BlueSafePort Project – Safety System for Maneuvering and Moored Ships at the Port of Sines

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ABSTRACT: This paper presents a safety system for maneuvering and moored ships at the Port of Sines developed in the scope of the BlueSafePort project. The system is described in terms of its development and architecture, the functioning of its numerical models, the data flow and processing and the risk assessment used to issue alerts. The web platform and the mobile application where the relevant results to assess the referred risks are disseminated are also presented. The system provides 3-day advance forecasts of sea agitation, wind and tide conditions, as well as ship motions, identifying situations that could have serious consequences for ships maneuvering or moored inside the port. The system issues alerts associated with risk levels based on safety and operability criteria for ships' motions and forces in their mooring systems.

1 INTRODUCTION

Port terminals downtimes lead to large economic losses and largely affect the port's overall competitiveness. It's essential to reduce the port's vulnerability by increasing its planning capacity and efficient response to emergency situations.

The BlueSafePort project aims at developing a safety system (both on web and mobile platforms) for forecasting and alerting emergency situations related to navigating, docking and moored ships in ports. A similar system was developed to the Praia da Vitória Port, followed by the ports of S. Roque do Pico and Madalena do Pico, in the Azores archipelago, under the HIDRALERTA and ECOMARPORT projects (Fortes *et al.*, 2015, 2020; Poseiro *et al.*, 2017 and Pinheiro *et al.*, 2020). Now it is being developed for the port of Sines, Portugal, adding to it the capability of forecasting risks for maneuvering (entering or leaving the port) and docking ships, and a mobile application.

The system uses available forecasts of regional wind and sea-wave characteristics offshore, together with astronomical tidal data as inputs to a set of numerical models. These numerical models provide accurate estimates of wave characteristics inside the port (including nonlinear wave interactions) and of the ship's response to those waves and wind forcings. The wave effects in terms of excessive vertical movements of a maneuvering ship that enters or leaves a harbor basin or in terms of forces on mooring lines and fenders as well as of motions of a ship moored at a quay, are then compared with pre-set maximum values. Probability assessment of exceedance of those values results in a risk level assessment. Finally, based on the forecasted risk level, emergencies, and situations where the safety of port operations is at risk can be foreseen in advance and corresponding warnings can be issued.

All the information provided by this system is available in a dedicated website and a mobile application. Port stakeholders will benefit from a decision-support tool in order to timely implement mitigation measures to avoid accidents and reduce economic losses. Therefore, this will be a valuable tool for monitoring and optimizing maritime operations in a port environment, such as, for example, route definition, berthing and mooring optimization systems.

The system prototype under development is the Port of Sines, but it will be flexible and scalable so that it can be easily replicated in other ports.

This paper is structured in 6 sections. The first section provides a brief background of the BlueSafePort project. Section 2 presents the safety system in terms of its architecture and development. The development and adaptation of the numerical models implemented in the system are shown in section 3. Section 4 presents the qualitative risk assessment used as a foundation for issuing alerts to emergency situations related to navigation. Section 5 presents the web and mobile platforms where the results issued by the system will be disseminated. Finally, in the last section, the final considerations of the paper are made.

2 THE SAFETY SYSTEM

On a daily basis, the safety system provides, 72 hours in advance and at 3-hour intervals, forecasts and alerts of emergency situations associated with maneuvering and moored ships due to extreme met-ocean conditions. The corresponding risk levels are based on safety and operational criteria for ship movements and for the stresses on the mooring system elements.

The developed system was implemented and will be validated in three terminals of the Port of Sines. This ensures the flexibility and scalability of the proposed system.

2.1 *Architecture*

The SAFEPORT system is structured in 4 modules (Figure 1): I - Sea wave characterization; II - Navigation in port areas; III - Monitoring and IV - Risk assessment and forecasting.

