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Mooring Safety Analysis of Cable Breaking Accident of a Very Large Ore Carrier under Extreme Windy Weather Based on Numerical Simulation

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***Abstract:* -** Mooring forces and their uniformity are important indexes used to ensure the safety of mooring systems. In this study, a process analysis for ship cable breaking accidents is conducted through numerical simulation based on OPTIMOOR to analyze the mooring conditions of a 300,000-ton very large ore carrier (VLOC) cable breaking accident under extreme windy weather. Numerical simulation of the cable force of the vessel mooring accident is performed by using the proposed method, which basically restores the cable breaking accident under the windy weather. On the basis of the accident analysis of the VLOC and the comparative test under the assumption, a reasonable conclusion is obtained by discussing mooring safety under two modes, namely, 'preadjusting the cable ' and 'not adjusting the cable'. The numerical simulation research methods and conclusions presented in this paper can provide reliable reference for ship engineering and Marine investigation.

Keywords: VLOC; mooring force; extreme windy weather; cable breaking; numerical simulation.

I. INTRODUCTION

With the development of computer technology, numerical simulation has been widely used in the field of ship industry and Marine investigation. The numerical simulation of ship mooring force is an important application of computer in the field of ship industry and Marine investigation and analysis.

The mooring force of ships is an important index that affects mooring safety. Predecessors have made many contributions to the safety analysis of ship mooring system. Ali C. K. et al. adopted A Fuzzy Fault Tree Analysis to perform systematic risk analysing on the case of ship mooring operation [1]. Vytautas Paulauskas et al. used a numeral simulation method to calculate the loads of a moored ship acting on quay wall mooring system under crosscurrent conditions [2-3]. Van der Molen et al. conducted some simulation tests based on mathematical model to simulate the mooring motion state of an LNG ship in swell waves, and proved the reliability of the model through the real ship measurement [4-5]. Natarajan R. et al. conducted a serial of physical model experiments to measure the cable force and hull movement of the ship under wind and waves, which provided a practical reference for the mooring scheme design [6]. Yue proposed a coupled analysis model to predict the dynamic response of the mooring ship and validated the numerical model using the physical model experimental data [7]. Shigeki Sakakibara et al. built a monitoring system to monitor the extruding force on fender of mooring ships. Through numerical calculation, the system can roughly estimate the force on mooring lines and the amount of motion of ships, providing practical guarantee for mooring safety [8]. Xueyuan Zhu et al. built a real ship test system for ship mooring force, and compared the measured results with the numerical simulation results to verify the accuracy of the measured data in the system [9]. Most previous studies focused on the numerical simulation of mooring ship motion or mooring force, physical model measurement and real ship measurement, while the process simulation of mooring accident based on numerical simulation was rarely involved.

In recent years, ship cable breaking and drift accidents have occasionally occurred under strong winds and waves because of insufficient cable retention which lightly causes ships to hit rocks, run aground and collide or capsize in wharfs or ports. The damage caused by cable breaking accidents has immensely increased with the continuous development of large-scale ships [10]. These accidents are the result of many factors. In this study, a major cable breaking collision accident involving a Hong Kong very large ore carrier (VLOC) vessel C moored in Port D in China is taken as an example. The actual cable breaking accident is re-enacted by numerical simulation, the causes of the accident are analysed, and the safety measures to avoid such accident are put forward through simulated calculation and comparative analysis. The results are expected to serve as a reference for maritime safety and security and accident analysis.

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II. ACCIDENT BACKGROUND

A Hong Kong 300,000-ton VLOC (vessel C) was moored at the shipyard wharf in Port D, China after its construction (Mooring position is shown in Figure 1). During the mooring, strong winds and many other factors caused all cables to break one after another. The ship drifted with the winds and waves in a short time before remedial measures were taken, and it collided with a number of moored ships nearby. The ship eventually crashed into the south side of the dock basin and became stranded.

Figure 1 Location of vessel C accident

III. MOORING CONDITIONS

Mooring safety at wharfs is influenced by many factors, such as ship conditions, wharf conditions, mooring cable characteristics and environmental conditions [11]. Ships and wharfs form a mooring system by combining some kinds of cable mooring [12]. The hull under the joint action of the wind, current, waves and other external environment factors is transmitted to the wharf by mooring force. As the construction of ships and wharf facilities generally meets design standards, the failure of mooring systems is frequently caused by cable breaking due to excessive force.

According to preserved data, the VLOC completed berthing under wind-free and wave-free weather conditions after its construction, and all the cables were tied to the shipborne bollards. During mooring, no crew was placed on duty. Figure 2 shows the mooring diagram of the VLOC. The detailed mooring conditions are summarised below.

