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Applying the SAFEPORT system in a storm situation

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ABSTRACT: This paper presents an application of the SAFEPORT safety system. It consists of a forecast and early warning system for emergency situations related to navigation, berthing, and mooring in port areas. The prototype of the system is being developed for the Port of Sines. The main objective of this paper is to describe the application of the numerical models in SAFEPORT to simulate the behavior of three different ships moored in three terminals of the Port of Sines, subjected to the sea-wave conditions of the Dora storm. The 3-day advance sea-wave forecasts provided by the WAM model were used. Tide levels and currents were obtained from the XTide model. It was concluded that the SAFEPORT system was able to forecast possible hazards and issue the expected alerts regarding the moored ships' motions and the forces on their mooring lines associated to the Dora storm.

1 INTRODUCTION

The significant increase of cargo volume in the Iberian Peninsula as well as the increase in the size of the ships calling at its ports has driven several port-expansion plans. The new ships require deeper waters, which leads them to be berthed in very exposed locations. In addition, the number of major storms that formed in the Atlantic Ocean reached a new maximum in 2020. The harbors of the Portuguese West coast are exposed to such storms, and this is a key factor for the safety of ships moored there.

In this new scenario, to ensure the efficiency of port operations, as well as the required safety levels during a storm situation, it is important to predict, in advance, the sea agitation inside the port and its consequences for ships that will enter the port or are berthed and moored inside. Due to the lack of systems addressing the hazards related to ships maneuvering and moored in ports, the SAFEPORT system, based on the HIDRALERTA system (Fortes *et al.*, 2015, 2020; Poseiro *et al.*, 2017 and Pinheiro *et al.*, 2020), is being developed as part of the BlueSafePort project.

SAFEPORT is a forecast and Early Warning System (EWS) for emergency situations related to navigation, mooring, and berthing in port areas. It provides 72-hour forecasts of the characteristics of sea agitation, its consequences related to ship movements and/or forces in the mooring systems and the associated hazard levels. A prototype of the SAFEPORT system is being developed for the Port of Sines.

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This paper presents an application of the SAFEPORT system, more specifically, the application of the numerical models developed to simulate the behavior of three different ships docked and moored at three terminals of the Port of Sines subjected to the sea-wave conditions of storm Dora, which reached mainland Portugal on December 4th, 2020.

To execute the numerical models for wave propagation and moored ship behavior, the safety system, herein presented, uses the integrated numerical tool, SWAMS — Simulation of Wave Action on Moored Ships (Pinheiro *et al.* 2013).

After this introduction, section 2 presents the SAFEPORT system in terms of its operation and numerical models. Section 3 describes the case study, the numerical models used, and the results produced by the SAFEPORT system. Finally, section 5 presents the main conclusions provided by this research.

2 THE SAFEPORT SYSTEM

The SAFEPORT EWS issues daily forecasts for the next 72 hours, at three-hour intervals, of sea agitation within a port and its consequences on ships (in maneuvering or moored).

2.1 *Methodology*

The SAFEPORT safety and alert system, similarly to the HIDRALERTA system (Poseiro, 2019 &

Pinheiro *et al.*, 2020), comprises 4 modules: I - Sea-wave characterization; II - Navigation in Port Areas; III - Monitoring; IV - Risk Assessment.

The first two modules integrate a set of numerical models. Some models are included in the SWAMS tool (Pinheiro *et al.* 2013). Those associated with the behavior of maneuvering ships are not included in this work and are carried out by the Centre for Marine Technology and Ocean Engineering (CENTEC). Numerical simulations run on the Central Node for Grid Computing (NCG) of the Portuguese Infrastructure for Distributed Computing (INCD), a 64-node high performance computing facility.

The third module consists of in situ monitoring required to validate the results produced by the numerical models.

The last module deals with risk assessment for moored ships, which is performed through the definition of hazard levels from 0 to 2 for the moored ships' motions and from 0 to 3 for the forces on their mooring lines.

