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WARNING SYSTEM FOR NAVIGATION AND MOORED SHIPS IN PORTS

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ABSTRACT

This paper describes the SWAMS ALERT system, a forecast, warning and risk assessment *system associated with navigation and mooring of ships in port areas. This system is based on HYDRALERTA, a previously developed system for overtopping and flooding in coastal and port areas. The basic idea is to use 72-hour sea waves' forecasts (short-term analysis) or long time series of historical data (long-term analysis) and simulate their effect on ships, either in port approach maneuvers or when they are moored inside.*
This modular system consists of four modules: I – Sea waves characteristics; II - Navigation and mooring in port areas; III - Risk assessment and IV - Warning System. The system is being developed using Python scripts and implemented on a fully interactive user-friendly web platform.
The system prototype is being tested on the port of Praia da Vitória, in the Azorean island of Terceira. This test case is illustrated in this paper and shows some of the system capabilities.

1. INTRODUCTION

The risks associated with navigation and mooring of ships are a major concern for port and maritime authorities. Sea waves can disturb and even disrupt port activities such as ship maneuvers and loading and unloading operations. In fact, excessive ship motions due to waves can put at risk the safety of people, goods, port infrastructures and the ships themselves.

Thus, the development of support tools that help prevent emergency situations and minimize risks associated with sea wave effects on ships is essential for correct planning and integrated management of port areas.

In this context, LNEC has been developing a forecasting, warning and risk assessment system for overtopping and flooding events in coastal and port areas, called HIDRALERTA (Fortes *et al.*, 2013, 2015; Poseiro *et al.*, 2014; Sabino *et al.*, 2014, 2015). This system is already in operation at the port of Praia da Vitória, in the Azorean island of Terceira and in the Costa da Caparica area, Almada.

To extend the functionality of this system to the forecast, warning and risk assessment of dangerous events associated with the navigation in port areas and the behavior of moored ships, a new system called SWAMS ALERT (Pinheiro *et al.*, 2013) is under development and it has been applied to the Praia da Vitória test case.

The SWAMS ALERT system uses measured and forecast sea wave characteristics to determine its effects in terms of excessive vertical movement 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. To do so, the system uses a set of numerical models. The comparison of the computed values of the relevant variables with pre-set maximum values enables:

i) Real-time evaluation of possible emergency situations or when the safety of port operations is at risk and to issue warnings to the competent authorities. Thus, port authorities can promote, in advance, a set of actions to prevent such emergency situations or to mitigate their consequences;

ii) Issuing warnings to the port stakeholders.

iii) Construction of risk maps, considering long time series of measured or forecast sea waves or predefined scenarios associated with climate change or extreme events. Those risk maps enable port authorities to perform a long-term planning and management of port areas.

The system consists of four modules: I – Sea waves characteristics; II - Navigation in port areas; III - Risk assessment and IV - Warning System. The system is being developed using Python scripts and implemented on a fully interactive user-friendly web platform.

Although the SWAMS_ALERT is a forecast, warning and risk assessment system, in the present paper only the forecast and warning functionalities of the system are described. So, after this introduction, the paper describes three modules of the SWAMS ALERT system (I, II and IV) (section 2) and illustrates the application of this system to Praia da Vitória's port, Terceira, Azores Islands (section 3 and 4). Section 5 presents some final remarks on the work.

2. SWAMS ALERT SYSTEM

The system consists of four modules as depicted in Figure 1:

