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Construction Practice and Innovation of "Deep Sea One" Energy Station

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Abstract: The "Deep Sea One" energy station is the first ultra-deep-water large-scale gas field that is independently explored and developed by China, and its proven reserves of natural gas exceed hundreds of billions of cubic meters. This energy station is also the first 100 000-ton deep-water semi-submersible production, storage, and offloading platform worldwide; it adopts a whole sea development mode that integrates a semi-submersible production, storage, and offloading platform, a subsea production system, and submarine pipelines. Moreover, the energy station was built based on an independent design, by optimizing its organization and management, and by strengthening technical research and innovation. This paper first reviews the construction background and challenges, introduces the optimization and breakthroughs of the development modes of deep-water gas fields, and then summarizes the major technological breakthroughs and experiences encountered during the design and construction of this energy station, including oil storage in columns of semi-submersible platforms, load lateral transfer of super-tonnage open structures via pre-inclination and return, and precise half-floating integration of super large structures. This study is hoped to provide a useful reference for efficient development of deep-water and ultra-deep-water oil and gas fields and for high-level construction of semi-submersible platforms.

Keywords: ultra-deep water; semi-submarine; energy station; oil storage in column; lateral transfer; half-floating integration

1 Introduction

Offshore oil and gas has great exploration and development potential. The deep sea has become a key area for replacing global oil and gas reserves, and it is also an innovation hotspot and frontier of exploration and development technologies [1]. In terms of the degree of exploration, the overall exploration rates of offshore oil and natural gas resources, which are still in their early stages of exploration, are 23.7% and 30.6%, respectively. Among them, the proven rates of oil resources in shallow water, deep water, and ultra-deep water are 28.1%, 13.8%, and 7.7%, respectively, and those of natural gas are 38.6%, 27.9%, and 7.6%, respectively [2]. Presently, deep-sea oil and gas have gradually become the key field and direction of oil and gas resources exploration and development in China [3]. Increasing the exploration and development of deep-sea oil and gas resources is the key to increasing reserves and production in the future and is of great significance to ensuring China's energy security.

From the end of the 20th century to the beginning of the 21st century, China has cooperated twice with other countries to explore the deep-water area of the Yingqiong basin in the South China Sea [4]; however, these cooperations were unsuccessful. Therefore, China National Offshore Oil Corporation (CNOOC) deeply realized that extensive deep-sea exploration is not in line with China's reality and insist on independent innovation, fine

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exploration, and intensive research. After nearly 10 years of repeated exploration, we finally implemented the hydrocarbon bearing structure of the Lingshui 17-2 block in the South China Sea (“Deep Sea One” large-scale field). In 2014, through drilling exploration wells, CNOOC obtained data on oil and gas accumulation, petroliferous and aerogenous property, reservoir stratum, the structure of an oil and gas well, and oil and gas field productivity, and they determined the mechanism of natural gas accumulation in the deep-water area of the Yingqiong basin. CNOOC (China) finally announced the discovery of an ultra-deep-water large-scale field in the South China Sea with reserves of over 100 billion cubic meters and a maximum water depth of over 1500 m.

In the face of such deep-water gas field development, the preliminary research and design team insisted on an orientation of the innovation. On the one hand, they comprehensively contrasted the development mode, technical scheme, construction practice experience, and lessons of typical deep-water gas fields used worldwide. On the other hand, they conducted a full investigation, determined domestic construction resources, and conducted a customized design, with the view of significantly reducing project investment and driving the development of the domestic industrial chain. Finally, the team creatively presented the mode of deploying a semi-submersible production, storage, and offloading platform with a column of oil storage function in deep water for gas field development. Based on the brief introduction of the large gas field and the “Deep Sea One” energy station, this paper systematically introduces the theoretical research method and design technology of the semi-submersible deep-water multi-column production, storage, and offloading platform that was established in the engineering design and that initiated the load lateral transfer technology of the world’s super-tonnage open structure via pre-inclination and return in the land construction as well as precise large deformation of the half-floating integrated technology of a 50000-ton super large structure. The establishment and successful application of these technologies have enriched the core technology system of China’s existing deep-water oil and gas field development engineering equipment and can provide a useful reference for China’s future deep-water oil and gas field development.

2 Optimization and breakthrough of deep-water gas field development mode

The distribution of gas reservoirs in “Deep Sea One” gas field is scattered and exists as follows: there are 7 well areas and 11 development wells; the stable production period is 10 years; the cumulative gas production is 5.615×10^{10} m^3, with cumulative condensate production of 3.491×10^6 m^3 and a maximum daily water output of 668 m^3/d; the length of the well location is 58 km (30.4 km in the longitudinal direction and 49.4 km in the transverse direction). The well location distribution of “Deep Sea One” gas field is shown in Fig. 1. In the design of gas field production scheme, if the dry Christmas tree platform is used, only two wells at most can be drilled, and connection to the underwater production system will become inevitable; however, if the “Deep Sea One” gas field adopts the development scheme of connecting back to the deep-water floating platform, the condensate oil will become a difficulty. If the Yacheng (YC) 13-1 gas field is selected for transport to the Hainan Nanshan terminal for treatment and then exported for sale, the condensate oil subsea pipeline will be as long as 180 km. This kind of oil subsea pipeline crossing deep and shallow water areas is extremely expensive and has poor economic benefits. Therefore, in consideration of the construction cost of the condensate oil export submarine pipeline, the technical team creatively proposed the scheme of storing the condensate oil in the floating platform and then exporting it through the shuttle tanker.

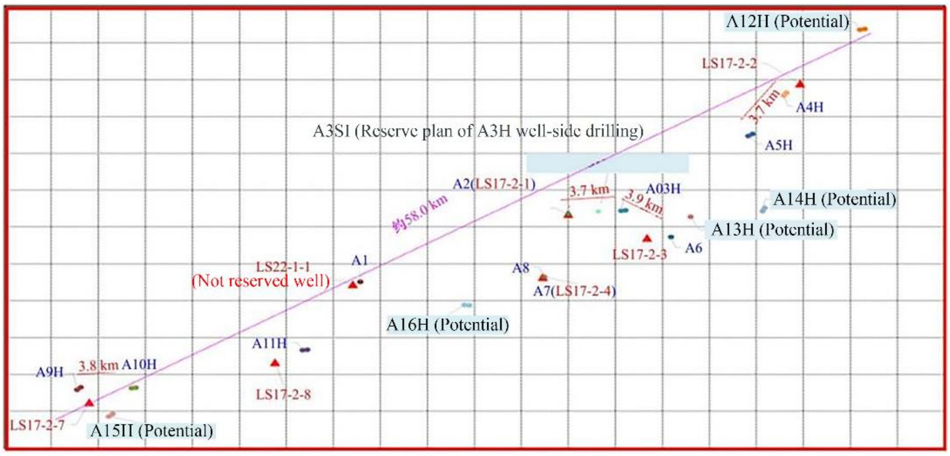

Fig. 1. Schematic diagram of well location distribution of “Deep Sea One” gas field.

2.1 Scheme comparison and selection of floating platform

Five kinds of deep-water floating platforms are commonly used internationally, including the tension leg platform (TLP), semi-submersible (SEMI) production platform, single-column deep draft platform (SPAR), conventional ship-type floating production storage and offloading (FPSO), and cylindrical FPSO. According to the engineering application experience and preliminary technical evaluation, the TLP is suitable for dry Christmas trees [5], the limit water depth of the TLP is presently 1500 m, the cost of tension leg system at this water depth is very high, and the platform is not suitable for oil storage and its investment is much higher than those of other schemes. China has rich experience in the construction and operation of conventional ship-type FPSO; however, conventional ship-type FPSO cannot adapt to the steel catenary riser of this project, a new single point turret system needs to be built, and the riser scheme needs to be changed to a flexible riser. The investment increased by a single point and the riser is high; thus, this scheme lacks technical and economic advantages.

