Research on Navigation Safety of FPSO Towing Operation

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Abstract. In order to avoid and reduce the impact of water and underwater activities on navigation, maintain navigation order, protect ocean resources, ensure navigation safety, and promote the development of water transportation economy. Through the investigation and analysis of the project and the scientific evaluation method, the navigation safety of the ships involved in the project under the relevant water environment is analyzed and studied. Taking "Petrobras 76" as an example, the safety of towing is evaluated from the aspects of Meteorology, hydrology and local waterway conditions. Combined with the specific implementation scheme of the project, targeted risk assessment research is carried out. Finally, from the perspective of ship navigation safety, the rationality of the project design scheme is comprehensively evaluated, and the relevant safety is proposed Countermeasures, measures and suggestions for navigation.

1. Introduction
In the future, energy acquisition will be mainly concentrated in the ocean. Floating production storage and Offloading Unit (FPSO) is the mainstream facility for offshore oil and gas production, storage and transportation. Due to its lack of self-propelled ability, FPSO needs to be towed by high-power tugs from the port to the sea area [1]. In the process of FPSO towing, due to the influence of wind, wave, current and other environmental factors, the situation of yaw and sway endangering the towing safety often occurs. However, the crew often take countermeasures based on experience, which lacks a certain theoretical basis [2].

The “Petrobras 76 (P76)” is a FPSO refitted by Dalian COSCO Shipping Engineering Co., Ltd. from VLCC, and has no self-propelled capability. The P76 ship of the project is planned to leave the COSCO Shipping terminal, and use the tug designated in port to tow it to the eastern water area of the anchorage of the first cargo ship in Dalian port (38°56′16″N, 121°44′40″E), and then connect the tow cables of two foreign oceangoing tugs. After the connection, the P76 will be towed to the designated waters outside the port boundary for ballast. After the draft reaches 10.5 meters, it will be directly towed to Rio de Janeiro, Brazil [3]. The tow organization chart is shown in Figure 1.
2. Towing force calculation and towing scheme

2.1. Towing force calculation

According to Classification Society of China guidelines for towing at sea, the total resistance of sea towing can be calculated according to the following empirical formula:

\[ \sum R = 1.15[R_f + R_B + (R_{ft} + R_{Bt})] \]  

where: \( R_f \) is the friction resistance of towed ship; \( R_B \) is the residual resistance of towed ship; \( R_{ft} \) is the friction resistance of tugs; \( R_{Bt} \) is the residual resistance of tugs.

1) Towing resistance

The resistance of the towed ship or object is determined by the following approximate methods:

\[ R_f = 1.67A_1V^{1.83} \times 10^{-3} \]  
\[ R_B = 0.147C_bA_2V^{1.74+0.15\nu} \]

where \( A_1 \) represents the underwater wet surface area of a ship or a structure over water; \( V \) is the towing speed; \( C_b \) is the block coefficient. \( A_2 \) represents midship cross section area of submerged part.

2) Towing resistance

Several tugs will be used in the actual towing operation. Since the tugs are basically similar in ship type and resistance, the resistance of tugs can be determined by tug design data. If there is no data available, an approximate calculation can be made according to the design data of the tug.

The ship may encounter the situation of wind and current in the towing process. The towed ship can only overcome the wind and current by relying on external force, so as to ensure that the ship does not “lose its position”. The wind and current force can be calculated by using the formula of wind force and flow force.

\[ \sum F_x = \frac{\theta}{2} (\rho_d \times C_d \times V_d^2 \sin^2 \theta \times B_d + \rho_W \times C_W \times V_c^2 \sin^2 \alpha \times L_w \times d) \times 10^{-3} \]  
\[ \sum F_y = \frac{\theta}{2} (\rho_d \times C_d \times V_d^2 \cos^2 \theta \times A_d + \rho_W \times C_W \times V_c^2 \cos^2 \alpha \times L_{w1} \times d) \times 10^{-3} \]

where \( \sum F_x \) is the transverse wind force (KN); \( \sum F_y \) is the Longitudinal wind force (KN); \( C_d \) is the wind power coefficient; \( C_W \) is the hydrodynamic coefficient; \( B_d \) is the projected area of hull side above waterline (m²); \( L_w \) is the ship waterline length (m); \( A_d \) is the projected area of hull front above waterline (m²).

Because there are many hydraulic structures in the harbor area, especially the narrow water area in the...
channel, if only considering the towing resistance in the forward direction of the ship, the resistance caused by wind and current may cause the ship to deviate from the course and run aground. In order to avoid the towing ship yawing, the towing force provided by the tug in the direction perpendicular to the channel must be balanced with the wind and current force in same direction. Namely, the towing force required in the forward direction (i.e. longitudinal direction) should be at least balanced with the sum of the resistance of the tug and the towed ship in that direction as well as the wind and current force; the towing force required in the vertical and forward direction (i.e., transverse) should be at least balanced with the wind and current force in that direction. According to navigation experience and towing practice, 20% reserve towing force should be reserved. Therefore, the total towing force required for towing operation can be calculated by the following formula [4].

The longitudinal towing force required for towing is the total thrust of the main tug:

$$\sum R_y = 1.38[R_f + R_B + (R_{ft} + R_{bt})] + 0.6g(\rho_a \times C_a \times V_a^2 \cos^2 \theta \times A_a + \rho_w \times C_w \times V_c^2 \cos^2 \alpha \times L_{w1} \times d) \times 10^3$$

(6)

Transverse towing force required for towing operation:

$$\sum R_x = 0.6g(\rho_a \times C_a \times V_a^2 \sin^2 \theta \times B_a + \rho_w \times C_w \times V_c^2 \sin^2 \alpha \times L_{w1} \times d) \times 10^3$$

(7)

2.2. FPSO information

Table 1 shows the information of the FPSO which in this project going towing.

| Items                | Values | Units | Items                | Values | Units |
|----------------------|--------|-------|----------------------|--------|-------|
| Total length         | 332    | m     | total ton            | 164980 |       |
| Width                | 58.00  | m     | Sea towing draft     | 10.5   | m     |
| Draught              | 6.621  | m     | towing draft in port | 6.5    | m     |
| Net ton              | 97671  |       | length between perpendiculares | 320.792 | m |
| depth                | 28.10  | m     |                      |        |       |

2.3. The tug information

The towing operation in the port of this project is jointly undertaken by six harbor tugs, and the main engine horsepower of each tugboat shall be no less than 4200hp. In addition, one tugboat is required to undertake the escort mission.

Two foreign ocean going tugs are responsible for the sea towing operation of the project.

2.4. Towing arrangement

The main towing arrangement are shown in Figure 2.

2.5. Towing operation process

The COSCO Shipping pilot and the pilot of Dalian Port pilot station boarded the P76 ship at the shipyard wharf, and the COSCO Shipping pilot was responsible for towing the P76 from the wharf to the yard turning area of COSCO Shipping.

The pilot of Dalian Port took over from the turnaround area of the shipyard and was responsible for directing the towing of the P76 to the eastern waters of the anchorage of the first freighter in Dalian port (38°56′16″N, 121°44′40″E).
In the eastern water area of the anchorage of the first cargo ship, the pilot of Dalian Port pilot station, with the assistance of tugs in the port, monitors the connection process of tow cables of two foreign ocean-going tugs [4].

![Figure 3. Schematic diagram of starting point and ending point of towing operation.](image)

After the towline connection is completed, under the escort of tugboat in port, the pilot of Dalian port will be responsible for directing the foreign tugboat to tow P76 out of the port. The pilot disembarked at the departure point (38°53′N, 121°44′5″E) of Dasanshan waterway, and the foreign tugboat towed the P76 to the designated ballast water area outside the port boundary. It is planned that after 2-3 days of ballast operation, the P76 ship will be towed to Brazil by two foreign tugboats.

The starting point of towing in the port of the project, the connection point of foreign ocean tug's towing cable and the terminal point of towing in the port (i.e. the designated ballast water area) are shown in Figure 3.

