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Definition of Mooring Plans for Vessels at Port Terminals Using Physical Models

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ABSTRACT: Physical scale models have a large range of application in studies of hydraulic works. In port engineering, they can be used to optimize the general layout of terminals, evaluation of protection structures, simulation of vessel maneuvers and investigation of mooring plans for vessels, among several subjects. Once physical modeling allows a high accuracy in the waves and currents representation as well as their interaction with the bottom and the vessels, the studies of mooring systems in coastal and estuarine ports based on physical modeling tests provide greater reliability in comparison with those grounded on distinct types of models. To highlight the importance of this kind of application, this article presents the case study of the Ponta da Madeira Port (PMP), located in the State of Maranhao, Brazil, developed with the support of the 1:170 scale reduced physical model conceived and calibrated for this area. This study analyzed several alternatives to improve the availability of the northern berth of the Pier III of PMP, including new mooring strategies and the construction of a new improvement structure. The results, which concerned on preliminary tests of the mooring lines tensions, evidenced structural intervention could substantially reduce the risk of mooring lines break, indicating that further investigations concerning different layouts for the improvement structure are promising in order to provide an increase of this berth availability.

1 INTRODUCTION

One of the most important aspects in assessing the safety conditions of the operation of a port terminal is the verification of mooring plans for ships. According to [1], the function of the lines and mooring systems is to keep the vessel moored, in order to allow a cargo handling operation within tolerable safety limits. In addition, mooring plans must work with as few lines as possible, in order to ensure higher efficiency in the ships entrance and exit operations.

In order to ensure a safe and efficient mooring system, the tension in mooring lines must not exceed its minimum breaking load and, at the same time, the vessel movements shall be minimum as it is possible, according to the cargo type handled. International recommendations such as [2] and [3] set out the basic guidelines to be considered when evaluating mooring plans.

Especially in regions where the port is subjected to severe environmental actions, such as waves, currents or winds of moderate to strong intensity, or in confined areas where the passage of other vessels occurs near berths, the moored vessel is subject to forces that may result in excessive movement. These movements, in turn, can result in excessive tension on the mooring lines, which, in extreme cases, can cause serious accidents in case of line break.

Thus, in places where there are adverse conditions for the maintenance of ships safely docked in the berth, the development of studies about mooring system is essential, considering each critical scenario for each mooring berth and type of vessel. In these cases, physical modeling stands out as one of the most reliable options to perform the analysis of mooring conditions

Physical models are generally small-scale representations of any physical system and its applications in Engineering are widely discussed in the international literature, in references such as [4], [5], [6] and [7]. In the case of port studies, hydraulic physical models, also shortly called *scale models*, can be used to represent the entire interest area, including topography, bathymetry, docking structures, vessels and also the environmental conditions, such as water level variations, waves, winds, and so on.

The scale models can be used in several types of port studies, among which [8] highlights:

- Shelter of waves and / or currents, intervening in the geometry of piers, breakwaters, jetties, access channels, maneuvering basins, etc.
- Characteristics of berths, intervening in their orientation, type of structure, etc.
- Mooring characteristics, intervening in the arrangement of bollards, or quick release hooks, arrangement and type of fenders, recommendations on the Number and type of lines, as well as pre-tension levels.

This article describes studies based on physical modeling developed to improve the mooring condition at a Brazilian Port, the Ponta da Madeira Port (PMP) located in the northeast of Brazil, in the Sao Marcos Bay. Considering iron ore exportations, PMP is the most important Brazilian Port.

The Sao Marcos Bay area is sheltered from wave action and is enough deep and wide to receive Very Large Ore Carriers (VLOC). However, this area is subjected to high water level variation, which can reach heights of up to 7 m in equinoctial spring tide. Consequently, the currents inside the bay are very strong, causing problems for navigation and safe mooring of vessels.

