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Simulation in Reduced Scale Hydraulic Models of the Mooring System of Ships Docked Under the Effect of the Passage of Other Vessels (Passing Ship)

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ABSTRACT: Vessels moored at port terminals may be subject to excessive strain on mooring lines, induced by other ships passing in their vicinity. This phenomenon is called hydrodynamic interaction, and well known in the international literature as Passing Ship. It occurs due to the displacement of the mass of water between the two vessels, which, consequently, induces hydrodynamic stresses on the two ships. Within this context, scale models are a powerful tool for hydrodynamics studies, being able of reproduce the complex water flow phenomena that take place around passing and moored ship. This paper presents a scale model technique to study the Passing Ship phenomenon and its application on a case study developed for the Santos Port. The study was based on the analysis of the results of simulations performed on a 1:170 scale model to compare the effect of various navigations conditions on the mooring lines of a docked ship.

1 INTRODUCTION

Moored vessels at port terminals may be subject to excessive strain on mooring ropes, induced by passage of other vessels in their vicinity. This phenomenon is called hydrodynamic interaction and is well known in the international literature as passing ship. It occurs due to the displacement of the water mass between the two vessels, which induces hydrodynamic stresses on both vessels (moving vessel and berthed vessel). The moored vessel may be subject to excessive displacement, and consequently overloading the mooring lines and fenders, which may result, in extreme circumstances, in breaking cables and damage to the fender system. In addition, according to the progress of the cargo handling operation, there may be damage to the ship.

The passing ship is particularly important to ports located at confined areas or in narrow channels, where the phenomena can be magnified, representing an important issue for the safety assessment of port operations.

In such situations, ASCE [1] recommends the analysis of the passing ship phenomena through scale or numerical modeling.

Numerical modeling utilizes simplified equations [3] and graphs based on the parameters: the berth depth, the distance between moored and passing ships, the passing ship speed, and coefficients that are related to vessel geometry. These equations estimate longitudinal and transversal forces, and the moment of force on the moored vessel generated by a ship passage, based on the distance between the ships and the relative size of the vessel. Therefore, this data provides information of force and moment according to the vessel position and geometry. The resultant force and moment are used as input data to calculate the force equilibrium at the mooring lines, to estimate the load on each line.

However, this numerical modeling technique does not consider the effect of important aspects concerning passing ship phenomena, such as: (1) channels physical characteristics (lateral slopes or bathymetric variations); (2) geometry, type and arrangement of mooring structures; (3) vessel`s hull geometry; and (4) second order effects caused by water displacement between the two vessels. Furthermore, it is only possible to apply this method when it is possible to consider ships navigating in parallel with the moored ship as an assumption. Despite the limitations, the numerical approach can be applied on low complexity situations or as an initial approximation for the problem.

The three-dimensional scale models, which are a small-scale reproduction of the problem are a powerful tool for hydrodynamic studies. When correctly built and calibrated, the scale models can emulate satisfactorily all the forces involved in the passing ship phenomena. The bathymetry, hydrodynamic processes, vessels hull (moored and in motion), the propulsion system, mooring lines, and port structures are all reliably reproduced in the model with respect to the real-life conditions. The calibration procedure covers all features separately to ensure a correct reproduction of the study area conditions.

The hydrodynamic conditions reproduction is guaranteed by the calibration of the current speed (kinematic) and direction and water level and currents direction. The mooring system representation demands the calibration of the elastic characteristics of the mooring lines and fenders. Finally, the mass and inertia of small-scale vessels are also calibrated, and simulations of the sea trial are performed to adjust sailing and maneuvering behaviors (CrashStop, Zig-Zag and Turning Circle maneuvers).

Therefore, this article presents the analysis of the Passing Ship phenomenon at the warehouse 39 berth in the Port of Santos (São Paulo, Brazil), based on simulations performed on a hydrodynamic physical model.

The Port of Santos is the main Brazilian port in cargo transport, being responsible for more than 50% of Brazil's gross domestic product (GDP) since that 25% of the country exports and imports pass through this port. The port is located at Santos Estuary, which is approximately 20 kilometers long, 400 meters wide and 14 meters deep. There are 16 kilometers of quays and more than 60 mooring berths. The Estuary of Santos is sheltered from the waves action and maximum tide currents are about 1,0 m/s. These hydrodynamics conditions are proper for port operations.

As it is the main Brazilian port, the Port of Santos has a high inflow and outflow of vessels, with an average of 12,000 maneuvers per year and 33 per day. Due to the restricted maneuvering area available and the increase of vessels dimensions, the maneuvers tend to be complex and riskier, and must be performed increasingly closer to the nearest berthing areas.

