J Coast Conserv (2012) 16:489–501
DOI 10.1007/s11852-012-0190-7

Application to the Port of Sines of a new tool for risk assessment in port navigation

Diogo Rúben Neves · Sara Rodrigues · Conceição Juana Fortes · Maria Teresa Reis · João Alfredo Santos · Rui Capitão

Received: 21 April 2010 / Revised: 14 October 2010 / Accepted: 5 November 2010 / Published online: 16 March 2012

Abstract This paper describes a first approach on the risk assessment in port navigation using GUIOMAR, an integrated system for port and coastal engineering modelling developed at the National Civil Engineering Laboratory (LNEC), Portugal, using a GIS software environment. A set of automatic procedures was designed to include a new methodology based on the amplitude of the wave-induced vertical movement of a ship along its trajectory. In this methodology, the risk in port navigation is assessed on the basis of a combination of the probability of exceedance of a pre-set threshold for the ship's vertical movements and its consequences. To test the new procedures, a set of sea wave records obtained at the Sines wave-buoy from 1988 to 2002 was transferred into Sines Port using two numerical models of sea wave propagation and deformation (SWAN and DREAMS), included in the GUIOMAR system. The numerical model WAMIT was used for estimating the wave-induced ship's vertical movements inside the port. By applying the new procedures, automatic generation of risk maps was carried out for navigation in the vicinity of the West breakwater of the Port of Sines. The recent developments contribute towards a more versatile and efficient GUIOMAR system, which results in a more adequate tool to support decision-making processes in port and coastal management.

Keywords Risk assessment · Navigation · Geographical information systems · Port of Sines · GUIOMAR · Marine modelling

D. R. Neves (✉) · S. Rodrigues · C. J. Fortes · M. T. Reis · J. A. Santos · R. Capitão
Departamento de Hidráulica e Ambiente,
Laboratório Nacional de Engenharia Civil,
Av. do Brasil, 101,
1700-066, Lisbon, Portugal
e-mail: dneves@lnec.pt

S. Rodrigues
e-mail: srodrigues@lnec.pt

C. J. Fortes
e-mail: jfortes@lnec.pt

M. T. Reis
e-mail: treis@lnec.pt

J. A. Santos
e-mail: jasantos@lnec.pt

R. Capitão
e-mail: rcapitao@lnec.pt

Introduction

One of the major issues in naval and port engineering is navigation safety within a port. In fact, since the consequences of the lack of security can be devastating, maritime industries are heavily penalized for losses of human lives, cargo disturbances and environmental impacts. Consequently, it has become increasingly important to develop methodologies and tools for risk assessment in port navigation.

To assess the risk in port navigation, it is necessary to integrate data from sea wave records with results from numerical models, in order to simulate relevant scenarios. With numerical models of wave propagation and deformation, it is possible, nowadays, to simulate such scenarios. However, since numerical models lead to large amounts of information, their implementation is complex and requires time for both preparation of the input data and analysis of the results. In this connection, Geographic Information Systems (GIS) are an asset to understand the temporal and spatial complexity of natural hazards, rapidly showing trends and patterns. In particular, GIS systems can easily produce risk maps, based on automatic analysis of data and model results, which are essential for quick, reliable and supported decisions for port and coastal management.

In this context, the GUIOMAR system (Neves et al. 2009a, b) has been developed at the National Civil Engineering Laboratory (LNEC), Portugal, to become an integrated system for port and coastal engineering modelling in Portugal. Since this system is based on the GIS commercial software ArcGis™, it enables the application of wave propagation models using all the functionalities inherent to GIS software. It was designed to help in the decision-making processes in the management of port and coastal zones.

This paper describes the new developments in the GUIOMAR system to assess the risk in port navigation associated to wave action. A new methodology was established based upon measured historical data, results from numerical models for wave generation, propagation and dissipation, SWAN (Booij et al. 1999) and DREAMS (Fortes 2002), and results from the numerical model WAMIT (Newman and Sclavounos 1988) for wave interaction with floating bodies. The methodology for risk assessment was implemented in the GUIOMAR system through a new module that automatically applies the risk assessment procedures and enables the user to produce pre-formatted risk maps.

The new GUIOMAR module was applied to the Port of Sines, one of the most important Portuguese and European maritime gateways, located on the southwest coast of mainland Portugal (37° 57′N and 08° 53′W). The case study involved: (a) establishing the wave regime at several points inside the port from data collected between 1988 and 2002 by the wave-buoy located offshore the Port of Sines (37° 55′N and 08° 55′W); (b) calculating the ship's vertical movements in each of the three regions considered in the ship's trajectory in the port; and (c) calculating the risk level associated with the exceedance of a pre-set threshold of the ship's vertical movements from the quantitative analysis of the probability of that threshold being exceeded and the qualitative analysis of the consequences. The results are depicted by risk maps associated with the ship's vertical movements when navigating along the West breakwater of the Port of Sines.

In the next chapters, the general methodology for risk assessment in port navigation and its implementation in the GUIOMAR system are described. Then, this methodology is applied to the case study of the Port of Sines. Finally, conclusions are drawn and suggestions are made for future developments of GUIOMAR.

Methodology

The new methodology for risk assessment in port navigation is based on the combination of the probability of exceedance of pre-set thresholds for the ship's vertical movements and its consequences. First of all, it is necessary to determine the amplitude of the ship's vertical movement along her trajectory induced by the waves in the study region.

The proposed methodology consists in four main steps:

- To define the wave regime offshore the port region;
- To establish the wave regime in pre-defined regions inside the port. In this work, this is performed by using two numerical wave propagation models;
- To calculate the ship's vertical movements in each of the regions considered in the ship's trajectory in the port. This is performed by using the numerical model WAMIT (Newman and Sclavounos 1988) for wave interaction with floating bodies;
- To calculate the risk level associated with the exceedance of a pre-set threshold of the ship's vertical movements from the quantitative analysis of the probability of that threshold being exceeded and the qualitative analysis of its consequences. The results are depicted in the form of risk maps associated with the ship's vertical movements.

The establishment of the wave regimes (offshore and inside the port) is performed by using the GUIOMAR system. Also, the methodology for risk assessment was implemented in the GUIOMAR system through a new module that automatically applies the risk assessment procedures and produces default risk maps.

In the next sections, the procedures associated to each step are described.

Establishment of the wave regime

The definition of the wave regime inside the port is based upon the offshore sea wave characteristics, measured or estimated at a location close to the port, usually transferred into the port using one or more numerical wave propagation models, such as the SWAN model (Booij et al. 1999) and/or the DREAMS model (Fortes 2002). The use of one or more numerical models for such propagation depends on the characteristics of the study region (for example, its dimensions).

