

Numerical Simulation of Ship Accessibility and Safety in Exposed Ports

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ABSTRACT: A numerical methodology is presented to assess ship accessibility and navigational safety in exposed ports through the simulation of wave propagation and three-dimensional hydrodynamic flow around the ship hull, accounting for the effects of wind and currents. The proposed methodology is applicable during both the planning and operational phases of port management and provides a quantitative basis for evaluating navigational constraints under adverse environmental conditions.

1 INTRODUCTION

Ports are increasingly challenged to balance economic growth, climate change adaptation, and the ongoing energy transition. The demand for larger vessels requires deeper and wider access channels, while climate change is increasing the frequency and intensity of extreme weather events that directly affect port operations. At the same time, the push towards decarbonisation and sustainable activities—such as offshore wind and other marine renewable energy developments—places additional pressure on ports to adapt and expand their infrastructure. Furthermore, stricter ship safety regulations are being implemented in response to a rising number of maritime incidents. In this context, numerical modelling has become an essential tool for accurately assessing the complex interactions between the ocean environment, port structures, and ships.

During the planning phase, the minimum safety depths and widths of port entrance channels can be defined based on the local wave climate and the characteristics of the vessels using the port. Numerical wave models are used to propagate

offshore wave conditions to locations along the access channel, thereby defining the operational wave regime. Three-dimensional simulation models are then employed to evaluate the effects of waves on ship motions. The maximum vertical ship motions are assessed as a function of wave characteristics, allowing the establishment of operability thresholds and the determination of minimum channel dimensions required to satisfy under-keel clearance (UKC) criteria.

During the operational phase, the proposed methodology is applied to evaluate safety conditions for vessels entering or leaving the port. This assessment is based on short-term forecasts of wind, wave, and sea-level conditions. Numerical models, such as SWAN and Boussinesq-type models, are used to propagate waves from offshore regional scales to nearshore and port basin scales. Ship responses are quantified through the computation of six-degrees-of-freedom (DoF) response amplitude operators (RAOs) using a three-dimensional hydrodynamic panel model. Among the motion components, heave and pitch are the main contributors to the vertical displacement of the ship hull and govern the maximum vertical motion at the stern.

This numerical methodology has been implemented in the HIDRALERTA-SAFEPOR Operational Forecast and Early Warning System (EWS) for navigation safety. The Port of Aveiro is presented as a case study. Located in a rapidly developing economic region, the port is exposed to the energetic Atlantic wave climate and is experiencing increased activity related to offshore wind and marine renewable energy projects. The proposed methodology enhances navigational safety and accessibility in ports exposed to energetic seas and supports more resilient and competitive port operations, particularly through the development and application of operational early warning systems.

2 SAFEPOR EARLY WARNING SYSTEM FOR NAVIGATION IN PORTS

2.1 General Structure

An effective Early Warning System (EWS) must be capable of predicting both the occurrence and the severity of hazardous events. Such systems reduce port vulnerability by enhancing planning capabilities and enabling timely and efficient responses to emergency situations. The SAFEPOR system—*Safety System for Manoeuvring and Moored Ships* (Pinheiro et al., 2020, 2022)—is an integral component of the HIDRALERTA EWS, which operates on a daily basis to issue emergency alerts related to wave overtopping, ship navigation safety, and operational constraints affecting port activities. The system currently covers seven ports and coastal zones in mainland Portugal, as well as three ports in the Azores Islands.

SAFEPOR employs a suite of numerical models running in near real time to simulate wave propagation and to compute ship motions and mooring forces. The modelling framework uses forecasts of offshore regional wind and wave conditions, combined with astronomical tidal data, as input to the numerical simulations. These simulations produce 3-hourly forecasts for a 3-day prediction horizon, which are subsequently evaluated against predefined operational and safety thresholds.

A probabilistic assessment of threshold exceedance is then performed to determine risk levels. Based on the forecasted risk, potential emergency situations and operational limitations

can be anticipated in advance, enabling the timely issuance of appropriate warning alerts to support safe and efficient port operations.

The current architectural framework of the system is illustrated in Figure 1 and consists of five main modules.