Concerning the moored ships' motions, 0 corresponds to no danger (green symbol), 1 corresponds to a situation of restricted loading and unloading operations (yellow symbol) and 3 corresponds to the maximum warning level (red symbol). The limits imposed on the ships' motions are the recommended ones in PIANC (1995).

As for the forces on ships' mooring lines, the hazard levels depend on the Maximum Breaking Load (MBL) of the mooring lines (OCIMF, 1992). 0 corresponds to no danger (green symbol), 1 corresponds to 50% of MBL (yellow symbol), 2 corresponds to 80% of MBL (orange symbol) and 3 corresponds to 100% of MBL (red symbol).

Figure 1 shows the symbols used in the system to issue alerts.

Figure 1. Symbols used by the SAFEPORT system to alert ships' motions danger (left) and ships' mooring systems failure danger (right).

2.2 *SWAMS numerical software package*

SWAMS (Pinheiro *et al.* 2013), acronym for Simulation of Wave Action on Moored Ships, is an integrated numerical tool capable of simulating the response of a moored ship within a harbor, subjected to the action of sea waves, wind and currents. This tool consists of a graphical user interface and a set of modules that deal with the execution of numerical models for wave propagation and the behavior of moored ships inside harbor basins.

SWAMS consists of 2 modules (Figure 2): the WAVEPROP module for wave propagation and the MOORNAV module for moored ship behavior. The objective of the first module is to determine the sea-wave characteristics in the study area. The second module estimates ship movements and the forces exerted on the mooring system.

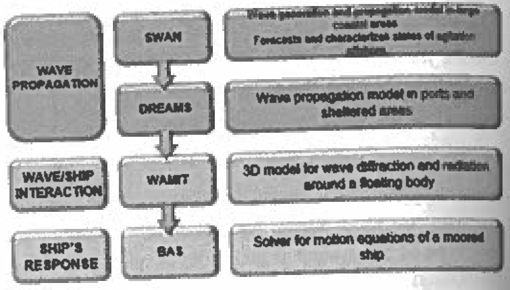

Figure 2. Structure of SWAMS numerical software package used in the case study (adapted from Pinheiro et al., 2013).

The WAVEPROP wave propagation module includes 3 numerical models for wave propagation and a finite element mesh generator, namely:

- SWAN (Booij *et al.*, 1996) is a spectral nonlinear model based on the wave action conservation equation, which simulates the propagation of irregular wave spectrum;
- DREAMS (Fortes, 2002) is a linear finite element model, based on the mild slope equation, to simulate the propagation of monochromatic waves;
- BOUSS-WMH (Pinheiro *et al.*, 2011) is a nonlinear finite element model, based on the extended Boussinesq equations deduced by Nwogu (1993), being able to simulate the propagation of regular and irregular waves;
- GMALHA (Pinheiro *et al.*, 2008) is a triangular finite element mesh generator specially defined to be used by DREAMS and BOUSS-WMH models, being the node density of the meshes variable according to the local wavelength and its construction optimized to reduce computational resources.

The MOORNAV moored ship behavior module includes 2 numerical models (Santos, 1994), namely:

- WAMIT (Korsemeyer *et al.*, 1988) which solves, in the frequency domain, the radiation and diffraction problems of the interaction between a free-floating body and the incident waves;
- BAS (Mynett *et al.*, 1985) that assembles and solves, in the time domain, the equations of motion of a moored ship, considering the time series of forces due to the waves incident on the ship, the ship's impulse response functions and the constitutive relations of the mooring system elements (mooring lines and fenders).

The numerical model SWAN transfers the wave characteristics from the offshore area to the harbor entrance. The DREAMS model and the BOUSS-WHM model, in turn, transfer the wave characteristics from the harbor entrance area to the harbor area, using the harbor mesh generated by GMALHA. The WAMIT numerical model determines the response of the free-floating ship to incident monochromatic waves. Then, with the hydrodynamic information obtained, it is possible to determine the moored ship response through the BAS numerical model.