The application of each model should be performed for each condition of the offshore wave regime. However, the computation time required to operate the models for long data series remains a restrictive factor, especially if the study region is large.

To overcome this difficulty, a methodology was devised (Pinheiro et al. 2004; Palha 2007) consisting in previously determining a transfer matrix for the study region, i.e., an estimation of values relating the offshore sea wave characteristics with the sea waves at specific points inside the port.

Once the transfer matrix is known, for each triad of significant wave height, mean period and mean direction

(HS, TZ and DIR, respectively), which corresponds to an offshore wave record, the REGIMES program (Pinheiro et al. 2006b) interpolates such conditions using the transfer matrix to estimate the sea wave characteristics at the study points.

To establish the transfer matrix, the ranges of HS, TZ and DIR should be defined to enable the definition of equally spaced trios of (HS, TP and DIR), where TP is the spectral peak period. Those values are the input wave conditions for which the numerical models will be applied. Based on these numerical results, the transfer matrix is built at each point inside the port.

In brief, to define the wave regime inside the port, the following steps are considered:

- Definition of the wave regime offshore the port region;
- Calculation of the matrix to transfer the wave conditions from offshore (wave-buoy) into the port, using a numerical model;
- Use of the program REGIMES and the transfer matrix, to transfer all the data from offshore (wave-buoy) to the points inside the port;
- Definition of the local wave regime, inside the port.

Ship's movement

Once the ship, whose behaviour is to be studied, is defined, the numerical model WAMIT (Newman and Sclavounos 1988) is employed to evaluate the ship's response, in terms of motion amplitude for each of the six degrees of freedom, Fig. 1, for a range of wave periods, water depths and angles between the longitudinal axis of the ship and the wave number vector that is deemed possible in the study region.

WAMIT is a numerical model that solves the integral equations for the linear potential associated to the interaction between sea waves and a floating body when such a body is placed in a horizontally unbounded region. WAMIT evaluates the motions of the ship's centre of gravity, which happens to be the origin of the reference system shown in Fig. 1. So, to get the amplitude of the vertical motion at any point in the ship, one has to evaluate the vertical component of the vector product of the angular velocity by the position vector of such a point with relation to the origin of that reference system. It must be pointed out that the angular velocity components are complex quantities since, in addition to the angular velocity module with relation to each of the axis shown in Fig. 1, one needs to know also the phase of such velocity.

In the end of this procedure, one should get a transfer matrix that produces the maximum amplitude of the vertical component of the ship motion given the water depth of the region the ship is sailing across, the wave period and the angle between the ship's longitudinal axis and the wave number vector of the wave that hits the ship.

In the preliminary approach described here, only one point was considered in the ship and neither the ship's advance speed nor the fact that waves hitting the ship are irregular is taken into account. Moreover, it is assumed that the port quays and other margins are far enough from the ship to have any influence on her response to wave action.

So, to get the amplitude of the vertical movement of a given ship point when she sails at one of the areas into which the region that may be occupied by her was divided, one only has to know the water depth at the centre of gravity of such area, the sea wave characteristics at the same point (wave height, wave period and wave direction) and the ship's heading. With such information (wave height excluded), one determines, using the transfer matrix, the motion amplitude of the ship point for a unit amplitude incident wave. Since the linearity of the interaction between the ship and the waves is assumed, to get the amplitude of the motion induced by a given wave, one only has to multiply the motion amplitude obtained from the transfer matrix by the amplitude of the incident wave.

Risk assessment

Methodology

In this paper, the risk assessment for port navigation takes into account only the vertical movement of a selected point in the ship obtained with the WAMIT

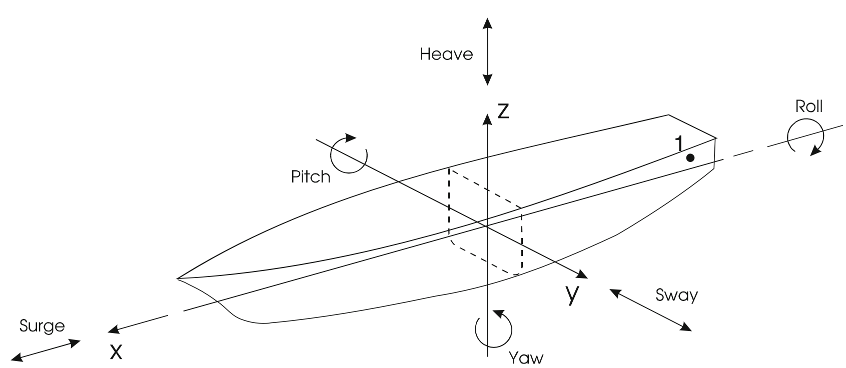

Fig. 1 Ship motions considered by the WAMIT model and study point 1

model. Thus, it is possible to qualitatively determine the navigation risk associated with the exceedance of a pre-set threshold for the amplitude of that movement in each of the stretches of the port area swept by the ship in her trajectory in the port.

The risk assessment methodology for a given port area is implemented into the GUIOMAR system, based on five main steps:

- Definition of the stretches where the ship's vertical movements are to be calculated using the WAMIT model (this requires knowledge of the sea wave conditions in the centroid of each stretch);
- Definition of acceptable thresholds for the amplitude of the ship's vertical movements;
- Development of a table of probability of exceedance for the pre-set thresholds of the ship's vertical movements and establishment of the level of probability for the different thresholds and stretches under study;
- Development of a table of consequences of exceedance of pre-set thresholds of the ship's vertical movements for each stretch under study;
- Combination of the values of the levels of probability and of consequences to obtain the risk level associated with the different pre-set thresholds and stretches.

Notice that it is mainly for shallow water ports that vertical motions of sailing ships can be problematic due to the inherent risk of grounding (or in the worse case scenario sinking).

Probability

Table 1 shows a preliminary classification of the probability of exceedance of pre-set thresholds of the ship's vertical movements. This probability is evaluated by using a frequency approach, i.e. by dividing the number of sea states for which the ship vertical movements exceed that threshold (the positive outcomes of the Bernoulli experiment) by the total number of sea states in the wave regime for which the ship's vertical movements are computed.

