Design and construction of Sutong Bridge deep-water main-pylon foundations

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Abstract: This paper, from three aspects including construction conditions, foundation design and construction, introduces some considerations in the designing of main-pylon foundations and some practical measures to deal with certain unfavorable construction conditions, such as deep water, tidal effect, soft stratum and heavy traffic, during the construction of main-pylon foundations.
Key words: Sutong Bridge; group-pile foundation; design; construction platform; steel cofferdam; scour protection

1 Introduction

Foundation is crucial to a successful super-span bridge. Sutong Bridge is the first cable-stayed bridge, with a main span of over 1 000 m, in the Yangtze River estuary of China. It is also an outstanding example of super-span bridges in China. Due to complicated construction conditions, high technological requirements and huge construction scale, design and construction of Sutong Bridge main-pylon foundation are the top challenge. This paper gives a comprehensive description of Sutong Bridge extra-large, deep-water foundations from the following aspects: structural choice of foundation design; establishment of bored piles construction platform; construction of extra-long, large-diameter bored piles; lowering of extra-large steel cofferdam; and scour protection.

2 Construction conditions

Sutong Bridge is located in Jiangsu Province of China. It crosses the Yangtze River approximately 108 km upstream from Shanghai. Construction of Sutong Bridge has encountered many adverse conditions, including poor meteorological conditions, complicated hydrologic conditions, deeply-buried bedrock and heavy traffic.

In terms of hydrologic conditions, the bridge location is mainly subject to flood and runoff volumes, with a flood season from May to October and a low water period from November to April of the following year. Flood peak normally happens from June to August. The width of Yangtze River at bridge site is approximately 6 km. The river features deep water and high water flow velocity, which is called medium tidal effect reach. This semi-diurnal tide has an average cycle of about 13 h, i. e. two high tides and two low tides per day. Therefore water levels at different times during a day differ greatly. High tide is mostly attributed to storm tide. Tidal height can exceed 7 m when astronomical tide encounters typhoon. Water around the main pier has a depth of about 30 m, and has a perennial flow velocity of over 2.0 m/s, a vertical line average flow velocity of 3.68 m/s and a max water flow velocity over 4 m/s. Tidal difference ranges from 2 m to 4 m, with a wave height of 1 m to 3 m.

In terms of geological conditions, the earth layer at the bridge location has a thickness of more than 270 m. The soil mainly consists of clay, silty clay and silty sands. Soil stratum with good bearing capacity lies in the depth of 65 m to 76 m. Riverbed, mostly consisting of clay and silty sands, is very susceptible to scour.

In terms of navigation, the bridge site has complicated navigational conditions with heavy traffic, featured by different kinds of navigational ships. Every day, more than 3 000 vessels pass by on average, and over 6 000 during peak time, among which 81 % is common cargo ships, 18 % is seacrafts. More than 400 are oil tankers, liquefied gas carriers, chemical carriers, dangerous cargo ships and large size or medium size vessel ships. Navigational peak time normally happens 1 h before or after turn of the tide[1, 2].

In terms of meteorological conditions, the bridge area is in the north wettish subtropical monsoon climate region featuring frequent typhoon, hot and rainy days in summer while in winter, it is cold and rarely rains

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due to monsoon. In general, the bridge area is characterized by abundant rain with a highest and lowest temperature of +42 and −13 ℃ respectively. There are 179 days in a year with wind speed no less than strong breeze (named as Class VI), over 120 rainy days and 31 foggy days on average in a year. Moreover it is threatened by some adverse weather conditions, such as rainstorm and tornado etc.

3 Structural alternatives of deep-water foundations

Common deep-water foundation, including caisson foundation and deep-water pile groups foundation.

Caisson foundation has the advantage of good integrity, high rigidity and good bearing capacity to transfer vertical and horizontal loads and is considered to be the first choice for extra-large bridge foundations. In case of caisson foundation, Sutong Bridge main-pylon foundation will have a dimension of 78 m × 40 m and buried depth of −81.7 m. As a result, the maximum scour depth during construction and with 300 years return period of hydrologic conditions will reach 32.7 m and 40.4 m respectively, which might further result in large deviation during the lowering of caisson and reduced bearing capacity during operational stage. Moreover, over 300 m long large anchor block, which is deemed necessary during construction of caisson, will occupy large offshore area and consequently have significant impact on navigation during construction. Further more, positioning accuracy of caisson can be hardly controlled with relatively bigger risk due to high current velocity.