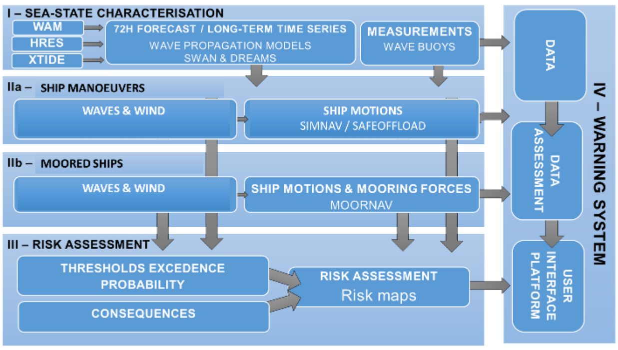


Figure 1. Safety system architecture

The purpose of module I is the characterization of the sea agitation offshore, at the port entrance and in several points within the port basin, in terms characteristics of the wave states. In addition, this module contains the forecast of other phenomena involved in the propagation of sea waves, namely wind fields, tide levels and currents. This first module includes most of the numerical models implemented in the system, namely, the WAM, NAVGEM, XTide, SWAN and DREAMS models. It also includes sea wave data collected *in situ*, essential in the validation of the sea wave characterization models.

Module II simulates the behavior of the ships, both maneuvering and moored, providing time series of the ship motions as well as of the forces on the mooring system elements (mooring lines and fenders). The results of this module are obtained by employing the WAMIT and BAS models.

Module III deals with monitoring the behavior of the ships in maneuvering and moored, by collecting and processing in situ data, necessary to validate the results produced by the WAMIT and BAS numerical models.

Module IV concerns the qualitative analysis of the risk associated with excessive values of ship motion and forces on the ships' mooring systems. This analysis produces a risk score which is the product of the degree of occurrence, established from ranges for the probability of occurrence of the hazardous event, and the degree of consequence associated with that event.

The safety system issues warnings based on the forecasts waves, the atmospheric conditions, and the risk levels.

2.2 *Development*

The main actions considered in the development of the safety system are as follows:

1. Data collection and survey;
2. Installation of two pressure sensors to register sea agitation;
3. Installation of a gyroscope on a moored ship to register the movements;
4. Development and adaptation of the numerical models;
5. Numerical simulations and systematic tests to validate the results with *in situ* measurements;
6. Simulation of ship maneuvers at the entrance and exit of the port based on the information provided by the system;
7. Implementation of the system in the operational prototype (Port of Sines);
8. Feeding of a database with the operational registers in order to learn and adjust the system;
9. Development of the web and mobile applications to disseminate the results.

3 THE NUMERICAL MODELS

This section presents the development and adaptation of the numerical models in the operational prototype, the Port of Sines. Procedures were established (script routines), based on python programming, to obtain the forecasts from the European Centre for Medium-Range Weather Forecasts, ECMWF (Persson, 2001) which provides WAM and HIRES model simulations. XTide provides tide levels. Further scripts couple all the numerical models and create outputs in various formats (images, maps, graphs and datafiles).

3.1 *Operational prototype*

The system was developed and will be validated for the Port of Sines and easily adaptable to other ports.

The Port of Sines is located at 37° 57′N and 08° 53′W, and is the only deep-water port in Portugal, with natural depths up to -28 m ZH. Three breakwaters protect the port basin: the so-called west breakwater, with a length of approximately 1600 m, and the function of directly sheltering the petrochemical (TPQ), liquid bulk (TGL) and natural gas (TGN) terminals; the so-called east breakwater, which is 1000 m long and shelters the port facilities of the multipurpose terminal (TMS); and the so-called eastern breakwater, 1500 m long and constantly extended, shelters the container terminal or terminal XXI (TCS), also in constant extension.

For the first application of this system, an oil tanker at TGL, a general cargo ship at TMS and a container ship at TCS were chosen (Figure 2).

Figure 2. Operational prototype, the Port of Sines, and the chosen terminals, TGL, TMS and TCS.