Table 1 Probability of exceedance of pre-set thresholds of the ship's vertical movements

Description	Probability (Guidelines)	Level
Improbable	0–1%	1
Remote	1–10%	2
Occasional	10–25%	3
Probable	25–50%	4
Frequent	>50%	5

Consequences

Table 2 shows a preliminary description of the consequences of exceedance of pre-set thresholds of the ship's vertical movements. This table is based on the guidelines of the New Zealand Maritime Safety Authority (2004) and has taken into account the consequences for human lives, the ship (both the ship herself and her cargo), the environment and the port management.

The levels for consequences were assigned in order to take into account the importance of the risk, in relation to its treatment and prioritization, in the assessment of the risk level (section 2.3.4). For example, it is important to distinguish between an event with high probability of occurrence but with low consequences and an event with a low probability of occurrence but with very high consequences, which is typically more important to manage.

Risk

In this work, risk is defined as the product of the probability of exceedance of pre-set thresholds of the ship's vertical movements and its consequences. In this context, the presented methodology is simply a qualitative assessment of the risk in port navigation, in which the risk level is obtained by multiplying the level values of the probability of exceedance (Table 1) and of the consequences (Table 2). The crossing matrix of these two levels is presented in Table 3, while Table 4 describes the assessment of the acceptability of the risk level.

The GUIOMAR system

The GUIOMAR system (Neves et al. 2009a, b) is an integrated system for port and coastal engineering modelling, developed in VBA programming language (Visual Basic for Applications), in a GIS commercial software ArcGis™. It has three main components:

1. the GIS software;
2. a set of 6 modules corresponding to different wave propagation and deformation models with different domains of application;
3. a Graphical User Interface (GUI), developed in VBA, that enables the liaison between the GIS software and the numerical wave models, that is, it enables: a) the execution of the models; b) the pre- and post-processing of the data and of the model results; and c) the use of the capabilities inherent to the GIS software, for instance to analyse and visualise data and results in both 2D and 3D.

At present, six wave propagation models are available: three models based on the mild-slope equation, DREAMS

Table 2 Consequences of exceedance of pre-set thresholds of the ship's vertical movements

Description	Consequences (Guidelines)				Level
	People	Property	Environment	Port Stakeholders	
Negligible	Possible very minor injury (e.g. bruise).	Insignificant	Negligible environmental impact. (<10^4 €)	Insignificant (<10^4 €)	1
Marginal	Single slight injury	10–10^2 €	Small operational spills (10^4–10^5 €)	Bad local publicity (10^4–10^5 €)	2
Serious	Multiple minor injuries or a single major injury.	10^2–10^3 €	Ship capable of being limited to immediate area within port zone. (10^5–10^6 €)	Bad widespread publicity; temporary navigation closure or prolonged restriction of navigation (10^5–10^6 €)	5
Critical	Multiple major injuries or single fatality.	10^3–10^4 €	Events with pollution outside port zone expected; potential loss of environmental amenity (10^6–10^7 €)	National Publicity; port faces temporary closure of a navigation channel, affecting port navigation and activity for several days; consequent loss of trade (10^6–10^7 €)	10
Catastrophic	Multiple fatalities	>10^4 €	Serious oil spill with international clean up funds; widespread beach contamination; significant threat to environmental amenity (>10^7 €)	International media publicity; port closes; navigation seriously disrupted for an extended period; serious and long term loss of trade (>10^7 €)	25

(Fortes 2002), REF/DIF1 (Dalrymple and Kirby 1991) and REF/DIF S (Kirby and Ozkahn 1994); two models based on the Boussinesq equation, FUNWAVE 1D and 2D (Kirby et al. 1998); and the spectral model SWAN (Booij et al. 1999). The program GMALHA (Pinheiro et al. 2006a) is responsible for generating unstructured grids for these numerical models, which can be run independently or coupled.

The modular nature of the system enables its easy expansion and upgrade, such as including more advanced models that may tackle different physical processes. GUIOMAR system is also characterized by the implementation of several automated procedures to reduce human errors and to speed up the user's familiarity with the procedures for operating the numerical models.

Figure 2 shows the GUIOMAR operating scheme.

Through GUIOMAR toolbar (Fig. 3), the user can select the most adequate model for the case study under consideration. Once the numerical model is chosen, a series of forms are displayed to help the user to enter, manipulate and visualize the input data, and to run the selected model. Subsequently, the output results can be displayed by accessing the displaying results area in the model form.

Table 3 Risk level

Risk Level		Consequences				
		1	2	5	10	25
Probability	1	1	2	5	10	25
	2	2	4	10	20	50
	3	3	6	15	30	75
	4	4	8	20	40	100
	5	5	10	25	50	125

The latest development to GUIOMAR includes a module to automatically produce risk maps based on the methodology presented in section 2.3.1. Figure 3 shows the GUIOMAR toolbar used to access the risk maps production area.

After choosing the "RiskAssessment" option, a new GUIOMAR interface (Fig. 4) opens, which is capable of establishing a navigation risk map for exceedance of pre-set thresholds of the ship's vertical movements and, if desirable, to export the results in a Google Earth™ format. This interface includes three steps:

1. *"Load site image"* – loads the geo-referenced image from the study area into the ArcGis™ work environment;
2. *"Load local risk Assessment"* – Reads the text file (*.txt) containing the risk level in each study point along the ship's trajectories and converts it into a shapefile

Table 4 Assessment of the acceptability of the risk level

Level	Description	Risk Treatment (Guidelines)
1–3	Negligible	Insignificant risk; no further consideration needed.
4–10	Acceptable	Risk can be considered acceptable/ tolerable provided the risk is managed.
15–30	Undesirable	Risk should be avoided if reasonably practicable; detailed investigation and cost/programme benefit justification required; top level approval needed; monitoring essential.
40–125	Unacceptable	Intolerable risk; it is mandatory to undertake risk treatment (e.g. eliminate the source of risk, change the probability and/or consequences, transfer risk).