3 PORT OF SINES CASE STUDY

The Port of Sines is a deep-water port located on the west coast of mainland Portugal (Figure 3). The port has 7 terminals, namely: the Liquid Bulk Terminal (TGL), the Liquified Natural Gas Terminal (TGN), the Petrochemical Terminal (TPQ), the Sines Container Terminal or Terminal XXI (TCS), the Sines Multipurpose Terminal (TMS), the Fishing Port and the Sines Marina.

Given its national relevance, its continuous economic growth and constant expansion, the port of Sines has been the subject of several research projects. The prototype of the SAFEPORT system, for example, has been developed and validated for the Port of Sines. For that, SWAMS (Pinheiro *et al.* 2013) was employed to simulate the behavior of three different ships docked and moored at three terminals of the Port of Sines subjected to the sea-wave conditions of storm Dora, namely: an oil tanker at the TGL, a general cargo ship at the TMS, and a container ship at the TCS (Figure 3).

Figure 3. Location of the Port of Sines and the TGL, the TMS, and the TCS.

Storm Dora reached its highest intensity during the afternoon of 4th December 2020, and the early morning of 5th December 2020. According to Civil Protection, there were more than 400 incidents along the Portuguese territory, most of which caused minor material damage. It was a storm characterized by wind gusts of more than 100 km/h (62 mph) in the areas near the coast, snow in the north of the country, rain, and rough sea with records of maximum wave height of 10.3 meters at the wave buoy in front of the Port of Sines.

3.1 *Basic Data*

The 3-day advance forecast of the offshore sea agitation was obtained through the European Centre for Medium-Range Weather Forecasts (ECMWF) (Persson, 2001), which uses the WAM model (WAMDI Group, 1988) used by. The forecasts for 4 and 5 December were collected every 3 hours for the following sea wave parameters: significant wave height (H_s), peak wave period (T_p) and mean wave direction (θ_m) (Figure 4).

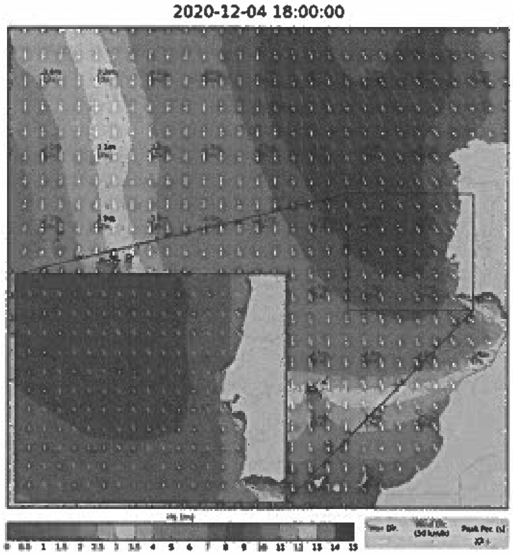

Figure 4. WAM model results offshore the Port of Sines (H_s, T_p and θ_m) for 4th December 2020, 6 p.m.

The WAM model predicted that the waves formed due to storm Dora would have a predominant θ_m of north, with H_s ranging between 3 and 8 m and a maximum T_p of approximately 18 s.

The tide levels were estimated with the XTide model (Flater, 1998). Wind data was obtained from the NAVGEM model (Reynolds et al., 2011). Bathymetry was provided by Sines and Algarve Ports Administration. The general geometric characteristics of the ships are shown in Table 1.

Table 1. General geometric characteristics of the simulated ships.

Ship	Draft m	Beam m	Length overall m
Oil Tanker	22.0	26.5	340
General Cargo	10.5	30.0	220
Container	8.0	19.0	120

3.2 *Sea-waves propagation and characterization*

3.2.1 *SWAN numerical model application*

The SWAN numerical model (Booij *et al.*, 1996) was applied to propagate the sea agitation parameters, from offshore to the entrance of the port of Sines. The theoretical JONSWAP spectrum was assumed to represent the real spectrum of the waves approaching the port.

To achieve a better numerical performance, the model domain was discretized into three nested rectangular grids (Figure 5). The physical phenomena accounted by SWAN were diffraction and dissipation by bottom friction. The simulations were performed in the two-dimensional stationary mode. In the third, the smallest, mesh one point was defined, in the vicinity of the port of Sines, where the wave characteristics i.e., H_s, T_p and θ_m, were extracted.