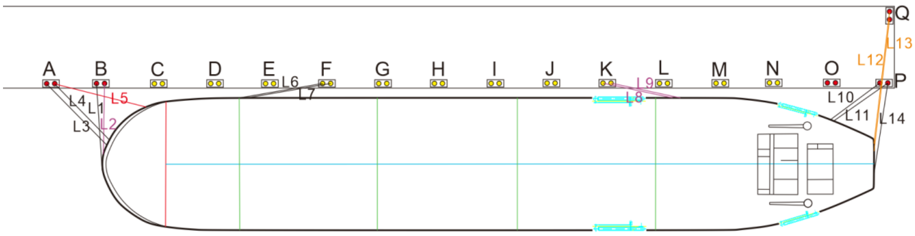

Figure 2 Mooring diagram of vessel C

A. Ship Condition

The main scale and loading status of a ship remarkably influence the external load force area, centre of force action, ship stability and cable angle. Vessel C without cargo and ballast water completed berthing in Port D with the assistance of several tugboats. The main characteristic parameters of the VLOC during mooring are shown in Table 1.

Table 1 Main characteristic parameters of Vessel C during mooring

Items	parameter values	Items	parameter values
Length Over All	329.9m	Moulded Depth	28.6m
Length Between Perpendicular	321.0m	Molded Breadth	57.0m
Deadweight Ton	300,000t	Light Displacement	38,005t
Mean Draft	3.68m	Trim	-3.37m

B. Wharf Conditions

In the designs of wharf, the mooring force of vessels is often considered, as well as the angles of cables and external loads. The VLOC-moored wharf is a gravity caisson structure with an elevation of 13 m (with zero local water gauge as the height reference plane). Twelve 1500 KN double-pillar ship bollards (yellow C–N bollards in Figure 2) and five 2000 KN double-pillar bollards (red A–B, O–Q bollards in Figure 2) are installed on top of the wharf. The fender is made of two-drum one-plate high-reaction DF-SC1000H fender and is evenly arranged along the quay wall of the wharf. The centre of the fender is located 2.5 m below the wharf surface, with a horizontal spacing of 24 m. The reaction of the fender is set to 578 KN, and the maximum reaction force is 616 KN. The mechanical performance curve is shown in Figure 3.

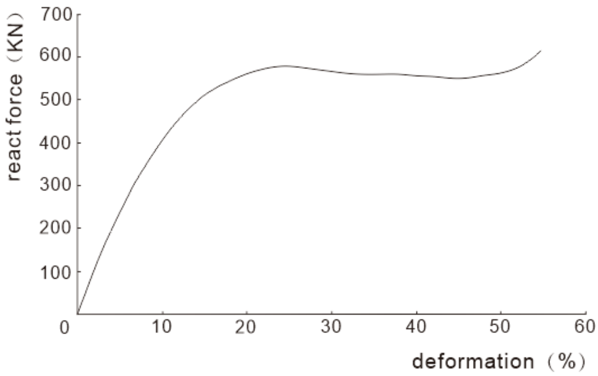

Figure 3 Mechanical performance curve of fender

C. Conditions of Mooring Cables

Mooring cable conditions include the parameters of each cable used for mooring and the overall geometric arrangement of the cables with the ship. The VLOC was moored using 14 cables (Nos. #1–#14), and the fore and aft are each tied to 7 cables. The specific mooring arrangement (Figure 2) is as follows: two fore breast lines, three head lines, two fore spring lines, two aft spring lines, two stern lines and three aft breast lines. The function, material, and designed minimum breaking load (MBL) parameters of each cable are shown in Table 2.

Table 2 Condition of mooring cables

No.	Material of the line	Specifications	MBL	Mooring Function
1	8-strand polypropylene	Φ100mm/L120m	992KN	Fore breast line
2	8-strand polypropylene	Φ100mm/L220m	1550KN	Fore breast line
3	8-strand polypropylene	Φ100mm/L120m	992KN	Head line
4	8-strand polypropylene	Φ100mm/L120m	992KN	Head line
5	8-strand Denima rope	Φ64mm/L150m	2358KN	Head line
6	8-strand polypropylene	Φ100mm/L120m	992KN	Fore spring line
7	8-strand polypropylene	Φ100mm/L120m	992KN	Fore spring line
8	8-strand polypropylene	Φ100mm/L220m	1550KN	Aft spring line
9	8-strand polypropylene	Φ100mm/L220m	1550KN	Aft spring line
10	8-strand polypropylene	Φ100mm/L120m	992KN	Stern line
11	8-strand polypropylene	Φ100mm/L120m	992KN	Stern line
12	8-strand polypropylene	Φ100mm/L220m	1100KN	Aft breast line
13	8-strand polypropylene	Φ120mm/L150m	1100KN	Aft breast line
14	8-strand polypropylene	Φ100mm/L120m	992KN	Aft breast line