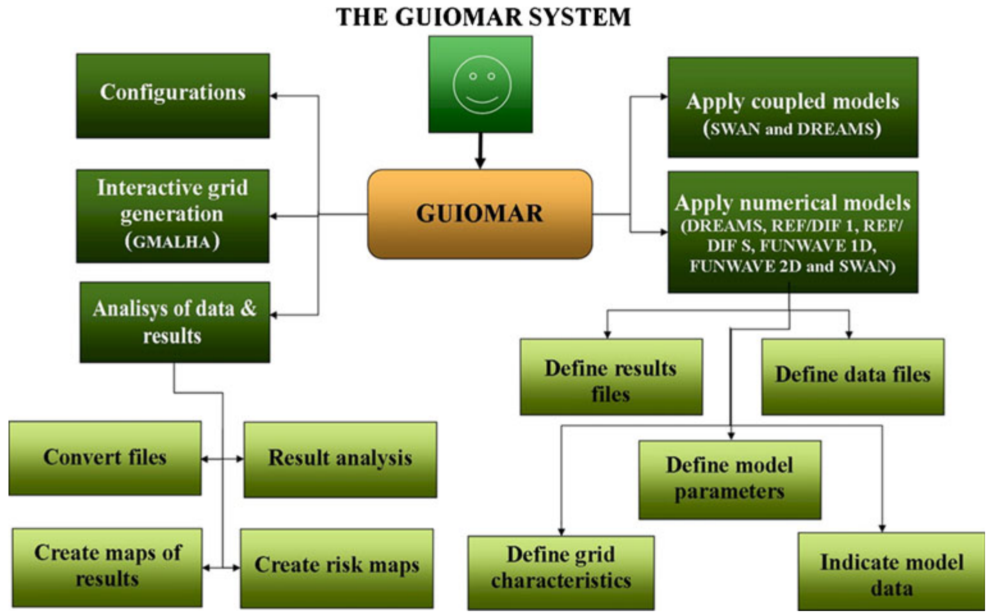

Fig. 2 GUIOMAR operating scheme

format, assigning different flag colours depending on the risk level;

3. *"Export to Google Earth"* – Exports the study points with the respective flag colours into the KMZ Google Earth™ format.

The file created during the risk assessment holds the geographic military coordinates of each study point and the calculated value of risk level.

Case study

The Port of Sines

The Port of Sines was selected to test the latest developments of the GUIOMAR system. This port is located at 37° 57′N and 08° 53′W and is one of the major trade and economic gateways of the Iberian Peninsula so that is considered a port of great geographic and strategic importance to Portugal and Spain, Fig. 5.

At present, there are several sheltering and berthing facilities in the Port of Sines that make it one of the few deepwater European ports that are able to receive large tonnage ships. Due to the large volume of goods handled in the Port of Sines (mainly bulk cargos, both liquid and solid), it has become the first Portuguese port in what concerns annual cargo handled.

Since the objective of the present work is to assess the risk associated with vertical movements of a ship that exceed preset thresholds when entering the Port of Sines, and since these are mainly wave-induced movements, this paper presents the sea wave climate along the ship's trajectory as well as the response of the selected ship to the wave action. Then, the risk assessment methodology (section 2.3.1) is applied.

Sines wave regime

Introduction

To characterize the wave regime along the ship's trajectory into the Port of Sines, data from the wave-buoy "Sines 1-D",

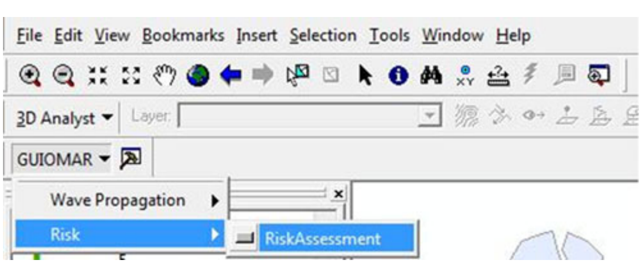

Fig. 3 GUIOMAR toolbar with the risk assessment option

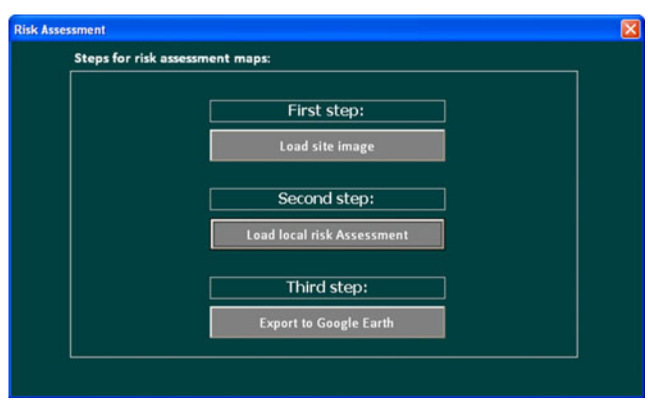

Fig. 4 GUIOMAR graphical interface for the establishment of navigation risk maps

Fig. 5 Port of Sines

located offshore the Port of Sines (37° 55′N and 08° 55′W) were used. The data set has a total of 32 807 records collected between May 1988 and December 2002 (Pinheiro et al. 2004).

These records were transferred into the port using two numerical models for wave propagation and deformation. Indeed, given the different areas of applicability of each model, and considering the sea area of the Port of Sines, it became necessary to couple those two models, Fig. 6.

For this test case, the SWAN (Booij et al. 1999) model was applied to propagate the sea wave conditions measured offshore up to the port entrance. From here, the DREAMS model

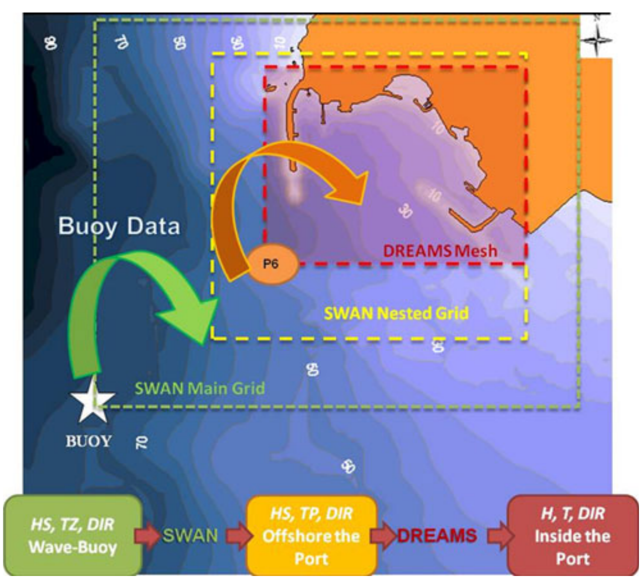

Fig. 6 Methodology to transfer the wave regime from offshore (wave-buoy) into the port

(Fortes 2002) was applied to propagate the predicted local wave conditions into the port. Note that the need for using these two models is a consequence of their own limitations. Within the port, the wave reflection on the port boundaries is one of the phenomena that determine the sea wave characteristics and that it is not properly simulated by SWAN. Thus, there is the need to use the DREAMS model, which takes into account this phenomenon, but that can be used only in small areas due to the computational effort involved.

However, the computation time required to run both models for such a long data series is excessive. The computation time using the two models is about 45 min for each simulation. This means that to perform the full calculation for the 32 807 records it would take several months.

