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Maintenance Technology and Practice of Mooring Anchor Leg in Deepwater Floating Production Facility

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Abstract: "Nanhai Shengli" is a floating production storage and offloading unit (FPSO) in the Liuhua 11-1 oil field in the South China Sea. During its service, the FPSO suffered severe broken anchor legs due to the hostile impact of several strong typhoons. In order to ensure the safety of its mooring system, emergency maintenance operations were carried out on 10 mooring anchor legs under the condition of non-release and non-production of FPSO, which was the first time in deep water in China. Its construction is difficult, high risk, weather and FPSO draft time window requirements are high, the use of reasonable technology and construction methods is the key to efficient completion of the operation, such as simulation analysis, reasonable selection of machinery and resources, efficient control of site construction, accurate environmental monitoring, etc. Taking the release and tieback of the mooring system of "Nanhai Shengli" FPSO in Liuhua 11-1 oilfield as an example, various technical difficulties and key points in the process of release and tieback construction are introduced, and the rules are summarized and analyzed. The safe and efficient completion of this construction operation is not only the embodiment of management level, but also the result of daring to innovate and face challenges. It has a typical guiding significance for the maintenance of mooring anchor leg of similar deep-water floating production facilities in China.

Keywords: Floating Production Facilities, Mooring Anchor Leg, Release, Hook up, Innovative Design

1. "Nanhai Shengli" FPSO Mooring System Introduction

With the development of offshore oil and gas drilling into deepwater, floating production facilities are widely used. Each floating production facility has a mooring system to ensure that the production facilities do not shift significantly during the development and production process. At present, the commonly used mooring systems include extended mooring system, multi-point mooring system, single point mooring system and dynamic positioning system [1]. Mooring system can be divided into permanent mooring system and mobile mooring system according to the service life of the mooring system or whether the mooring platform often changes the location during the service period [1].

"Nanhai Shengli" is a floating production storage and offloading unit (FPSO) in Liuhua 11-1 oilfield. Designed by SOFEC and classified into ABS (American Bureau of Shipping) class, it adopts a permanent internal turret single point mooring system. It was put into operation in 1996 with an operating water depth of about 300 m, making it the first deep-water FPSO mooring system in China. The mooring anchor leg was damaged by a typhoon in 2006 and was extended to 2017 after repairs were completed in 2007. It has been in service more than 20 years.

Mooring system consists of 10 evenly distributed anchor legs, each of which has a maximum mooring capacity of 6,000kn, and is connected to the ship through a turret mechanism in a cavity in the front of the tanker's hull. Each anchor leg of the mooring system is mainly composed of six parts of steel cables or anchor chains: top chain, upper steel cable, lower steel cable, counterweight chain, laying cable (diameter 114mm) and gripping anchor. The entire single mooring steel cable and anchor chain are connected to the corresponding connecting plate and triangle plate through their respective cable joints and ungraded chain links, and finally connected to the gripping anchor on the seabed. A water buoy is connected to the triangular plate at the joint of the upper and lower steel cables. With a diameter of 4.06m and a height of

3.48m, the floating buoy weighs 15720kg in air and has a net buoyancy of 257500 kn. The width of the gripping anchor is 9.656 m and the height 7.579 m. Each anchor weighs about 40,00kg. Each triangle plate weighs about 1160kg, and each connecting plate weighs about 856kg. Figure 1 shows the structural form of anchor legs of FPSO [7].

Figure 1. *Structural form of anchor legs of FPSO.*

The FPSO mooring system of "Nanhai Shengli" has been operating underwater more than 20 years, and its underwater components are seriously corroded and aging. In addition, it had been hit by three strong typhoons in recent years. After the strong typhoon Nida in August of 2021, the number of broken anchor leg wires increased, and the lying cable twisted. CNOOC (China National Offshore Oil Corporation) completed the emergency maintenance work of the damaged anchor leg under the condition that the FPSO was not released or stopped production. The maintenance of the entire mooring anchor leg mainly includes the replacement of the suspended chain segment of the mooring anchor leg and the sea bed chain segment. This maintenance project includes two parts of the replacement work. From the perspective of specific operation, the operation is divided in four phases: the first phase is release and towing the FPSO, the second phase is the recovery of the old mooring, the third phase is the pre-installation of the new mooring, and the fourth phase is the towing and tie-back of the FPSO. Of course, the acquisition and arrival of mooring materials are also an important part of the preliminary preparation work, as well as the investigation of the FPSO situation and the pre-investigation of the marine environment [8].

