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PASSING SHIPS INTERACTION IN THE OIL TERMINAL OF SÃO SEBASTIÃO (BRAZIL): AN APPLIED STUDY TO DEFINE THE OPERATIONAL LIMITS

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SUMMARY

The passing ship effect in a moored vessel is a well-known problem discussed in the literature that involves harbour operations. The consequences of these interactions are dynamic loads in the mooring system that can exceed the design values and lead to severe accidents as, for example, the one occurred with the Yusho Regulus and Coal Hunter ships in Santos port (Brazil). This paper presents the application of a numerical method for the evaluation of mooring loads due to passing ship problems in São Sebastião port (TEBAR), which is one of the most important oil terminals in Brazil. The specific operation studied is a Ship-to-Ship transfer considering several vessels (VLCC-VLCC, VLCC-Suezmax), a condition where no simplified regressions is available to estimate the passing ship forces. Therefore a Rankine Panel Method (RPM) is applied to evaluate these effects. The forces computed by means of the panel method are applied in the mooring integrity analysis code (MeDuSa) to verify the maximum loads, which are then compared to design criteria so as to define the maximum operational conditions. The mooring arrangement, cable properties, fender etc. are determined by following OCIMF STS recommendations, as well as the Q88 form available for the design vessels.

1 INTRODUCTION

In a near future, the exploration and transportation of Brazilian pre-salt layer petroleum will demand a large number of support, transport and offloading vessels in order to supply all operations, increasing waterway and port traffic and consequently the chances of berthed ship-passing-ship interaction events.

Consequently, the berthed ship -passing ship interaction prediction is very important for the safety of waterways, port facilities and open sea operations that can be critical if the ships are sailing close to each other and/or through a constrained channel, in which wall effects may increase those interactions, justifying a specific study.

In the past, model scale tests were commonly performed for estimating the hydrodynamic loads involved in such a problem. The reference [1] presented an extensive passing ship experimental campaign in which several arrangements relating distance, ship size and speed were investigated. Other experimental results may be found in [2], [3] and [4], among others. However, this approach is a very costly way to study the phenomena, especially if the number of distinct setups/operations is large.

In this sense, some researchers were motivated to create empirical regressions that can be extended for other conditions as may be observed, for example, in [4] that provides expressions for estimating forces and moments based on model tests data with series 60 ships in shallow water, which may be useful for simple hand calculations or for use in spreadsheet predictions. Other empirical regressions are also proposed in [5] and [6].

Another approach, based on mathematical models, is presented in [7], which applied the slender body theory for evaluating the interaction effects involved in the passing ship problem. This method, however, is limited to simple and slender hull forms and might not be properly applied in situations involving large oil carriers, such as the ones used in Oil & Gas operations.

The advances in computational capability and numerical methods allowed the continuous improvement of mathematical models for hydrodynamic problems. The reference [8] presented calculations considering two identical and parallel Wigley hulls using RANSE CFD method (RNG k-ε turbulence model) and compared the results with the potential flow boundary elements method (BEM) proposed by [9], demonstrating a good agreement between both solutions. The reference [10] presented numerical solutions and validations for conditions involving non-zero ship drift angle obtained via the CFD code ReFRESCO and a 3D BEM, in which the authors conclude that for drift angle higher than 7.5 degrees, the CFD is a better option to be applied. For zero drift angles, however, fortunately the 3D BEM is a sufficient method for the problem, providing efficient solutions in terms of computational time.

The present paper presents briefly the formulation of the 3D BEM code developed in the Numerical Offshore Tank of the University of Sao Paulo (TPN-USP) used to solve the passing ship problem. The code was compared in [11] to empirical expressions proposed by [4], the strip body theory method presented by [7] and experimental data obtained by model tests carried out in the State of São Paulo Institute for Technological Research (IPT), presented in [12].

The numerical method is then applied to compute the hydrodynamic forces in the case of a berthed ship-to-ship operation in São Sebastião Port (Brazil), one of the most important oil terminals in Brazil, illustrated in Figure 1. For this specific operation, no simplified regression is available considering 3 vessels (2 of them only separated by pneumatic fenders), and a 3D BEM numerical model was applied to evaluate the berthed ships - passing ship interaction forces.