3.2 *Sea wave characterization models*

An early warning system is only possible due to the accuracy achieved by met-ocean forecasting models at regional and local level, which can provide, a few days in advance, estimates for the relevant parameters.

WAM is a third-generation ocean wave prediction model (WAMDI Group, 1988), used by the European Centre for Medium-Range Weather Forecasts, ECMWF (Persson, 2001). Its implementation in the safety system enables forecasts, 72 hours in advance (with results every 3 hours), of the significant height (H_s), the peak period (T_p) and the average direction (θ_m) of the wave states (Figure 3).

Predictions of wind fields and sea level of astronomical tide are obtained from NAVGEM model (Whitcomb, 2012) (Figure 3) and XTide model (Flater, 2016), respectively. These constitute the required boundary forcing data to run the SWAN model.

SWAN (Booij *et al.*, 1999) is a spectral nonlinear model based on the wave action conservation equation, which simulates the propagation of irregular wave spectrum. The SWAN model was used to perform the propagation of the sea agitation from offshore to the coast. For this model a discretization for the directional spectrum as well as bathymetric meshes have been established (Figure 4).

The boundary conditions in the larger bathymetric grid are the predictions of wave state characteristics provided by the WAM model, the regional wind fields used in the SWAN model result from the NAVGEM model while the tide levels, considered constant at all points in the SWAN domain, result from the XTide model.

In the system herein developed, the SWAN model operates in stationary mode, having been calibrated all the parameters necessary for this operation. One point was defined, near the Sines buoy, to extract the results of the model.

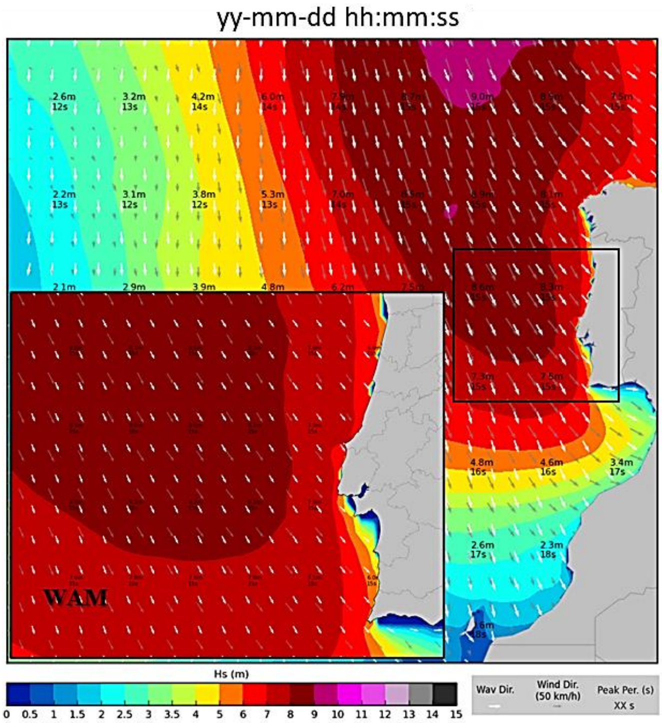


Figure 3. Graphical representation of the WAM model results for waves and HIRES model results for wind field.