The successful released and tie-back of the mooring anchor legs were the first time in China deep water. Including the first independent towing scheme design: towing scheme, towing plan, towing stability calculation; Innovative design of deep water riser release and tie-back installation method; The innovative using of anchor mooring for reverse release and transfer, complete the establishment of protective wet storage tube, avoid using the VLS (Vertical pipe Laying Ship) boat; Anti-torsion technology of anchor chain; Water buoy disassembly and repair technology; Innovative design of large tonnage removal tooling for deep water mooring pin shaft; Innovative design of temporary suspension structure of mooring system dynamic riser. The key technologies in the process of releasing and tie-back of the mooring anchor leg of "Nanhai Shengli" FPSO will be introduced in the following sections, Including technical scheme, simulation analysis, selection of machinery and resources, domestic control, etc., so as to provide some references for the similar operation of the mooring anchor leg releasing and tie-back in deepwater floating production facilities [9].

2. Technical Plan for Releasing and Tie-Back of Anchor Legs of "Nanhai Shengli" FPSO

The FPSO mooring system of "Nanhai Shengli" is a permanent single-point mooring system with 10 anchor legs evenly distributed. When the position of FPSO changes with the bow turret, the stress state of each anchor leg also changes accordingly. Therefore, in order to ensure no mooring safety problems of FPSO caused by "missing legs" in typhoon and monsoon seasons, mooring leg releasing and tie-back operation had the characteristics of continuity and non-repetition. In the process of steel cable replacement in suspension chain segment, the FPSO needs to ensure that the watertight cover at the bottom of the single-point tank was located above the waterline (i.e. the draft of FPSO is less than 6 m), and the operations such as air diving, ROV (Remote Operated Vehicles) and steel cable replacement also have strict requirements on field wave height and wind speed, so the operation of mooring anchor leg releasing and tie-back is restricted by multiple time Windows. It has the characteristics of stage feasibility. Therefore, in order to complete this operation, scientific simulation, technical analysis, accurate field control, pre-investigation and post-investigation of the operation are very important.

According to the inspection, the anchor legs of "Nanhai Shengli" FPSO were attacked by strong typhoons, and the outer steel wire began to break under corrosion and stress. In August 2018, the anchor leg of No. 1, No. 2 and No. 9 suffered severe damage to varying degrees, mainly due to the broken wire of the steel cable of No. 2 and No. 9 anchor leg, and the twisted cable of No. 1 anchor leg. According to the two kinds of operation contents involved in the whole mooring anchor leg maintenance, the mooring anchor leg releasing and tie-back operation introduced in this paper takes the replacement of steel cables of No. 2 suspension chain segment and No. 1 seabed chain segment as the core objectives for simulation analysis and scheme design.

Plan for releasing of the anchor leg of "Nanhai Shengli" FPSO: (1) The operation of replacing suspended chain segment started from the FPSO. The top chain was released and lowered through air diving cooperation, and then the operation ship HYSY291 was assisted by ROV to recover the top chain. After the connection between the top and the FPSO cable was released, the upper steel cable, middle water buoy and lower steel cable were recovered in turn along the anchor leg. At the end of recovery operation, laying and tie back the mooring anchor leg in the opposite direction. (2) The operation of sea-bed chain section replacement starts from the ship. The triangle plate between the 1100 m laying

cable and the 345 m weight chain will be recovered and released by ROV coordination, and the 345 m weight chain will be lowered. Then, the laying cable will be recovered, the laying cable will be replaced, the cable joint will be made, the replaced laying cable will be recovered, the 345 m weight chain will be recovered, and the mooring anchor leg will be connected back.