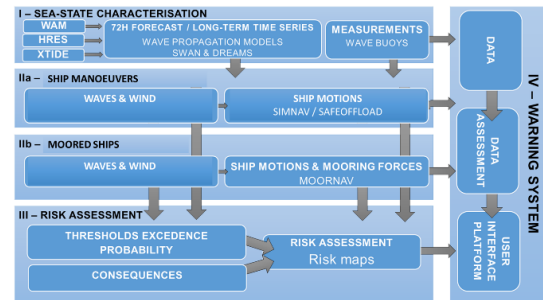


Figure 1. SAFEPOR-EWS architectural framework incorporating neural-network (NN) modelling.

2.2 Module I – Sea-state characterisation.

In this module, sea-state characteristics, water levels, and wind conditions are defined. The system employs a suite of numerical models that utilise forecasts of offshore wind and wave conditions, in conjunction with astronomical tide information.

Offshore wave and wind conditions, both hindcast and forecast, are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Copernicus Marine Environment Monitoring Service (CMEMS). A 3-day forecast of offshore sea-state and wind conditions is downloaded daily from ECMWF’s High-Resolution Forecast (HRES) system, which currently operates at a horizontal resolution of approximately 9 km. HRES provides detailed atmospheric predictions up to 3.5 days ahead and is updated twice daily, at 06 UTC and 18 UTC. HRES is tightly integrated with two key numerical models:

- ECWAM (the ECMWF implementation of the WAM wave model; WAMDI, 1988), used to simulate and forecast wind-generated waves and sea-state conditions;
- NEMO (Nucleus for European Modelling of the Ocean), a dynamic ocean circulation model that supports the simulation of ocean currents and ocean–atmosphere interactions, particularly relevant for the development and tracking of tropical storms.

The ECWAM model provides predictions of the following wind and wave parameters:

- significant wave height (H_s),

- mean wave period (T_m),
- peak wave period (T_p),
- mean wave direction (θ_m),
- wind velocity components (V_x, V_y).

The spatial resolution of the ECMWF HRES wave and wind fields is $0.1^\circ \times 0.1^\circ$.

To complement the meteorological and oceanographic data, astronomical tide levels are computed using the XTide software (Flater, 1998), which implements the harmonic tide prediction algorithm of the U.S. National Ocean Service (NOS).

Wave propagation from offshore to nearshore regions is simulated using a nested modelling approach. The third-generation spectral wind-wave model SWAN (Booij et al., 1996) is applied at the regional scale to propagate wave conditions from the open ocean to the vicinity of the harbour. Simulations are carried out over several hundred kilometres around the study area using three nested computational grids with progressively finer spatial resolution.

SWAN is operated in stationary mode and includes key physical processes such as wave refraction, approximate diffraction, whitecapping, bottom friction, and depth-induced breaking. Due to the simplified representation of diffraction in SWAN, higher-resolution models are required for harbour-scale analysis.

For wave propagation into sheltered port basins, two local-scale models are employed: the mild-slope refraction–diffraction model DREAMS (Fortes, 2002) and the non-linear Boussinesq-type model BOUSS-WMH (Pinheiro et al., 2011). These models resolve complex wave transformations and harbour resonance phenomena, providing detailed sea-state information required for moored-vessel motion analysis.

Numerical simulations are executed on the National Distributed Computing Infrastructure (INCD), using a high-performance computing cluster with 64 nodes. A finite-element mesh generator supports the implementation of local-scale models, ensuring adequate spatial resolution for irregular coastal and port geometries. The runtime of a complete forecast cycle is approximately 30–40 minutes, as the 24 forecast instants are computed in parallel using 24 cluster nodes. Most of the computational time is associated with the high-resolution harbour-scale wave propagation model (DREAMS).

2.3 Module II – Ship Manoeuvring and Mooring Safety

The wind and sea-state conditions derived from Module I are used to assess: a) Ship manoeuvring safety, through the numerical evaluation of dynamic under-keel clearance (UKC) along approach routes; b) Mooring safety, including ship motions and forces acting on mooring lines and fenders, evaluated using the *Simulation of Wave Action on Moored Ships* (SWAMS) software (Santos, 1994; Pinheiro et al., 2013).

The central contribution of this paper is a novel methodology for assessing manoeuvring safety based on time-domain simulations of ship motions and dynamic UKC, as described in Section 3.