D. Environmental Conditions

Environmental conditions exert an important effect on the force of the hull. On the day of the VLOC mooring accident, the weather suddenly became cold and windy. The meteorological data of the wharf show that the sustained wind speed at the front of the wharf before the accident was at 7–8 levels (Beaufort scale) and suddenly increased by 16:00. The instantaneous maximum wind speed reached level 10. The mooring cables were successively broken within minutes under the influence of the northwest wind. Then, the hull drifted and hit several moored ships nearby. The main meteorological and hydrological data before and after the incident based on the record of the on-site automatic monitoring station are shown in Table 3.

Table 3 Main meteorological and hydrological data during the accident

Time	Water level	Current		Wind		Wave	
		Speed	Direction	Speed	Direction	Height	Period
12:00	9.9m	67cm/s	030	16.6m/s	235	1.2m	4s
13:00	9.5m	46cm/s	028	19.1m/s	286	1.2m	4s
14:00	9.3m	21cm/s	085	18.7m/s	272	1.3m	4s
15:00	9.5m	51cm/s	208	20.3m/s	339	1.4m	5s
16:00	9.9m	77cm/s	210	28.0m/s	345	1.4m	5s
17:00	10.4m	57cm/s	217	25.7m/s	340	1.4m	5s

IV. Simulation analysis of cable breaking

A. Simulation Principle of Cable Force

As previously mentioned, ships and wharfs form a mooring system by combining certain types of cable mooring. The internal elements of a mooring system interact under the action of external load, and the mooring system interacts with the environmental load, the ship, the cable mooring system and ship mooring structure in the wharf. The proposed simulation of mooring force was conducted on OPTIMOOR mooring analysis software. The changing process of the force state of each cable with the external load was calculated by using the numerical optimisation algorithm. The state of hull motion during the accident simulation was analysed on the basis of the force of the hull to simulate the accident to a certain extent.

A moored ship under the joint action of winds and waves can be conducted along three axes to make a flat movement and around the three axes for rotation, such as heave, sway, surge, yaw, pitch, roll, which is a space movement with six-freedom [13] (Figure 4).

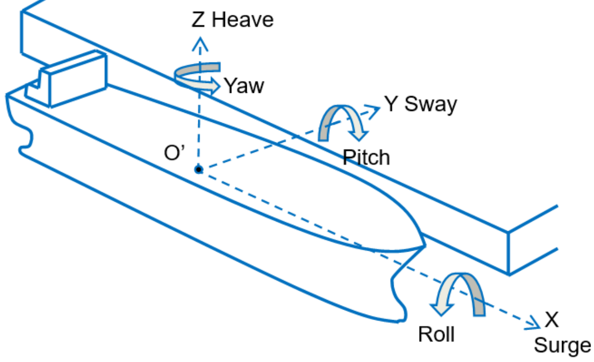

Figure 4 Six-freedom movement of the hull under the action of external forces

The force exerted by hull movement on mooring cables is mainly influenced by surging, swaying and yawing. Therefore, the force balance of ship mooring under the action of the cable, fender and external force is expressed in Formula (1) to simplify the control process of hull movement.

$$\begin{cases} \Sigma F_x + \Sigma P_x = 0 \\ \Sigma F_y + \Sigma P_y = 0 \\ \Sigma M_{xy} + \Sigma N_{xy} = 0 \end{cases} \tag{1}$$

where F_x is the component force acting on the ship in the x direction, P_x is the component force of cable tension in the x direction, F_y is the component force acting on the ship in the y direction, P_y is the component force of cable tension in the y direction, M_{xy} is the moment of external force in the xy plane and N_{xy} is the moment of cable or fender produced in the xy plane.

The forecasts of wind and flow pressures can be calculated on the basis of the empirical formula given by the OCIMF [14].

