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Analysis on Safety of Removing the Closure Segment in a Prestressed Concrete Cable-stayed Bridge

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Abstract

Aiming at failure of closure segment in a prestressed concrete cable-stayed bridge, a strengthening technology, namely replacing the closure segment, was firstly put forward. But removing the old closure segment was a process of release of internal force and had great risk. So the structural safety possibly induced by removing must be analyzed and confirmed. Based on FEM and summary of engineering experience, the construction stages for removing the old closure segment were simulated, and then some analysis relevant to safety, including thermal effect, dynamic characteristics and global stability of the whole bridge structure, were systematically presented. According to these analysis results, corresponding prevention and control measures were provided to ensure construction safety. Studies showed that, variation range of its structural state between before and after removing is not obvious, and its dynamic characteristics changed little after removing. In addition, structural instability could not be induced by removing, but for the sake of improving construction safety reliability, necessary safety prevention and control measures were indispensable. Analysis on safety of removing the old closure segment constituted the important part of the strengthening technology of replacing the closure segment, and became the theoretical basis of removing partial structural members for existing bridges.

Keywords: Prestressed concrete cable-stayed bridges; Strengthening; Replacing; Removing; Safety

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1. Introduction

The closure segment, usually cast in place to make main girder continuous, was one of key structural members in a long-span prestressed concrete segmental bridge. Due to differences in loading age and shrinkage of concrete, the joint between the closure segment and its adjacent segments often became weak parts. Once joint failure, connection of the closure segment for the bridge span could be reduced greatly, even a major hidden danger would be evolved eventually. Conventional strengthening techniques, such as External Prestressing Reinforcement Technology, Enlarging cross-section Method and Adhesive Reinforcement Technologies, could not treat this kind of structural disease effectively and could not ensure safe and sustainable operation of bridge. Therefore, a new strengthening technique, called Replacement of the Closure Segment, was born. Similar to Concrete Replacement Method in building structures, the basic processes of this new strengthening technology included removing the old closure segment, then reconstructing the closure segment, and finally enhancing the link between the new closure segment and the original main girder and establishing a rational stress condition of the new closure segment by some effective strengthening measures. Thus the connection of bridge span was rehabilitated, and the hidden danger was eliminated completely [**1**]. Removal of the old closure segment is the precondition of replacement. However, for any existing bridge, its structural state was of great fuzziness or uncertainty over time, and so removal of the old closure segment might be a process of release of internal forces and had a greater construction risk. Based on this, the structural safety possibly induced by removal must be considered and confirmed. According to analysis results, necessary engineering measures must be adopted to improve construction reliability. In this paper, Yonghe Bridge in Tianjin was taken as the background bridge, and corresponding safety analyses and engineering measures for replacement of its closure segment were presented.

2. Overview of Yonghe Bridge

Yonghe Bridge, located in Tianjin, China, had one continuous and floatable main girder with 5 spans, and the length of main span was 260 meters. Also, it was a suspended structural system with double pylons, which were fixed with the piers, and double cable planes (see Figure 1). Its girder segments were precasted by match casting and erected on scaffoldings at side spans and by cantilever-splicing at middle spans. Its cross-section of main girder was typical of P-K section, formed by a semi-closed box section with two triangles and its height was 2.0m. The deck width, including the width of wind fairing, was 14.5m, as shown in Fig.2. Yonghe Bridge was completed in 1987. After 18 years, the joint between the closure segment of its main span and its adjacent precast segment at the south side cracked severely , as shown in Fig.3. The crack width at the bottom of joint reached 10cm, and fractures of steel bars and prestressing tendons appeared simultaneously at the joint. When vehicles cross, activity of the crack width was obvious, and the measured width amplitude arrived at 9mm [**2**]. To eradicate this structural hidden danger, a strengthening technology on replacement of the closure segment was undertook for the first time in the world.

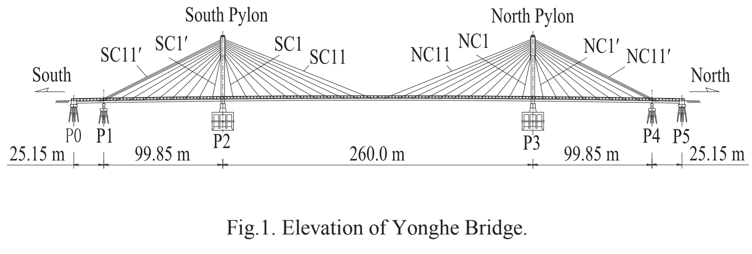

Fig.1. Elevation of Yonghe Bridge.

