The Systematic Construction Method of Kao Ping Hsi Cable-Stayed Bridge

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Abstract: Kao Ping Hsi cable-stayed bridge, which is purposely designed to be the landmark in the southern Taiwan after completion, is a single plane and single pylon cable-stayed bridge with an asymmetrical hybrid girder system composed of a 330m steel-girder main span and a 180m PC-girder side span. The construction of the bridge was completed in December 1999, which is three months earlier than the official preset schedule. Considering its size and construction difficulty, it is constructed in a quite short period. The purpose of this paper is to present the construction plan and schedule of several important parts of the Kao Ping Hsi cable-stayed bridge.

Keywords: Kao Ping Hsi, Cable-Stayed Bridge, Construction Method, Construction Plan, Construction Schedule.

1 INTRODUCTION

The Kao Ping Hsi bridge, constructed over Kao Ping Hsi river between Pingtung county and Kaoshiung county, is one part of the southern second freeway. The main bridge, crossing the channel of Kao Ping Hsi river, is 510m long. Including the prestressed concrete box girder approaches the bridge leads the total length of 2617m. The main bridge is a single pylon cable-stayed bridge with an unequal span arrangement as shown in Fig.1. To compensate the unbalance effect due to the unequal span arrangement, prestressed concrete box girder is designed for 180m side span and steel box girder is adopted for 330m main span. A 183.5m high inverse Y shape pylon is designed based on the consideration of stability and aesthetic. On both sides of the pylon, a single plane cable system along the centerline of the deck is used to support the girder system and allow the open view for drivers.

The Kao Ping Hsi cable-stayed bridge is a record-breaking engineering achievement. It is the largest bridge in Taiwan and also a second longest single pylon cable-stayed bridge so far in the world. Considering its remarkable size, the bridge has four critical parts, PC girder 、steel girder 、pylon and stay cable system, needed to be investigated and constructed carefully in order to complete the bridge on time. Therefore, a well-considered construction scheme for this four parts had to be proposed in the preliminary stage and then conducted during the construction stage. The puropose of this paper is to present the construction scheme and construction situation of the Kao Ping Hsi cable-stayed bridge.

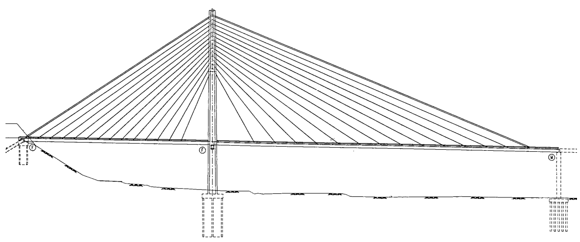


Fig.1 Bridge Arrangement

2 PRESTRESSED CONCRETE BOX GIRDER

2.1 Description

The side span of the bridge, 180m long and 34.4m wide, was a double-cell PC box girder with precast diagonal panels. One end of the span was situated on A1 abutment and the other end was continuously connected with the main span on the cross beam of the pylon. It contained fifteen box girder segments according to the separation by means of the location of the diaphragm. Each segment was about 11.8m long and was cable supported only in the intermediate location of the diaphragm.

To build the PC box girder segments, several construction methods were studied to replace the span by span cast in-situ method proposed in the design stage. According to the evaluation of construction efficiency 、 enviromental impact and safety, a combined systematic construction method was adopted to cast the central box cell and cantilever slabs, individually. The central box cell was cast by using advancing shoring system and then both cantilever slabs and precast diagonal panels beneath were erected by using a cantilever hanging frame.

To match the suitable length arranged for the advancing shoring method, the side span was separated by seven temporary supporting frames to eight subspans and then each subspan contained two segments. The construction procedure began with the installation of the advancing shoring system between A1 abutment and the first temporary supporting frame and then carrying out the rebar work and concreting of the central box cell for the first two segments, consecutively. When the first subspan was finished and then the advancing shoring system moved forward to the next subspan the cantilever hanging frame was set up on both sides of the cast central box cell and then the installation of precast diagonal panel as well as the concreting of cantilever slab would proceed. From the second to seventh subspans, the same construction procedure were used to finish the central box cells and cantilever part. The eighth subspan would not be cast until the first steel segment was installed.

