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Key Techniques in the Integral Salvage of Ancient Sunken Vessel *Nanhai No 1*

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SYNOPSIS

Nanhai No 1, a Nansong-dynasty vessel loaded with porcelain which sank eight centuries ago in the waters near Guang Dong's Yangjiang city, is one of the most important maritime archaeological discoveries in Chinese history. In order to protect and excavate the vessel, including its cultural relics, expediently, an Integral Salvage Plan was presented for the first time. The paper firstly introduces this Integral Salvage Plan, and then a series of key techniques will be discussed, such as the underwater positioning of the ancient sunken vessel, the sinking of a steel open caisson, the threading of bottom-supporting steel beams, the hoisting of the steel protective container, etc.

1. INTRODUCTION

Nanhai No 1, a Nansong-Dynasty ancient sunken vessel was first discovered in August 1987. At that time, Guangzhou Salvage and a British Salvage company were jointly conducting a search for shipwrecks and unexpectedly found the Nansong-Dynasty vessel in the waters near Shang Chuan Island in Guang Dong Province. This ancient sunken vessel was later named ***Nanhai No 1***.

After conducting many on-site surveys, some basic information about the vessel was discovered:

- Approximate dimensions: 30.4m × 9.8m × 4.2m;
- The hull material was wood;
- Most of the cargo was porcelain;
- The exact position was N20° 30.618'/E112° 22.176'.

The vessel sank about 800 years ago with no heel and no trim, both sides of the shipwreck burying in mud to a depth of about 1m. Mud accumulation at the bow and stern left just 1-2m of the vessel exposed above its surface. The water depth was about 22-24m, and the marine geology of the seabed is mud on the surface and silt soil at the bottom. Underwater visibility is very poor – nearly zero – except from March to April every year, when it is a little better; on-site flow direction was southwest, and the maximum flow rate was about 0.7m/s.

Currently, the world's approach to underwater archaeology prevalently utilises the following pattern: firstly, divers collect relics from the sunken vessel piece by piece, then dismantle the vessel prior to the wreck removal operation, and finally reassemble the whole vessel ashore. This method has some shortfalls. First of all, the ancient hull would be severely damaged, which often causes irreversible loss. Secondly, because the entire excavation process is completed by divers working underwater, it depends on divers with considerable experience, and it is very time consuming. As a result, the cost of the excavation will increase. Although ***Nanhai No 1*** has been under water for more than 800 years, the hull is still well preserved. It is fully loaded with precious relics such as porcelain, gold, silverware and coins, all containing a wealth of historical and cultural information. Both for China and the world in terms of underwater archaeology, the protection, excavation and research of the vessel have milestone significance. In order to better preserve ***Nanhai No 1*** and avoid secondary damage from the salvage process, underwater archaeologists wished to move the whole vessel to a safe place, and then conduct meticulous excavation and research.

For this reason, an Integral Salvage Plan suitable for ancient sunken vessels was proposed for the first time in 2003[1]. The basic concept is: firstly conduct precise positioning and install positioning piles. Secondly, lift down a bottomless box-type steel open caisson alongside the positioning piles and place it around the hull, and then sink it to a pre-designed location, so that it covers the entire vessel. Thirdly, excavate the mud around the caisson and thread the bottom-supporting steel beams through special holes at the bottom of the caisson. The caisson is intended to support the ancient sunken vessel, providing a steel protective container to wrap around its entire body. Finally, use a crane barge to hoist the protective container from the seabed with the sunken vessel inside it as well as the protective mud surrounding it, and then place them on to a submersible barge. The barge will emerge from under the water, and then, carrying the sunken vessel, be towed to a designated place for further archaeological excavations.

In order to verify the feasibility of the Integral Salvage Plan, Guangdong Provincial Institute of Cultural Relics and Archaeology specially entrusted the Naval Architecture and Ocean Engineering Institute of South China University of Technology to carry out an Integral Salvage model test for ***Nanhai No 1*** in 2005[2]. This model test was mainly aimed at studying the technical difficulties which might arise during the sinking process of the steel open caisson, the threading of the steel beams, the hoisting of the protective container etc, and also to work out solutions to them. The test results indicated that the Integral Salvage Plan was completely feasible by using a steel open caisson and bottom-supporting steel beams, whose structure had been properly designed, as well as by adopting appropriate construction techniques and equipment.

2. UNDERWATER POSITIONING OF THE ANCIENT SUNKEN VESSEL

Accurate positioning would have a direct impact on whether the steel caisson could accurately cover the ancient sunken vessel and determine the success or failure of the Integral Salvage Project. The Underwater Positioning Plan was to firstly find the centre position of the bow and stern of the vessel, and place a tube, 36m long, 8cm wide and 8cm deep, on the centre line of the vessel to use for positioning.

