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Overview of Design and Construction Points Analysis for the Rotating Continuous Girder Bridge

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Abstract: With the advancement of the economy, the construction of roads and bridges has assumed a crucial role in the development of China's highway transportation system. The interplay between the design and construction technologies of road bridges is pivotal, as it directly impacts the subsequent operation and maintenance phases. Although the design and construction techniques for continuous girder transitions have been progressively improving, challenges still persist. This paper takes the example of the continuous girder design for the T-structure (75 m + 75 m) of the Xintai Highway Crossing Yanzhou-Shijiusuo Railway Separation Interchange Project and delves into an analysis of the structural design calculations for the bridge transition, the transition structure's design, and critical considerations during construction. The findings presented here can serve as a valuable reference for similar project designs.

Keywords: Bridge design; Continuous girder; Transformer bridge

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1. Project overview

The Yanzhou-Shijiusuo Railway comprises two electrified railroad tracks, and the bridge under consideration spans both the upper and lower lines of the railway. This specific section pertains to the roadbed, with a roadbed filling height of approximately 1 m, and experiences significant railway traffic.

The section of the Xintai to Taierzhuang (Lu-Su border) highway, situated between Xintai and Malantun of Taierzhuang, encompasses a design scope that extends from the starting point at milepost K45+631.0 to the endpoint at milepost K45+841.0, with a total length of 210 m. The bridge intersects with the Yanzhou-Shijiusuo Railway, with the highway's milepost at K45+743.6 and the railway's milepost at K104+700. The intersection angle is set at 50°. Following the railway department's specifications, a T-structure with an uninterrupted span is employed for the bridge crossing over the railroad. The bridge across the Yanzhou-Shijiusuo Railway is designed to incorporate the full width of a transverse T structure, ensuring that the clearance width meets the railroad's passage limit requirements, with a minimum clearance height of ≥ 8.5 m. Upon the completion of both bridges, they will be capable of accommodating double-decker container transportation beneath them.

The span arrangement consists of 2 × 75 m T-type rigid structures and 2 × 30 m simply supported small box girders, with a right deviation angle of 90°. The main bridge utilizes a 2 × 75 m T-type rigid structure transfer construction, with each transfer span measuring 2 × 70 m.

2. Structural analysis and calculations of the main bridge

2.1. Load calculation and combination

The components for load calculation are as follows:

(1) Permanent load: The permanent load in the first phase includes the self-weight of the main girder and diaphragm beam, among others. Self-weight is calculated based on the actual cross-sectional properties, with a capacity of 26 kN/m^3. The permanent load in the second phase includes the sidewalk, anti-collision guardrail, anti-throwing net, bridge deck pavement, etc., and is calculated at 218 kN/m^3.

(2) Creep and shrinkage coefficient: Determined according to the "Design Code for Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG D62-2004) [1].

(3) Prestressing force: Controlled tension under anchoring is set at 1,395 Mpa, with a pipe resistance coefficient μ = 0.15 and a pipe deviation coefficient κ = 0.0015. Additionally, the anchorage deformation and beam retraction value (at one end) Δ = 6 mm.

(4) Live load: 1.3 times the highway = Class I load

(5) Temperature: The effective temperature action effect considers a concrete structure temperature difference of 34°C for heating and -10°C for cooling. The gradient temperature of the main girder is determined according to the "General Specification for the Design of Highway Bridges and Culverts" (JTG D60-2015) [2].

(6) Foundation displacement (uneven settlement): assumed to be 10 mm.

The load combinations include:

(1) Combination 1: Permanent load + Live load

(2) Combination 2: Permanent load + Live load + Heating effect + Braking force

(3) Combination 3: Permanent load + Live load + Cooling effect + Braking force

(4) Combination 4: Permanent load + Heating effect + Longitudinal wind load limit

The heating effect is the addition of a positive temperature difference system with the main beam gradient heating, whereas the cooling effect is the addition of a negative temperature difference system with the main beam gradient cooling.

2.2. Analysis and calculation

The main bridge superstructure is designed as a fully prestressed concrete member. Transverse calculations adhere to the design standards for Class A prestressed concrete and reinforced concrete members, while the substructure is designed as reinforced concrete biased members, and the pile foundation follows the column pile design approach.

3. Rotary structure

The rotary structure consists of several key components, including the lower turntable, rotary support, upper turntable, and rotary traction system (see **Figure 1**).

