A METHODOLOGY FOR OVERTOPPING RISK ASSESSMENT IN PORT AREAS. APPLICATION TO THE PORT OF PRAIA DA VITÓRIA (AZORES, PORTUGAL)

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Abstract

A methodology to assess the risk associated with wave overtopping in port areas is presented. The methodology is implemented in the HIDRALERTA system, which is an integrated system for port and coastal engineering modelling developed in a GIS commercial software. The evaluation of mean overtopping discharge per unit length of the structure crest is performed by using tools based on neural network analysis. 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 several structures along Praia da Vitória port and bay, at the Terceira Island, Azores, Portugal, considering sea-wave conditions predicted for the period between 2008 and 2012 and taking into account wind effect, as well as tide level influence on sea-wave propagation.

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, do 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 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), Portugal, has been developing the HIDRALERTA system, which is a set of integrated decision support tools for port and coastal management, whose focus is to prevent and support the management of emergency situations and the long-term planning of interventions in the study area.

HIDRALERTA is an upgrade of the GUIOMAR system (Neves *et al*., 2009, 2010), which is 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 sea-wave characterization. This system is intended as a tool for long-term planning. Therefore, using long-term (years) time series for 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.

This system has already been tested for flood and wave overtopping risk assessment at different

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places in Portugal: Vale do Lobo beach, in the Algarve, and port of Praia da Vitória, in the Azores islands.

For Vale do Lobo beach, empirical formulations, based on experimental or field data, were used to calculate run-up on beaches and coastal defence structures and the corresponding flood levels (Raposeiro *et al*., 2010), while for port of Praia da Vitória, neural network tools were applied for overtopping calculations, which give an estimate of mean overtopping discharges per unit length of the structure crest (Neves *et al*., 2012).

In both cases, flooding and overtopping risk assessment was carried out by (i) the determination of probability levels associated to flooding or overtopping events that exceed pre-determined thresholds; (ii) the establishment of the levels of consequences associated to the occurrence of flooding or overtopping that exceeds those thresholds; and (iii) the combination of the above steps to assess flooding and overtopping risk levels, which are the product of the probability levels by the consequence levels.

In the case of Praia da Vitória, this methodology was applied to three cross-sections of maritime structures: the south breakwater stretch that protects quay 12; the root of groyne number 3 of the bay groyne field; and a typical cross-section of the bay seawall. Only a two-year period (2009 and 2010) with sea-wave information was considered, Rocha *et al*. (2013). A larger period with sea-wave information (5 years) is considered in this paper, extending previous work and including wind effect and tide level variation on sea-wave propagation. The overtopping risk assessment methodology is applied to eight structure stretches along Praia da Vitória bay and port and risk maps are built to provide information on bay and port regions where mitigation actions may be implemented.

After this introduction, section 2 presents the three main steps of the methodology for overtopping risk assessment: sea-wave characterization, overtopping determination and risk analysis, including the preparation of risk maps. Section 3 describes the case study and the application of the overtopping risk assessment methodology. The paper closes with some conclusions and directions for future work (section 4).

2. Methodology

The methodology implemented in the HIDRALERTA system to assess overtopping risk follows three steps: I - Sea-wave characterization; II - Wave overtopping determination; III - Overtopping risk analysis. The next sections describe in more detail each of these three steps.

2.1. Step 1: Sea-wave characterization

The sea-wave regime within a port can be obtained from sea-wave data measured in situ (with wave buoys, for example) or it can be defined with numerical models for sea-wave propagation. In the first case, the sea-wave regime is the result of buoy data only. In the second case, numerical models are employed to transfer into the harbour region the offshore sea-wave regime (obtained either from offshore data measured close to the study region or from other numerical models that predict sea waves from wind fields at a regional level).

The use of one or more numerical models for sea-wave propagation depends on the study region characteristics (for example, the size of the computational domain) and on the phenomena involved in wave propagation. In this study, numerical models SWAN (Booij *et al*., 1999) and DREAMS (Fortes, 2002) were applied to the results of WAVEWATCH III (Tolman, 1999), a numerical model for sea-wave prediction at regional level.

2.2. Step 2: Overtopping determination

A predictive tool based on neural network modelling, NN_OVERTOPPING2, was employed to evaluate overtopping. This tool was 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). Prototype mean overtopping estimations, allowing for scale and model effects, are also provided.

