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ARTICLE

Application of Prefabrication and Assembly to Hong Kong-Zhuhai-Macao Bridge

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ABSTRACT

The Hong Kong-Zhuhai-Macao Bridge (HZMB) project, which has just been opened to traffic in 2018. The special location, construction conditions, quality requirements and multiple functions of HZMB brought many challenges, such as management, technology, safety and environmental protection. To meet these challenges and ensure the achievement of high quality and 120 years design service life, the HZMB project first introduced the completely new concept of "Large size, Factory production, Standardization and Assembly", which was fundamental to the design and construction. This was developed in consideration of the difficulties of the offshore environment.

The core idea was Prefabrication and Assembly, which was to change this HZMB project into onshore work as much as possible by cutting this mega sea-crossing into large sized components, which could be prefabricated on land and then transported to the offshore site for assembly. The success of the HZMB undoubtedly has led the technology of prefabrication and assembly to a new height and recognized scale. This paper describes the implementation process of the concept; "Large size, Factory production, Standardization and Assembly" (LFSA) to the HZMB.

1. Project Introduction

The Hong Kong-Zhuhai-Macao Bridge (HZMB) is a 55km long project crossing the wide Pearl River Estuary of South China, connecting the Hong Kong Special Administrative Region (SAR) with Guangdong (Zhuhai) and the Macao Special Administrative Region. It is also a mega infrastructure project and the first to be constructed under the political concept of one country, two systems. HZMB forms an important part of the Pearl River Delta and national highway networks of China.

With a total investment of over 12 billion Yuan (approximately 1.7 billion dollars), the HZMB project includes three parts; the first is the main work in the sea and this section was constructed and managed by the Three Goverments; the second is the Boundary Crossing Facilities, and the third is the local links to Hong Kong, Zhuhai and Macau.

The main work includes: 22.9km of marine viaducts; three navigation channel bridges; two artificial islands,

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and a 6.7km immersed highway tunnel (figure 1).

Figure 1. Layout of the completed Hong Kong-Zhuhai-Macao Bridge

A project on this scale can never exist in isolation, and a key factor influencing all aspects of the HZMB was that it exists within a critical, committed, and highly diverse environment spanning three judicial districts.

As the landmark project of the Greater Bay Area, HZMB attracted much more attention from the governments and the public. Most of the project's technical decision-making was based on the principle of 'selecting the highest not the lowest' when conflicts occurred.

As a result, this project was expected to be accomplished safely, economically, innovatively, be environment friendly, achieve high quality and be completed within a tight schedule. All this brought the greatest challenges to the engineers.

2. General Introduce

HZMB has a total length of 55 km. Though it is called a bridge, actually it is a mega sea-crossing project which integrates bridges, islands and tunnels. As the longest sea-crossing in China, it used over 20km of steel box girder and over 2,600,000 m^3 of concrete. HZMB has many unique features which differentiate it from other projects, such as; being located in the preservation area for the Chinese White Dolphin (a rare marine mammal); having 120 years design service life; incorporating the deepest (-45m below sea level) immersed highway tunnel, and the longest sea-crossing bridge (over 30 km). Without doubt, there were many challenges and difficulties which needed to be solved in the design and construction process of this project. HZMB is regarded as the most complicated and difficult sea crossing project in China transport engineering.

Despite the main challenges mentioned above of the mega size, high technical standards, unique location, sensitive environment and so on, one point that should be stressed particularly is that it is a completely off-shore project, which meant that the previous experience of bridges and tunnels in China were not sufficient.

After studying worldwide projects, a construction concept was developed in the design phase, which was called large size, Factory production, Standardization and Assembly (LFSA). The core idea of this concept is to change the offshore works into onshore works and this was realized in the following way.

Firstly, the project was divided into many sections made up of standardized structural components which could be prefabricated on land. These components were then transported to site and assembled by machinery or equipment piece by piece. Through this, the project was realized in an industrial way, using production line methods with a minimized workforce.

Using this concept minimized the offshore construction work and improved the quality and safety, as well as shortening the construction time.

As a result, this project was realized by assembling the various components offshore, as if the engineers were playing a super building block game.

3. Application of Prefabrication and Assembly

The key points of LFSA are prefabrication and assembly. Large-size and standardization of components were two key features applied to prefabrication and assembly. To fully demonstrate the application of prefabrication and assembly, details of LFSA are described in the following four sections, according to the concept headings.

3.1 Large-size

The HZMB has a total length of 55 km, including over 30km of sea-crossing bridges, a 5.7 km long immersed tunnel (which is the longest immersed highway tunnel), and nearly 20km of local link highways. Based on these data, it is really a Super Project in the engineering industry.

HZMB is located in the Pearl River Delta, crossing Lingdingyang where there is an ecologically sensitive area and habitat of the endangered pink dolphins. Least disturbance in the water during construction and minimum obstruction to water flow were primary considerations in the design and construction.