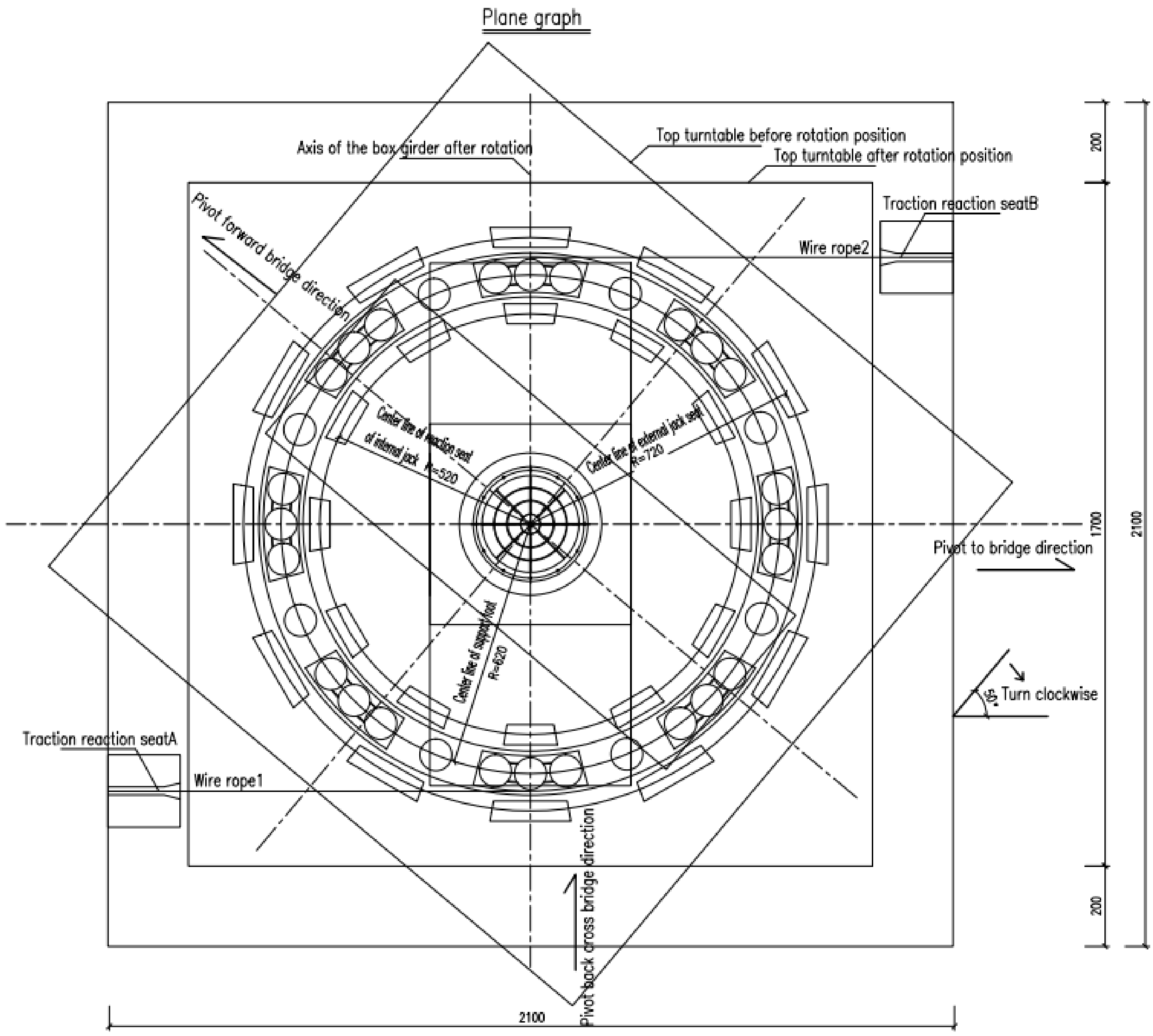

Figure 1. Plan view of the main pier turning structure

3.1. Lower turntable

The lower turntable serves as the foundation supporting the entire weight of the rotary structure. After assembly, it forms the foundation together with the upper turntable. The lower turntable is constructed using C40 concrete and incorporates various elements, including the turntable system's support, a ring slide made of steel pipe concrete support feet, and a turntable drag jack reaction seat. The clearance between the legs and the slide is set at 20 mm. To initiate, stop, and finely adjust the position of the rotary structure, a jack counterweight is employed.