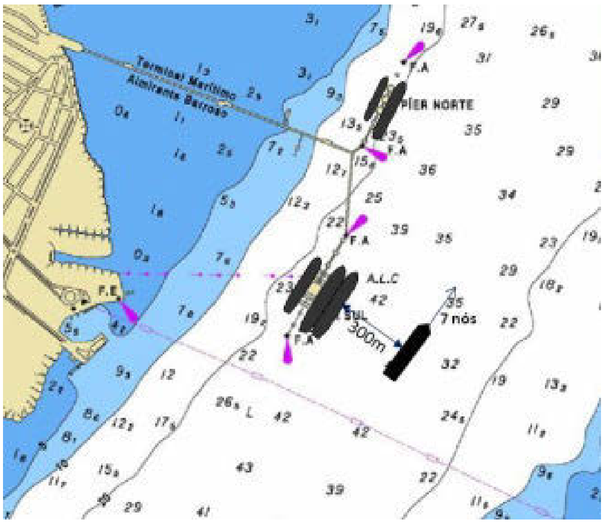

Figure 1. STS operation in the berth and a passing vessel along the channel

After the hydrodynamic loads are computed in each vessel, the mooring integrity is evaluated using the MeDuSa code, also presented, that considers the dynamic loads due to passing ships, current and wind forces. The last two forces (current and wind) are computed using CFD, taking into account the "shadow effect" due to the proximity of the STS vessels, and providing the forces in each vessel independetly.

2 MATHEMATICAL MODEL

2.1 HYDRODYNAMIC MODEL FOR THE CALCULATION OF THE PASSING SHIP INTERACTION LOADS

The procedure used to estimate the forces and moments originated by the problem of a ship passing on the side of a berthed ship may be also treated by means of the double body potential flow. Under the hypothesis of incompressible and irrotational flow, and inviscid, isotropic and homogeneous fluid, the velocity vector field $\vec{V}$ is assumed conservative and, therefore, may be written as the gradient of a scalar potential function φ, as presented in equation (**1**), therefore the continuous equation is replaced by the Laplace equation (**2**) in volume Ω.

$$\vec{V} = \nabla\varphi \tag{1}$$

$$\nabla^2\varphi = 0 \quad \text{in } \Omega \tag{2}$$

Following [13] and [14], the free surface effects were not considered, since its influence was assumed small upon the low Froude number values evaluated.

Within this scope, the appropriate boundary conditions for determining the potential flow are described by the impermeability condition (**3**) and (**4**) on the lateral walls, bottom and ships wetted surfaces, and a zero flux equation (**5**) at the mean water level $z = 0$, as follows:

$$\frac{\partial\varphi}{\partial n} = 0 \quad \text{on the captive ship surface, domain bottom and lateral walls} \tag{3}$$

$$\frac{\partial\varphi}{\partial n} = \vec{U}\cdot\vec{n} \quad \text{on the passing ship surface} \tag{4}$$

$$\frac{\partial\varphi}{\partial z} = 0 \quad \text{at } z = 0 \tag{5}$$

where $\vec{n}$ and $\vec{U} = (-U,0,0)$ are the normal vectors of the ships wetted surfaces and the ship forward speed vector, respectively.

Through the use of the Green's Second Identity, the volume problem may be rewritten in terms of a boundary formulation expressed by the second type Fredholm integral equation (**6**).

$$\iint_{\partial\Omega}\left[\left(\frac{1}{r}+\frac{1}{r'}\right)\frac{\partial\varphi}{\partial n} - \varphi\frac{\partial}{\partial n}\left(\frac{1}{r}+\frac{1}{r'}\right)\right]d\partial\Omega = 2\pi\varphi \tag{6}$$

in which $1/r$ is the Rankine source and $\partial\Omega$ is the boundary surface. The source image is assumed in order to avoid the above free surface discretization and guarantee the no-flux condition in the z=0 plane.

A three-dimensional Boundary Element Method (BEM), developed in TPN-USP, is then used to solve the boundary value problem specified. By the use of this method, the wetted surfaces of the ships, the lateral walls and the bottom are subdivided into a set of N quadrilateral panels with N collocation points. Moreover, the velocity potential, normal vectors etc. are assumed as constant values over each panel, leading to the so called Low Order Boundary Elements Method, firstly presented by [15]. An example of a typical panel mesh is illustrated in Figure 2.