Secondly, the idea was to place a framework of the same size as the periphery of the caisson to cover the perimeter of the ancient vessel. The framework's location would therefore be the same as that where the caisson was to be sunk, and this positioning would thus ensure that the sunken vessel would be fully covered by the caisson. Both sides of the framework were 7.20m from the central positioning tube and both ends were 2.7m respectively from bow and stern of the sunken vessel. For convenience of sinking and for accurate location of the caisson, four sets of positioning piles were installed, which stuck out above the surface of the water on the outer sides of the positioning framework. During its sinking process the steel open caisson could be placed closely alongside the positioning piles to ensure a quick and precise operation; this procedure would also guarantee its stability as it was lowered into and through the water.

According to the Integral Salvage Plan, we carried out the installation of positioning piles on 6th May, 2007. However, because of bad weather and severe sea conditions, the piling vessel could not carry out the work. In order not to affect the progress of the venture, the project team decided to adopt the alternative plan of directly sinking the caisson without installing positioning piles. A 900 tonne crane barge ***Nan Tian Long*** was used to replace the 500 tonne crane barge, ***Nan Yang***, to lift and sink the steel caisson. Furthermore, high-precision Ultra-short Baseline Underwater Positioning Equipment was adopted to carry out the positioning[3]. At the same time, divers conducted underwater monitoring to ensure the accurate location of the caisson. This required the initial use of the Ultra-short Baseline Positioning Equipment to measure the co-ordinates of the four corners of the positioning framework. While sinking the steel open caisson it was necessary to place beacons on its four corners. We knew that the steel open caisson was located precisely when the co-ordinates displayed by the four corners of caisson were identical to those of the four corners of positioning framework.

3. LIFTING AND SINKING OF THE STEEL OPEN CAISSON

The steel open caisson is not only the most important structure of the Integral Salvage Project, but also the carrier of all follow-up processes; almost all working procedures of the salvage project were carried out around it. Whether the design of the steel open caisson is reasonable or not will directly affect the success or failure of the whole archaeological salvage project. After numerous underwater inspections and measurements, we could confirm that the main particulars of the vessel were: 30.4m × 9.8m × 4.2m. Accordingly, we decided that the net length of the steel caisson inner side should be 33m long, leaving an extra 1.3m on each end. The net width of the inner side would be 12m, leaving an extra 1.1m on each side. The outer size of the caisson would be 33.3m×14.4m.

The steel open caisson is a combination, vertically, of upper and lower parts. There are two functions of the lower part:

- To ensure that the mud inside the caisson will not drain through the bottom during excavation and to avoid mud rising on the outer side of the caisson.
- To serve to support and fasten the whole uppper part upon starting the excavation on its outer side.

The purpose of the upper part is to wrap around the ancient sunken vessel and there are reserve holes at the bottom for threading through the bottom-supporting steel beams. After the threading of these beams is completed, the upper and lower parts will be separated by hoisting up the upper part, leaving the lower part on the seabed. The height of the upper part was 7.2m while the effective height for carrying ***Nanhai No 1*** was 6.15m; the leeway in the vertical direction is 1.95m. The height of the lower part was determined based on Anti-rising Stability Analysis of mud at the bottom of the steel caisson[4]. After calculations, it was determined that the lower part was 5m high.

Due to the fact that most of the work was carried out underwater during the hoisting and sinking of the steel caisson, many traditional measuring instruments could not function. Therefore Ultra-short Baseline Equipment was mainly adopted to carry out its positioning. During the pressing-down process for the caisson, we adopted GAPS instrumentation to carry out 24-hour monitoring of its status in order to ensure that it could be sunk stably to its designed position.

Figure 1: Steel open caisson.

At 13.00 on 17th May, 2007, the connection and testing of the positioning devices were completed. All the preparation of ***Nan Tian Long*** for the lifting and sinking of the steel caisson was finished. It was time to lift it. At 14.00, the water began to flood into the caisson, and at the same time the Ultra-short Baseline System and GAPS instrument started to carry out the positioning and monitoring for it. The sinking position, sinking depth and balance of the caisson were constantly monitored. At 16.30, it was about 50cm from the mud surface of the seabed. Two divers went underwater to confirm whether its position was correct or not by examining the position of the framework. At 17.10, the correct positioning of the steel open caisson was confirmed and it entered the mud smoothly.

