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Design and construction of the lower structure of the bridge based on prefabricated concrete caisson technology

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ABSTRACT

To find a methodology for constructing bridge lower substructures that are resilient to harsh hydrological conditions, this paper analyses fundamental forms and construction methods of bridge substructures. As a result of our analysis, we propose a prefabricated quick assembly technology for precasting of prefabricated concrete structures. Our proposal includes an overall design methodology, a framework to measure size and load effects, a scheme to calculate structural properties, and various construction techniques. We show that the prefabricated quick assembly technology can be widely used in the design and selection of a bridge's lower substructures, especially to achieve high durability of prefabricated components in a marine environment.

1 Introduction

The bridge substructure is an important part of the entire bridge. The requirements of it for basic and hydrological conditions are relatively strict. At present, China is in the period of rapid development of large-scale cross-sea bridge construction. However, due to the large tidal range and the rapid flow of water, the meteorological conditions at sea are complex and changeable. Typhoons, tornadoes, thunderstorms, and sudden small-scale disastrous weather occur from time to time. Under the influence of the above-mentioned wind, rain, fog, waves, currents, and tides, there will be insufficient working time for construction throughout the year. Therefore, the construction difficulties of the substructure of the cross-sea bridge will often affect the overall project quality and progress. There are many lower structural forms for existing bridges. For basic forms, FAN (2012) has suggested that they can be divided into: open excavation foundation,

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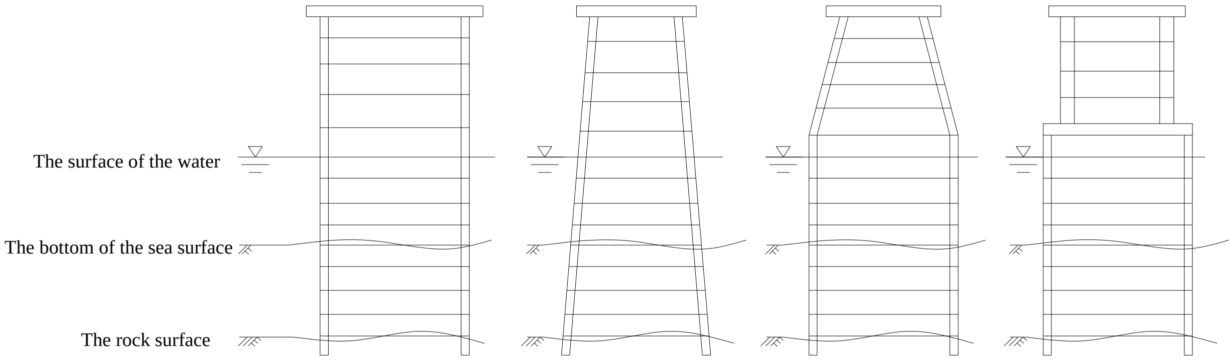
pile foundation, caisson foundation, caisson foundation and pillar foundation; for construction methods, they can be divided into: Integral precast and integral cast-in-place. This paper presents a prestressed assembly technology of prefabricated concrete structures for substructures of caisson-type bridges, that is, the prefabricated concrete is connected to each other to form a splicing layer, and then the splicing layer is spliced layer by layer to form the lower structural body of the bridge. For the cross-section form, it can be divided into: equal section, variable section, equal section and variable section combination, equal section combination (Figure. 1). This assembly technology is affected by meteorological conditions and can be adapted to the severe weather or extreme requirements of specific periods, shorten the construction period and improve the quality of the project.



(a) Equal section(b) Variable section(c) Combination of equal section and variable sections(d) Equal section combination

Figure 1 Schematic diagram of the lower part of the bridge

2 Advantages of prefabricated caisson foundation

2.1 Compared with pile foundation and column foundation

In deep foundation bridges, pile foundations are a basic type with less structural forms and better economic effects. However, National standard (2007) have suggested that the pile foundation is not suitable for bridges (suspension bridges, cable-stayed bridges, continuous beam bridges) that the requirements for basic stability are high in harsh hydrological conditions.

