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Safe Mooring of Ships Under the Influence of Wind and Currents

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Abstract: In this paper, the simplified calculation method in the "Load Code for harbor Engineering" to quickly calculate the force on moored ship's lines and wharf bollards under the influence of wind and currents is introduced. In view of the fact that real ship had happened mooring lines breakage accident at berth under ballast condition, use the actual ship X moored at NBGB wharf as an example to verify and calculate the force on ship's lines and wharf bollards when the ship suffers the most adverse influence. The result show that when the ship encounters a gale (class 8) and a current (velocity 2.6 knot) in ballast condition, some of the mooring lines are subjected to forces close to their breaking strength under the combined effect of wind and current. If there is uneven force on the mooring lines, the possibility of mooring line breakage is great, which is consistent with the actual situation. By calculating and analyzing, give the ship's mooring stabilize conditions under specific environment. The calculation method in this paper facilitates the captain to judge whether the ship can be safely and steadily moored, and facilitates the port to make clear regulations on the ship's mooring stabilize according to the actual situation of the berth, which provides important theoretical support for the decision of stability and safety of the moored ship, the proposed preventive measures for the safety risks of stability and safety have reference value for improving the safe operation efficiency for the ship and the terminal.

Keywords: Influence of Wind and Currents, Ship Mooring, Safety Assessment, Preventive Measures, Safe Berthing

1. Introduction

With the development of global shipping industry, ships are showing the development trend of large-scale, the variety of cargo transported by ships is an increasing number of diversity, so, in order to meet the special needs of deep draught of large ships and cargo diversity, the design and construction location of port berths are far from the shoreline, poor shielding and are greatly affected by wind and waves, the current is more complicated, all of these will pose security risks to the safety of ships moored on the wharf. Therefore, study on the stability and safety of moored ships under complex port condition, on the one hand, it can provide reasonable suggestions for the design of the proposed berth, and avoid the safety hazards brought by unreasonable berth design, on the other hand, it can also provide positive guidance for the safety and stability of moored ships during the later operation of the terminal. At present, a number of professionals have conducted research on the safety and stability of moored ships at specific berths and proposed some security measures.

Chen Jie [1] calculated the theoretical number of mooring lines required for moored ships by studying the influence of external wind and currents on moored ships at berth 11 of Ningbo Far East Terminal, and proposed the improvement mooring measures when large ships moored at berth 11 of Ningbo Far East Terminal. However, the theoretical calculation of the number of mooring lines required is only based on the force under ideal conditions of use, without considering factors such as elevation angle, angle of external tension, effective length during actual mooring.

Chen Weifeng [2] systematically analyzed the causes of line breakage accidents of super-large ships from the aspects of design and use according to the practice of operation and management of major super-large terminals in Zhoushan Port, and proposed safety measures to prevent line breakage accidents, but only according to the actual situation of the terminal, which is mainly concerned with the influence of currents during actual mooring.

Han Gang [3] discovered the changes in tide level, current direction and current velocity during spring tide by establishing current data model according to the tide level and tide forecast table of the crude oil terminal waters, took targeted optimization measures for stability and safety of moored ships to ensure the safety of large oil tankers in port. The study only verified the influence of the current according to the characteristics of the terminal, but did not demonstrate the influence of wind in detail.

Mao Huiyuan [4] analyzed and evaluated risk of stability and safety of moored heavy-laden VLOC according to the specificity of berth location, tide and other factors, but did not analyze the stress on ship's mooring lines and wharf bollards during actual mooring.

Lázaro Redondo [5] obtained the results from the experiments, greater impact when wind effect is considered. when waves and wind impact together, a superposition effect is observed, taking the wind into account in berthed vessel tests, achieving safer and more realistic results.

Huiming Tan [6] obtained the results from the model test, the wave force is the greatest influential factor on the movement of vessel, and the increase of wave height and wave period will cause the movement values increased. The influence of berth length on vessel movement is not obvious. The increase in berth length will cause an increased in maximum tension force on mooring lines, due to the increase in the length of mooring lines. Therefore, the shorter berth length is helpful to reduce the tension force of mooring lines.