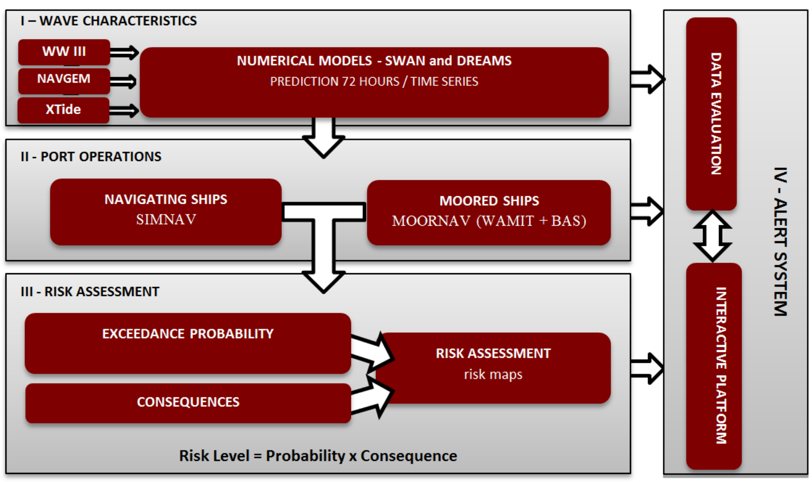

Figure1. Architecture of the SWAMS ALERT system.

2.1 Module I – Sea Wave Characteristics

The purpose of this module is to evaluate sea-wave characteristics - the significant wave height (Hs), wave period (average, Tm, or peak, Tp) and average direction (ɵ) - along its propagation from offshore up to coastal and port areas. These sea wave characteristics can be forecast 72 hours in advance (with results every 3 hours) or can be obtained from historical data.

The sea-wave characteristics along the coast or within a port can be obtained by means of one or more numerical models for sea-wave generation and propagation. The type and number of numerical models to be applied depend on the study region characteristics (for example, its size) and on the phenomena involved in the sea-wave propagation.

In the SWAMS ALERT system, the following models for sea-wave propagation are used: regional wave forecast model WAVEWATCH III, WW III, (Tolman, 1999); nonlinear spectral wave generation and propagation model SWAN (Booij *et al.*, 1999); and linear wave propagation model for sheltered areas DREAMS (Fortes, 2002). The wind data at regional scale required to run WW III and SWAN models are available through the NAVGEM model (Whitcomb, 2012).

Regarding the warning system, 72-hour sea wave predictions provided by WW III model are used, and transferred to the SWAN model and ultimately to the DREAMS model. Thus, sea-wave characteristics can be forecast 72 hours prior to their occurrence at the point of interest in the study area, in terms of Hs, Tm or Tp, and ɵ. For the definition of sea level, predictions of astronomical tide obtained by XTide software are used (Flater, 1998).

2.2 Module II – Port Operations

Module II deals with two potential hazards related to port operations: maneuvering and moored ships. Excessive movement, particularly in the vertical plane, when a ship maneuvers to enter or leave a port can lead to emergency situations. The same applies to excessive moored ship motions, although restricted by the mooring system, that can lead to interruption of loading and unloading operations but also to increased risk of rupture of a mooring system element (mooring line or fender) or ship collision with port infrastructure. At this stage, only the evaluation of the risk associated to excessive moored ship motions is implemented in the SWAMS ALERT system.

The determination of the ship's movement moored to a berth subject to incident agitation is performed using the numerical package MOORNAV, Santos (1994). It is essentially two numerical models and a set of routines that makes the connection between them:

- WAMIT, Korsemeyer *et al.* (1988), which resolves, in the frequency domain, radiation and diffraction problems of the interaction of a free-floating body with the sea waves incident on it;
- BAS, Mynett *et al.* (1985), which assembles and solves, in the time domain, the equations of motion of a ship moored at the berth, by considering the time series of the forces due to the incident waves on the ship, the impulse response function of the ship and the constitutive relations of mooring system components (mooring lines and fenders).

The WAMIT model, Korsemeyer *et al.* (1988), was developed at the Department of Ocean Engineering of the Massachusetts Institute of Technology and uses a panel of method for solving in the frequency domain radiation and diffraction problems of a free-floating body. This model is based on the second Green identity to determine the intensity of the source and dipole distributions in the panels used in discretization of the hull’s wetted surface. With these distributions, it is possible to generate the harmonic potential of the flows associated to radiation and diffraction problems of the ship interaction with waves when the ship is placed in a constant depth, horizontally unbounded region.

In the diffraction problem, the forces along each of the six degrees of freedom of the ship motion are determined for regular incident waves that hit a ship that is held motionless whereas in the radiation problem it is the ships that oscillates in otherwise calm water. In this case, it is the forces in phase with the ship accelerations and velocity – respectively, the so-called added mass and damping - that are evaluated.