Thus, a small-scale hydraulic physical model was built and calibrated within the Hydraulic Technological Center (CTH), which is the Hydraulic Laboratory of the University of São Paulo, in order to develop studies concerning the PMP operations. The present article discusses one of the case studies carried out for this port, with support of physical modeling, which aimed the reduction of the downtime of the north berth of the Pier III. During this study case different alternatives, such as new shelter or berthing structures and different mooring plans, were analyzed to allow safe mooring in this berth, even for the most severe tidal current conditions.

2 MATERIAL AND METHODS

2.1 *Study area description*

The Sao Marcos Bay, the largest Brazilian bay, is located in the Northeast of Brazil, in the State of Maranhao, , bounded to the west by the continent, to the east by the city of Sao Luis and to the south by the mouth of the Mearim River.

This bay has great potential for port installation, because of high depths and wave protection within it. For this reason, several important Brazilian ports are grouped in this place, among which stands the Ponta da Madeira Port (PMP): a private port specialized in iron ore exportation. Figure 1 illustrates the study site. This port comprises three main piers, named in the order of its construction, as Piers I, III and IV (Pier II is located a little further south and it was not considered in this study). Figure 2 shows the location and arrangement of piers PI, PIII and PIV.

Figure 1. Location of the Sao Marcos Bay and the Ponta da Madeira Port (PMP).

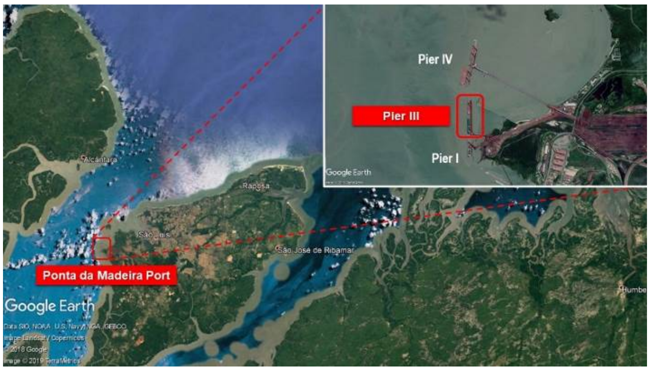

Figure 2. Location of the PMP and Piers I, III and IV, with emphasis on Pier III, which will be the subject of this article.

Although it is a region with great potential for the installation of ports, San Marcos Bay presents a natural condition that imposes great difficulty for the navigation and mooring ships. Average tidal amplitude is about 4.5 m, reaching approximately 7.0 m in equinoctial spring tides. This huge variation of the water levels within the bay results in very high current speed, which hinder safe maneuvers and docking during loading or unloading operations.

2.2 *Scale Model Description*

Concerning the Sao Marcos Bay environmental dynamics, and considering the PMP is the most important iron ore export port in Brazil, the CTH was hired to develop physical modeling studies to support its port operations. The limits of the three-dimension physical model built are represented on Nautical Chart 413 of the Brazilian Navy illustrated in Figure 3. The main purpose of these studies is to assure the safety of port operations, considering the goals of improving operating conditions to receive larger vessels and increase efficiency.