For moored-ship safety assessment, the SWAMS model computes vessel response to wave and wind loading. It integrates a three-dimensional hydrodynamic panel method (WAMIT; Korsmeyer et al., 1988) with a time-domain motion solver (BAS; Mynett et al., 1985), enabling dynamic modelling of ship behaviour. The system resolves the equations of motion using time series of environmental loads in combination with the mechanical properties of the mooring system.

2.4 Module III – Risk assessment

Simulated hourly ship motions and mooring line tensions are evaluated against predefined operational thresholds. Risk levels are quantified by comparing the model outputs with the maximum breaking load (MBL) of mooring lines, in accordance with OCIMF recommendations (OCIMF, 1992), and with allowable ship motion limits based on PIANC guidelines (PIANC, 1995, 2012).

2.5 Module IV – Warning system

This module generates and disseminates 72-hour forecasts, updated daily through a web-based platform, and issues daily bulletins containing alerts related to wave overtopping, moored-ship safety, and under-keel clearance (UKC). These bulletins are distributed via email to the relevant port authorities and stakeholders.

A four-tier alert system is implemented to communicate operational risk levels:

- Level 0 – Green: Normal operations; no restrictions.
- Level 1 – Yellow: Conditional operations; reinforcement of moorings recommended.
- Level 2 – Orange: Operations suspended; mooring reinforcement required.

- Level 3 – Red: Operations halted; high risk of mooring failure or structural damage.

The alert levels are represented using colour-coded indicators to support rapid decision-making by port operators with respect to loading and unloading activities, navigational safety, and mooring integrity.

3 METHODOLOGY

3.1 Ship Manoeuvring Safety

The proposed numerical methodology, based on the under-keel clearance (UKC) criterion, was developed to accurately assess ship accessibility and navigational safety. It combines the simulation of non-linear wave propagation and transformation in complex, sheltered environments—such as ports—with three-dimensional hydrodynamic flow around the ship hull, accounting for wind and current effects. This methodology can be applied both during the planning phase and operationally to support port management decisions.

A set of numerical models is used to propagate waves from the regional scale to the local scale. This modelling chain consists of the SWAN model (Booij et al., 1996), coupled with either a non-linear Boussinesq-type model (Pinheiro et al., 2011) or a linear mild-slope model (Fortes, 2002), depending on the required spatial resolution and physical processes.

The ship's response amplitude operators (RAOs) for the six degrees of freedom (6DoF) are then computed using a three-dimensional hydrodynamic panel method (Korsmeyer et al., 1988).

Heave and pitch are the main contributors to the vertical motion of the ship hull (Figure 2). The combination of these two motion components for each wave frequency yields the maximum vertical displacement of the stern, Δz , given by:

$$\Delta z = \Delta X_3 + \Delta X_5$$

where ΔX_3 is the vertical displacement of the ship's centre of gravity and ΔX_5 is the vertical displacement of the stern due to pitch rotation, expressed as:

$$\Delta X_5 = \frac{LOA}{2} \sin X_5$$

where LOA is the ship's length overall.

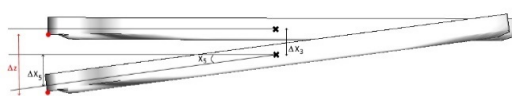


Figure 2. Motion amplitude of the ship hull.

This is followed by an assessment of the expected UKC given by:

$$UKC = D - d_1 - d_2 - \sum_{i=3}^5 d_i - \sum_{i=6}^9 d_i$$

Where:

D - is the local depth (varying with tide level);
 $d_1 = \Delta z$ - is the draft of the ship (varying with ship loading);

d_2 - is the maximum vertical ship motion induced by waves;

d_3 - is the difference in draft between stern and bow (trim), dependent on ship loading;

d_4 - is the squat induced by current effects;

d_5 - is the set-down due to atmospheric pressure variations

d_6 - is a safety margin;

d_7 - is a tolerance accounting for measurement uncertainties;

d_8 - is a tolerance accounting for sediment accretion between dredging operations;

d_9 - is a tolerance accounting for dredging inaccuracies.