If steel cofferdam is adopted as Sutong Bridge main pylon foundation, the steel cofferdam will have a dimension of 104.5 m × 48 m and local scour might exceed 38 m. Steel cofferdam must be lowered into more depth and accordingly, both construction difficulty and cost will be increased. Moreover, later scour will have a result that loads of tremie concrete for the steel cofferdam (6 m thick) will be fully applied to main pylon if the cofferdam can not be lowered into designated place as specified in design. Further more, a giant positioning system must be provided during lowering of steel cofferdam, which will not only increase construction cost but also have negative impact on ship navigation. Another disadvantage of steel cofferdam is that force transfer mechanism of steel cofferdam under impact of reference ship collision is not very clear.

Group pile and thick pile cap are also common structures adopted to be deep-water foundation structures. Designing idea of this alternative is to ensure foundation safety against ship collision by increasing the number of piles instead of steel cofferdam and further improve group-pile foundation ship-collision performance by guaranteeing sufficient thickness of pile cap for the purpose of ensuring rigidity of pile cap, even stress distribution of piles and enhance integrity of foundation. Although this alternative involves with more piles, positioning system via positioning barge, guide ship and pulling cables etc. is avoided. And moreover, construction can be easily controlled with smaller risks due to strong penetration capacity of pile foundation.

Taking all factors into account, including construction conditions at Sutong Bridge site, project cost, experience and technical competency of design and construction teams in China, the alternative of using group piles and thick pile cap as foundation structure was finally adopted.

4 Design of deep-water group pile foundation

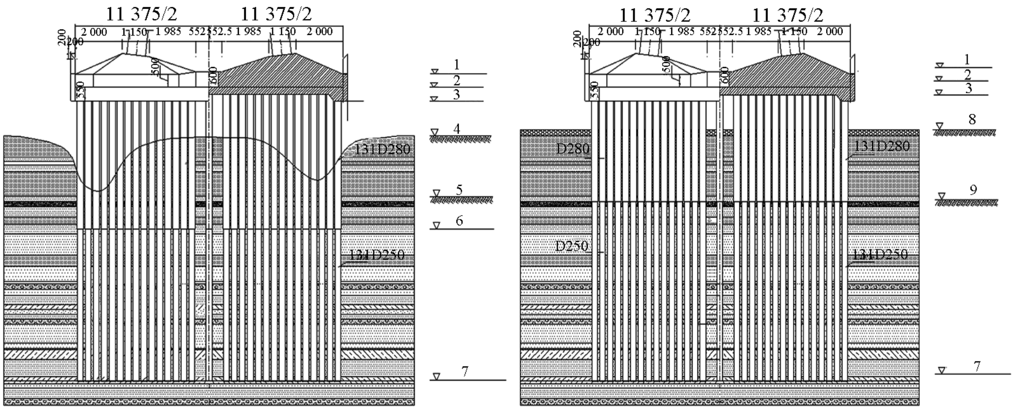
The main-pylon foundations are both supported by 131 bored piles with a diameter of 2.85 m/2.5 m (The external diameter of the steel casing is 2.85 m and the diameter of concrete bored piles is 2.5 m). The piles are designed as friction type piles with length of 117 m and are distributed by a spacing of 6.75 m. To reduce dead load of foundation, the pile cap is shaped as a dumbbell. The dimension of the half symmetrical pile cap is 51.35 m × 48.1 m. The thickness is varied from 5 m at the edge to the maximum of 13.324 m. The two caps under the two pylon legs are connected by a cross beam with a dimension of 11.05 m × 28.1 m and 6 m thick. The steel casing is designed to participate in force transfer. And the accuracy of steel casing shall be the same as that of bored piles with verticality smaller than 1/200 and deviation smaller than 10 cm.

In order to ensure sufficient transverse bearing capacity of the foundation, it is necessary to consider steel casing as permanent part of foundation. The key to foundation design is to determine embedded depth of steel casing. The following two factors need to be taken into account.

