Simulation research on mooring stability of oil tankers in Changxing Island Port Area considering open environmental conditions

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Abstract. The contribution of this paper is to study the mooring stability of oil tankers by OPTIMOOR software considering the open environmental conditions in Changxing Island Port Area. Firstly, influence factors on mooring stability is analyzed, which are considered as the inputs in the numerical models. Then, the experimental cases under the combinations of waves, water level, tidal current, and wind are developed. Next, the standard of mooring stability used in this paper is given after comprehensively considering the standards used in Norwegian, German, Japan and British. Finally, by feeding the environmental conditions in Changxing Island Port Area, all the numerical experimental tests are conducted and six motion components of moored ships are obtained. The results show that (1) The water level has little effect on six motion components. (2) Compared with oblique sea and following sea, beam sea has the greatest impact on the mooring stability of oil tankers.

1. Introduction
At present, considerable attention is being given to mooring stability of oil tankers along with the emergence of ultra-large ships and open-sea terminals. Due to the open marine circumstances in Changxing Island Port Area, mooring stability of oil tankers is easily affected by severe natural conditions, such as heavy current, tough wave and strong wind, which can cause huge damage to ships and terminal structure. On the one hand, the failure probability of mooring cables gets higher with the increase of mooring force given the severe conditions, which can cause great harms to ships, especially the large ships. On the other hand, given the poor mooring stability, there is a huge collapsing force of oil tankers to terminal structure, which can give huge economic losses to terminal operators. Therefore, it is urgent to study mooring stability of oil tankers faced with open and severe environmental conditions in Changxing Island Port Area.

For the mooring stability of ships, several researchers have given much attention and studied. For example, Gao et al. analyzed the ship motion, mooring force and impact force for three different mooring cable arrangements involving two alternative mooring points under the combined action of wave and flow [1]. YH Rho et al. performed static and dynamic mooring analyses to evaluate the stability of a spider buoy after disconnection from a turret during cyclone environmental conditions [2]. Shen and Zhou studied the roll motion of a moored ship under the wave and loading conditions by taking a 100000-ton cargo ship as a test ship and analyzed the peak value of the roll motion amplitude [3]. Chen et al. conducted the model test by taking a 3000-ton deck barges as a research object to
study the mooring stability of ships, and analyzed the impact factors of the mooring force and the change law of the mooring force [4]. Liu et al. studied the movement law of moored ships at large open terminal under irregular traverse waves through theoretical analysis and physical model test, and gave a complete formula for estimating the movement of moored ships [5]. Zhang et al. proposed a semi-empirical and semi-theoretical calculation formula with higher precision for the motion components of moored ships through theoretical analysis and physical model tests [6]. Sakakibara et al. studied the effect of the asymmetry coefficient of the mooring system between cable elasticity and fender elasticity on the motion components of moored ships using numerical calculations [7]. Liu proposed an estimation formula for the surge, roll and heave movements of moored ships under the action of lateral irregular waves considering the conditions of wave height, wave length, ship load and roll period [8]. Van et al. numerically simulated the motion response and mooring load of a moored LNG in the Withnell Bay in northwestern Australia by using a six-degree-of-freedom model, and proposed an estimation formula for the roll motion of the moored ship [9].

Apart from physical model experiments and mathematical models, some researchers have used the mooring analysis software to study the mooring stability of ships, such as MOSES software [10], MATLAB software [11] and OPTIMOOR software [12-15]. For example, Q Chen established a mooring mathematical model for a 300,000-ton bulk carrier by using the mooring analysis software MOSES, and calculated the ship movement response and cable mooring force of the mooring system under different wave periods, heights and directions [10]. Q Zhang studied the force control system of the mooring cable by using the MATLAB platform, and analyzed the stability balance and cable vibration of the ship mooring [11]. Y Li studied the effects of wave periods, heights and directions on the mooring force and ship movement by OPTIMOOR software, and discussed the mooring response of ships under long-period waves [12]. JF Flory et al. analyzed the influence of mooring cable properties on the stability of 10,000-ton ships under the unfavorable conditions under different properties by OPTIMOOR software [13].