The wind acts above the surface of a ship’s waterline when ship mooring is affected by wind, and the vertical and horizontal components acting on the wind pressure on the ship are calculated by Formula (2) and Formula (3).

$$F_{xw} = \frac{1}{2} C_{xw} \rho_a V_w^2 A_L \tag{2}$$

$$F_{yw} = \frac{1}{2} C_{yw} \rho_a V_w^2 A_T \tag{3}$$

The deflection moment of ship mooring affected by wind is calculated by Formula (4).

$$M_{xyw} = F_{yw} \frac{X_w}{L_{BP}} \tag{4}$$

The deflection moment and arm of force of ship mooring affected by wind are calculated by Formula (5).

$$X_w = \frac{C_{xyw}}{C_{yw}} L_{BP} \tag{5}$$

where F_{xw}, F_{yw} are the vertical and horizontal components (KN) of wind pressure acting on the ship, respectively; A_L, A_T are the vertical and horizontal wind areas above the hull surface, respectively (m^2); V_w is the wind speed (m/s); C_{xw} is the vertical wind pressure coefficient; C_{yw} is the horizontal wind pressure coefficient; C_{xyw} is the wind-induced deflection moment coefficient; L_{BP} is the length between the stem and stern bollards of the ship; M_{xyw} is the deflection moment caused by wind; X_w is the arm of force of the deflection moment caused by wind and is the air density .

The flow acts below the waterline surface of the ship when ship mooring is affected by flow. The vertical and horizontal components of flow pressure are calculated by Formula (6) and Formula (7).

$$F_{xc} = \frac{1}{2} C_{xc} \rho_w V_c^2 L_{BP} T \tag{6}$$

$$F_{yc} = \frac{1}{2} C_{yc} \rho_w V_c^2 L_{BP} T \tag{7}$$

The deflection moment of ship mooring influenced by flow is calculated by Formula (8).

$$M_{xyc} = \frac{1}{2} C_{xyc} \rho_w V_c^2 L_{BP}^2 T \tag{8}$$

The horizontal arm of force Xc is obtained by Formula (9).

$$X_c = \frac{C_{xyc}}{C_{yc}} L_{BP} \tag{9}$$

where F_{xc}, F_{yc} are the vertical and horizontal components (KN) of flow pressure acting on the ship, respectively; A_L, A_T are the vertical and horizontal flow areas below the hull surface, respectively (m^2); V_c is the flow rate (m/s); C_{xc} is the vertical flow pressure coefficient; C_{yc} is the horizontal flow pressure coefficient; C_{xyc} is the flow-induced deflection moment coefficient; L_{BP} is the length between the stem and stern bollards of the ship; M_{xyc} is the deflection moment caused by flow; X_c is the arm of force of the deflection moment caused by flow; is the air density and T is the ship draught.

The wave force simulation uses a spectrum method to randomly superpose a certain number of ocean waves with varying amplitudes, frequencies, directions and phases simulated by wave force simulation software. The amplitude or phase of a constituent wave is a random amount and is superimposed into a random function to reflect the randomness of the wave [15].

B. Simulation of the Force of Mooring Cables

The force process of cables is divided into three stages. Stage 1 is the initial force state when the ship is moored and the cables are tied with the shipborne bollards at the moment without wind and flow. The cable pretension is set to 20 KN to simulate the degree of tension when the cable is on the pile. Stage 2 is the force state before cable breaking with the sustained wind speed of 8 levels. Cable force simulation is performed by using environmental load at 12:00 to 15:00. Stage 3 is the state in which the cables successively break because of the change in force when the wind speed suddenly increases to level 10. The simulation in Stage 3 is more complex as it involves the force changing process of multiple sets of cables. The algorithmic flow of the simulation is shown in Figure 5. To maximise the simulation results for restoring the accident process, the elongation and tightness of cables under the three states are not adjusted because no crew was on duty at the time of the VLOC's actual mooring.