1) The embedded depth of steel casing into soil. The maximum local scour occurred to foundation with 20 years return period of hydrologic conditions can reach 21.5 m and the maximum local scour occurred to foundation with 300 years return period can reach 27.1 m. Moreover, the maximum scour might occur during one time flooding. Therefore, sufficient embedded depth of steel casing must be assured to ensure sufficient bearing capacity of the foundation.

2) The difficulty of steel casing placing. It is very hard for steel casing to penetrate soil stratum with elevation from −52.0 m to −54.0 m where lies a thick layer (approximately 2.0 ~ 4.0 m thick) of hard sand and gravel.

In order to solve this problem, two alternatives were proposed (Fig. 1):



Unit: cm
(a) Sketch of alternative 1

Unit: cm
(b) Sketch of alternative 2

1— -1.800 m (remove level of the stell cofferdam); 2— -7.000 m (bottom surface of the pile cap); 3— -12.500 m (bottom surface of the subsealing); 4— -26.423 m (ground line); 5— -52.190 m (erosion line); 6— -62.20 m (steel casing); 7— -124.000 m (bottom level of pile); 8— -26.423 m (erosion protective layer); 9— -52.190 m (bottom level of steel casing)

Fig. 1 Design alternatives for group pile foundation

The basic idea of the first alternative is to consider riverbed scour as acceptable and ensure sufficient embedded depth of steel casing by driving it to the elevation of −62.0 m. This method has the advantage of avoiding scour protection under deep-water and high current velocity conditions, but it has also the disadvantage of increasing placing difficulty of steel casing.

The basic idea of the second alternative is to implement scour protection to avoid excessive riverbed scour. This method has the advantage that it is satisfactory to drive steel casing at the elevation of −52.0 m thus, accordingly, placing difficulty of steel casing can be avoided. But it has the disadvantage of implementing permanent scour protection, which is deemed to be a must.

Test results show that if the first alternative was adopted, steel casing might crimp significantly and difficult to be fixed. Moreover, a supplementary protection is still necessary, which increases maintenance difficulty during operational stage. As a result, the second alternative was adopted.

Ship impact analysis shows that foundation itself as indicated in the second alternative has better resistance capacity against ship collision. And the major risk of ship impact lies in local damage of pile cap. On the basis of test results, a ship anti-collision scheme with combination of active and passive protection measures was adopted. Active protection measures against ship collision include establishment of Vessel Traffic Services (VTS) a system on bridge site, monitoring and control of ship navigation to avoid deviation from navigational channel (this deviation is deemed to jeopardize safety of bridge foundations), and implementation of vessel traffic emergency system to take emergent measures to control ships out of control and avoid direct collision with bridge piers. Passive protection measures against ship collision means to use steel cofferdam to further improve foundation ' s resistance against ship collision.

5 Construction of deep-water group pile foundation

5.1 Establishment of deep-water bored pile construction platform

Common method of platform construction is to use small diameter steel pipe piles as support piles to establish construction platform. In spite of small rigidity of platform and low safety margin and accuracy of this method, efforts was made to verify its feasibility by carrying out test pile works on Sutong Bridge site. Pile test was carried out at very deep place of main navigational channel with water depth of 35 m and current velocity of 2.5 m/s. The platform comprised 12 steel pipe piles with a diameter of 1.4 m. Test results show that small diameter supporting piles were seriously shaking and finally breaking due to tidal effect. Therefore, traditional method can not be used for this deep-water situation and instead, large diameter steel casings were adopted in Sutong Bridge to establish construction platform and increase single pile bearing capacity and platform rigidity.

The river at north pylon features deep water and high current velocity. And construction platform is preferably established from upstream to downstream. The construction platform has a dimension of 154 m × 57 m, with an initial platform, an auxiliary platform and a boring platform sitting respectively from upstream to downstream. The initial platform is supported by 12 steel pipe piles, while the auxiliary platform is supported by 10, with a same diameter of 2.54 m. Boring platform is supported by 131 steel casings with a diameter of 2.85 m. Construction of these platforms are described as follows (Fig. 2). Firstly, carry out riverbed pre-protection to avoid reduced embedded depth of steel pipe piles and steel casings due to riverbed scour as introduced by placing of steel pipe piles and steel casings. Secondly, use (2.54 m steel pipe piles to set up an initial platform upstream of pile cap to increase single pile bearing capacity, improve rigidity of auxiliary platform and enhance positioning accuracy of steel casings. Thirdly, install specially made cantilever guide framework on this initial platform, helping to guide positioning of steel casing and ensure accuracy of steel casing placing. Fourthly, place steel casing by using two interlocked vibration hammers. And finally, integrate already placed steel casings as a whole, move guide framework and place remaining steel casings from upstream to downstream so as to form a new construction platform[3].