2.2 Construction facilities

To construct the PC girder segment of the side span, a set of combined construction equipment including advancing shoring system and cantilever hanging frame was designed and worked with temporary supprting frame. The advancing shoring system was mainly composed of launching girder system 、 form system and hydraulic jack system. To carry the total weight of one subspan, four steel girders were designed and arranged on the top of the temporary supporting frames. Each girder, including nose beam 、 main girder and tail beam, was designed to be 49m long to fulfil the moving requirement between two subspans. To push the launching girder moving forward, four 50 tons horizontal hydraulic jacks were requested and set on the top of temporary supporting frame. The outer form was divided into two equal parts along the girder centerline and moved with girder system. The inner form was a semi-automatic form system of which top form sat on launching rail as well as moved forward by using chain block and side form was dismantled by workers. The shoring system was combined together to proceed rebar work and concreting job but separated into two sets of subsystems, each containing two launching girders, in launching stage.

The cantilever hanging frame used to construct cantilever slab was mainly composed of the triangular steel truss. The front end of the truss suspended the outer edge of the precast diagonal panel as well as the bottom form of the cantilever slab 、 the middle support was located right on the top of outer webs and the rear end was anchored at the top slab of the cell. The anchor would be released when the frame moved forward. Even though the frame itself was designed to be stable in moving stage without any assistance, the counterweight block was still put on the top of the frame to increase the moving stability.

2.3 Construction schedules

The first PC box girder segment was cast in November 1997 and entire construction was completed in November 1998. In the beginning stage of this job, the work would not be done smoothly because the box cell was a little bit sophisticated and contained many embedded items, like longitudinal tendon system 、 transverse tendon system 、 recess tube of stay cable and so on. According to the schedule record, it took more than forty days to complete the first segment, which was much longer than the preset working time. Later on, the construction cycle time for each segment became shorter and stable when engineers were familiar with the process.

3 STEEL GIRDER

3.1 Description

The main span of the bridge is a 330m five-cell steel box girder continuously connected to the PC box girder at one end and seated on the top of pier P2 at the other end. The central cell housed the anchorages of stay cable system. Based on the consideration of workability, the whole span was divided into sixteen standard segments and one joint segmemet as well as one end segment. Each standard segment was 20m long and around 370 tons.

The working process of the segment included fabrication stage 、 assemblage stage and erection stage. The segments were fabricated in China Steel Structure Company. Considering the transportation capacity by truck, each segment was separated into twenty small blocks. After twenty blocks were finished and the geometry shape of the pre-assembled segment was checked, one by one block would be transported to the assemblage yard in bridge site. Then, twenty blocks would be reassembled to the fabrication shape of the segment and then welded. Before being lifted up to the welded location in air, the completed segment would pre-erect with the adjacent segments to check the geometry alignment and set up the match lines used later for the erection of the segment in air. When the lifted segment was adjusted to the right geometry alignment welding process was executed in air.

To move the segment form assemblage yard to welded location in air, many erection methods had been considered. The erection method proposed in the design stage was to transport the segment on the ground and then vertically lift the segment up to the welded position. To transport segments according to the method proposed by the designer, a temporary access bridge over Kao Ping Hsi channel needed to be built in advance and remained until all segments were finished. When the contractor reviewed the proposed erection method, it was decided to make a change because the temporary access bridge would change flow condition of the river and could not be available during flood period. In order to avoid the change of the river area and guarantee a workable erection condition during flood period, an efficient erection method was developed.

The main difference between the original and updated erection methods was how to transport the segments to the lifted location. The developed erection method was to transport the segment in air instead of on the ground considered in the original proposal. The transportation equipment of the proposed erection method, that was first used to deliver the steel segment of the bridge, was a developed hanging carrier moving beneath the existing cantilever part of the steel box girder. The hanging carrier could move back and forth along the rail fastened on steel deck.

According to the updated transportation manner, the erection procedure of the segment could be separated into several stages. First of all, the segment was connected to the hanging carrier after the pre-erection work was done. Then, release the supporting jacks and move the hanging carrier forward. When the hanging carrier with the segment moved to the lifted location the segment was transferred to lifting crane and then lifted up to the welded position. After the lifted segment was adjusted to the right alignment, the full section welding work between two segments would proceed. Finally, the hanging carrier moved back for the next segment. All segments followed this way until the steel girder was completed except the last segment, which was assembled on the deck of the approach and lifted by lifting crane directly.

Hanging Carrier

The hanging carrier was designed by Kawada Company specially for the erection of the steel girder segment of the Kao Ping Hsi cable-stayed bridge. The carrier was an efficient equipment to transport the heavy segment in case that ship transportation and full staging could not be used. The function of the carrier is to carry and transport the segment in air, and then make a transfer for the segment to the lifting crane shown in Fig.2.