3.2. Rotary support

The rotary bearing adopts a ZTQZ-190000 ball-type bearing. The concrete base's strength grade is no less than C50, with a height of 65.5 cm. The height difference among the top four corners must not exceed 5 mm. Before device installation, the top surface of the base is chiseled, and a 30 mm thick layer of M80 epoxy resin mortar is applied. The device is then installed, compacted, and leveled, ensuring that the relative height difference on the top surface does not exceed 1 mm. The connection between the rotary support and the base is achieved through ground bolts and sleeve screws. Holes are pre-drilled on the top surface of the base, with a diameter ranging from 70 to 100 mm and a depth of 70 to 100 mm. The deviation between the center of the reserved hole and the center of the support should not exceed 5 mm.

3.3. Upper turntable legs and chutes

The upper turntable support legs function as safety supports to maintain the smooth operation of the turntable during rotation. To evenly distribute the load during rotation, the centerlines of the two symmetrical safety legs align, ensuring that all eight safety legs are symmetrically arranged on both sides of the longitudinal axis. Under each support leg (i.e., the top surface of the lower plate), there is a 1.5 m wide chute with a radius of 6.2 m at the chute's centerline. This allows the safety support legs to slide within the chute during rotation, ensuring the stability of the rotating structure. The entire sliding mechanism must maintain a horizontal plane, with a relative height difference not exceeding 2 mm. Each upper turntable is equipped with eight groups of cylindrical support feet, each featuring a 24 mm thick steel walking board. The cylinder itself is constructed from Φ 800 mm × 24 mm steel pipe, into which C50 non-shrinkage concrete is injected.

3.4. Upper turntable

The upper turntable plays a critical role in the overall structural stability during rotation, experiencing multi-directional and three-dimensional stresses. The upper plate is reinforced with longitudinal and transverse prestressing steel bars. The upper turntable is rectangular, with a height of 3.5 m. It has a diameter of 13.4 m and a height of 0.8 m. The turntable is the point of connection for the rotating body device, the supporting feet, and the upper turntable. It also directly experiences the traction force applied to the rotating body. Inside the turntable, traction cables are pre-embedded, with P-type anchorage used at the pre-embedded ends. These cable anchorages are symmetrically positioned along the same diameter line in the center of the circle. It is crucial to ensure that the pre-embedded height and traction direction of each cable are consistent. Each cable buried in the turntable must be at least 3 m in length, with exit points symmetrically arranged at the center of the turntable.

The upper turntable is constructed using C50 concrete. Once the concrete on the upper plate reaches its design strength, the entire turntable system is converted into a support system. The cushion plate is removed, allowing the turntable to be supported by the rotating body device. Rotating torque is applied to initiate the turntable's rotation along the center axis of the rotating body device. A thorough assessment is conducted to verify the proper operation of the rotating body device, determine its friction coefficient, and provide the basis for further construction of the rotating body.

The friction coefficient is calculated using the following formula:

$$\mu = 3 \times M \div (2 \times R \times G)$$

Here, represents the friction coefficient, represents the torque of the rotating body (in Newton-meter), represents the radius of the plane of the rotating device (in meters), and represents the total weight of the turntable (in tons).

The design static friction coefficient is 0.1, while the kinetic friction coefficient is 0.06. If the measured actual friction coefficient significantly deviates from the design value, a thorough analysis is conducted to identify the causes and implement appropriate adjustments.

4. Guiding construction plan

4.1. Substructure construction

The substructure of this bridge utilized drilled pile foundations, employing conventional construction methods to complete the construction of the side pier section of the pier body, as well as the main pier rotary support and bearing platform. Once the bearing construction is completed, support structures are placed on the pallet framework to secure the pre-embedded parts of the slipway. It is crucial to note that the entire bearing platform and slipway must ensure the flatness of the entire T structure while also withstanding the substantial load of up to 19,000 tons imposed by the pier and the main girder. As such, the concrete compactness and slipway smoothness requirements are exceptionally high. The design specification mandates that the slipway's levelness must not exceed 2 mm. To address potential temperature-induced deformation cracks in the large-volume concrete of the bearing platform, construction guidelines for relevant content are referred to.