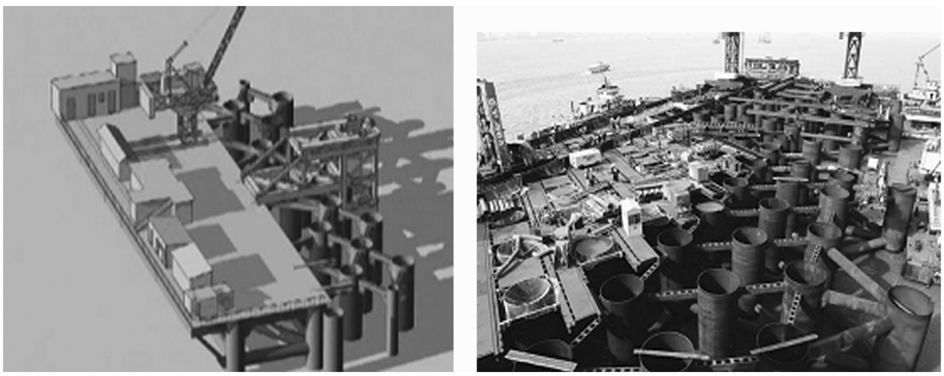


Fig. 2 Establishment of north and south pylon foundations construction platform

Water depth at south pylon is relatively low and steel pipe piles are relatively stable, therefore, (2.85 m steel casings were used to set up boring platform and small diameter steel pipe piles were used to set up working platform (upstream platform and downstream platform). The boring platform has a dimension of 168.15 m × 56.90 m and construction sequence is as follows: Take advantage of piling barge to drive 5 rows of total 9 rows steel casings at interval along water flow direction and establish an initial platform with sufficient rigidity and then use specially made guiding framework and piling hammer on initial platform to drive remaining steel casing and establish bored pile construction platform finally. After establishment of initial platform, use 13 and 25 φ1.42 m steel pipe piles respectively to set up upstream platform and downstream platform[4].

5.2 Construction of extra-long large diameter bored piles

Soil at Sutong Bridge main pylons mainly consists of sand and silty clay. Therefore hole collapse might happen during bored pile construction, which will result in reduced quality of bored pile construction, decreased bearing capacity and excessive settlement. To solve these problems, pile tip grouting was used and PHP slurry system was developed in Sutong Bridge.

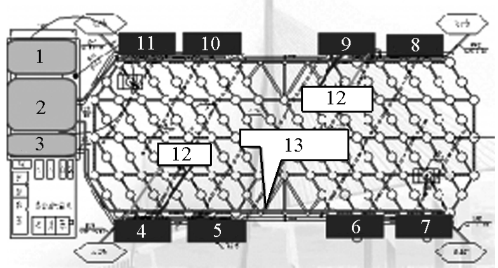
5.2.1 Pile tip grouting of extra-long large diameter bored piles

In order to reduce settlement and increase integrity of foundations, pile tip grouting was carried out for bored piles outside Sutong Bridge main-pylon group-pile foundations. The bottom of each grouting pipe for four loops, at the tip of the shaft, has a U-shape. Grout was discharged through eight holes (φ8 mm in diameter) in the underside of each U-shaped pipe, which was encased by a bicycle tire to act as a tight fitting rubber sleeve, creating a one-way valve. Grouting operation is primarily controlled by grouting quantity, with grouting pressure as a secondary control parameter. Grouting quantity of each bored pile is 8 t. And grouting is carried out in three cycles, with 40 %, 40 % and 20 % in each cycle. On completion of the first cycle, the second cycle of grouting begins in 2.5 ~ 3 h. And on completion of the second cycle, the third cycle begins in 3.5 ~ 6 h. Use clean water to flush pipes after each cycle of grouting. The first and the second cycle of grouting shall be controlled mainly by grouting quantity while the third cycle grouting shall be controlled mainly by grouting pressure. Pile tip grouting test results showed that pile tip grouting test can significantly improve bearing capacity, side friction and ultimate friction of the foundation. In general, 40 % increase of pile bearing capacity can be achieved.