Li, Y. [7] studied the influence of factors such as mooring line conditions, fender arrangements, dolphin arrangements, vessel loading degree, long-term waves, wave direction, and wind on the impact energy of a moored tanker. Developed a semi-empirical formula to calculate the impact energy of the moored ship on the berthing facilities under the action of regular waves.

T. E. Schelfn [8] discussed issues related to the safe mooring of ships in port, including the environmental forces applied to the ship, general principles that determine how the applied forces are distributed to the mooring lines, and application of these principles to establish a good mooring arrangement. Issues addressed include an overview of good mooring principles, guidance for berth layout and shipboard mooring equipment, and forecast of wind and current loads on the ship.

Mr. R. Haddara [9] presented a review of the available methods for calculating wind loads on ships and offshore structures. Based on the review, four methods were selected and implemented in order to carry out a comparative study of the wind loads on ships.

R. Natarajan [10] derived the equations of static equilibrium for mooring lines when the ship is subjected to surface wind, current and restricted waves, also provided a methodology to assist the designer to predict the mooring forces on mooring cables, bollards, etc.

In summary, it is clear that most of the current studies focus only on the stability and safety analysis of specific ports or ships. The consideration of the influence of external environment, such as meteorological factors is not complete, and it cannot systematically provide the ship operator with the simple method of analysis of the stability and safety of the moored ship under external environmental conditions at different terminals. In this paper, according to the customary practice of ports, the design scheme of the wharf and the hydro-meteorological conditions near the wharf waters, By finding ship-related information, detailed analysis of the force situation of the ship's mooring lines and wharf bollards when the moored ship suffers the most unfavorable influence by referring to the relevant details of the ship, obtaining the mooring stabilize conditions of the berths and proposing preventive measures for the safety risks of moored ships. It has certain reference significance to carry out safety risk analysis and formulate safety precautions for different terminals.

2. Accidents of Ship Mooring

2.1. Ship Mooring Accidents [11]

At 13:47 on March 31, 2021, the vessel "S" moored at NO. 1 berth of TC Power Plant Terminal (47600 tons of coal on board). During the mooring, the vessel was affected by the strong currents, and six mooring lines were broken due to uneven force on the lines. The vessel drifted upstream to the recommended channel and occupied the channel for 1.5 hours.

2.2. Analysis of the Cause of the Accident

According to the investigation, the main reason for this accident as follows:

1) The vessel "S"did not payed sufficient attention to the influence of the strong current on the safety of the moored vessel, had not made a correct assessment of the vessel's mooring stability conditions;
2) The vessel "S" did not adjust the force on mooring lines in time or increase mooring lines when affected by strong current.
3) The vessel "S" did not fasten the fore spring lines on the ship's bollards according to good seamanship.

This accident was equivalent to reducing the number of mooring lines under stress at the same time, resulting in some mooring lines breaking when the external force is greater than the breaking force of the lines under impact of strong currents.

Figure 1. *Diagram of mooring lines breakage accident.*

3. Safety Analysis of Moored Ship

The above accident is caused by the influence of strong current and uneven force on the ship's mooring lines. Ship mooring lines breakage accidents due to the influence of strong wind or combined wind and current factors also occur from time to time, correct assessment of the ship's mooring stabilizing conditions can only be obtained by analyzing the combined effects of wind and currents.

3.1. Calculation Method of Force on Mooring Lines

According to the "Load Code for harbor Engineering", when the current is parallel to the longitudinal axis of the ship or the flow angle is less than 15° or more than 165°, the transverse current force perpendicular to the front of the structure and the longitudinal current force parallel to the front of the structure may be calculated according to the "Load Code for harbor Engineering":

According to the "Load Code for harbor Engineering", The transverse force Fxw and longitudinal force Fyw of wind pressure act on the ship are calculated as follows:

$$F_{xw}=73.6\times10^{-5}A_{xw}V_x^2\zeta_1\zeta_2$$

$$F_{yw}=73.6\times10^{-5}A_{yw}V_y^2\zeta_1\zeta_2 \quad (1)$$

In the formula, Axw is the transverse wind area of the hull above the water surface (m^2), Ayw is the longitudinal wind area of the hull above the water surface (m^2), Vx and Vy are the transverse and longitudinal components of wind speed respectively (m/s), ζ_1 is reduction coefficient for uneven wind pressure, ζ_2 is correction coefficient for a change in wind pressure altitude.