Before using the BAS model, the radiation problem results are used to determine the so-called impulse response functions or retardation forces - i.e. the time series of the forces along each degree of freedom after the impulsive motion of the ship along the same or another degree of freedom in otherwise still water – as well as the added masses for infinite frequency – the forces associated to the flow acceleration around the hull.

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 solution of such equations are the time series of the motions of the ship’s center of gravity as well as of the efforts in the mooring system elements.

Summing up, to apply the WAMIT and BAS models, knowledge of the ship characteristics is needed, together with the physical representation of the harbor borders and its surroundings that may directly or indirectly have some influence on the sea-wave field that acts on the ship, as well as of the characteristics of the mooring system and of the sea-waves incident at the boundary of the study domain.

2.3 Module IV - Warning System

The warning system (Sabino *et al*., 2014, 2015, Lopes *et al*. 2016) consists of two components: data evaluation and user interaction.

In the data evaluation component, the system includes all relevant information for dangerous events identification and warning. This information consists of: the topography and bathymetry of the area; sea-wave forecasts and the characteristics of the berth and of the ship moored at the study area. Pre-set limits to the moored ships motions are defined to ensure the minimum operational conditions and the safety of the port terminal (PIANC, 1995). Safety limits can and should also be defined for the maximum forces in the elements (mooring lines and fenders) of the mooring system of the studied ship, since their breakage may lead to considerable damage. These limits are based on the characteristics of the ship and of its mooring lines and fenders. The warning signal is triggered when such thresholds are exceeded.

The results generated by the data evaluation component take different forms, namely, graphs, maps and reports. These are then transmitted to the user interaction component to allow the assessment of the situation.

The user interaction component is embodied in a Web application, in which all the warning system is parameterized. The web platform was created to allow viewing and analysis of results through user-friendly features, such that the results are easily read by the common user. This platform contains of a set of features that pass through the display of forecasts obtained by the system for each of the numerical models used as well as, and mainly, warning maps that highlight the range of endangered activities.

In the Web platform, the results generated by the different numerical models are presented in various formats. All relevant results are presented statically through images, to be quickly and easily readable, even when the user has a limited or poor access network.

3. CASE STUDY: THE PORT AND THE BAY OF PRAIA DA VITÓRIA

The bay and the port of Praia da Vitória are located on the east coast of Terceira Island, one of the nine islands of the Azores archipelago (Figure 2).

The bay coastline is characterized by the existence of a seawall and a groin field, with five groins, in the central area in front of the existing gap between the jetties, rooted on the front defense. These have different lengths and are deployed parallel to the direction of WSW-ENE.

The bay is protected by two breakwaters: the so-called north breakwater, which is 560 m long and houses the port facilities to support the Lajes Air Base; and so-called south breakwater, which is 1300 m long and has a curved planform and houses the port facilities of the commercial sector and fisheries. This port is the second largest Azorean port infrastructure being surpassed only by the port of Ponta Delgada, in what concerns the volume of ship and goods movements.

Benefiting from the shelter provided by the North breakwater, a marina was built by the Praia da Vitória Municipality, in the late 1990s, between Prainha and Praia Grande. It has about 210 berths, a reception pier and supporting infrastructure.

Figure 1. Aerial view of the bay and port of Praia da Vitória.

4. APPLICATION OF THE SWAMS ALERT SYSTEM

The application of SWAMS ALERT system to the port of Praia da Vitória is made every day and allows the prediction, 72 hours in advance, of sea-wave effects in terms of moored ships movements docked at the main berth (Berth 12).

4.1 Module I – Wave Characteristics

To characterize the sea waves (Hs, Tm, Tp, θ) off Praia da Victoria, the system uses, once a day, the WW III sea-wave predictions, for 72 hours with a 3-hour interval, which are provided by The Fleet Numerical Meteorology and Oceanography Center (FNMOC). For study area, the WW III model data is available with a resolution of 1º, since September 2003. The regional wind data required to run the SWAN model are also available from FNMOC through NAVGEM model (Whitcomb 2012), whereas the tidal data is provided by the XTide model. This is one astronomical tide prediction model that has tide information from 1700 to 2100. For example, Figure 2 presents one layout generated by the system for the WW III data, Hs and θ.