2.1. Mooring Leg Releasing and Tie-Back Simulation and Technical Analysis

OrcaFlex software was used to simulate and analyze the whole process of the FPSO anchor leg releasing and tie-back operation. The stress state of the machinery, equipment and steel cable in each key operation step was intuitive and clear, which was conducive to the control and adjustment of the field operation. With the aid of OrcaFlex, the operation situation of the operating ship HYSY291 in recovery, laying and small angle heading adjustment is virtually presented. See Figure 2 and 3 for details.

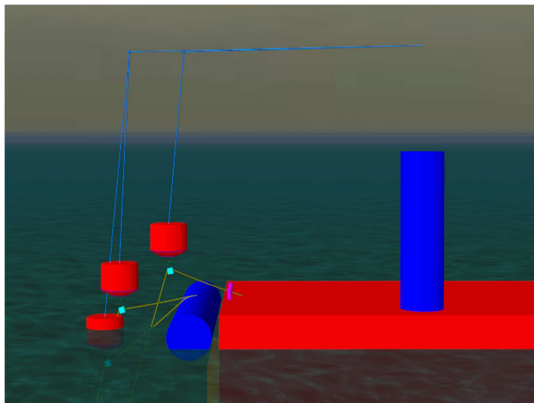

Figure 2. *Simulation of floating buoy lowering.*

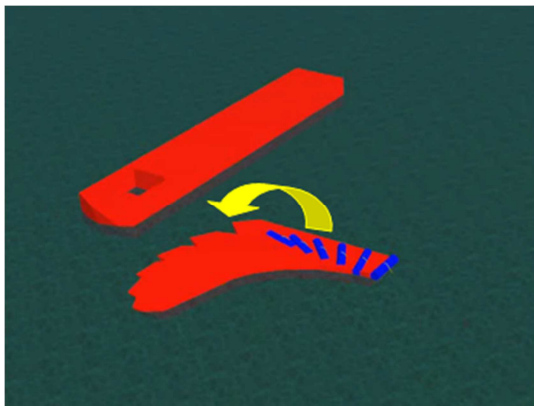

Figure 3. *Simulation of ship heading adjustment.*

In this operation, OrcaFlex was mainly used to combine FPSO, HYSY291, mooring anchor leg, crane, winch rigging and so on through the model, and then input the corresponding environmental data during the operation period, and then through the output results to simulate the entire operation process. The water depth of FPSO "Nanhai Shengli" in the operating area of Liuhua 11-1 oilfield is 295m, and the tidal variation range is +1.62 ~ -1.06m. According to the variation law of wave height and period in the statistical data of waves in the sub-South China Sea, the conventional wave height and period variation range should be considered during operation, and the wave height usually floats between 0.5m and 3m. The period is 5~15s. See Table 1 for the relationship between wave height and period. Isolated wave is an unconventional and common wave flow in the working area of Liuhua 11-1 oilfield. Isolated wave will form instantaneous strong current and produce strong impact on the working area. This kind of solitary wave is usually easy to form in summer and autumn, and the direction of incoming flow is between 75°~ 155° due north. The actual weather condition is usually better when the solitary wave is formed, and the maximum intentional wave height is less than 2m. The relationship between water depth, solitary wave and base flow is shown in Table 2.

Table 1. *Wave height and period.*

Water deep	Solitary wave	Annual velocity	
		Solitary1	Solitary2
25	0.3	2.4	2.1
60	0.3	2.35	2.05
100	0.25	2.25	2
140	0.25	1.95	1.7
180	0.25	0.95	0.7
200	0.2	0.3	0.1
220	0.2	-0.1	-0.3
270	0.2	-0.6	-0.8
275	0.2	-1.55	-1.75
280	0.2	-1.2	-1.4
294	0.2	0.2	0

Table 2. *Water depth and solitary wave and base current.*

Water deep	Solitary wave	Annual velocity	
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200	0.2	0.3	0.1
220	0.2	-0.1	-0.3
270	0.2	-0.6	-0.8
275	0.2	-1.55	-1.75
280	0.2	-1.2	-1.4
294	0.2	0.2	0