So, following the methodology described at section 2.1, one computes the transfer matrices for each model and then applies the REGIMES program to obtain the wave regime inside the port. Briefly, the steps involved are:

- Calculation of the transfer matrix using the SWAN model, to relate the offshore wave conditions and the ones at the port entrance;
- Calculation of the transfer matrix using the DREAMS model, to relate the entrance wave conditions and the ones inside the port;
- Use of the program REGIMES and of the calculated matrices to obtain the wave characteristics at the desired points (located at the entrance and inside the port) from the wave-buoy data.

The main conditions for the application of each model, the transfer matrices and the wave regime inside the port are described below.

SWAN transfer matrix

Figure 7(a) shows the domain and the bathymetry used to perform calculations with the SWAN model (version 40.41). The bathymetry was build up through bathymetric data from the Portuguese Hydrographical Institute, in particular, the nautical charts PT324204 (December 2005), PT32205 (December 2005) and PT426408 (March 1995).

Two computational meshes were defined. The largest mesh is 8 km by 8 km with a node spacing of 80 m. The second mesh is also square-shaped, with 5 km side and 40 m spacing between nodes. The SWAN computational meshes were built with the GUIOMAR system.

To define the transfer matrix, the SWAN model was executed 2 906 times in advance, one for each of the offshore sea states that resulted from combining: a) 9 different values of the significant wave height (HS) – 1 m to 9 m; b) 17 values of the peak period (TP, where TP was obtained assuming a JONSWAP spectrum with the following TZ-TP relationship: TP=1.27 * TZ) - 4 s to 20 s; and c) 18 equally-spaced values of the peak direction (DIR) - 180° to 360°.

In the SWAN computations, the directional spectrum was defined by a JONSWAP-type spectrum, with a peak enhancement factor γ=3.3, and a directional dispersion function of the type cosine to the power of 20. A frequency discretization of 23 intervals was considered, from 0.04 Hz to 1 Hz, with a directional discretization of 2° covering the 360° range (which gives 180 directional intervals).

All the SWAN runs were carried out in stationary mode, without the presence of currents or wind. The physical phenomena included in the two meshes were: refraction, diffraction, shoaling, wave breaking due to bottom influence and whitecapping, and the triad wave-wave interactions. Both wind and current phenomena were not considered in the calculations due to the small extension of the domain and to the lack of information, respectively.

Figure 7(a) shows the 11 study points defined as SWAN model outputs. In this case, the SWAN transfer matrix from P6 point was used in the subsequent calculations. Note that preliminary calculations showed that P6 point is representative of the wave regime at the port entrance (Neves et al. 2009b).

DREAMS transfer matrix

The DREAMS model was used to propagate the waves from the entrance into the port, considering wave refraction, diffraction and reflection phenomena. The considered computational domain and bathymetry are shown in Fig. 7(b).

The computational domain was discretized with a finite element mesh with 300 139 elements and 151 669 nodes. This finite element mesh was generated with the grid generation module GMALHA (Pinheiro et al. 2006a), a component of the GUIOMAR system.

The incident sea waves were imposed at the south and west boundaries, Fig. 7(b). In the remaining boundaries, the reflection coefficients were calculated according to the method of Seeling and Arens (1995).

The calculations were carried out considering regular waves, wave periods (T) from 5 s to 20 s, with 1 s intervals, and wave directions (DIR) between 180° and 360°, with 20° intervals. A total of 135 combinations (T, DIR) were considered.

DREAMS results were obtained at 7 different points (A, B, C, D, E, F and G), Fig. 7(b), located at the port entrance and inside it. For each of those points, it was possible to define the corresponding transfer matrices.

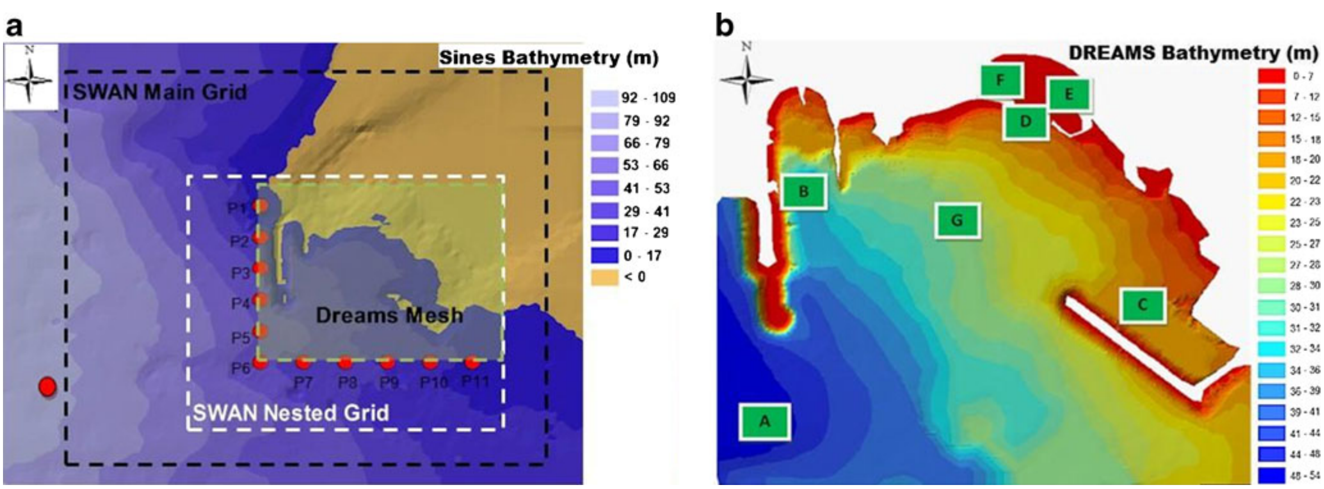

Fig. 7 **a** SWAN bathymetry, computational meshes and results points; **b** DREAMS bathymetry with the location of points A to G at the entrance and inside the port