The carrier was mainly composed of four parts, main structure 、 jack system 、 lift system and transfer system. The main structure, like a crab from the appearance, was constituted by steel truss member. Two legs, belonging to the upper part of the carrier, would seat on the fastened rail and be pushed by means of horizontal jacks. To push the carrier stably and safely, one 40 tons oil jack with the stroke of 1100mm combined with a safety device for each leg was employed. To lift and adjust the transported segment, two main lifting bars with the allowable capacity of 400 tons and two auxiliary wire ropes were connected to the bottom part of the main structure. In addition, a triangular eye bar structure was used to transfer the transported segment to the lifting crane.

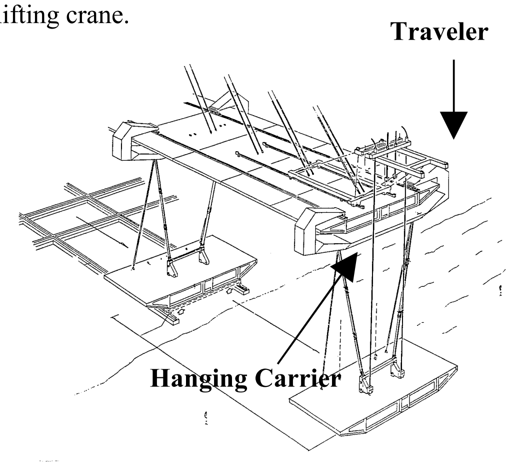


Fig.2 Erection Procedure

3.2 Erection schedule.

To complete the steel girder on schedule, the whole process from fabrication stage to erection stage should be well arranged. As long as anyone of the stages was delayed, the whole process would be affected and the completion schedule would be postponed. In accordance with the fabrication record, CSSC spent around nine months to complete the first segment, which was much longer than the preset production schedule. What made this situation happen was that each block, containing many U-shape ribs, was a fully-welded steel structure and could not be fabricated accurately without the enough information to estimate and handle the welding shrinkage effect in the beginning stage. Later on, each segment could be produced within four months when the problem was solved and the production line could run in proper way.

In the assemblage yard, the most difficult and time-consuming job was still welding process. It took around two months to finish one segment in the early stage. Based on the consideration of the completion schedule, the contractor decided to increase the amount of welding operator and extend the working time. Then, the production cycle time for each segment reduced to one month. For the erection stage, there were two important working procedures that might affect the cycle time. One of the important procedures was moving froward of the lifting crane, which cost three days in first few segments and one day for the remaining segments. The other one was alignment adjustment as well as welding operation, it took twelve days in average for first six segments and then reduced to nine days for the remaining. Generally speaking, the production cycle time to erect one segment shown on Tab.1 was twenty days and then fifteen days.

The first steel segment was erected in July 1998 when the last PC girder segment was ready as well as the closure segment of the Pylon was finished. The entire erection procedure was completed in July 1999, which was around three months earlier than the completion schedule.

Table1 Erection Schedule of Steel Girder

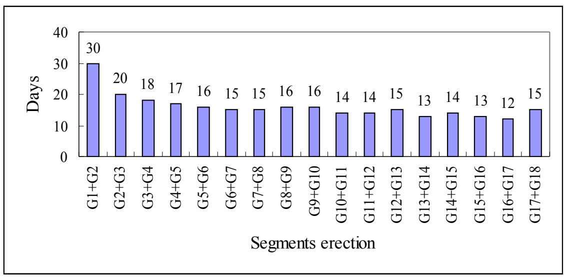
4 PYLON

4.1 Description

The pylon of the bridge, 183.5m high, was designed to be inverse Y shape with variable cross section. Two inclined pylon legs were hollow box reinforced concrete structure and joined together at the height of 110m above the ground. The pylon post from the closure segment of two pylon legs to lighting chamber was a solid RC structure with the embedded anchor plates and maintenance ladder on the front and rear sides. To support the superstructure a cross beam was designed to be rigidly connected with two pylon legs. In addition, an earth beam connected with two pylon foudations, was designed to resist the huge lateral force of the pylon legs.

Based on the consideration of workablity of the adopted climbing form each standard segment was 4.2m high and then each pylon leg was divided into twenty-six segments and the pylon post was sixteen segments. The anchor plate was also separated into eight steel pieces for being lifted and welded in air. The length of steel plates ranged from 6.0m to 7.7m. To cast the concrete segemnt, two sets of PERI ACS 75 automatic climbing form system was employed and a heavy tower crane, with the lifting height of 191.4m and working capacity of 650T-M, was set to lift working equipments and materials.