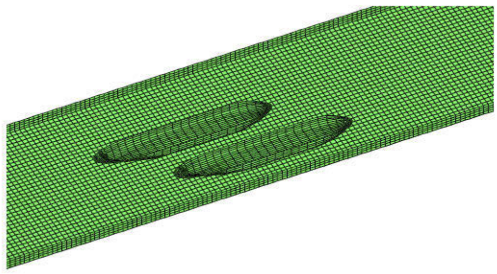

Figure 2. Example of a panel mesh with the two ships, domain bottom and lateral walls

By applying the collocation method, the integral equation (6) is discretized in equation (16), and the velocity potential determined by the solution of a linear system of N equations,

$$2\pi\varphi_i + \sum_{j=1}^{N}\varphi_j\iint_{S_j}\frac{\partial}{\partial n_j}\left(\frac{1}{r_{ij}}+\frac{1}{r_{ij}'}\right)dS_j = \sum_{j=1}^{N}\frac{\partial\varphi_j}{\partial n_j}\iint_{S_j}\left(\frac{1}{r_{ij}}+\frac{1}{r_{ij}'}\right)dS_j \tag{7}$$

where the indexes $i = 1,2,3\ldots N$ and j denote to collocation and source panels, respectively, and S_j is the surface of the panel j.

Once the velocity potentials for each panel of the berthed ship are determined, the hydrodynamic pressure is evaluated through the use of the Bernoulli's equation (8), in which the time derivative term is evaluated by means of a centered difference scheme. Notice that the quadratic velocity term was neglected since the disturbance velocities were assumed small. The hydrostatic restoration term is neglected since it is assumed that the induced roll, pitch and heave are small (which is also in accordance to the double body model) and it is balanced by the gravitational forces.

$$p = -\rho \frac{\partial \varphi}{\partial t} \tag{8}$$

in which ρ is the density of water.

Hence, the hydrodynamic forces and moments are obtained by simply pressure summation over the panel collection for each body, as presented in expressions (9) and (10), respectively.

$$\vec{F}^{t+\frac{\Delta t}{2}} = -\rho \sum_{J=1}^{N_c} \frac{\left(\varphi_j^{t+\Delta t} - \varphi_j^t\right)}{\Delta t} \vec{n}_j A_j \tag{9}$$

$$\vec{M}_o^{t+\frac{\Delta t}{2}} = -\rho \sum_{J=1}^{N_c} \frac{\left(\varphi_j^{t+\Delta t} - \varphi_j^t\right)}{\Delta t} \vec{n}_j \wedge \vec{r}_{jo} A_j \tag{10}$$

where A_j is the area of the panel j, N_c is the set of panels which belong to the captive ship and the index O is the pole from which the moment is calculated.

The linear system of equations resultant from equation (7) is solved for discrete time steps Δt as the passing ship advances, since the relative positions between the vessels change during the calculations. Consequently, the coefficients that multiply the velocity potential and its normal derivative, which are expressed by the two surface integrals in equation (7), must also be recalculated and the influence matrix inverted at each instant of time t. This procedure is responsible for most of the consumption of time and computational memory during the simulations and, therefore, only the quantities involving panels from different ships, in which the relative distance changes, were updated.

The convergence of the meshes was checked by comparing the forces in x and y directions, as well as the moment in z using the results obtained with three different meshes for the ships with an increasingly number of panels (511, 1022 and 2044). Through this analysis it was possible to set the number of panels of each ship to 1022 , since the results obtained with the two most dense meshes did not present significant differences.

An example of a typical panel mesh used for all the simulations is illustrated in Figure 3.

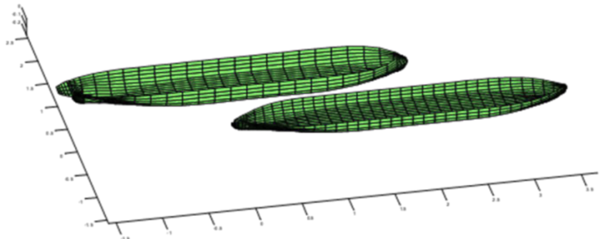

Figure 3. Example of a panel mesh disregarding domain bottom and lateral walls

2.2 MOORING ANALYSIS SOFTWARE (MEDUSA®)

The MeDuSa software for mooring analysis can perform static, quasi-static and dynamic analysis. The static and quasi-static solutions are based on a linearization procedure therefore the solution is fast, allowing the simulation of thousand of environmental conditions, while the dynamic one is based on Cummins equation requiring more computational time. The static analysis is applied to define the critical conditions to be studied in more details using the dynamic one. This methodology will be discussed in details in a future work.