Most of the existing researches have considered the wave characteristics such as wave periods, heights and directions to study the mooring stability of ships through physical model tests and mathematical model tests. Besides, studies by mooring analysis software mainly concentrated on the influence of one factor on the stability of ships. Therefore, to overcoming the limitations of mathematical models, this paper applies OPTIMOOR software used widely to study the mooring stability of ships under complicated natural environments, such as wind, wave and tidal current in Changxing Island Port Area.

2. Method

2.1. Factors on mooring stability

There are many factors affecting the mooring stability of ships, such as the natural characteristics of wind, wave and tidal current. Besides, another factor influencing mooring stability that must be considered is the attributions of ships, such as the tonnages, load and length of ship. A gust of wind, a passing ship or changes in tide and freeboard can cause mooring cable failure and sudden movement of ships. Such an accident can result in costly damage to cargo handling equipment or other nearby structures [13]. Therefore, this paper classifies the factors on mooring stability of ships into five categories: waves, water level, tidal current, wind and the attributions of ships. The following concentrates on the experimental cases of mooring stability considering the combinations of the influence factors.

2.2. Experimental cases

The following experimental cases involve a 300,000-ton oil tanker moored alongside a terminal. The length of the ship is 334 m and the molded depth is 31.5 m. This tanker is used because it is the test ship used for the terminal construction in Changxing Island Port Area. The mooring arrangement which is used in stability analyses is shown in figure 1.
Under the condition that ships are fully loaded, mathematical simulation tests are carried out on various test combinations of waves (beam sea, oblique sea and following sea), water level (extreme high-water level, design high-water level and design low-water level), tidal current (flow and edd) and wind (no wind, across-wind and along-wind). The schematic diagram of experimental cases is shown as follows.

![Figure 2. The schematic diagram of experimental cases.](image)

2.3. Standard of mooring stability

Under the action of wave and tide, the motion state of a moored ship can usually be described by six motion components, which are surge, sway, heave, pitch, roll and yaw. In this paper, the six motion components are selected to evaluate the mooring stability of ships. The schematic diagram of six motion components is shown in figure 3.

![Figure 3. Six motion components of moored ships.](image)

With consideration of the port construction in the real life, this paper refers to the standards of six motion components of moored ships issued in Norwegian, German, Japan and British to determine the standard used in this paper, which are shown in Table 1.
Table 1. The standard of six motion components of moored ships.

| Types of the standard | Surge (m) | Sway (m) | Heave (m) | Yaw (°) | Pitch (°) | Roll (°) |
|-----------------------|-----------|----------|-----------|---------|-----------|----------|
| Standard used in this paper | 2.0       | 2.0      | 0.5       | /       | 3         | 4        |
| Norway                | ±2.3      | ±1.0     | 0.5       | /       | 4.0       | ±3.0     |
| Germany Per Bruun     | 2.0       | ±0.5     | 0.5       | 1       | /         | /        |
| Japan                 |           |          |           |         |           |          |
| Outer                 | ±1.5      | ±0.75    | ±0.5      | ±2.0    | ±4.0      | ±4.0     |
| Inner                 | ±1.0      | ±0.75    | ±0.5      | ±1.5    | ±3.0      | ±3.0     |
| British norms         | 0.5~2.0   | 0.5~2.0  | /         | /       | /         | /        |

3. Case study

3.1. Parameter settings

In the mathematical simulation tests, the wave height (H4%) of the beam sea and oblique sea is set as 2.0 m, and the wave height (H4%) of the following sea is set as 2.5 m. Besides, the period of all types of waves is set as 7.0 s. The wind speed of across-wind and along-wind are set as 20.8 m/s to 24.4 m/s. Under the condition of extreme high-water level, only the effect of no wind is considered. Under the conditions of design high-water level and design low-water level, the effects of no wind, across-wind and along-wind are considered. High tides and low tides are considered under all conditions of water level in this paper.

3.2. Results

After conducting all the numerical simulation models, the results of six motion components of moored ships at full load are shown in Tables 2-Table 4. Besides, the contrast between maximum six motion components and standard is shown in Table 5.