For environmental considerations, 85-110m spans with single pier columns to support either two separate decks or a single wide deck have been used for the marine viaducts in HZMB, with pile caps for the bridge piers recessed below the seabed, so as to provide the least obstruction to water flow.

As mentioned above, in order to minimize the works insitu, the engineers divided the project into sections of large components. The bridge elements insists of pile cap and pier, steel box girder, steel-concrete composite box girder and steel pylon, all of which were fabricated in var-

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ious precast yards or fabrication yards.

The pile caps and piers were prefabricated as complete units. The tallest of such kind of pile cap and pier unit was about 50 meters high and weighed over 3000t (figure 2).

Figure 2. Precast pile-cap and pier units

Long spans of steel box girder were assembled and erected. The longest piece was 152.6 m long, weighed 350t and was erected onto the piers by a large floating crane with a lifting capacity of 4000t (figure 3).

Figure 3. Erection of a full span steel box girder

The 5.7 km long immersed tunnel was divided into 33 elements, each of which has a length of 180m and a width of 38m. Each element is still a big block, with a weight of 76000t (figure 4).

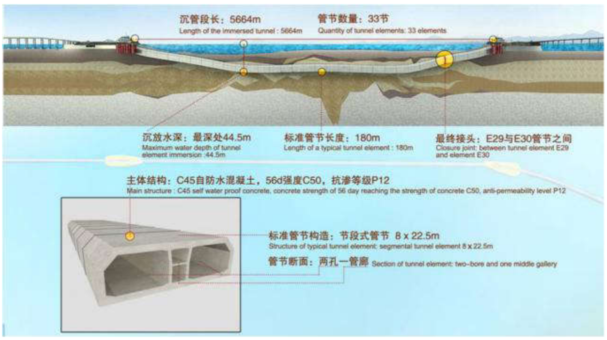

Figure 4. Longitudinal profile of immersed tunnel elements

The body of the two artificial islands was formed using other big elements; steel cylinders with a height of 45m and each weighing over 500t were used to enclose these sand-filled reclamations (figure 5).

Figure 5. Steel cylinder for drilling into the ground to form island

Based on the above structural components, the whole construction of HZMB was realized by assembling by production line methods, which greatly reduced the work offshore, minimized the risks for safety, the environment, quality and cost, and greatly shortened the construction time. Of course, such methods largely changed the offshore work of HZMB into onshore work. As a result, this encouraged a system to promote technology development for the construction methods, equipment and management.

3.2 Factory Production

As mentioned above, the HZMB is very long and the quantity of work was huge. The various standard components which were prefabricated in factories were very large size. All these components were produced in various dedicated factories surrounding the assembling sites. In order to save work time, each fabrication factory set up a linear flow production line, which was similar to the systems used by the mature industrial manufacturing industry.

It is not the first time tunnel or bridge elements have been produced in an industrial manner at ground level, under controlled factory-type conditions. However, it is the largest and widest application due to the scale of HZMB.

The typical factory for HZMB components can be classified into three main kinds; prefabrication facility for the immersed tunnel; steel girder fabrication facilities, and pile-cap and pier prefabrication facilities. These are described in more detail below.

3.2.1 Factory for Tunnel Elements

The immersed tunnel of HZMB has 33 elements, of which

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28 are a standard size and 5 are curved elements. Each standard element is 180m long and has a weight of over 76000t. It was the first time for China to prefabricate such huge tunnel elements. Even worldwide, it is only the second time immersed tunnel elements have been prodiced in a factory type manner.

Considering the transportation distance and convenience for the immersion, a specialized prefabrication facility was set up on Niutou Island, which is only 7 miles by sea away from the immersed tunnel location. The total area of this facility was about 40000 m^2. It was divided into four zones; material zone; concrete mixing zone; element production zone, and the dock zone (figure 6).

Figure 6. Layout of fabrication factory for tunnel elements

The tunnel element production zone was set up with a linear work flow arrangement. Each 180m element was made up from 8 equal segments of 22.5m, which were concreted using 3400m^3 concrete in one continuous operation. The factory had two production lines which could be working at the same time and overall, the facility had the capability to produce two elements every two months.

The production process of a tunnel segment was as follows; fix the reinforcement for bottom slab, side wall, interior wall and top slab; slide the reinforcement cage into the formwork (bottom form, inner form and side form); place concrete using a pumping system (the temperature of concrete before placing was controlled to be below 25 ℃), and curing, which was conducted after the forms had been stripped. The internal and external temperature of the concrete during curing was monitored using a digital monitoring system.

After curing for 72 hours, the segments could be pushed forward 22.5m, to clear the bed, ready for the next one。Each segment was match cast and the launching cycle was repeated 8 times until all the segments of one element had been completed. The entire element was then pushed forward into the shallow dock for outfitting.