Given the WW III model results one selects the values that are closer to Terceira Island which can represent the boundary conditions for sea-wave propagation models to be used then. These values are transferred into the bay and port of Praia da Vitória using two models for sea-wave propagation and deformation: the SWAN model and the DREAMS model. The use of models and their application conditions are described in Neves *et al.* (2012) and Poseiro *et al.* (2014). Figure 2 presents the type of layouts generated by the warning system for the SWAN and DREAMS model results, Hs and θ.

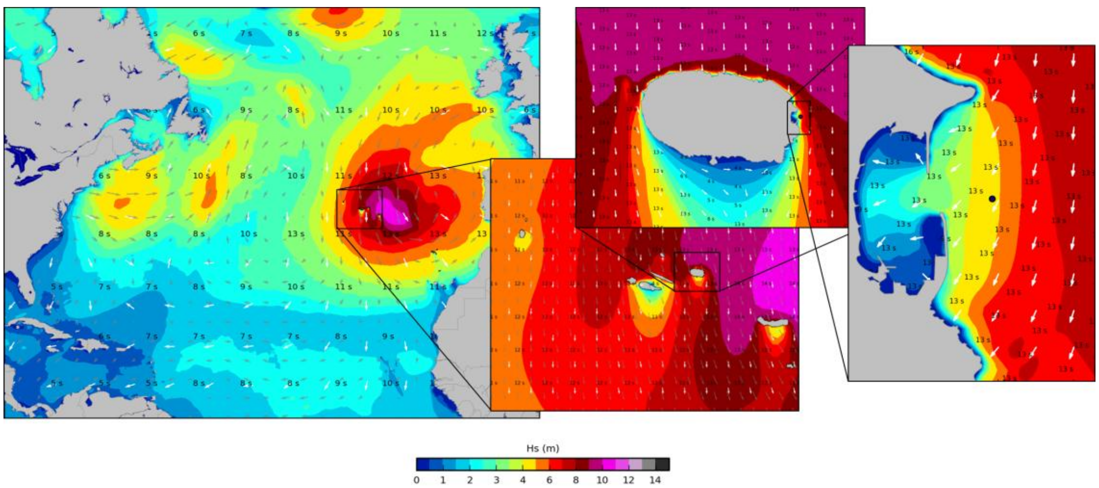

Figure 2. Example layout generated by the system for the WW III data (left), SWAN model (center) and DREAMS model (right), Hs and θ.

4.2 Module II – Port Operations (moored ship)

For the first application of this module it was chosen a ship and berth in the container terminal of the Praia da Vitória port. For the application of WAMIT and BAS models, it is necessary to define the characteristics of the vessel and mooring system. The methodology is described in Pinheiro *et al.* (2013).


Figure 3. Container terminal of Praia da Vitória port.

The studied ship is a generic container with a displaced volume of 12,717 m3, a length in the floating area of 120 m, a beam of 19 m and a draft of 8 m. The hull form was discretized with 3464 rectangular and triangular panels as shown in Figure 4. It was considered that the vessel was placed on a horizontal area whose water depth was 10 m.

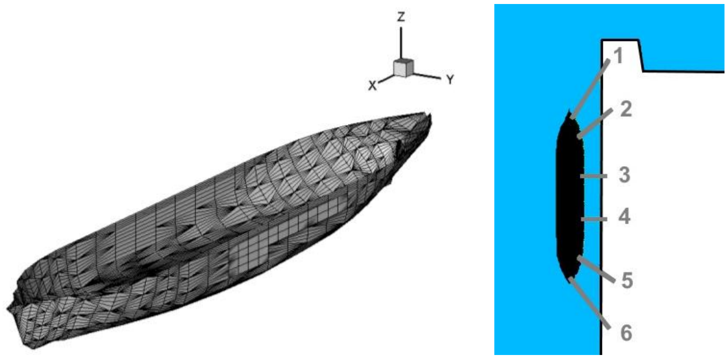

Figure 4. Hull paneling of the simulated vessel (left). Mooring system configuration (right).