Axw and Ayw can be found in the ship's general arrangement plan, Vx and Vy can be calculated according to the wind direction and wind speed at that moment, ζ_1 and ζ_2 can be found in Table 1 and Table 2 according to the floating state of the ship at that moment.

Table 1. *Reduction coefficient for uneven wind pressure.*

The maximum size of the ship above the water surface (m)	**≤50**	**100**	**200**	**≥250**
Reduction coefficient for uneven wind pressure ζ_1	1.00	0.90	0.70	0.60

Table 2. *Correction coefficient for wind pressure altitude change.*

Ship's Height above the water surface (m)	**≤5**	**10**	**15**	**20**	**30**
correction coefficient for wind pressures altitude change ζ_2	1.00	1.18	1.30	1.39	1.54

The transverse force of the current on the ship is divided into the bow transverse force Fxsc and the stern transverse force Fxmc, calculated by the following formula:

$$F_{xsc}=C_{xsc}\frac{\rho}{2}V^{2}B'$$

$$F_{xmc}=C_{xmc}\frac{\rho}{2}V^{2}B' \quad (2)$$

In the formula, Cxsc and Cxmc are the transverse force coefficients of current on the bow and stern respectively, V is the current velocity (m/s), ρ is the water density (t/m³), B′ is the transverse projected area below the ship's waterline (m^2).

ρ and V can be obtained according to the actual situation at that moment, Cxsc and Cxmc can be found in Table 3.

Table 3. *Transverse force coefficients of current on the bow and stern.*

relative depth (depth of berth/Average draft of the ship)	Angle between current and berth (0°~15°)		Angle between current and berth (165°~180°)	
	Cxsc	Cxmc	Cxsc	Cxmc
1.1	0.14	0.08	0.08	0.11
1.3	0.10	0.05	0.07	0.08
1.5	0.09	0.04	0.06	0.06

B' can be calculated by the following formula:

$B'=10^{0.484+0.612\log(DW)}$ (bulk carrier)

$$B'=10^{0.508+0.612\log(DW)} \text{ (oil tank)} \quad (3)$$

The longitudinal force Fyc of the current force generated by the water flow on the ship can be calculated by the following formula:

$$Fyc=[0.046\ (VL/v)^{-0.134}+b]\ \rho V^2\ (1.7LD+C_bLB)]/2 \quad (4)$$

In the formula, V is the current velocity (m/s), ρ is water density (t/m³), L is the length of the ship (m), D is the draft of the ship (m), Cb is the square factor, B is the breadth of the ship (m), v is the kinematic viscosity coefficient of water (m^2/s), and b is the coefficient.

V, ρ, D can be obtained according to the actual situation at that moment, L, Cb, B can be found in the ship's particulars, v and b can be found in Table 4 and Table 5.

Table 4. *Kinematic viscosity coefficient of water.*

water temperature (°C)	0	5	10	15	20	25	30	40
kinematic viscosity coefficient ($10^{-4}m^2/s$)	1.79	1.52	1.31	1.14	1.00	0.89	0.80	0.66

Table 5. *Coefficients.*

C_b	Breadth/Maximum draft	b	
		Angle between current and berth (0°~15°)	Angle between current and berth (165°~180°)
0.825	2.2	0.009	0.015
	3.5	0.006	0.008
0.625	2.2	0.000	0.002
	3.5	0.004	0.009