Therefore, motivated by the increase in the dimensions of the ships operating in the Port of Santos, and the complexity of Passing Ship phenomenon, a study was carried at a scale model to evaluate the mooring system performance for a vessel with 125.000 DWT, docked at warehouse 39 during the passage of a ship with LOA = 366 m (L366m).

The objective of this article is to present the analysis method for the Passing Ship phenomenon utilizing scale modeling, presenting the technique for carrying out the tests and the results from the case study.

2 MATERIAL AND METHODS

According to ASCE [2], the passage of a vessel near to a moored ship disturbs the body of water between the two vessels, forcing the moored one to move in a characteristic pattern:

1 1. The moored ship is shifted to the same direction of the passing ship;
2 2. The moored vessel moves in opposite direction of the sailing ship;
3 3. The moored ship translates away from the berth;
4 4. The docked ship moves to the same direction of passing ship one more time;
5 5. The moored ship dislocates to the opposite direction of the passing ship again;
6 6. The moored ship returns close to its initial position, reestablishing the load balance at the mooring lines.

The main variables involved in this phenomenon are: the geometry of the vessels hull, the speed of the passing ship, the position and location of the sailing vessel, the channel and berth region geometry, the moored ship orientation, and dynamic properties of the mooring system.

Due to the high complexity of this phenomenon, this study was performed using a scale model of the Santos Estuary, built on an undistorted scale of 1:170. The model occupies approximately 2,280 m² at the CTH-USP (Technological Hydraulics Center of São Paulo University) and reproduces the region of the Santos Estuary (Figure 1).

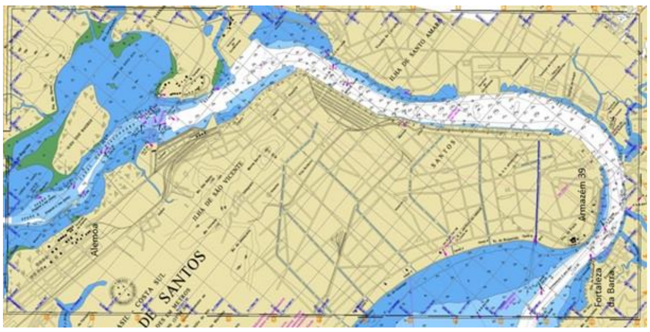

Figure 1. Nautical Chart Nº 1711 form the Hydrographic and Navigation Board from the Brazilian Navy, with the scale model area highlighted.

The bathymetry of the model was reproduced accordingly with HS (Hydrographic Surveys) provided by CODESP and the nautical chart number 1711, edited by the Hydrographic and Navigation Board (DHN) from the Brazilian Navy. The only environmental condition reproduced are tide currents, since, as previously described, the inner portion of the Santos Estuary is sheltered from waves and the wind stress does not exert great influence on the vessels.

Therefore, after a careful environmental data analysis, the spring tide condition was chosen to be simulated during the tests, with amplitudes of 1.83 m for the ebb tide and 1.70 m for the flow tide, both with a speed of approximately 1m/s. The georeferenced environmental data used in the calibration process were extracted from a numerical model developed by the CTH for the Santos Estuary region.

In addition to the boundary conditions, the geometry of the vessel models hull is reproduced accordingly with the Line Plan (ship's structural project with its curvature) of the real ships (Figure 2 and Figure 3) respecting the adopted geometric similarity constraints. Furthermore, the nature of Passing Ship phenomenon imposes the necessity to calibrate the mass and inertia characteristics of both vessel models, and the sailing model are submitted to sea trial simulations to calibrate its maneuverability and propellant system. To further details, see [2].

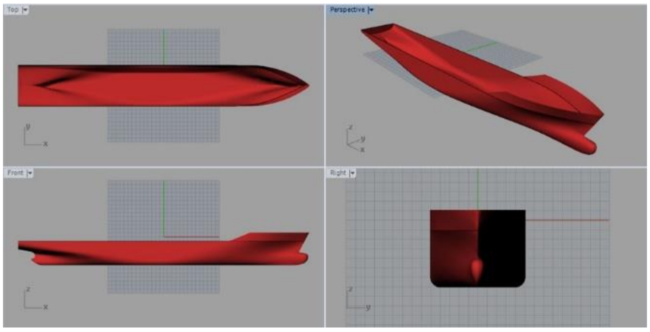

Figure 2. Real project of the Line Plan of the 366 m long vessel.