In the process of mooring leg releasing and tieback analysis, the model was established to simulate waves, and the maximum wave height and maximum isolated wave were always used to simulate the entire sea state (wind speed was not included in this simulation analysis) [2]. This analysis method was aimed at the worst possible situation in the operation process, so the analysis results had a larger safety space compared with the conventional situation. In the whole simulation analysis, by inputting environmental parameters, position and state parameters of operating equipment and tools, position and state parameters of mooring anchor leg and various basic parameters, the stress state of operating tools and mooring anchor leg in each step can be obtained. The simulation results can be used to effectively adjust and

evaluate the rigging selected during the operation and the approximate travel with each operation equipment. The simulation analysis ensures the success rate of the operation, and provides strong guidance and guarantee for the preparation of some non-adjustable key steps, which plays a vital role in protecting the cable from distortion during the operation. See Figure 4 and Table 3 for the specific stress process of simulation and analysis output.

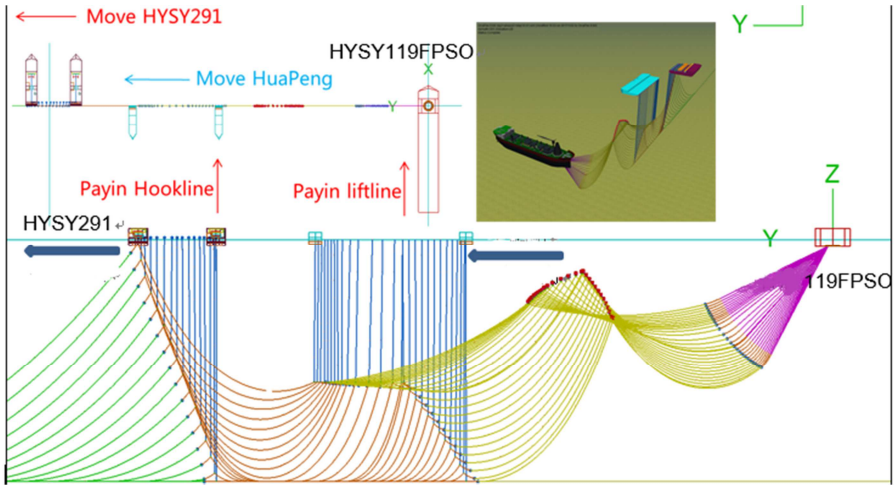

Figure 4. *Simulated and analyzed the process relationship of the output force.*

Table 3. *Specific force values of simulation and analysis output.*

Moving distance of HYSY291 (m)	Change distance between single point and HYSY291 (m)	Working winch length change of HYSY291 (m)	Working winch tension change of HYSY291 (Te)	Moving distance of HuaPeng (m)	Change distance between single point and HuaPeng (m)	Working winch length change of HuaPeng (m)	Working winch tension change of HuaPeng (Te)
3	780	353	21.0	0	542	174	46.9
5	785	333	30.4	10	552	174	47.5
7	792	313	38.3	15	567	174	48.1
6	798	293	46.5	13	580	174	49.1
7	805	273	54.4	18	598	174	49.7
7	812	253	61.3	10	608	174	49.3
8	820	233	65.1	10	618	174	46.4
6	826	213	69.3	6	624	174	43.6
6	832	193	73.6	4	628	174	40.7
10	842	173	77.7	4	632	174	37.7
10	852	153	81.9	4	636	174	34.5
8	860	133	86.5	4	640	174	31.1
8	868	113	91.5	4	644	174	27.3
4	872	93	97.6	4	648	174	23.1
3	875	73	104.4	4	652	174	18.1

2.2. Technology Selection of Mooring Leg Releasing and Tie-Back Construction Equipment

Mooring leg releasing and tie-back operation requires a large number of vessels with high risks. As this operation involves the mooring stability of FPSO in the "legless" state and the requirements of air diving, limiting vessels and main operating vessels on wind and wave, it is appropriate that the meaningful wave height of waves should not exceed 2.5m in general [2]. Therefore, mooring leg releasing and tie-back operation is very strict on the time window, and it is not recommended to perform similar operations in the South China Sea monsoon season except for special emergencies.