The mooring line force N generated jointly by wind and current on the ship can be calculated by the following formula:

$$N=\frac{K}{n}\left(\frac{\Sigma Fx}{\sin\alpha\cos\beta}+\frac{\Sigma Fy}{\cos\alpha\cos\beta}\right) \quad (5)$$

In the formula, ∑Fx is the sum of the transverse forces of wind and current at the same time, ∑Fy is the sum of longitudinal force of wind and current at the same time, n is the number of bollards under simultaneous force, K is the coefficient of uneven force on the bollard (take 1.2 when n=2, take 1.3 when n>2), α is the angle between the horizontal projection of the mooring lines and the front edge of the berth (°), β is the angle between the mooring lines and the horizontal plane (°), α and β are shown in Figure 2.

According to the above method, the tension of different mooring lines can be calculated, the force of each bollard can be calculated from the tension of the mooring lines, it can be judged whether the ship can safely moored according to the comparison between the tension of mooring lines, the force of the bollard and the breaking strength of the mooring lines, the safety load of the bollard.

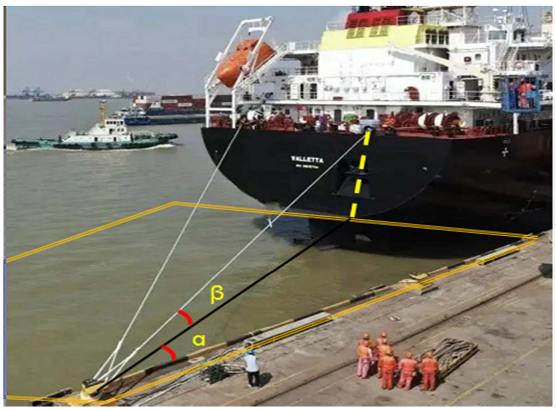

Figure 2. *Schematic diagram of α and β.*

3.2. Analysis for Actual Ship

According to the above mentioned calculation method, under the premise of comprehensive consideration of the influence of external wind and currents, take the actual ship X moored at NBGB wharf as an example to analyze and determine the mooring stabilizing conditions of the moored ship. Table 6 shows the basic information for ship X.

Table 6. *Ship's particulars.*

LOA	223m
Breadth	32.3m
Load draft	12.8m
Ballast draft	6.5m
Moulded depth	17.9m
Maximum height above the keel	48m

According to the general arrangement plan of ship X, when the ship is fully loaded, the transverse wind area of the hull above water Axw1=1830m^2 and the longitudinal wind area Ayw1=518m^2; when the ship is in ballast condition, the transverse wind area of the hull above water Axw2=3090m^2 and the longitudinal wind area Ayw2=723m^2.

NBGB wharf bollards configuration scheme: the wharf is designed with 14 bollards, the design standard safety load of bollards 1/2/12/13/14 are 1500kN, and the design standard safety load of other bollards are 1000kN, as shown in Figure 3.

Figure 3. *NBGB wharf bollards configuration scheme.*

According to the design scheme for the terminal, ships moored at NBGB terminal, whose total length is greater than 180m, should be moored by mooring method 4+2+2, i.e. 4 head lines + 2 forward breast lines + 2 fore spring lines at the bow and 4 stern lines + 2 aft breast lines + 2 rear spring lines at the stern. The mooring method is shown in Figure 4.