After the pylon foundations were finished, two sets of climbing form systems were assembled and then the concreting work proceeded. After the cast concrete reached to the design strength the outer form was automatically lifted up to the next segment. When the rebar fixing work was completed, the inner form lifted by using tower crane was set up. Then the concrete was poured after the form alignment was adjusted to the right position. All pylon leg segments followed this procedure for the concreting work and rebar fixing work except the segments adjancent to the cross beam. The cross beam with the connected pylon leg segments were cast by using full staging method. During the construction stage of the pylon legs, the jack-apart operation were conducted three times to compensate the bending moment due to the selfweight of the inclined pylon leg.



After the pylon leg segments were finished two sets of climbing form systems were integrated into one set. Then, the pylon post would follow the construction procedure used for pylon leg to construct the segments. The recess tube and anchor plate of stay cable would be embedded during construction stage of the segments. As soon as the last segment was completed the lighting chamber was built and then lightning conductor and aviation warning system were installed.

Climbing Form System

The ACS 75 automatic climbing form system produced by the Germany PERI Company was divided into four subsystems during climbing stage. Each subsystem contained its working platform 、 hydraulic jack and the corresponding climbing rail. The hydraulic jack could provide the lifting velocity of 0.5m/min and lifting stroke of 710mm. The maximum working capacity of the platform was calculated according to the most critical construction condition. The climbing procedure of the system could be separated into three stages. First, the outer form was pulled off concrete surface when the cast concrete reached to the design strength. Then, the climbing rail was pushed up to the anchoring location by hydraulic jack. Finally, the subsystem was pushed up to the location of the next cast segment each by each and then four subsystems were integrated and adjusted for the concreting work.

4.2 Construction schedule

Overall, the main pylon construction was to finish sixty-eight segments 、 one lighting chamber 、 one cross beam and one earth beam. The construction of the segment was a cyclic process which could be broken down into rebar fixing work 、 form climbing work and concreting work. It could be said that the cycle time to cast one segment was only depended on the process of rebar fixing because the time needed to climb the form system and concrete the segment was almost fixed.

Due to the importance of the rebar fixing work, several rebar fixing methods were taken into account in the beginning stage, for example precast rebar cage method 、rebar fixing in-situ with an auxiliary fixing frame method and so on. Finally, rebar fixing in-situ with pulling wire method was used because the other methods were not workable when the detailed analysis was made. The time needed to fix the rebar for one segment was clearly related to the total amount of the rebar fixed for that segment. Therefore, the cycle time to complete one segment would gradually shortened because the pylon cross section shrunk from bottom to top.

According to the recorded construction sechedule, to complete one segment the cycle time changed from twelve days for the segments nearby the foundation to ten days for the segments close to the cross beam and then twelve days for the segments beneath the pylon post. The pylon post segments cost much longer time to complete all related jobs because two more working items were included. The first segment was cast in April 1997 and the pylon was completed in May 1999, which was earlier than the preset schedule.

5 STAY CABLE SYSTEM

5.1 Description

Based on the consideration of the apperance of the bridge, a single plane semi-fan arrangement was adopted for the cable system of the bridge. The system consisted of fifteen pairs of stay cable on each side of the pylon. The cable length ranged from 80m to 330m. Each cable was composed of tension element 、 anchorage apparatus and corrosion protection barrier. The tension elememt of the cable was high strength parallel strand, which could provide good mechanical characteristic and fatigue resistance. To meet the high static and dynamic demands, the VT HIDYN type anchorage was adopted. The protection barriers was divided into three components, inner protection 、outer protection and surface protection. Base on the consideration of reliability, the monostrand was sheathed by small size HDPE tube as well as grease and then the large size HDPE tube with coextrusion color coating was used to protect the inner barrier. In addition, wax produced by elf company was injected between inner barrier and outer barrier to increase the damping and also provide additional protection.

Due to the importance of stay cables in the bridge, all constituent components of the stay cable should be tested in the planning stage, for example strand relaxation test 、anchorage fatique test 、wax trial injection test and HDPE tube butt-weld test. Besides, a well-considered construction plan, including assemblage 、 installation and stressing, was proposed. The working sequence set for the cable was assemblage at the jobsite first and then installation and stressing.

5.2 Construction

Assemblage

Considering its huge size, the stay cable system was assembled on the side span. Operations began with the strands, as coiled by VT company, being placed and cut. Meanwhile, the butt-weld operation of the HDPE tube, 11.8m for each piece produced in manufacturer, was conducted. Then, the cut strand bundle was inserted into the completed tube to the preset location and the monostrand were threaded one by one into the achorages. After both anchorages were set up, wax was injected from the lower side of the tube.

