Case study on the Synchronous Swivel of Large-Weight T-rigid Frame Bridge

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Abstract. Swivel technique has been vividly recognized and generally adopted for the T-rigid frame bridge in practice, and this has been achieved by tensioning the prestressed stranding via the ball hinge at the centre of the rigid frame bridge. Although the technique has been adopted and used, very limited study has been devoted to the feasibility of synchronous swivel for double-swing synchronous swivel T-rigid frame bridges to date. This study aims at analysing the construction control of a synchronous swivel T-rigid frame bridge with the self-weight of 12,000 ton for each wing, and providing simplified procedures to determine the unbalanced weight and friction coefficient of the rotating bridge. This study will provide guidance for the future similar projects.

1. Introduction
In recent years, with the continuous development of expressways and high-speed railways in China, a large amount of new bridges need to cross the existing railways according to the transportation requirements. In this case, the construction of new bridges may have a certain impact on railway transportation. The rational use of swivel technology for bridge construction can effectively resolve the contradiction between the construction of new bridges and the operation of existing railways [1]. The main issues of the bridge are completed outside the railway line and thereafter, the railway "skylight" time is generally very short to complete the turning of the bridge and merge the dragons. For detached bridges, double-swing synchronous swivel construction method can be adopted, and the left and right two bridges parallel to each other can be established on both sides of the railway at first, and then use the same power control equipment to make these two wings to rotate at the same time. In this case, one of the controlling factors is to ensure that the speed of the bridge rotation is consistent [2].

Scholars have carried out a wealth of research on the construction technology of bridge swiveling on existing railways. For example, Zhang et al.(2012) [3] analyzed the construction accuracy of the large-span T-frame bridge swivel; Li (2014) [4] studied the design and construction scheme of the synchronous swivel of a short-span double-span T-frame bridge; Che et al.(2014) [5] conducted a theoretical study on the anti-overturning performance of large-tonnage T-frame bridges and adopted high-pressure rotary spray water-proof curtain to deal with slurry leakage problem; Zhang (2016) [6] conducted research on the stress and deformation monitoring technology of a T-frame bridge during turning; Gao (2017) [7] studied the construction technology of double-span synchronous rotation of T-bridge. In addition, some scholars have also conducted corresponding research on the rotation
technology of cable-stayed bridges [8], curved bridges [9] and variable-section bridges [10]. To date the weight of the T-bridge is limited due to the construction technology [11-12].

In this context, based on the particular project as a case study, this paper aims to analyzes the construction control of a synchronous swivel T-rigid frame bridge with the self-weight of 10000 ton for each wing, and to provide simplified procedures to determine the unbalanced weight and friction coefficient of the rotating bridge. The particular T-bridge has a large swivel weight, a high main pier, and a long span; furthermore, it also spans existing railways and highways and the construction is difficult, and the quality requirement is extremely high. This paper combines field analysis with theoretical analysis and monitoring of construction to put forward a targeted double-width synchronous swivel construction scheme for reference of subsequent projects.

2. Engineering Practice of the Swivel Procedures

The particular bridge locates in the south of China, and crosses the Shanghai-Kunming railway project. The left and right two wings are concrete T-frame bridges. The left main pier is 10.0 m high and the right main pier is 14.0 m high. The deck width is 20.25 m with the clear distance of 0.5 m and with the longitudinal gradient of 2.7%, and the horizontal intersection angle with the existing railway line is 87.3°. In order to reduce the impact of the construction process on the operation of the existing railway, the project adopts double-wing synchronous swivel construction, and the weight of each wing is 12000 t. As shown in Fig.1, the turn length is 141m, with left swivel angle of 90 ° and right swivel angle of 93.1°. The left and right main piers of the T-frame bridge are located between the Shanghai-Kunming Railway and the G320 Expressway, and the corresponding centers are 10.5 m and 39.3 m away from the Shanghai-Kunming Railway, respectively. The bottom of the beam is 14.3 m and 13.3 m higher than the railway track, for the left and right wings, respectively.

The turning part of the T-bridge is mainly composed of upper and lower turntables and ball hinges, as shown in Fig. 2. The ball hinge not only plays a role of rotation, but also provides support for the superstructure. The upper and lower turntables are reinforced concrete structures and their surfaces are fixed with upper and lower ball hinges, respectively. In order to ensure the smooth rotation process, after the ball hinge is finished, the surface is also filled with PTFE slides with low friction coefficient and high compressive strength. In order to prevent the structure from overturning during the turning process, the upper turntable is provided with 8 sets of Φ800 mm concrete-filled steel tube supporting feet, and a ring-shaped steel plate slide is arranged below it. A gap of 20 mm is reserved between the
feet and the slide. If the T-bridge is tilted during the rotation, the contact force between the foot and the slide way is used to prevent it from overturning. The power required for the turning of the T-bridge is provided by 4 jacks. The traction ropes embedded in the upper turntable are tensioned to exert traction. After the T-frame bridge is turned to a predetermined position, the ball-hinged area and the beam end are combined with concrete to transform the T-frame bridge into a fixed system.