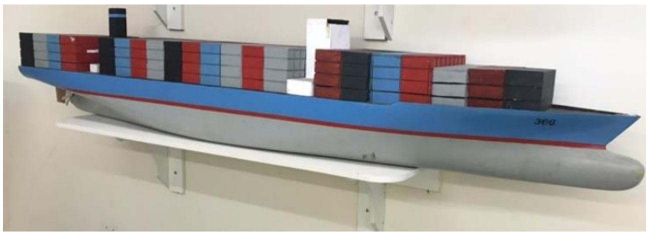

Figure 3. Scale model of the 366 m long vessel.

To control the ship the maneuvers were executed with the Analogical Maneuvering System (SIAMA). The system is an analog simulation tool for ships unmanned maneuvers in three-dimensional scale models that can be applied to any waterway scale model that has sufficient scale reduction and reproduction area to perform maneuver tests. The system is controlled by software developed by CTH-USP, which, during the maneuvers, is capable to control and monitor the conditions of engine power, rudder angle and, if necessary, actuation of the tugs, among other information of interest. This tool also has a ship tracking system, known as ship tracking, which works through images generated by a set of digital cameras installed in zenith and distributed along the model, to cover the entire actuation area of the vessel during the maneuvering tests (Figure 4).

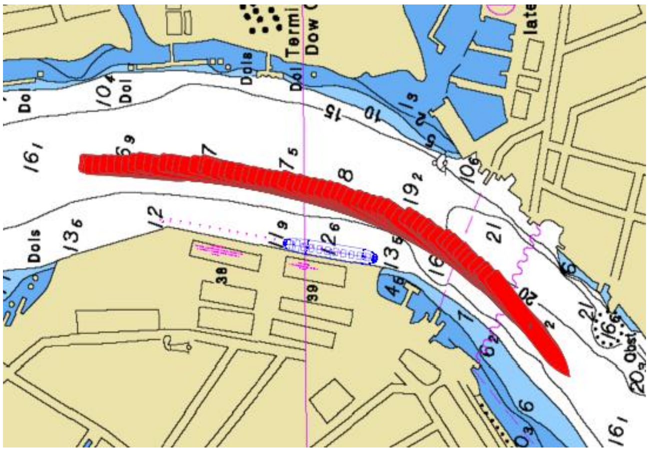

Figure 4. Sample ship trajectory registered by the ship tracking system utilized in the scale model.

The mooring plans of the ships, which are the projects that present the position of the cables and their characteristics, were elaborated considering cables working as sterns, heads, breasts and springs (as schematically represented in Figure 5). In scale models, it is often not possible to represent all cables individually due to the reduction scale. When this occurs, cables composed by same material and performing the same function (such as forward breasts, after springs, etc.) are represented in the tests by a single line, without compromising the individual analysis of each real cable, since stress can be easily decomposed between them later.

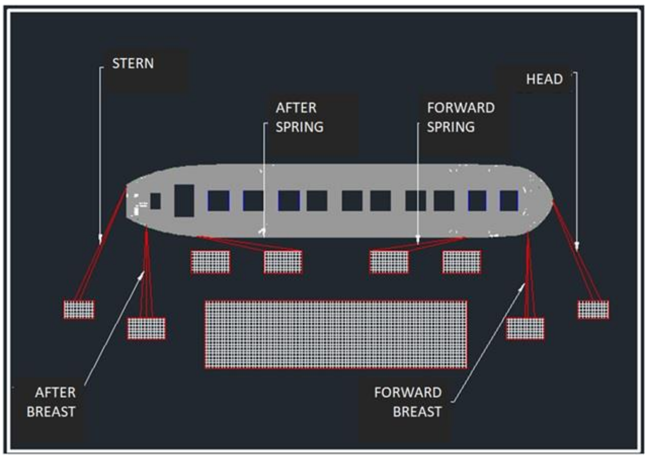

Figure 5. Simplified sketch of the main line types utilized in the mooring plans of vessels docked at portuary terminals.

As well as the physical modeling of the mooring system is obtained through rope assemblies connected to coiled springs. The springs are calibrated on a specific bench to reproduce the real rope linear modulus of elasticity in a reduced scale, respecting the curves of strength x deformation for each rope to be represented. The sensors that measure the spring displacements in the physical model are called LVDT (Linear Variable Differential Transformer), and the obtained values are recorded every second in a computational database for subsequent strength pattern analysis in the lines throughout the whole test.

The positions and elevations of the mooring devices on the vessel and on the pier are precisely respected, ensuring the correct representation of the angles between the lines and pier and the lines and the vessel observed in the Terminal. Prior to the start of the test itself, with the vessel fixed at the berthing line and centered on the berth, the lines are strenghtened to 10% of the MBL (Minimum Breaking Load, which is the reference of the minimum nominal breaking load of one rope), like what happens in the mooring of an actual vessel.

