Construction Techniques for Strengthening of Dongming Yellow River Road Bridge by the Cable-Stayed System

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Abstract. The Dongming Yellow River Highway Bridge (75+7×120+75 m), is a large span prestressed concrete rigid frame and continuous combination beam bridge, which was the first bridge strengthened by cable-stayed system in China. Using towers and stay cable system, the main bridge was transformed to provide vertical support with superstructure. For the foundation reconstruction, bored piles were constructed as new pile foundations on both sides of the original pile foundations. After cofferdam pumping, to ensure the positioning of the protective tubes, the reinforcing bars, concrete cover and concrete piles left in the river bed were removed by using brush drilling rigs, long arm digging machines and frogmen, while the "U-tube" method was used to grout at the bottom of the piles. The diamond wire saw cutting technology was adopted to complete the transformation of the old caps and insert shear nails. Using the post-pouring strip temporary shields, the new caps and old caps were connected until the tensioning of the cables was finished. To ascertain the arrangement of the reinforcement on the floor and the prestressed reinforcement, and then stick the positioning plates on the floors, bonded rebars holes were drilled utilizing the hydraulic core drill that was made. The joists and the brackets are manufactured by the factory and assembled in the construction site. Gantry cranes and angle fine-tuning devices were used to install the joists and brackets, and then the connecting bolts were inserted. Concurrently, material was transported through the hole in the roof of the middle-span, and the steel supports within the box were installed. From the middle towers to the side towers, from the short cables to the long cables, cables were tensioned by batches and levels with constant monitoring throughout the whole process of this tensioning construction. Finally, the external prestressed strands inside the box were adjusted and the bridge deck construction was completed.

1. Introduction
The Dongming Yellow River Highway Bridge, Fig. 1 is located over the Yellow River between Dongming County, Heze, Shandong province and Puyang city, in the Henan province, China. The bridge, completed in October, 1993, is a large span prestressed concrete rigid frame and continuous combination beam bridge built by the balanced cantilever, cast-in-place, and box girder construction method. The
The main bridge structure consists of nine spans made from a single-cell, three-dimensional post tensioned concrete box girder. The center span is 120 m long and the two side spans are 75 m long each. The depth of the box girder changes from 6.5 m at the pier support to 2.6 m in the center of the main span.

This bridge went through four detections periods during 1997~2013 and one reinforcement of the main bridge was performed in 2003 by means of adding the external prestressed strands at the bottom slab of the box girder, increasing the thickness of the web and bounding steel plates, pasting carbon fiber reinforced polymer (CFRP) to the girder bottom. The main purpose is to enhance the shear strength of the web and the transverse bending strength of the top and bottom slabs [1, 2]. However, after the reinforcement in 2003, new cracks and deflection continued to appear in some spans. In the vicinity of L/4, the web of the box girder had more diagonal cracks with a 40°~60° angle, which belong to the typical shear cracks. Causes of the cracks are analyzed as follows: Screw-thread steel bars were designed as the vertical prestressed reinforcement, poor tensile effect of the vertical prestressing caused many cracks; additionally, during the reinforcement in 2003, curved prestressed tendons were missing too. Deflection problems, especially that in the mid span, still existed after the reinforcement in 2003. The mid-span deflection was always accompanied with and was further aggravated by cracks in the web plates which reduce the stiffness of the bridge. Deflection and cracks interacted with each other and led to a vicious cycle. The main problems resulted from the improper design of the structure and size of the bridge with a large side and mid-span ratio, the loss in the prestressing force caused by concrete shrinkage and creep, inadequate construction quality and big number of the overloaded vehicles and large traffic flow, which both exceeded the design level [3, 4].

Extensive literature relating to the construction technology of reinforcement of existing bridges and the new bridge have been reported, but the literature for the strengthening of the cable stayed system is scarce, especially in the field of bridge construction. The Puttesund Bridge in Norway was strengthened by adding steel pylons and stay cables [5, 6]. The solution chosen was to build a cable-stayed construction around the existing bridge thereby listing the in-span superstructure and effectively reducing the forces on the structure due to dead load. However, it is a single cell box-girder cantilever bridge. The structure has the advantages of clear mechanical behavior and convenient construction. The coupling effect between the cable force, anchorage position and the tower height for the Dongming Yellow River Highway Bridge adopted by the cable-stayed system is more obvious because its structural characteristics. By this method, change the system of the structure, which cause more serious degree of local concrete stress concentration in anchorage zones and further brings great difficulty to the bridge construction.