3. Analysis of interaction between towing operation and natural environment

3.1. Wind effects

The sea area belongs to East Asian monsoon region, with significant seasonal changes, with the south wind in summer and northerly in winter. Table 2 shows the wind direction frequency from 1951 to 2003, the normal and secondary wind directions in this area are N and S, with the frequency of 15% and 12% respectively. The strong wind direction is N, and the frequency of wind with the direction ≥ 6 is 1.99%. The frequency of wind occurrence in all directions ≥ 6 and ≥ 7 is 4.62% and 1.65% respectively, which is converted into 17 days and 6 days in the whole year. The maximum wind speed in N direction is 34m/s, which occurs in April 1964 and March 1965.

![Table 2. Wind direction frequency from Dalian meteorological station (1951 – 2003) (%).](image)

When the wind force acts on the ship, it will produce wind-induced deflection, wind-induced drift and so on. Before the towing of the project, the weather conditions that meet the towing conditions should be selected according to the weather forecast. If the towing conditions cannot meet the requirements, the start date of towing should be adjusted according to the weather forecast. In case of strong gust during towing, the wind pressure difference should be correctly pre-allocated according to the wind direction and intensity, and the ship should be operated carefully to ensure the safety of towing operation.

3.2. Wave influence

The frequency of wave influence is low, especially when the wave height is greater than 1.0 m, only 0.54%.
The wind waves in the small wind area of Dalian Bay are mainly affected by the directions of WSW, W and WNW. Large waves have a great impact on the towing operation, and the wave height shall not exceed 1 m when the project starts towing from the shipyard [5].

3.3. Current influence
The tidal current in Dalian Bay goes deep in counterclockwise and clockwise at high tide and low tide respectively. At high tide, the tidal current enters from Dagushan sea area, and part of the water flows into each sub Bay after entering the Bay, and most of the water body flows to the tiger beach sea area after reaching the middle of the bay. The sea area belongs to the irregular semi diurnal tidal current area. The periods of the twice daily rising and falling tides are different, and the tidal current intensity is also different, one strong and one weak. According to the chart data, the current velocity of rising tide is about 1kn, and that of ebb current is about 1.5 kn. The larger current changes the speed of the ship, and also causes the ship to deviate from the planned route or to roll and drift. During the towing operation, we must be cautious, pay attention to safety, correctly pre allocate the flow pressure difference, control the heading and avoid yaw.

3.4. Fog influence
Fog days (including cloudy days, rain and snow) with visibility less than 1km are mainly from April to July. When the project is towed from the shipyard, the visibility must be greater than 3000m. In case of heavy fog during towing operation, relevant regulations shall be strictly observed, fog signal shall be sounded according to regulations, and safe speed shall be adopted to ensure towing safety.

4. Navigation safety assessment of towing operation

4.1. Estimation of water depth required for towing operation
The towing draft of P76 wheel of the project is 6.5 m, and the required towing depth is 7.15 m based on 10% surplus water depth. Except for the waters near COSCO’s turning area, the water depth of the other sections is greater than 7.15 m, meeting the towing requirements. The shallowest water depth near COSCO’s turning area is 5 m, and the P76 needs to ride the tide for 2.15 m. The tidal water level in Dalian Bay is 2.45 m with a guarantee rate of 90%, which meets the towing requirements of the project. Towing can be arranged before the high tide to ensure the safety of towing. According to the tide table of navigation Guarantee Department of the Chinese People's Liberation Army command, the tide situation of Dalian port from October 23 to 27, 2014 is shown in Table 3.

| data     | time of tide     | height of tide | When the tide height is 2.15 m in the morning of that day |
|----------|------------------|----------------|----------------------------------------------------------|
| 10.23    | 0407; 0955 1610; 2218   | 0.37; 2.60 0.28; 2.92 | 0734～1234                                               |
| 10.24    | 0442; 1024 1641; 2246   | 0.41; 2.63 0.33; 3.06 | 0839～1218                                               |
| 10.25    | 0515; 1053 1711; 2314   | 0.51; 2.68 0.38; 3.17 | 0902～1254                                               |
| 10.26    | 0549; 1124 1743; 2345   | 0.57; 2.68 0.38; 3.20 | 0932～1325                                               |
| 10.27    | 0626;1159 1818      | 0.58; 2.60 0.31 | 1015～1350                                               |
| 10.28    | 0023; 0706 1239; 1856 | 3.15; 0.53 2.46; 0.24 | 1112～1411                                               |