5.2.2 Centralized PHP slurry system

Taking advantage of good thixotropy, high viscosity and thin mud cake of PHP slurry, purification, circulation, flocculation and dilution process of Centralized PHP slurry system will be optimized by rational arrangement of devices to recycle slurry and dispose residue to a designated place. Therefore, a slurry system with high quality and efficiency of slurry-making process, cost-saving and environmentally friendly features can be achieved finally.

As south pylon is quite close to shore and construction platform has a relatively sufficient work space, a method featuring centralized slurry-making and scattered purifying was adopted. With this method, slurry was purified by a purification system consisting of rotary screen, slurry purifier, slurry tank, sediment discharging chute and sediment transportation barge placed on both sides of boring platform (Fig. 3). Slurry coming out of drilling machine shall first go through rotary screen and slurry purifier, by which particles with grain size more than 0.074 mm will be removed. And afterwards, purified slurry will deposit in slurry tank and finally re-circulate into bored hole for drilling operation. Residue will be discharged to a barge and transported to a designated place for further disposal. By using this centralized PHP slurry system, recycling ratio of slurry can reach approximately 50 %.



1—Pulp making pool; 2—Pulp storage pool;
3—Settling tank; 4—Purifier 5; 5—Purifier 6;
6—Purifier 7; 7—Purifier 8; 8—Purifier 4;
9—Purifier 3; 10—Purifier 2; 11—Purifier 1;
12—Drilling rig; 13—The pipeline of central pulp

Fig. 3 Sketch of centralized PHP slurry system for north pylon

As work space on construction platform for north pylon is relatively small, a method featuring scattered slurry-making, purifying and circulating was adopted. With this method, slurry will be circulated with already placed steel casing as slurry storage tank. And this process, compared with centralized slurry-making process, has lower efficiency.

5.3 Lowering of steel cofferdam

Steel cofferdam is an integral part of permanent protection structure against ship collision. Meanwhile, it is a water-blocking structure to ensure a dry environment for construction of pile cap. The bottom plate of **steel cofferdam will be used as a reference elevation to control tremie concrete. Inner wall of side plate of the steel cofferdam will be used as side formwork during tremie concrete casting. Pile cap casting and top of steel cofferdam will be used as work surface for concrete casting. Therefore, steel cofferdam must be lowered with high accuracy. In reality, it is very difficult to lower steel cofferdam with high accuracy due to its large size, complicated construction conditions and long lowering distance of steel cofferdam.**

The cofferdam for south pylon, which was integrally constructed, had a dimension of 117.35 m × 51.7 m × 16.9 m and a weight of approximately 5 800 t. 12 lifting points, as well as 40 jacks, were used to lower the cofferdam (Fig. 4). These 12 lifting points and 40 jacks were centrally controlled by a computer by the principle of synchronous displacement and even load. In case of over 1 cm height deviation, lowering would be automatically stopped for further adjustment. In order to control sway of the cofferdam, a limiting and guiding device was installed on both exterior and interior sides of the cofferdam. Vertical positioning of the cofferdam was realized via 32 vertically-positioned reverse brackets installed on neighboring steel casings. On completion of vertical positioning, plan position of the cofferdam was adjusted and fixed tightly during low tide.

The steel cofferdam (north pylon), when initially constructed, had a dimension of 118 m × 52.3 m × 18.5 m and was lowered into water in three sections. The first section of steel cofferdam is 6.6 m high and weighs 2 615 t. Master and slave control hydraulic system consisting of 16 jacks was used to lower the steel cofferdam. Two mast cranes and two floating cranes were used to assembly and to extend cofferdam sections symmetrically. On completion of assembly work, water was injected into perimeter wall to lower the cofferdam. During lowering operation, plan position of the steel cofferdam was adjusted via a rubber fender placed