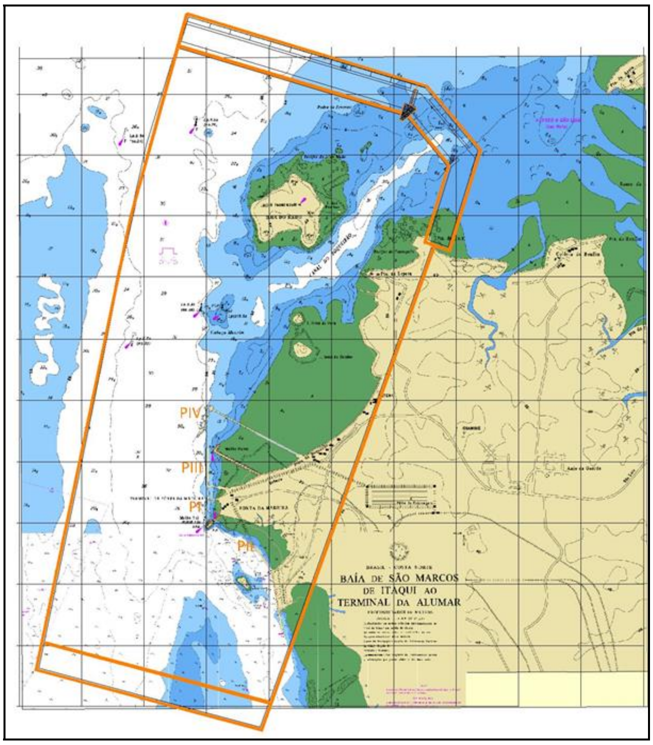

Figure 3. Nautical chart nº 413 and the limits of the physical model of the Sao Marcos Bay.

The physical model was built on the non-distorted linear geometric scale of 1: 170, considering the similarity criteria of Froude, and was reproduced with fixed bottom. Figure 4 shows an overview of the model, which has an area of approximately 1,700 m².

Figure 4. General view of the three-dimensional physical model of the Sao Marcos Bay in CTH-University of Sao Paulo.

The use of the scale models to represent real environmental conditions is based on the Similarity Theory.

The complete similarity between two flows is obtained when there is equality between all the relevant dimensionless obtained using Buckingham's Theorem [4]. In the case of free surface flow, usually the dimensionless that govern the phenomenon are the Reynolds Number, the Froude Number and the Weber Number, detailed as follows:

$$Re = {U \cdot D}/{\nu} \quad \text{: Reynolds Number} \tag{1}$$

$$Fr = {U}/{\sqrt{g \cdot y}} \quad \text{: Froude Number}^{8} \tag{2}$$

$$We = {\rho \cdot U^2 \cdot D}/{\sigma} \quad \text{: Weber Number} \tag{3}$$

in which:
U : mean velocity of the flow (m/s)
D : linear dimension (m)
ν : kinematic viscosity of water (m²/s)
g : gravity acceleration (m/s²)
y : depth of the flow (m)
ρ : specific mass of water (kg/m³)
σ : coefficient of surface tension of the water (N/m)

The Reynolds Number is given by the ratio between the inertial forces, represented by the velocity and the viscous forces (kinematic viscosity coefficient). The Froude Number is the ratio between velocity and gravitational force. The Weber Number relates the forces of inertia to the forces of surface tension.

Mathematically, it is possible to verify that, for two distinct flows, the equality between all the dimensionless occurs only if the geometric scale between both is equal to 1. Of course, for practical applications in studies of port structures, it is not possible to build models in real scale (1:1). In other words, for the practical use of scale models, it is necessary to apply the principle of *incomplete similarity*, in which the equality of the more important dimensionless for accurate representation of the phenomenon is prioritized. In the case of free flow, the equality between the model and prototype (real environment) Froude Numbers guarantees an adequate reproduction of the flow conditions, and allows the determination of important physical quantities through the tests performed in scale models. It is important to mention that the *incomplete similarity* in modeling implies some *scale effects* and limitations during the tests, which need to be considered according to the objective of the study.

The scale model of Sao Marcos Bay was designed based on the Froude similarity criteria for free surface flows. This condition, by itself, establishes the relations of extrapolation for the prototype of the several quantities measured in the model.

Establishing equality between the Froude Numbers of the model (subscript "*m*") and the prototype (subscript "*p*") by Equation (2):

$$U_m/\sqrt{g \cdot y_m} = U_p/\sqrt{g \cdot y_p} \tag{4}$$

Knowing that the geometric scale (λ) can be written as a relation between prototype and model of any linear quantities (L):