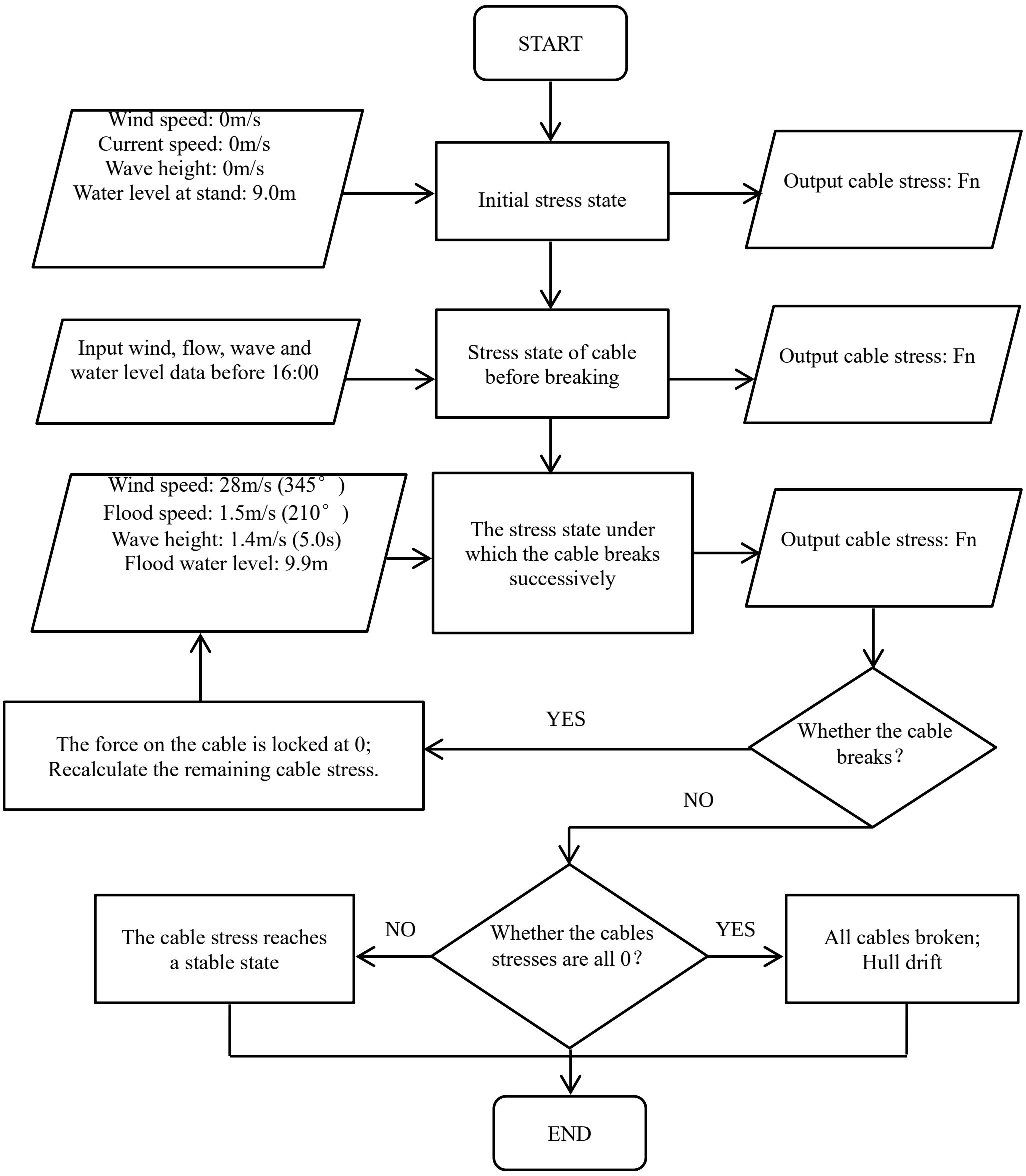

Figure 5 Algorithmic flow chart of simulation

Flowchart Fn is the size of the mooring force of the cable numbered n, cable breaking is distinguished based on the ratio of cable force to MBL as the break indicator, and the breaking index of cable En=Fn/MBL ≥ 100% at a certain time shows the occurrence of cable breaking. Breaking indicator En<100% does not necessarily represent cable safety. On the basis of OCIMF's conclusions, a mooring risk may occur when the ratio of polypropylene cable force to its MBL is Fn/MBL>55. The breaking indicator is set to En≥100% because the cables used in this study were recently purchased and the time to complete the breaking test was insufficient. Such test has a certain degree of rationality for accident restoration (the resulting multiple sets of cable forces do not reach the critical value at the same time because of small indicator values).

The forces of each cable calculated by simulation (Fn) and the percentage of MBL (En) based on the above algorithmic process are shown in Tables 4 and 5. The moment of simulation is selected as the moment when the cable is tied, the safe mooring time is from 12:00 to 15:00 on the day of the accident, and the process time of cable breaking is 16:00 and 16:aa–16:ii. The moment that the simulation result is 0 is the state that the cable is loose and unstretched because the hull movement is close to the wharf bollards. The simulation result is the moment represented by symbol '-' which is the state that the cable is broken and cannot provide the hull with mooring force.

Table 4 Simulation results of cable (L1–L7) force (Fn unit: KN)