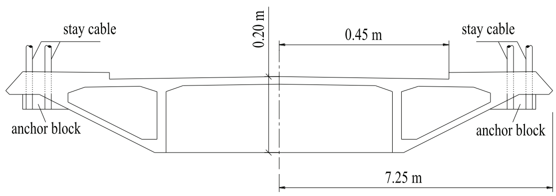

Fig.2. Typical section of main girder.

Fig.3. Crack at the wet joint.

3. Construction stage analysis on removal of the closure segment

Referred to the closure process in new bridges, a method for removal of the old closure segment in Yonghe Bridge was established. On the one hand, the idea of balance weight was followed, that is, some temporary weights (e.g. water tanks) were placed at bridge deck to substitute for the weight of old closure segment to maintain the load balance for its main span. On the other hand, after removing deck pavement near the old closure segment, the old closure segment was locked by using an external stiff frame (made by section steel) to make the main girder still continuous after removal of the old closure segment. The removal construction sequences included releasing prestressing tendons at the old closure segment, Chiselling the concrete by step, and removing steel bars and prestressing tendons [**3**]. Structural mechanical modes before and after removing the old closure segment were different as shown in Fig.4.

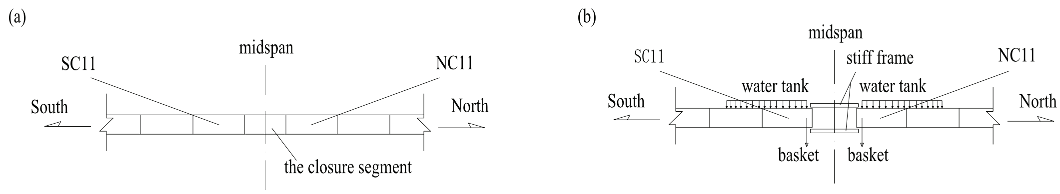

Fig. 4. (a) Structural mode before removal of the closure segment; (b) Structural mode after removal of the closure segment.

To analyze and predict structural state changes induced by removal of the closure segment, a structural initial calculation model was established by original construction process of Yonghe Bridge, and then a corrected or adjusted model was obtained by considering a variety of operation factors and inspected results before removal of the closure segment to simulate the structural current state [4]. Based on these, the removal process was simulated according to aforementioned removal construction sequences. Simulation results showed that, the local upward deflection near the closure segment approached 5.5cm under the premise of following the idea of balance weight and externally locking the closure segment. Corresponding to this, axial forces of stay cables near the closure segment decreased 340kN (SC11 or NC11), while other cable forces changed little. In the meanwhile, concrete tensile stress increment at the bottom of main girder near riverside long cable was induced, and the maximum tensile stress increment approximated 3.5MPa. Besides, the longitudinal inclined displacements at top of pylons were 0.67cm (riverside) for the south one and 0.72cm (riverside) for north one, respectively. However, longitudinal displacement of main girder was small (lower than 0.5mm), and reaction forces at piers and abutments were not obvious, but the reaction force at each auxiliary pier could decrease with increasing of balance weight. Detailed calculation results could be found in the literature [5]. From the above calculation results, the vertical deformation and concrete stress of main girder should be the main objective of construction safety control for removal of the closure segment.

4. Thermal effect analysis

To analyze difference in the thermal deformation rule before and after removal of the closure segment and to find the influence of various thermal loads on structure, two structural modes, including the structure before removal and after that, were selected to calculate the thermal effects. The thermal loads were determined by the original design for Yonghe Bridge. The temperature gradient at the top and bottom of main girde, labeled with Load Case Ⅰ, was 5℃. The temperature difference between stay cables and the main girder, labeled with Load Case Ⅱ, was 10℃. The temperature difference between the left and right side of each pylon, labeled with Load Case Ⅲ, was 5℃. The global temperature difference, labeled with Load Case Ⅳ, was 16℃. The vertical deflections of main girder under these thermal loads were shown in Fig.5.

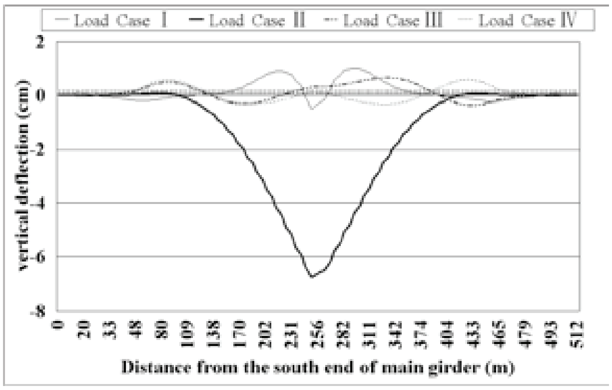

Fig.5. Vertical deflection of main girder under various thermal loads before removal of the closure segment.