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[8] Shallow water conditions

$$\lambda = {}^{L_p}\!\!\diagup\!{}_{L_m} \tag{5}$$

Other fundamental quantities can be written in relation to this scale factor, such as:

$$U_p / U_m = \lambda^{1/2} \text{ : velocity scale} \tag{6}$$

$$Q_p / Q_m = \lambda^{5/2} \text{ : Volume flow rate scale} \tag{7}$$

$$t_p / t_m = \lambda^{1/2} \text{ : time scale} \tag{8}$$

$$F_p / F_m = \lambda^{3} \text{ : force scale} \tag{9}$$

2.3 *Scale Effects and Calibration of the physical model of Sao Marcos Bay*

The effects due to not represent the viscosity of the water (represented by the Reynolds Number) in small-scale models, for example, can be ignored if the flow in the model is rough turbulent. This can be achieved by observing a minimum reduction scale for the physical model $(1{:}\ \lambda)_{min}$, which can be obtained by the Zeghzda criterion [4]. Using the logarithmic expression for the characterization of turbulent flow velocity distribution, the minimum scale of the physical model can be calculated from the expression:

$$\frac{1}{\lambda} = \left\{ \left(\frac{126}{Re_p} \right) . \left(\frac{D_H}{\varepsilon} \right)_p . \left[-2log \left(\frac{\varepsilon}{3,71.D_H} \right)_p \right] \right\}^{2/3} \tag{10}$$

where:
D_H : hydraulic diameter
ε : bottom roughness, which can be estimated by $\varepsilon = (26.n)^6$ [5]
n : Manning Number.

Thus, in the berthing area of the PMP, in which the flow velocities are close to 6 knots (approximately 3 m/s), the mean flow depth is about 25 m (the hydraulic diameter can be approximated by 4 times this value) and the Manning Number is close to 0.035 (value obtained from calibration in a computational model presented later in this paper), the minimum scale calculated by Equation (10) results in: $(1 / \lambda) \approx 1/179$. Therefore, the scale adopted for the scale model of Sao Marcos Bay (1/170) has scale effects due to viscosity that can be ignored in the berthing area.

In addition to the topographic and bathymetric characteristics of the region, the vessels are also reproduced in small scale. For this, based on the arrangement of lines and the general arrangement of the real vessel, the hull model and the mooring elements are conceived according to the geometric similarity. Furthermore, the vessel's model is calibrated for real vessel building data, mainly using of its gravity center and rotation radius.

The flow calibration process was based on water level, current speed and direction data, extracted from a numerical hydrodynamic model conceived for the same interest area, which is further described in this paper, at twenty-four homologous points. This model was calibrated for seven different points within the interest area, where current speed, direction and water level data were acquired during a one-year field survey.

During physical model tests, flow speed and direction are acquired with a MicroADV (Acoustic Doppler Velocimeter), and water level is measured with depth probes, applying the methodology presented in [9].

2.4 *Forces and Displacement Measurement Systems*

The parameters controlled and measured during mooring tests are basically the ship movements and the forces induced in the mooring lines systems by these displacements. The tests are performed considering the elastic stress limits applied in the mooring lines. For this representation and tension measurement in the lines, a helicoidal spring is connected to a displacement sensor. Each line is positioned on the projection corresponding to a real mooring element. This system is installed in each set of lines that support and obey the real geometry, maintaining the same angle in relation to the vertical obtained in prototype. The efforts on the mooring system are acquired by the electromechanical calibration of this set, which reproduces the lines characteristics in scale. The Figure 5 illustrates the forces measurement system.

Figure 5. Forces measurement system in the scale model of Sao Marcos Bay – CTH – University of Sao Paulo.

The ship displacements on the horizontal plane of are acquired through a software developed at the CTH, based on two cameras equidistant from the instantaneous center of rotation of the boat and two fixed targets in the same deck, according to Figure 6. The cameras are able to measure the vessel movements during the test from its initial position in three degrees of freedom: Yaw, Surge and Sway.