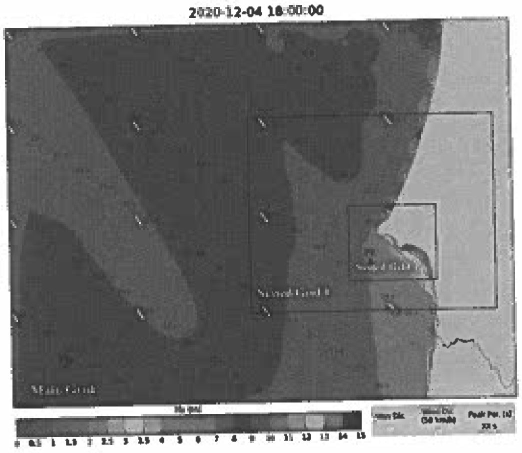

Figure 5. SWAN model results at port of Sines (H_s, T_p and θ_m) for 4th December 2020, 6 p.m. PO stands for the North offshore point of the WAM model and PE stands for the transfer point from SWAN to DREAMS.

On the 1st day of the storm, the observed waves in front of the port had their T_p between 15 s and 17 s, and H_s between 3 m and 7.55 m (maximum Hs occurred at 6 p.m.). The most frequent situation corresponds to H_s between 6 m and 6.5 m. As for θ_m, Northwest incidences represent the predominant direction of the waves. For the 2nd day of storm Dora, the sea agitation conditions were less severe. A maximum H_s of 6.94 m was obtained at 12 a.m. with a T_p of 15.09 s. The predominant θ_m was also northwest.

3.3 *DREAMS numerical model application*

The DREAMS model simulates the propagation of monochromatic waves on gently sloping bottoms, considering the combined effects of refraction, diffraction and partial or total reflection of the port area boundaries.

To do the modelling, a finite element mesh generated by GMALHA (Pinheiro *et al.*, 2008) was used to characterize the morphology of the Sines harbor. In addition, a file containing information about the absorption coefficients of each section of the port boundary was assigned to the model. Results (Figure 6 and Figure 7) were extracted at three points near the three terminals where the ships' behavior was simulated.

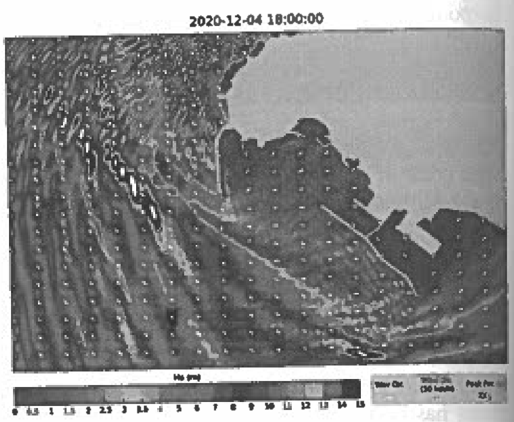

Figure 6. DREAMS model results at port of Sines (significant wave height and mean wave direction) for 4th December 2020, 6 p.m. PE stands for the transfer point from SWAN to DREAMS.

Sea waves approach the TGL with θ_m from south to southwest and H_s ranging between 0.1 m and 1.2 m. The peak was recorded at 9 p.m., on December 4th, with $H_s = 1.2$ m, $T_p = 15$ s and $\theta_m = 210°$.

The TMS, in turn, is affected by waves coming from the west with H_s not exceeding 0.7 m. The peak occurred at 6 p.m., on December 4th, with $H_s = 0.7$ m, $T_p = 15$ s and $\theta_m = 280°$.

Finally, at the container terminal, the incident wave action was characterized by south swells with Hs ranging from 0.12 m to 0.84 m. The peak occurred at 3 a.m., with $H_s = 0.8$ m, $T_p = 17$ s and $\theta_m = 174°$. Although wave heights offshore ($H_s \sim 4$ m) were not close to the highest recorded (at 6 p.m. on December 4th), the waves rotating slightly to the west led to the largest impact inside the port.

