Opinion Article

Research Status of Static Performance of Multi-Span Cable-Stayed Bridge

Abstract：The use of multi-span cable-stayed bridge is becoming more and more common. By collecting a large number of domestic literature in China, this paper mainly summarizes the research results of different research methods on the static performance of multi-span cable-stayed bridges. It shows the research on the mechanical properties of multi-tower cable-stayed bridges by different Chinese scholars. It has reference for the study of static performance of multi-span cable-stayed bridge.

Key word：multi-span cable-stayed bridge；static performance；review

Introduction

Multi-span cable-stayed bridge refers to a four-span or more than four-span cable-stayed bridge, that is, there are three towers or more than three towers. The multi-span cable-stayed bridge is a bridge structure composed of tower, beam, cable and foundation. The structure is a bridge that directly pulls the main beam on the bridge tower with many cables. The superstructure of the cable-stayed bridge is composed of a pressure-bearing tower, a tensioned cable and a curved beam. According to the number of bridge towers, cable-stayed bridges can be divided into double span cable-stayed bridges, three-span cable-stayed bridges and multi-span cable-stayed bridges.The multi-span cable-stayed bridge has developed rapidly in the past thirty years due to its excellent spanning ability. It is especially suitable for occasions that need to cross a wide area and has become a bridge type choice with strong spanning ability.

The Maracaibo bridge, designed by Morandi in 1962, marks the birth of the world 's first multi-span cable-stayed bridge. Maracaibo bridge is a concrete cable-stayed bridge, which later became the cornerstone of structural design and theoretical calculation of multi-tower cable-stayed bridge. YueyangDongting Lake Bridge built in China in 2000 is the first four-span cable-stayed bridge in China. It is a three-tower prestressed concrete cable-stayed bridge with unequal height and span of (130 + 2 × 310 + 130) m.

In the context of human pursuit of stronger spanning capacity of bridges, the concept of multi-tower cable-stayed bridges has appeared at the beginning of the development of cable-stayed bridges, but almost no multi-tower cable-stayed bridges have appeared. One of the reasons is that the structural stiffness of multi-tower cable-stayed bridges cannot meet the requirements. The middle tower of a multi-tower cable-stayed bridge is difficult to control the bending deformation of the middle tower due to the difficulty of installing end anchor cables and the absence of auxiliary piers. As a bridge supported by cables, the bending of the middle tower is bound to affect the overall deformation of the main girder. The deformation coordination of the whole bridge caused by the structural deformation of the multi-tower cable-stayed bridge under local load is more difficult to control than the single-tower cable-stayed bridge and the double-tower cable-stayed bridge. The main girder is supported by the cable of the flexible structure. If the stiffness problem of the middle tower cannot be solved, the overall flexibility of the structure will be greater, resulting in excessive deformation of the structure under local load and destruction of the structure.

1 Static characteristics of multi-span cable-stayed bridge

The cable of the cable-stayed bridge constitutes a triangular structure between the cable and the main girder and the cable tower to bear the load. In general, the main girder bears its own weight and transmits its own weight to the cable tower through the stay cable. In addition to providing the main girder with an upward bearing force, the stay cable also provides a horizontal force in the direction of the cable tower to make the main girder compressed. Therefore, the main girder is in a state of bending and compression. In addition to the axial force caused by self-weight, the cable tower also bears the axial pressure and horizontal force transmitted by the stay cable. Therefore, the cable tower bears both huge axial force and large bending moment, which belongs to the compression-bending member. Whether it is the construction stage or the operation stage of the bridge, the stress state of the structure can be changed by adjusting the cable force of the cable. All the loads of the superstructure are transmitted to the pier through the tower, and then to the foundation, from the foundation to the foundation. Therefore, the pier belongs to the bending member, and the foundation generally bears a large vertical force and bending moment.

The general three-span cable-stayed bridge and the multi-span cable-stayed bridge are different in appearance, and the mechanical behavior of the two is also different. When the load is applied to a certain intermediate span, in the loaded span, the main girder will produce downward deflection, the cable force will increase, and the bridge tower will produce deflection in the direction of the loaded span, which will cause the adjacent bridge span to produce upward deflection. In the adjacent span, the other bridge tower produces a displacement opposite to the loaded bridge tower. Because there is no side anchor cable to control the displacement of the middle tower, the role of the cable system has not been fully utilized. The overall deformation of the multi-span cable-stayed bridge is limited by the stiffness of the main beam and the bridge tower. When the load acts on the adjacent span, the load hole will be deflected, and the bridge tower will have a reverse deformation from the previous situation, which will still lead to excessive deformation of the whole structure. At the same time, it also means that each component of the structure must bear two internal forces in the opposite direction, which will lead to a higher stress amplitude in the component.