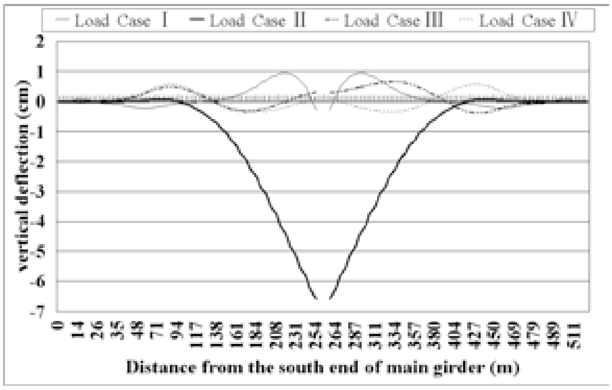

Fig.6. Vertical deflection of main girder under various thermal loads after removal of the closure segment.

Structural deformations due to various thermal loads after removal of the closure segment were shown in Table 1. As shown in Fig.5, the rule of deformation of main girder before removal induced by various thermal loads was agreed with the one after removal, and the values were roughly close. Moreover, it could be seen from Table 1 that, the effect of the temperature difference between stay cables and the main girder on the vertical deformation was most significant, and the effects of the global temperature difference and the temperature difference between the left and right side of each pylon on the longitudinal displacements at each end of main girder and at the top of pylons were relatively great.

Table 1. thermal effects of Yonghe Bridge after removal of the closure segment(units: cm)

Load Case	Displacement at the end of main girder*	Deflection of main girder**		Longitudinal displacement at the top of pylons***
		Minimum value	maximum value	
Ⅰ	-0.54	-0.26	0.94	-0.50
Ⅱ	-0.04	-6.59	0.07	1.18
Ⅲ	-2.01（South） 2.01（North）	-0.36	0.65	-2.34（South） 2.21（North）
Ⅳ	4.08	-0.32	0.56	-2.15

Displacement at the end of main girder*: positive value represented a riverside displacement; Deflection of main girder**: positive value represented upward deflection; Longitudinal displacement at the top of pylons***: positive value represented riverside displacement.

During the period of removal of the closure segment, the bridge structure was simultaneously subjected to not only the temperature difference of stay cables and main girder, the temperature gradient of main girder and the temperature gradient of pylons in one day, but also the seasonal global temperature difference. These deformations due to temperature loads were coupled in the total structural deformations. So the thermal effect analysis was an important basis for effectively estimating structural state changes and distinguishing normal or abnormal deformations [6]. Deformations induced by temperature loads belong to normal structural response and should not be restricted and limited, otherwise some secondary internal forces could be caused in the bridge structure, which analysis difficulties could increase. Especially for a longitudinally floating structural system like Yonghe Bridge, the rule and characteristics of structural deformations due to temperature loads must be fully considered when adopting safe prevention measures. It must become a principle that structural deformations due to temperature loads were freely produced.

5. Dynamiccharacteristics analysis

To find structural dynamic characteristics changes induced by removal of the closure segment , a three-main-girder model of Yonghe Bridge was established by the programme MIDAS/Civil, as shown in Fig.6. By comparison of measured frequencies and vibration modes between the structural state before removal of the closure segment and its original completion state, validity of this three-main-girder model was confirmed [7]. Then the states before and after removal of the closure segment were respectively selected to be used for dynamic analysis, and its first ten frequencies and vibration modes were calculated, as listed in Table 2. It could be seen from Table 2 that its structural dynamic characteristics varied little before and after removal of the closure segment, and its basic frequency was especially close. For the bridge structure, a structural parameter sensibility analysis was conducted. Results showed that, the rigidity of external stiff frame itself contributed little to the basic frequency of bridge structure. With greater rigidity, the basic frequency value was larger. Besides, the connection way between the external stiff frame and cantilever ends of half the bridge had some influence on the basic frequency. When fixed, the basic frequency was large. But when hinged, it was small.