As mooring plan evaluation criteria were considerate two limiting factors: the mooring lines load, which should not be higher than 55% of the lines MBL [6], and the vessel motions, which should not exceed the maximum horizontal limit for belt loaders presented in PIANC [6]:

1 1. Surge – 5,0 m (peak to peak)
2 2. Sway – 2,5 m (from the berthing line)
3 3. Yaw – 3,0° (peak to peak)

Thus, the tests simulated were with the passage of a ship with a LOA = 366 m (L366), fully loaded (14m), sailing with 8 knots in three pre-defined trajectories: right margin (RM), center of the channel (C) and left margin (LM). The tests simulated the ship entering and exiting the port area (Figure 6)

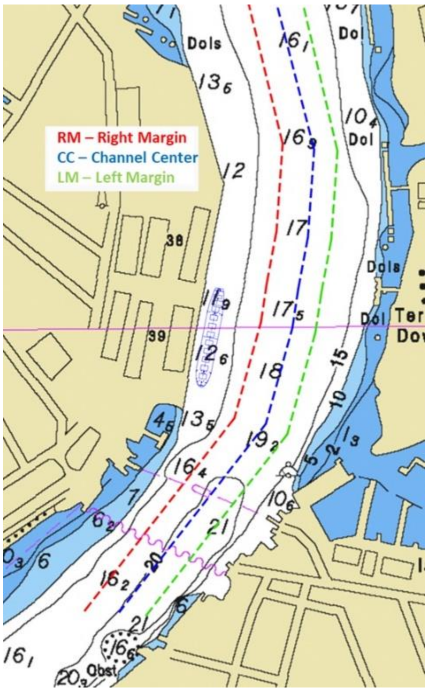

Figure 6. Passing ship trajectories tested in scale model.

The 125,000 DWT ship was docked with a mooring plan (ARM39) based on the standard mooring utilized at Port of Santos, informed by CODESP (Figure 7). The plan is composed of 12 lines of Polyblend 8 legs, with 72 mm diameter and 84 tf MBL (Minimum Breaking Load), arranged symmetrically, from stern to bow, being: 2 Sterns (St), 2 After Breasts (AB), 2 After Springs (AS), 2 Forward Springs (FS), 2 Forward Breasts (FB), and 2 Heads (Hd).

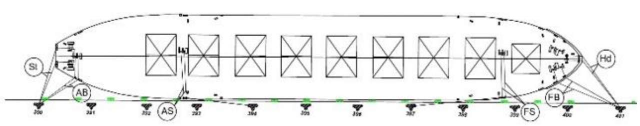

Figure 7. Mooring Plan "Arm 39".

Considering that, the maneuver of the passing ship is carried out in a freeway, being controlled only by its propulsion system (propeller and rudder), some degree of variations in its trajectory is expected, similarly to the actual maneuver. Therefore, for each scenario, several replications were performed to consolidate the results. However, the results of only three trials will be exposed, selected by presenting one of the following criterions: the smaller deviations presented in Ship Tracking and the exact 8 knots of the passing ship during the course in each trajectory.

3 RESULTS AND DISCUSSION

The following results were extracted from the Technical Report number 5, from the Hydraulics Laboratory from USP's Escola Politécnica [4]. The results will be presented for the four sceneries combinations of the passing L366 ship (entrance/exit – ebb/flow tide). The data is divided into three tables, one for each trajectory, exposing the mooring line load values and the moored ship motions.

The tables present the maximum, mean and standard deviations values of the mooring lines loads, and the measured motions of the moored ship for each test repetition. When the values exceed the recommended limits, they are marked in red.

Due to the low variability of obtained results, the graphs with temporal series of the moored ship movements and its mooring lines loads will be presented in attachment, as well the trajectories of the container ship L366.

3.1 *Scenario 1– Passing ship entering the port in the flow tide*

Table 1. (SC1) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Right margin trajectory.

Right Margin - Scenario 1

		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
RM1	L máx	52	29	48	29	46	28	6,2	3,6	1,6
RM3	L máx	50	25	43	23	43	32	4,9	3,3	1,8
RM8	L máx	55	27	46	24	46	35	5,4	3,6	1,5
Mean		**52**	**27**	**45**	**26**	**45**	**32**	**5,5**	**3,5**	**1,6**
máx. máx.		**55**	**29**	**48**	**29**	**46**	**35**	**6,2**	**3,6**	**1,8**
Stan. Deviation		**3**	**2**	**3**	**3**	**2**	**4**	**0,7**	0,2	**0,1**

Table 2. (SC1) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Channel center trajectory.