The first step of the mooring analysis is to compute the pretension of each individual line keeping the balance of the vessel, which is performed using a linear optimization model since the problem is usually hyper static. The objective function is to reduce the sum of all cables pretension (11), under the equilibrium constraints in the longitudinal, transversal directions and the moment, described in equations (12), (13) and (14), respectively. In these equations N_i and N_f are the number of cables and fenders, (x_{i0}, y_{i0}) or (x_{j0}, y_{j0}) are the fairleads coordinates, (X_{CG}, Y_{CG}, Z_{CG}) the vessel center of gravity position, θ_{i0} is the mooring line angle, F_i is the cable pretension, F_j the fender forces in transversal directions and F_j^* the friction forces in the fenders. The constraint (15) is used to guarantee that the fenders only "push" the vessel, constraint (16) is used to define the range of allowed pretensions in the cables (usually based on the winch capacities) and (17) is used to define the limits of friction forces.

$$min \sum_{i=1}^{N_i} F_i \tag{11}$$

$$\sum_{i=1}^{N_i} F_i \cos\theta_{i0} + \sum_{i=1}^{N_f} F_j^* = 0 \tag{12}$$

$$\sum_{i=1}^{N_i} F_i \sin\theta_{i0} + \sum_{j=1}^{N_f} F_j = 0 \tag{13}$$

$$\sum_{i=1}^{N_i} F_i[\sin\theta_{i0}\,(x_{i0} - X_{CG}) - \cos\theta_{i0}(y_{i0} - Y_{CG}) \tag{14}$$
$$- \sum_{i=1}^{N_f} F_j^*\,(y_{j0} - Y_{CG})$$
$$+ \sum_{i=1}^{N_f} F_j\,(x_{j0} - X_{CG}) = 0$$

$$F_j > 0, j = 1,2, \dots N_f \tag{15}$$

$$F_{refmin} < F_i < F_{refmax}, i = 1,2, \dots N_i \tag{16}$$

$$-\mu_{max}F_j \leq F_j^* \leq \mu_{max}F_j, j = 1,2, \dots N_f \tag{17}$$

After the pretensions are computed the linear static solution is computed based on Hooke's law (18), considering the linearized cable elongation (19), where $(\Delta x_i, \Delta y_i, \Delta z_i)$ are the fairlead motions, which can be computed from the rigid body motions $(X_1, X_2, X_3, X_4, X_5, X_6)$=(surge,sway,heave,roll,pitch,yaw) using equation (20), assuming a linearization hypothesis.

$$F_i = K_i \Delta l_i \tag{18}$$

$$\Delta l_i = \frac{1}{l_0}(\Delta x_{i0}\Delta x_i + \Delta y_{i0}\Delta y_i + \Delta z_{i0}\Delta z_i), \quad i = 1,2, \dots N_i + N_f \tag{19}$$

$$\begin{Bmatrix}\Delta x_i \\ \Delta y_i \\ \Delta z_i\end{Bmatrix} = \begin{Bmatrix}X_1 \\ X_2 \\ X_3\end{Bmatrix} + \begin{Bmatrix}X_5(z_{i0} - Z_{CG}) - X_6(y_{i0} - Y_{CG}) \\ X_6(x_{i0} - X_{CG}) - X_4(z_{i0} - Z_{CG}) \\ X_4(t_{i0} - Y_{CG}) - X_5(x_{i0} - X_{CG})\end{Bmatrix} \tag{20}$$

Therefore the additional cable forces (in relation to the pretension) can be computed from the rigid body motions, the 6 variables to be solved. The forces in each cable or fender can be decomposed in forces and moments in the 6 DoF. The sum of all cable forces provides an equivalent stiffness matrix $[K_t]_{6X6}$ and the environmental forces acting in the vessel are defined by a vector $\{F\}_{6X1}$. The linear system (21) is then solved to compute body motions and after that the cables/fender elongation. If the cable forces are negative or the fender forces positive (considering the pretensions computed previously) the cable/fender contribution to the stiffness matrix is eliminated and the solution recomputed.

$$[K_t]_{6X6}\{X\}_{6X1} = \{F\}_{6X1} \tag{21}$$

The procedure is summarized in Figure 4.

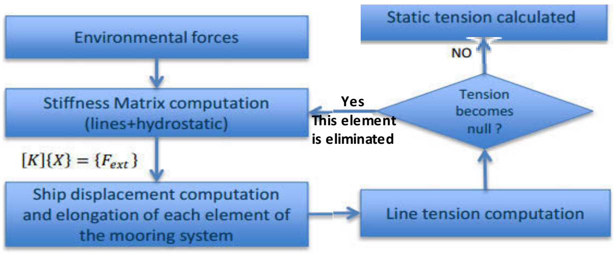

Figure 4. Summary of the linear mooring model.