According to geological prospecting data obtained by the calculation[5], the maximum static pressure required for the steel caisson to sink into the right position (ie entering into the mud layer at a depth of 11.5m) was about 18,000KN. At 17.30 on 17th May, a sand carrier carrying about 400 tonnes of sand arrived at the site. It proceeded to fill the upper part with sand. In order to prevent the steel caisson from tilting during the sand-filling process, the double hooks of ***Nan Tian Long*** always maintained a force of 500KN. At 15.30 the next day, all 400 tonnes of sand had been transferred into the upper part of the caisson, which then entered the mud layer to a depth of about 4m. At 01.00 on 19th May, the upper part was filled with sand. At 03.00, ***Nan Tian Long*** released the double hooks, and the steel caisson sank into the mud layer to a depth of 5-5.5m. At this point, the static pressure on the caisson had reached about 10,000KN. At 11.30 on 24th May, ***Nan Tian Long*** lifted 500 tonnes of concrete precast blocks on to the steel caisson which then sank into the mud to a depth of 6-6.5m. At 12.00 the following day, more precast concrete blocks one of 500, one of 300 and two of 150 tonnes were placed on to the caisson. At 18:00, sand continued to fill the lower part. At 21.30 on 26th May, all compartments of the lower part were filled with sand. By this time it had sunk about 8.5m into the mud, and the static pressure on it had reached about 22,000KN.

The pressing-down process of the caisson indicates that the mud of the seabed is actually much harder than that described in the prospecting data. In order to ensure the steel caisson sank to the right position, the on-site project team decided to continue increasing static pressure on the steel caisson as long as its structure permitted it. The method is firstly to place the bottom-supporting frame across the top of the open caisson to serve as a crossbeam to withstand the static pressure applied to the caisson; secondly, concrete blocks of jetty construction are used to serve as static pressure blocks. Each block weighs about 300 tonnes, whilst the underwater weight is about 180 tonnes. Thirdly, sand was poured into the concrete blocks to increase static pressure. Each block can carry about 120 tonnes of sand underwater. Concrete anchors can also be used as static pressure blocks – each weighing about 150 tonnes (underwater weight about 90 tonnes).

From 30th May to 14th June, ***Nan Tian Long*** installed a total of six concrete blocks and four concrete anchor blocks on to the steel open caisson and each block was filled with sand. The steel caisson sank into the mud to about 10.5m which was about 1m less than the original design. At that time the total static pressure applied on the caisson had reached 44,000KN.

If the bottom-supporting steel beams had been threaded through the reserve hole when the steel caisson was about 10.5m into the mud, the steel beam might have punctured the bottom of the sunken vessel. However, at that time, the structural intensity of the steel caisson could no longer withstand further static pressure. In the circumstances, the project team decided to firstly excavate the mud surrounding the steel caisson. There were various advantages of doing this:

- To eliminate friction between the outer side of the steel caisson and the mud, and to reduce friction drag during the sinking of the caisson, so it could go further.
- Because it is necessary to excavate mud surrounding the open caisson when threading through the bottom-supporting steel beams, and since the excavation of the mud was carried out in advance, it was no longer necessary to worry that the steel open caisson would continue to sink during the excavation of the mud after it had sunk to the desired depth.

In order to ensure that the steel caisson could sink stably, mud had to be excavated while maintaining 37,000KN static pressure on it. For the convenience of threading the steel beams and to maintain slope stability, the digging width on both sides of the caisson was 25m, while the digging depth was 8m. The digging width on both ends was 10m while the digging depth was 6m. After 10 days – by 5th July – a large dredger had excavated down into the mud to a depth of 8m, that is to say the excavation depth was sufficient to satisfy the needs of the threading steel beams. However, after underwater inspection by divers and testing of equipment, it was found that the caisson's height remained the same, which did not reach the designed depth for threading the steel beams.

Therefore other measurements had to be taken to sink the steel open caisson to the design depth.

After strict analysis, the project team thought that the main reason that the caisson could not continue to sink was that the bottom of it had encountered a sandy layer, and it was bearing too large a loading force at both ends. Therefore the project team decided to use an air-lift pumping method to pump out the sandy mud on the cutting-edge of the caisson to reduce the load to be carried by the mud at the bottom of it. We finally managed to sink the open caisson to the correct depth.

On 3rd July, Guangzhou Salvage dispatched ***Nan Yang*** (a 500 tonne crane barge) to the salvage site to co-operate with ***Nan Tian Zhu*** (a 300 tonne crane barge) to pump out the mud using large-diameter air-lift pumping equipment. During the pumping process, we carried out symmetrical pumping operations and enhanced monitoring, so that the caisson could sink in a balanced and stable manner. On 12th July, after a 10-day continuous operation, the stern part of the steel caisson finally sank slowly to the desired position. It was deep into the mud at a depth of approximately 11.5m. On 24th July, the fore part of the caisson also sank to the desired position. After 76 days of hard effort, the first barrier to the overall salvage project of ***Nanhai No 1*** was overcome.