Time	L1		L2		L3		L4		L5		L6		L7	
	F1	E1	F2	E2	F3	E3	F4	E4	F5	E5	F6	E6	F7	E7
Initial	61	6%	79	5%	43	4%	44	4%	109	5%	32	3%	31	3%
12:00	84	9%	115	7%	75	8%	76	8%	394	17%	21	2%	21	2%
13:00	352	36%	532	34%	228	23%	232	23%	645	27%	68	7%	67	7%
14:00	426	43%	647	42%	284	29%	290	29%	835	36%	70	7%	70	7%
15:00	356	36%	541	35%	208	21%	212	21%	419	18%	78	8%	78	8%
16:00	528	53%	814	53%	298	30%	304	31%	558	24%	123	12%	123	12%
16:aa	520	53%	802	52%	292	29%	299	30%	657	28%	120	12%	120	12%
16:bb	457	46%	711	46%	223	22%	235	24%	878	37%	139	14%	141	14%
16:cc	6	1%	120	8%	0	0%	0	0%	0	0%	1897	192%	1905	192%
16:dd	635	46%	1797	116%	0	0%	0	0%	0	0%	-	-	-	-
16:ee	1028	104%	-	-	143	14%	193	19%	1291	55%	-	-	-	-
16:ff	-	-	-	-	724	73%	1058	107%	0	0%	-	-	-	-
16:gg	-	-	-	-	1416	143%	-	-	607	26%	-	-	-	-
16:hh	-	-	-	-	-	-	-	-	2769	118%	-	-	-	-
16:ii	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5 Simulation results of cable (L8–L14) force (Fn unit: KN)

Time	L8		L9		L10		L11		L12		L13		L14	
	F8	E8	F9	E9	F10	E10	F11	E11	F12	E12	F13	E13	F14	E14
Initia	25	2%	25	2%	46	5%	47	5%	80	7%	80	7%	128	13%
12:00	45	3%	46	3%	32	3%	32	3%	69	6%	68	6%	114	12%
13:00	42	3%	44	3%	133	13%	136	14%	324	29%	323	29%	431	44%
14:00	51	3%	52	3%	148	15%	152	15%	375	34%	374	34%	494	50%
15:00	48	3%	50	3%	210	21%	214	22%	458	42%	456	41%	591	60%
16:00	61	4%	64	4%	351	35%	358	36%	757	69%	753	68%	1001	101%
16:aa	128	8%	136	9%	501	51%	512	52%	1142	104%	1136	103%	-	-
16:bb	816	53%	863	56%	1841	186%	1868	189%	-	-	-	-	-	-
16:cc	1364	88%	1411	91%	-	-	-	-	-	-	-	-	-	-
16:dd	1891	128%	2392	154%	-	-	-	-	-	-	-	-	-	-
16:ee	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16:ff	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16:gg	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16:hh	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16:ii	-	-	-	-	-	-	-	-	-	-	-	-	-	-

C. Analysis of Simulation Results of Cable Mooring Force

The simulation results showed that the L14 cable force was the first to exceed the MBL and broke at 16:00 under the combined influence of strong winds, currents and waves. Subsequently, the other sets of cables broke because of excessive force. The cable that broke later was rapidly increased to supplement the mooring force of each cable that broke first in the hull. The first cable to the last cable that broke in a short time period presented a chain effect. The order of the sequential breaking of cables during the accident is shown in Figure 6.

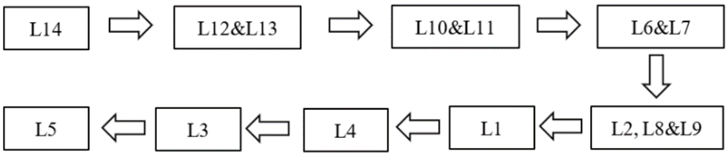

Fig. 6 Schematic of mooring cable breaking order

During the hull movement, the hull lost the restraint, and the stern casted outwards under the wind effect because the mooring cables broke from the stern to the stem, resulting in the loss of effectiveness of the cable. For the first cable L14 to the last cable L5 breaking, which exceeds the cable's MBL, the hull movement schematic caused by cable successively breaking is shown in Figure 7. After the last cable (L5 cable) broke, the hull completely lost control, causing the ship to drift with the combined action of winds and waves.