Mooring leg releasing operation has strict requirements on sea conditions. Therefore, in order to better control and complete the operation and enhance the anti-risk ability of the operation, the main operation vessel must have DP dynamic positioning system, which is required to be above grade 2. In addition to stability, the most important thing is that the construction capacity of the main working vessel should be effectively guaranteed, in which the crane, working winch, auxiliary winch, ROV, etc., should meet the design capacity [3]. Although the limiting vessel and the air submarine support vessel are not on the critical operating path, these two auxiliary working vessels directly determine the safety and feasibility of the operation [4]. According to the requirements of this work, HYSY291 was selected as the main working ship, HUAMING and HUAFA as the limiting ships [5], and HUAPENG as the air diving support ship. In addition, we also innovated and developed two kinds of working tooling to facilitate the smooth completion of the project.

a) Laying cable joint pin removal tool

Due to the long-time immersion of the anchor leg members in seawater, the attachment and reproduction of a large number of sea creatures, it is difficult to remove the laying cable joint latch. The project team, through innovative design and brainstorming, innovated design is suitable for the removal of large-tonnage deep-water anchor mooring pin shaft. In the offshore construction, the application effect is remarkable: removing a pin with a diameter of 262mm and a length of 650mm reduces the time from the original 20h to 1h, improves the on-site construction efficiency, greatly saves the on-site ship-day cost, and brings remarkable economic benefits [11].

b) Mooring dynamic riser temporary suspension structure

Due to the need to disassemble and assemble the riser in the process of releasing and tie-back of FPSO, the construction should not only consider the time spent on the riser construction, but also consider the impact of sea conditions, the replacement of drawstring rigging and other factors. From the perspective of safety, it is necessary to temporarily suspend the opposite pipe and find a suspension point of sufficient strength underwater. However, due to the absence of the original suspension design at a single point, the structural strength of the ship's bottom was found to be untestable during the land survey. The project team innovated the design of a large-tonnage riser suspension structure suitable for deep-water anchor chain, as a safe and reliable suspension point. Through the design calculation (OrcaFlex working condition analysis, get the maximum load; ANSYS modeling, finite element analysis; Design strictly in accordance with DNV specifications), the suspension card can perfectly match the needs of the project, and very safety, reliable, easy to remove. After the special riser suspension clip is installed on the anchor chain, the potential problems and risks such as no safety temporary suspension point and slip of the suspender are effectively solved in the suspension process of the riser [12].

3. Accurate Control of Mooring Anchor Leg Releasing in Field Operations

Suspension chain segment replacement mooring anchor leg releasing for field operation according to the timeline [4], the main operation process is as follows: Open the top chain stopper, top chain down, top chain transfer, top chain recovery, upper steel cable recovery, middle water buoy recovery, lower steel cable recovery, new lower steel cable laying, middle water buoy down, new upper steel cable laying, top chain transfer, top chain recovery and lock. As the water operation involves the main operation vessel, FPSO, limiting vessel and air diving support vessel in the process of operation, the underwater operation includes ROV, air diving and various elements such as locks, steel cables and anchor chains. In order to complete the operation task accurately, efficiently and safely, it is necessary to accurate the control system and positioning system, strict procedures should be controlled in the operation process. Unified command and strict execution.

Seabed chain segment replacement mooring anchor leg releasing and tie-back field operation According to the timeline, the main operation process is as follows: Recover the triangle plate between 1100m lying cable and 345 m counterweight chain, release and lower 345m counterweight chain, recover lying cable, replace lying cable, make cable joint, lay the replaced lying cable, recover 345m counterweight chain, and tie back mooring anchor leg. Compared with the replacement operation of the suspended chain segment, the distance between the operating vessel and the FPSO and the limiting vessel is longer during the replacement of the seabed chain segment, and there is no collision risk. Although there are few operation elements, the operation still needs precise control and unified command.

3.1. The Main Work Stages Are as Follows

3.1.1. The First Phase of FPSO Is Release and Towered to the Shipyard

To complete the land preparation work, including the FPSO relief program expert review, the release of the risk analysis of the operation, the completion of the major homework double record, the completion of the towing air and the navigation police and other certificates to handle the work. During the sea operation, the joint of HYSY291 and the empty submarine support ship, through the divers assistance to solve the joint of the FPSO and 3 vertical pipes, and then release the FPSO and 10 anchor legs, and the temporary wet storage and anchor legs from the sea floor.