4.2. Pier column and main beam construction

The pier is constructed using the full-tower bracket method. For the box girder construction, a bowl buckle-type steel pipe scaffolding is erected on the solidified foundation, and the girder is cast in sections using the bracket method.

4.3. Weighing

The T-structure relies on a self-balancing system, necessitating the assurance of a balanced moment between the transverse bridge and the center of the turntable. Before the rotation, the body must undergo weighing to verify this balance. If the rotating body is found to be unbalanced, adjustments are made using counterweights on the girder. The weighing process involves:

(1) Installing counterweights, jacks, and sensors at the beam's end.

(2) Applying an upward load to one end to lift the beam, simultaneously monitoring the moment of rotation using a displacement meter set between the turntable and the bearing platform. The jacking force from the sensor is recorded.

(3) Calculating the moment from the jacking force and the force arm.

(4) Applying the moment equilibrium equation for the center of the bearing to calculate the bearing resistance.

Under normal circumstances, the moment resistance of the rotating support exceeds the unbalanced moment of the rotating body. However, if significant construction errors are present, the moment resistance of the rotating support may fall short of the unbalanced moment of the rotating body.

4.4. Flat turn traction system

The flat-turn traction system comprises the traction counterweight, the upper turntable, and traction ropes. The installation steps are as follows:

(1) Cleaning the tensioning groove on the counterweight and the periphery of the upper turntable, removing any rust or impurities on the hauling rope's surface [3].

(2) Placing the platform behind the counter-force seat, adding a padding plate in the stressed area behind the counter-force seat, and ensuring that the jack is correctly installed.

(3) Straightening the traction cable steel hinges, winding them around the upper turntable about 3/4 of the way, and inserting the free end into the jack counter-force seat tensioning slot. The strands must remain straight, without twisting or kinking.

(4) Introducing the steel hinged line sequentially into the jack anchor ring, clip sheet, support foot, jack, anchor ring, and clip sheet to assemble the LSD200-type continuous tensioning jack.
(5) Installing the oil pipe and distribution cabinet.
(6) Conducting adjustments to the jack, traction cable, anchorage, and pump station.

4.5. Boosting system

The boosting system is used to overcome the difference between static and dynamic friction torque, enabling the initiation of the entire rotating body. The system consists of the boosting distribution beam and the boosting jack, which is placed between the steel pipe support foot of the turntable and the boosting counter-force seat.

4.6. Fine adjustment system

To correct any offset that may occur during the rotation of the rotating body, four YCW6000 jacks are placed under the turntable. These jacks are used to fine-tune the orientation of the rotating body in both the bridge's longitudinal and transverse directions. The positioning is carried out symmetrically.

4.7. Limit system

To prevent the girder from continuing to move forward after rotating into position, a limiting system is installed by placing the booster jack and the counter-force seat in the reverse direction under the booster counter-force seat before the rotating body reaches its final position.

4.8. Measurement and monitoring markers

Before the transfer, corresponding line monitoring points should be established on the beam and turntable. This mainly includes the following points:

S/N	Type of measurement point	Measurement point location	Requirements and uses of measurement points
1	Girder linear measurement points	Centerline of girder face and end of girder	Monitor changes in girder alignment by taking one section every 5 meters
2	Level observation point	Middle and sides of girder top	Monitor the change of girder elevation (deflection and lateral inclination)W
3	Limit observation point	Girder end of closing opening, side of turntable	Rotary body leveling and positioning control
4	Rotation speed observation point	Between footing and chute	Control the linear speed of the rotating body
5	Cross-bridge inclination measurement point	Upper turntable and bearing platform	On the same horizontal plane, observe the inclination of the rotating body in the transverse direction

4.9. T-structure turn

The transformation process is a critical phase in the entire T-construction project and involves the following steps:

(1) Cleaning both the inside and outside of the box girder, removing any debris and excess load. A thorough review of key components is conducted, including pier and beam consolidation points, upper turntable, ball hinge, and other elements, with confirmation and verification.
(2) Ensuring that monitoring personnel and instruments are in position.
(3) Removing the weighing bracket and the supports in front of the girder's bottom, allows it to stand for 24 hours. Subsequently, stress and line monitoring is performed to confirm equilibrium.
(4) Conducting an on-site technical briefing and assigning specific tasks to each observation point,

controlling signals, communication links, and other personnel, with a clear and comprehensive division of labor.

(5) Closing off each traffic intersection and initiating the formal rotation of the body.