The preliminary research team conducted economic and technical research on the remaining three different types of floating types (Fig. 2), as shown in Table 1. (1) In terms of technology, SEMI, SPAR, and cylindrical FPSO can technically meet the requirements of a large-size steel catenary riser (SCR). Among them, the SPAR's riser scheme technology is the best, and the SEMI and cylindrical FPSO must be customized for large-size SCRs. (2) In terms of construction, there is no construction and installation experience on the SPAR in China, and the cylindrical FPSO cannot be integrated as a whole topside owing to its structural form; thus, the construction cycle is long. The SEMI was used to construct the lower floating body and the topside separately and then to integrate them on the site; therefore, the land construction is the simplest and its construction period is the shortest, and SEMI construction experience on domestic shipyards is the most abundant. (3) In terms of investment, the SEMI has the smallest engineering quantity and capital investment, and better economic advantages; and it has better bargaining power than SPAR and cylindrical FPSO.

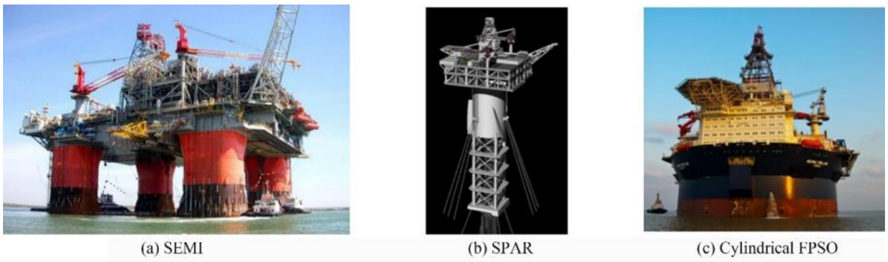
(a) SEMI (b) SPAR (c) Cylindrical FPSO

Fig. 2. Type of floating production platforms applicable to "Deep Sea One" gas field.

2.2 Innovatively solve the problem of condensate oil storage and export

Condensate oil storage and export was a key problem considered during the development of the "Deep Sea One" gas field project. Compared with the special construction of a 180-km long submarine pipeline for export, storage on the platform was the best choice. For the SEMI platform, which is currently in operation across the world, the Na Kika platform in the Gulf of Mexico has designed an oil storage function in the floating tank, which is suitable for storing dead oil with a slow change in quantity and can store up to 6400 tons of dead oil. According to the process requirements, the condensate oil tank of the "Deep Sea One" energy station is 2×10^4 m^3 and the storage capacity of condensate oil changes frequently. If it is stored in the buoyancy tank, the height of the compartment is only 6 m after deducting the 1.5 m size of the isolation tank required by the specification, and the maximum design capacity is merely 2×10^4 m^3. The main problems it faces are: (1) the layout of the inlet and outlet pipelines, the layout of the inert gas and vent pipelines, the distance between the measuring tank system and the top of the column, the condensate oil export pipeline needs to completely pass through the platform column, and the design of the turbine system faces safety risks. (2) The export of condensate oil is more difficult, the performance requirements of the export pump are higher, and the energy consumption is greater. (3) The inspection and maintenance of the isolation tank outside the condensate tank are extremely difficult, which brings inconvenience to offshore operations. (4) The ballast tank needs to be set on the column. Owing to the requirements of damage, the ballast tank needs to be arranged upward and downward, which is not conducive to the design of the unloading system and to the unloading operation. (5) Under ballast condition, the column will be loaded with 5×10^4 m^3 ballast water, which will lead to a significant increase in the center of gravity of the platform operation, and the insufficient stability of the platform will lead to a significant increase in the main scale, which will lead to a substantial increase in engineering investment. (6) Frequent loading and unloading operations of floating tanks will make the load distribution between floating tanks and columns more uneven and bring new challenges to the reliability of key structures in place.

For this reason, the technical team of the “Deep Sea One” gas field project creatively proposed the scheme of using the semi-submersible platform column for oil storage, which well solved the above problems. Considering the factors of design, construction, installation, construction period, and others, the “Deep Sea One” gas field proposed and successfully implemented the deep-water semi-submersible production storage and offloading platform (“Deep Sea One” energy station), which is a new deep-water gas field development model, and a remote underwater production gathering and transportation system for the first time worldwide. Compared with connecting back to shallow water, it greatly saves capital investment and can produce approximately 3×10^9 m^3 more natural gas.

Table 1. Comparison of three deep-water floating platforms.

Platform index	SEMI	SPAR	Cylindrical FPSO
Company who have the Design ability	Over five companies with design ability	Only Technip	Only Sevan Marine
Adaptability of water depth and SCR	Adaptation, deep draft of hull	SCR friendly	No application precedent, but technically feasible
Oil storage function	Technically achievable	Technically achievable	Technical advantages
Platform construction	The hull is constructed as a whole, and the TOPSIDE is constructed as a whole, which is integrated using a large gantry crane or wharf crane in the shipyard; domestic shipyards have rich experience in construction	The hull is constructed as a whole, and the topside is constructed separately; the integrated operation ise completed offshore; China has no construction experience	The hull is constructed as a whole, and the topside is constructed in blocks, which are integrated using a large gantry crane or wharf crane in the shipyard; only a few shipyards in China have construction experience
Offshore installation	Overall towing and offshore tie-in	The hull is towed as a whole, and upending was performed offshore and tie-in was conducted back to the mooring system; the topside is integrated in blocks and commissioned offshore	Overall towing and offshore tie-in
Duration of Construction, installation, and commissioning	Short	Long	Average
Investment	Low	Average	Average
Application of deep-water gas field	Commonly applied in dispersed deep-water gas fields	Commonly applied in dry Christmas trees	No application precedent, but technology is feasible

3 Overview of the construction of “Deep Sea One” large-scale gas field project

3.1 Overview of “Deep Sea One” large-scale gas field

The “Deep Sea One” large-scale gas field is located in the northern sea area of Southeast Hainan Basin, approximately 150 km from Sanya, Hainan, and approximately 160 km from the in-service YC13-1 gas field. The sea area where the gas field is located belongs to a low latitude tropical marine climate. The sea state is affected by typhoons and monsoons. The maximum tidal range is 2.24 m, and the maximum water depth of the gas field exceeds 1500 m. The development plan of the “Deep Sea One” large-scale gas field adopts the floating platform plan. The engineering facilities of this scheme are composed of a subsea production system, a floating semi-submersible production storage and offloading platform (“Deep Sea One” energy station), and submarine pipelines (Fig. 3). Among them, the “Deep Sea One” energy station is the brain and center of the whole gas field and is the core and key facility for the successful construction and production of the project. After the gas field is put into operation, it can export approximately 3.25×10^9 m^3 high-quality clean natural gas to Guangdong, Hong Kong, and Hainan annually. The completion of the project also marked the final formation of the large offshore natural gas pipeline network around Hainan Island and radiating Hong Kong, Guangdong, and Guangxi.

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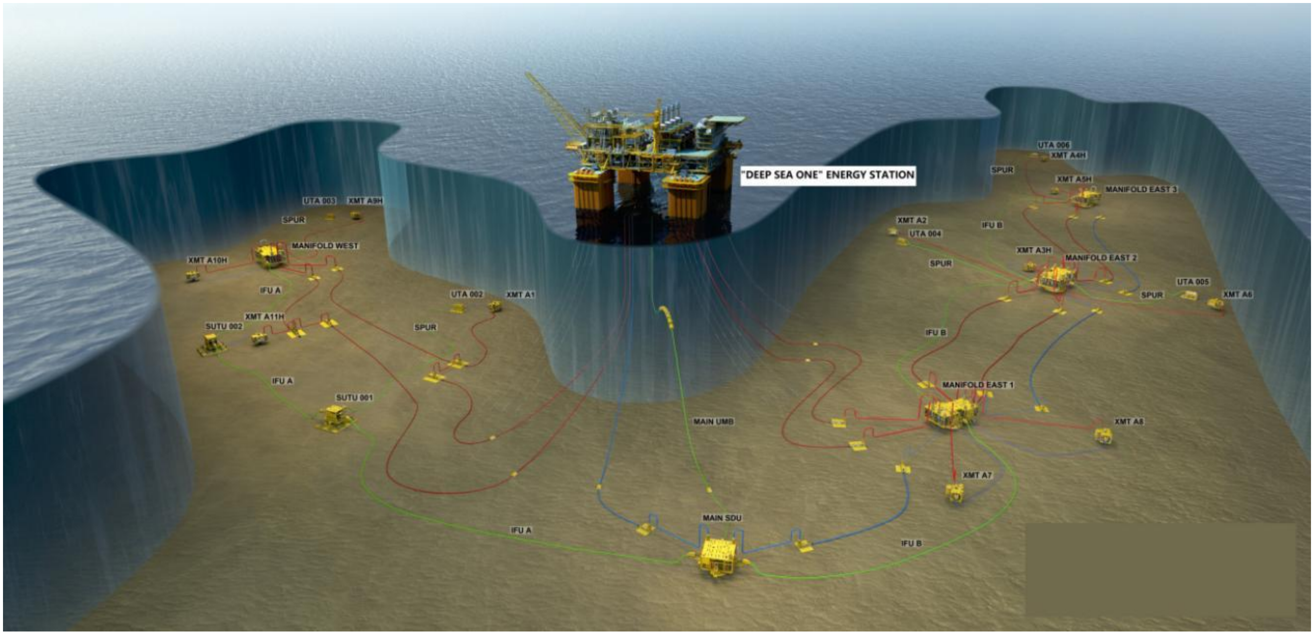