The construction process of the reinforcement work comprised: (1) Construction of the pile foundations, caps and bridge towers; (2) Demolishing of the deck component that needed to be replaced; (3) Manufacturing and assembling of the joists and brackets to the site; (4) Drilling holes in the bottom of the concrete girder box; (5) Hoisting the joists and brackets and embedding anchor bolts; (6) Installing the steel supports within the box; (7) Installing the cable; (8) Tension construction; (9) Readjusting the
external prestressed reinforcement; (10) Deck system construction; (11) Adjusting the cable force; (12) Construction of the post-cast zone of new and old pile caps.

During the reinforcement, 32 pile foundations were laid, 16 bridge towers were constructed, 64 stay cables were increased 8 pile caps were expanded, in size and total 1373 cubic meters of bridge deck pavement and 1980 meters of barrier were replaced [7].

2. Engineering features and difficulties

Not only hydrogeologic conditions are complex, but also some unexplored debris, such as the numerous concrete blocks, steel bars, pipe piles and other wastage left from the old bridge construction, which increased the difficulty of construction in the pile foundations No.59~63.

The joists and brackets and the box girder of the main bridge were connected by the anchor bolts, which requires high processing precision for the steel components, and created great difficulty for drilling holes because the layout of the general reinforcement and prestressed tendon is complicated.

There were hundreds of bolt holes at each side of the brackets that must align with the bolt holes in the box girder and the bottom surface of box girder adopted the quadratic parabola as the distribution function of longitudinal displacement along the girder width, in this way, the hoisting difficulty increased.

As the vertical alignment of the existing bridge had a sharp difference with the original design and because of the numerous cracks in the main girder, the mechanical properties of structures is complex. Hence, it is very important to arrange the tension sequence, the control of cable force and the monitor of concrete box girder. Deviation of operation may lead to irreparable damage.

3. Strengthening construction technology of the cable-stayed system

3.1. Pile foundation and cap

The new pile foundations which consist of 32 columns with the same diameter and length were built to share the bridge load on both sides of the old pile foundations. The pile diameter is 2.4~2.0 meter from top to bottom, the length is 84 meter, center distance is 5.75 meter between new and old pile. The main construction flow added pile is as below: (1) Installing temporary steel bridge and construction platform; (2) Construction of steel casings; (3) Drilling with rotary drilling machine; (4) Grouting at the bottom of the piles using the "U-tube" method.

Since riprap was taken as control measure for some dangerous reaches and due to the numerous concrete blocks, steel bars, piles and other wastage that was left from the old bridge construction, driving bored pile steel casings was hindered by debris for construction of piles No.59~63, which worsened the existing difficulties.

One solution to this problem is to dump the wasted steel and steel strand with brush drill at first, then clear up the concrete blocks by mechanical and manual means. The concrete cover layer was firstly broken by impact drills and then the crushed concrete blocks were dragged out with a long-boom crane. However, the debris that could not be handled by machine were cleared up after cofferdam pumping, then a manual cleaning method had to be used. In addition, other clean-up measures were used as large diameter steel casing protection method, frogmen, etc.

The other problem was that pulling out the deformed steel casing which arose from the construction waste in the river bed is difficult. First, water jetting by the high pressure method was used to reduce the pressure of the casing wall and then the coordination of pulleys and vibratory hammers was tried in order to lift the casing, but neither of them worked. Ultimately, a large steel beam counter force device supported by four jacks was used and succeeded.

Before construction of the pile cap, an integral steel plate cofferdam was built, which then carried the water away from the cofferdam to meet the space requirement of construction. Finally, to protect it, it was backfilled by pumping sand. The diamond wire saw cutting technology was adopted to complete the transformation of the old caps and insert shear nails. In order to save cost and for safety concerns,
the steel cofferdam were removed. Using the post-pouring strip temporary shields, the new caps and old caps were connected until the tensioning of the cables was finished and ground settlement became stable.