Figure 4 shows the mooring system configuration in which the ship is moored to the berth by 6 mooring lines (1 lay line at bow and another at stern, two spring lines and two breast lines). The contact between the ship and the quay is prevented by five pneumatic fenders. The same constitutive relations were considered for all mooring lines: linear range from 0 kN to 931 kN maximum load which corresponds to an elongation of 8%. The constitutive relations for the fenders is also linear with a maximum compression force 4900 kN for a deflection of 1 m.

For each sea-wave condition identified in module I the time series of the sea-wave forces exerted on the ship can be determined. With that information and the above mentioned constitutive relations, as well as with the free ship impulse response function matrix, its infinite frequency added mass matrix and the ship mass matrix and hydrostatic restoration matrix, it is possible to set up the moored ship motion equations. The solution of these equations provides the time series of the motions at the center of gravity of the ship and of the efforts on the mooring system elements.

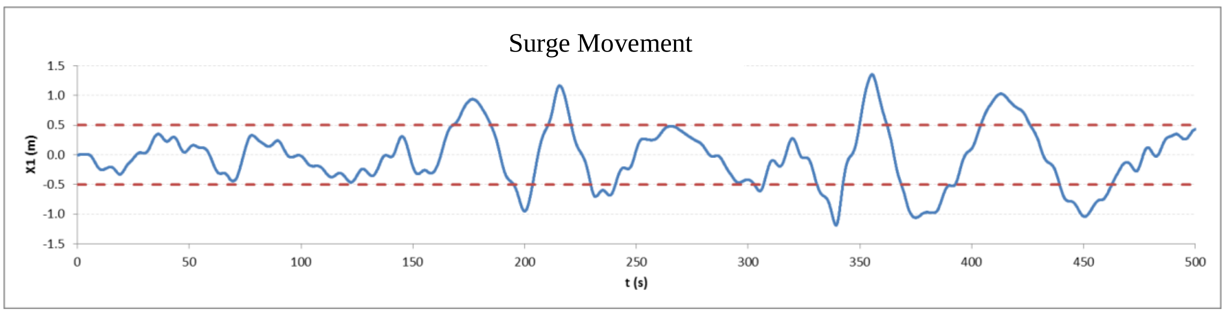

Figure 5. Time series of computed surge movement.

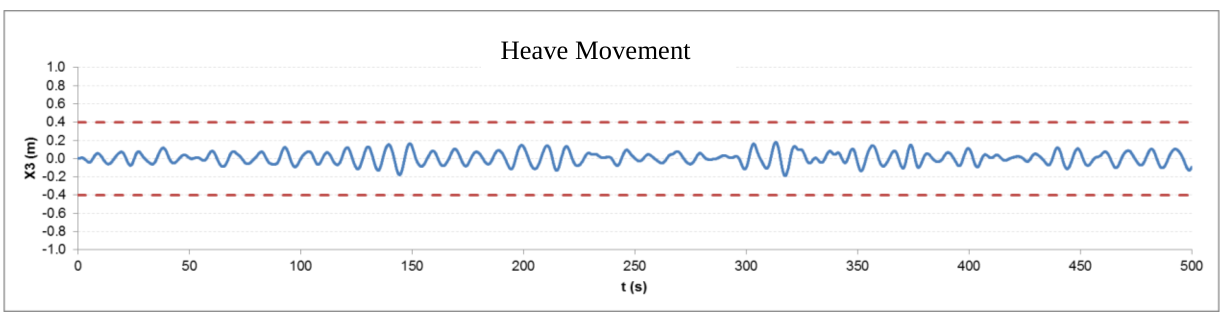

Figure 6. Time series of computed heave movement.