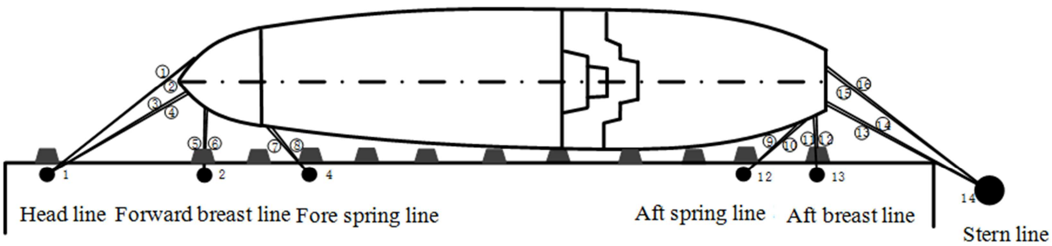

Figure 4. *Schematic diagram of mooring lines.*

According to the "Load Code for harbor Engineering", when the current is parallel to the longitudinal axis of the ship or the flow angle is less than 15° or more than 165°, the transverse current force perpendicular to the front of the structure and the longitudinal current force parallel to the front of the structure can be calculated according to the "Load Code for harbor Engineering", at NBGB wharf, flow angle is 20°, the greater flow angle, the greater vertical force of the current, but the smaller force on the mooring lines and bollards. Therefore, in order to calculate close to the actual situation, the maximum flow angle 15° is used in calculation.

In view of the case of ship mooring lines breakage when the ballast ship is moored at NBGB terminal with a gale of class 8, here we analyze ship's mooring lines strength under such conditions.

In the wind force calculation, the wind speed is taken as the maximum wind speed of the class on the Beaufort wind scale, and the wind direction is taken as offshore wind, i.e. the wind direction is perpendicular to the bow and stern of the ship, according to ship's draft and overall length:

ζ_1= 0.7ζ_2=1.2136, from which it can be calculated that Fxw = 827.8480kN in ballast condition with a gale of class 8.

In the calculation of current force, flow angle θ=15°, Cxsc=0.09; Cxmc=0.04, V=133cm/s, b=0.009, chart depth 14.95m, tide height 1m, ship's fore draft 5.5m, aft draft 7.5m, according to the ship's mooring method, the number of bollards stressed at same time: n=8, from which it can be calculated that Fxsc=81.6146kN, Fxmc=36.2732kN, Fyc=105.9595kN in ballast condition with a gale of class 8.

To sum up, the transverse force on the ship in ballast condition with a gale of class 8 is: Fx=Fxw+Fxsc+Fxmc=827.8480+81.6146+36.2732=945.7358kN.

Longitudinal force: Fy=Fyc=105.9595kN.

The force on each mooring line can be calculated according to the formula:

$$N = \frac{K}{n}\left(\frac{\Sigma Fx}{sin\alpha\ cos\beta} + \frac{\Sigma Fy}{cos\alpha\ cos\beta}\right) \tag{6}$$

The result is the value of force on mooring lines and bollards as shown in Table 7:

Table 7. *Force on mooring lines and bollards.*

Bollards		Mooring lines			
Bollard NO.	**Force on bollards (kN)**	**Mooring lines NO.**	**Horizontal angle of lines α (°)**	**Vertical angle of lines β (°)**	**Force on lines (kN)**
1#	718.6777	①#, ②#	27.6	11.6	172.8944
		③#, ④#	14.3	12.7	315.0110
2#	253.4625	⑤#, ⑥#	89.9	54.3	126.7313
4#	849.9126	⑦#, ⑧#	13.2	38.5	424.9563
12#	1005.9	⑨#, ⑩#	10.3	37.0	502.9417
13#	298.7361	⑪#, ⑫#	89.9	62.0	149.3681
14#	602.7701	⑬#, ⑭#	19.0	10.1	228.2073
		⑮#, ⑯#	22.3	9.9	196.8613

The calculation results show that if all mooring lines are stressed at the same time, as the horizontal angle of the mooring lines secured on the bollard 12 is only 10.3°, the actual force on the line is 502.9417kN, which is close to the design standard of lines (588kN), and the force on the corresponding bollard is 1005.9kN, which does not exceed the design standard safety load of bollard 12, but has exceeded the safety load of other bollards by 1000kN. The result is consistent with the case of ship lines breakage when the ballast ship is moored at NBGB wharf in a class 8 gale.