The same foundation as the deep foundation is similar to the circular caisson foundation, but its wall thickness is not as thick as that of the caisson foundation. YIN (2003) has pointed out that the stability of deep foundation is not as good as the caisson foundation and it needs to rely on a large vibration pile driver to force it to subside, and the economic effect is not as good as caisson foundation.

As a common deep water foundation, caisson foundation is characterized by large rigidity, good stability, reliable transmission, and adaptability to various complex geological and hydrological conditions. QU (2007) has pointed out that there are relatively few machines used in the construction process, and it is not necessary to set the cofferdams as the foundations of the piles and the columns, which itself is the main force and waterproof structure. Because of its high stiffness, it can overcome the large bending moments transmitted by the superstructure and increase the overall stability of the structure.Compared with the foundations of piles and columns, the foundations are smaller in displacement and less affected by earthquakes, which increases the safety performance of the bridges.

2.2 Compared with overall cast-in-place and integral prefabrication methods

The overall in-situ cast-in-place piles, pile caps and bridge piers are greatly affected by the meteorological conditions and geological environment, and the structural quality is difficult to guarantee. In addition, the construction of cast-in-place concrete is subject to weather restrictions and the duration of construction is relatively long. The concrete of the upper part of the lower structure needs to wait until the concrete at the bottom reaches the design strength before being poured and requires time for maintenance. The construction of the integral prefabricated bridge substructure requires strict construction equipment. It requires special large-scale transportation vehicles, ships and cranes, which make transportation and installation difficult. The prefabricated concrete of the substructure of the caisson-type bridge is divided into a number of caisson blocks with large cross-section concrete walls and connected with prestressed high-strength bolts. This solves the problem of requirements for special large-scale transport vehicles, ships and cranes, and it can not be constrained by weather and hydrological conditions. The upper and lower structures can be constructed simultaneously and the construction period is relatively short.

3 The form of caisson assembly

The prestressed prefabricated concrete system design of the bridge substructure consists of four parts, including reinforced concrete blocks, prestressed high-strength bolts, joints and holes, and waterproof seal materials. The reinforced concrete blocks can be divided into four types according to the cross-sectional shape of the lower structure of the bridge (Figure 2), namely circular section concrete blocks, round-end shaped concrete sections, and elliptical section concrete blocks (short major axis ratio 1:1 to 1: 2), flat oval section concrete blocks (short major axis ratio 1:2 to 1:6). The waterproof sealing material uses a raw rubber or a polyether polyurethane elastomer that is added with a water-absorbent resin.

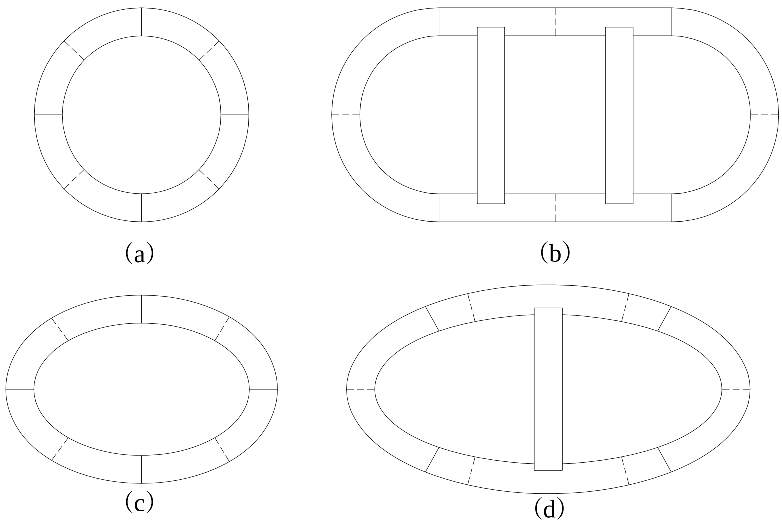


Figure 2# The cross-section of the bridge structure
(a) Circular section; (b) Round-end shaped section; (c) Elliptical section; (d) Flat oval section.