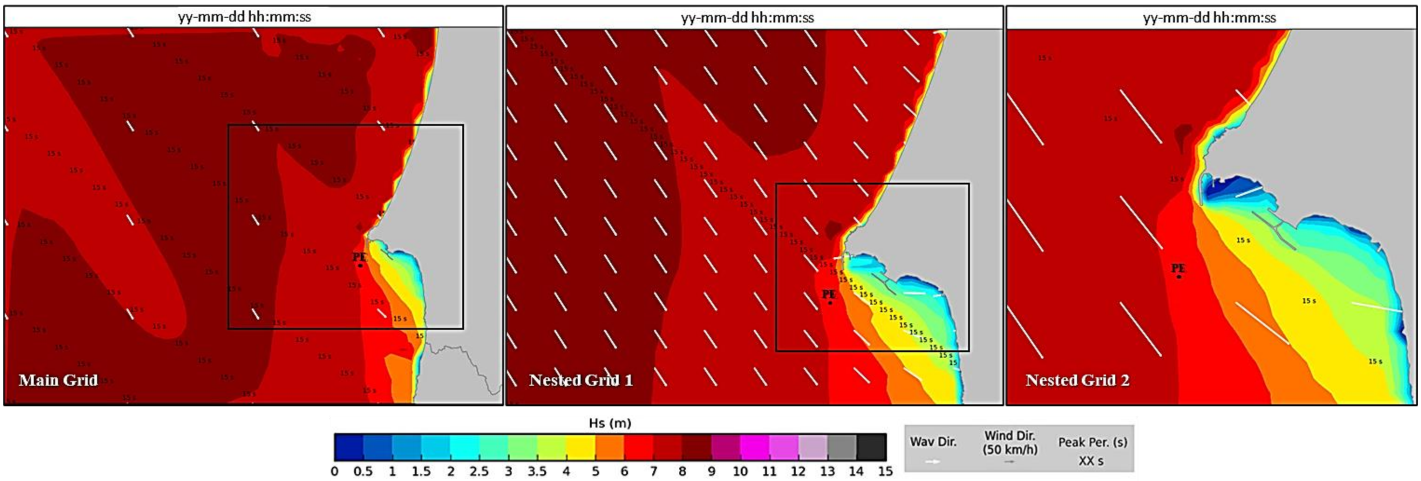


Figure 4. Graphical representation of the SWAN model results at the three nested grids.

The transfer of the characteristics of the wave states into the port is performed with the DREAMS model (Fortes, 2002). DREAMS is a linear finite element model, based on the mild slope equation, to simulate the propagation of monochromatic waves in port basins. For this model, it was generated, with the GMALHA tool (Pinheiro, 2008), a finite element mesh that characterizes the port area, in terms of its bottom morphology and its solid boundary (Figure 5). The solid boundary was characterized in terms of its structures and their reflection coefficients.

The boundary conditions of the model calculation domain were defined from the H_s, the T_p and θ_m extracted at the point defined in the SWAN model. The DREAMS model provides the characteristics of the sea agitation inside the sheltered area of the port required to assess the behavior of the moored ships.