Fig. 3. Schematic diagram of “Deep Sea One” gas field development project hub.

3.2 Introduction to “Deep Sea One” energy station

The “Deep Sea One” energy station is the core and hub of the “Deep Sea One” large-scale gas field development project. Oil, gas, water, and other logistics from the underwater wellheads of the eastern and western districts are continuously transmitted to the platform through two 10-inch (1 inch =25.4 mm) and two 12-inch subsea pipelines as well as SCRs and enter the main process system of the platform for efficient oil, gas, and water separation. The treated, dried, and pressurized natural gas is exported to the subsea natural gas pipeline from the YC13-1 platform to Hong Kong through approximately 90 km of an 18-inch main gas pipeline. The treated qualified condensate oil is stored in the four column oil storage tanks of the energy station and regularly exported through dynamic positioning tankers.

The “Deep Sea One” energy station is the world’s first deep-water submersible production and operation platform that uses columns as oil storage tanks to store condensate oil and exhibits the functions of oil and gas processing and export. This platform is composed of a topside and hull, with a total weight and total height of 5.3×10^4 t and 120 m, respectively, and which is designed and built according to the high standard of 30-year non docking maintenance. The fatigue life of some key structures is as high as 300 years, and these structures can resist a super typhoon with a 100 year return period. Among them, the topside is the world’s largest assembled truss SEMI platform module and is composed of 23 deck plates, equipped with nearly 200 sets of key oil and gas processing equipment, and includes a living building that can accommodate 120 peoples. The design weight of the topside is nearly 2×10^4 t, with a total cable length of 4.3×10^5 m. The hull has a dead weight of approximately 3.3×10^4 t and is 91.5 m long, 91.5 m wide, and 59 m high. It is composed of a hollow-square-shaped bottom pontoon and four columns, with a maximum displacement of 1.05×10^5 t. Four condensate oil tanks are located in the four columns of the hull (Fig. 4), which can store condensate oil of approximately 2×10^4 m^3.

3.3 Construction difficulty analyses of engineering

The “Deep Sea One” large-scale gas field is the first deep-water gas field independently developed and constructed in China. There is no precedent in China and there is a lack of experience. Under the condition that some key technologies and equipment are highly monopolized by the other countries, the design, construction, and installation of the world’s first 100 000 ton deep-water SEMI production, storage, and offloading platform were independently completed for the first time within a short construction period, which is generally considered as an impossible production goal by the industry. The difficulties and challenges faced by this project in terms of project progress, technology, risk, safety, quality, and cost are as follows.

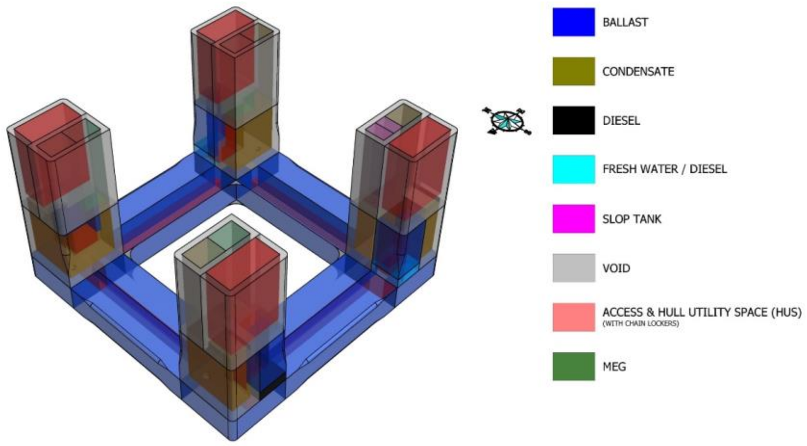

Fig. 4. Schematic of the column oil storage technology of the SEMI platform pioneered by the “Deep Sea One” energy station.

3.3.1 Various engineering and technical problems

The construction of the “Deep Sea One” energy station faced many engineering and technical problems that needed to overcome unprecedented problems, such as the design and construction technology of a 100 000-ton SEMI deep-water multi-column production, storage, and offloading platform, the precise large deformation of the half-floating integrated technology of 50000 ton super large structures, and the load lateral transfer technology of 30 000 ton structures via pre-inclination and return. It was necessary to overcome many domestic and industry top technical problems, such as the research and design parent ship technology of the SEMI production, storage, and offloading platform, design and construction technology of a 50-meter-span integral truss topside, and fatigue design and detection technology of the floating structure without a need for docking maintenance for 30 years.

3.3.2 High requirements for construction quality and accuracy

Because the water depth of the sea area where the gas field is located is up to 1500 m, there are many connections between the platform and both the mooring system and SCR, and the technical difficulty was high; thus, for the sake of technical risk and cost, the “Deep Sea One” energy station has formulated the design requirements of a 30-year non-docking maintenance, especially the high standard design of a 300-year fatigue life in some key areas, such as the structure and coating pipelines, thereby complying with extremely stringent technical standards and accuracy requirements. Several world-class construction difficulties are superimposed on the hull: the length and width of the bottom hollow-squre-shaped pontoon are both 91.5 m, and the height of the four columns is 59.5 M; therefore, there were ultra-high requirements for the site where hull assembly is carried and for its bearing capacity. The free open hull structure form of four columns created great challenges to deformation control and to the integration of the topside and hull. Therefore, the maximum allowable deviation of diagonal construction of 59.5-m-high columns is only ± 13 mm, which is 4 times higher than the ± L/1000 mm set by the International Association of Classification Societies standard [6].

3.3.3 Extreme difficulty in safety control

The construction period of the project was short, and the maximum number of construction personnel on the construction site exceeded 3000. Large operations such as the assembly operation of the topside deck pieces, loadout and unloading barge of the hull sections, and assembly operation on the slide site of the hull sections were frequent, and there were world-class difficulties encountered during large operations such as the whole integration of the topside and hull. In addition to the sudden epidemic of COVID-19, there were many high-risk operations such as high-altitude operations, limited space operations, cross operations of large floating cranes and crawler cranes, and diving operations as well as many construction vessels; thus, both construction equipment and personnel management and safety control faced great challenges in terms of health, safety, and environmental protection management.

3.3.4 Various internal and external factors

The project construction process was influenced by many internal and external factors. For example, during the development and construction of the gas field, due to the trade friction impact between China and USA, the introduction of some key equipment and key core technologies was restricted, which greatly affected the implementation of the project; The Covid-19 pandemic delayed the entry and exit of foreigners, and the

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construction, delivery, imports, and export custom clearance of equipment to varying degrees, which had a great impact on the already-short construction period and the urgent construction progress. This project had a large amount of offshore installation work to complete, such as subsea production system manifold operation, electro-hydraulic distribution terminal operations, laying of subsea pipelines, umbilical cables, anchor piles, mooring system, and SCRs, and other offshore installations, and the resources of construction vessels and machines were few and limited.