4.2. Estimation of required width for towing operation
According to the actual situation of tugboat configuration of the project, during the towing process of P76 in COSCO Shipping Channel, as there are auxiliary tugs on both sides of P76 to assist in controlling the ship...
position, the actual dimensions of P76 and its auxiliary tugs on both sides are used to check the required water area width for towing operation [6].

If the captain of port tug is 35 m and the width of P76 ship is 58 m, the width of water area required for towing combination is calculated as follows:

\[
(35 + 15) \times 2 + 58 = 158 \text{ m}
\]

If P76 is kept in the middle of the channel, there are still 21m channel surplus widths on the left and right sides of P76. This shows that the 200 m wide channel of COSCO Dalian can meet the needs of safe towing of P76.

4.3. Assessment of designated ballast water area

The designated ballast water area of the project is located between the encountering rock and the circular island, which is a square area with a side length of about 8 nautical miles. The nearest distance between the ballast water area and the encountering rock area is about 13’52, and the nearest distance to the round island is about 3’45.

The customary route near the designated ballast water area of the project is shown in Figure 4. The ballast waters are designated to avoid the customary routes of Dalian Laotieshan waterway, Dalian to Yantai waterway and Dalian Weihai waterway, which have little influence on the customary navigation routes of Ro-Ro ships in Dalian Yantai direction and Dalian Weihai waterway. However, the designated ballast water area of the project is located on the customary route of Dalian to Chengshanjiao, which has a certain impact on the passing ships on the customary route from Dalian to Chengshanjiao. In this project, tugboat monitoring measures can be taken in the port, and ships passing by can avoid the designated ballast water area to ensure the safety of ballast operation.

Therefore, the designated ballast water area is appropriate under certain conditions [7].

4.4. Depth assessment of designated ballast waters

The draft of P76 ship in this project needs to be adjusted from 6.5m in harbor to 10.5m at sea in designated ballast water area.

In the designated ballast water area of the project, the shallowest water depth is about 47m, meeting the ballast requirements of P76 wheel.

4.5. Analysis of influence of towing operation on navigation safety and environment

The towing route of the project crosses the northeast corner of the oil tanker anchorage, the southwest corner of the second cargo ship anchorage and Ganjingzi channel. The ballast operation occupies a certain range of water area. The ship traffic flow on the towing route and the designated ballast water area is relatively dense, and the towing operation and ballast operation have a certain impact on the past ships. According to AIS statistics, in 2012, the vessel traffic flow of Ganjingzi channel was 2891, and the average daily flow was about 7.9. Among them, oil tankers and non-transport ships account for a large proportion, accounting for
about 78% of the total, and the others are cargo ships and passenger ships. The AIS track distribution of ships in Ganjingzi channel is shown in Figure 5.

Figure 5. AIS track distribution of ships in Ganjingzi channel.

However, as the project is a temporary project, and the towing combination is only carried out along a single planned route, the ballast operation is only limited to the designated water area, which will not increase the traffic flow in the sea area and the designated ballast water area. The water area occupied by the operation at a certain time only affects the navigation ships near the water area. As long as the safety measures are implemented on the basis of the implementation of the international collision prevention rules, the impact is controllable.

As the project is towing and ballast operation, no hydraulic structures will be produced after completion, so the navigation safety of water area will not be affected after completion.

5. Conclusion
Towing operation of FPSO is a systematic project. Before towing, proper towing scheme and emergency plan should be formulated to clarify the responsibilities and obligations of all parties involved in towing. Under the premise of scientific management, strict organization and careful planning, according to the method proposed in this paper, the risk can be minimized and the towing task of the project can be successfully completed.

6. References
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