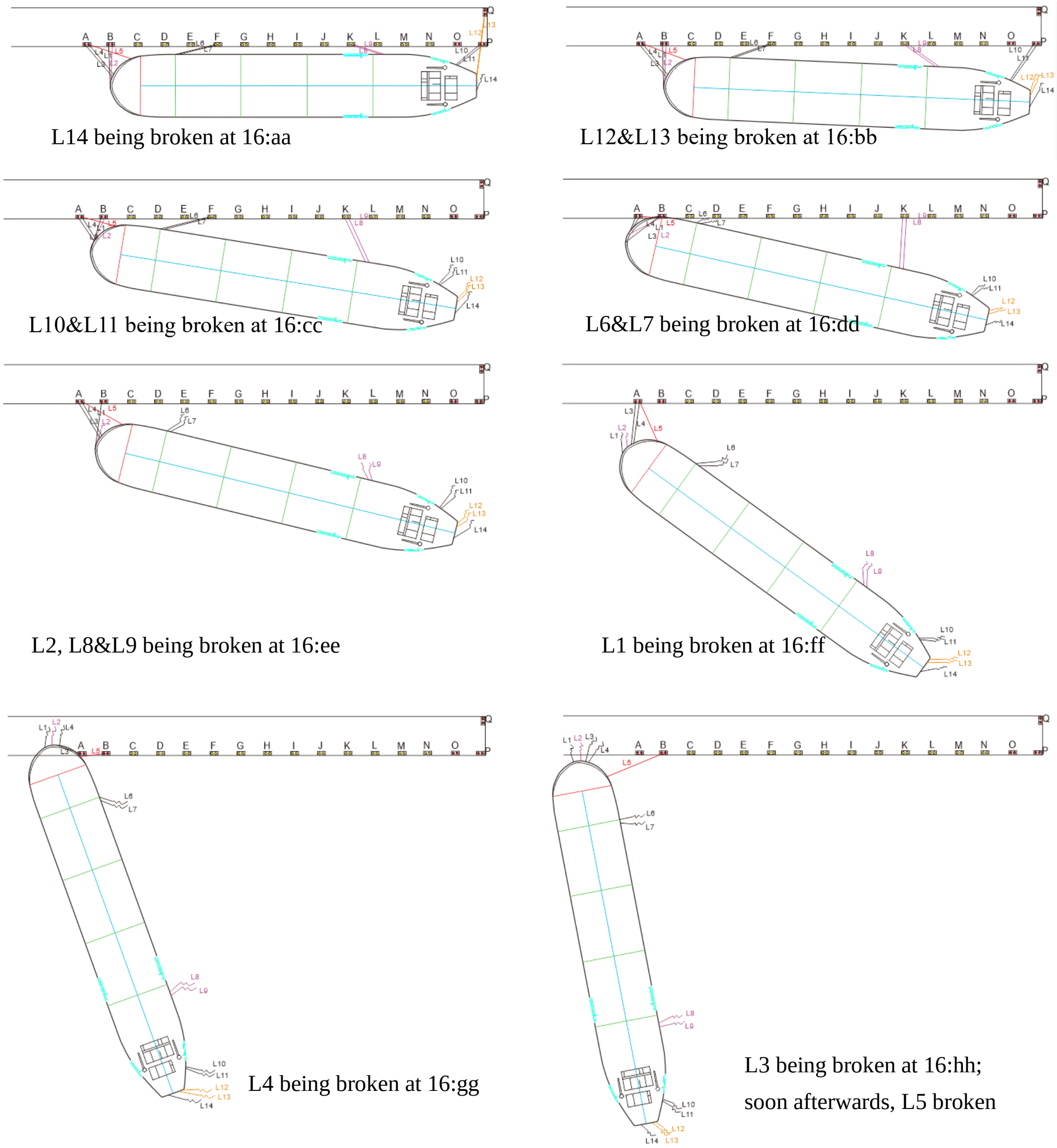

Figure 7 Schematic of hull movement caused by cable breaking

D. Comparative Simulation Analysis

Extreme windy weather is the direct cause of the VLOC mooring accident accord to the above analysis. On the basis of the general requirements of the SMS Manual of Ship Operations and Management Instructions for the protection of ships against inclement weather at the wharf, emergency measures against severe weather should be implemented early to strengthen the mooring cable, the number of mooring cables at the maximum force direction should be increased to be sufficient, and the cables tied in all directions should be uniform [16].

Therefore, the cable load conditions of the crew using the winch to manually retract the elongation of the mooring cable were simulated in this study to analyse the management factors of the VLOC mooring accident. In particular, the cables were properly retracted before the arrival of cable force environment at 16:00, and the tension of cables in each direction were adjusted on the basis of the degree of force. The cable force conditions after adjustment at 15:00 and 16:00, assuming that the cable force adjustment time is 15:00, are shown in Tables 6 and 7.

Table 6 Simulation results of cable (L1–L7) force (Fn unit: KN) after adjustment

Time	L1		L2		L3		L4		L5		L6		L7	
	F1	E1	F2	E2	F3	E3	F4	E4	F5	E5	F6	E6	F7	E7
15:00	347	35%	566	37%	205	21%	215	22%	591	25%	91	9%	91	9%
16:00	526	53%	853	55%	295	30%	308	31%	699	30%	126	13%	126	13%

Table 7 Simulation results of cable (L8–L14) force (Fn unit: KN) after adjustment

Time	L8		L9		L10		L11		L12		L13		L14	
	F8	E8	F9	E9	F10	E10	F11	E11	F12	E12	F13	E13	F14	E14
15:00	110	7%	116	8%	381	38%	390	39%	482	44%	479	44%	433	44%
16:00	130	8%	138	9%	540	55%	553	56%	799	73%	794	72%	779	79%

As shown in the above tables, the cable force is uniform to some extent after its adjustment at 15:00. The L14 cable force is significantly less than that without adjustment (the force decrease is approximately 20%) when the strong wind arrives at 16:00. The cable does not break, but the hull drifts. At the same time, the total force algebra of all cables is reduced (e.g. at 15:00, under the premise that the external load remains unchanged, the total force algebra of all cables is reduced from the original 4497 KN to 3919 KN after the adjustment of cables), as shown in Figure 8. After uniform adjustment, the cables can optimise the bearing of the mooring system to a certain extent. The cable force comparison at the two time points where the cable is and is not adjusted is shown in Figure 9.