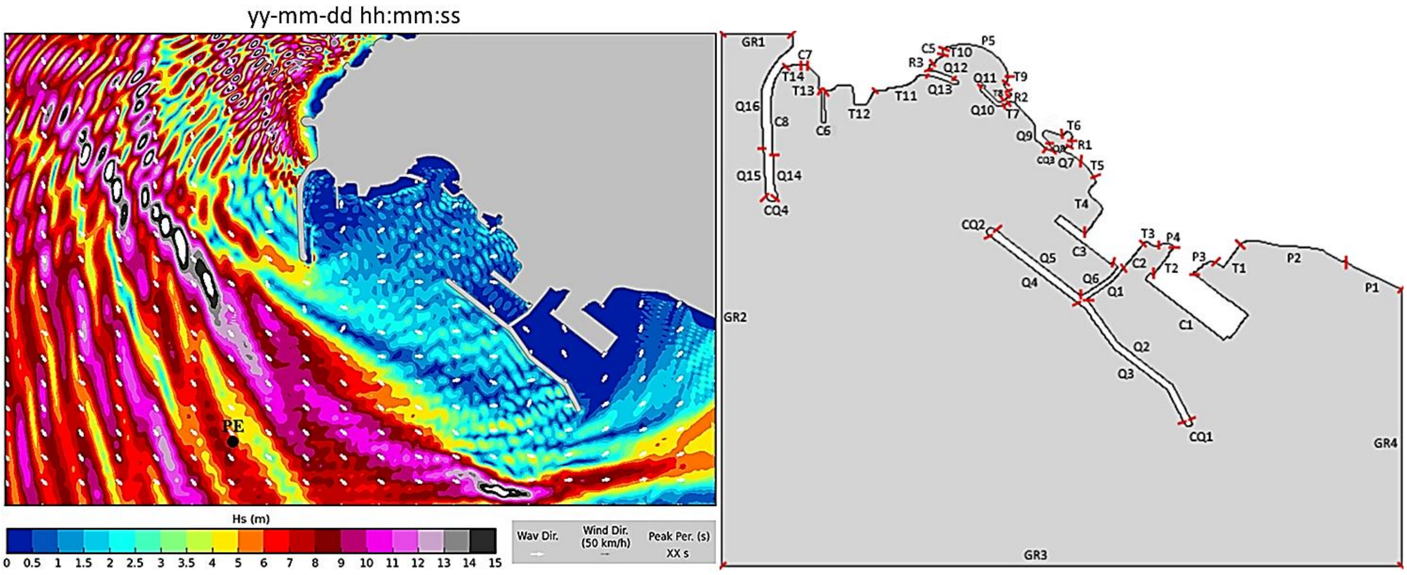


Figure 5. Graphical representation of the DREAMS model results (left) and the contour of the solid boundary (right).

3.3 *Navigation in port area models*

The numerical models of this module deal with the time-domain formulations, relating instantaneous values of forces and movements, to evaluate the behavior of the moored ships.

The WAMIT model (Korsemeyer *et al.*, 1988 and Newman & Sclavounos, 1988) uses a panel method for solving in the frequency domain radiation and diffraction problems of a free-floating body. This model uses the second Green identity to determine the intensity of the source and dipole distributions in the panels of the hull's wetted surface discretization. The forces along each of the six degrees of freedom of the ship motion are determined for regular incident waves that hit the ship. Its application provides the required information to run the BAS model, namely: the wave exciting forces and moments, the impulse response functions obtained from the damping coefficients, and the added-mass coefficients for infinite frequency, obtained from the frequency domain added-mass coefficients and the corresponding impulse response functions.

To produce the expected results, WAMIT was provided with the models of the ships to be simulated, discretized into flat panels. The selected ships represent, in the most comprehensive way possible, the ships that operate in the Port of Sines, more specifically in the bulk liquid (TGL), container (TCS) and multipurpose (TMS) terminals, which will benefit most from the safety system.

All the hydrodynamic coefficients and transfer functions from the WAMIT numerical model, are stored in a database and stored into the system.

The BAS model uses the impulse response, the mass (including added mass) and hydrostatic restoration matrices, together with the time series of the forces exerted by the waves on the ship and the constitutive relations of the mooring system elements (mooring lines and fenders) to set up the equations of motion of the moored ship.

The forces due to mooring lines and fenders can be determined from their constitutive relations. The wave diffraction forces result from a synthetic time series generated from the characteristic values of the wave field obtained with DREAMS model.

Strictly speaking, this is a set of six equations whose solutions are the time series of the ship movements along each of her six degrees of freedom, $x_j(t)$ as well as of the forces in the mooring lines and fenders.Figure 6 shows the results of the safety system in terms of the forces on the mooring system of a generic tanker moored at the TGL.

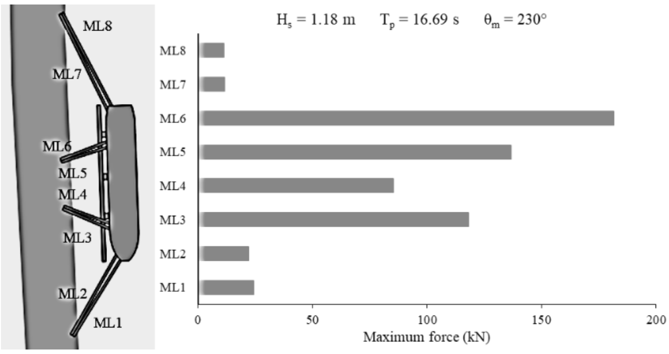


Figure 6 Oil tanker ship moored at TGL. Wave conditions and maximum forces on the mooring lines provided by the safety system on December 4th, 2020, at 9 p.m.