3.2. Pile foundation and cap

Turnover formwork technique was applied to the pylon construction, using auto cranes to install the form and concrete steel on top of the box girder. The turnover mold was composed of three sections of large combined templates, brackets and a working platform. Each formwork segment was mainly composed of internal and external formwork, formwork fixing frames, surrounding belts and drawbars. According to the actual situation, the formwork was designed into big combined forms, of which the surface steel plate was 6 mm thick to reduce the weight and make it easy for turning it over. The internal form was designed into a steel assembled form. The turning over of both internal and external formworks was completed by auto cranes. Because of the higher pier, and full consideration of the segmental construction time, the machine length, reinforcement materials and decrease in the construction joint quantities, two sections of the form with a concrete height of 4.5 meters were cast each time, in other words, 2 layers of formwork were turned over each time.

Multiple sliding cable saddles were applied for construction of side tower No.58 and the secondary side towers No.59 and 64. The cable saddle set was composed of saddles, roller components, bottom plates and standard steel cage. As the gap between the top of the cable saddle and the bottom plate of the steel cage was too small to allow the anchor head and the cable to be installed, the entry work of the cable into the saddle groove was carried out on the bridge deck for towers No. 58, 59, 64, 65 first and then the integral hoisting the stay cable and sliding cable saddle. When embedding the cable into the saddle groove, the saddle was laid on the foundation. A section-steel door frame was set outside of the saddle hanging a vertical chain hoist, and a horizontal chain block was set on the foundation. Besides the chain device, the lifting jack stood by as an assistant measure. When the center mark of the cable coincided with the middle point of the saddle groove after fine-tuning the position and angle, the whole cable was laid down and it entered the saddle smoothly. The saddle and cable set were hoisted on the sliding roller assembly by a 50- ton crane and two 25-ton cranes and screwed up.

To facilitate the installation, the stay cable sleeve was manufactured in 2 parts. The reserved section was welded with the steel anchor box in the factory, and the other part was delivered to the construction site and connected with the reserved part using high strength bolts. The steel anchor box on the top was set as a spare box. Pylon tops No.60-62 were designed into steel anchor style, the top of which was set as the anchor ends, and tensioning operation was performed at the joist anchor ends.

3.3. Drilling in the box-girder bottom and installation of new steel members

The new steel members are composed of 32 steel joists, 64 steel brackets and 32 steel supports. Each joist is 23.5 meters in length, 0.9 meters in width, 2 meters depth in the middle and 1.2 meters at end and weighs about 39 tons. The anchor bolts between the brackets and the box girder are high strength 450 mm, M22 bolts with a performance level of 10.9 S. A total of 109 pcs are used on long cables and 99 pcs on short cables; bolts of the same strength and performance level but with longer size of 80 mm are used as the anchor bolts between the joists and the brackets. Forty pcs are used for both longer and short cables.

The steel brackets and joists were manufactured and assembled in a factory and then delivered integrally to the construction site. Before installation, a working platform is set up in the bottom slab, located and avoided the reinforcement and the prestressed reinforcement detected by the metal detector, then it was located in the precise position of the connecting plates of the brackets with an optical theodolite and the level gauge. Next, the surface was leveled up with epoxy mortar after creating the work by chiseling away at the surface of the bottom slab, and finally pasted the connecting plates of the bracket.

Considering the weight of the steel members and the construction conditions on the site, a set of 2×50 tons double cantilever gantry cranes with a large span of 17.5 meters was ultimately used for the hoisting work. When drilling holes vertically in the bottom of the box girder using the normal drilling machine,
cold water could not be supplied to the drill bit, which cause it to heat up and burn up. In additional, the cold water overflew and damaged the motor. This problem was solved with a self-made hydraulic jet coring drill. After the steel joists and brackets were hoisted, adjusted and located, the bracket was regarded as the positioning plate. By restricting the bracket construction, 25 holes were marked in the interior angle of the bracket, the bracket was lowered down, and the rebars were drilled and bonded. Then, utilizing a temporary hanger rod with a fixed angle to fix the joist and the bracket, the remaining holes were drilled and the rebars were bonded. As the hoisting was operated with relatively stable wind, the installation of the steel members was not affected much. Due to the thin web, it was necessary to enhance the transverse stability of the cross section by adding the steel supports within the box. The steel supports were brought into the box in parts through the hole opened in the top slab of the mid span, welded and connected with the girder box by means of the post-installed rebar method.

3.4. Cable installation and tension control technology
Technological process of cable installation at the top of the pylon: the traction head was installed, the sling was twined around the stay cable at the appropriate position and connected with the automobile hoist, the cable anchor head was hoisted by the automobile hoist to the orifice of the pipe embedded in the steel anchor box outside the pylon, the chain in the pylon was led through the cable nut and connected to the traction head. The cable anchor head was pulled out of the anchor plate with the cooperation of an automobile hoist and a chain, and then the nut was screwed into place.

The stay cable should be stretched cautiously, because the tension would cause the stress change of the main girder, in particular, the stress in some part of the section would be seriously centralized with the increasing tension. If the tension could not be stopped in time or there was an unbalanced load, the box girder would crack and the loss of stiffness would occur, resulting in a collapse accident. Before stretching, the stress of the key section of the concrete box girder should be identified at the scene to ensure that the stress during the tension process is under control. There are 64 tension points in the whole bridge, which are located in the anchorage ends of the stay cable steel joists, where 1 lifting jack was installed. It was ideal if all the lifting jacks could work at the same time, but that would increase the cost significantly. Accordingly, it was ultimately decided that 8 lifting jacks would work together.

During the operation of the cable tension, the long cables No. 61 and 62 were first stretched to the hierarchic controlling force, then the short cables were stretched, after that, the whole day’s work was completed. The next day, the long and short cables No. 60 and 62 were stretched in turn. From the middle towers to the side towers, from the short cables to the long cables, the cables were symmetrically stretched by batches and levels. To reduce the influence of the temperature on the bridge, the tension time was arranged at night between the 20:00 and 24:00 h. The trials were completed during the day to ensure sufficient time for preparation.

The tension was divided into eight levels, ranging from 30, 50, 65, 75, 85, 90 and 95% to 100% of the tension controlling force. The error of the tension force was no more than ±2.5%, the error of tension force during construction was 5% in each period, and took less than 10% as the criterion for the systematic error (the difference between the measured cable force and the theoretical value) to control the tension force. According to the actual data collected during the tension process, the working procedure could be adjusted to ensure the safety. The cable force is measured and controlled by a frequency cable force dynamic measuring instrument and the pressure sensor.

Two controls should be adopted to manage the stress, to control both the variables and the absolute value of the stress. Stress variable control means that the actual stress change value should be lower than the calculated stress change value. The absolute value of the stress control means that the sum of the actual stress change value and the calculated stress value should meet the requirements. The horizontal deviation of the bottom of the pylon is no more than ±10 mm, the inclination of the pylon is 1/3000 of the height of the pylon and no more than 30 mm, and the controlled inclination of this pylon is 15 mm according to its height.

The typical cracks in the concrete box girder were documented and measured. The limited value was collected after the tension on the same day, and the cable stress, deformation and tension stress were
documented and analyzed for setting a more appropriate tension next time. In case of abnormality, the application of the tension should be stopped at once. Finally, the external prestressed reinforcement inside the box was adjusted and the bridge deck construction was completed. The Dongming Yellow Highway Bridge strengthened by the cable-stayed system is shown in Fig. 2.

![Figure 2. The Dongming Yellow Highway Bridge strengthened by the cable-stayed system.](image)

### 4. Conclusion

In view of the design features and the construction conditions for the strengthening of the Dongming Yellow River Highway Bridge by the cable-stayed system, this paper describes the strengthening of the existing bridge in detail. In addition, a series of key construction technology, such as, construction technology for building new pile foundation on an old bridge, anchorage and installation technology of the new steel members and tension controlling technology of the stay cable, are implemented. The reinforcement work started on December 8, 2014 and was completed on December 24, 2016. When the cable forces varied between 95% and 100%, the final result was a deformation of 33 mm at the mid-span sections No. 59~61 caused by this tensioning, and meet the appropriate specifications. By this tensioning the shear-relieved girder would meet full traffic load requirements, even more important, the reinforcement solution elegantly solved the shear problem. The strengthening of the Dongming Yellow River Highway Bridge around the existing bridge is considered a success and provides a valuable reference for a large span prestressed concrete continuous box girder bridge by means of the cable stayed system in the future.

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