3.4 *Behavior of the moored ships*

3.4.1 *WAMIT numerical model application*

The WAMIT model (Korsemeyer *et al.*, 1988) was applied to calculate the hydrodynamic coefficients of the free ships, i.e., the damping and added-mass coefficients. For this purpose, one needs the geometry of the submerged hulls discretized into rectangular/triangular flat panels and the mass distribution (inertias) of the ships. The submerged hull of the oil tanker was

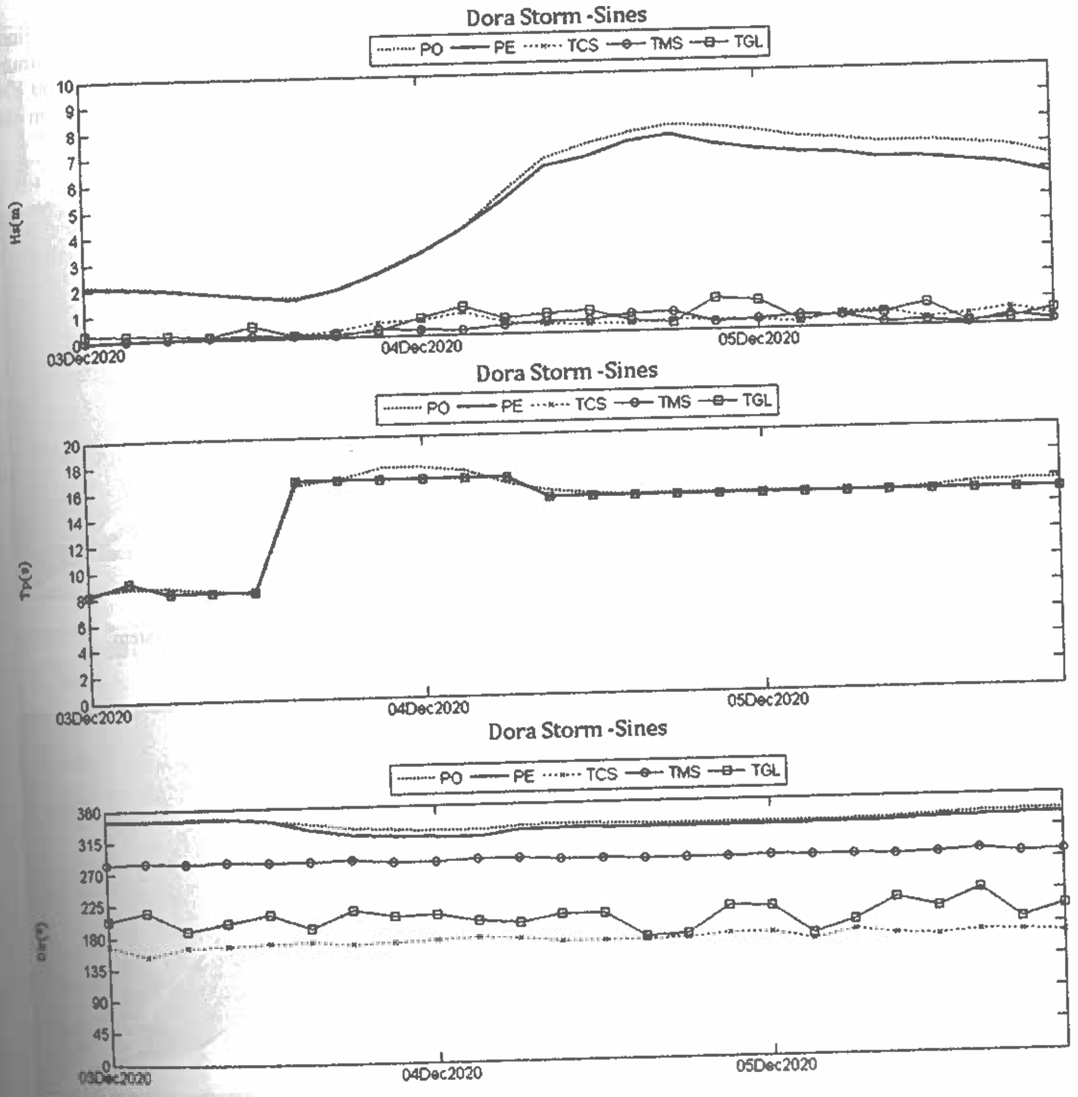

Figure 7. DREAMS model results at each terminal of the port of Sines (significant wave height (Hs), period peak (Tp) and mean wave direction (Dir)). PO stands for the North offshore point of the WAM model and PE stands for the transfer point from SWAN to DREAMS.

discretized with 1004 panels, the general cargo ship with 1992 panels and the container ship with 3464 panels (Figure 8). The tool used was NPP, acronym for Nautical Pre-Processor (Santos, 1994).