The non-linear solution considering the "real" fender/cable curves ($K_i = K_i(\Delta l_i)$) can also be computed assuming the linearized solution as the initial point in order to simplify the convergence. The dyamic solution can also be computed based on Cummins equation from the pretension values, as described previously. However the computation time rate is about 1:100 considering the static (quasi-static) and dynamic approach, therefore only for some critical conditions the dynamic approach is applied. The wave model will not be described since the studied terminal is sheltered from waves.

The wind and current coefficients were evaluated using CFD models to compute the forces in each vessel, considering the "shadow" effect, for two different loading conditions (VLCC-starboard-loaded/VLCC-portside-ballast and VLCC-starboard-ballast/VLCC-portside-loaded), assumed as the most critical from the operational point of view. Some examples of exposed areas assumed for CFD computations can be seen in Figure 5 and Figure 6. An example of the pressure field obtained can be seen in Figure 7.

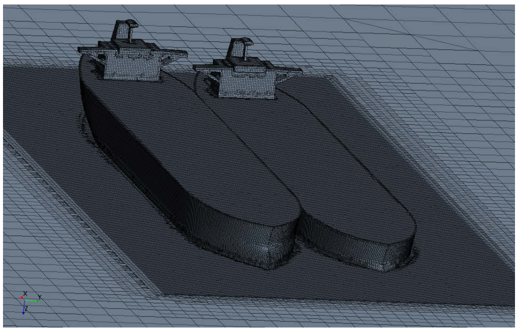

Figure 5. Exposed wind surface for wind forces computation using CFD.

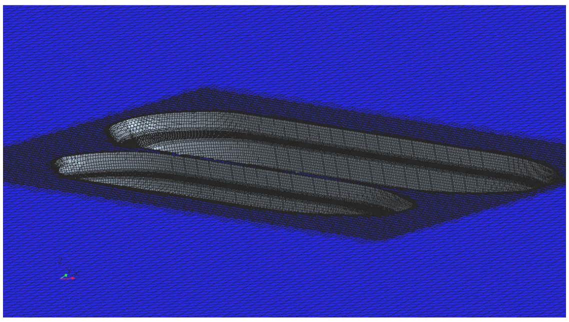

Figure 6. Exposed current surface for current forces computation using CFD.

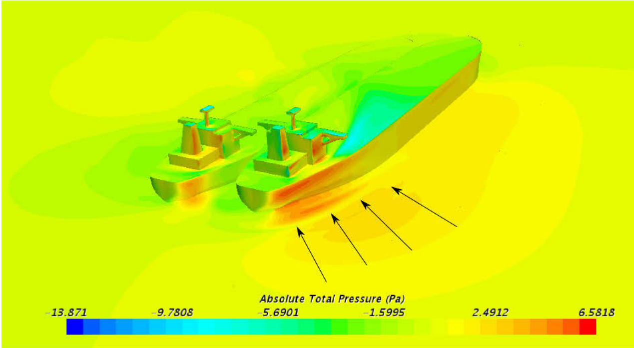

Figure 7. Pressure field in STS simulations using CFD.

The forces are non-dimensional following OCIMF recommendations and some examples of wind coefficients regarding both vessels can be verified in Figure 8, where it can be verified that the forces acting in the vessel in the shadow region are considerably smaller. A similar behavior is verified for current forces.

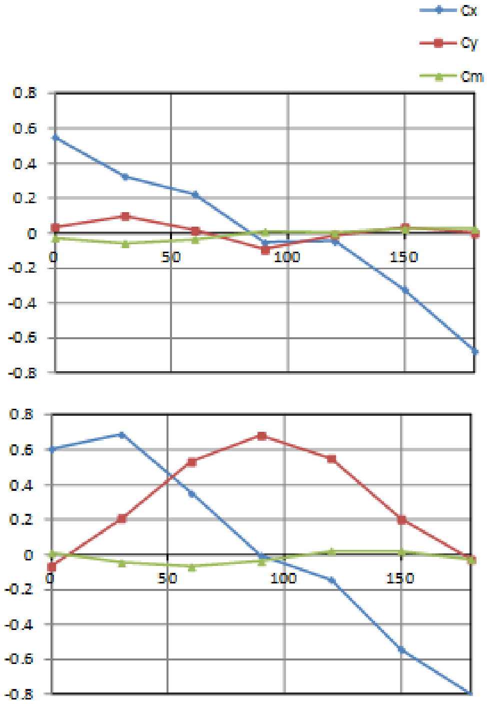

Figure 8. Wind coefficients for both vessels in STS simulation (bottom-exposed in ballast and top-shadow region loaded).