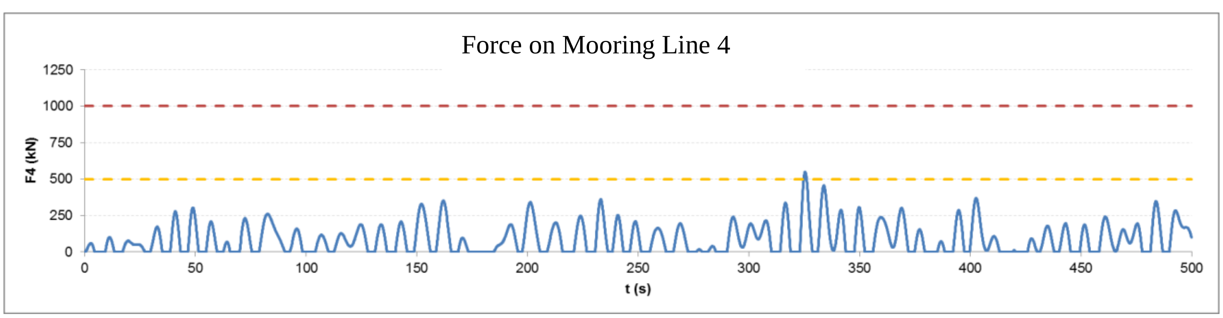

Figure 7. Time series of computed force on mooring line 4.

In this case pre-set limits established were the following:

- Surge amplitude of 1m (from -0.5m to 0.5m);
- Heave amplitude of 0.8m (from -0.4m to 0.4m);
- 50% of Maximum Breaking Load (MBL) approximately 500kN;
- 100% of MBL approximately 1000kN.

4.3 Module IV - Early warning system

The Web platform displays for each day the forecast results obtained by the system for the several numerical models (WW III, SWAN and DREAMS), for the 72 hours in advance, with a 3-hour interval. An example of SWAN and DREAMS layouts is presented in Figure 8.