A database with about 8400 test conditions from scale model tests carried out at several laboratories was employed to build the neural networks in this tool. Each neural network has the same fifteen input parameters, which include three that characterize incident sea-wave conditions (spectral significant wave height at the structure toe, H_{m0}; mean spectral wave period at the structure toe, $T_{m-1,0}$; and angle of wave attack, β) and twelve for the structure geometry, Figure 1 (water depth in front of the structure, h; water depth on structure toe, h_t; toe width, B_t; armour layer roughness / permeability factor, γ_f; structure slope below berm, $\cot(\alpha_d)$; structure slope above berm, $\cot(\alpha_u)$; horizontal berm width, B; water depth on the berm, h_b; berm slope, $\tan(\alpha_B)$; crown wall freeboard, R_c; armor crest freeboard, A_c; and crest width, G_c), (Coeveld *et al.*, 2005).

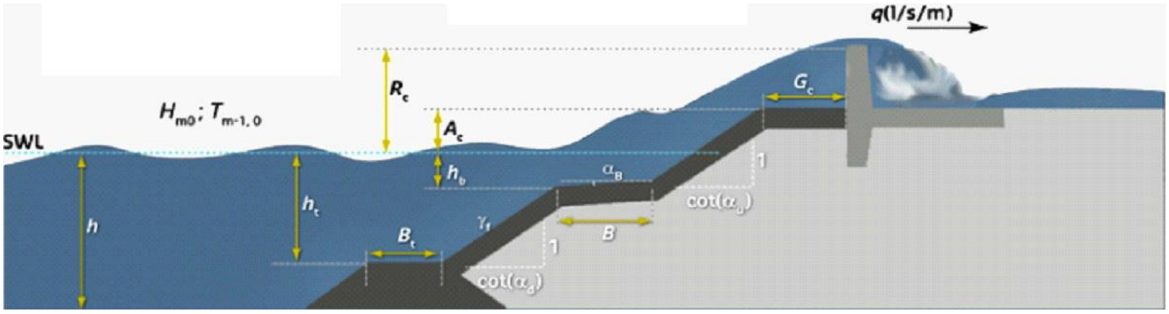


Figure 1. NN_OVERTOPPING2 input and output parameters.

2.3. Step 3: Risk analysis

The analysis of risk is based upon the concept of risk level given by:

Risk level = Probability level X Consequences level (1)

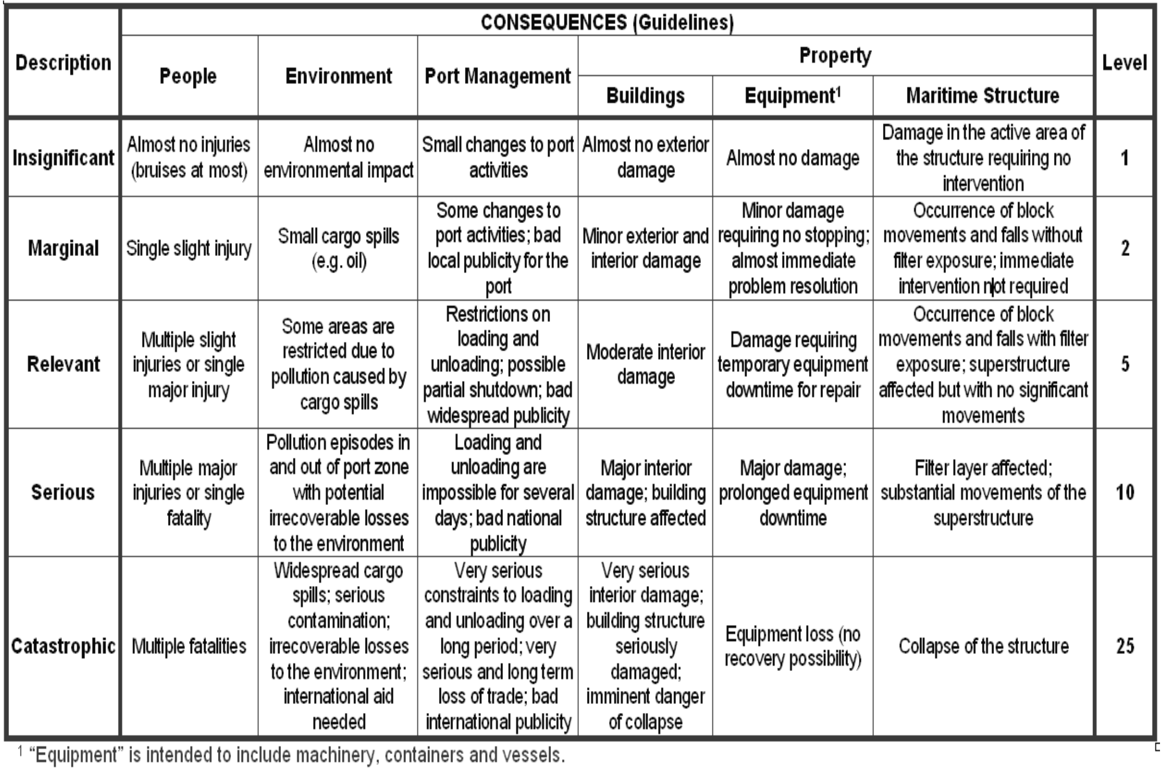
that is, risk level is the product of the probability level associated with the probability of the mean overtopping discharge per unit length of the structure crest exceeding a pre-set threshold by the consequences level associated to such threshold being exceeded.