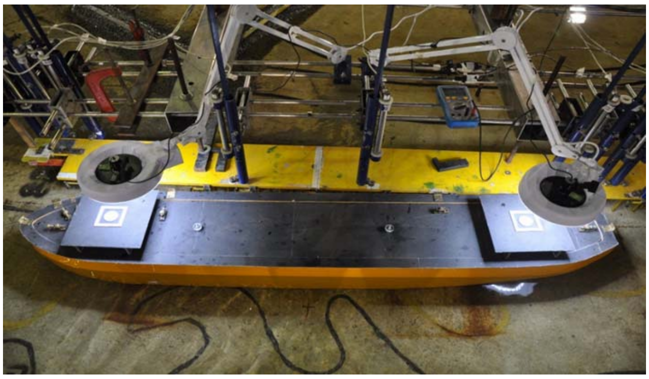

Figure 6. Measurement of vessel movement System by images.

The fenders are reproduced by steel blades, which are calibrated from the stiffness curve in addition to the absorption energy. These elements are fixed to the homologous places on the berths walls observed in the prototype, for reproduction of the real mooring conditions.

3 RESULTS AND DISCUSSION

The North Berth of Pier III of the PMP receives vessels of the Capesize class of 180,000 DWT. For the higher tidal amplitudes that occur in the Sao Marcos Bay, this berth has operational restrictions, which represents a reduction in its availability throughout the year. In order to reduce this downtime, engineering solutions were analyzed in numerical and physical model tests, looking for increasing this berth’s availability, considering safety limits and without causing significant impacts on the sediment dynamics at the interest area and its adjacencies.

For preliminary tests, a hydrodynamic and morphologic computational model of the region was applied. This model was conceived and calibrated on the MIKE3® platform, developed by DHI (Danish Hydraulic Institute). The results of these tests allowed the definition of the most promising alternatives to be investigated in the physical model at a later stage of the studies.

The computational grid covers the entire Sao Marcos Bay, with a grid of more than 30 thousand cells, which density increases in the vicinity of the PMP piers. The Figure 7 shows the elements of the numerical grid. The main problem, which restricts the operation of the northern berth of Pier III, is the action of the currents, during the flood tide. In this condition, the velocities can be very intense near the north end of this berth, pushing the vessel hull out of the berth, and forcing mainly the forward breast lines. The Figure 8 presents an output of the computational model illustrating the current field in the northern berth of PIII.

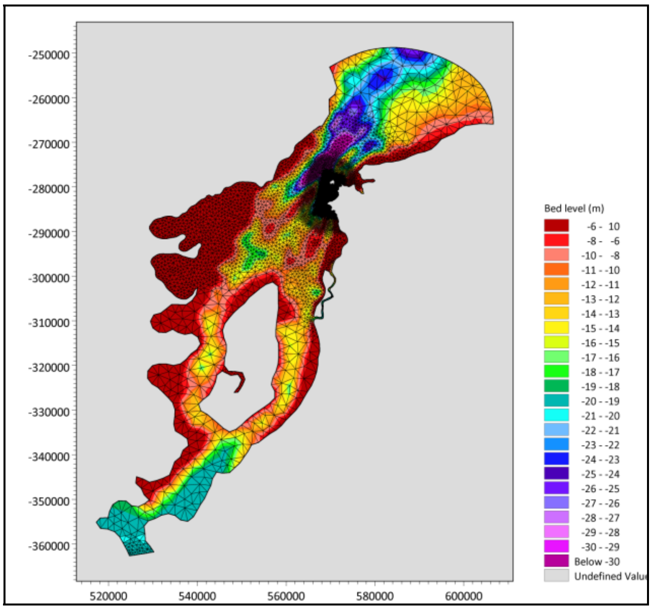

Figure 7. Numerical grid of the three-dimensional hydrodynamic computational model of Sao Marcos Bay on the Mike 3® platform.