The research methods of static load of multi-tower cable-stayed bridge mainly include experimental method, theoretical calculation method and numerical simulation method.

2 Study on static performance of multi-tower cable-stayed bridge based on experimental method

Limited by the technical level in the 1980 s, China has not developed a numerical simulation method based on finite element software. It mainly uses experimental method and theoretical calculation method and the combination of the two methods. Professor Zhang Qisen[1], Dr. Yan Donghuang and their research group members from Changsha Communications University are the first to study the experimental method of multi-tower cable-stayed bridge in China. They conducted a 1 : 30 scaled model test on the Dongting Lake bridge, the first three-tower cable-stayed bridge in China. The experimental study compares the experimental results with the theoretical calculation results, and verifies the correctness of the theoretical calculation results, which provides experimental support and theoretical calculation support for the feasibility construction of Dongting Lake bridge. On this basis, the members of the research group also studied the stress analysis of the construction process of the Dongting Lake bridge and the geometric nonlinear analysis of the beam tower, which provided the basis for the design and construction of the multi-span cable-stayed bridge in China.

Based on a Yangtze River bridge, the static experiment and theoretical calculation analysis of three different cable-adding schemes are carried out by Xiao Mingkui[2], Wang Xiaowei and Liu Gang. The research shows that adding the lower cable can effectively improve the structural stiffness of the multi-tower cable-stayed bridge structural system and reduce the bending moment at the root of the tower pier and the mid-span of the main beam.

A new type of shell-shaped tower cable-stayed bridge is proposed for the first time by Yuan Hui-hui[3]. The shell-shaped tower is composed of five concrete filled steel tube (CFST) tower arches (PAs) and arc-shaped hollow steel braces. In order to explore the force transmission mechanism of the new CSB, the static loading test of the 1 : 25 scale model of the whole bridge and the finite element analysis of the prototype bridge were carried out. The results show that under the action of vehicle load, the shell-shaped bridge tower and the main girder share the load in a 1 : 9 distribution ratio. The stress level of the middle part of the tower arch (PAm) and the tower arch adjacent to the tower arch (PAn) is much larger than that of the outermost tower arch (PAo), and the maximum stress occurs at the bottom section of the tower arch. However, under the action of permanent load, the position where the maximum stress occurs will shift to the junction of the PAs curve and the straight line segment. At the same time, under the action of temperature load, the stress levels of PAm, PAn and PAo are almost equal, and the maximum stress appears at the vault. In addition, the refined finite element analysis results of the steel-concrete composite bridge tower show that there is obvious stress concentration at the tubular joints of PAm and PAn and the connection area between the steel plate and the steel pipe. Nevertheless, in the limit state, the tower support is still elastic.

3 Study on static performance of multi-tower cable-stayed bridge based on theoretical calculation method

Since the 1960 s, many foreign experts and scholars have carried out theoretical analysis and research on multi-tower cable-stayed bridges. The General Rafael Urdaneta Bridge across Maracaibo Lake in Venezuela was built in 1962.Through theoretical analysis and research, its designer Riccardo Morandi believes that with the increase of span and the increase of tower number, the problem of insufficient bridge stiffness can be formed by adding V-shaped diagonal braces to the human-shaped bridge tower to form a cable tower with great stiffness, and the two sides are suspended respectively. The main beam of the arm is pulled up with a pair of stay cables to form a stable symmetrical independent double cantilever large unit, thus proposing the Morandi system. Subsequently, some scholars studied the multi-tower cable-stayed bridge scheme of the Dabeier Bridge in the 1970 s. The results of this study are as follows : A new multi-tower cable-stayed bridge form, namely the dense cable system, which is completely different from the Morandi system of the Maracaibo Bridge, is proposed. The beam is more flexible, and the structural stiffness is guaranteed by the rigid tower or the cross cable.

Hu Jianhua[4], Liao Jianhong and others are the first to study the multi-tower cable-stayed bridge in China.In the process of verifying the design of Dongting Lake Bridge, they discussed the structural arrangement and mechanical properties of multi-tower cable-stayed bridge. They mainly studied and determined the best stress balance method for the reasonable completion state of multi-tower cable-stayed bridge. At the same time, they believed that the influence of prestress, secondary internal force and live load on the bridge should be paid attention to.

Taking Yangluo Bridge as the engineering background, Zheng Chun[5] and Liu Xiaodong compared the stress conditions of four forms of multi-tower cable-stayed bridges based on the theoretical calculation method of bridge plane bar system. The research shows that the overlapping arrangement of stay cables between each two towers and the addition of stable cables between each two towers can improve the stress form of multi-tower cable-stayed bridges. At the same time, the weight of side and middle spans also helps to improve the overall structural stiffness.