In order to define those levels, Table 1 and Table 2 were developed (Neves *et al.*, 2012). It must be pointed out that the number of levels, as well as the boundaries for such levels, should reflect the characteristics of the studied problem. Table 1 presents a proposal for the probability levels associated to the occurrence of mean overtopping discharges exceeding a pre-set threshold (to be defined according to the studied stretch of the structure and its expected function).

Table 1. Probability levels.

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

Table 2. Consequences levels.



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 2, the consequences level table, was developed in close collaboration with the Praia da Vitória Port Authority and it takes into account the consequences of dangerous events for human lives, the environment, the port management and the property. The levels in this table were set in order to reflect in the risk level assessment the importance of dangerous events in what concerns their treatment and prioritization. For example, it is important to distinguish between an event with high probability of occurrence but with low consequences from an event with a low probability of occurrence but with very high consequences, which is typically more important to manage.

So, a qualitative assessment of overtopping risk, using the risk level concept, can be carried out by applying the following five-step methodology:

- Definition of acceptable thresholds for q values with the guidance of Pullen *et al*. (2007) according to structures characteristics and utilization;
- Establishment of the probability level for the different thresholds with Table 1;
- Selection in Table 2 of the consequences level for each threshold;
- Computation of the risk level associated with the different pre-set thresholds;
- Production of risk level maps and analysis of risk level acceptability.

3. Application to the study area

3.1. General characterization

The port of Praia da Vitória, Figure 2, is located on the Praia da Vitória bay, at Terceira Island, the second largest of the Azores archipelago. Praia da Vitória bay is bordered to the north by Ponta da Má Merenda and to the south by Ponta do Baixio.

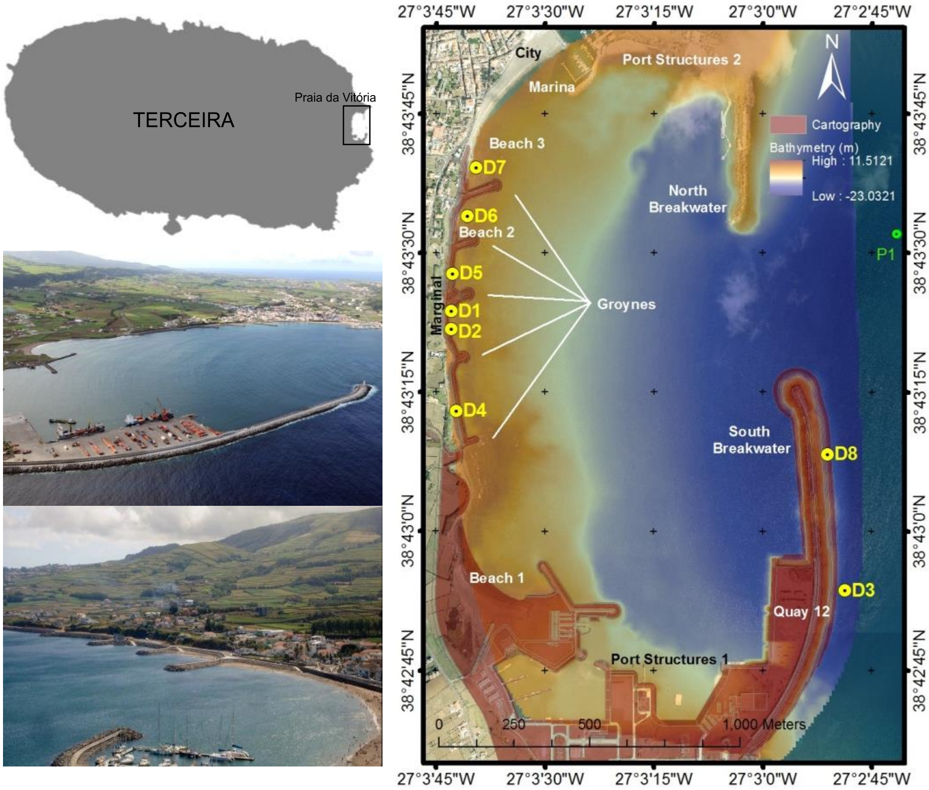


Figure 2. Terceira Island (Azores), port of Praia da Vitória.

In the early sixties, the so-called north breakwater was built to protect the port facilities that support the Lajes airbase. It is a rubble-mound breakwater, 560 m long, with a north-south alignment, rooted in the Ponta do Espírito Santo. Later, in the eighties, the second breakwater (south breakwater) was built, rooted on the south side of the bay, near the Santa Catarina fort. The breakwater is approximately 1300 m long, with a straight alignment (north-south) that bends close to its shore connection. It protects the facilities (commercial sector and fishing port) of the Praia da Vitória port. Taking advantage of the shelter provided by these breakwaters a marina was built in the late nineties by the Municipality of Praia da Victoria at the location of the former fishing harbour (Figure 2). The port basin is approximately 1 km x 2 km.

The bay shoreline has a coastal defence which is 1 km long. In front of the port entrance and rooted to the coastal defence there is a field of five groynes. These groynes do not have the same length but they have approximately the same alignment (WSW-ENE) and are referred to herein as groynes 1 to 5, from south to north. At the root of groyne 3 there is a building in which currently there is a bar. Between some of the groynes there are narrow beaches whose sand volume decreases as one moves south. The longest beach is located between groyne 5 and the marina jetty (Figure 2).

In the port area, there are now several sea-wave measuring devices that can characterize the sea-wave regime within the port. In fact, within the scope of the CLIMAAT project, (Azevedo *et al.*, 2008), a directional wave-buoy was deployed 4 km northeast from the port, in a region about 100 m deep, whose data were used to validate the methodology for wave propagation applied in this study.

3.2. Risk assessment

In the next sections, the risk assessment methodology is applied to several structures along Praia da Vitória bay. First, the wave regime in front of each structure is evaluated based upon numerical model results, for a period of 5 years: 2008-2012. After, wave overtopping is calculated for each structure, for the same time period. Finally, risk level associated with overtopping events such that the mean overtopping discharge q exceeds a given threshold is evaluated.

The structures considered correspond to six stretches of the coastal defence of the bay (D1, D2 and D4 to D7), Figure 3, and two stretches of the south breakwater of the port, one in front of quay 12, D3, and the other in the middle of the breakwater, D8, Figure 4.

Figure 3. Studied stretches along the coastal defence of Praia da Vitória bay.

Figure 4. Studied stretches along the Praia da Vitória south breakwater.

Table 3 illustrates the main characteristics of the cross-sections of the selected stretches of each structure for a water level of +1.7 m (CD), which corresponds to mean high water spring tide.

Table 3. Geometry of cross-sections of the selected stretches for a water level of +1.7 m (CD).

Stretch	**Structure toe location (m CD)**	**Wall height (m)**	**h_t (m)**	**B_t**	**Υ_f (-)**	**cot (α_d) (-)**	**cot(α_u) (-)**	**R_c (m)**	**B (m)**	**h_b (m)**	**tan(α_B) (-)**	**A_c (m)**	**G_c (m)**
D1	-1.00	1.00	2.70	0	0.5	1.5	1.5	4.8	11	-0.8	0	3.8	5.25
D2	-1.40	1.45	3.10	0	0.5	1.5	1.5	5.25	0	0	0	3.8	5.25
D3_1	-18.00	3.9	19.70	0	0.35	4.3	1.5	9.3	0	10.45	0	6.9	8
D3_2	-18.00	3.9	19.70	0	0.35	4.3	1.5	9.3	0	10.45	0	6.9	16
D4	-1.70	1.56	3.40	0	0.5	1.5	1.5	5.36	0	0	0	3.8	5.25
D5	-1.00	0.84	2.70	0	0.5	1.5	1.5	4.64	0	0	0	3.8	5.25
D6	-1.00	1.37	2.70	0	0.5	1.5	1.5	5.17	0	0	0	3.8	5.25
D7	-0.55	1.20	2.25	0	0.5	1.5	1.5	5.00	0	0	0	3.8	5.25
D8_G1	-18.00		19.70	0	0.4	6	1.5	5.4	0	11.5	0	6.9	8.25

3.2.1.Sea-wave characterization

For the sea-wave characterization at the study region, 5 years (2008 to 2012) of sea-wave characteristics predicted offshore by WAVEWATCH III were propagated onshore, first with the spectral wave model SWAN up to the port entrance (point P1) and from there into the port with the mild slope wave model DREAMS (points D1 to D8, Figure 2). It must be pointed out that for 2008, 2011 and 2012 offshore sea-wave characteristics were obtained from USGODAE Data Catalog (http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html), which contains WAVEWATCH III results for all the oceans, namely significant wave height, Hs, peak period, Tp, and peak direction, Dir_p, every 6 hours. Data for the remaining years were obtained from WAVEWATCH III results when this model was applied to the Azores region only, every hour. Tide levels were obtained from summing the tide constituents at Angra do Heroísmo (a couple of miles away from Praia da Vitória) obtained from DEGGE/FCUL (http://webpages.fc.ul.pt/~cmantunes/hidrografia/hidro_mares.html). A constant storm surge of 0.4 m was assumed and added to those levels. Wind fields were extracted from NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html), every six hours, with a 0.25º resolution.

Figure 5 presents the time series of significant wave height (Hs) for points D1 to D8 in the study period (January 2008 to December 2012), as well as the wave rose diagram of the mean wave direction. It can be concluded that the highest significant wave heights occur outside the harbour, namely at points D3 and D8, where Hs can reach almost 8 m. In front of the coastal defence, wave heights are depth limited, and so, the Hs values are always below 3 m. Points D4 and D2 are the ones more exposed to incident waves, while D7 is the most protected one. Most waves in front of the coastal defence come from the 60-110º sector.

3.2.2.Overtopping determination

The NN_OVERTOPPING2 tool was employed to evaluate time-series of mean overtopping discharges at the studied structures, with incident sea-wave characteristics obtained at each point, for the five-year period mentioned before (Figure 5), and the geometric characteristics of the corresponding cross-section (Table 3).

Since the crest of the south breakwater (Figure 6) does not fit the NN_OVERTOPPING2 typical structure geometry (Figure 1), to get mean overtopping discharges at stretch D3 one has to consider two different fictitious cross-sections (D3_1 and D3_2, in Table 3), which differ on the crest width parameter, G_c, only. The mean overtopping discharge at this stretch is the average of the two values obtained for each fictitious cross-section. At stretch D8 one is interested in assessing overtopping influence on the armour layer stability and on the use of the superstructure by people and vehicles, so that discharge is evaluated at point G1 (Figure 6).

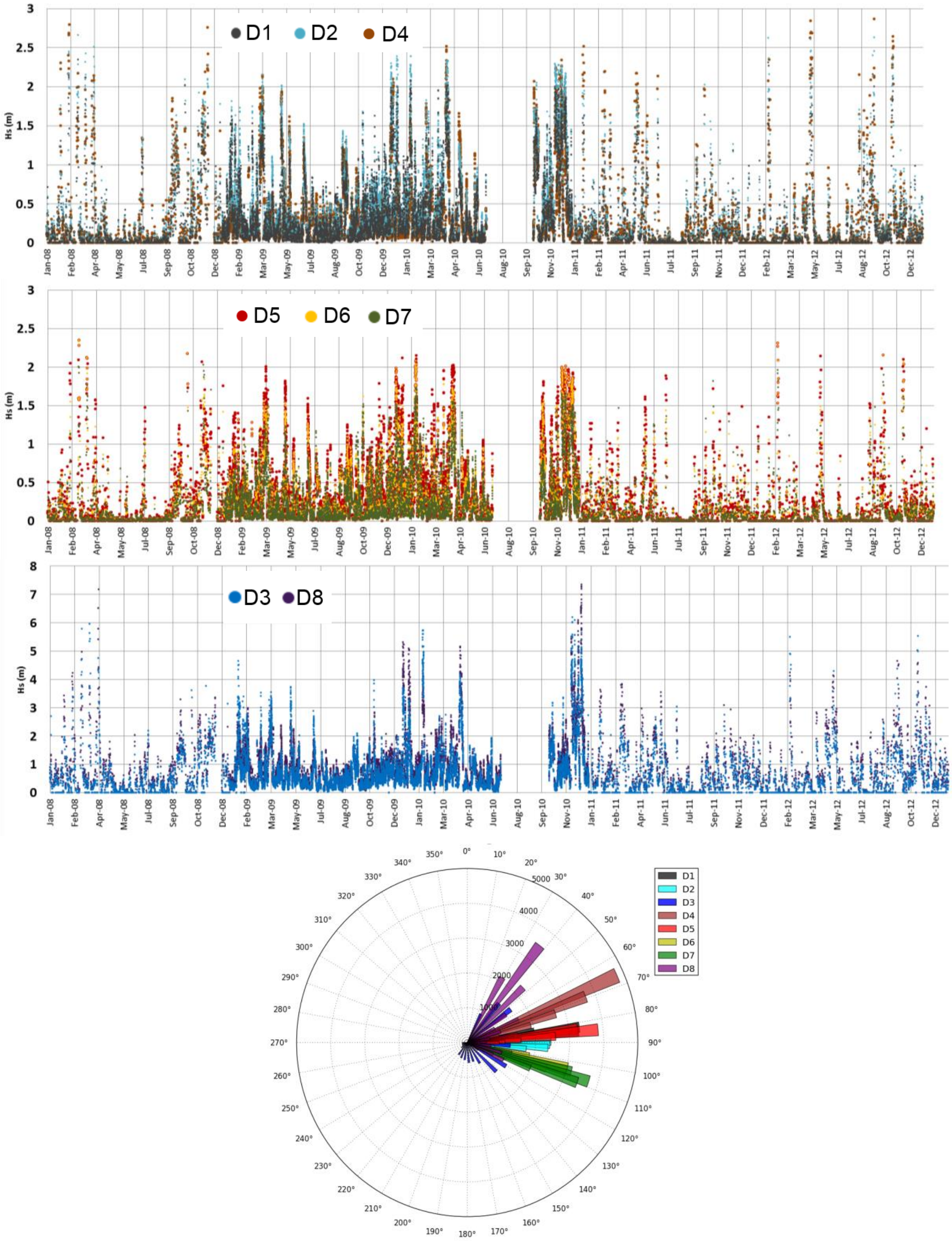


Figure 5. Hs values for points D1 to D8 in front of the selected structures, from January 2008 to December 2012. Wave rose diagram of the mean wave direction.

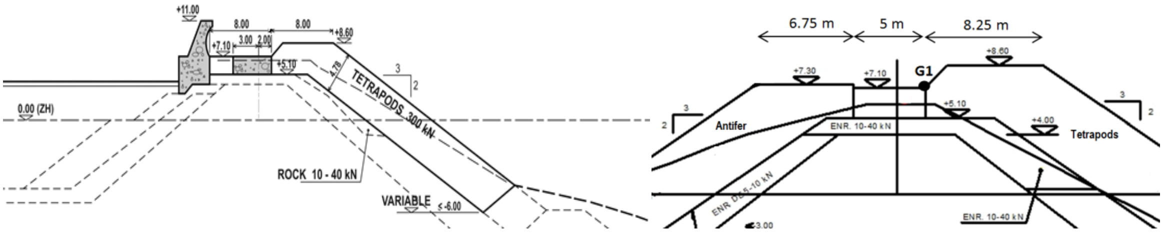


Figure 6. Cross-section of stretches D3 (left) and D8 (right).

Studied stretches along the Praia da Vitória bay coastal defence have quite simple cross-sections. So, they can be represented using the typical structure geometry of NN_OVERTOPPING2 to get the desired results.

Figure 7 shows the calculated q values for the five years of predicted sea-wave data at points D1 to D8. From that figure it may be concluded that D8 has the highest number of overtopping events and the more intense ones. At this stretch, mean overtopping discharges can reach more than 5 l/s/m. On stretch D3 the number of overtopping events and the mean overtopping discharge are significantly lower, which is mainly due to the effect of the wave returned wall on wave overtopping. Along the bay coastal defence, stretches with the highest mean overtopping discharge are D2 and D4. D7 is the most protected stretch of the studied ones.

3.2.3. Risk analysis

Once evaluated the mean overtopping discharges, the next step is the threshold definition for q for each of the studied stretches, according to the nature of the activities carried out in the area sheltered by it and the overtopping impact on the safety of the structure itself, people and infrastructure.

Thus, taking into account the limits of the mean overtopping discharge per linear meter of the structure described in Pullen *et al*. (2007), the following thresholds were adopted:

- Containers on quay 12 are 5-10m away from the structure - 0.4 l/s/m;
- Users of quay 12 are not easily disturbed or frightened by overtopping events and also they move in a large area - 0.1 l/s/m;
- People moving along the coastal defence have a clear view of the sea and also they move in a large area - 0.1 l/s/m;
- The analysed stretches D1 to D7 are backed by a landfill and so they can be considered as revetment seawalls - 200 l/s/m;
- Stretch D8 can be considered as an embankment seawall with well protected crest and rear slope - 200 l/s/m;
- Damage to the building located in the root of groyne 3 and to the lighthouse of the south breakwater: 1 l/s/m;
- All vehicles travel at low speed - 10 l/s/m.

Since quay 12 is approximately 130 m wide, ships moored there are too far away from the overtopped structure to be disturbed by overtopping events. In what concerns stretch D8, it is assumed that ships do not sail near the lee of the structure.

Given the above mentioned thresholds, the number of times those thresholds are exceeded in the relevant structures is counted, the associated probability of exceeding such thresholds is estimated and so the probability level, based on Table 1, can be established. For each structure, the consequences level associated to the occurrence of mean overtopping discharges that exceed the same thresholds is established using Table 2. Finally, the risk level is obtained by the product of the probability levels by the consequences levels.

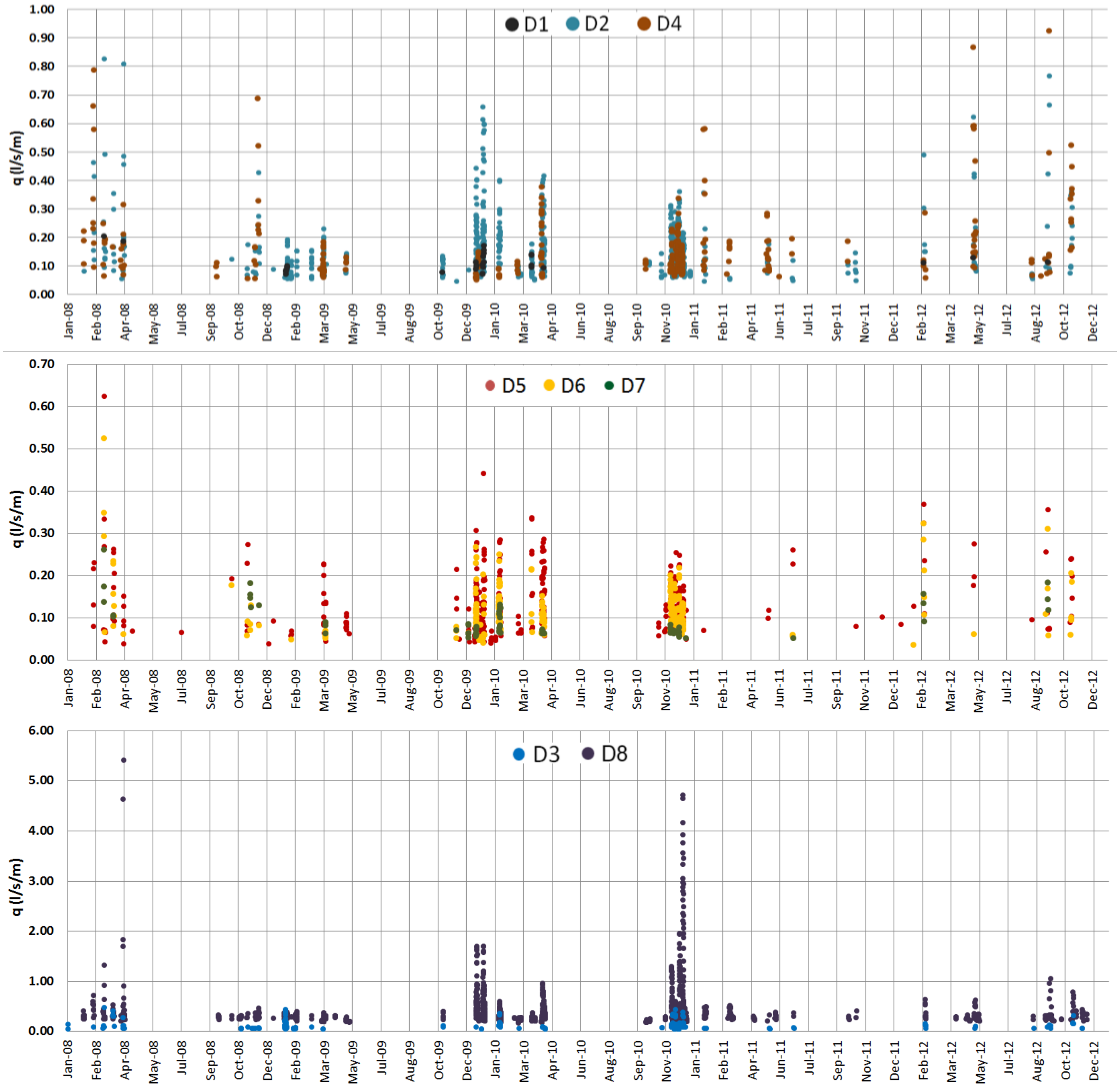


Figure 7. Mean overtopping discharges, q, predicted by NN_OVERTOPPING2 for the five years of wave data obtained at points D1 to D8.

Table 4 presents the probability values for the different thresholds considered at stretches D1 to D8 for the five years of wave data obtained in front of them. As expected, the thresholds leading to more frequent overtopping events are associated to hazards involving people. Consequently, as an example, Table 5 shows the levels of probability, consequences and risk for these hazards only.

Consequences levels were established as follows:

- For the south breakwater stretch that protects quay 12 (D3), a maximum level of consequences equal to 2 was considered, due to the need for some changes in port activities in order to ensure the safety of people and property. There is no need for interruption in port activities, because the quay width allows for safe loading and unloading of ships and for re-deployment of equipment endangered by overtopping events. For D8, the occurrence of injuries to people is considered marginal since the access to the superstructure is limited to trained staff.
- For D1, a consequences level equal to 1 was considered because, if necessary, it is

possible to close the building to safeguard the security of people and goods within or nearby.

- In the case of the coastal defence structure (D2 and D4 to D7) a consequences level of 2 was adopted. This structure essentially protects a coastal road, the vehicles move at low speed and, if necessary, they can park aside to avoid overtopping water. Besides, there is a wide berm that prevents direct overtopping to the road. Also, during severe overtopping events, the area can be sealed and there is an alternative road.

Table 4: Probability values at stretches D1 to D8 for the five years of wave data.

Stretch	Probability (%)				
	Structure	Vehicles	Equipment.	Building	People
D1	0.00	0.00	-	0.00	0.08
D2	0.00	0.00	-	0.00	2.63
D3	0.00	0.00	0.02	-	0.87
D4	0.00	0.00	-	-	1.27
D5	0.00	0.00	-	-	1.49
D6	0.00	0.00	-	-	0.81
D7	0.00	0.00	-	-	0.13
D8_G1	0.00	0.00	-	0.50	7.55

Table 5: Levels of probability, consequences and risk for hazards associated to people at stretches D1 to D8 for the five years of wave data.

Stretch	Probability (%)	Probability Level	Consequences Level	Risk Level
D1	0.08	1	1	1
D2	2.63	2	2	4
D3	0.87	1	2	2
D4	1.27	2	2	4
D5	1.49	2	2	4
D6	0.81	1	2	2
D7	0.13	1	2	2
D8_G1	7.55	2	2	4

After evaluating the risk in the studied structures and having in mind the guidelines for risk acceptability of Simm and Cruickshank (1998), it may be concluded that Praia da Vitória port and bay present low or even insignificant risk to people in relation to the overtopping phenomenon. Only some control measures are needed and those have already been taken by the responsible entities. Figure 8 shows the overtopping risk map built with the results from this study. In addition to the risk level, the map includes qualitative information on the frequency of overtopping events and on the maximum value of mean overtopping discharges at each stretch.

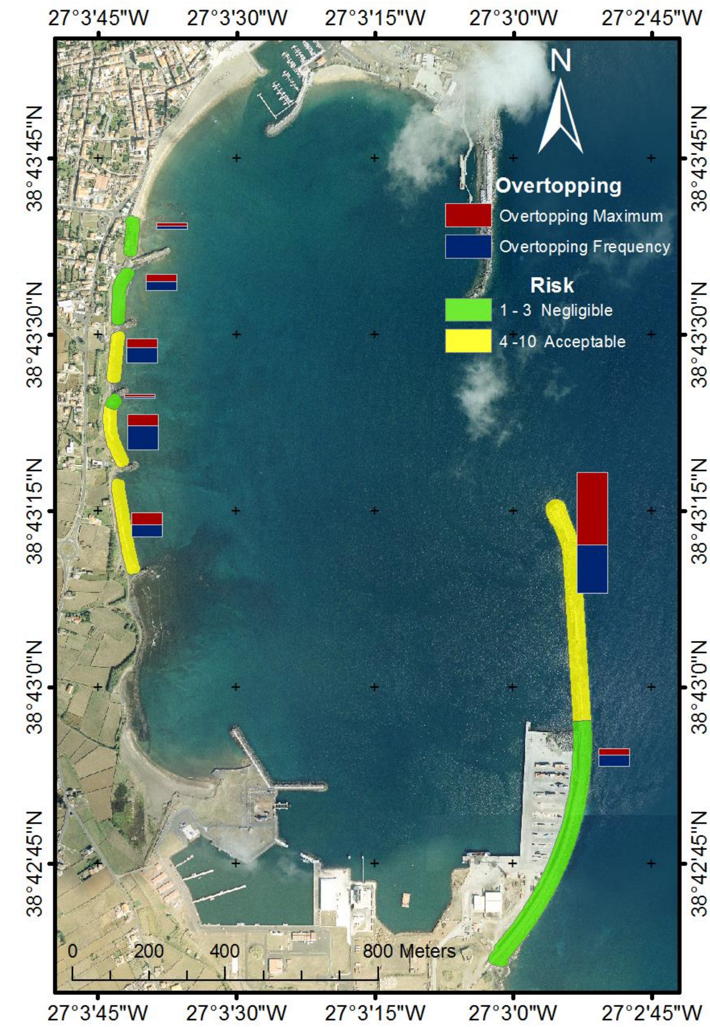


Figure 8. Risk map for hazards involving people at Praia da Vitória bay and port. Overtopping maximum and frequency.

4. Conclusions

This paper presents recent developments to HIDRALERTA, 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 2008 to 2012 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 HIDRALERTA system. The tool NN_OVERTOPPING2, based on neural network analysis, was used to study the mean wave overtopping discharges for the several structures along Praia da Vitória port and bay. Finally, the risk level was established, based on the combination of the probability level associated to exceeding pre-set thresholds for mean overtopping discharge and of the corresponding consequences level, and risk maps were generated. It was concluded that Praia da Vitória port and bay present low or even insignificant risk to people in relation to the overtopping phenomenon.

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