The main body of the bridge lower structure is stitched by stitching layers (Figure 3-5). The splicing layer is connected by the precast concrete blocks end to end. The precast concrete blocks in the horizontal layer of the same layer are connected by horizontal prestressed high-strength bolts. Concrete block joints which are provided with weather-resistant elastic gaskets are formed between precast concrete blocks in the same splicing layer (Figure 6).

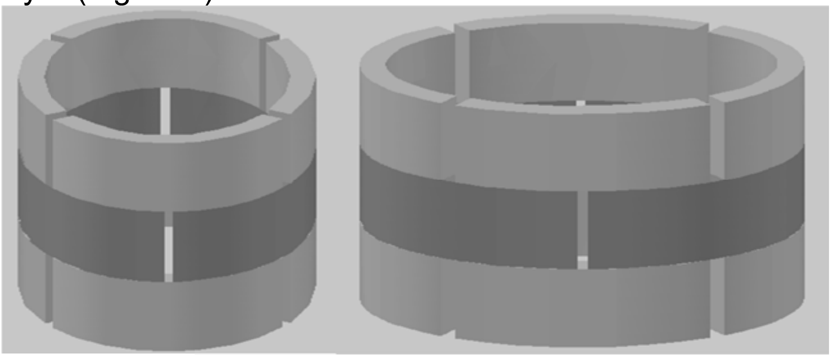


Figure 3# Schematic diagram of assembling staggered joints of reinforced concrete blocks

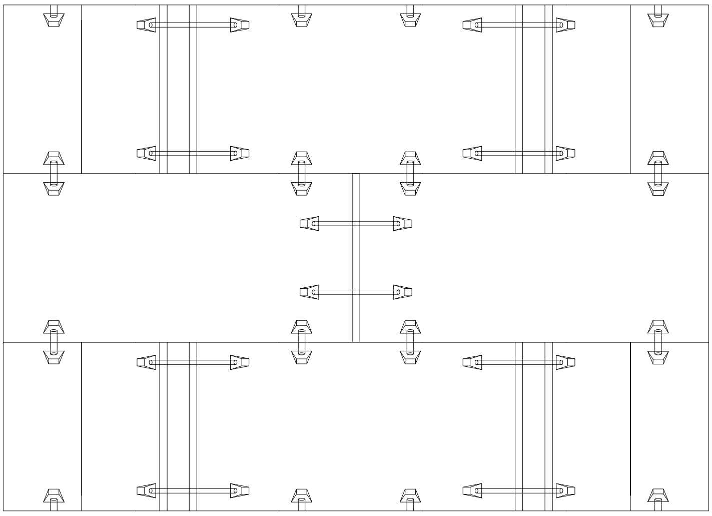


Figure 4# Longitudinal section of the bridge structure

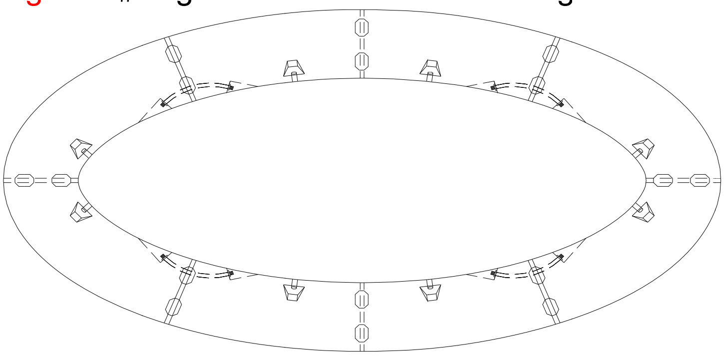


Figure 5# Cross-section of the lower structure of the bridge

Both the horizontal prestressed high-strength bolts and the vertical prestressed high-strength bolts adopt the internal post-tensioning method (Figure. 7), and their degree of bending is determined by the curvature of the prefabricated concrete block. Under special conditions, prestressed stretching is considered outside the block or even under water.