3.1.1 Channel Design Based on Manoeuvring Safety Criteria

During the planning phase of port development, the minimum safe depths and widths of entrance channels can be defined based on the local wave climate and the characteristics of vessels calling at the port. Using numerical wave propagation models, offshore wave conditions are transferred to a set of key locations along the access channel. This process enables the identification of the operational wave envelope—typically represented by peak period versus significant wave height ($T_p-H_{s,max}$) pairs—under which the under-keel clearance (UKC) criterion must be satisfied.

The impact of wave conditions on the six-degrees-of-freedom (6DoF) ship motions is evaluated using three-dimensional hydrodynamic simulation tools. The maximum vertical ship motion at each location along the channel is determined by analysing the most critical combinations of wave parameters (T_p , $H_{s,max}$, and wave direction). This approach defines the worst-case scenario for UKC compliance.

Alternatively, a required operability level—defined as the percentage of time during which port access must be ensured—can be specified. Based on this criterion, the minimum channel dimensions required to satisfy UKC

requirements under the expected wave regime can be systematically determined.

3.1.2 Operational safety conditions

During the operational phase, the same methodology applied in the planning stage can be used to assess the safety conditions for a specific vessel navigating into or out of the port. This assessment is based on short-term forecasts of offshore wind and wave conditions, combined with sea-level information. By applying numerical models to propagate the forecasted sea states into the port domain, ship motions and under-keel clearance can be evaluated along the intended navigation route.

This methodology forms the basis of the Operational Forecast and Early Warning System (EWS) for navigation safety, initially developed for the Port of Sines (Pinheiro et al., 2023) and currently being extended to additional locations, including the Port of Aveiro, within the framework of the C2Impress project (Co-creative Improved Understanding and Awareness of Multi-Hazard Risks for a Disaster-Resilient Society; www.c2impress.com).

The primary objective of the EWS is to reduce port vulnerability by enhancing situational awareness, improving planning capabilities, and enabling timely responses to adverse environmental conditions. In doing so, the system contributes to both navigational safety and port competitiveness by minimising disruptions to vessel traffic and operational activities.

4 CASE STUDY: PORT OF AVEIRO

The Port of Aveiro, located on the north-west coast of mainland Portugal, is a key hub for general cargo, containerised freight, and bulk transport. This case study illustrates the application of the proposed numerical methodology during both the planning and operational phases of port access management.

4.1 Planning Phase: Channel Design and Ship Manoeuvring Safety

During the planning phase, the methodology was applied to assess the minimum safety dimensions required for the entrance channel, based on the local wave climate and representative vessel characteristics. Offshore wave conditions derived from long-term hindcast datasets were propagated to key locations along the access channel using the SWAN model. This enabled the definition of the operational wave

envelope, represented by $T_p-H_{s,max}$ pairs, corresponding to the most critical sea states under which navigation must remain safe.

Figure 3 compares the current bathymetry (left panel) with the planned dredging configuration (right panel), designed to improve channel depth and safety margins. These modifications are expected to significantly influence wave transformation patterns and vessel manoeuvrability within the access channel.

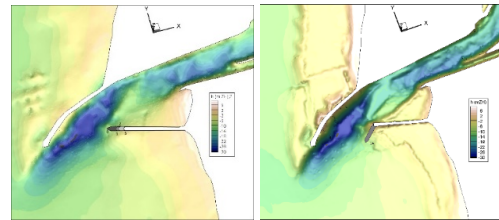


Figure 3. Present (left) and planned (right) bathymetry

Using three-dimensional numerical ship-motion models (WAMIT and BAS), the six-degrees-of-freedom (6DoF) responses of a representative container vessel were evaluated at multiple locations along the channel. Maximum vertical motions associated with worst-case wave combinations were used to verify compliance with under-keel clearance (UKC) criteria under operational conditions. The results informed recommendations for minimum channel depth and width, either for extreme scenarios or to achieve a specified operability target (e.g. 95% annual accessibility).

The ship's 6DoF response amplitude operators (RAOs) were computed using a 3D hydrodynamic panel method (Korsmeyer et al., 1988), as illustrated in Figure 6.

Figure 4 shows the wave transformation patterns along the port's access channel simulated with the DREAMS model. The results highlight the refraction and diffraction processes governing wave propagation into the channel, which are critical for assessing nearshore wave conditions relevant to vessel navigation.