4. Analysis of the Causes of Ship Mooring Accidents

There are many reasons that can lead to stability accidents for ships moored at berth. However, the ultimate reason is that the external force is greater than the breaking force of the lines and bollards under the influence of a combination of external factors, summarize the causes of ship mooring stability accidents as follows:

1) During mooring, the floating status of the ship will change due to the tide and cargo operations, if the mooring lines are not adjusted in time, the uneven force will cause the mooring lines to break. [12].
2) Affected by the offshore currents. The hydrodynamic pressure on the hull is proportional to the square of the current velocity [13], the higher the flow velocity, the greater hydrodynamic pressure, when the offshore velocity reaches a certain value, the hydrodynamic pressure on the hull will exceed the breaking force of the mooring lines, resulting in mooring lines breakage accidents.
3) Affected by strong offshore wind [14]. Moored ship under the action of strong offshore wind, the hull is subjected to great dynamic wind pressure, the force pushes the ship off the berth, increasing the load of the mooring lines, resulting in uneven force on the mooring lines, and causing mooring lines to break.
4) Affected by swells. Moored ships sway violently due to the influence of strong swells, increasing the force on the mooring lines, if the mooring lines are not adjusted in time and there are no measures to reduce ship's sway, mooring lines breakage accidents will happen.
5) Other unfavorable factors. Insufficient number of mooring lines, lines in poor condition, traveling waves generated by passing ships near the berth [15], all of these are also the causes of mooring lines breakage accidents.

5. Preventive Measures for Safe Mooring

Combined with the above analysis of the causes of ship mooring stabilizing accidents, the following preventive measures can be taken to ensure the safety of ports and moored ships.

1) The port authority can make clear regulations on stability and safety conditions of the moored ship in accordance with the above-mentioned analysis method, take strict supervision measures on the actual compliance of the moored ship.
2) The ships should be familiar with the relevant port mooring regulations before arrival, decide on the mooring method in advance and keep all the ship's mooring lines in good condition.
3) During the mooring, the crew should strengthen the watch, adjust the mooring lines in time when loading and unloading cargo or the tide changes, keep all the lines

evenly stressed, contact and remind the passing ships that will affect the moored ship.

4) Before other auxiliary stability and safety conditions are available, in order to continue the production of terminals or to ensure the safety of large ships, only temporarily adopt the way of high-powered tugs pushing at a time of strong current according to the tidal information, which can guarantee the stability and safety of moored ships. [16].
5) During the mooring, close attention should be paid to the weather forecast, once received the forecast of strong gales, especially special weather conditions, such as typhoons, etc., be vigilant, always pay attention to the changes in wind level and wind direction, and apply for leaving the berth before the stability and safety conditions stipulated by the port, so as to avoid the tugs being unable to play with their efficiency due to the influence of wind and waves, resulting in a situation where a large ship cannot leave its berth and endangers the ship and the dock.

6. Conclusion

There are many factors affecting the safety of a moored ship, for example, deep draft ships are greatly affected by the current when they are fully loaded; ballast ships are greatly affected by the offshore wind; VLOC or VLCC encounter a strong current, the pressure on the hull by the current will obviously increase, the stern line is wide and blunt, the current resistance is huge, the situation of the stern facing the strong current when mooring is very unfavorable, the force on the lines increases at this time, and the risk of breaking the lines increases. The ship operator should take into account the actual situation of the berth and the type of the ship, consider the limited situation that the ship may encounter during mooring, make early predictions, and then calculate the force on the ship's mooring lines and wharf bollards under different working conditions according to the relevant specifications, analyze stability and safety of the moored ship, get the stability and safety conditions and formulate preventive measures for the stability of the ship's mooring risk.

This paper provides references for port construction and ship safe mooring. The calculation methods in this paper can be applied in the construction of ports, and the research on the ship’s safe mooring conditions of terminals, especially on deep-water terminals can, can be applied to the construction of deep-water terminals in general, and provide a strong technical support for ship safe staying in berth; The calculation on the stresses on mooring facilities and equipment in complex environments can improve the safety of moored ships when building large deep-water terminals in the future. In summary, this paper, by using proper methods to calculate and simulate various states in ship mooring, gives safety criteria to referred to by ports and ships in mooring operation, thus ensuring the safety of ships and ports and reducing accidents.

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