4 Design and construction technology innovation of “Deep Sea One” energy station

The “Deep Sea One” energy station is the core equipment of the development mode of the deep-water SEMI production, storage, and offloading platform, which is the first in the world, and greatly improves the efficiency and feasibility of gas field development. However, to build the “Deep Sea One” energy station, many design and construction problems were present: (1) there was no development mode of the “subsea production system connected to the SEMI production, storage, and offloading platform” for reference; (2) “Deep Sea One” has many integrated functions and a complex structure, which created great challenges to the structural design; (3) there was a lack of independent construction experience on deep-water SEMI oil storage platforms; (4) the topside lifting weight is large, and the resources that can be used for lifting and integration as a whole are scarce; (5) there was no experience on load lateral transfer of 30000-ton open large deformation structures worldwide. Therefore, the technical team of the Lingshui 17-2 gas field development project overcame a number of world-class problems and created three world-class innovations, 13 major domestic technological breakthroughs, and over 10 industrial technological problems. This paper selects the most representative technological breakthroughs to elaborate.

4.1 Design and construction technology of the world’s first 100 000-ton SEMI deep-water multi-column production, storage, and offloading platform

4.1.1 The design and analysis method of the SEMI production storage and offloading platform parent ship is proposed for the first time

The characteristic and difficulty associated with the SEMI oil storage and offloading platform was the instability caused by high requirements for tank capacity and large load changes. A reasonable ship type design was the most critical and first step. Breaking through the suppression mechanism of damping on Matthew instability [7], the flat pontoon design was innovatively carried out on the “Deep Sea One” energy station, the coupling technology of stability and low-frequency motion of the deep-water small waterline floating structure was thoroughly studied, and the prediction method of low-frequency motion under wave current coupling and high wave steepness characteristics in the South China Sea was established.

During the operation of the “Deep Sea One” energy station, the condensate oil tank is always loaded and replaced with the ballast tank in the buoyancy tank. The position difference of the cabin leads to a change in the overall center of gravity of the platform, which has a significant impact on the rolling period of the platform. If the natural period of rolling reaches twice the natural period of the heave, it will produce potential Matthew instability, which was an important challenge faced by the “Deep Sea One” SEMI production, storage and offloading platform during the design and had to be solved using low-frequency response prediction technology [8].

According to the different loading conditions of the SEMI platform, the design and analysis method of the SEMI production storage and offloading platform was established for the first time, focusing on the full load condition of a 37-m draft to calculate the motion performance of the platform. The hydrodynamic performance was improved by controlling the main dimension of the platform. The heave natural period (Fig. 5) is 22.5 s, and the maximum rolling natural period is 42.4 s (full load). The rolling natural period is controlled below two times the heave natural period, effectively avoiding Matthew’s unstable area. Meanwhile, the motion characteristics of “Deep Sea One” are verified using model tests, which ensures the accuracy of motion performance prediction. This technology overcomes the technical problems caused by the sharp change in the center of gravity of the SEMI production storage and offloading platform.

4.1.2 The hull design technology of multi-column SEMI platform with large oil storage tanks was developed

As the world’s first SEMI with oil storage and export functions, the “Deep Sea One” energy station needed to arrange ballast tanks, equipment tanks, slop tanks, and other compartments while arranging the oil storage tanks in the internal structure design of the hull. The structure is very complex. In terms of the structural design, it was necessary to meet the safety requirements of oil storage, export operation, and the change of the platform draft caused by oil storage and offloading. To ensure the safety of oil storage, a circle of isolation tanks are set around the condensate oil tank; to ensure the safety of export operation, an anti-collision design is adopted for the hull structure near the water surface; to ensure the change in the platform draft, a special design is adopted in the scope of the splash zone and outer plate structure of the platform, and the whole structure is also designed and analyzed under different draft conditions.

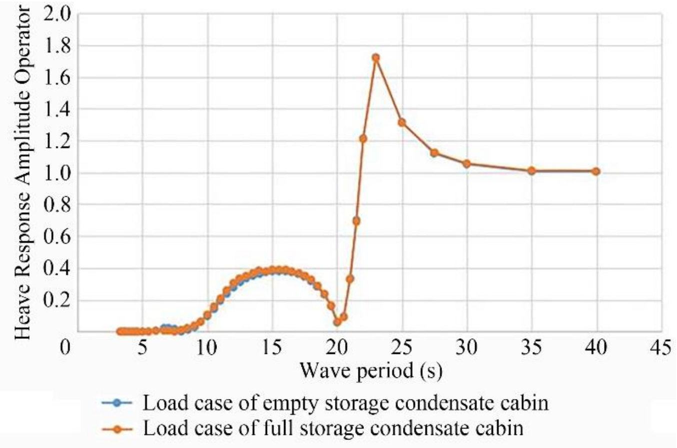

Fig. 5. Study on heave motion characteristics of “Deep Sea One” energy station.

In the column design, to ensure a sufficient storage capacity, the column size is designed to be 21 m × 21 m. Such a large scale requires full consideration of the internal structural support. In consideration of ensuring fatigue life, the greater the continuity of the support structure, the better. However, since the condensate oil that stored inside needs to achieve better liquidity, the support structure should not be too closed. Through the design iteration of multiple optimization, the bulkhead structure in the form of a large opening was finally determined (Fig. 6). Through the large span structural support technology of a multi-column large oil storage tank, improved fluidity in the middle area of the cabin and improved continuity of the bulkhead connection area were achieved.

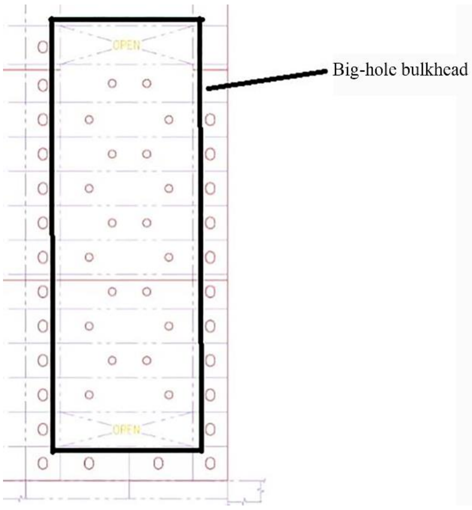

Fig. 6. Large span structural support design of large oil storage tank in multi-column SEMI platform.

To ensure the structural safety of the condensate oil tank during the export operation, a new double-layer shell structure design (Fig. 7) was adopted in the column structure design. A horizontal plate was used to replace the strong beam support on the inner and outer shells. The new anti-collision technology not only saves the amount of steel, but also improves the structural continuity. In the design, numerical analysis was used to simulate the structural stress and deformation of the hull when the ship collides, and the anti-collision ability of the column structure was verified. In addition, the anti-collision protection frame and rubber fender were specially set on the platform shell, which can provide a good buffer protection for the platform.

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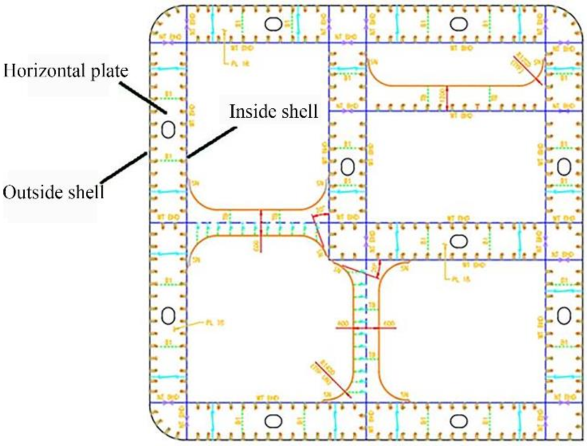

Fig. 7. Anti-collision design of double shell and horizontal plate structure.