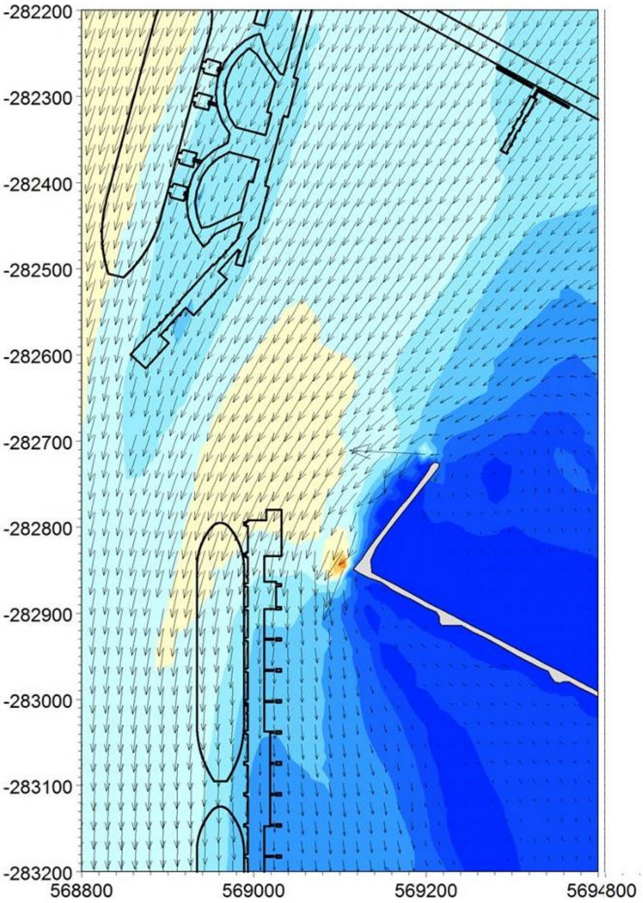

Figure 8. Currents of the flood tide near Northern Berth of PIII.