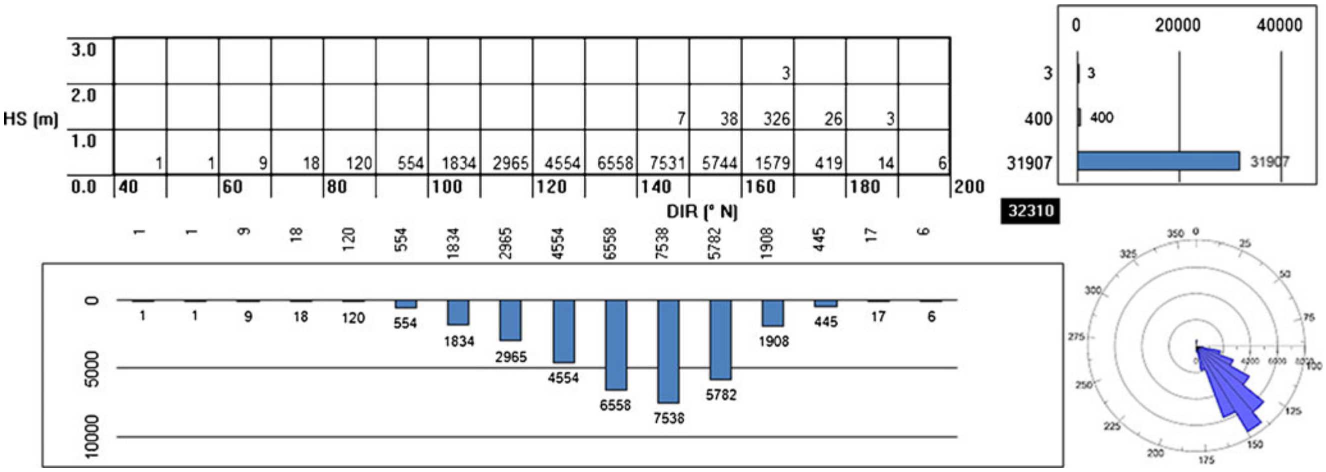

Fig. 8 Wave regime at point B: joint histogram (HS, DIR) and its marginal distributions. Wave direction rose

Wave regime inside the port

By using the two transfer matrices (one associated to the SWAN model and the other associated to the DREAMS model), the REGIMES program enabled the 32 807 offshore data records to be transferred from the wave-buoy to each point at the entrance and inside the port. With this, the wave regime at each point could be established.

Table 5 Sea wave statistical parameters for the wave buoy location and for points P6 and A to G considering data collected between May 1988 and December 2002

Points \ Statistical parameters		Maximum	Average	Minimum	Standard Dev.	Most Frequent Range
Buoy	HS (m)	7.35	1.60	0.27	0.899	[1.0–2.0] (48.05%)
	TP (s)	19.8	8.8	4.2	2.325	[6.0–7.0] (17.78%)
	DIR (°)	358	299	5	18.609	[300–310] (32.68%)
P6	HS (m)	7.04	1.49	0.27	0.811	[1.0–2.0] (49.02%)
	TP (s)	18.9	8.9	4.2	2.248	[9.0–10.0] (22.28%)
	DIR (°)	352	299	180	17.305	[300–310] (34.90%)
A	HS (m)	8.05	1.50	0.15	0.835	[1.0–2.0] (48.60%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.61%)
	DIR (°)	353	299	179	17.218	[300–310] (37.94%)
B	HS (m)	2.20	0.17	0.01	0.204	[1.0–2.0] (98.75%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.61%)
	DIR (°)	198	137	48	17.253	[140–150] (23.30%)
C	HS (m)	2.20	0.17	0.01	0.151	[0.0–1.0] (99.59%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.56%)
	DIR (°)	360	124	0	150.930	[0–10] (19.95%)
D	HS (m)	3.83	0.31	0.01	0.327	[0.0–1.0] (95.72%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.61%)
	DIR (°)	246	220	160	7.734	[220–230] (59.70%)
E	HS (m)	2.54	0.23	0.01	0.220	[0.0–1.0] (98.83%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.49%)
	DIR (°)	244	224	192	6.720	[220–230] (56.45%)
F	HS (m)	0.98	0.05	0.01	0.058	[0.0–1.0] (100%)
	TP (s)	18.9	9.0	5.2	2.208	[9.0–10.0] (25.06%)
	DIR (°)	153	102	46	11.269	[100–110] (37.59%)
G	HS (m)	4.28	0.44	0.01	0.380	[0.0–1.0] (91.77%)
	TP (s)	18.9	8.9	5.2	2.208	[9.0–10.0] (22.59%)
	DIR (°)	314	221	28	35.591	[240–250] (28.83%)