3 CASE STUDY

The methodology discussed in the previous sections is now applied to the analysis of limiting operational conditions of a mooring system of two ships in ship-to-ship arrangement berthed at the PP1 of the São Sebastião Oil Terminal (TEBAR). The TEBAR is located in the São Sebastião Channel, defined by the land and the São Sebastião Island. The natural navigation channel is approximately 800m wide and more than 24m deep, as indicated in the Figure 9.

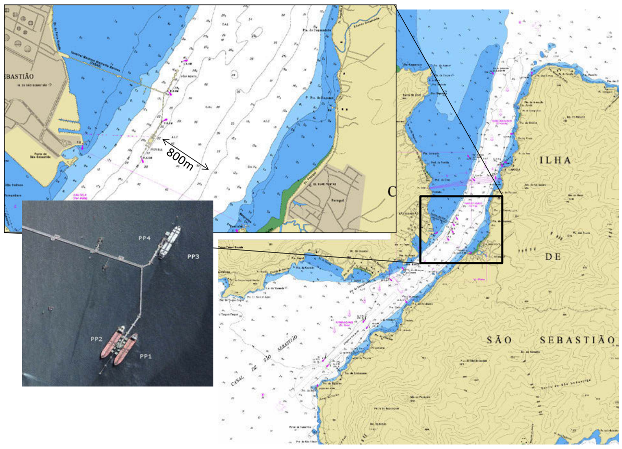

Figure 9. São Sebastião Terminal Location and Channel Dimension

In order to optimize the oil exportation logistics, Petrobras (the Brazilian oil state company) and its subsidiary Transpetro (owner of the Terminal) intends to perform a ship to ship (STS) oil transfer in the external berth (PP1), involving VLCC´s and Suezmax´s classes tankers.

Analyses of different aspects of these operations have been carried out by the University of São Paulo and the company Argonautica Engineering & Research. The analyses include an updated bathymetry, current measurements campaign, hydrodynamic flow modelling, fast and real time manoeuvring simulations, different mooring arrangements, prediction of the loads in the terminal equipments, cables and structures, definition of environmental window and availability of the operation in general.

Besides the analysis of the ship-to-ship operation itself, an additional concern of the Maritime Authority is the possible restrictions that the STS operations might bring to the navigation along the channel, as illustrated in Figure 10. As may be observed in the figure, the ships must navigate along the channel in order to reach the anchorage area in the north and hence any additional restriction in the navigation speed or safe distance to the oil terminal must be properly evaluated.

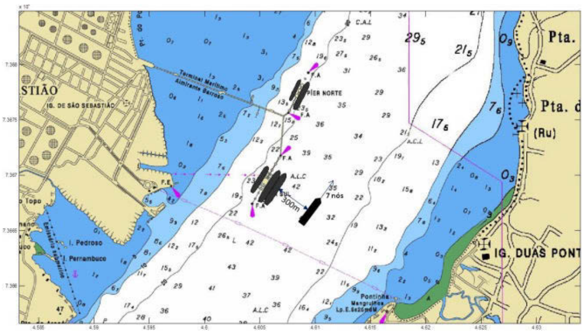

Figure 10. STS operation in the berth PP1 and a vessel along the channel

The critical case is represented when two VLCC vessels are berthed in STS configuration, and a VLCC tanker in full load condition is navigating along the channel. The main characteristics of the vessels considered in the present study are presented in the **Table 1**.

Table 1. VLCC mains characteristics

VLCC Characteristics	Ballasted	Full Loaded
Displacement (ton)	143920	347937
Draft (m)	10.0	22.3
Total Length LOA (m)	332	
Length Bet. Perp. LBP (m)	320	
Beam (m)	58	
Depth (m)	31	
Lateral Windage Area(m^2)	7673	3744
Frontal Windage Área (m^2)	1833	1132

The analyses were performed by considering not only the passing ship loads, but also including the effects introduced by current and wind. At TEBAR, the current velocity along the channel may reach up to 4 knots, and an extensive monitoring campaign and hydrodynamic model has been performed in order to predict the current close to the berths. The current flow is aligned to the central axis of the channel, going to NE or SW as indicated in the Figure 11.