Channel Center - Scenario 1

		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
CC4	L máx	16	12	16	14	16	12	2,4	1,1	0,6
CC5	L máx	20	13	22	15	23	16	2,9	1,5	0,7
CC7	L máx	20	13	23	14	23	17	2,9	1,4	0,5
Mean		**19**	**13**	**20**	**14**	**21**	**15**	**2,7**	1,3	**0,6**
máx. máx.		**20**	**13**	**23**	**15**	**23**	**17**	**2,9**	1,5	**0,7**
Stan. Deviation		**3**	**0**	**4**	**1**	**4**	**3**	**0,3**	0,2	**0,1**

Table 3. (SC1) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Left margin trajectory.

Left Margin - Scenario 1										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
LM2	L máx	5	3	6	7	8	9	0,8	0,3	0,5
LM5	L máx	6	6	5	10	8	9	0,9	0,5	0,5
LM6	L máx	6	5	7	8	10	10	1,0	0,6	0,6
Mean		**5**	**5**	**6**	**8**	**9**	**9**	**0,9**	0,4	**0,5**
máx. máx.		**6**	**6**	**7**	**10**	**10**	**10**	**1,0**	0,6	**0,6**
Stan. Deviation		**1**	**1**	**1**	**1**	**1**	**1**	**0,1**	0,1	**0,0**

In this scenario, the obtained results shows that the mooring line loads and the moored ship displacements exceeds the established limits only in the tests were the passing ship navigated by the right margin trajectory, the closer trajectory to the warehouse 39. The most tensioned lines were the Stern (St), After Spring (AS), and Forward Breast (FB).

For the L366 trajectories by the channel center and the left margin, the evaluated criteria did not exceed the adopted limits. Furthermore, is possible to observe that results are coherent, as it possible to observe the expected reduction in the mooring lines loads values and measured motions of the moored ship as the distance between the two ships increased. In addition, the lines of the moored ship behaved similarly in the tests of different trajectories, with the same lines being the most tensioned in all trials, just differing in the magnitude of the values obtained.

The graph of Figure 8 compares the mooring lines loads obtained in the three tested trajectories, illustrating the previous observations.

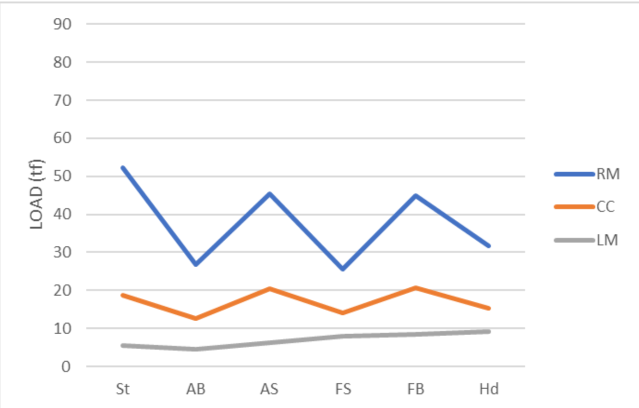

Figure 8. Mean maximum mooring line loads for all the tested trajectories.

3.2 *Scenario 2– Passing ship entering the port in the ebb tide*

Table 4. (SC2) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Right margin trajectory.

Right Margin - Scenario 2										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
RM2	L máx	85	39	53	36	53	44	6,6	5,2	2,2
RM6	L máx	79	47	56	36	56	38	7,6	4,8	2,7
RM9	L máx	84	50	51	39	55	47	6,6	5,1	3,2
Mean		**83**	**46**	**53**	**37**	**55**	**43**	**6,9**	5,1	**2,7**
máx. máx.		**85**	**50**	**56**	**39**	**56**	**47**	**7,6**	5,2	**3,2**
Stan. Deviation		**3**	**6**	**3**	**2**	**1**	**5**	**0,6**	0,2	**0,5**

Table 5. (SC2) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Channel center trajectory.

Channel Center - Scenario 2										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
CC1	L máx	35	25	29	23	31	27	3,8	2,6	1,4
CC2	L máx	34	28	25	24	26	24	3,5	2,4	1,5
CC4	L máx	33	27	27	24	27	24	4,0	2,4	1,3
Mean		**34**	**27**	**27**	**24**	**28**	**25**	**3,7**	2,4	**1,4**
máx. máx.		**35**	**28**	**29**	**24**	**31**	**27**	**4,0**	2,6	**1,5**
Stan. Deviation		**1**	**1**	**2**	**0**	**3**	**2**	**0,3**	0,1	**0,1**

Table 6. (SC2) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Left margin trajectory.