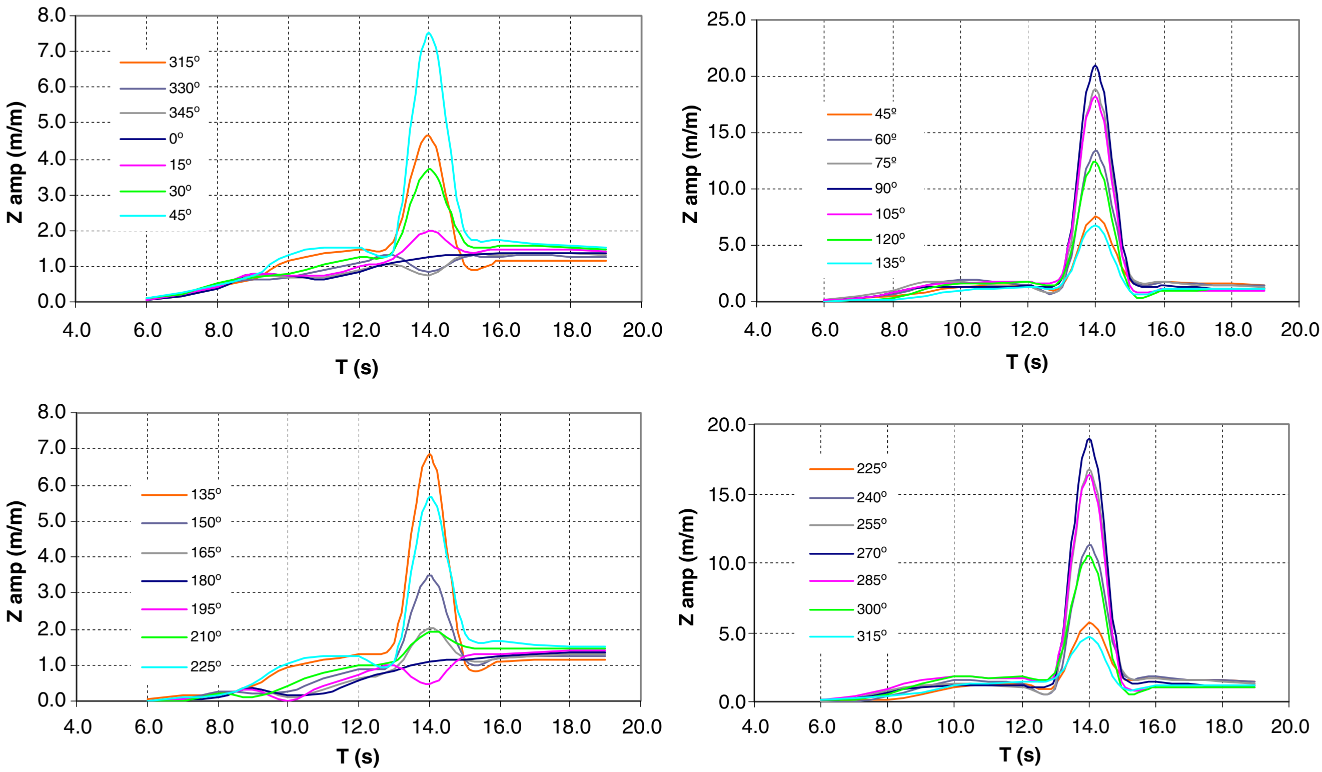

Fig. 9 Variation of point 1 vertical motion amplitude with the period of the incident wave and with the angle between the ship's longitudinal axis and the incident wave direction, when the ship is at a region 42 m deep

As an example, Fig. 8 shows the HS-DIR histogram, its marginal distributions and the wave direction rose obtained at point B (inside the port, close to the West breakwater).

Table 5 presents the values of the statistical parameters (maximum, average, minimum, standard deviation and most frequent range) for the sea wave characteristics both at the buoy location and at each selected point (P6 and A to G), considering data collected between May 1988 and December 2002 (14 years).

The results indicate a clear modification of the sea wave characteristics from point A, near the port entrance, to point F, in the most sheltered part of the port (fishing port).

In fact, in terms of the significant wave height, there is a maximum of 8.05 m at point A (average equal to 1.5 m) while at the entrance of the fishing port (point D) the maximum reduces to 3.83 m (average equal to 0.31 m). As the waves propagate into the port, the HS values decrease, due to the fishing port protection; for instance, at point F they are smaller than 1 m (average 0.05 m). Comparing with point A, the West and East breakwater areas also present relatively small maximum values of significant wave height, just over 2 m.

Regarding the wave directions, the results show a clear rotation from the port entrance to the selected points inside the port. As expected, at the port entrance (point A) there is no significant variation between the wave direction computed for that point and the wave direction measured at the buoy (average direction of 299°). However, close to the West and East breakwaters (points B and C) there is a clear change of the wave direction that depends on the point's location. At the fishing port entrance, point D, the average wave direction is 219° while inside the fishing port, point F, the average wave direction is about 102° and at Sines beach, point E, there is a clear rotation in the opposite direction, reaching an average wave direction of 224°.

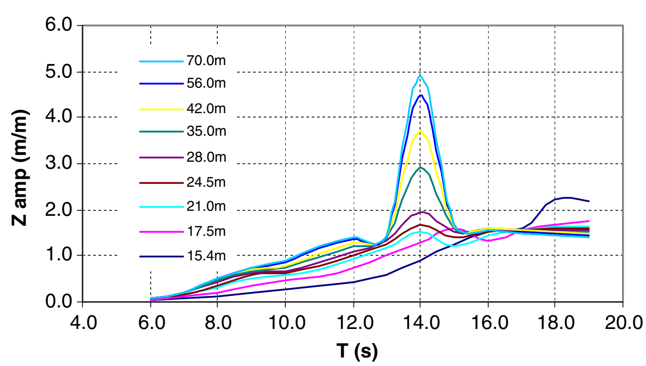

Fig. 10 Variation of point 1 vertical motion amplitude with the period of the incident wave and the water depth of the region where the ship is for an angle of 30° between the ship's longitudinal axis and the incident wave direction

Fig. 11 Modelling scheme for the evaluation of the ship movements and location of the points where the WAMIT results were applied (Google Earth™ image)

Ship motion evaluation

The studied ship has a displacement of 122 714 kg, a length of 236 m, a beam of 43 m and a draught of 14.1 m. Point 1 in Fig. 1, whose coordinates are (-106.2, -15.2, 0), was considered as the test point. This point was selected because it is expected to be one of the hull points with the largest vertical movement due to the combination of the pitching and the heave motions.

WAMIT computations were carried out for incident monochromatic waves whose period (T) ranged from 6 s to 19 s with 1 s steps, the wave direction (DIR) ranged from 0° to 360°, with 15° steps, for nine different values of the water depth (DEP) such that the draught/water depth ratio ranged from 1.1 to 5.0. This resulted in a grand total of 3 024 different values of (T, DIR, DEP).

Figure 9 depicts for a water depth of 42.0 m (approximately 3 times the ship draught) the variation of the vertical motion amplitude at point 1 with the incident wave period and the angle between the ship's longitudinal axis and the wave direction. It is clear in those plots, one per quadrant, that beam waves and nearly beam waves (angles between the ship's longitudinal axis and the wave number vector from 45° to 135° and from 225° and 315°) are the ones that make large amplitudes of the motion vertical component for the selected point. In those angle ranges it is the rotation around the x-axis (roll) and the low ship inertia around the same axis the major cause for such large amplitude.

Figure 10 presents the evolution with the water depth of the motion vertical component amplitude for an angle of 30° of the ship longitudinal axis to the wave direction. It may be concluded from that figure that, for each wave period, apart from periods around 14 s, as the water depth increases the motion amplitude approaches a constant value.

In conclusion, to evaluate the amplitude of the ship's vertical motion at each stretch of the region that may be swept in the journey, one has to know the sea wave characteristics obtained with the numerical models SWAN and DREAMS at the centres of gravity of those stretches, namely points P6, A and B, Fig. 11.

Risk assessment using the GUIOMAR system

This section presents the application to the Port of Sines of the new methodology/tool for risk assessment in port navigation, which takes into account only the vertical movement of a selected point in a ship. As mentioned previously, the ship vertical movements are problematic mainly due to the risk of grounding. Usually this is not a major problem in a deep water port, like the Port of Sines. However, the aim of this application is related to the analysis of the utility of the methodology/tool itself and not its applicability to a navigation route in the vicinity of the West breakwater of the Port of Sines.