Table 2. Six motion components of moored ships subjected to beam sea at full load.

| Water level               | Tidal | Waves | H4% (m) | T (s) | Surge (m) | Sway (m) | Heave (m) | Pitch (°) | Roll (°) | Yaw (°) |
|---------------------------|-------|-------|---------|-------|-----------|----------|-----------|-----------|----------|---------|
| Extreme high-water level  | Flow  | 2.0   | 7.0     | 0.2   | 0.4       | 0.03     | 0         | 0.2       | 0        | 0       |
|                           | Ebb   | 2.0   | 7.0     | 0.4   | 0.34      | 0.03     | 0         | 0.2       | 0        | 0       |
| Design high-water level   | Flow  | 2.0   | 7.0     | 0.2   | 0.4       | 0.02     | 0         | 0.2       | 0        | 0       |
|                           | Ebb   | 2.0   | 7.0     | 0.3   | 0.4       | 0.02     | 0         | 0.2       | 0        | 0       |
| Design low-water level    | Flow  | 2.0   | 7.0     | 0.2   | 0.38      | 0.03     | 0         | 0.2       | 0        | 0       |
|                           | Ebb   | 2.0   | 7.0     | 0.4   | 0.38      | 0.03     | 0         | 0.2       | 0        | 0       |

From the results in Tables 2-Table 5, it can be drawn: (1) The maximum sway of the moored ship at full load in these numerical experiments is 0.4m, and the maximum surge is 0.8m, and the maximum heave is 0.04m, and the maximum value of the roll angle is 0.2°. (2) The maximum value of sway and roll appears in the case of beam sea, and the maximum surge of the moored ship appears in the condition of design low-water level along with following sea, ebb and along-wind. Other motion components change little with changes in external environmental loads. (3) From the results in Table 5, the mooring stability of oil tankers in Changxing Island Port Area is satisfied according to the standard used in this paper.
### Table 3. Six motion components of moored ships subjected to oblique sea at full load.

| Water level       | Tidal | Wind condition | Waves \( H_{Ew} \) (m) | \( T \) (s) | Surge (m) | Sway (m) | Heave (m) | Pitch (°) | Roll (°) | Yaw (°) |
|-------------------|-------|----------------|--------------------------|-------------|-----------|----------|-----------|-----------|----------|--------|
| Extreme high-water level | Flow  | No wind        | 2.0                      | 7.5         | 0.3       | 0.1      | 0.04      | 0         | 0.1      | 0      |
|                    | Ebb   | No wind        | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0.1      | 0      |
| Design high-water level | Flow  | No wind        | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0.1      | 0      |
|                    | Ebb   | No wind        | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0.1      | 0      |
| Design low-water level | Flow  | No wind        | 2.0                      | 7.5         | 0.3       | 0.1      | 0.04      | 0         | 0        | 0      |
|                    | Ebb   | No wind        | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0        | 0      |
| Design high-water level | Flow  | Across-wind    | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0.1      | 0      |
|                    | Ebb   | Across-wind    | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0.1      | 0      |
| Design low-water level | Flow  | Across-wind    | 2.0                      | 7.5         | 0.3       | 0.1      | 0.04      | 0         | 0        | 0      |
|                    | Ebb   | Across-wind    | 2.0                      | 7.5         | 0.4       | 0.1      | 0.04      | 0         | 0        | 0      |