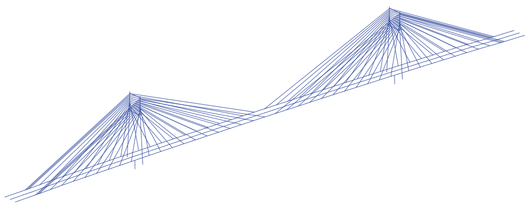

Fig.6 Three-main-girder dynamic model of Yonghe Bridge

Table 2. Calculation results of dynamic characteristics of Yonghe Bridge before and after removal of the closure segment

Order	Before removal of the closure segment		After removal of the closure segment	
	Frequency (Hz)	Vibration mode	Frequency (Hz)	Vibration mode
1	0.1941	Longitudinal floating	0.1940	Longitudinal floating
2	0.2754	Transverse bending	0.2424	Transverse bending
3	0.4465	Vertical bending	0.2988	Transverse bending
4	0.6172	Vertical bending	0.4475	Vertical bending
5	0.6847	Transverse bending	0.6111	Transverse bending
6	0.9329	Vertical bending	0.9194	Vertical bending
7	1.0832	Bridge deck twisting a little with transverse bending of pylons	0.9819	Bridge deck twisting a little with transverse bending of pylons
8	1.1547	twisting	1.1093	twisting
9	1.2822	Vertical bending	1.1254	Vertical bending
10	1.5525	Vertical bending	1.3765	Vertical bending

6. Global stability analysis of whole bridge

For a prestressed concrete cable-stayed bridge, the structure after removal of the closure segment was more prone to fail by instability under external loads (e.g. wind loads, construction loads) than the original structure, although the existence of external stiff frame made its main girder still continuous. So necessary analyses must be undertook to confirm it. A global stability model for Yonghe Bridge was established by ANSYS, as shown in Fig.7. Structural geometric nonlinearity and material nonlinearity were also taken into account in this model to calculate safe coefficients before and after removal of the closure segment [8]. Calculation results showed that, regardless of before and after removal of the closure segment, the first order instability mode was longitudinal bending instability of pylons. Before removal of the closure segment, the global stability coefficient was 2.643 , which was greater than the limited value in the literature [9]. So at this time, the bridge structure was stable enough. But after removal of the closure segment, the global stability coefficient was 2.162, which was slightly lower than the limited value in the literature [9]. However, this coefficient was the multiple for all loads applied on the bridge structure, including structural selfweight, superimposed dead loads, prestressing of main girder, wind loads, etc.), and so the overall loads throughout removal of the closure segment could not reach this magnitude. Therefore, the problem of instability could not exist after removal of the closure segment, but controlling appropriately construction loads could contribute to make the bridge structure safe with great global stability coefficient.

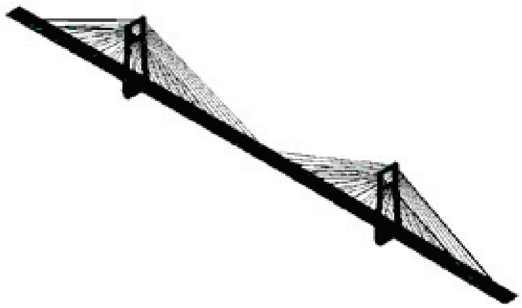

Fig.7 FE model for stability analysis of Yonghe Bridge

7. Safe prevention measures

7.1. Prevention and control for structural abnormal deformations

To avoid abnormal structural deformations induced by external unforeseeable factors and improve the structural safety in the period of removal of the closure segment, various possible structural deformations must be analyzed and estimated, and then some effective engineering measures could be adopted to prevent them.

Because principles of balance weight and equilibrium or symmetric construction during removal of the closure segment were obeyed, the torsional deformation of main girder was small. Before removal, the external stiff frame was installed to lock the closure segment, and so the transverse deformation of main girder was limited. To be further safer, PTFE sheet rubber blocks were pushed in the gap between the main girder and pylons to restrict the possible transverse deformation of main girder. Besides, it could be seen form the former analyses, the vertical deformation of main girder, forces of stay cables, and displacements at the top of pylons could be controlled by adjusting temporary weight at the bridge deck.

However, the longitudinal deformation of main girder was especially noteworthy. As the main girder of Yonghe Bridge was a completely floating structural system, the construction for removal of the closure segment could not be completed instantly, so the period of construction was relatively long. In fact, the time consuming for removal of the closure segment of Yonghe Bridge was 20 days. In order to prevent the abnormal floating or shifting displacement of main girder, adjustable horizontal jacks could be presetted between the ends of main girder and each abutment to limit it. In Yonghe Bridge, two horizontal jacks were installed at each abutment, and the tonnage of every jack was no less than 1000 kN. Whether or not jacks were started was dependent on observations of longitudinal displacements of main girder. Under normal circumstances, there was no any contact between the main girder and jacks, and normal structural deformations could be permitted under external factors, such as thermal loads. Certainly, whether or not structural deformations were normal were judged or determined by calculation and construction monitoring results. During construction, the distance between each end of main girder and abutment was traced real-timely to capture the longitudinal displacement of main girder. If the longitudinal displacement exceeded calculation or predicted value too much and was abnormal, jacks should be started to adjust the position of main girder.

