment should keep the design alignment, so the deformation of the bridge tower needs to be paid attention to.

![Figure 3. Displacement of bridge tower under dead load.](image)

Note: "-" indicates the displacement of the bridge tower to the duty-free mall, "+" indicates the displacement of the bridge tower to the river central island. The same below.

Figure 3. Displacement of bridge tower under dead load.

It can be seen from Figure 3 that under the action of dead load, the maximum displacement of the structural system connected by the steel tower and the tower base is about 30m away from the tower bottom, with the displacement of 74mm. At the same time, the maximum displacement in the opposite direction occurs at the tower tip, with the displacement of 69mm. However, for the structure system with steel tower and tower base connected by one-way hinge, the deformation of bridge tower is basically the same as that of universal hinge system. The displacement of the steel tower and tower base connected by consolidation is much smaller than that of the other two systems at a distance of 30m from the tower bottom. The displacement is 41mm, about 58% of the hinged system, and the displacement at the tower tip is 15mm, which is about 22% of the hinged system. In order to ensure that the completed bridge alignment is the design alignment, the corresponding pre camber should be set in the construction process. Due to the consolidation of the tower bottom, the deformation of the bridge tower is greatly reduced. Therefore, the pre camber that needs to be set in the construction process is less than that of the hinged system.

5.2. Displacement of bridge tower under moving load

In the design of the bridge, an elevator leading to the viewing platform is designed at the back of the bridge tower. In order not to affect the use of the elevator, the deformation of the bridge tower under the moving load also needs to be paid attention to.

It can be seen from Figure 4 that the displacements of the three systems in the anchorage zone are all close to 40mm. The tower bottom and the anchorage zone (about 0.65L) are connected by a straight line. It is found that the displacement of the bridge towers of the three systems deviates from this straight line very little under the action of moving load. Therefore, it can be judged that under the moving load,
the bridge tower mainly deflects around the tower bottom, and the bending deformation of the bridge tower is small. Because the two hinged systems can rotate freely along the bridge, the bending deformation is greater than that of the consolidated system. In general, the three systems have little impact on the use of elevators in the operation process, and the consolidation system is the best.

![Figure 4. Displacement of bridge tower under moving load.](image)

6. Dynamic characteristic analysis
Dynamic characteristic analysis is the basis of seismic response analysis and pedestrian bridge comfort analysis. The first four order vibration frequencies of the three systems are shown in Table 4. The first vibration mode of the bridge structure is the lateral deflection of the viewing platform. Due to the release of the bending moments at the bottom of the tower of the universal hinge system, the stiffness of the structure system is small and the frequency is low, while the stiffness of the unidirectional hinge system and the consolidation system is higher, and the frequency is the same. The second-order vibration mode of the three systems is the main beam symmetric vertical bending, and the frequency is almost equal. The third mode girder is antisymmetric vertical bending with the same frequency. The fourth mode is the longitudinal bending of the bridge tower. Due to the high stiffness of the consolidated system, the frequency is large.

To sum up, the dynamic characteristics of unidirectional hinge system and consolidation system are basically the same when the bridge tower is bent laterally. When the bridge tower is longitudinally bent, the dynamic characteristics of universal hinge system and unidirectional hinge system are basically the same. For the main beam, the dynamic characteristics of the three systems are basically the same. Moreover, the first vertical bending frequency of the main beam of the three systems is lower than the 3Hz given in the code, so it does not meet the requirements of pedestrian comfort, so special design is needed.

| Table 4. Vibration frequency of three structural systems. |
|---------------------------------------------------------|
| Universal hinge (Hz) | Unidirectional hinge (Hz) | Consolidation (Hz) |
|----------------------|---------------------------|-------------------|
| 1                    | 0.31                      | 0.98              |
| 2                    | 1.09                      | 1.09              |
| 3                    | 1.27                      | 1.27              |
| 4                    | 1.52                      | 1.52              |

7. Analysis of structural stability characteristics
The bridge structure is a special-shaped cable-stayed bridge, so the stability problem should not be ignored. The first five order stability coefficients of the structure under different boundary conditions are shown in Table 5, and the first five order instability modes are shown in Figure 5.

It can be seen from Table 5 and Figure 5 that the boundary conditions at the bottom of the bridge tower have little influence on the stability coefficient of the structure. The stability coefficient of the consolidated system is slightly greater than that of the unidirectional hinge system, and that of the unidirectional hinge system is slightly greater than that of the universal hinge system. The first four order instability modes of the three systems are basically the same, that is, the overall instability of the main beam. The fifth order instability mode of universal hinge system and unidirectional hinge system
is the overall instability of bridge tower, while the fifth instability mode of consolidated system is local instability of main beam. Generally speaking, the instability of the tower of the universal hinge system and the unidirectional hinge system is earlier than the local instability of the main beam, and the consolidation system is the opposite. However, because this result appears in the high-order instability mode, and the stability coefficient reaches about 30, the probability of this instability mode is very low in reality. Therefore, it is not necessary to pay too much attention to the influence of stability when selecting the boundary conditions, and pay more attention to the internal force of the structure when selecting the structural system.

Table 5. Stability coefficient of structure under different boundary conditions

| Boundary Condition | Universal Hinge | Unidirectional Hinge | Consolidation |
|--------------------|-----------------|----------------------|--------------|
| 1                  | 12.63           | 12.66                | 13.34        |
| 2                  | 17.65           | 17.75                | 18.64        |
| 3                  | 23.71           | 24.01                | 25.16        |
| 4                  | 26.58           | 26.93                | 28.50        |
| 5                  | 30.04           | 30.11                | 31.85        |

Figure 5. Instability modes under different boundary conditions

8. Conclusion

(1) Through the analysis of the internal force and deformation of the bridge tower, the universal hinge connection between the tower and the tower base can reduce the internal force, and the consolidation method can reduce the structural deformation, but there will be huge torque and transverse bending moment at the bottom of the tower, so this system should not be selected first.

(2) Through the dynamic performance analysis, the stiffness of the tower is different due to the different boundary conditions of the tower, so the dynamic characteristics of the tower are different, while the dynamic characteristics of the main beam are basically the same. For comfort requirements, the three systems need special design.

(3) The influence of boundary conditions on the low-order instability modes of the structure is not significant. In the selection of structural system, attention should be paid to the influence of boundary conditions on the internal force of the structure, so as to select the appropriate structural system.

References

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