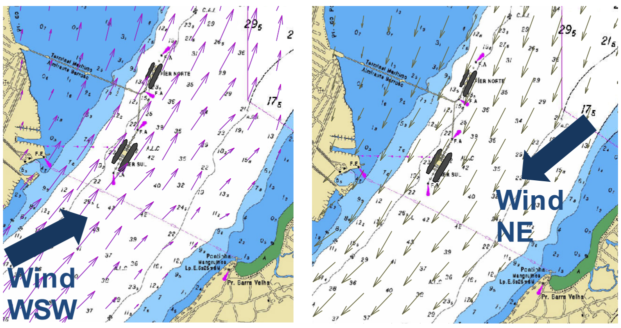

Figure 11. Current flow in the Terminal: (left) NE; (right) SW

The wind direction is mainly NE, but some strong wind gusts can be verified from WSW direction, reaching up to 40 knots. Therefore, in order to perform a conservative analysis, wind is assumed to come from the same direction as the current flow, as indicated in the Figure 11.

The mooring arrangement is defined following the OCIMF STS Guide recommendations, using 42mm diameter steel wire and 121ton maximum breaking load (MBL). A 55% MBL is adopted as failure criterion of the lines whereas for the fenders the maximum allowed compression loads are considered. Figure 12 shows the mooring arrangement and indicates the number of each type of mooring lines.

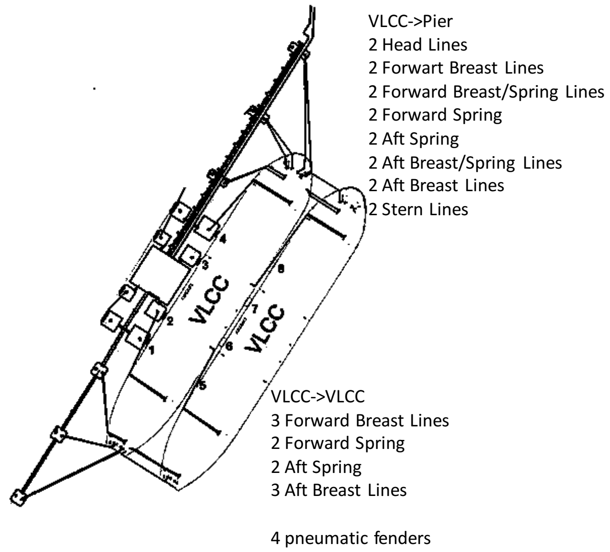

Figure 12. Mooring Arrangement for 2 VLCC in STS configuration

Firstly it is discussed the evaluation of the mooring loads in a 1-year operation, with no passing vessel along the channel. In this analysis, it was observed that the critical lines are the spring lines connecting the vessels and the aft breast line between the quay and the inner vessel. The maximum extreme load observed in these 1-year environmental conditions was 40% of the line MBL. Analogous analysis concerning the prediction of maximum loads was also performed for the pier structure and inland equipment (Figure 13), indicating that the loads on these structures reached 45% of the maximum dimensioning load of the dolphins.

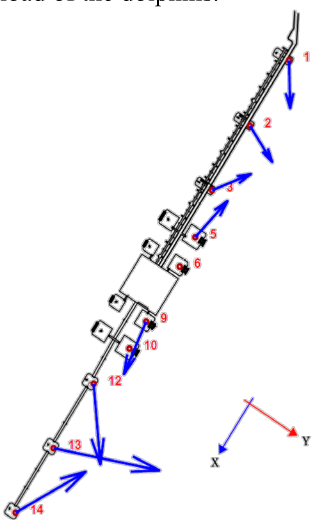

Figure 13. Loads in the pier and equipments

The limiting environmental conditions are obtained by exhaustive calculation of the loads in the mooring lines, structures and equipments, in which several current and wind values are taken into account. Figure 14 shows the results, in which the red markers indicate a combination of wind and current speed that induces a non-admissible load, whereas the green ones indicate safe conditions. The blue line indicates the limiting environmental conditions for the scenario disregarding the passing ship effect, which illustrates that for safe conditions the current and wind must be lower than 2.8knots and 30knots, respectively.

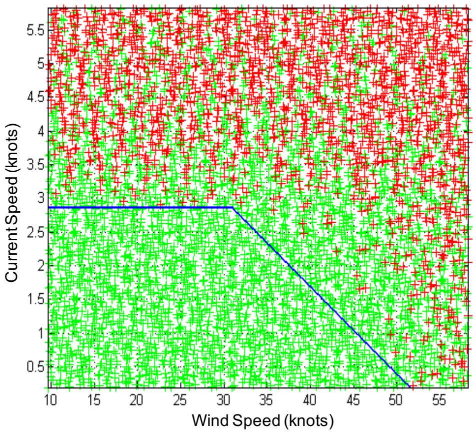

Figure 14. Maximum environmental conditions for VLCC-VLCC STS operation

Now, results considering the extra loads induced in the mooring system by a full-loaded VLCC navigating at 7knots along the channel are discussed. This ship speed was informed by the Maritime Authority as being a common ship navigation velocity at the port channel.
In this analyses, the 3 vessels are modelled using the Rankine Panel Method aforementioned, and the forces in each moored vessels are obtained and used as input data to MeDusA® software, which is applied for the mooring load calculations.