The WAMIT simulations were performed for the possible wave directions approaching each terminal and a range of 89 frequencies. Once the damping coefficients of the ships were computed, the impulse response functions (Figure 9) were obtained. The infinite frequency added masses were estimated based on the corresponding frequency domain added mass values for a given frequency and on the corresponding retardation functions.

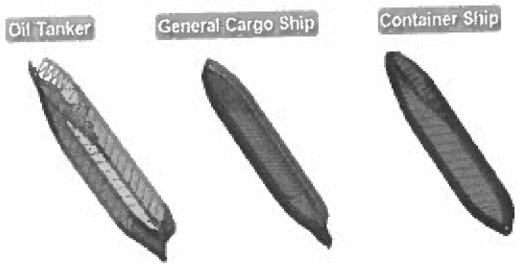

Figure 8. Panel discretization for the 3 ships.

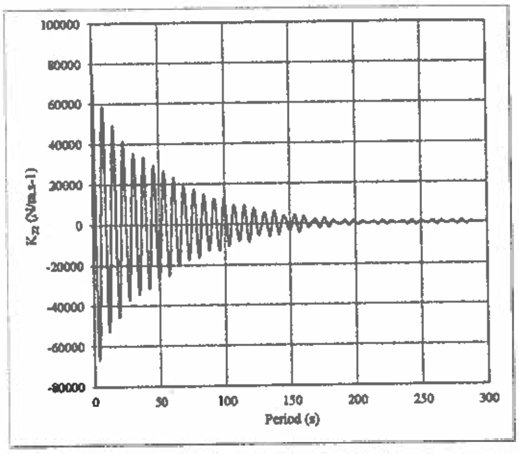

Figure 9. Impulse response (top) and infinite frequency added-mass (bottom) of the general cargo ship for the motion mode j, k = 2, 2.

3.4.2 *BAS numerical model application*

The application of the BAS model (Mynett *et al.*, 1985) to the moored ships allows one to obtain the motion of these ships and the forces in their mooring systems. As input parameters, in addition to the sea wave conditions, the BAS model used the information computed by the WAMIT model, the coordinates of the mooring points and the coordinates of the contact points between the ships and the fenders.

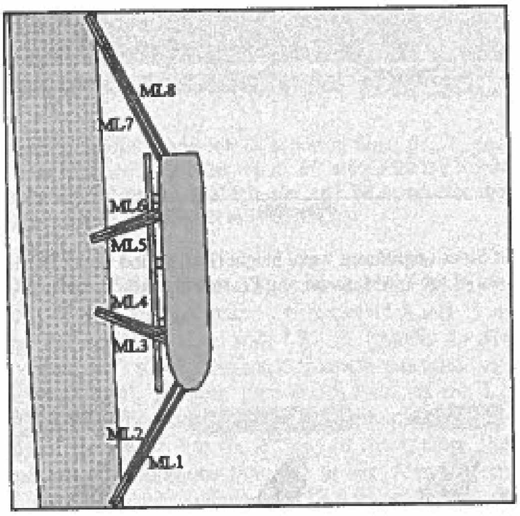

Figure 10. Oil tanker ship mooring system.