4. THREADING OF STEEL BEAMS

"Difficult" is not a term strong enough to describe the positioning of 36 steel beams, each weighing 5.3 tonnes, to the caisson with an allowance for error of less than 10cm, particularly at 31m down into the dark sea. This was a key procedure and the toughest part of the entire salvage project. Most of the operation's diving time was accounted for during this part of the process; the requirements from the divers were great, as was the difficulty level of the diving.

Each steel beam measured 15.059m × 825mm × 450mm. Through calculation[6], it was concluded that the maximum traction power required for the steel beam to cross the steel open caisson was 523KN. The threading of the steel beams required high accuracy in the axis direction. During the threading process of the 15m distance, axial deviation had to be limited to within 100mm, to ensure a successful threading operation. Threading steel beams with a jack will reduce the axial deviation. Therefore a jack was a key component of the whole threading process, and divers needed to operate inside the jack frame. So, the safety of the jack and jack frame had to be a high priority. In the case of pulling, two jacks would be used at the same time, each of which was designed with a 700KN safety pull. The steel beam was designed to be watertight to reduce underwater weight, which was not only beneficial for the divers installing it, but also for reducing the overall weight when hoisting. If threading the steel beam did not go well, it would have to be withdrawn from the caisson. A bolt installation hole was set on the bottom of the steel beam and two 50t pushing jacks were also equipped. The connection was conducted by pushing a connection box girder and threading could be assisted with a pull-in jack in case of insufficient pull. Thus the steel beam could be moved smoothly.

On 23rd August, threading of the first beam, which would go from the stern of the sunken vessel, began. Unfortunately, when it came to threading this first beam through the last hole, due to the larger up-down axial deviation, it would not go through. It was tried three times without success. After research, the project team decided to improve the steel beam. It re-arranged a spraying head on the surface of the beam and set an up-down spraying head to adjust up-down axial deviation. Then the adjusted beam went from the bow of the shipwreck. On 3rd September, this first beam finally went through the caisson successfully; the operation had taken 12 days.

Following the first beam, the threading of the second one was begun. While it was threading through the last hole, again another problem appeared, which was left-right axial deviation. The project team performed further research and discussion regarding the new issue. They finally decided to place a spraying head at the side of the beam and installed a stop on the beam. After further improvement, the problem of axial deviation was finally resolved.

During the threading procedure, the whole threading time was always limited by the installation of the jack frame. How to efficiently reduce the installation time became a common research topic for all the engineers and constructors. Engineers further improved the jack frame by designing much thinner beam thicknesses without affecting the strength, producing a design more convenient for installation. The construction team also proposed a lot of improvements on the installation tools to make installation much easier. Through joint effort, the installation time of the jack frame had been significantly reduced, and therefore increased the efficiency of threading.

After threading five steel beams successfully, the engineers on the project team summarised a set of threading procedures, which could greatly improve the efficiency of threading. Threading time had been improved from 12 days for the first beam to an average of one day per beam. On occasion it was as little as 15 hours for threading one beam.

As of 11.30 on 13th November, all 36 beams had been successfully threaded through the caisson. The second obstacle of the ***Nanhai No 1*** salvage project had been overcome.

The threading procedure began on 23rd August and was completed on 13th November, with a general construction period of 82 days. It was mainly based on a number of diving operations comprising 2,016 diving trips throughout the whole process with up to 53 divers on site at most times. These diving operations accounted for 67 per cent of the diving operations during the entire salvage exercise. The successful completion of the threading established a firm base for the successful integral salvage project, as well as providing a reference and guidance for similar projects in the future.

5. HOISTING OF STEEL PROTECTIVE CONTAINER

After the completion of the threading of all steel beams, the upper part of the caisson became a steel protective container encasing ***Nanhai No 1***. The next crucial step was to hoist the whole container steadily and safely from the seabed. This job was carried out by ***Hua Tian Long*** (4,000 tonne floating crane). Based on calculations, the gross weight of the caisson hoisted from the seabed was approximately 3,119 tonnes (taking into account the mud adhesion), and the weight would be 3,406 tonnes when the top of container was about 1.5m above water surface – not exceeding the lifting capacity of ***Hua Tian Long***. However, when the container was fully out of water, the total weight would reach 5,386 tonnes which was far beyond the lifting capacity of the floating crane.