Results of the interaction forces induced by the passing ship on the berthed ones at the quay are presented in Figure 15, where it may be noticed that the forces reach relatively high values of 22tonf and 75tonf for distances between the vessels of 200m and 300m, respectively.

By applying these interaction loads on the mooring system of the ships, the maximum environmental conditions could be re-evaluated as shown in Figure 16 for the ship distance between the vessels of 300m. As may be observed, results show that when considering the 300m distance, the new current speed limit was slightly reduced from 2,8knots to 2,75knots. This small change is considered to be within the limits of uncertainty of the prediction technique.

The same calculation was done for the smaller passing ship distance, and the limit current speed was reduced, thus increasing the restrictions to the STS operations at the berth.

As a final recommendation, the study indicated that the STS operation can be carried out and the navigation along the channel is not affected, as soon as the vessel maintains a minimum distance of 300m to the vessels in the berth and keeps the maximum speed of 7 knots.

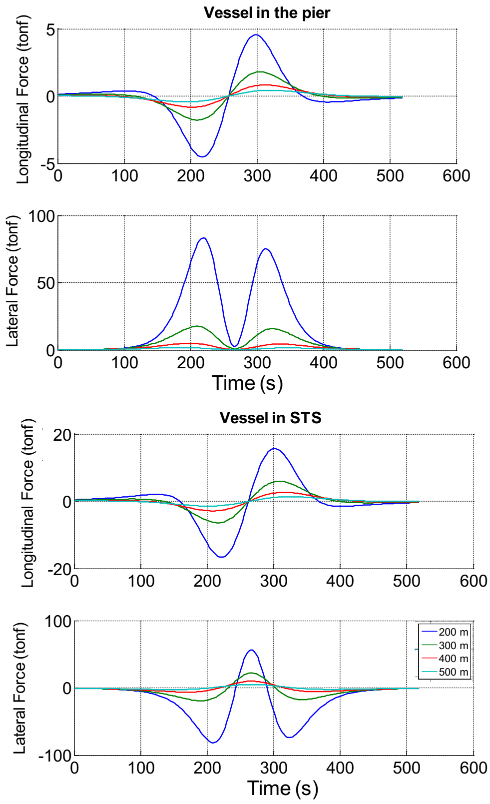

Figure 15. Hydrodynamic interaction forces

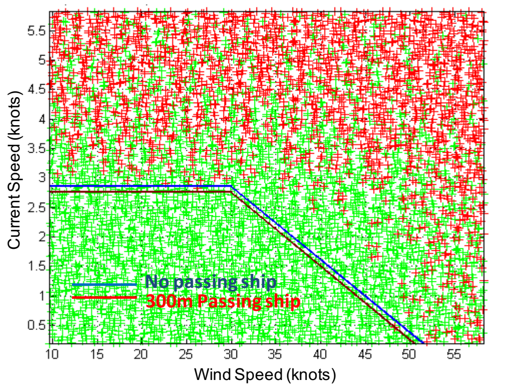

Figure 16. Maximum environmental conditions for VLCC-VLCC STS operation for the passing ship case

4 CONCLUSION

The application of a numerical method for the evaluation of mooring loads due to passing ship problems in São Sebastião Port (TEBAR) was presented in this paper. The specific condition studied is the passing ship problem involving a VLCC vessel navigating along the port channel and two other ones arranged in a ship-to-ship configuration at one of the port quays.

The analyses were performed by calculating the passing ship interaction forces by means of a Boundary Elements method. These forces were then imposed as input data on MeDuSa® software, which was responsible for the calculation of the loads on the mooring lines and fenders.

Besides, current and wind loads were also taken into account.

The results were focused on the definition of limiting environmental conditions to the ship-to-ship operations at the port quay, which were determined for scenarios with and without the influence of the VLCC navigating along the channel.

Results have shown that the VLCC navigating at the port channel at 7 knots in a distance shorter than 300 m was responsible for the imposition of a restrictive condition of current speed for the STS operations. Moreover, the results have also illustrated that as soon as the navigating vessel maintains a minimum distance of 300m to the vessels in the berth and keeps the maximum speed up to 7 knots the STS operations are not significant affected.

5 ACKNOWLEDGEMENTS

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