For the oil tanker and the general cargo ship, 8 mooring lines grouped in two and 3 fenders were defined (Figure 10 and Figure 11). For the container ship model, a total of 10 mooring lines and 5 fenders were defined (Figure 12).

The constitutive relations for all the mooring lines are linear. For an elongation of 4%, the maximum load on mooring lines of the oil tanker is 2100 kN, on the general cargo ship is 1900 kN and, on the container is 1860 kN.

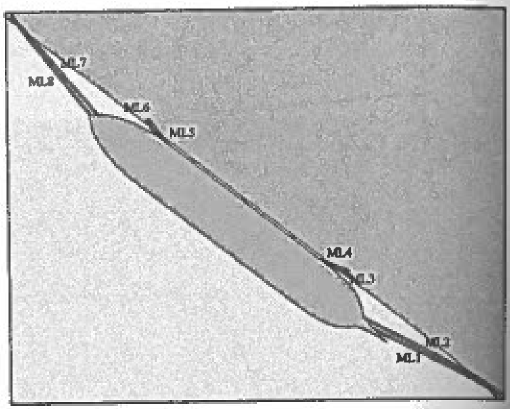

Figure 11. General cargo ship mooring system.

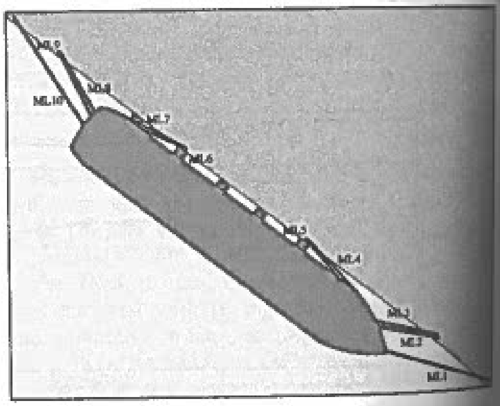

Figure 12. Container ship mooring system.

The same constitutive relations were considered for the oil tanker and the general cargo ships' fenders: non-linear range from 0 kN to 880 kN maximum load, with a maximum deflection of 0.4 m. As for the container ship, its fenders have a linear compression with a maximum force of 8900 kN for a deflection of 1 m.

4 RESULTS AND DISCUSSION

Sea wave results provided by the WAM and SWAN models show that at 6 p.m. on December 4th, 2020, corresponds to the most critical time of storm Dora. However, according to the DREAMS model results within the port, i.e., in the vicinity of the terminals under study, the storm peaks occurred at different times (Figure 7).

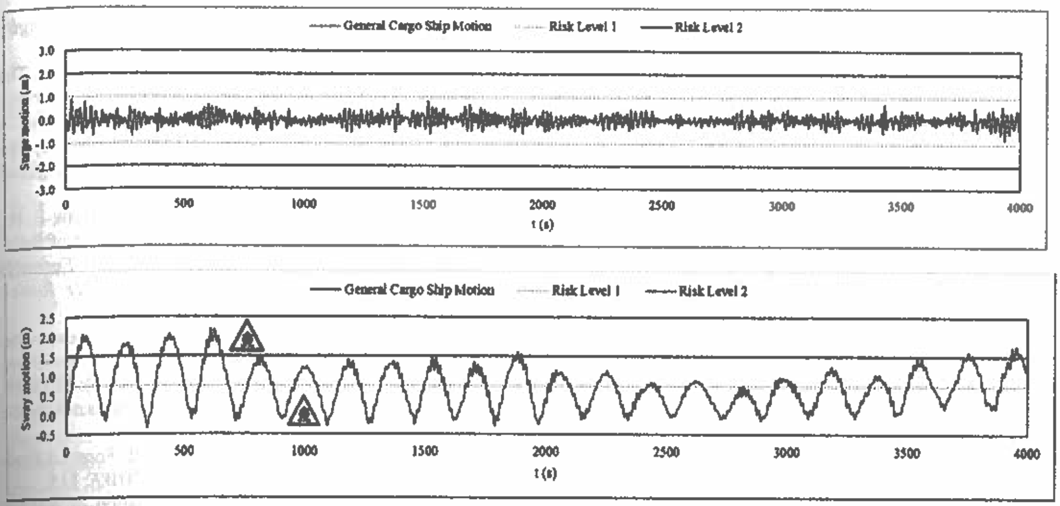

Figure 13. General Cargo Ship's surge and sway motions alerts.