The hydraulic system for launching the elements into the outfitting area was controlled by the computer to ensure balanced support and directional control. After the outfitting of a pair of elements had been finished, the sliding dock gate between the dock and the production line was closed and the dock flooded to the highest level to float the elements. The floating elements were then moved sideways into the deep wet dock area for storage. When required, the floating elements were moved out of the wet dock and towed to site for installation.

3.2.2 Steel Girder Production Factory

HZMB is also the largest and longest steel box girder bridge. It is calculated that over 400,000 tons of steel have been used for the steel box girder. To deal with such a huge amount of steel girder, the contractors set up 4 steel panel fabrication factories in different places of China, such as Shanhaiguan, Wuhan, Yangzhou and Nantong. At the same time, three steel box girder assembly line factories were set up in the Zhongshan area, near to the bridge site. The production flow is shown in figure 7.

The plates and stiffeners were cut and welded using CNC systems. The stiffened panels were then transported to the assembly factories in Zhongshan and assembled into span-long sections. All the processes were set-up and controlled as linear flow production lines. The completed steel box sections were transferred to special blasting and painting enclosures, after which the span-long sections were transported on special barges to the installation site and erected by very large floating cranes.

Figure 7. Production process for steel box girder

3.2.3 Pile Cap and Pier Production Factory

To meet the requirement raised by the marine authorities for a limit to the water flow obstruction rate, HZMB adopted pile caps for the piers that were recessed below the seabed. All the pile-caps and piers were prefabricated as units and the piers were divided into one to three sections, depending on the capability of the contractors' cranes. All the pile-cap and lower pier sections was made

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as one unit, with all site joints for the piers made above sea level.

An innovation was developed to make the connections between piles and some of the pile-caps (figure 8). A steel cofferdam on the pile cap was lowered over the piles so that work could be done in the dry. The precast pile cap with stub columns had oversize holes in them with shear keys. The pile cap was lowered onto the flanges off the piles. A gasket type water seal closed the gap between the bottom of the soffit of the pile cap and the pile, and then the hole was concreted (figure 9).

Figure 8. Steel cofferdam for connection between pile cap and pile

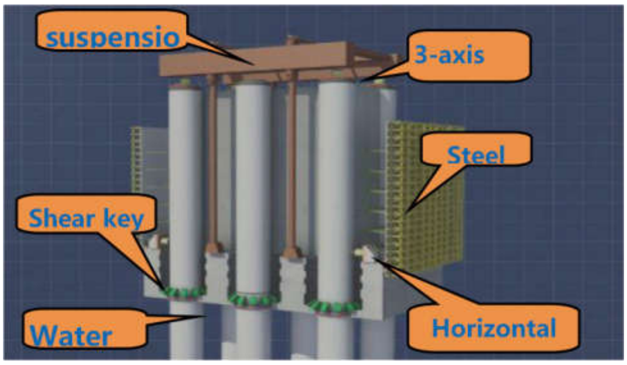

Figure 9. Inside view of steel cofferdam

All the pile-cap and piers were prefabricated in the land factories and assembled at the offshore site. The whole prefabrication process is shown in the figure 10.

The prefabrication of the pile-cap and pier units was modernized. The factories were equipped with automatic CNC cutting and bending equipment for the steel reinforcement bars. All prepared reinforcement was moved to an assigned position after inspection. The reinforcement was assembled into preformed reinforcement cages and then the cages were slid or lifted on to the fixed casting beds. After the forms had been positioned, the concrete was cast in one continuous operation without construction joints. The forms were stripped away after the concrete reached sufficient strength to allow the pile-cap and pier unit to be pushed forward to clear the casting bed, which could then be prepared for the next unit.

Figure 10. Production process of pile cap and pier unit

3.3 Standardization

Standardization of components was deliberately chosen and implemented. Moreover, the components were designed to be the largest practical size to minimize the offshore assembly work. Standardized components were the basis for implementing subsequent construction by prefabrication and assembly. The typical key components were; immersed tunnel element; pile-cap and pier unit, and steel box girder. As well as the design of standardized components, the construction management system for the project called for Centralized Standards to be implemented in all the production and fabrication plans to ensure proper control of the production management for concrete, steel and other components.

During the whole construction period, there were; nineteen concrete mixing plants (figure 11); three steel box girder production factories; three pile-cap and pier production factories (figure 12); one tunnel element production factory, and several small component factories, which produced the necessary sub-components (such as dolos or cover slabs) for HZMB.

The extensive use of industrial type production under factory conditions in HZMB had many advantages. These industrial type factories centralized all the factors and processes for production of the structural components and allowed standardized management systems to be implemented. Under the centralised control of the factory type production line, the workforce, materials and working time were all greatly reduced, and the working environment was much improved. These arrangements also promoted mechanized and automatic production. Efficiency, quality and safety were promoted as well. It is believed that all these represented modern engineering methods and trends.