7.2. External stiff frame

For removal of the closure segment in an existing prestressed concrete cable-stayed bridge, the selection of the external stiff frame could be referred to its original design. But the strength and stability of the external stiff frame itself must be calculated and confirmed so as to meet the requirement of structural safety. The calculation method could be referred to the literature [10]. The construction stages and thermal loads should be considered to calculate the internal forces, and then these load effects should be combined. To enhance the transverse rigidity of the stiff frame, some transverse connection configurations could be provided. At the same time, engineering measures, including increasing the length of welding seams and implanting anchor bolts, should be adopted to make the connection between the stiff frame and the main girder more reliable. Calculation results showed that, the strength and stability of external used in Yonghe Bridge could meet the requirements of corresponding codes, and the adopted transverse connection configurations and enhancing measures ensured the construction safety for removal of the closure segment.

7.3. Adjusting the balance weight

Theoretically, the temporary weight on the bridge deck should equal to the weight of the closure segment removed. However, in the view of mechanics, the temporary weight could only counteract the shear force at the joint between the closure segment and its adjacent segments of main girder while the axial force induced by removal of the closure segment could be born by the external stiff frame, but a certain amount of upward deflection could be produced due to the existence of partial bending inevitably at the joint. Thus a certain amount of tensile stress increment could be induced at the local range of main girder, which was unfavorable for the segmental precast main girder. The aforementioned simulation results for removal of the closure segment had explained it. Therefore, possible temporary weight may be appropriately increased on the basis of the initial balance weight to control structural variations induced by removal of the closure segment. In fact, the actual temporary weight was 36.3% larger than the weight of the closure segment in Yonghe Bridge. Certainly, the normal structural response of main girder itself was moderately permitted in construction, that is, a certain amount of upward deflection near mid-span and concrete tensile stress increment (less than 1MPa) of main girder were permitted. This was because applying the temporary weight on bridge deck was a intermediate process after all. If controlling the vertical deformation and the concrete stress of main girder was only dependent on increasing the temporary weight, cable forces of long riverside stay cables would alter obviously or severely, and meanwhile, upward reaction forces at auxiliary piers could be also decreased significantly, even downward reaction forces could appear, which the bearing burden of tension rocker bearing cables at auxiliary piers could increase (Tension rocker bearing cables were set to serve as tension supports at auxiliary piers in Yonghe Bridge).

7.4. Monitoring structural state indexes

The structural state of an old bridge was indefinite, and Replacement of the Closure Segment was a new and exploratory strengthening technology, which distinguished from conventional reinforcement techniques, so it was very important to monitor structural state indexes in construction. Through observing consecutively and thus capturing variations of structural state, validity of theoretical analysis and prediction, the guidance of construction, was not only checked, but also construction measures could be corrected in time to avoid structural failure. In the period of removal of the closure segment in Yonghe Bridge, all stay cable forces, the bridge deck deflection, displacements at the top of pylons, the longitudinal displacement of main girder, and stresses in external stiff frame were monitored carefully, which had provided an very effective way to guide construction and ensure structural safety.

8. Conclusions

Some valuable conclusions could be obtained in this paper as follows:

(1) Local structural changes could be induced by removal of the closure segment in Yonghe Bridge, including the upward deflection near mid-span of main girder and axial force variations of long stay cables near the closure. The construction process simulation of removal of the closure segment could provide objectives and principles for construction control, and was the important part and basis of structural safety in removal of the closure segment.

(2) The thermal effect analysis revealed structural deformation rules before and after removal of the closure segment, and also predicted variation ranges of structural deformations due to temperature loads. So it was an important basis of estimating structural state, whether normal or not, in the period of removal construction.

(3) Structural dynamic analysis showed, no visible variation in structural dynamic characteristics was induced by removal of the closure segment, but the rigidity of external stiff frame itself and its connection with the original main girder could slightly influence the structural dynamic characteristics after removal of the closure segment. So they should be improved before removal construction.

(4) The global stability analysis showed, the structural instability could not be induced by removal of the closure segment.

(5) The practice of Yonghe Bridge showed that it was very necessary to adopt some prevention and controlling measures in construction, including reliable connection between the external stiff frame and the original main girder, adjusting of the temporary weight on bridge deck, prevention of structural abnormal deformations and adequate construction monitoring ways, and etc.. These safe and prevention measures were obtained on the basis of safety analyses and were of much operability in engineering. They are the important and indispensable component of the technical system of Replacement of the closure segment for existing prestressed concrete cable-stayed bridges.

Acknowledgements

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