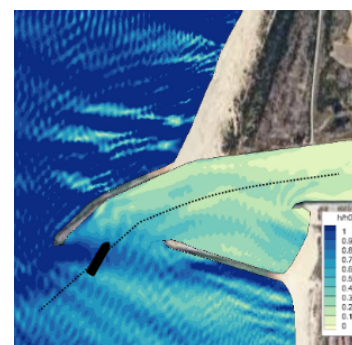


Figure 4. Wave transformation patterns along the access channel simulated with the DREAMS model.

Accurate prediction of ship motions requires detailed modelling of wave–ship hydrodynamic interaction.

Figure 5 presents the discretisation of the vessel hull into panels, forming the basis of the three-dimensional boundary element method used in the hydrodynamic simulations. This panelisation enables precise computation of wave-induced forces and moments acting on the vessel.

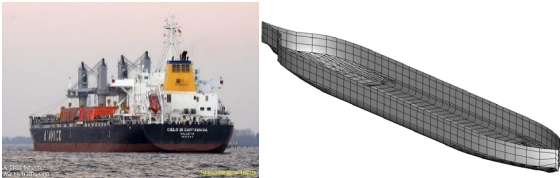


Figure 5. Ship hull panel discretisation.

The resulting ship motion response to wave forcing is characterised by the amplitude of hull motions, revealing spatial variations that influence overall vessel behaviour under different sea states.

To quantify this response, Figure 6 presents the RAOs for the two dominant vertical motion components—heave (X_3) and pitch (X_5)—for a general cargo vessel. These RAOs describe the ship’s response across wave frequencies and are essential for estimating vertical motions affecting UKC.

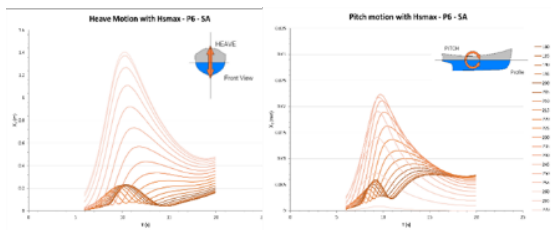


Figure 6. Heave (X_3) and pitch (X_5) RAOs for a general cargo vessel.

Environmental forcing conditions in the study area are summarised in Figure 7, which depicts the prevailing wind and wave regimes affecting the Port of Aveiro.

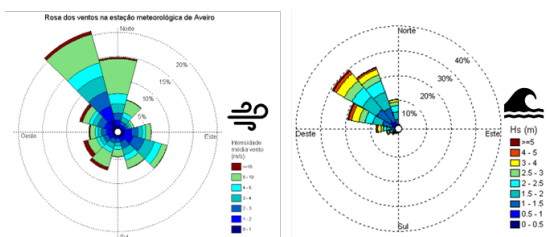


Figure 7. Wind and wave regimes.

Based on the joint distribution of significant wave height (H_s) and mean wave period (T_m) for the period from 1 January 1979 to 17 December 2020, the maximum H_s values associated with each T_m were identified (red circles in the first panel of

Figure 8). A third-degree polynomial was then fitted using a minimum root mean square error criterion, defining the maximum wave-height envelope as a function of wave period along the access channel and within the harbour.

This envelope was derived for both the current configuration (SA) and an alternative layout (ALT14).

Figure 8 shows the joint H_s – T_m distribution at monitoring point P6, comparing the present configuration (blue) with a hypothetical scenario involving a 200-m rotation of the south breakwater head (yellow). The red dots delineate the operational wave envelope.

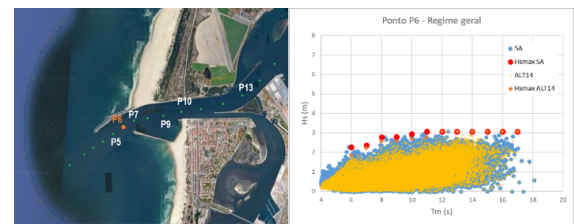


Figure 8. H_s – T_m distribution at point P6. Red dots represent the envelope of maximum H_s for each T_m ; blue indicates the current configuration (SA), and yellow the modified configuration (ALT14).

The effects of these wave conditions on the vessel’s 6DoF motions were computed using the three-dimensional ship hydrodynamic models. The maximum vertical motion of the ship, resulting from the most unfavourable combination of wave parameters (T_p , $H_{s,max}$, direction), was assumed to represent the worst-case scenario at each point along the channel.

Figure 9 presents the maximum vertical displacement of the vessel’s stern (Δz) under two wave condition sets. The left panel includes all wave records, representing the full variability of the local sea state, including extreme conditions. The right panel considers operational harbour conditions only, defined here as $H_s < 3.0\text{m}$ at the harbour entrance (point P1). The comparison demonstrates a substantial reduction in vertical motions during normal operational conditions, highlighting the importance of wave filtering in UKC assessments.

Using the computed vessel motions and local bathymetry, the minimum UKC along the vessel route was calculated.

Figure 10 shows the resulting minimum UKC values under wave forcing. These results identify potential bottlenecks within the access channel or harbour basin where safety margins may be insufficient, particularly during low tide or elevated wave conditions.

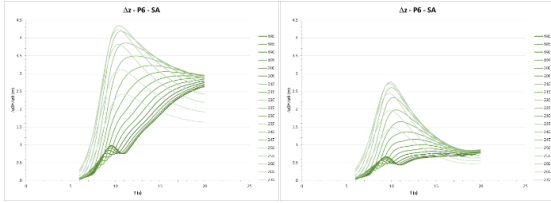


Figure 9. Maximum vertical displacement of the stern (Δz). Left: all wave records; right: operational harbour conditions ($H_s < 3.0$ m).

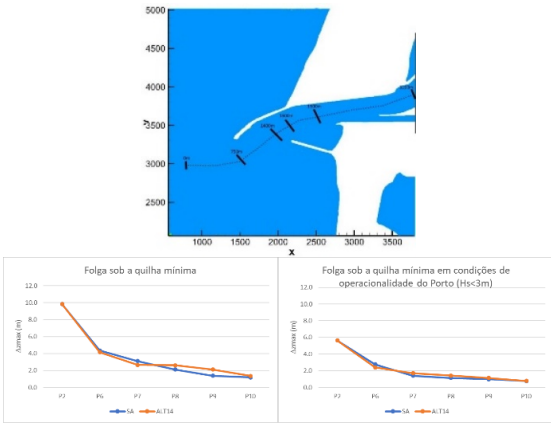


Figure 10. Minimum under-keel clearance under wave action.

Alternatively, an operability level—defined as the percentage of time that port access must be guaranteed—can be specified, and the corresponding minimum channel dimensions required to satisfy UKC criteria can be derived.

Figure 11 presents the average annual number of days at point P6 when H_s exceeds predefined operational thresholds, for both the current configuration (SA) and the planned configuration (ALT14). The results indicate that extending the south breakwater leads to a noticeable reduction in wave energy entering the channel, thereby improving operability by reducing the number of days with unsafe navigation conditions.

This information provides a key input for cost–benefit analyses of infrastructure upgrades, supporting decisions on dredging strategies,

breakwater optimisation, and port accessibility targets (e.g. achieving 95% annual operability).

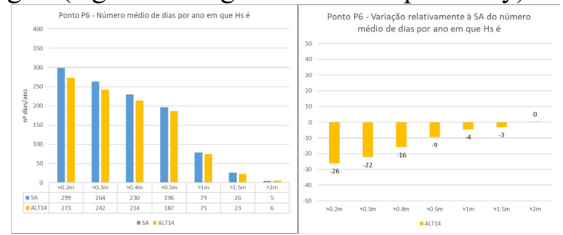


Figure 11. Average number of days per year at point P6 when H_s exceeds defined thresholds, for the present (SA) and planned (ALT14) configurations.

4.2 Operational Phase: Forecast-Based Safety Assessment

During the operational phase, the same modelling framework supports a real-time Early Warning System (EWS) that provides dynamic assessments of navigational safety. The EWS ingests daily forecasts of wind, wave, and sea-level conditions from ECMWF and CMEMS and propagates these conditions through nested computational grids down to the port entrance using the SWAN and DREAMS models.

For the Port of Aveiro, a representative container vessel scenario was simulated under a forecasted moderate storm event. Ship motions and under-keel clearance (UKC) were evaluated for both inbound and outbound routes. In this case, red alerts were issued for a six-hour time window along two segments of the vessel's route (see figures 12 and 13).