Left Margin - Scenario 2										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
LM2	L máx	20	15	18	18	19	18	2,6	1,6	1,0
LM6	L máx	25	17	17	18	19	17	2,8	1,6	1,0
LM7	L máx	23	17	21	17	22	17	2,8	1,6	0,8
Mean		**23**	**16**	**19**	**18**	**20**	**17**	**2,8**	1,6	**1,0**
máx. máx.		**25**	**17**	**21**	**18**	**22**	**18**	**2,8**	1,6	**1,0**
Stan. Deviation		**2**	**1**	**2**	**1**	**2**	**0**	**0,1**	0,0	**0,1**

For the passing ship (L366) entering the port in the ebb tide, practically all the mooring lines (except the Forward Spring – FS) of the bulk carrier docked at the warehouse 39 presented tension values that exceeded the established limits during the tests of the right margin trajectory. The ship's motions also exceeded the imposed limits in this condition.

For the tests where the ship sailed through the center of the channel, the mooring lines loads decreased noticeably, not exceeding the limits adopted. However, the moored ship displacements still exceeded the PIANC [6] recommendations.

The results obtained in the tests with the passing ship sailing in the farther trajectory does not presented any mooring line load or ship motion value above the established limits.

Similarly, to the previous condition, the results of this scenario tests showed consistency, with the reduction of mooring lines loads as the passing ship navigated through trajectories farther from the mooring berth. The same loading distribution pattern was observed in the mooring lines in all trajectory conditions, as illustrated in Figure 9.

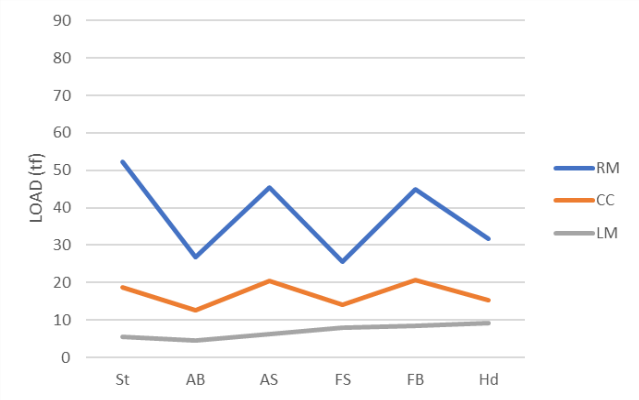

Figure 9. Mean maximum mooring line loads for all the tested trajectories.

3.3 *Scenario 3– Passing ship exiting the port in the flow tide*

Table 7. (SC3) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Right margin trajectory

Right Margin - Scenario 3										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
RM1	L máx	26	75	20	61	22	40	6,1	4,9	4,2
RM2	L máx	32	76	22	64	25	42	7,2	4,9	4,3
RM4	L máx	23	73	26	62	29	40	7,0	4,7	4,3
Mean		**27**	**75**	**23**	**63**	**25**	**41**	**6,7**	4,8	**4,3**
máx. máx.		**32**	**76**	**26**	**64**	**29**	**42**	**7,2**	4,9	**4,3**
Stan. Deviation		**4**	**1**	**3**	**2**	**4**	**1**	**0,6**	0,1	**0,0**

Table 8. (SC3) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Channel center trajectory.

Channel Center - Scenario 3										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
CC1	L máx	9	26	9	26	10	15	2,8	1,9	1,9
CC3	L máx	10	25	6	26	8	16	2,5	2,0	1,9
CC4	L máx	12	30	9	33	12	19	3,4	2,4	2,4
Mean		**10**	**27**	**8**	**28**	**10**	**17**	**2,9**	2,1	**2,1**
máx. máx.		**12**	**30**	**9**	**33**	**12**	**19**	**3,4**	2,4	**2,4**
Stan. Deviation		**2**	**3**	**2**	**4**	**2**	**2**	**0,4**	0,3	**0,3**

Table 9. (SC3) Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Left margin trajectory.

Left Margin - Scenario 3										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
LM2	L máx	8	11	3	13	7	12	0,9	1,4	0,9
LM5	L máx	4	12	3	13	6	7	1,4	0,9	0,9
LM7	L máx	5	14	3	15	6	8	1,3	1,2	1,0
Mean		**6**	**12**	**3**	**14**	**6**	**9**	**1,2**	1,2	**0,9**
máx. máx.		**8**	**14**	**3**	**15**	**7**	**12**	**1,4**	1,4	**1,0**
Stan. Deviation		**2**	**2**	**0**	**1**	**1**	**3**	**0,2**	0,3	**0,1**

For the exiting passage of the ship L366 through the right margin on the flow tide condition, the mooring plan of the berthed ship did not meet the established requirements, neither for mooring lines load nor for the ship movements. The more tensioned mooring lines were the After Breast (AB), Forward Spring (FV), and the Head (Hd). The ship movement's results exceeded the adopted limits for all three measured freedom degrees.

For tests simulating the ship passing through the channel center and left margin, farther from the docking berth, all the mooring line loads and moored ship motions measurements were below the established limits.

Like the previous scenarios, the results showed good consistency, presenting a reduction in mooring lines loads as the distance between the two ships increased. In addition, it was possible to observe that the most tensioned lines (AB, AS, Hd) were the same for all tested conditions, as presented in Figure 10.

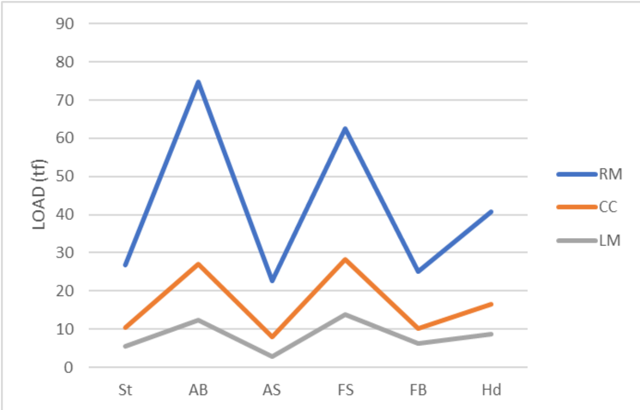

Figure 10. Mean maximum mooring line loads for all the tested trajectories.

3.4 *Scenario 4– Passing ship exiting the port in the ebb tide*

Table 10. Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Right margin trajectory

Right Margin - Scenario 4										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
RM2	L máx	18	38	11	37	12	21	3,9	2,9	2,5
RM3	L máx	18	41	11	39	11	25	3,7	3,4	2,8
RM5	L máx	21	40	12	38	13	25	3,8	3,2	2,7
Mean		**19**	**40**	**12**	**38**	**12**	**24**	**3,8**	3,2	**2,6**
máx. máx.		**21**	**41**	**12**	**39**	**13**	**25**	**3,9**	3,4	**2,8**
Stan. Deviation		**2**	**2**	**1**	**1**	**1**	**2**	**0,1**	0,2	**0,2**

Table 11. Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Channel center trajectory.

Channel Center - Scenario 4										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
CC1	L máx	6	14	2	14	6	8	1,3	1,0	0,8
CC5	L máx	7	14	1	13	3	9	1,1	1,1	0,7
CC7	L máx	5	16	2	14	4	9	1,1	1,2	0,9
Mean		**6**	**15**	**2**	**14**	**4**	**9**	**1,2**	1,1	**0,8**
máx. máx.		**7**	**16**	**2**	**14**	**6**	**9**	**1,3**	1,2	**0,9**
Stan. Deviation		**1**	**1**	**1**	**1**	**1**	**0**	**0,2**	0,1	**0,1**

Table 12. Mooring lines loads results for the bulk carrier ship moored at warehouse 39 – Left margin trajectory.

Left Margin - Scenario 4										
		Load (tf)						Displacement		
Test	Load	St	AB	AS	FS	FB	Hd	Surge (m)	Sway (m)	Yaw (°)
LM1	L máx	6	9	1	12	2	4	1,0	0,6	0,6
LM5	L máx	6	9	1	10	2	5	0,9	0,6	0,6
LM6	L máx	5	8	1	10	2	5	0,8	0,5	0,7
Mean		**6**	**9**	**1**	**11**	**2**	**5**	**0,9**	0,5	**0,6**
máx. máx.		**6**	**9**	**1**	**12**	**2**	**5**	**1,0**	0,6	**0,7**
Stan. Deviation		**1**	**1**	**0**	**1**	**0**	**0**	**0,1**	0,0	**0,1**

The tests results revealed that the passage of the ship L366 during its exit from the port at flow tide do not induce mooring line loads above the established operational limits in any proposed trajectories. The ship motions measurements presented values above the established limit for the sway displacements during the tests of the trajectory closest to the berth (right margin). The other trajectories did not yield ship movements above the adopted limits.

However, it is worth mentioning that the loads results for the After Breast (AB) and Forward Spring (FS) are close to the established limit, requiring more attention to this condition.

Like the previous scenarios, it was possible to notice a good consistency in the results achieved for the three simulated trajectories, as illustrate at Figure 11.

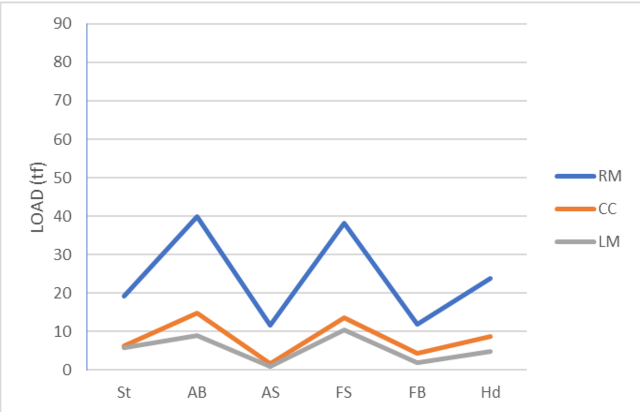

Figure 11. Mean maximum mooring line loads for all the tested trajectories.

The scale model tests results indicate that the passage of the L366 ship through the right margin trajectory, entering or exiting the port area, tensioned the mooring lines of the ship docked in Warehouse 39 above the established limit by OCIMF [5]. In addition, the movement of the moored ship also remained above the limits established by PIANC [6]. The worst scenario for the moored vessel, during the passage of the L366 in the right margin trajectory, was the entry in ebb tide condition, where the greatest mooring lines loads occurred, and more cables presented values above the recommended limit.

Regarding the trajectories through the channel center and the left margin, the mooring line loads always remained within the established limits for all the tested conditions. The same can be said for the ship motions measurements obtained in almost all tests for these trajectories, the only exception being the scenario of the passing ship navigating through the channel center at ebb tide when the sway displacement slightly exceeded the limit established by PIANC [6].

The results of the entire test series were considered consistent since it was possible to observe a low dispersion in the mooring line loads observations between the repetitions of each simulated condition. The results also yielded foreseen patterns, as the reduction in the mooring lines loads and moored ship movements as the trajectories of the passing ship were pushed farther from the berth. Moreover, the tests of the same scenario produced a similar pattern in the distributions of the mooring lines loads for the three trajectories simulated, with same lines being the most tensioned regardless of the ship trajectory.

4 CONCLUSIONS

Regarding the navigation conditions near warehouse 39, a curved sector of the channel, the hardest maneuver to execute during the tests was the ship entrance in the Port at the ebb tide condition. Due to the curvature of the channel, when the vessel approaches the warehouse 39 the water ebbing to Santos Bay strikes the L366 ship perpendicularly, displacing it toward the left margin.

From the point of view of the hydrodynamic interaction between the L366 and the 125,000 DWT ship moored at warehouse 39, the scale model results allowed to conclude that, using the proposed mooring plan, it is not possible to assure safety in the moored ship operations when the right margin trajectory is utilized. These conclusions are based on the criteria established by the OCIMF [5] and PIANC [6] recommendations.

In the tests simulating the passage of L366 through channel center, the only scenario that the moored ship presented excessive motions was the entrance navigation at the ebb tide, which is, in fact, the most critical scenario for the hydrodynamic interaction at warehouse 39.

Regarding the sceneries with the left margin trajectory, the tests results did not indicate any restrictions to the proposed mooring plan, however, the viability of the channel navigation through this trajectory must be verified.

The Table 13 summarizes the mooring plans conditions for each tested scenario. The plan condition is identified by the colors:

Red: Denotes that the mooring lines loads or ship motions measurements surpassed the limits recommended by OCIMF or PIANC It is advised to not execute the ship passage;

Yellow: Denotes that the mooring lines loads or ship motions measurements are close to the limits recommended by OCIMF or PIANC. It is advised to have great caution with the passage conditions;

Green: Denotes that the mooring lines loads or ship motions measurements are within the limits recommended by OCIMF or PIANC. None restrictions to ship passage were indicated by the tests.

Table 13. Summary of the mooring plan conditions for each test.

Scenario	Condition of passage	Condition of tide	Trajectory	Condition mooring plan
1	Entrance	Flood	RM	
			CC	
			LM	
2	Entrance	Ebb	RM	
			CC	
			LM	
3	Exit	Flood	RM	
			CC	
			LM	
4	Exit	Ebb	RM	
			CC	
			LM	

It is noteworthy that the tests can be complemented with new studies in scale model to optimize the proposed mooring plan, in order to try to mitigate the operational restrictions identified in this paper. In the new tests would be possible to evaluate the utilization of mooring lines composed by different materials, mooring plans with more lines, new mooring structures, or even modify the vessels characteristics, like the draft, aiming to determine the conditions that ensure a greater safety to ship's passages in the warehouse 39.

Finally, it is important to highlight that these tests aimed to evaluate the hydrodynamic interaction of the ship L366 with a ship moored in the warehouse 39 for three predefined passage trajectories. It was not the objective of this study to evaluate the technical feasibility of these maneuvers (trajectories), especially because these tests were not performed with the pilots participation, who are professionals qualified to make evaluations of this nature.

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