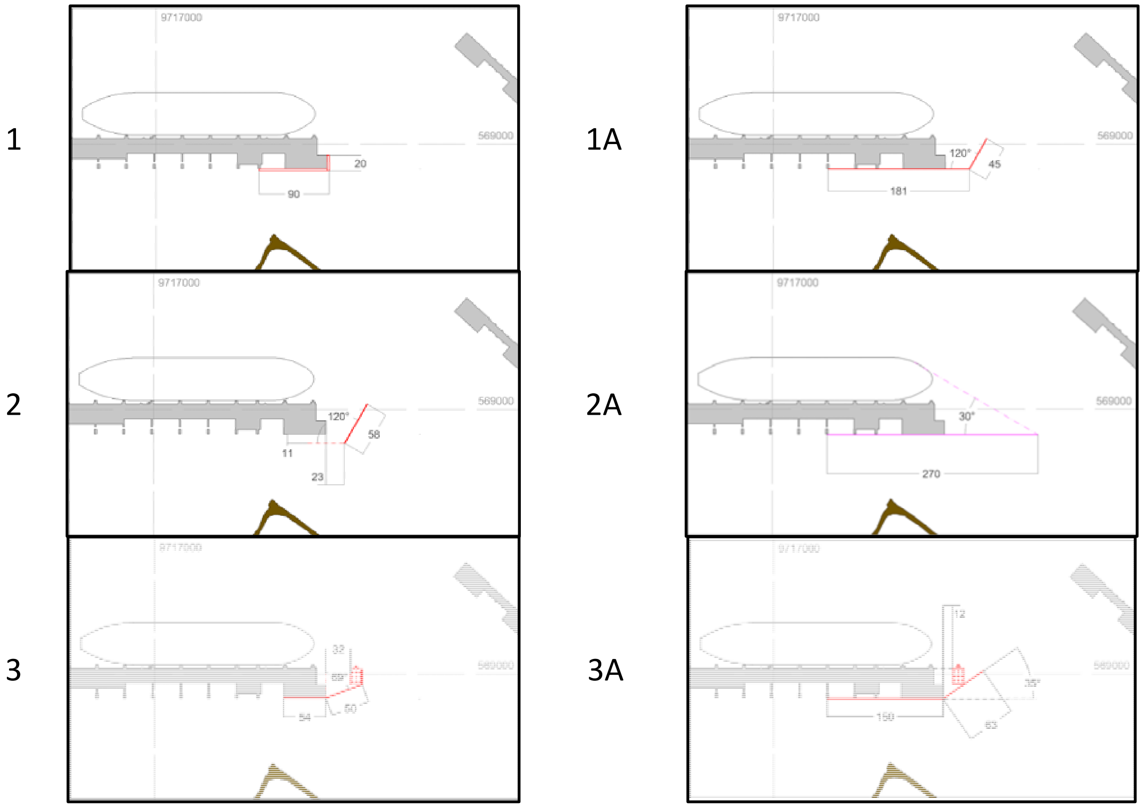

Figure 9. Alternatives of shelter wall (highlighted in red color) to decrease the currents action on the vessel in Northern Berth of PIII.

The study of alternatives to find a solution that decreases the downtime of the Northern Berth of Pier III, analyzed the implantation of two types of structures: a shelter wall at the north end of the Berth; and a mooring dolphin to the north of the berth.

For the shelter wall, six different layouts (1, 1A, 2, 2A, 3 and 3A) were analyzed in the computational model, as shown in Figure 9. The alternatives studied were defined to cause the least possible impact on the mooring plans of the other berths and on the sediment dynamics of the area.

The study of alternatives performed preliminary in the computational model analyzed the variation of velocities along all the berths and possible changes in orders of the magnitude of the sediment deposition.

The computational simulations indicated the layouts 1A and 2A had the best performance considering the mentioned criteria. Both alternatives caused a significant decrease of the velocities near the berthing area in the Northern Berth of Pier III, and in periods of flood tide, as well as they reduced the velocities in the other berths of Piers I and III. However, during periods of ebb tide, especially the Alternative 2A causes an increase in the current velocity near Pier I berthing line and the southern Berth of Pier III. For these conditions, Alternative 1A presented more similar and favorable results.

In addition, the results of the computational simulations showed both Alternatives 1A and 2A do not significantly cause changes in the sediment distribution of the PMP area.

Based on these results, only the alternatives 1A and 2A were tested in the scale model of Sao Marcos Bay for mooring lines tension analysis. These tests were performed considering vessels docked in in all berths of the PMP, which represents a critical condition for this port operation. The Table 1shows the vessels used in the each PMP berth and Figure 10 illustrates this typical test condition.

Table 1. Class of vessels used in the scale models tests for evaluation of forces on the mooring lines.

Pier	Berth	Vessel	DWT
PI	---	VLOC	350,000
PIII	North	Capesize	180,000
PIII	South	Capesize	180,000
PIV	North	VLOC	400,000
PIV	South	VLOC	400,000

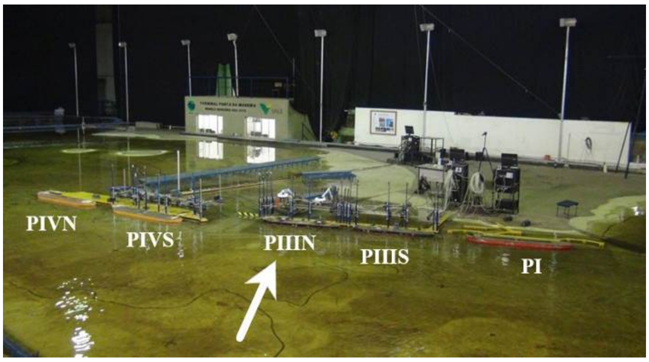

Figure 10. Picture of the Physical Model of Sao Marcos Bay with all the berths occupied by a vessel (according to the Table 1). Highlighted the Northern Berth of PIII (PIIIN).