This application, developed within the C2Impress project, demonstrates how operational numerical modelling enhances port resilience by providing actionable information to support harbour master decision-making. The system enables real-time risk evaluation, optimises berth scheduling, and minimises operational downtime associated with uncertain or rapidly changing weather conditions. Forecast data on sea states and tidal levels are dynamically integrated into the EWS to assess navigation safety conditions in near real time. This includes the continuous evaluation of UKC along the vessel's route and the issuance of risk-based alerts to guide operational decisions.

Figure 12 presents an alert map for the entrance channel of the Port of Aveiro, generated using forecasted wave and sea-level data. The map provides a spatial representation of navigational risk levels along the channel, using a colour-coded scale to highlight critical zones where UKC may be compromised. This visualisation supports operational planning by

indicating when and where transit restrictions should be considered for safety reasons.

Complementarily, Figure 13 shows the forecasted UKC along the entrance channel, illustrating the temporal evolution of the clearance margin under the combined effects of bathymetry, tidal variation, and wave-induced vertical ship motions. This information allows the identification of safe navigation windows for both incoming and departing vessels.

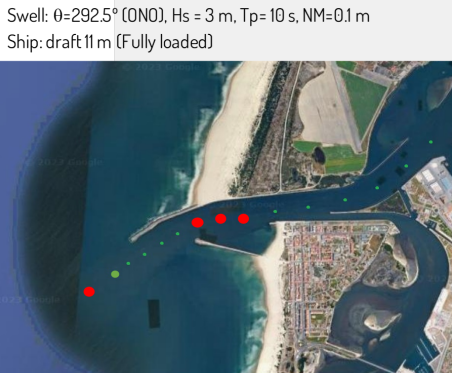


Figure 12. Alert map for the entrance channel of the Port of Aveiro

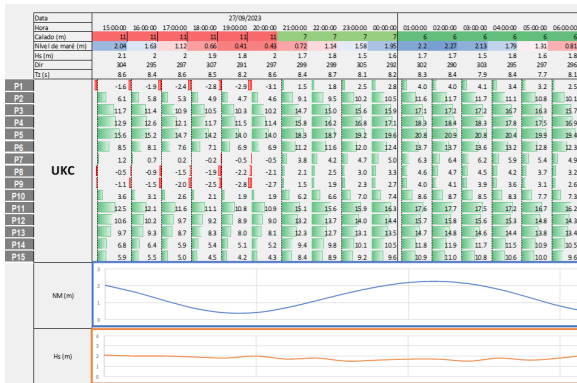


Figure 13. Under-keel clearance forecast for the entrance channel

5 CASE STUDY: PRAIA DA VITÓRIA

5.1 Operational Phase: Forecast-Based Moored Ships safety

The Port of Praia da Vitória is located on the eastern coast of Terceira Island, in the Azores archipelago, Figure 14. Wave propagation from offshore to nearshore regions is simulated using the SWAN model, implemented through a nested grid system with three spatial resolutions: 200 m (coarse), 100 m (medium), and 25 m (fine). Outputs from the finest grid are subsequently used as input to the DREAMS model, which

resolves local wave transformations within the port basin.



Figure 14. Praia da Vitória Port. Aerial views of the port and the container ship quay.

For the simulation of moored ship response, the WAMIT and BAS models are applied, requiring a detailed definition of vessel characteristics and mooring system parameters. The prototype vessel considered is a generic container ship with a displacement volume of 12,717 m³, a length overall of 120 m, a beam of 19 m, and a draft of 8 m. The vessel is moored at a berth with a water depth of 10 m.

The mooring system consists of ten mooring lines and five pneumatic fenders. Each mooring line has a Maximum Breaking Load (MBL) of 931 kN and an elongation capacity of 8%. The fenders exhibit a maximum reaction force of 4,900 kN at a deflection of 1 m. This configuration ensures adequate resistance to the dynamic loads imposed by wave and wind action during both berthing and operational conditions.

The prototype harbour layout includes two main terminals: the multipurpose terminal (quay 12) and the container terminal (quay 10). Two vessel types—a general cargo ship and a container ship—are modelled using the described mooring arrangements. The mooring configurations for both vessels, comprising ten mooring lines and five fenders each, are illustrated in Figure 15.