Fig.2 Ball hinge used in the rotation

3. Key Influential Factors of the Swivel Procedures

When the T-bridge is turned, its weight passes through the upper ball joint and the friction surface between the ball joints (i.e., the Teflon slide). When transmitted to the lower ball joint and the bearing platform, the total weight of the T-bridge will be borne by the friction surface between the ball joints. Ideally, the centre of gravity of the swivel part coincides with its geometric centre; however, considering the quality of concrete pouring, ball hinge manufacturing and installation errors, etc., it often deviates from its geometric centre. There is an eccentricity $e_0$ in the longitudinal weight distribution of the T-bridge, which generates an unbalanced moment $M_G$ under the self-weight, and the corresponding counterweight scheme could be determined. At the same time, it is necessary to overcome the static friction resistance generated at the friction surface between the ball joints during rotation, and the corresponding static friction coefficient $\mu_0$ and starting traction force $T_0$ are the key factors for the smooth construction of the rotation.

The unbalanced moment $M_G$ of the T-bridge is determined by the rigid body displacement method. In particular, the jacks are slowly loaded to make it rotate in the vertical plane. It is determined by the loading situation when a significant rigid body displacement occurs. Before turning, there are two possibilities for the equilibrium state of the T-bridge:

(1) The unbalanced moment $M_G$ is smaller than the static friction moment $M_z$ of the ball hinge. In this case, there is a certain gap between the support foot and the slideway, and there is a need to apply thrust forces $P_1$ and $P_2$ on both sides in order to observe the obvious rotation;

(2) The unbalanced moment $M_G$ is greater than the static friction moment $M_z$ of the ball hinge. Particularly, after the temporary support is removed, the T-bridge will rotate under the action of its own unbalanced moment, resulting in contact between the support foot and the slide-way to prevent further rotation. Meanwhile, after pushing thrust $P_1$ on one side, unloading to $P_1'$ can observe the obvious rotation.

For the above two cases, the corresponding unbalanced moment $M_G$ and the ball joint static frictional moment $M_z$ are shown in Equations (1) and (2), respectively, and the specific derivation process can refer to Fig. 3.

$$M_G = \frac{P_1L_2 - P_2L_1}{2}$$  \hspace{1cm} (1a)

$$M_z = \frac{P_1L_2 + P_2L_1}{2}$$  \hspace{1cm} (1b)

$$M_G = \frac{P_1L_1 + P_1'L_1}{2}$$  \hspace{1cm} (2a)
The relationship between the friction moment $M_z$ of the ball hinge and the geometric parameters of the contact surface and the static friction coefficient of the material. Using a spherical coordinate system, as shown in Fig. 4, the friction surface between the upper and lower ball hinges is divided into several small surface elements. When the T-bridge is about to rotate around the horizontal axis $O_y$ where the ball hinge ball centre is located, a static friction force $d_1$ that hinders this turning tendency will be generated in each surface element, and the product of the product and the distance $d$ between the horizontal axis $O_y$ constitutes the static friction moment $dM_z$. By integrating $dM_z$ along the surface of the ball joint, the relationship between the static friction torque $M_z$ and the geometric parameters of the ball joint can be obtained. As shown in Equation (3):

$$
\begin{align}
M_z &= \mu_\sigma R_s dA \\
\sigma &= \frac{G}{R_p^2} \cos \theta \\
M_z &= \frac{2(1 - \cos^2 \alpha)}{3 \sin^2 \alpha} \mu_\sigma G R_s
\end{align}
$$

where $\theta$ is the angle from the point on the surface of the ball hinge to the centre of the ball and $O_z$ angle between shafts, $\theta \in [0, \alpha]$; $\alpha$ is the angle from the ball hinge plane to the centre of the ball and $Oz$ angle between shafts. $\alpha = 13.7^\circ$; $R_s$ is the ball hinge radius, $R_s = 8m$; $R_p$ is the ball hinge radius. $R_p = 1.9m$; $\sigma$ is the compressive stress on the lower surface of the ball hinge; $G$ is the T-bridge weight, $G = 117,600$ kN.
To ensure the safe and stable rotation of the T-frame bridge, it is necessary to counterweight it, and an absolute balance counterweight solution is often used. It is assumed that the cantilever beam is balanced under static conditions, the counterweight must ensure that the centre of gravity of the cantilever beam passes through the axis of the ball hinge. In this solution, the weight of the counterweight is small, and the traction force required to rotate is also small. In order to reduce the risk of small cantilever vibration of the cantilever beam when turning, a longitudinal segmented weight is adopted, and the corresponding weight is determined by Equation (4):

\[ \sum W_i L_i = M_0 \]  

(4)

where \( W_i \) and \( L_i \) is the \( i \)-th weight of the counterweight and the distance to the centreline.