4.1.3 General assembly technology on slideway of hull sections of SEMI platform is applied for the first time in China

The common construction of the SEMI hull structure was carried out in the dock, hull sections were assembled using a gantry crane, and finally the whole hull was floated and launched in the dock. In the absence of a suitable dock for the Lingshui 17-2 gas field project, the construction site of Offshore Oil Engineering (Qingdao) Co., Ltd. improved the bearing capacity of the site by reconstruction of the No. 5 slideway, reasonably allocated site resources, gave full play to its own resources, creatively paved slide blocks on the slideway, and transported the L-shaped general section in place using heavy-duty transport vehicles or self-propelled modular transport vehicles. The construction of hull of the “Deep Sea One” energy station was efficiently completed using a crawler crane and floating crane to assemble the main sections of the hull column. This construction technology has created a wharf slideway construction method for the hull of the SEMI platform and solved the problems of the absence of a dock, insufficient dock bottom bearing capacity, and other site constraints, for which improvements and innovations were made in the following aspects.

(1) The cushion block was reused to save material costs. Based on the site capacity, construction process, equipment use requirements, hull structure, loadout mode, and other factors, the reusable loadout cushion block and transportation cushion block were designed. During the hull structure constructed on the wharf, the cushion block was placed on the general assembly slide in advance for construction support; during the loadout stage, it was used for hydraulic slipper jacking support; during the sea transportation stage, it was used for sea-fastening support. A large number of cushion blocks were reused during the stages of prefabrication, transportation, accuracy adjustment, and overall assembly, which saved a lot of material costs.

(2) The large-scale overall section transported in place improved the construction efficiency. The bottom node and pontoon of the hull were divided into two 3000-ton large L-shaped sections (Fig. 8). After the two large-scale overall sections are completed, they were directly transported in place, which increased the work volume in a safe and stable environment in the workshop, reduced the open-air high-altitude work in the overall assembly site, and greatly improved the operation quality and production efficiency.

Fig. 8. Assembly on slideway of hull large-scale L-type overall section.

(3) The crawler crane and floating crane assembled the hull column sections simultaneously to shorten the project duration. For the overall assembly in the slideway, there were a few site restrictions, and multiple large cranes were used to assemble the section integrated in coordination with, or parallel to, the floating crane (Fig. 9), thereby breaking through the limitations of the rated lifting capacity of the dock crane and the number of cranes. On the one side, it increased the weight of the total section and reduce the number of large-scale sections, thereby reducing the workload of high-altitude welding and scaffolding erection, saving labor costs, and making the construction safer. On the other side, parallel assemble operations were performed to improve the work efficiency and considerably reduce the project duration.

Based on the above optimization and improvement measures, the construction and overall assembly period of the hull of the "Deep Sea One" energy station was reduced from 12 months to 6 months, creating the fastest record of SEMI construction and overall assembly of similar scales domestically and abroad.

Fig. 9. Simultaneous lifting assembly operation by sea and land.

4.2 The world's first large-deformation, half-floating precise integration technology for 50 000-ton super-large structures

The SEMI platform of the "Deep Sea One" energy station is composed of an integral truss-type topside and a multi-column hull with oil storage tanks. Selecting a reasonable integration scheme for a super-large structure of approximately 50 000 tons determined the success or failure of the project. The integration methods of SEMI in the offshore engineering industry usually include block lifting integration, overall lifting integration, jacking integration, and floating integration. [9] Different methods have their advantages and disadvantages. After a long-term demonstration, the technical team of the project finally chose the overall lifting integration method by comprehensively considering the technical maturity, construction period, operation risk, and other aspects.

The domestic 20000-ton Taishan dock crane was selected for the overall lifting integration operation of the "Deep Sea One" energy station. The spacing between the double lifting beams is 42.5 ± 7.0 m, and the lifting span does not exceed 49.5 m, which also became the maximum span of the general design of the platform. Meanwhile, due to the limitation of dock water depth, the method of bottom sitting during integration operation was selected. During the actual operation, two key technical problems that make bottom sitting safety and docking active control accurate had to be solved.

4.2.1 Hull precise positioning and bottom sitting technology in the dock

To ensure smooth integration, the key is to achieve an accurate positioning of the hull and topside. The whole process of precision positioning operation involves many links, such as construction precision, installation precision, and positioning precision. It is complex system engineering that ensures that each link falls within the allowable range of precision and achieves the final precision matching. In the past, the winch was usually used to pull the hull for positioning during the integration operation, and the accuracy was 100 mm, which did not meet the accuracy control requirements of ± 13 mm. Therefore, it was proposed to add positioning auxiliary devices in the scheme design. The function of the positioning auxiliary device is to increase the positioning accuracy of the hull and limit the inclination of the hull during the integration operation. In the structural design, not only was the structural strength of the device itself considered, but it was also ensured that the platform structure could not be damaged at the point of contact. Finally, two sets of dock limit devices (Fig. 10) were arranged on the north and west sides, together with hydraulic jacks for precise adjustment of the hull during integration operation. To avoid the interference between the limit device and the external structure of the lower floating body, the limit device was designed as an external probe, which was installed during the stage of dry docking, and the site positioning was based on the large dock sample line when positioning. Meanwhile, rubber was added to prevent damage due to collision with the hull structure.

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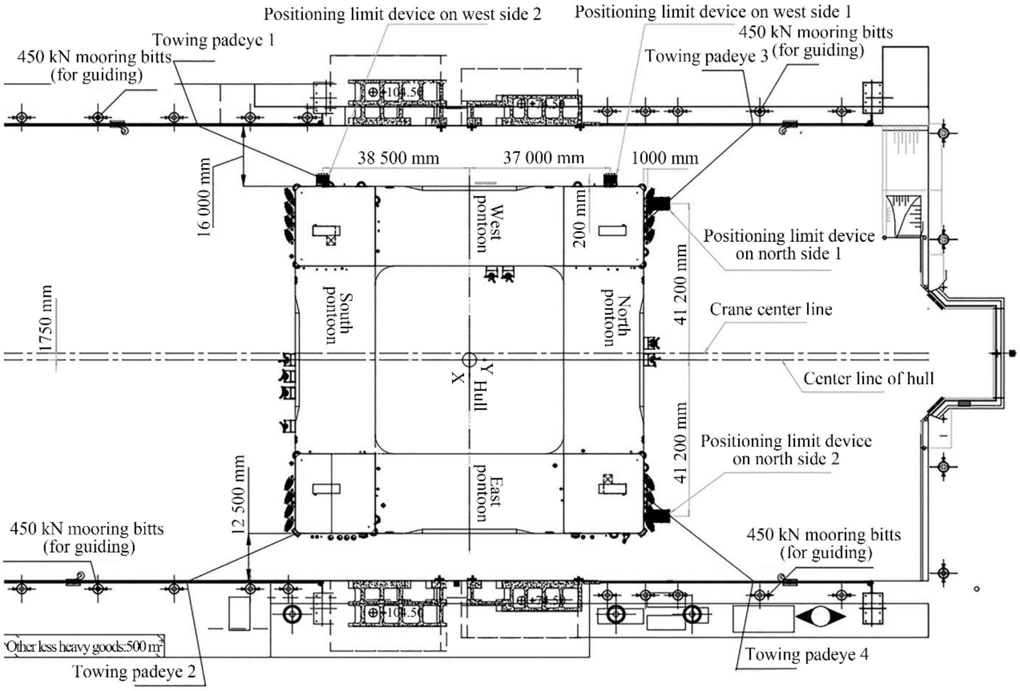
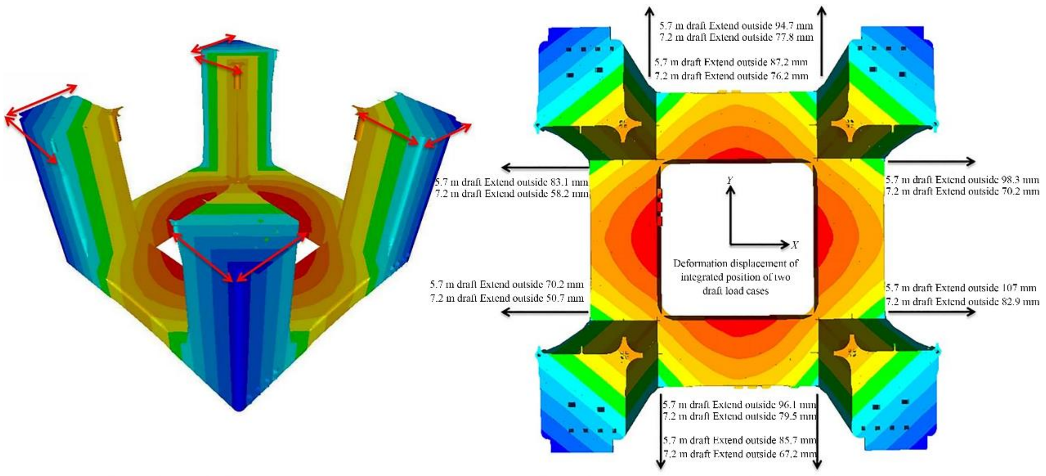


Fig. 10. Precise positioning limit device and its layout.