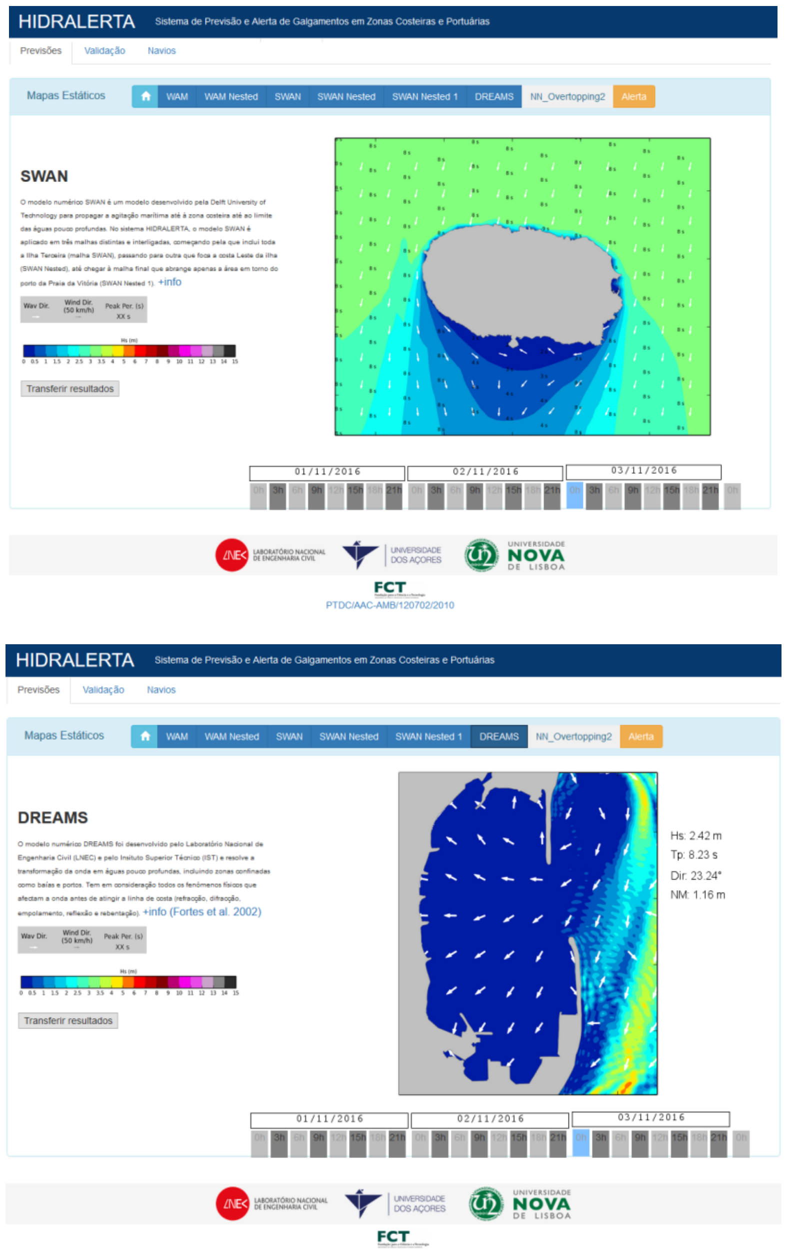

Figure 8. Layout of the SWAN (up) and DREAMS (bottom) warning map generated by the system.

The Web platform allows also to view the sea-wave characteristics close to the ship position, the maximum values of the surge, sway and yaw motion, as well as of the efforts in the mooring lines (Figure 9 and Figure 10).

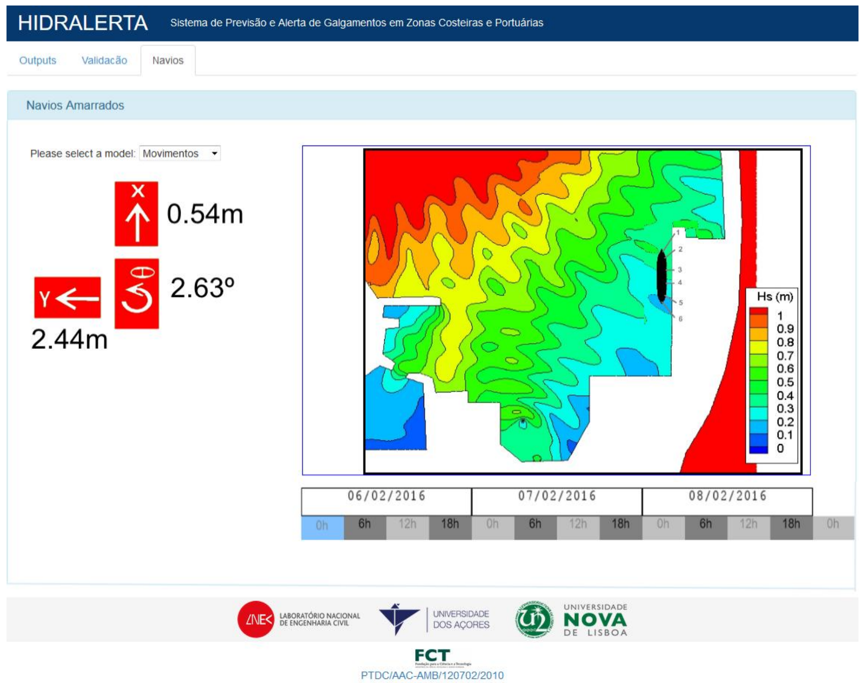

Figure 9. Layout of the ship-motion warning map generated by the system.