To assemble stay cable, the production length for strand and tube were caculated in advance based on the design alignment of the cable system and several influence factors. The influence factors included the sag effect as well as temperature effect of the cable and the camber effect of the bridge. Besides, before wax injection started the injection amount was calculated and the injection temperature 、 pressure and direction were determined according to the test result of the wax trial injection done in the planning stage. To guarantee the quality of the injected wax, the temperature and condition of the wax flowing from the outlet on upper end of the tube were observed.

Installation

The installation operation of the assembled cable began as long as the wax inside of the tube already cooled down to solid state, which might need twenty-four hours. According to the construction procedure of the bridge, two pairs of stay cables on both sides of the pylon were installed for each cable construction stage. To be consistent with the schedule of the steel segment erection, the cable on the side-span side was installed first. For each cable, the anchorange at pylon had to be fixed before that at girder. Otherwise, it would be very difficult to install and adjust the anchorage at pylon because the force needed to install and adjust the anchorage would be too big, which could not be provided by the machine mounted on pylon.

The tower crane was used to lift the installing cable and then a chain block mounted on anchor plate would pull the anchorage through the recess tube embedded before. To install the anchorange at girder, several mobile cranes would be arranged along the cable to overcome the sag effect and then reduce the anchorange installation force as well as ease the operation of anchorage installation. A pulling winch or jack, which was dependent on the magnitude of the pulling force, was employed to assist the installation of the anchorage at girder. During installation stage, the wind velocity was monitored to guarantee the safety of the operation, which should be less than 50km/hr.

Stressing

The point of the stressing operation of the installed cable was to generate the correct cable force corresponding to the pre-defined construction stage. To achieve the construction requirement in the stressing stage, a series of the preliminary studies about stressing equipment 、 stressing location 、 stressing procedure 、 stressing timing and so on were conducted. In addition, the cable force has been monitored and checked from the installation stage of the cable to the completion stage of the bridge.

The stressing equipment, designed by VT Company, was composed of jacking system 、 blocking device and anchor chair. To transport the equipment easily inside of the box girder, it was always dismantled after stressing and then moved unit by unit. Based on the workability consideration during stressing and maintenance stages, the lower end of the cable at girder was arranged to be the stressing point. Theoretically, the stressing procedure should be consistent with the procedure set in the analysis, in which stay cables on both sides of the pylon was designed to be stressed simutaneously. Practically, this was almost impossible to proceed because of the limitation of jacking device. Therefore, the stressing procedure was divided into several stages to finish and then cables on both sides of the pylon were stressed to the stage force almost in the same time but not simutaneously. Besides, the temperature effect should be considered in the stressing stage to obtain the correct cable force. In general, two ways could be used to deal with the temperature effect. Considering the uncertainty of the temperature coefficient and the variety of the cable sag effect, to calculate the force variation due to the temperature effect was replaced by setting the stressing timing at nightime so that the force variation was almost zero and the calculation was no need.

5.3 Construction schedule

To analyze the cable construction scehdule, the cycle working time calculated was for one cable group, which contained two pairs of stay cables. As mentioned before, the cable construction could be divided into assemblage stage 、 installation stage and stressing stage. The assemblage stage was consisted of HDPE tube buttwelding 、 parallel strand cutting 、 anchorage setting and wax injection. The time needed to complete the first two items was dependent on cable length, that varied from two to four days and three to five days to finish tube buttwelding and strand cutting, respectively. Then, it took around three days to set up the anchorages and one or two days to complete wax injection work.

The installation for the first several cable groups always started after the erection of steel girder segment was completed. Later on, in order to accelerate the cable construction schedule the cables on PC-girder side were installed almost whenever the assemblage operation was done. In addition, the upper end of the installed cables on steel-girder side were anchored only after the erected steel segement was temporarily fixed. For the stressing operation, it was always conducted right after the erection procedure of the steel girder segment was finished. Because three working stages for each cable construction could not be proceeded sequentially, the construction cycle time shown on Tab.2 was roughly calculated. The first cable was installed in September 1998 and the whole system was completed in July 1999.

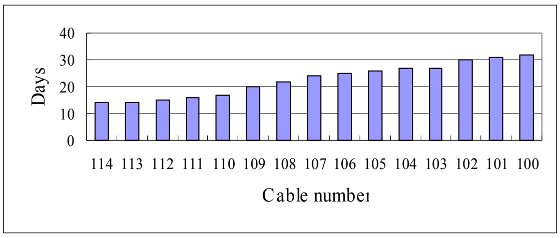


Table2 Stay cable construction schdule

6 CONCLUSION

The construction of the bridge began in April 1996 and was completed in December 1999, which was three months earlier than the official completion date. The schedule of the work always maintained 5% to 8% ahead until the end of the project even though many unexpected construction problems took place during working period.