4.2.2 Deformation analysis and control technology of large opening hull structure

Generally, during integration operation, the hull of the SEMI platform needs to set up a special support frame to control the deformation of the hull structure during the transportation and integration operation stage [10]. However, owing to the large span and the impact of wave slapping, the support frame requires a large amount of structural steel, and the connection position of pipe joints will cause a local stress concentration; thus, there is a risk of failure during the service process. The "Deep Sea One" energy station stores condensate oil in the column, which objectively causes the weight of the hull to concentrate on four columns, and the hull will become more deformed during transportation and integration operation (Fig. 11). If the horizontal support is set according to the precedent, it will not only cause structural waste, but also increase the risk of failure during servicing. After careful analysis and confirmation, the horizontal support design was cancelled, the strength of the hull structure could meet the requirements during the transportation stage, and the deformation of the hull structure during the integration operation could meet the integrated accuracy requirements by adjusting the ballast water scheme. One week before the integration operation, the dynamic changes of the deformation of the butt joint was continuously monitored together with the ballast and temperature to ensure the smooth implementation of the integration operation.



(a) Deformation trend of large-open hull structure (b) Deformation control technology of large-open hull structure

Fig. 11. Deformation analysis and control technology of large open hull structure.

4.2.3 Docking structure design and analysis technology in overall integrated operation

The pin-post type was adopted in the design of the docking structure for the overall lifting integration [11], and a total of four groups were set. The temporary guide system adopted a conical cross structure, and its installation and grinding were completed before launching to ensure qualified accuracy and easy sliding during alignment. The strength and hardness of the guide wedge (Fig. 11) were analyzed according to the actual operating conditions, and there was a certain margin to ensure that it can bear the docking load within the error control range. Before the formal operation, a computer simulation operation analysis was carried out using special software (Fig. 12). The capture range of the integrated operation docking structure can reach 250 mm. Combined with the precise hull operation control scheme, the deformation can be adjusted back through the self-weight of the topside in the case of large deformation, and precise integration can be achieved skillfully. In addition, being the docking structure between the hull and topside, the docking structure can bear the weight static load and offshore dynamic load of the upper module. The convenience of the construction stage and the feasibility of double-sided penetration welding after the integration operation were considered in the design of the docking structure, and the inspection and maintenance during in-service was also considered.

Through technical research and careful organization, the overall lifting integration operation of the “Deep Sea One” energy station was successfully implemented from October 28 to 29, 2020, achieving a series of technical and management innovations such as the overall integration scheme implementation, structural design, hull deformation control, precision control, interference management, risk management, operation simulation, and implementation of floating docking and pier welding. It pioneered the large-deformation half-floating precise integration technology for 50 000-ton super large structures.

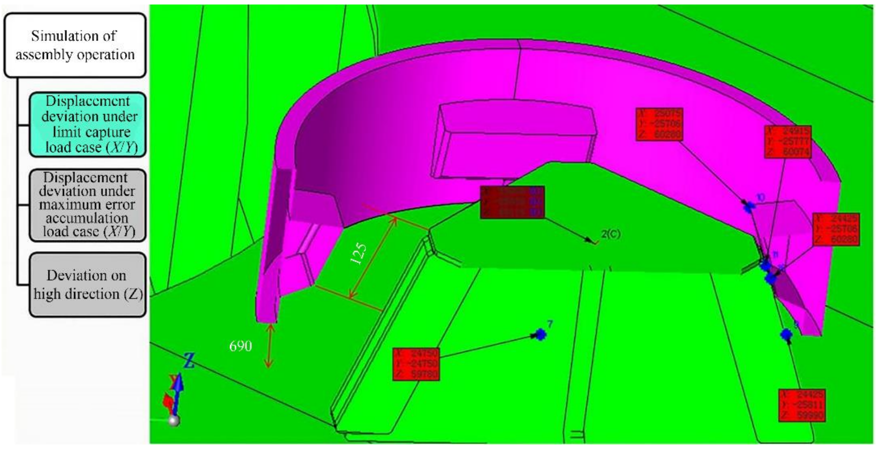


Fig. 12. Docking structure design in integrated operation and computer simulation.

Note: X represents the distance from the north-south direction to the center of the hull; Y represents the distance from the east-west direction to the center of the hull; Z represents for the height from the baseline.

4.3 Load lateral transfer technology via pre-inclination and return for open structures with the world's largest tonnage

The hull of the “Deep Sea One” energy station is built on the slideway, weighs approximately 3.3 × 10^4 t, and is 91.5 m long and 59 m wide. The flat pontoon design was adopted, and there is no connection between the columns. It is a large open plate and shell structure, with weak local strength and large column deformation. If the traditional longitudinal loading is adopted, the deck strength of the “XinGuangHua” semi-submersible barge faces extreme challenges, the loading slide is too long, and the efficiency is low. If horizontal loading is adopted, there is no problem of deck strength, the loading slide is short, and the operation efficiency will be significantly improved; however, the ballasting and unloading of the semi-submersible barge is relatively difficult. The biggest difficulty associated with the horizontal loading method is to constantly adjust the draft of the barge to keep the dock slide relatively flush with the barge slide under the changing tide of the wharf. Meanwhile, it is also necessary to control the posture of the barge to balance the tilting moment created by the load transfer on board. The greater the weight and the faster the speed of the load transfer, the higher the difficulty. Therefore, the technical team has developed a plate and shell structure load transfer and deformation control tooling to replace the traditional sliding traction equipment (such as the tension jack and hydraulic drum winch). The problem of deformation and stress control associated with large-sized plate and shell structures during the process of sliding loading was solved. It pioneered

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the lateral transfer technology via pre-inclination and return for large opening structures with the world's largest tonnage and successfully achieved a large-scale hull structure loadout on the semi-submersible barge laterally as well as floating unloading and launching in the open sea. An innovative positive attitude control technology of pre-tilting of the semi-submersible barge was developed to avoid the risk of instability and overturning of the semi-submersible barge. The optimal and most economically feasible loading and launching scheme was also selected.

4.3.1 Research plate and shell structure device for load transfer and deformation control

The device is composed of a multi-purpose lightweight support structure, hydraulic slipper system, and low friction split berthing parts. The multi-purpose lightweight support structure is used to balance the deformation of the plate and shell structure due to its own weight, and it plays a supporting role in its construction, loadout, and transportation process. The hydraulic slipper system can compensate for the height difference between the barge and the land during the loadout process, thereby controlling the deformation of the plate and shell structure. The low friction split berthing parts greatly reduce the friction between the barge and the wharf and can achieve a smooth transfer of load from the land to the barge.

(1) A multi-purpose integrated support structure was innovatively researched. The supporting structure is a box structure spliced using steel plates. Wood with high compressive strength is installed on the top, which can simultaneously support the large floating structure during the stages of land construction, skid loadout, and barge transportation, and they also play the role of a collision buffer during the floating and unloading process of large floating structures. In the past, most projects used different forms of support structures during different construction stages, resulting in a waste of resources and increasing the local damage risk of large-scale plates and shell structures during the conversion process between different types of support structures.

(2) The hydraulic slipper system is optimized. The system is a type of skid loadout equipment that can adjust (hydraulically controlled) the support height in the vertical direction and, at the same time, has the ability of horizontal propulsion. The system includes hydraulic slippers, crawlers, special slides, bridging beams, hinged supports, power stations, and control systems. Among them, the hydraulic slipper system and crawler were selected and configured according to the weight and size of the structure as well as the number and layout position of the pre-installed support structure.