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Figure 11. Concrete batching plant

Figure 12. Layout of production factory of pile cap and pier units

3.4 Assembly

As mentioned above, the large size components and factory production were designed to implement offshore assembly, so that the blocks of components could be built up. However, the offshore assembly also needed big and suitable equipment. Fortunately, by learning from other countries and projects, the HZMB contractors were able to develop a lot of new equipment.

During the construction period for the immersed tunnel, the largest gravel bed placing and levelling barge was made by the Chinese contractor and this was the core equipment for placing gravel on the sea bed in deep water to form the foundation for the immersed tunnel elements. The immersed tunnel contractor also developed a set of automatic operation systems for immersion and monitoring the tunnel immersion process.

Actually, many other large machines and equipment were developed for use in the construction of HZMB to realize the offshore assembly concept, such as for installing sand compaction piles to greater depths, a 4000t gantry crane for load out of steel box girder elements, 4000t floating cranes for offshore installation (figure 13, figure 14), and so on.

In China, if a company cannot invent or make the necessary equipment, they will search for cooperation with foreign companies or import the equipment directly. For instance, in order to realize automation of the production lines for the steel box girders, CNC systems with cutting and welding robots were introduced and locally developed. For the bridge deck paving work, blasting machines and asphalt mixing plants were purchased from Europe directly.

Some equipment was developed by the contractors to meet the requirements of the local environment. Examples were the automatic spraying line for the MMA waterproofing in the steel deck paving work, and the aggregate production plant for crushing, screening and packing the coarse and fine aggregates for the deck paving mastic asphalt.

The development, optimization and automation of such advanced equipment was greatly promoted in this project, and this has been a critical aspect in achieving the increased efficiency and quality. These measures had a great influence on pushing forward the HZMB project and also in upgrading the construction industry in China. This progress is very significant for the development and strength of Chinese construction.

Figure 13. 4000t Floating crane for erecting girders

Figure 14. 12000t Floating crane for installing tunnel closure element

4. Benefit

The concept of Large Size, Factory Production, Standardization and Assembly (LFSA) successfully changed offshore work into onshore work and realized the benefits of industrial production in the bridge construction industry. In the HZMB project, the large structural components have been prefabricated in factories, transported and erected by large capacity, automated cranes. All of the 23km long bridges have been built from modules and standard-

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ized components. 190 no. pile-caps and piers were prefabricated and embedded in the seabed. 420,000 tons of steel box girders were produced on automatic production lines, and then erected in span-long sections.

It has been calculated that the implementation of LFSA has saved a lot of work time. For instance, for the bridge portions, when using the method of casting on site, one pile-cap and pier would need 165 days. Now, HZMB required just 53 days to finish the whole precasting and installation. When it comes to the case of the steel deck box girders, HZMB needed just 57 days to finish all the production for a 130m long girder and 1 day to install it.

The two artificial offshore islands needed just 210 days to finish the core of each island using large diameter steel cylinders for the enclosurers, which is 2 years faster than the traditional way of dredging and fill reclamation. The closure joint for the immersed tunnel needed just 1 day to install using a prefabrication and assembly method and a 12000 tons crane.

It can be seen that the concept of LFSA has greatly reduced the work time, improved the work efficiency and ensured quality and safety as well.

5. Conclusion

The HZMB Project is the first to adopt the concept of LFSA in China. During the construction process, various enclosed factories were set up to prefabricate immersed tunnel and bridge elements.

The extensive investment required for temporary installations and custom tailored equipment were justified by the extraordinary size of the project and the high quality it produced to the full satisfaction of the owner and governments.

After a hesitating start-up, the concept of LFSA was eventually shown to be viable. The diligence and perseverance of the engineering crews and staff made it possible to catch up lost time by constantly improving production rates and finally, to complete the whole project in 8 years, as expected.

6. Expectation

The core idea of LFSA is prefabrication and assembly. The essence is based on the accumulative achievements of China's 30 years of reform and development, which combines advanced research and manufacturing competence and then transfers this into the construction engineering industry.

Nowadays it is obvious that the prefabrication and assembly method is a future trend for the buildings and bridges. With the accomplishment of the HZMB, the technology and equipment for assembly of bridges have been improved and promoted. HZMB has set a successful example. The experience, methods and research results are useful for future design and construction. Of course, the prefabrication and assembly of big bridges is just at the initial stages, and the experience, concepts and technology need to be promoted widely and greatly. Design, equipment, production line, supply train and so on, all need to be considered in more detail in the future.

Overall, prefabrication and assembly is an irresistible trend in construction engineering. The opportunities and challenges are both great. The successful will always be those who are aware of and prepare for this.

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