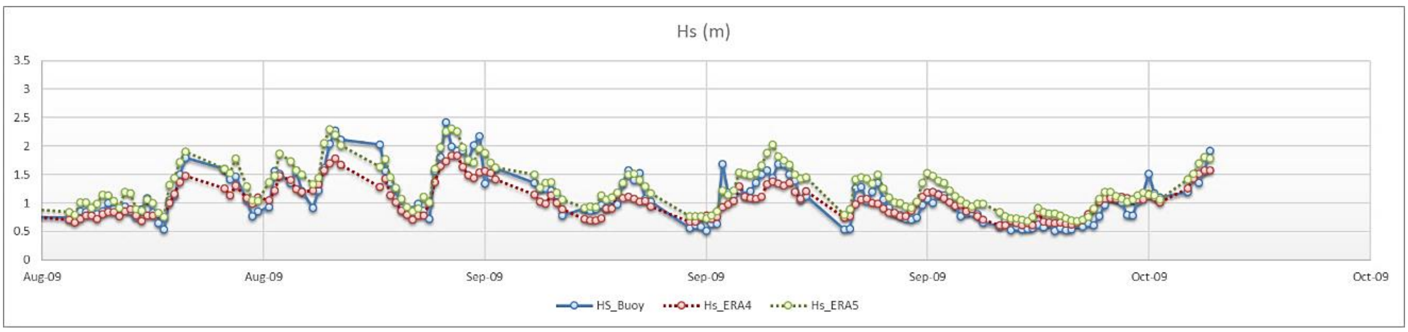
3.4 *Numerical models validation*

An important data source that allows a solid validation of the numerical models is the Sines wave buoy, named Sines 1D, installed on the -90 m bathymetric (ZH) in front of the port. The system downloads, daily, the 30-minute measurement values from the wave buoy (significant heights, average directions and peak periods).

For the validation of the SWAN model forcing boundary wave data, requests were submitted to ECMWF to obtain reanalysis data from the ERA4 and ERA5 models corresponding to 40 years of data between 1988 and 2018 of wave and wind regimes (Figure 7). Correlation coefficients were computed for Hs (r=0.949), Tp (r=0.888) and Dirm (r=0.624), and the results showed that the ECMWF WAM model results have an excellent agreement with measurements in terms of Hs and Tp but a very good agreement in terms of wave direction.

For the validation of the SWAN model results, a data extraction point on the Sines 1D buoy location is requested as output of the model. This allows real-time validation of the system's meteo-oceanographic forecasts (Figure 8). Correlation coefficients computed for Hs (r=0.92), Tp (r=0.770) and Dirm (r=0.74), and the results showed that the SWAN model results still have an excellent agreement with measurements in terms of Hs. As for Tp correlation is not as good as ECMWF source data. In terms of wave direction, agreement is slightly better in SWAN model results than the one obtained with the ECMWF source data.

Other sources of model validation include *in situ* data collection of wave characteristics inside the port basin as well as ship motions and mooring forces. To accomplish this task, it is intended to install pressure sensors near the terminals, gyroscopes on ships and forces sensors on moorings. This data will enable the validation of the sea agitation characteristics inside the Port of Sines, as well as the behavior of the simulated ships.