(3) Research was conducted on low friction split berthing parts. This device can reduce the friction between the barge side and the wharf, achieve a smooth adjustment of the barge posture, and ensure the smooth transfer of load. The low-friction split-type berthing parts, including wharf berthing parts and barge berthing parts, are composed of steel berthing parts and Teflon plates, which are installed at their points of contact with each other when the wharf and barge are berthing. According to the form of the barge and wharf, the berthing parts were designed, manufactured, and installed on the barge side and wharf, respectively, before the barge berths. The barge side of the berthing parts (Fig. 13) were spliced using section steel. The position of the section steel on the ship should correspond to the position of the strong frame and strong structure of the barge, and it should be fixed on the barge through rib plate welding. A steel plate is installed on the outer vertical surface of the berthing parts, and a Teflon plate is installed on the surface of the steel plate. The dock-side berthing parts (Fig. 14) are slightly wider than the barge-side berthing parts and are made of steel sections that are fixed on the dock embedded parts using stiffeners. The outer vertical part of the berthing part is close to the wharf, a steel plate is installed on the vertical surface, and the surface of the steel plate was polished until smooth.

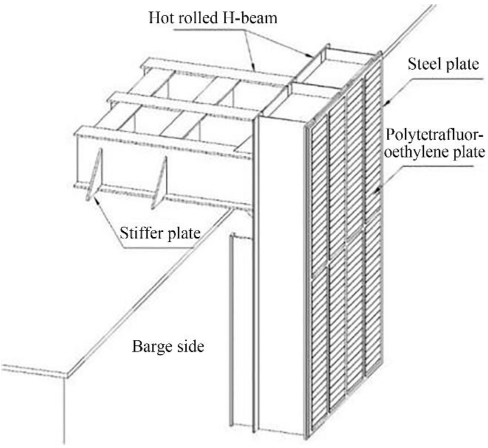


Fig. 13. Low friction split berthing parts - barge side.

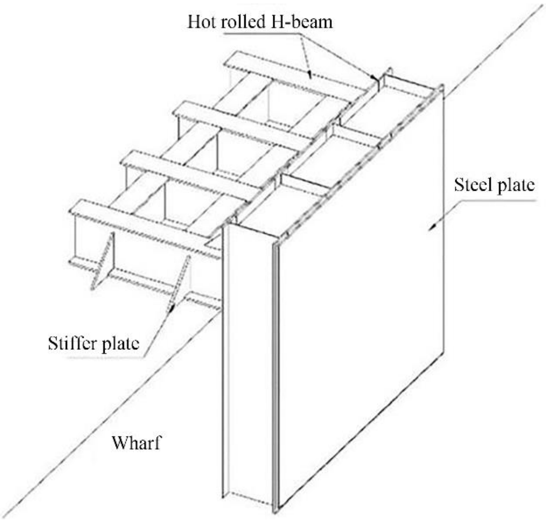
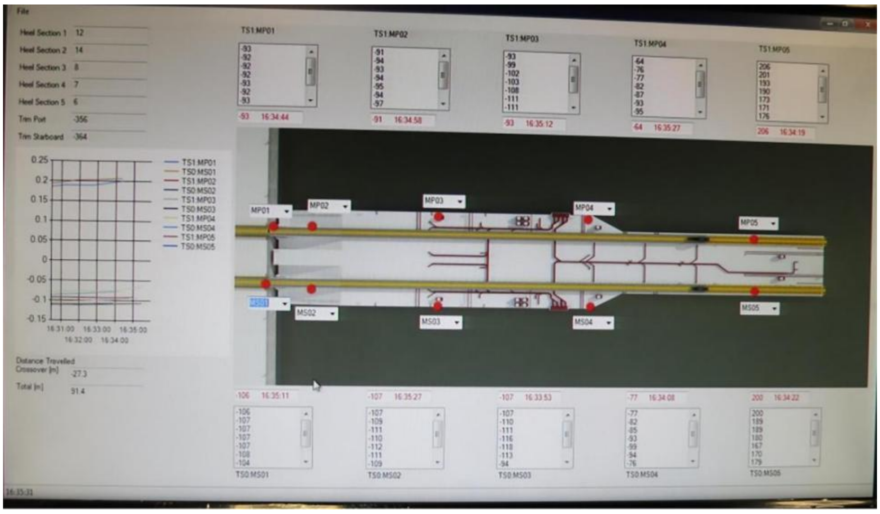


Fig. 14. Low friction split berthing parts - wharf side.

4.3.2 Real time attitude monitoring technology for semi-submersible barge loading

The conventional skid loadout operation is to manually use the total station electronic distance meter to measure the transverse and longitudinal inclination of the barge. In terms of measurement accuracy, speed, and reliability of data transmission, this measurement method is greatly affected by factors such as the skill level of the measurement personnel, light, and noise at the operation site, especially during the large tonnage load lateral transfer operation, and small measurement errors, slow data measuring, and data transmission delays will greatly affect the barge’s load adjustment operation and even lead to the failure of the whole loadout operation.

To safely and efficiently implement the load lateral transfer of the super large tonnage hull, a set of a barge-attitude real-time monitoring system (Fig. 15) was innovatively developed based on the total station instrument used to measure the electronic distance, which can achieve 24-h monitoring of the roll, pitch, and four corner draft of the barge, and the refresh speed of the measured data is approximately 20 s/time (in an ideal state, the single speed of manually using the total station instrument used to measure the electronic distance to measure the barge attitude is approximately 2 min). The system has the following characteristics: (1) it is equipped with an automatic laser line of sight and positioning system, (2) remote operation of the total station electronic rangefinder can be achieved using a notebook computer, (3) the effective distance of measurement is up to 1000 m, (4) the measurement accuracy is up to 0.5 mm, (5) it can display the roll and pitch attitude of the barge in real time, (6) and the sliding distance of the structure can be monitored in real time.



Heel Section 1 12
Heel Section 2 14
Heel Section 3 8
Heel Section 4 7
Heel Section 5 6
Trim Port -356
Trim Starboard -364

Distance Travelled Crossover [m] -27.3
Total [m] 91.4

16:35:31

TS1.MP01	TS1.MP02	TS1.MP03	TS1.MP04	TS1.MP05
-93	-91	-93	-64	206
-92	-94	-99	-76	201
-92	-93	-102	-77	193
-92	-94	-103	-82	190
-93	-95	-108	-87	173
-92	-94	-111	-93	171
-93	-97	-111	-95	176
-93 16:34:44	-91 16:34:58	-93 16:35:12	-64 16:35:27	206 16:34:19

TS0.MS01	TS0.MS02	TS0.MS03	TS0.MS04	TS0.MS05
-106 16:35:11	-107 16:35:27	-107 16:33:53	-77 16:34:08	200 16:34:22
-106	-107	-107	-77	200
-107	-109	-110	-82	189
-107	-111	-111	-85	189
-107	-110	-116	-93	180
-107	-112	-118	-99	167
-108	-111	-113	-94	170
-104	-109	-94	-76	179

Fig. 15. Display interface of fully automatic SEMI attitude monitoring system.

4.3.3 Loading and unloading technology via pre-inclined and return of semi-submersible barge

A schematic diagram of the lateral sliding loadout of the hull structure of the “Deep Sea One” energy station is shown in Fig. 16. The whole sliding distance is 91.56 m, while the sliding distance where load transfer occurs is only 31.2 m. The creeping speed of the hydraulic slipper system is approximately 0.25 m/min, which is required to complete the transfer of a 33 450-t load, which is equivalent to 268 t of the load being transferred to the barge every minute.