Solving the problem of insufficient lifting capacity was one of the critical issues for the salvage project. After plenty of calculations and research carried out by technical personnel, a semi-submersible barge was selected as a carrier to float the steel container[7]. Firstly, the floating crane was used to hoist the top of the container approximately 1m above the surface of the water and place it on to ***Zhong Ren 1601,*** the 15,000DWT semi-submersible barge which was submerged in advance. After the container was confirmed ready in accordance with requirements, ***Zhong Ren 1601*** would de-ballast to float, while simultaneously the main hook of ***Hua Tian Long*** would be still maintaining a certain load until the semi-submersible emerged to the design draft. The container was then fastened on the deck of the transport barge and taken to a temporary jetty at Zhapo in Yang Jiang City for the purpose of rolling it ashore and then moving it to Crystal Palace in the Maritime Silk Road Museum.

During the hoisting operation, the contractors carried out a number of innovative technical measures to resolve a series of technical problems:

- For hoisting requirements, 16 x 300-tonne lifting points were pre-designed on top of the container; as far as possible, these kept every lifting point in balance at an even level of force, thus maintaining a horizontal floating condition. The 16 lifting points were divided into four groups, ie four sets of wire ropes were grouped together at each side by four equalizer pulleys.
- The lifting wire ropes needed to be connected by divers underwater, and there were numbers of wire ropes, totalling 16 groups of slings. It was necessary to identify the various wire ropes – otherwise it would have been very difficult for the divers to distinguish between them, and to connect them correctly underwater. For the purpose of resolving this problem, we specifically designed a rope positioning rake to separate and locate each one.
- As for structure design requirements, there was a 500mm gap between the steel beams and the bottom of the container.

From 17th December, when the 4,000-tonne floating crane ***Hua Tian Long*** arrived at site, to 22nd December when ***Zhong Ren 1601***, the semi-submersible barge, floated from the water, the whole hoisting operation had lasted for six days. The Integral Salvage Project for the sunken ship ***Nanhai No 1*** has been successfully achieved (*see Figure 2, below*).

The final step was to roll the container ashore and move it into Crystal Palace using airbags. For the airbag rolling operation it was necessary for the bottom of the container to be flat. Therefore we designed a bottom rolling tray to meet the needs of the operation. Based on the shape of the caisson structure, the rolling tray was designed as a 凸 shape, whose higher plane was in contact with steel beams and lower plane was in contact with the bottom of the container, so that the weight of the whole container could be evenly spread to the tray via the contact surface. In addition, the tray should be pre-fixed on to the deck of barge prior to the submerging of the semi-submersible barge. Furthermore, six limit piles would be set at both sides of the tray for the purpose of accurate location of the container.

Figure 2: The protective container on the semi-submersible barge.

6. ROLLING ASHORE AND MOVING INTO CRYSTAL PALACE.

In order to berth ***Zhong Ren 1601*** and roll the container ashore as well as moving it into Crystal Palace, a temporary pier was specially designed and built in the Silver Oriental sea area, 3km east of Zhapo Town in Yangjiang City, on the beach opposite the Maritime Silk Road Museum of Guangdong Province.[8]

The rolling process of the container was the last part of the whole project. The gross weight of the container and bottom tray was about 5,500 tonnes. The airbag rolling operation was finally selected after the comparison of many options[9-10]. On 24th December, ***Zhong Ren 1601*** berthed alongside the front of the temporary pier. On 27th December, the container was successfully rolled off the barge to the shore. The next day, ***Nanhai No 1***, enclosed in its protective container, was safely moved into the Crystal Palace (*see Figure 3*). In this airbag rolling operation, the weight of 5,500 tonnes created a new record in China, of rolling a single heavy object; the linear distance of the rolling operation was about 450m.

Figure 3: The protective container inside Crystal Palace.

7. CONCLUSION

The total success of the ***Nanhai No 1*** archaeological salvage reflects China's now comprehensive ability in cultural heritage conservation and marine engineering, and represents the formation of a new model for underwater heritage conservation, characterised by multi-discipline co-operation.

Throughout this salvage operation, archaeologists, scientists, technicians, and workers in various fields devoted themselves to the challenges in hand to a remarkable degree, struggling to overcome many obstacles, finally completing their mission in triumph. Breakthroughs were made in many technical sectors. Large engineering vessels, notably the floating crane barge ***Hua Tian Long***, ensured the safety and efficiency of the salvage operation, while multi-discipline co-operation, technical innovation, and advanced equipment all came together to realise an extraordinary and historic archaeological feat.

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