4. Field tests of the unbalanced weight and trial rotation test

After removing the temporary support of the T-frame bridge, it was observed that the T-frame bridge turned, and the supporting feet were in contact with the slide way. It can be determined that the T-frame bridge is in the second situation, that is, the unbalanced moment \( M_0 \) is greater than the ball joint static friction moment \( M_z \). When performing an unbalanced weight test on site, four 500 ton hydraulic jacks are arranged symmetrically along its longitudinal direction, and a displacement transducer is arranged on the opposite side to obtain the change of displacement during loading. When determining the unbalanced weight test, the changes of load and displacement were recorded to grasp the rotation of the ball hinge. After comparing the load-displacement curves, as shown in Fig. 5, the load \( P_1 \) and \( P_2 \) were determined to be \( P_1 = 13,080 \text{ kN} \) and \( P_2 = 2,374 \text{ kN} \). By following above procedures, during the time course of "skylight" of Kunming Railway, a 30-minute trial rotation test was performed. To verify the preparation of the swivel construction and the impact of key factors, the trial rotation angle is 5 °, and T-bridge swivel control adopts jog operation. Particularly, the system is controlled immediately after the traction force is applied briefly to ensure the T-bridge to rotate slowly. During the trial, the rotation of the T-bridge was recorded to provide the basis for the formal rotation.

5. Conclusions

Generally, when the bridge crosses an existing transportation line, swivel technique could be used in the construction. This paper was based on the construction of a 12,000-ton double-wing synchronous swivel bridge, theoretical analysis and field tests were used to determine the unbalanced weight distribution and static friction coefficient; and a trial rotation was performed to verify the reliability of the rotation scheme. Based on the study of this paper, the key influence factor for bridge rotation is to determine its detailed construction plan, and to focus on determining unbalanced weight distribution and static friction coefficient. Based on these two data, the construction plan of the rotating ball hinge is determined and real-time construction monitoring helps to improve construction safety of swivel bridges. In the future, BIM and monitoring information technology can be combined to provide technical supports for bridge rotation construction.
Fig. 5 Diagram of Force-Displacement Curve

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References
[1] Yuan Ke. Analysis of key control points of bridge swivel construction. Railway Construction Technology, 2016, (5): 9-11.
[2] Wang Zhenjiang, Li Zaijing, Wang Zhaohui. Scheme Selection and Detail Control of Large Swing Bridges for Passenger Dedicated Railways. Construction Technology, 2015, 44 (10): 117-121.
[3] Zhang Zijie, Gao Xiangzhong. Precision control technology for turning process of T-shaped rigid frame large cantilever box beam swivel bridge. Construction Technology, 2012, 41 (378): 26-28.
[4] Li Keyin. Research on Design and Construction of Double-frame Short-range Synchronous Swivel Rigid Frame Bridge. China and Foreign Highway, 2014, 34 (22): 157-160.
[5] Che Xiaojun, Zhang Xiedong. Overturning resistance of large tonnage T-shaped rigid frame bridge during turning process. China Journal of Highway and Transport, 2014, 27 (8): 66-72.
[6] Zhang Xiangxi. Research on Beam Stress and Deformation Monitoring during Construction of Synchronous Swing Bridge Across Railway. Railway Construction Technology, 2016, (8): 23-26.
[7] Gao Rongfeng. Construction Technology of 2 × 100m T Swing Bridge on Upper-Span High-speed Railway. Construction Technology, 2017, 46 (S1): 963-966.
[8] Chen Wen, Meng Qingchun, Lin Hongzhen, et al. Construction technology for rotation of the Beijing-Kowloon Railway Cable-stayed Bridge. Construction Technology, 2017, 46 (15): 70-74.
[9] Zhou Leping, Huang Chengwei, Sun Yanpeng, et al. Self-balancing method for translation of T-shaped cable-stayed bridge with large tonnage curve. China and Foreign Highway, 2018, 38 (3): 213-216.
[10] Tang Qingming. Construction control of large-span super-wide variable cross-section unbalanced continuous beam with rotating construction. Construction Technology, 2017, 46 (5): 66-69.
[11] Jiang Lanchao, Gao Ri. Deformation monitoring during removal of the supporting of T-type rigid frame bridge constructed by rotation method. Procedia Engineering, 2010, 4(1): 355-360.
[12] Song Lizhong, Li Xiaozhen, Zheng Jing, Guo Ming, Wang Xinxin. Vibro-acoustic analysis of a rail transit continuous rigid frame box girder bridge based on a hybrid WFE-2D BE method. Applied Acoustics, 2020, 157(1): 1-12.