Yao Sisi[7] conducted an in-depth study on the mechanism of cross-rope action. It is assumed that the small displacement at the top of the side tower is ignored. The relationship between the horizontal external force and the displacement of the top of the middle tower was analyzed twice by using the principle of deformation coordination. Therefore, the estimation formula of the anti-push stiffness of the multi-tower cable-stayed bridge to the middle tower under the influence of the tower beam stiffness is derived. The results show that the error between the analytical solution and the finite element solution is less than 8 %, which meets the conceptual design requirements of the multi-tower cable-stayed bridge. The cross cable can reduce the deflection of the main beam and improve the stiffness of the bridge. After setting up 10 pairs of cross cables, the displacement of the middle tower is reduced by 51 %. The stiffness of multi-tower cable-stayed bridge increases with the increase of the number of cross cables, but the increasing trend of stiffness gradually slows down. Increasing the stiffness of the tower or beam can improve the structural stiffness to a certain extent, but the effect is far less than that of the cross cable.

Chai[8] derived the analytical expression of the longitudinal stiffness constraint of the cross cable to the bridge tower, which can solve the constraint function of the cross cable under different tower heights. The analytical solutions of tower top displacement and mid-span deflection of main girder under live load are obtained. The analytical solutions can consider the influence of tower stiffness, main span number and cross cable parameters on structural deformation at the same time. In addition, they carried out finite element simulations to verify the accuracy of the proposed equations. The numerical results are consistent with the theoretical results calculated by the formula, indicating that the formula can provide an accurate estimate of the structural deformation required for bridge design in the preliminary design stage.

4 Study on static performance of multi-tower cable-stayed bridge based on numerical simulation method

At the beginning of the 21 st century, with the introduction of the first batch of finite element simulation software from abroad, China began to develop engineering research based on numerical simulation method. The common finite element simulation software includes Ansys, Midas, Abaqus, Opensees and so on.

Yu[9] established a cable-stayed bridge model with two towers, three towers and four towers by maintaining the length of the main span and increasing the tower. The study shows that under the same main design parameters of the structure, the multi-tower cable-stayed bridge has stronger spanning capacity than the double-tower cable-stayed bridge, but the structural deformation is larger than that of the double-tower cable-stayed bridge.Based on the project of Yiling Yangtze River Bridge, the static analysis of Shao[10] is carried out by using different combination schemes of main girder form, auxiliary pier and stiffening cable. It is found that because the weight difference between concrete box girder and steel box girder is huge and the cable scheme is different, it is not comparable to use concrete box girder or steel box girder for the box girder structure of thisbridge. Adding auxiliary piers and stiffening cables to Yiling Yangtze River Bridge can effectively improve the stiffness of the middle tower, thus improving the overall stress state of the bridge.

Zhang[11], Gao and Mei used numerical simulation software to study the mechanical properties of multi-tower cable-stayed bridges with different tower forms, different cable arrangements and various girder forms under static load for a five-tower cable-stayed bridge in the Yangtze River. The research shows that for the five-tower cable-stayed bridge of the long-span railway, the double-wall pier bridge tower with tower top and horizontal tie cable combined with steel box truss is the optimal scheme.

Lin[12], Li, Wang and others took Jiashao Bridge as the structural foundation, and quantitatively analyzed the internal force of multi-tower cable-stayed bridge and the variation law of vertical deflection of main girder. It is found that with the increase of bridge towers, the deformation of tower top and the internal force of tower bottom increase under static force. At the same time, it is proposed that the influence of different floating systems on the bridge should be discussed separately according to local conditions. For the Jiashao Bridge, the consolidation system is helpful to improve the stress of the bridge for the three-tower cable-stayed bridge whose tower and main beam are concrete.

Based on YibinLingang Yangtze River Bridge, Zhang[13], Zhu, Luo and others studied the force transmission mechanism of cable-girder anchorage structure of cable-stayed bridge, and discussed the influence of the thickness of important plate of steel anchor box on the stress of anchorage zone. The research shows that there are three main directions after the cable force is transmitted to the anchor web : most of the cable force is transmitted obliquely to both sides along the anchor web after passing through the bearing plate, and is transmitted to the weld position between the anchor web and the lower side of the beam web, which is transmitted to the beam web in the form of compressive stress ; a small part of the cable force is transmitted to the anchor web and the weld position on the upper side of the beam web, which is transmitted to the beam web in the form of tensile stress. The change of the thickness of the anchor web of the steel anchor box has a greater impact on the overall stress of the steel anchor box. Appropriately increasing the thickness of the anchor web helps to reduce the peak stress of the steel anchor box and make the force of the steel anchor box more uniform.

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