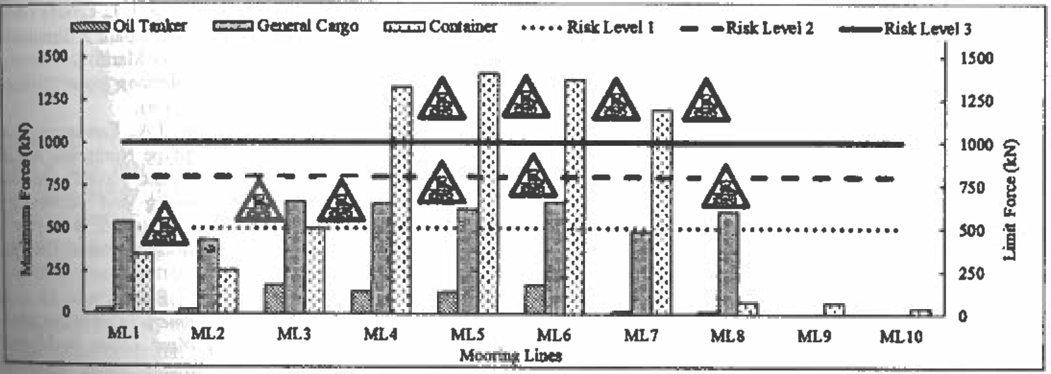

Figure 14. Forces on the ships' mooring lines alerts.

To comply with the objectives of the SAFEPORT system, the ships' motions and the forces on their mooring lines were analyzed, considering the storm peak recorded in the vicinity of the terminals where they are docked. Thus, Figure 13 presents some results for the general cargo ship (ship motions), at 6 p.m., on December 4th, obtained by the SAFEPORT system. Figure 14 displays the forces on the ships' mooring lines at the time when the peak occurred.

During storm Dora, no alerts were issued concerning the oil tanker moored at the liquid bulk terminal. Despite being the most exposed ship, given its large displacement, no excessive motions of the ship were forecast and, consequently, the forces on its mooring lines are not expected to reach the maximum limits.

As for the general cargo ship moored at the multi-purpose terminal, yellow and red alerts (danger level 1 and 2, respectively) were issued to sway and heave motions. 6 yellow alerts, i.e., danger level 2, were issued to mooring lines 1, 3, 4, 5, 6 and 8. The mooring lines received a maximum load of more than 500 kN. For the others no alerts were issued. This is an expected result, since among the 3 terminals, the TMS is the most protected from sea waves.

The container ship docked at the container terminal was the most affected ship by the storm Dora. Therefore, the system issued 2 red alerts to surge and sway motions, and 1 yellow alert to heave motions. 4 yellow alerts, i.e., danger level 2, to mooring lines 4, 5, 6 and 7. They were exposed to a maximum load of more than 1000 kN. No alerts were issued for the remaining lines.

5 CONCLUSIONS

The SAFEPORT system is intended to predict, alert, and assess the occurrence, 72 hours in advance, of emergency situations associated with the safety of moored ships. To this end, it is essential that the system operates properly in current and storm situations.

This research is part of the SAFEPORT system testing phase. The performance of the system in a storm situation was tested. The developments made to date consist of the application of the prototype developed for the port of Sines in the simulation of the impact of storm Dora on three ships moored at different terminals of the port.

The alerts issued by the system were in accordance with the reported occurrences. It should be noted that these are only preliminary results, as the system is still being validated and tested.

The SAFEPORT system proved to be a useful tool in managing the safety of ships moored in the port of Sines during storm Dora. To ensure that the system provides consistent and reliable information in any situation, further tests and in-depth validation with buoy data are under development.

ACKNOWLEDGEMENTS

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