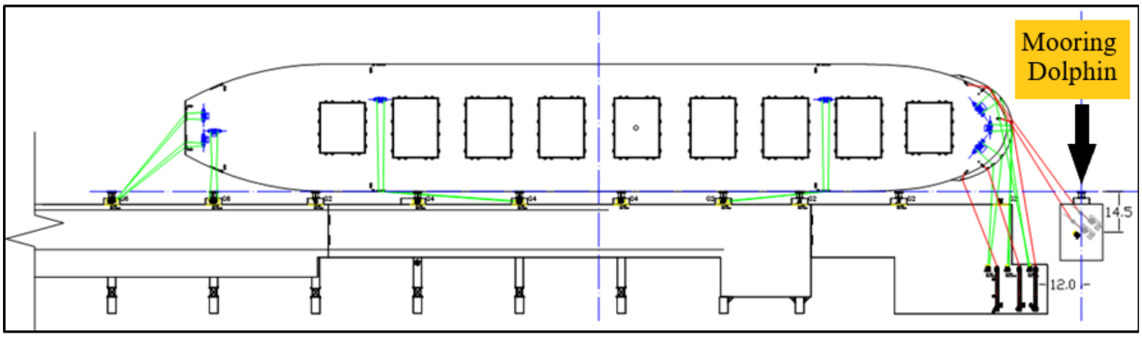

Figure 11. Alternative with an implantation of a mooring dolphin and the mooring plan "P3N9".

The physical model tests indicated that both implantations of the shelter walls 1A and 2A lowered the mooring line tensions at the vessel's bow, when it is moored at the northern berth of Pier III. However, an increase in mooring line tensions was detected at this ship's stern. An increase in mooring line tensions was also detected at forward breast of the ship moored in the southern Berth of the same pier for the two alternatives.

Regarding these results, another structural alternative was investigated in the scale model. It was an additional mooring dolphin, near the northern end of Pier III. Two positioning alternatives were studied for this dolphin, as well as five different mooring plans, four of them with a more distant dolphin and one with a dolphin closer. The best results were obtained for the mooring plane called "P3N9", with the dolphin closest to Pier III. This alternative is illustrated in Figure 11.

The physical model tests showed that the closest dolphin alternative allowed the implantation of a mooring plan which assures docking safety for practically all tidal amplitudes that occur in Sao Marcos Bay. P3N9 plan (Figure 11) enabled an increase of approximately 60% on the availability of northern berth of Pier III, when compared to the original condition

Moreover, since the dolphin structure is relatively slender, it practically does not interfere in the local current field and, thereafter, does not affect the mooring conditions in the other PMP berths nor causes any significant impact on sediment deposition at the PMP and its adjacencies.

4 CONCLUSIONS

Small-scale hydraulic physical models are a powerful tool for engineering studies. In the case of the evaluation of the safety of mooring conditions at ports, the experience of the work developed by CTH has shown that the results obtained in these studies accurately represent the reality. Several measures of tensions on the mooring lines of real ships have been compared over the years with the physical model tests results, allowing confirmation of the effectiveness of this tool.

In the case of the studies developed for the Northern Berth of the Pier III of the PMP, presented in this article, preliminary studies of alternatives in computational modeling allowed to define the two better layouts of a shelter wall structure, which reduced the current speed near this berth and with minimum interference on sediment transport. ,. However, when these alternatives were tested in the physical model, both proved to be inefficient in decreasing the downtime of this berth, as well as their implementation caused an increase on the mooring line tensions for vessels docked at adjacent berths

Further investigations of alternatives in the physical model concluded that the most promising solution is the implantation of a dolphin near the north end of Pier III. This solution allowed the use of a new morring plan (P3N9), with a reinforcement of the forward breast lines, that was able to keep the vessel moored in safety for almost all environmental conditions. Considering the implementation of this alternative, the downtime of the Northern Berth of the PIII was reduced significantly.

In addition, the alternative of the dolphin had no effects on the mooring conditions of ships in other PMP berths, as well as this solution showed no significant change in the complex and intense sediment dynamics of the region.

From the study developed for the Northern Berth of PIII, future studies in the physical model will allow the optimization of the mooring plans for this berth, using the new structure of the dolphin and aiming to suppress any operational restriction.

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