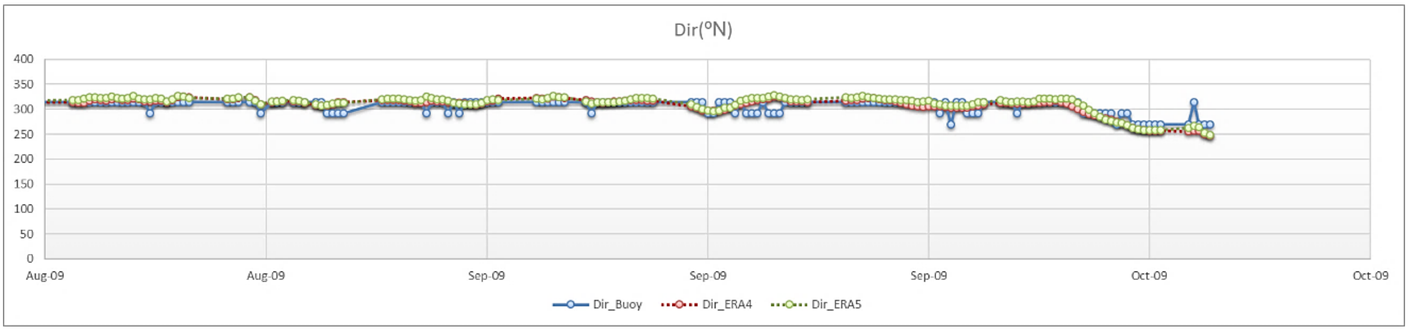


Figure 7. Comparison of the Sines 1D buoy records (significant height, Hs and Direction, Dir) with the forecasts obtained at the closest ECMWF point, using two datasets: Era4 and Era5. Period from August to September 2009.

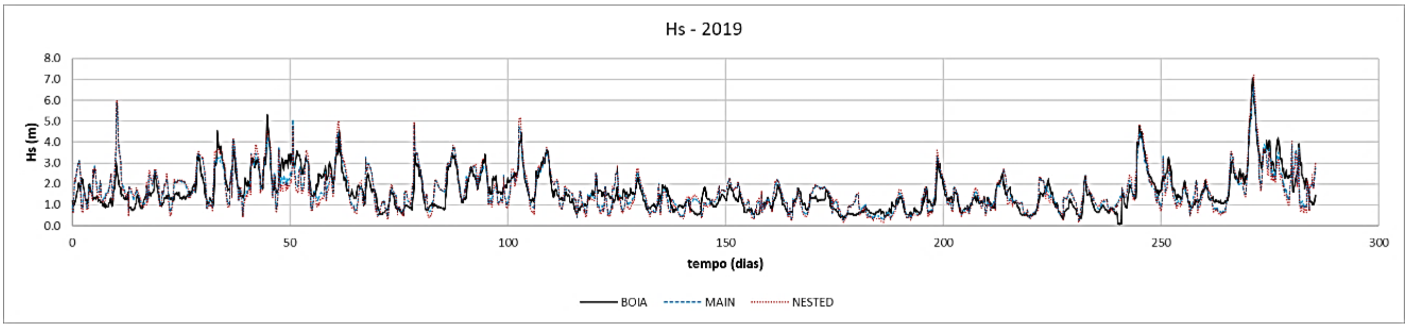


Figure 8. Comparison of the Sines 1D buoy records with the SWAN numerical model results (extracted from the main grid - MAIN and the nested grid 1 - NESTED), in the year 2019.

4 RISK ANALYSIS AND WARNING SYSTEM

A risk analysis combines the possible consequences of an event with the probability of its occurrence. The safety system herein presented, issues alerts based on a qualitative risk assessment, associated with the probability of exceeding a pre-established threshold for the amplitude of ships' motions and for the forces on their mooring system (Pinheiro *et al.*, 2018).

Excessive ship motions make loading and unloading operations unviable and can also cause excessive forces on ship's mooring systems. The breakage of a mooring element can lead to considerable damage.

The pre-established thresholds considered are those recommended by organizations concerned with maritime and port activities. Table 1 shows the preset limits for ships' motions amplitude (PIANC, 1995 & PIANC, 2012) and Table 2 the ones for the forces on the mooring systems (OCIMF, 1992 & PIANC 1995). Considering the nature of the activities, the characteristics of the vessel and the need to ensure the safety of persons and infrastructure, consequence levels have been attributed to the threshold values. These values can be adjusted to reflect each port administration internal criteria and rules.