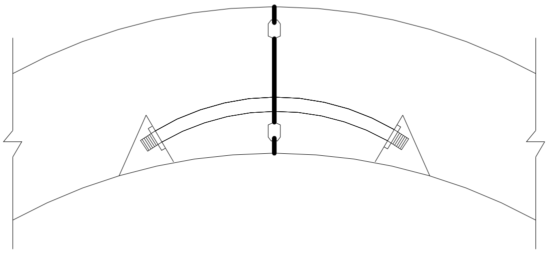


Figure 6#Detailed view of joints of reinforced concrete block# #

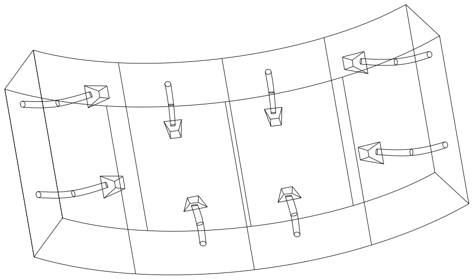


Figure 7 Partial enlarged view of oval section

The precast concrete blocks connected by precast concrete blocks with horizontal prestressed high strength bolts and vertical prestressed high strength bolts can improve the overall rigidity and durability of the structure, so that the bearing capacity is also increased accordingly.

4 The Design of Caisson Size

4.1 Calculation Principles

The size of reinforced concrete block is determined according to the geological environment of the site, the safety level of the bridge, and the construction equipment. The size of reinforced concrete block is determined according to the geological environment of the site, the safety level of the bridge, and the construction equipment. Wherein: the outer diameter of the block depends on the internal diameter of the open caisson; the thickness of the block depends on the hydrology, soil conditions, and mainly the load conditions; the width of the block depends on the construction equipment, choosing economical and reasonable geometry; the number of blocks in a block can be determined based on the number of blocks in the shield tunnel and the actual application.

4.2 Calculation Method

For the lower structure of the bridge, the loads acting on it generally have a permanent and variable effect: the gravity of the upper and lower parts, the shrinkage and creep of the concrete, the buoyant force of the concrete, the vehicle load, the impact force of the vehicle, the braking force of the vehicle, the hydraulic force, and the wave force, wind force, impact force. When the occurrence of a variable effect has a favorable effect on a structural or structural component, the effect does not participate in the combination.
When designing the bridge piers, the function combinations are: gravity of the upper and lower parts structure + creep effect of the concrete + water buoyancy + vehicle load + vehicle impact force + max (vehicle braking force; hydraulic force; wave force)
Water buoyancy standard value acting on the pier can be found in National standard

(2015) and are illustrated in Eq. (1):

$$F=\gamma V_w \quad (1)$$

In the formula: F is the buoyancy standard value of water (kN); γ is the weight of water (kN/m^3); V_w is the volume of water discharged from the structure. (m^3).

The vehicle load can be calculated based on the road grade and the most unfavorable loading method.

The vehicle impact force can be found in National standard (2015) and it is the vehicle load standard value multiplied by the impact coefficient μ, where the impact factor can be calculated based on the fundamental frequency of the structure:

When f<1.5Hz,μ=0.05

When 1.5Hz≤f≤14Hz, μ=0.1767ln$f$-0.0157

When f>14Hz, μ=0.45

The standard value of flow hydraulic force acting on the pier can be calculated according to Eq (2) of National standard (2015):

$$F_w=KA\gamma v^2/2g \quad (2)$$

In the formula: F_w is the flow hydraulic standard value (kN); γ is the weight of water (kN/m^3); v is the design flow rate (m/s); A is the pier sealing area (m^2), calculated to the general flushing line ; g is the acceleration of gravity, 9.81m/s^2; K is shape factor of the pier.

The wave force can be calculated by inputting data such as wave trough and wavelength into ANSYS software according to the actual situation of the location of the bridge pier.

The normal section compressive bearing capacity of circular section reinforced concrete eccentric compression member can be found in National standard. (2012) and are illustrated in Eq. (3):

$$N=N_h+N_g,\ M=M_h+M_g \quad (3)$$

In the formula: N_h, M_h are the resultant force and resultant moment of the concrete; N_g, M_g are the resultant force and resultant moment of the reinforcement.