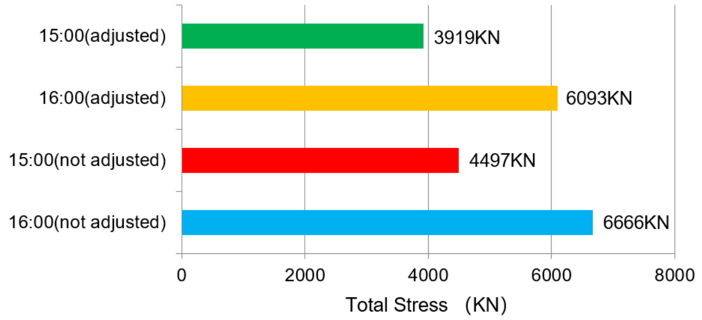

Figure 8 Comparison of total force of all cables when the cable is and is not adjusted

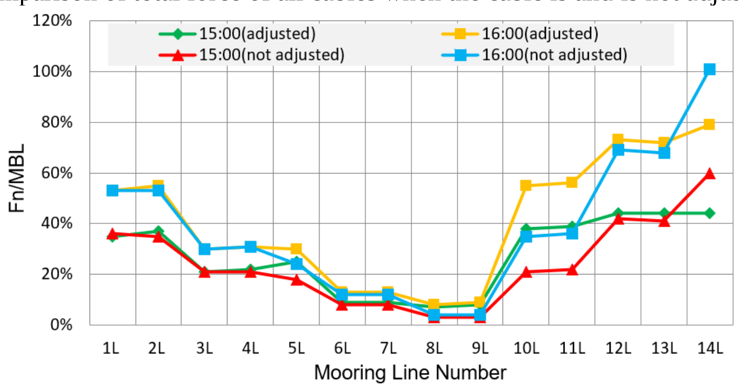

Figure 9 Comparison of cable forces when the cable is and is not adjusted

The comparative analysis shows that the mooring force at 15:00 after adjustment is obviously more uniform than that without adjustment under the influence of the same external conditions. For the mooring force at different moments and minimum breaking force percentage, the mooring system after the cable adjustment is resistant to strong winds, and the safety of the system is satisfactory.

V. Conclusions

A process analysis of a ship cable breaking accident involving a 300,000-ton VLOC is conducted on OPTIMOOR mooring analysis software to analyse the mooring conditions of a cable breaking accident. The numerical simulation of cable force of the mooring accident is performed to basically re-enact the cable breaking accident under extreme windy weather conditions. This study provides a new reference for the marine investigation of mooring accidents.

The following conclusions based on the Vessel C accident analysis and comparative test under the assumption are obtained by discussing the Vessel C mooring safety under the two modes of 'preadjusting the cable' and 'without adjusting the cable'.

(1) The simulation results showed that the environmental load on Vessel C suddenly increased at 16:00 and that the L14 cable broke after exceeding the minimum breaking force. Then, other cables under the action of strong external load broke, causing the hull to drift out of control. Therefore, extreme windy weather was the direct cause of the Vessel C mooring accident. The failure of a cable in the mooring system caused by the external environment resulted in the collapse of the entire mooring system because of the chain effect.

(2) The comparative simulation analysis showed that the mooring system after cable force adjustment did not crash at 16:00 under the environmental load. This finding indicated that improving the uniformity of cable force can optimise the mooring effect of the mooring system and benefit the resistance to the mutation of environmental load. The ineffective adjustment of Vessel C mooring before the accident was the important reason for the mooring accident.

In this study, the importance of having adequate and competent personnel on duty aboard ships during mooring was confirmed through the numeral simulation of a major cable breaking accident involving a 300,000-ton VLOC. If Vessel C is equipped with sufficient competent crew and the crew on duty can perform their functions diligently under high wind conditions, then the cables can be timely adjusted, and the cable force in all directions can be made as uniform as possible. Such measures should help avoid similar accidents. Finally, this paper also provides a new method for the application of computer numerical simulation in the field of maritime investigation

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