The prototype system for the Praia da Vitória harbour includes the multipurpose terminal, quay 12, and the container terminal, quay 10. Two ships are modelled – a general cargo ship and a container ship. The mooring arrangement of each ship, comprising 10 mooring lines and 5 fenders, is shown in Figure 15.

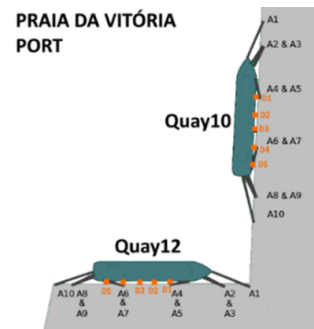


Figure 15. Mooring arrangements at quays 10 and 12.

A representative scenario illustrating system performance is presented for Hurricane Lorenzo. Forecasted mooring forces, significant wave height, and wind speed are shown in Figure 16 and form the basis for the risk-based alert system. The corresponding alert maps for the most critical hour are presented in Figure 17, highlighting the spatial distribution of mooring safety levels throughout the port.

With respect to mooring forces acting on the simulated vessels, no critical warnings were triggered during Hurricane Lorenzo. Mooring loads remained within the operational limits of the mooring system, indicating stable conditions for the prototype ships. Only Level 1 (yellow) alerts were issued, limited to the period between 03:00 and 06:00 UTC, primarily due to elevated wind speeds and wave heights. These conditions did not pose a significant risk to mooring integrity or overall operational safety.

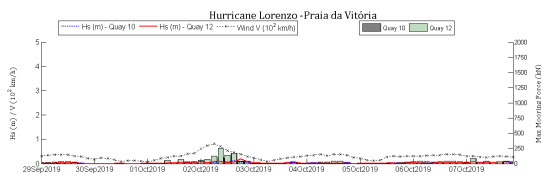


Figure 16. Hurricane Lorenzo: forecasted mooring forces, significant wave height, and wind speed.



Figure 17. Hurricane Lorenzo alert maps for the critical hour.

6 CONCLUSIONS

The integration of medium-range wave forecasts with high-resolution numerical models for wave propagation enables the daily prediction of potentially hazardous sea states affecting coastal areas, port infrastructure, moored vessels, and port operations. This represents a significant advancement over traditional Early Warning Systems (EWSs), which typically rely solely on

general sea-state parameters such as significant wave height and wave period.

Port and vessel safety are governed by complex wave–structure and wave–ship interactions, and associated risk assessments often require site-specific, dynamic modelling approaches. The HIDRALERTA system addresses this need by providing risk levels based on the actual physical impacts of forecasted waves on critical infrastructure and moored ships, rather than relying exclusively on environmental thresholds.

This impact-based approach enables port authorities and stakeholders to implement proactive mitigation strategies, enhancing personnel safety, preventing structural damage, and reducing operational downtime. By delivering real-time, actionable information, HIDRALERTA improves port resilience and preparedness in the face of extreme weather events, ultimately contributing to greater operational continuity and economic efficiency. In the case of Praia da Vitória, the EWS has been operational for more than five years, and feedback from pilots, port authorities, and civil protection services has been crucial for the ongoing fine-tuning and optimization of the system, particularly with respect to moored ship safety.

Complementing this framework, the newly proposed methodology for Under-Keel Clearance (UKC) assessment advances safety management for manoeuvring vessels during both the design and operational phases. In the design phase, the methodology combines numerical wave propagation and three-dimensional ship motion simulations to define minimum safety depths and widths for access channels based on the local wave climate and vessel characteristics. This ensures compliance with UKC criteria under the most critical wave conditions, thereby improving channel design reliability and operability.

During the operational phase, the same modelling framework integrates real-time forecast data to dynamically assess UKC and ship manoeuvring safety along navigation routes. This enables EWSs to issue timely alerts regarding access conditions, supporting informed decision-making, optimized vessel scheduling, and risk reduction. By explicitly linking environmental forecasts with ship dynamic response and clearance requirements, this methodology addresses a critical gap in maritime safety management.

Together, these developments support a holistic, physics-based approach to port safety, ensuring both infrastructure protection and safe vessel operations under variable and extreme sea conditions.

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