3.1.2. Old Anchor Leg Recovery New Anchor Leg Installation

The old top chain was recycled, and the upper and lower cable is abandoned (the steel cable is abandoned in the area of the operating area), the protective recovery of the steel cable, and the protective recovery of 10 water buoy and the connecting pieces, the grip of the anchor and the bottom on the sea will keep using [13].

3.1.3. New Anchor Leg Installation

After the dock was poured down to the main winch by the inverted cable, the new anchor chain was poured to the hawser [17], and the new anchor leg was gradually completed, the new anchor leg was wet store and waited for the FPSO to return. The main process of the new anchor system is putting 10 weight chains and 9 top chains in the anchor chain, which is stored in the drum of the big winch, and then the circle was connected by the chain of the weight, the water buoy, the upper steel cable and the top chain are connected in order, and the order is the #3, #4, #5, #9, #10, #1, #2, #6, #8, #7. An anchor leg shall be laid for each voyage, and the ROV shall be investigated for the routing and the new anchor system [14].

3.1.4. FPSO Dock Towing and Hooking After Dock Repaired

During the installation of the new anchor leg, the team will prepare the communication coordination meeting, implement

the expert review, form the hazid report, complete the major operation double record, complete the towing flight and the navigation police, and the help of the shipyard to complete the single point turret rotation test, and the replacement of the tira cable. The FPSO will be carried out after the dock is repaired by the ship's shipyard, and the oil field will be carried back to the flow field. Then, three tugs of "HUAHU", "HUAFA", "HUAPENF" to limit the FPSO, the aided by the divers and the HYSY291, returning 10 anchor legs, and then return 3 pipes. After the completion of the vertical tube and the trial pressure is finished, all the operating vessel gone.

3.2. Position Control of the FPSO, Operation Vessel, Air Submarine Support Vessel and Limiting Vessel

In this operation, multiple technical means such as surface differential GPS positioning system [2], central control communication system, ROV underwater accurate positioning, air diving and underwater observation were applied for on-site control [5]. The central control communication system establishes real-time communication of each ship, and the ship carries out the operation task for the main line of the operation, issues instructions to each ship, and makes unified dispatch and command to ensure that the operation is carried out according to the procedure, avoiding unnecessary crossing operation and other risks. At the same time, the position of each operating vessel and ROV underwater positioning can be monitored in real time on the operating vessel through the surface positioning system, so that the main operating vessel can provide accurate information for the formulation of its operation instructions. All relevant parties involved in the operation have an intuitive global concept of the operation task and the overall situation. The precise control of surface, underwater and operational procedures ensured the efficient and smooth completion of the operation. See Figures 5 and 6 for details of the surface positioning system and ROV underwater operation [10].