Table 1. Consequence levels of exceeding movement amplitude (Pinheiro et al., 2018).

Consequence	Level	Surge	Sway	Heave	Roll	Pitch/Yaw
		m	m	m	°	°
Insignificant	0	0.1	0.10	0.1	0.5	0.1
Mild	1	0.3	0.20	0.2	1.0	0.3
Serious	2	0.4	0.25	0.3	1.3	0.4
Critical	3	0.5	0.30	0.4	1.5	0.5

Table 2. Consequence levels of exceeding forces on mooring system (Pinheiro et al., 2018).

Consequence	Level	Mooring Lines	Fenders
		kN	kN
Insignificant	0	40%MBL	50%ML
Mild	1	50%MBL	70%ML
Serious	2	80%MBL	90%ML
Critical	3	MBL	ML

To associate the consequence levels with the risk levels, 3600 seconds time series are produced for each variable (ship motions and mooring system forces). Each time series undergoes a Fourier transform and a power density spectrum is obtained. From this spectrum, statistical information can be derived from spectral moments (Pinheiro *et al.*, 2018). The statistical distribution is assumed to be a Rayleigh distribution (Longuet-Higgins, 1952).

Thus, relating the probability of exceedance of the Rayleigh distribution, discretized into levels, with the consequence levels, it is possible to obtain risk levels for each variable (Table 3).

Table 3. Risk levels (Pinheiro et al., 2018).

Exceedance Probability (P) Levels		Consequence levels			
		Insig.	Mild	Serious	Critical
		0	1	2	3
Rare (P<0.001%)	0	0	0	0	0
Unlikely (P<0.1%)	1	0	1	2	3
Possible (0.1<P<10%)	2	0	2	4	6
Critical (P>10%)	3	0	3	6	9

Based on the risk levels, the system issue alerts, through the definition of danger alerts (color coded):

- Green alert: Risk level of 0 or 1. No danger
- Yellow alert: Risk level of 2 or 3. Low danger Loading and unloading operations conditioned.
- Orange alert: Risk level of 4 or 6. Moderate danger Loading and unloading operations cannot be performed.
- Red alert: Risk level of 9. Maximum danger Loading and unloading operations are suspended. Possibility of breakage of mooring system elements and structural damage.

Figure 9 shows the symbols used in the safety system to issue the color alerts.

Figure 9. Symbols used by the SAFEPORT system to alert ships' motions danger (left) and ships' mooring systems failure danger (right).

5 DISSEMINATION OF RESULTS

A web platform (HTML page) and a mobile application (for android platforms only) were developed for the dissemination of the results. In these, it is possible to access and view, in graphic and numerical form, the forecasts of sea agitation, wind, currents and occurrence of long waves and monitor possible emergency situations in real time. In addition, it is also possible to visualize the alerts for navigation and access the system database and continuous validations (forecasts *vs* observations).

The development of the web page (Figure 9) for Port of Sines has some particularities inherent to the port in question and with features, such as the simulation of ships in maneuver. The mobile application (Figure 10) has the same functionalities as the web platform, presented in a simpler manner.

Figure 10. Web tool for the dissemination of results.

Figure 11. Mobile tool for the dissemination of results.

Furthermore, daily reports in pdf, constructed with the 3-day forecasts of the system's wave and navigation results, are sent by email to the interested parties.

6 FINAL CONSIDERATIONS

The ultimate goal of this project is to reduce the vulnerability of ports by increasing their capacity for efficient planning and responses to emergency situations. In addition, this project aims to provide greater access to information and communication by providing specific information on a specific ship and/or port terminal.

The ability to anticipate the effects on ships of potentially hazardous sea agitation and weather conditions enables to take informed decisions on navigation routes and berthing procedures and to increase the safety of ships moored and in maneuvering. Thus, the system will alert the responsible authorities in order for them to take timely mitigation measures to avoid accidents and reduce economic losses.

7 ACKNOWLEDGEMENTS

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Contents