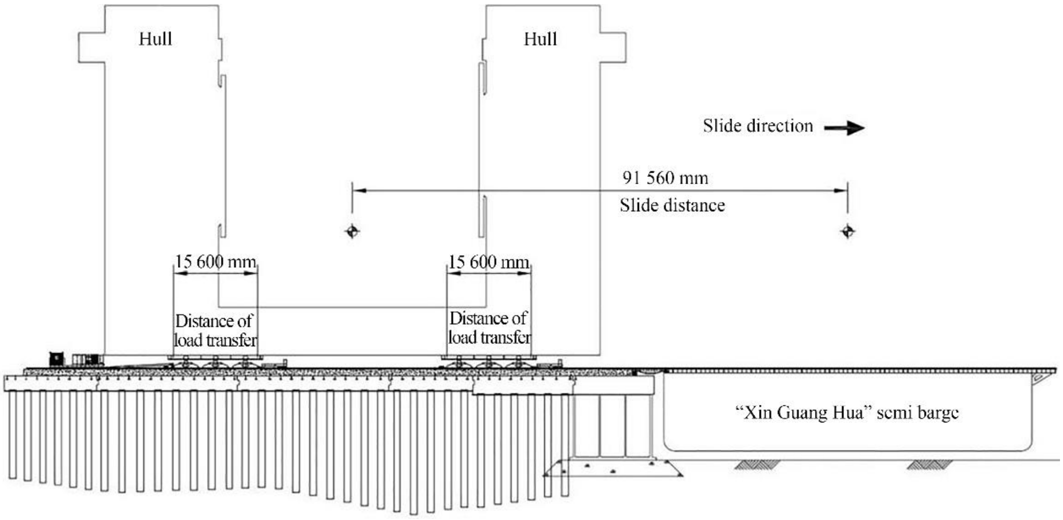
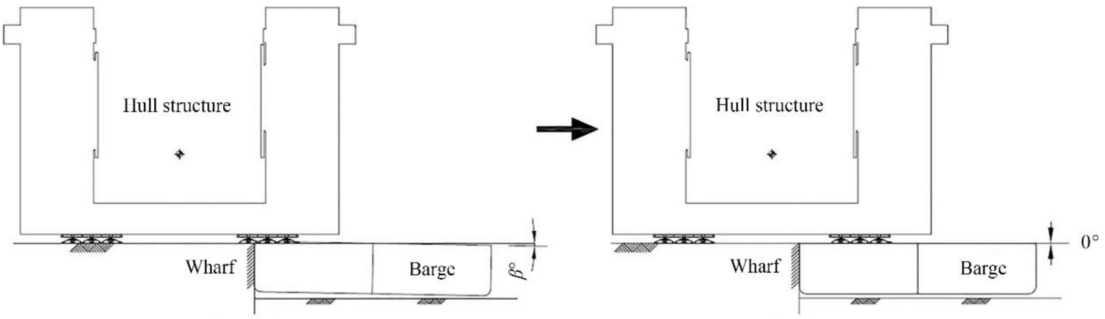


Fig. 16. Schematic of lateral sliding loadout of hull structure of "Deep Sea One" Energy station.

For the lateral sliding loadout operation of super tonnage structures, due to the excessive load transferred to the barge in a short time, a great transverse moment will be exerted on the barge: (1) when the load of the structure is transferred at the nearshore end of the barge (the load is not transferred to the midship of the barge), the barge will have a large nearshore inclination (the side near wharf is low and the side far wharf is high), which will increase the height difference between the barge and the wharf. Finally, the structure will be greatly deformed and damaged. (2) When transfer of the load of the structure starts at the far shore end of the barge (the load is transferred through the midship of the barge), the barge will have a large far shore inclination (the side near wharf is high and the other side is low), which will also increase the height difference between the barge and the wharf and finally cause great deformation and damage to the structure. In addition, the most serious problem is that it is very easy to cause the structure to accelerate to slide to the far shore side of the barge, which will eventually cause the barge to overturn or the structure to fall into the sea. During the load lateral transfer operation of a small tonnage, the above risks can be avoided by accurately controlling the barge load adjustment. However, for the large tonnage load lateral transfer operation, the above risks cannot be completely avoided by merely accurately controlling the load adjustment of the barge.

In view of this situation, based on the air compressor load adjustment system of the "XinGuangHua" semi-submersible barge, breaking the conventional load adjustment idea, the pre-inclined and return ballast adjustment technology was proposed for the first time [12]. This method can successfully solve the problems of large deformation and damage of the structure, large inclination, and even overturning of the barge caused by a too large and too fast load transfer. The specific principles are as follows:(1) when the load of the structure is transferred at the near-shore side of the barge (the load is not transferred to the midship of the barge), adjust the barge to tilt to the offshore end in advance, and the inclination angle is that caused by this load transfer to the barge (Fig. 17). (2) When the load of the structure is transferred to the far-shore side of the barge (the load is transferred through the midship of the barge), the barge is adjusted to tilt to the nearshore end in advance, and the inclination angle is that caused by this load transfer.

The lateral sliding loadout operation of the ultra large weight and ultra large size "Deep Sea One" energy station hull created the world record of the largest tonnage of lateral sliding loadout of structures, developed and integrated a multi-purpose integrated support structure and low friction split berthing parts to prevent stress damage to structures, and optimized the hydraulic slipper system and other technologies, filling the domestic technical gap.



Before load transfer

After load transfer

Fig. 17. Schematic of barge attitude control of loading and unloading technology via pre-inclined and return.

5 Conclusions

The “Deep sea One” large-scale gas field development project is the first large-scale ultra-deep-water project independently explored, discovered, designed, constructed, and installed in China, creating the world’s first new deep-water gas field development mode of a deep-water 100 000-ton SEMI platform with oil storage and a remote subsea production and transportation system. The design and construction of the “Deep Sea One” energy station was carried out without any preceding reference. The engineering team successfully solved many difficult problems such as those related to technology, management, and construction, and they safely and efficiently completed the construction of the “Deep Sea One” energy station with high-quality in the face of severe challenges such as trade friction between China and USA, the outbreak of COVID-19, and the tight construction period. The beneficial practices obtained during the construction of the “Deep Sea One” energy station are as follows.

(1) Breaking through the conventional management mode. During the implementation stage of the project, the integration of design and construction, bold innovation of five control management modes, and use of a number of incentive policies that have injected super spiritual impetus into the project construction was achieved.

(2) The preliminary research team developed a damping mechanism to restrain Matthew’s instability, innovated the flat pontoon design, developed the first deep-water multi column production storage and offloading platform parent ship, and achieved safe oil storage of columns.

(3) According to local conditions, the engineering and technical team has overcome the loadout problem of the 30 000-ton open multi-column hull structure, created the analysis and design technology of the lateral sliding loadout of a large floating structure of hydraulic slippers, and achieved load lateral transfer via pre-inclined and return of the world’s first 30 000-ton structure.

(4) The engineering construction team worked together to learn from each other and pioneered the precise integration of wet half-floating technology in the dock, achieving the world’s first precisely integrated 50000-ton super large half-floating structure.

(5) During the process of promoting the progress and implementation of the project, the project team paid attention to the collection and arrangement of assets during the organization process and precipitated advanced theoretical research methods, standard technical systems, and valuable construction experience when the project is completed.

The “Deep Sea One” large-scale gas field was officially completed and put into operation in June 2021, raising the natural gas production and supply capacity of CNOOC in the South China Sea to 1.3×10^{10} m^3 per year. This is equivalent to 2.6 times the annual gas consumption of Hainan Province and plays an important role in ensuring national energy security, improving the energy structure, promoting energy transformation, and helping to achieve the carbon peaking and neutrality goal. The completion and successful operation of the “Deep Sea One” energy station marks that China has mastered a set of the overall technology of the SEMI production, storage, and offloading platform with independent intellectual property rights, which is suitable for deep-water complex sea areas, forming a complete set of an efficient development technology system for China’s offshore deep-water gas fields and filling a number of international and domestic technological gaps. Meanwhile, the project is also a milestone in the development history of China’s deep-sea engineering, marking the entry of China’s offshore oil industry into the ultra-deep-water era. Additionally, the project informs the world that China has the initiative of oil and gas development in the whole sea area, has the technical strength required to enter the ultra-deep-water sea area in the central and southern South China Sea, and changes the current situation whereby deep-water oil and gas

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development depends on European and American countries,. Moreover, the project is of great significance for improving the construction capacity of China’s marine deep water engineering equipment, supporting the construction of the Belt and Road and China Manufacturing 2025, ensuring national energy security, and building a marine power.

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