Taking circular ring section reinforced concrete as an example, its normal section compressive bearing capacity as shown in Eq. (4):

$$\gamma_0\ N_d \le A(R^2-r^2)f_{cd}+C\rho R^2 f'_{sd},\ \gamma_0\ N_d e_0 \le B(R^3-r^3)f_{cd}+D\rho g R^3 f'_{sd} \quad (4)$$

In the formula: A, B are the coefficient of concrete bearing capacity; C, D are the coefficient of bearing capacity of steel bar; R is the outer radius of circular section; r is the inner radius of circular section; The ratio of the radius Rs to the radius R of the circle section, g=Rs/R; ρ is the reinforcement ratio of the longitudinal reinforcement.

Shear bearing capacity of annular section member be found in LYU (1995) and are illustrated in Eq. (5):

$$V=0.07\ f_c(2\delta)\ \bar{h}_0+1.0\ f_{yv}\ A_{sv}\,\text{sina}\ \bar{h}_0/s \quad (5)$$

In the formula: δ is the wall thickness of the annular section; $\bar{h}_0$ is the equivalent effective height; A_{sv} is the entire cross-sectional area of the stirrups arranged in the same section, and the same rectangular section is calculated; s is the length of the stirrup along the length of the member. f_{yv} is the design value of the tensile strength of the stirrups; D is the outer diameter of the annular section for the calculation of $\bar{h}_0$.

Finally, the size of the reinforced concrete block is determined based on the calculated resultant force and resultant moment, and then the prefabricated block size is determined according to the existing construction and installation capabilities.

5 Technology Difficulties of Construction

5.1 Countersink Control

When the prefabricated concrete block is lifted into place by the crane, misalignment between the assembly layers may occur due to deviations in positioning points, sliding damage between bolt holes and bolts of prefabricated assembly concrete blocks, and loss of prestress of high-strength bolts. SHEN (2005) has suggested that in order to avoid this problem, the following precautions need to be taken:

(1) When prestressing the high-strength bolts, the position of the prefabricated concrete block should be timely adjusted to avoid secondary torque;

(2) Each prefabricated concrete block should be preliminarily tightened at the time of installation of each splicing layer. After the assembly of the entire splicing layer is completed, the prestressing force should be tightened twice, so that the force applied between each precast concrete block is the same;

(3) In the process of prefabrication and maintenance of prefabricated concrete blocks, the concrete block surface should be smooth and the bending angle should be standard;

(4) Adjust the position of the prefabricated concrete ring so that its centerline coincides with the vertical axis of the lower structure of the bridge.

5.2 Caisson Seam Joint Quality Control

During the installation process of prefabricated concrete blocks, the quality of the joints may not be guaranteed due to the construction environmental impact, other debris into the seam, Inconsistent prestressing of high-strength bolts on the same joint surface. Therefore, LI (2017) has suggested that attention should be paid during construction:

(1) The prestressing of high-strength bolts should be synchronized and reasonable, and corrective errors should be corrected in time;

(2) The water-swollen material should be coated with a slow swelling agent before being placed in the mat hole, and the special synthetic rubber resin should be standardized when it is applied.

6 Conclusion

Through the different forms of the bridge under the basic structure, the analysis of construction methods, calculation of load effects, the lower structure of the bridge based on pre-assembled concrete structures with the caisson prestressed assembly technology is:

(1) The requirements for the foundation of the foundation are not very high, and it can be applied to the construction of the bridge under the most hydrological conditions;

(2) The whole process of pushing down, unearthing, assembling, etc. of the whole foundation can achieve rapid operation, and the construction labor intensity is low;

(3) All concrete blocks can be prefabricated in the factory and assembled in the on-site waterworks, greatly shortening the construction period;

(4) The assembly line process and the low demand for large-scale equipment make the entire project economical.

Therefore, it is feasible to apply this construction technology to harsh hydrological environmental conditions.

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