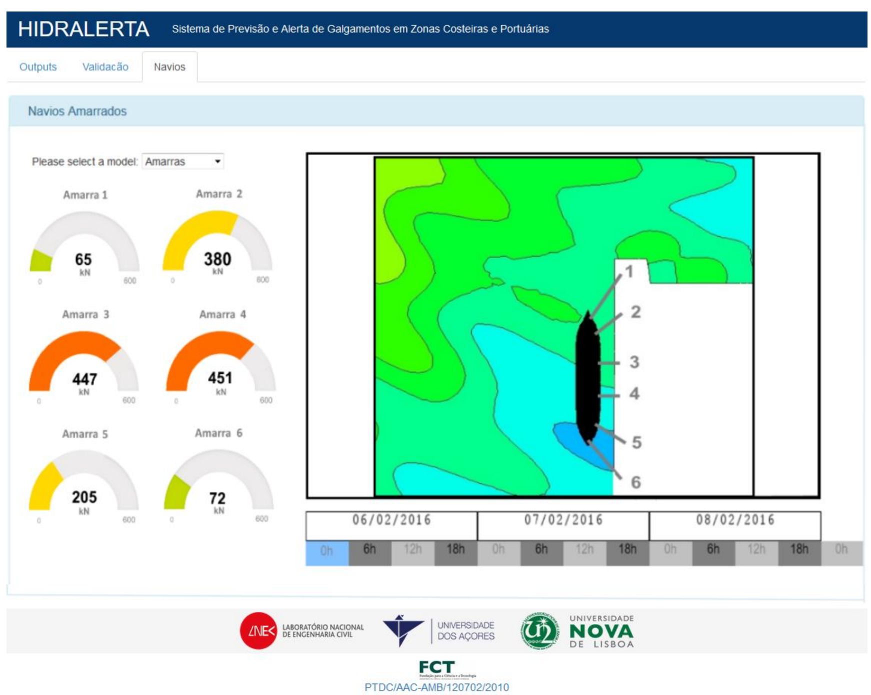

Figure 10. Layout of the mooring line forces warning map generated by the system.

You can also view the warning levels issued for the study area in a specific date and time.

Warning levels are set following an a priori analysis of the maximum values for the ship movements and for the efforts in the mooring system elements, considering their consequences for the loading and unloading activities and the safety of people, goods and the ship. Several organizations concerned with maritime and port activities have issued recommendations to limit wave heights, the velocity amplitudes of ship motions as well as the tensions in the mooring system elements (OCIMF, 1992, PIANC 1995). The adopted values in this paper are based on the PIANC (1995) recommendations but they can be set case by case considering each port administration internal criteria and rules.

The limits to horizontal, vertical or rotational movements depend on the associated consequences. PIANC organization has established working groups issuing regular reports with recommendations on moored ships maximum movements, Table 1. There are operational limits, Table 1, above which the cargo handling is conditioned or even impossible and safety limits, above which there is a risk to people, property or the structures, Table 2.

Regarding the limits on the mooring system forces, OCIMF recommends that they must be distributed evenly by each mooring line and not exceed 55% of Maximum Breaking Load (MBL).

Table 1 - Maximum recommended movement amplitude for safe loading / unloading (PIANC 1995).

Type of vessel	Surge	Sway	Heave	Roll	Yaw
	(m)	(m)	(m)	(°)	(°)
Tanker	2.5	2.0	1.5	4.0	2.0
Container	0.5	0.3	0.4	1.5	0.5
RO / RO	0.3	0.2	0.1	-	-

Table 2 - Maximum recommended movement velocities for moored ship safety (fishing, ferries and RO / RO) (Elzinga *et al.*, 1992).

Size of the vessel (DWT*)	Surge	Sway	Heave	Roll	Yaw
	(m/s)	(m/s)	(m/s)	(s)	(s)
1000	0.6	0.6	-	2.0	2.0
2000	0.4	0.4	-	1.5	1.5
8000	0.3	0.3	-	1.0	1.0

*DWT – Dead Weight Tonnage

Recently, a PIANC working group updated the guidelines for the maximum movements of moored container ships that ensure efficient unloading operations (PIANC, 2012). In that report, it was concluded that for large container ships, limiting the surge motion is essential, since the cranes have limited translation margins. The same report states that when the surge motion is kept within the prescribed limits, the motion along the other degrees of freedom, eventually, are also within acceptable limits.

At this first phase, the different warning levels have the following meaning:

- Green (0) - No danger;
- Yellow (1) - Freight activity and loading and unloading operations conditioned;
- Red (2) - Maximum warning level. Loading and unloading operations cannot be performed. Possibility of breakage of mooring system elements. The infrastructure can be seriously damaged.

It should be noted that the system validation for this port is an ongoing process. So far, the system validation for module I was performed (Neves, 2013), using data from the wave buoy of Lisbon´s Port Authority. Module II validation is to be carried out during this winter.

5. FINAL REMARKS

Currently, the SWAMS ALERT system has already in operation all the necessary elements to issue real-time warnings, but there are still some aspects to be improved, especially in module IV, in what concerns the definition of warning levels to be considered.

Future work necessarily involves the validation of the system, including modules II and IV, with the collaboration of local authorities and the use of historical data, to ensure system reliability. Further, it is important to develop a table of consequences with operational costs associated with vessels.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE