Methodology for overtopping risk assessment in port areas. Application to the Port of Praia da Vitória (Azores, Portugal)

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Abstract

In this paper, a methodology to assess the risk associated with wave overtopping in port areas is presented. The methodology is implemented in the GUIOMAR system, which is an integrated system for port and coastal engineering modelling, developed in a GIS commercial software. The overtopping determination is performed by using empirical tools. To assess the risk of overtopping, the combination of the probability of occurrence of an event of wave overtopping and of the consequences of that occurrence is considered. The paper illustrates the application of this methodology to the Port of Praia da Vitória, at the Terceira Island, Azores Archipelago, considering the sea-wave conditions between 2009 and 2010.

Keywords: Wave overtopping, Risk assessment, Geographic information systems, Numerical models, Port of Praia da Vitória

1 Introduction

The length of the Portuguese coast, the severity of the sea conditions and the importance of the coastal zone regarding the socio-economic activities, justify the relevance of studying wave-induced risks, and in particular, overtopping due to wave action. Indeed, emergency situations caused by adverse sea conditions are frequent and put in danger the safety of people and goods, with negative impacts for society, the economy and the environment. Therefore, a methodology to assess the overtopping risk in port or coastal areas is essential for a proper planning and management of these areas. A detailed characterization of tide levels, currents and sea waves is essential to improve the risk assessment methodologies, increasing the reliability of the results, enabling the issue of warnings and supporting the preparation of mitigation plans.

In this context, the National Laboratory for Civil Engineering (LNEC) has been developing two integrated decision support tools for port and coastal management, whose focus is to prevent and support the management of emergency situations (MOIA system) and the long-term planning of interventions in the study area (GUIOMAR system).

The MOIA system (Santos *et al.*, 2008, 2011) is a real-time tool to evaluate sea-wave action and its effects on port and coastal activities and to issue warning messages whenever the safety of such activities are deemed to be at risk. In this system, the wave regime characteristics are determined 1 or 2 days in advance, using numerical models that forecast the wind generated sea waves at a regional scale. The corresponding consequences for port and coastal activities (e.g. for navigation) are defined using empirical formulae or numerical models. This *a priori* knowledge of the characteristics of the waves and their consequences allows timely issues of warnings to the relevant authority members when there is a possibility of occurrence of emergency situations (short-term management).

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The GUIOMAR system (Zózimo *et al.*, 2008; Neves *et al.*, 2009, 2010) is an integrated system based on a geographic information system (GIS) for the management of numerical wave propagation models in port and coastal areas that enables the user to calculate the risk for various port and coastal activities, based on the sea-wave characterization. This system is intended as a tool for long-term planning. Therefore, using long term (years) time series for the sea wave characteristics, the system evaluates the sea-wave consequences for the activities, allowing the construction of GIS based risk maps. These maps aim to support decision-making of the responsible entities regarding long-term management.

These systems have already been tested for the navigation risk in two Portuguese ports: the GUIOMAR system has been used to create risk maps in the Port of Sines (Neves *et al.*, 2010) and the MOIA warning system has been tested for the Port of Praia da Vitória (Santos *et al.*, 2011).

The GUIOMAR system has also been tested for flood risk assessment in Vale do Lobo beach, in the Algarve, Portugal. A methodology is implemented for the run-up calculation on beaches and coastal defence structures, for the estimation of the corresponding flood levels and for the creation of flood risk maps. This methodology applies empirical formulations based on experimental or field data (Raposeiro *et al.*, 2010).

This paper focus on the prediction of wave overtopping of maritime structures for risk assessment purposes using the GUIOMAR system. Section 2 describes the case study and section 3 presents the three main steps of the methodology for overtopping risk assessment: the sea wave characterization, the prediction of overtopping and the risk assessment, including the preparation of risk maps. The paper closes with some conclusions and directions for future work (section 4).

2 Study Area

The Port of Praia da Vitória, Figure 1, is located at the Terceira Island, the second largest of the Azores archipelago.

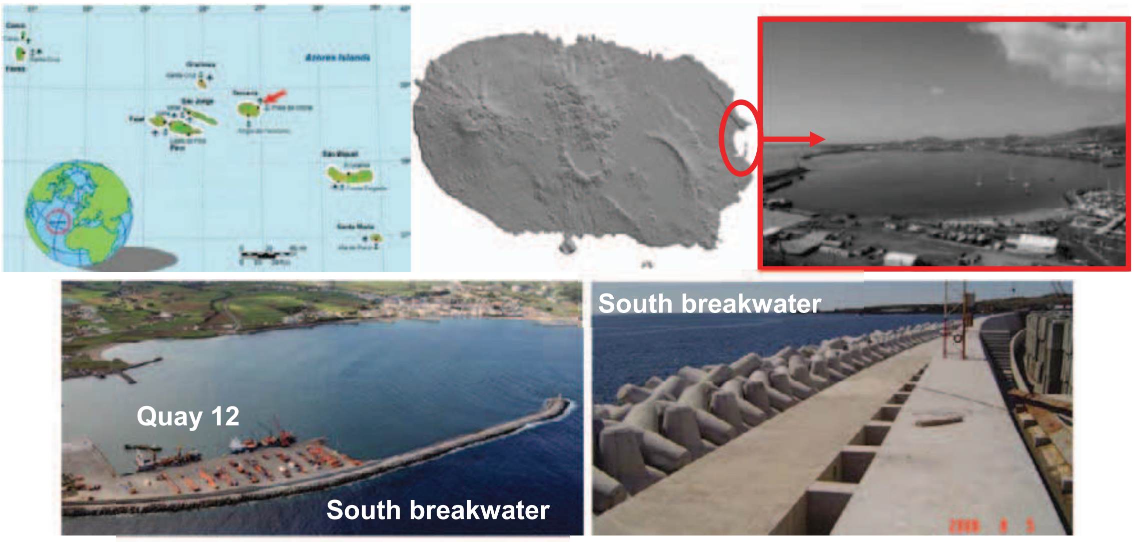


Figure 1: Azores, Terceira Island, Port of Praia da Vitória, south breakwater and quay 12

The port basin, which is approximately 1 km x 2 km, is protected by two breakwaters: the north and the south breakwaters. The south breakwater directly protects quay 12 (Figure 1).

In the port area, there are now several measuring devices that can characterize the sea wave regime within the port. In fact, within the scope of the CLIMAAT project, a directional wave-buoy was installed 4 km northeast from the port, in a region 100 m deep, which was used to validate the methodology for wave propagation applied in this study.

3 Methodology

The methodology implemented in the GUIOMAR system to assess the risk of overtopping of the south breakwater of the Port of Praia da Vitória, and especially at quay 12, follows three main steps (Figure 2):

1. Sea wave characterization at the breakwater;
2. Determination of wave overtopping over the breakwater;
3. Overtopping risk assessment.

The next sections describe in more detail each of these three steps and the GUIOMAR system.

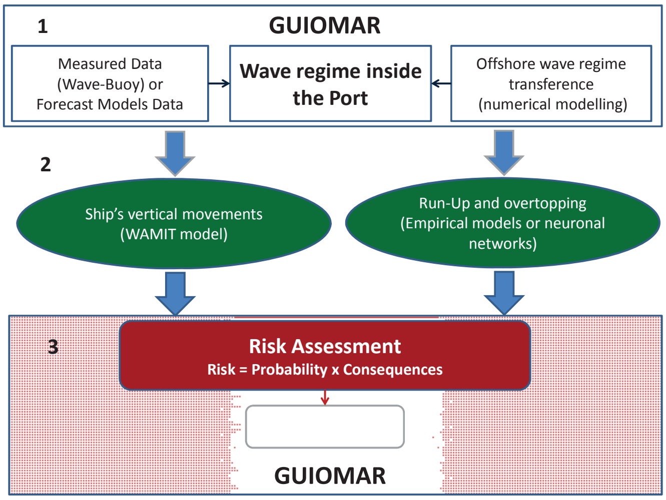


Figure 2: Methodology for risk assessment implemented in the GUIOMAR system

3.1 Sea wave characterization (GUIOMAR)

For the sea wave characterization at the studied port, two years of sea wave characteristics predicted offshore by WAVEWATCH III (WWIII), a third generation wave model developed at NOAA/NCEP (Tolman, 1999), were propagated onshore, first with the spectral wave model SWAN (Booij *et al.*, 1999) up to the port entrance (point P1) and from there into the port with the mild slope wave model DREAMS (Fortes, 2002) (Figure 3). Point P19, located in front of the south breakwater, was pre-defined as an output point for the DREAMS model to determine the wave characteristics at the breakwater section that directly protects quay 12. Figure 3 presents the time series of significant wave height (HS) for point P19 in the study period (January 2009 to December 2010). The reason for coupling two wave propagation models was the lack of a single model that can simulate, in a computationally efficient way, the spread of the wave climate in this vast region, taking into account all the relevant phenomena.

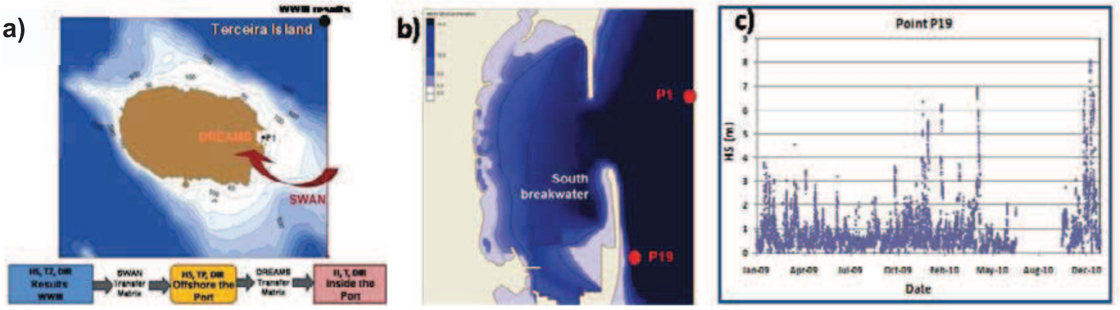


Figure 3: (a) Coupling scheme for the numerical models; (b) point P1 (SWAN) and studied point P19 in front of the south breakwater; (c) Hs (m) for the two-years at P19

The numerical simulations were made for a constant water level of +1.4 m (ZH), which is the sum of a mean water level of +1.0 m (ZH) and a storm surge of 0.4 m.

The sea wave characterization was carried out using the GUIOMAR system (Neves *et al*., 2009, 2010), which 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^{TM}. It has three main components (Figure 4): the GIS software; a set of 6 modules corresponding to different wave propagation and deformation models with different domains of application; and 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: i) the execution of the models; ii) the pre- and post-processing of the data and of the model results; and iii) the use of the capabilities inherent to the GIS software, for instance to analyse and visualise data and results in both 2D and 3D.

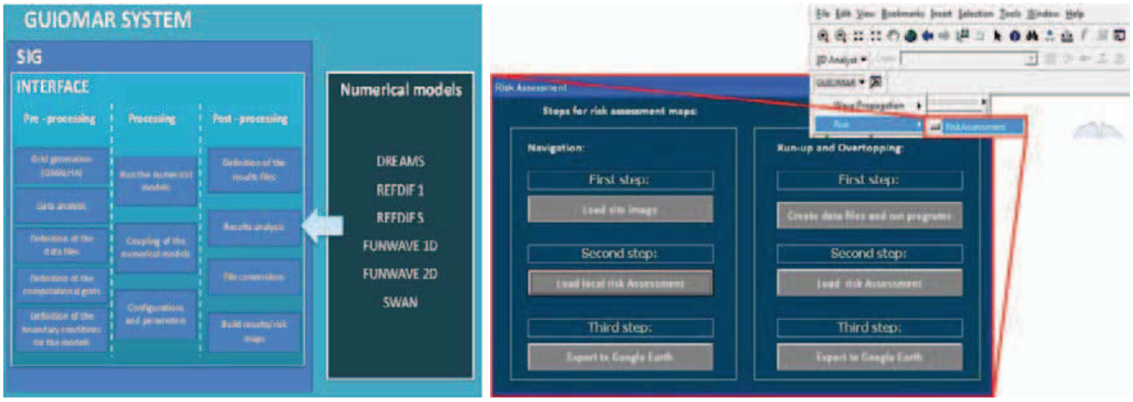


Figure 4: The GUIOMAR system and its toolbar for risk assessment

The modular nature of the system enables its easy expansion and upgrade, such as including more advanced models that may tackle different physical processes. The 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.

The latest development to GUIOMAR includes a module to automatically produce risk maps based on the methodology presented in section 3.3. Figure 4 shows the GUIOMAR toolbar used to access the risk maps production area.

3.2 Overtopping Determination

In this study, the overtopping determination was performed by using the tool NN_OVERTOPPING2, which is a prediction tool based on neural network (NN) modelling, developed as part of the CLASH European project (Coeveld *et al.*, 2005) to predict Froude-scaled mean wave overtopping discharges, q, and the associated confidence intervals for a wide range of coastal structure types (such as dikes, rubble mound breakwaters, and caisson structures). In addition, prototype mean overtopping estimations, allowing for scale and model effects, are provided.

The results from this tool are built on a database of about 8400 tested conditions from small-scale physical model tests at many different laboratories. The method uses fifteen input parameters, which include three about the wave conditions (the spectral significant wave height at the toe of the structure, H_{m0}; the mean spectral wave period at the toe of the structure, $T_{m-1,0}$; and the direction of wave attack, β) and twelve on the geometry of the structure (the water depth in front of the structure, h; the water depth on the toe of the structure, h_t; the width of the toe, B_t; the roughness / permeability of the armor layer, γ_f; the slope of the structure downward of the berm, $\cot\alpha_d$; the slope of the structure upward of the berm, $\cot\alpha_u$; the width of the berm, B; the water depth on the berm, h_b; the slope of the berm, $\tan\alpha_b$; the crest freeboard of the structure, R_c; the armor crest freeboard of the structure, A_c; and the crest width of the structure, G_c).

In this work, the mean overtopping discharge per unit length of structure, q, of the breakwater section that directly protects quay 12 (Figure 5) was calculated using the two years of wave data obtained at point P19 (Figure 3c). For this section of the breakwater and for a water level of +1.4 m (ZH), $h=h_t=19.4$m, $B_t=0.0$m, $\cot\alpha_d=4.3$, $h_b=10.15$m, $B=0.0$m, $\tan\alpha_B=0$, $\cot\alpha_u=1.5$,

A_c=7.2m, R_c=9.6m and γ_f=0.35 (tetrapod armour layer with a wave return wall - Coeveld *et al.*, 2005). Since the crest berm does not have the same configuration throughout its width, the value of q considered for the cross-section of the breakwater for each sea-state condition (H_{m0}, $T_{m-1,0}$, β) was obtained from the average of two values of q calculated with the NN_OVERTOPPING2 for G_c=8m and G_c=16m.

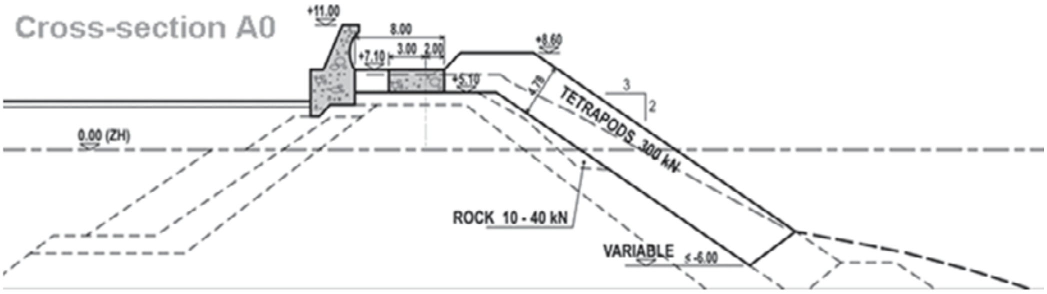


Figure 5: Cross-section of the south breakwater that directly protects quay 12

Figure 6 shows the calculated values of q for the two years of wave data obtained at point P19. The figure also shows $gHST_{m-1,0}$ (with $HS=H_{m0}$), a parameter commonly used to non-dimensionalise q (Reis, 1998).

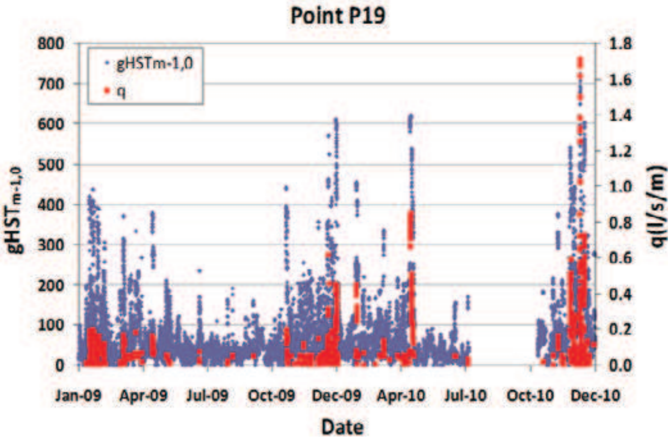


Figure 6: Overtopping calculation for the breakwater section that directly protects quay 12 using NN_OVERTOPPING2 and the two years of wave data obtained at point P19

3.3 Risk assessment

After determining the mean overtopping discharges, q, of the breakwater section that directly protects quay 12 for the two years of wave data obtained at point P19, a qualitative assessment of the risk of overtopping was carried out by applying the following methodology, which is based on five main steps:

- Definition of acceptable thresholds for the values of q based on the Pullen et al. (2007) guidance;
- Development of a table of probability of exceedance of the pre-set thresholds of q (Table 1) and establishment of the level of probability for the different thresholds;
- Development of a table of consequences of exceedance of the pre-set thresholds of q (Table 2) and establishment of the level of consequences for the different thresholds;
- Combination of the values of the levels of probability and of consequences to obtain the risk level associated with the different pre-set thresholds, considering that the level of risk is the product of the two other levels (Table 3);
- Production of risk maps and analysis of risk acceptability (Figure 7).

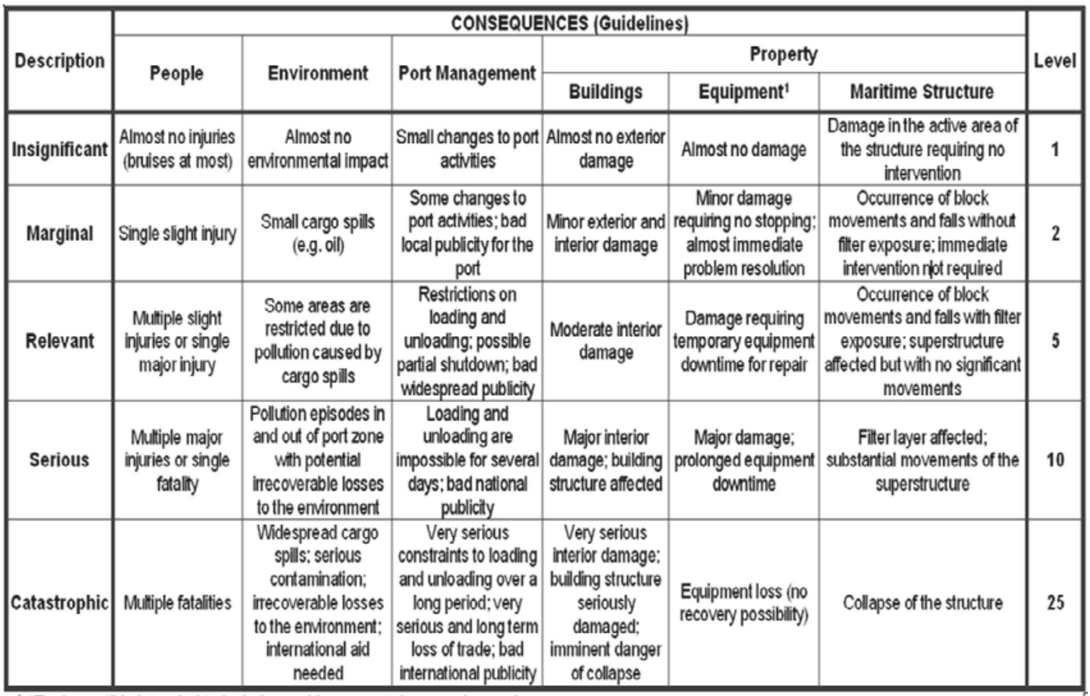
The probability of exceedance was evaluated by using a frequency approach, i.e. by dividing the number of sea states for which overtopping exceeded a pre-set threshold by the total number of sea states in the 2-years wave regime for which the overtopping was computed.

Table 1: Probability of exceedance of overtopping pre-set thresholds

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

The table of consequences was developed in straight collaboration with the port authority and has taken into account the consequences for human lives, the environment, the port management and the property. The levels of 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. 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.

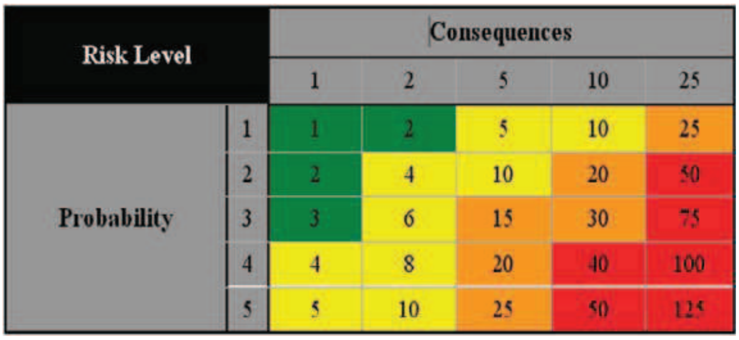
Table 2: Table of consequences (guidelines)



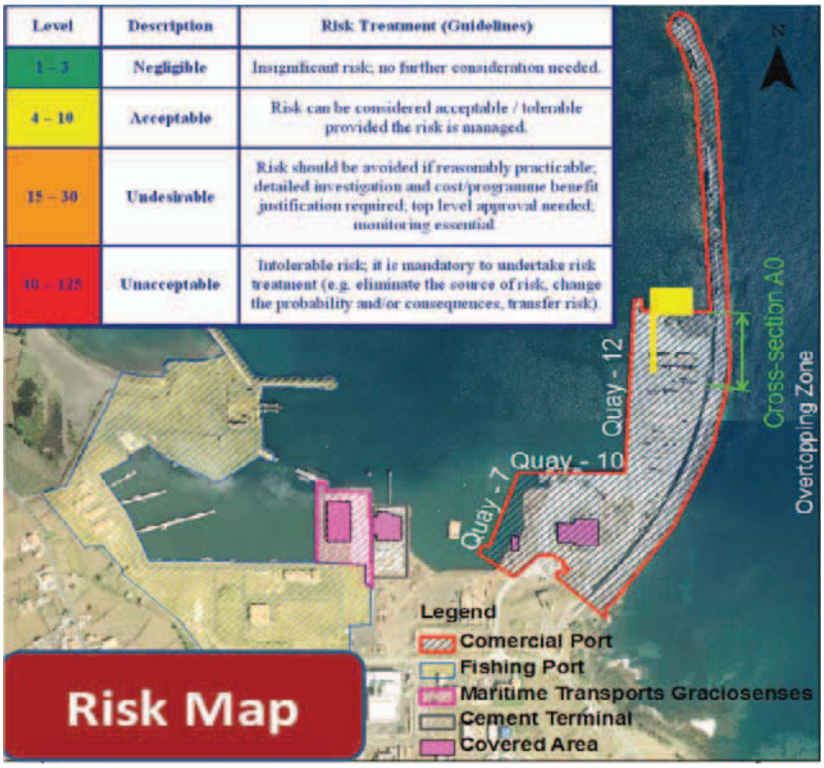
Description	**CONSEQUENCES (Guidelines)**						**Level**
	People	**Environment**	**Port Management**	**Property**			
				Buildings	**Equipment[1]**	**Maritime Structure**	
Insignificant	Almost no injuries (bruises at most)	Almost no environmental impact	Small changes to port activities	Almost no exterior damage	Almost no damage	Damage in the active area of the structure requiring no intervention	**1**
Marginal	Single slight injury	Small cargo spills (e.g. oil)	Some changes to port activities; bad local publicity for the port	Minor exterior and interior damage	Minor damage requiring no stopping; almost immediate problem resolution	Occurrence of block movements and falls without filter exposure; immediate intervention not required	**2**
Relevant	Multiple slight injuries or single major injury	Some areas are restricted due to pollution caused by cargo spills	Restrictions on loading and unloading; possible partial shutdown; bad widespread publicity	Moderate interior damage	Damage requiring temporary equipment downtime for repair	Occurrence of block movements and falls with filter exposure; superstructure affected but with no significant movements	**5**
Serious	Multiple major injuries or single fatality	Pollution episodes in and out of port zone with potential irrecoverable losses to the environment	Loading and unloading are impossible for several days; bad national publicity	Major interior damage; building structure affected	Major damage; prolonged equipment downtime	Filter layer affected; substantial movements of the superstructure	**10**
Catastrophic	Multiple fatalities	Widespread cargo spills; serious contamination; irrecoverable losses to the environment; international aid needed	Very serious constraints to loading and unloading over a long period; very serious and long term loss of trade; bad international publicity	Very serious interior damage; building structure seriously damaged; imminent danger of collapse	Equipment loss (no recovery possibility)	Collapse of the structure	**25**

[1] "Equipment" is intended to include machinery, containers and vessels.

Table 3: The 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



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).

Figure 7: Risk map for wave overtopping in the south breakwater of the Port of Praia da Vitória

4 Conclusions

This paper presents recent developments to GUIOMAR, an integrated system for port and coastal engineering modelling. A set of automatic procedures was developed to implement a methodology for overtopping risk assessment in port areas. To illustrate and test the new procedures, offshore wave predictions from 2009 and 2010 of the WAVEWATCH III third generation wave model were transferred into several points inside the Port of Praia da Vitória, Azores, Portugal, using two numerical models for sea wave propagation and deformation (SWAN and DREAMS), included in the GUIOMAR system. The tool NN_OVERTOPPING2, based on neural network analysis, was used to study the mean wave overtopping for the south breakwater section that directly protects quay 12. Finally, the risk level was established, based on the combination of the probability of exceedance of pre-set thresholds for wave overtopping 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 the overtopping risk assessment in port and coastal areas using the numerical simulation of scenarios based upon historical sea wave data.

A test of the new functionality of GUIOMAR, using the case study of the Port of Praia da Vitória, confirmed that this integrated system is a valuable tool for port and coastal engineering studies and an important tool for supporting decision-making processes in port and coastal management. However, the comparison of forecast results to prototype measurements is essential to improve the reliability of the integrated tool.

5 Acknowledgements

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6 References

Booij, N.; Ris, R.C.; Holthuijsen L.H. (1999): A third-generation wave model for coastal regions, Part I, Model description and validation. In Journal of Geophysical Research, 104(C4), pp. 7649-7666.

Coeveld, E.M.; Van Gent, M.R.A.; Pozueta, B. (2005): Neural Network. Manual NN_OVERTOPPING 2. CLASH WP8, WL | Delft Hydraulics, Delft, The Netherlands June.

Fortes, C.J.E.M. (2002): Nonlinear wave transformations in harbours. A Finite element analysis. PhD thesis, Mechanical Engineering, IST (in Portuguese).

Neves, D.R.; Rodrigues, S.; Reis, M.T.; Fortes, C.J.E.M.; Santos, J.A. (2010): Application to the Port of Sines (Portugal) of a new methodology for risk assessment for harbour navigation based upon the GUIOMAR system. In Journal of Integrated Coastal Zone Management, 10, 4, pp. 483-504. ISSN 1646-8872 (In Portuguese)

Neves, D.R.C.B; Zózimo, A.C.; Pinheiro, L.V.; Fortes, C.J.E.M. (2009): GUIOMAR: Geo(graphical) User Interface for cOastal and MARine Modeling. Supported Decision System. In Journal of Coastal Research, SI 56, pp. 1542-1546.

Pullen, T.; Allsop, N.W.H.; Bruce, T.; Kortenhaus, A.; Schuttrumpf, H.; Van Der Meer, J.W. (2007): EurOtop: Wave Overtopping of Sea Defences and Related Structures: Assessment Manua, Environment Agency, UK, Expertise Netwerk Waterkeren, NL, and Kuratorium fur Forschung im Kusteningenieurwesen, DE, August.

Raposeiro, P.D.; Fortes, C.J.E.M.; Reis, M.T.; Ferreira, J.C. (2010): Development of a methodology to evaluate the flood risk at the coastal zone. In Geographic Technologies Applied to Marine Spatial Planning and Integrated Coastal Zone Management, Calado, H. e Gil, A. (Eds.), Universidade dos Açores – Centro de Informação Geográfica e Planeamento Territorial, August, pp. 129-137. ISBN: 978-972-8612-64-1.

Reis, M.T. (1998): Probabilistic Assessment of the Safety of Coastal Structures. PhD thesis, Department of Civil Engineering, University of Liverpool, UK, January.

Santos, J.A.; Guilherme, L.; Fortes, C.J.E.M.; Palha, A.; Simões, A. (2008): Methodology for wave forecast in the MOIA package. In O Sector Marítimo Português, Edições Salamandra, Lda., Lisbon. (In Portuguese)

Santos, J.A.; Rodrigues, S.; Neves, D.R.; Vieira, A.; Fortes, C.J.E.M.; Reis, M.T.; Simões, A.; Azevedo, E.B. (2011): MOIA: an integrated decision support tool for port management, in Proc. ISCRAM 2011, 8th International Conference on Information Systems for Crisis Response and Management: From early-warning systems to preparedness and training, 8-11 May, LNEC, Lisbon.

Tolman, H.L. (1999): User manual and system documentation of WAVEWATCH-III version 1.18. NOAA / NWS / NCEP / OMB technical note 166, 110 pp.

Zózimo, A.C.; Fortes, C.J.E.M.; Neves, D.R.C.B. (2008): GUIOMAR: Geographical User Interface for cOastal and MARine modeling. Recent developments and assessment of potential geographical errors, in Proc. Med Days of Coastal and Port Eng., Palermo, 7-9 October.