### Table 4. Six motion components of moored ships subjected to following sea at full load.

| Water level       | Tidal | Wind condition | Waves \( H_{Ew} \) (m) | \( T \) (s) | Surge (m) | Sway (m) | Heave (m) | Pitch (°) | Roll (°) | Yaw (°) |
|-------------------|-------|----------------|--------------------------|-------------|-----------|----------|-----------|-----------|----------|--------|
| Extreme high-water level | Flow  | No wind        | 2.5                      | 7.5         | 0.3       | 0.0      | 0.02      | 0         | 0.0      | 0      |
|                    | Ebb   | No wind        | 2.5                      | 7.5         | 0.4       | 0.0      | 0.02      | 0         | 0.0      | 0      |
| Design high-water level | Flow  | No wind        | 2.5                      | 7.5         | 0.3       | 0.1      | 0.01      | 0         | 0.0      | 0      |
|                    | Ebb   | No wind        | 2.5                      | 7.5         | 0.4       | 0.1      | 0.01      | 0         | 0.0      | 0      |
| Design low-water level | Flow  | No wind        | 2.5                      | 7.5         | 0.3       | 0.1      | 0.01      | 0         | 0.0      | 0      |
|                    | Ebb   | No wind        | 2.5                      | 7.5         | 0.4       | 0.1      | 0.01      | 0         | 0.0      | 0      |
| Design high-water level | Flow  | Across-wind    | 2.5                      | 7.5         | 0.5       | 0.1      | 0.01      | 0         | 0        | 0      |
|                    | Ebb   | Across-wind    | 2.5                      | 7.5         | 0.6       | 0.1      | 0.01      | 0         | 0        | 0      |
| Design low-water level | Flow  | Across-wind    | 2.5                      | 7.5         | 0.8       | 0.2      | 0.01      | 0         | 0        | 0      |
|                    | Ebb   | Across-wind    | 2.5                      | 7.5         | 0.6       | 0.2      | 0.01      | 0         | 0        | 0      |

### Table 5. The contract between maximum six motion components and the standard.

| Motion components | Surge (m) | Sway (m) | Heave (m) | Pitch (°) | Roll (°) | Yaw (°) |
|-------------------|-----------|----------|-----------|-----------|----------|---------|
| Maximum values    | 0.8       | 0.4      | 0.04      | 0         | 0.2      | 0       |
| Standard          | 2.0       | 2.0      | 0.5       | 3         | 4        | 0       |
In addition, in order to validate experimental results, this paper compares the results obtained from the OPTIMOOR test and the physical model test. The experimental cases in the physical model test are same as the cases in the OPTIMOOR test, as shown in section 2.2. After conducting the models, the experimental results from the physical model test are shown in Table 6, consisting of the maximum six motion components of ships subjected to beam sea, oblique sea and following sea at full load.

As shown in Table 6, the experimental results from the physical model test are larger than the results from the OPTIMOOR test, respectively. This is because wave force is presented as static superposition to wind load, which ignores the excitation effect of wave force to mooring force and results in the inaccuracy of the OPTIMOOR simulation results. Therefore, in the design work of oil terminals, the study of ship mooring stability needs to be correlated with the results from physical model test or the dynamic superposition of wave force and wind force from the OPTIMOOR simulation results.

### Table 6. The maximum six motion components of ships at full load from physical model test.

| Test conditions of waves | Surge (m) | Sway (m) | Heave (m) | Pitch (°) | Roll (°) | Yaw (°) |
|--------------------------|-----------|----------|-----------|-----------|----------|---------|
| Beam sea                 | 0.87      | 1.08     | 0.28      | 0.23      | 0.70     | 0.49    |
| Oblique sea              | 1.07      | 0.85     | 0.11      | 0.40      | 0.44     | 0.43    |
| Following sea            | 1.10      | 0.77     | 0.09      | 0.39      | 0.40     | 0.46    |

4. Conclusion

The contribution of this paper is to study the mooring stability of oil tankers by OPTIMOOR software considering the open environmental conditions in Changxing Island Port Area. Firstly, influence factors on the stability of moored ships are analyzed, which are considered as the inputs in the numerical models. Then, the experimental cases under the combinations of waves, water level, tidal current, and wind are developed. Next, the standard of mooring stability used in this paper is given after comprehensively considering the standards used in Norwegian, German, Japan and British. Finally, by feeding the environmental conditions in Changxing Island Port Area, all the numerical experimental tests are conducted and six motion components of moored ships are obtained.

1) The water level has little effect on six motion components.
2) Compared with oblique sea and following sea, beam sea has the greatest impact on motion components of moored ships.
3) The mooring stability of oil tankers in Changxing Island Port Area can be analyzed by OPTIMOOR software and is satisfied according to the standard used in this paper.

The results and proposed method can be applied to study the mooring stability of oil tankers in complicated environments. However, this paper only considers the influence of natural conditions and the contributions of ships on the stability. Future study should consider the characteristics, quality, and arrangement of the mooring cables on the mooring stability.

5. References

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