Once the sea wave climate (based on 14 years of data) at the three points along the ship's trajectory (P6, A and B;

Table 6 Risk assessment associated with vertical movements of a ship that exceed the pre-set threshold of 1 m

Points	Probability	Consequences	Risk (Probability × Consequences)
P6	Occasional (10–25%): Level 3	Serious: Level 5	Undesirable: Level 15
A	Occasional (10–25%): Level 3	Critical: Level 10	Undesirable: Level 30
B	Occasional (10–25%): Level 3	Catastrophic: Level 25	Unacceptable: Level 75

Fig. 12 Navigation risk map at the Port of Sines (points P6, **a** and **b**) associated with vertical movements of a ship that exceed the pre-set threshold of 1 m

Table 6) was defined and the corresponding ship's vertical movements were calculated, the risk assessment methodology (presented in section 2.3.1) was applied. First, a threshold of 1 m was chosen for the amplitude of the ship's vertical movement. This threshold of 1 m was chosen arbitrarily. Second, for each point along the ship's trajectory, the number of sea states, from the 14 years of data, for which the ship's vertical movements exceeded the threshold was counted and the corresponding probability of exceedance was evaluated. Third, by using Tables 1 and 2 for each point along the ship's trajectory, the risk associated with the vertical movements of the ship that exceeded the 1 m threshold was assessed considering the probability and the consequence levels obtained at the three points (Table 6).

The results show that, at points P6 and A, the risk is undesirable, whereas at point B it is unacceptable. Figure 12 shows the corresponding risk map established using the risk assessment maps module of the GUIOMAR integrated system. In the figure, the colour of the flags represents the colour associated with the risk level established for each point (Table 6).

Conclusions and future developments

This paper presents recent developments to GUIOMAR, an integrated system for port and coastal engineering modelling. A set of automatic procedures was developed for implementing a methodology for risk assessment in port navigation. To illustrate and test the new procedures, wave records from 1988 to 2002 of the Sines wave-buoy were transferred into several points inside Sines Port using two numerical models for sea wave propagation and deformation (SWAN and DREAMS), included in the GUIOMAR system. The numerical model WAMIT was used to study the wave-induced ship movements at three points of the ship's trajectory in the vicinity of Sines West breakwater. Finally, the risk level was established, based on the combination of the probability of exceedance of pre-set thresholds for the ship's vertical movements at these three points and of its consequences, and risk maps were generated.

The recent developments in the GUIOMAR system are a step forward in the implementation of a methodology for risk assessment in port navigation using the numerical simulation of scenarios based upon historical sea wave data.

A testing of the new functionality of GUIOMAR, using the case study of the Port of Sines, confirmed that this integrated system is a valuable tool for port engineering studies and an important tool for supporting decision-making processes in port and coastal management.

In this application, the ship behaviour was analysed for monochromatic waves only. Since it is a well known fact that irregular waves have a significant effect in the sailing ship response, this will certainly be taken into account in future developments. Moreover, the choice of thresholds for the ship's vertical movements, which was done arbitrarily in this work, will be improved by considering PIANC methodology for depth design of approach channels (PIANC 1997). The comparison of forecast results to prototype measurements will also be valuable to improve the reliability of the integrated tool.

Finally, the newly developed module for risk assessment in port navigation will be extended to include risk assessment of overtopping of port structures, of mooring operations and of ship loading and unloading operations. Also the enhancement of the automatic and interactive visualization of data, of the model results and of risk maps are foreseen improvements of this system.

Acknowledgements The authors gratefully acknowledge the financial support of Fundação para a Ciência e a Tecnologia, Portugal, through projects PTDC/AMB/67450/2006, PTDC/ECM/67411/2006 and PTDC/ECM/73145/2006.

References

Booij N, Ris RC, Holthuijsen LH (1999) A third-generation wave model for coastal regions, Part I, model description and validation. J Geophys Res 104(C4):7649–7666

Dalrymple RA, Kirby JT (1991) REF/DIF 1. Version 2.3 Documentation manual. Combined refraction/diffraction model. CACR Report n.° 91–2, University of Delaware

Fortes CJEM (2002) Nonlinear wave transformations in harbours. A Finite element analysis. Ph.D thesis, Mechanical Engineering, IST (in Portuguese)

Kirby JT, Ozkahn HT (1994) REF/DIF S Version 1.1 documentation and users manual. CACR Report n.° 94–04, University of Delaware

Kirby JT, Wei G, Chen Q, Kennedy AB, Dalrymple RA (1998) FUNWAVE 1.0 – fully nonlinear Boussinesq wave model documentation and user's manual. Research Report No.CACR-98–06, Center for Applied Coastal Research, University of Delaware

Neves DRCB, Zózimo AC, Pinheiro LV, Fortes CJEM (2009a) GUIOMAR: geo(graphical) user interface for coastal and marine modeling. Supported decision system. J Coast Res, SI 56 (Proc. 10th International Coastal Symposium), pp 1542–1546

Neves DRCB, Zózimo AC, Pinheiro LV, Fortes CJ (2009b) GUIOMAR: new developments and application to Sines harbour. Proc. 6ªs Jornadas Portuguesas de Engenharia Costeira e Portuária, Funchal, 8 and 9 of October (CD-Rom) (in Portuguese)

New Zealand Maritime Safety Authority (2004) New Zealand port & harbour marine safety code

Newman JN, Sclavounos PD (1988) The computation of wave loads on large offshore structures. Proc. BOSS 88, Norway, pp 1–19

Palha AC (2007) pyMOIA – Real time predicting for sea waves in port areas. Proc. 5ªs Jornadas Portuguesas de Engenharia Costeira e Portuária, Lisbon, 11 and 12 of October (in Portuguese)

PIANC (1997) Approach channels. A guide for design. PTC II-30 final report of the joint working group PIANC and IAPH, in cooperation with IMPA and IALA. Supplement to Bulletin no 95

Pinheiro LV, Coli AB, Capitão R, Santos JA (2004) Sea wave characterization of the port of Sines west breakwater. Extreme wave regime and events. Report 370/04- NPE, Lisbon, November (in Portuguese)

Pinheiro LV, Fernandes JLM, Fortes CJEM (2006a) A finite element mesh generator with bathymetry conditionated local density for wave propagation models in port zones. Proc. I Conferência Nacional de Métodos Numéricos em Mecânica dos Fluidos e Termodinâmica, Lisbon, 8 and 9 of June (in Portuguese)

Pinheiro LV, Fortes CJEM, Santos JA, Neves MG (2006b) Wave regime characterization using SOPRO tool. Proc. 8°Congresso da Água, Figueira da Foz, 13 to 17 March (in Portuguese)

Seeling WN, Arens JP (1995) Wave reflection and energy dissipation by coastal structures. In: Koboyashi N (ed) Wave forces on inclined and vertical wall structures. ASCE, pp 28–55