(6) Tensioning the flat-turn traction cable and maintaining tension until the cable force reaches the designated traction force, while also maintaining the oil pressure.

(7) Activating the booster jack and applying a graded load of 100 kN symmetrically to the center of the turntable according to the design booster.

(8) Continuously applying traction force to the jack until the structure initiates movement, ensuring a uniform and controlled flat rotation of the turntable, with an angular velocity not exceeding 0.02 rad/min.

(9) While maintaining a constant-speed rotation, monitoring personnel continuously observe and survey the axial deviation of the bridge piers and the elevation changes at the girder's ends.

(10) When the rotating body approaches the edge of the girder body close to the side pier, a limit system is installed simultaneously between the upper and lower turntables.

(11) When the centerline of the girder's end of the rotating body is approximately 1 m away from the designated position, the oil supply to the traction cable jack is reduced to decelerate the rotating body.

(12) Continuous monitoring of the beam end's centerline, commanding the oil pump station to move to the beam center axis aligns with the axis of the beam. A coping pad is placed between the limit distribution beam and support foot to prevent the rotating body from sliding further and ensuring it reaches its intended position.

4.10. Fine positioning

After the rotating body reaches its final position, comprehensive measurements are taken to assess deviations in the axis and elevation of the beam body. The boosting system, fine-tuning system, and leveling traction system collaborate to precisely align the ends of the girder through the displacement of the entire rigid body and local deformations at the girder's end.

4.11. Other

The turning gear is removed, and the top support of the side pier is promptly installed, enabling progress to the joint section construction phase.

5. Technical requirements and precautions for the installation of the rotational device [4]

(1) During the assembly of the turning device in the factory, meticulous attention should be paid to ensuring proper leveling. The upper and lower seat plates must be precisely centered, and temporary connecting devices should be employed to assemble the components into a single structure, securely locking them in place. These temporary connecting devices should not be dismantled or loosened before the final bridge rotation. When transporting and lifting the device, it should be handled carefully to avoid any violent impacts that could alter the device's alignment.

(2) Before installing the rotational device, a thorough inspection of the device's connections should be conducted to ensure they are in proper working order. However, the temporary connecting devices should not be arbitrarily loosened.

(3) On-site installation of the rotational device should include the fitting of upper and lower ground bolts

and socket screws. It is advisable to install these components in a position where epoxy mortar is not yet applied, confirming the correct positioning of the reserved holes.

(4) The areas of the base surface where the device will be placed should be chiseled as necessary. Debris within the holes should be removed, and three support pads should be positioned along the edges of the device's placement area, ensuring that the top surface of these pads has a height difference of no more than 1 mm.

(5) Prior to grouting, an initial calculation should be made to determine the required volume of slurry. The amount of slurry used in the grouting process should closely align with the calculated value, avoiding excessive slurry or insufficient coverage in the middle. The compressive strength of epoxy resin mortar should not be less than 80 MPa.

(6) Following the calculation of the required amount of epoxy resin mortar, the components should be proportioned and thoroughly mixed. The entire batch of mixed mortar should be centrally piled up within the device's placement area. The rotational device should then be slowly lowered into place, relying on its own weight to compress the mortar effectively. Care should be taken to ensure that the epoxy resin mortar does not enter the sleeve screw in the reserved hole. Prior to the solidification of the mortar, the height difference between the upper seat plate of the device should not exceed 1 mm.

(7) In line with the calculated quantity, a high-strength non-shrinkage grout should be proportioned and stirred. The gravity grouting method should be used to fill the reserved holes in the base and thoroughly compact the grout until it is observed to fill the gap between the edge of the device and the hole's edge.

(8) After the grout beneath the device has solidified, protective measures should be implemented at the gap between the upper and lower seat plates of the device. This prevents debris from entering the device prior to the bridge's rotation and safeguards the sensors and sliding surface of the device.

6. Conclusion

The Yanzhou-Shijiusuo Railway Bridge stands as the sole railway bridge along the Xintai Expressway, representing one of the most challenging engineering endeavors. This bridge construction project entailed a substantial scale, a tight construction schedule, elevated safety risks, advanced technical complexities, and intricate process methodologies. This paper documents the successful execution and subsequent opening of this vital infrastructure, delivering commendable social and economic advantages. It serves as a valuable reference for similar projects in the future.

Disclosure statement

The author declares no conflict of interest.

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