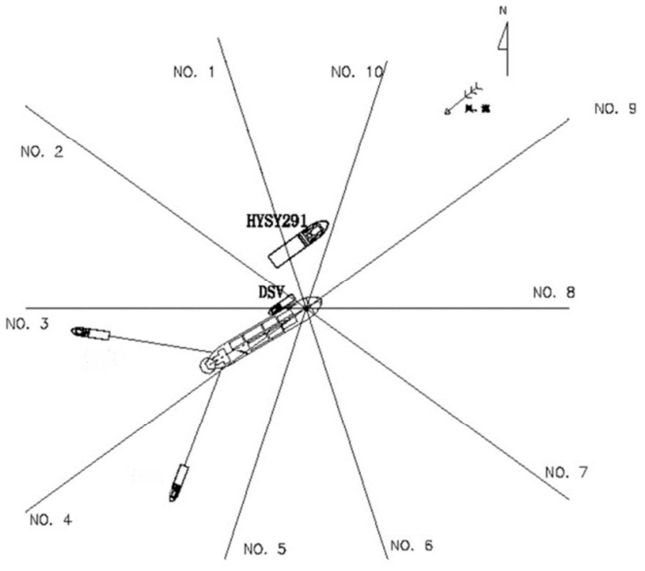

Figure 5. *Display of the water surface positioning system.*

Figure 6. *ROV underwater operation.*

3.3. Monitoring and Warning of Isolated Waves

In the operating area of Liuhua 11-1 oilfield, isolated wave is an unconventional common wave flow [6], which will form an instantaneous strong current and have a strong impact on the operating area. When the mooring anchor leg is released for top chain transmission or recovery transmission, the ROV of the main operating vessel needs to conduct lock hook underwater, and the working winch rigging of the main operating vessel will be released into the water. At the same time, the air diving support vessel is in the state of cable FPSO. In this operation, the distance between the main operation vessel and the FPSO and the air support vessel is very small (the minimum instantaneous distance is less than 20 m), and the underwater rigging, anchor chain and ROV are also gathered in multiple parties. If the isolated wave attacks in this part suddenly, it may cause collisions between ships or entanglement of various underwater parts. It is a big security risk. Therefore, isolated wave monitoring and warning system must be carried out [8].

Over the years, we do not have a deep understanding of the harm degree of isolated internal waves, and its formation is temporary and uncertain, which makes it difficult for us to make empirical judgment. Therefore, we must monitor isolated waves throughout the operation period. In this operation, one of the operating vessels is designated to conduct real-time monitoring about 2 nautical miles upstream of the incoming stream. Once the isolated wave strikes, the monitoring vessel will immediately inform each operating vessel, so that the ROV and each operating vessel (especially the main operating vessel and the limiting vessel) can adjust the ship position to mitigate the impact of the isolated wave, and avoid dangerous situations [15]. Real-time monitoring of isolated wave provides effective safety guarantee for mooring leg releasing and tie-back operation.

4. Pre-Survey and Post-Survey of Mooring Leg Releasing Operations

Mooring leg releasing and tie-back operation was underwater operation, which was more unknown and uncertain than conventional offshore engineering operation [16]. Due to the limitations of draft time window and weather time window

of FPSO, these operations had the characteristics of stage feasibility, continuity and non-repeatability. Therefore, field pre-investigation before field operation can effectively master the latest state of mooring anchor leg before releasing, and provide the latest information on preparation before operation, possible difficulties encountered in operation, deviation from expected operation, etc. The pre-investigation was conducted by ROV underwater observation, and the mooring anchor leg that needed to be replaced with steel cable was thoroughly inspected to determine whether there were any abnormal conditions. The pre-investigation can eliminate the hidden danger of unknown underwater state before the release operation of the anchor leg in the field, which lays a solid foundation for the smooth development of the field operation.

After the completion of mooring anchor leg releasing operation, ROV will be used to conduct whole-process inspection and record along the direction of steel cable laying [6], and check the operation results to ensure that the newly replaced steel cable has no distortion, broken wire and other operating damage that cannot be monitored by human resources during the operation. The formulation and implementation of the investigation plan after special operation provide effective guarantee for the replacement of new steel cable with zero damage and zero hidden trouble left.

5. Conclusion

The emergency maintenance of the anchor leg of "Nanhai Shengli"FPSO in Liuhua 11-1 oilfield was successfully completed. This maintenance project achieved zero reverse work and zero accidents through simulation, calculation and control technology releasing and tie-back of mooring anchor legs. It included the two major operation contents of the entire mooring anchor leg maintenance, namely suspension chain segment replacement and seabed chain segment replacement. The actual operation time was reduced by about 30% compared with the planned time, which effectively saved the operating costs of ship machinery and tools. At the same time, this operation was carried out under the condition that the FPSO would not be released or shut down, which effectively eliminated the major operational risks without reducing production in the operating area of the oilfield.

It is the first time that releasing, tie-back and steel cable replacement of the anchor leg of the FPSO permanent internal turret single point mooring system in deep water in China. The releasing and tie-back operation of the anchor leg of the FPSO achieved a complete success by skillful management and daring innovation in the aspects of technical scheme development, equipment technology selection and on-site accurate control. It provides a valuable reference for the maintenance of anchor leg in domestic deep-water floating production facilities.

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