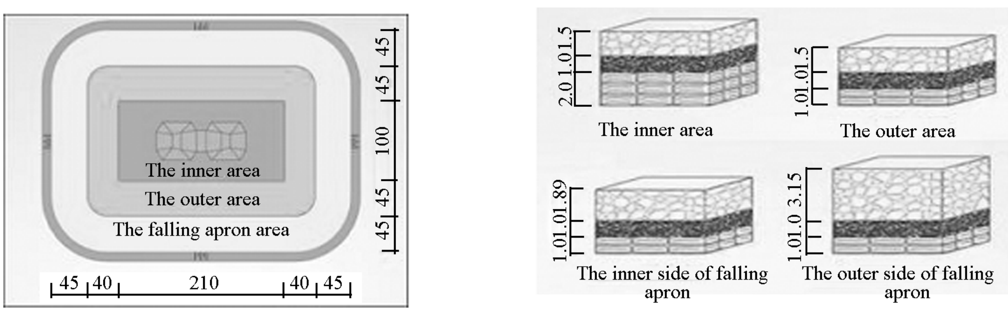
Fig. 4 Sketch of lowering of south pylon

between the inner wall of steel cofferdam and drilled shaft casings, while its verticality was adjusted via winch or chain block. Moreover, the position of steel cofferdam was slightly adjusted by injecting water into double wall[5, 6].

5.4 Scour protection

Sutong Bridge site features deep water and high current. And riverbed is highly susceptible to scour. model tests show that 20 ~ 30 m scour may occur at north and south pylon foundations upon completion of this bridge construction. In order to reduce maintenance cost upon operation and to ensure safety during foundation construction, a new concept combining both riverbed pre-protection and riverbed permanent protection was adopted for Sutong Bridge.

The concept of riverbed protection to resist scour was adopted to carry out permanent riverbed scour protection. In terms of position and function, protection area was divided into three areas-the inner area, the outer area and the falling apron area (Fig. 5). The inner area covered an area of 100 m × 210 m and the outer area extended 40 ~ 45 m out from the inner area. Slope gradient for the falling apron area was designed to be 1∶3 and the width of the falling apron area was 1.5 times of the maximum expected scour depth. Protection structure in the falling apron area consisted of filtering layer and armoring layer. Filtering layer consisted of sandbags and graded stones while armoring layer consisted of armor stones.



Unit: m

Fig. 5 Structural diagram of foundation scour protection

Pre-protection in the inner area must be carried out before placing of steel casing and permanent protection must be carried out simultaneously with pile construction. Due to large area of permanent scour protection, construction would be carried out in miscellaneous grids. The dimension of a grid for north and south pylon foundations is 25 m × 20 m and 15 m × 10 m respectively. Both located dumping and random dumping were adopted for dumping operation. Located dumping means to use GPS to position positioning barge, berth split barge at sides of positioning barge to fill sandbags or to lift graded stones and armor stones, and to dump them directly. Random dumping means to use self-navigating barge to fill sandbags or lift graded stone and armor stones outside dumping area, and to travel to a designated place for dumping operation. For construction of graded stone and armor stones around construction platform in the inner area, a travelling system with chain hoist was installed under a supporting beam of the construction platform to lift and dump stones as existing platform might hinder dumping operation by traditional method.

Scour protection works started in July 2003 and completed in May 2004. 300 000 m^3 sandbags, 260 000 m^3 graded stones and 530 000 m^3 armor stones were dumped into the river with a total protection area of 210 000 m^2. Monitoring record in recent three years indicates that the structure at protection area is stable. Scour is within tolerance specified in scour experiment, although local scour occurred in falling apron. In general, the riverbed is stable, which is in reasonable agreement with the expectation[7].

6 Conclusions

Sutong Bridge has set a world record of deep-water group-pile main-pylon foundation. Many challenges and difficulties were overcome during the process of foundation design and construction. And accordingly, lots of innovative results were achieved with the following conclusions:

1) The foundation Scheme with combination of group piles and thick pile cap is a good solution for foundations of extra-large bridges. This solution is less risky and more economical. In order to ensure foundation bearing capacity, steel casing, steel cofferdam and permanent scour protection measures can be considered for implementation[8].

2) Utilization of pile steel casing to establish construction platform can not only effectively solve the problem of stability of construction platform in deep-water and tidal reach but also improve accuracy and save cost[9, 10].

3) Centralized PHP slurry system can not only help to maintain stability of deep bored hole but also improve construction efficiency and be favorable for environmental protection.

4) Successful integral and synchronized lowering of large steel cofferdam shows that multiple jacking synchronized control technology can be used to lower large steel structure in water.

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