WAVE OVERTOPPING AND FLOOD RISK ASSESSMENT IN HARBOURS: THE PORT OF LAS NIEVES AND ITS FUTURE EXPANSION

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ABSTRACT
This article presents the analysis of the probability of occurrence of wave overtopping events as well as its consequences at the Port of Las Nieves in Agaete, Gran Canaria Island, with the evaluation of the resulting level of flood risk. The study involves both the existing breakwater and its planned future expansion toward deeper waters and has been conducted using a third-generation spectral wave model, to reproduce wave propagation from deep to shallow water depths considering the associated mean sea level, and a neural network-based model, for estimating mean wave overtopping discharges. Results reveal that, in both cases, the access area to the infrastructure presents a risk level substantially higher than that associated with the cross-sections of the main body of the breakwater. Thus, control actions to reduce overtopping in the initial sections are required for the existing structure, and this fact should be seriously taken into account in the planning and construction phases of its extension, due to the important socioeconomic implications regarding the infrastructure inoperability.
Keywords: flood risk, neural networks, Port of Las Nieves, wave overtopping.

1 INTRODUCTION

Coastal harbours play a vital role as economic hubs in terms of trade, communications and tourism. The adequate development of port activities depends on the ability of the protecting structures for providing shelter and facilities to the users. In particular, coastal harbours must be able to offer operating conditions during most of the year and withstand extreme wave conditions, minimizing economic risks as well as risks for humans, their properties and the environment.

The performance of coastal and harbour structures is often measured in terms of the wave overtopping discharge behind it and, as a consequence, the safety limits are set at specific overtopping discharges, defining the allowable rate under operating and design conditions. Accordingly, frequency, pattern and severity of wave overtopping events have to be examined to determine critical locations along the structure, to define proper control measures and to minimize flooding of the infrastructure as much as possible, thus attaining the expected standard of performance.

Consequently, wave overtopping is one of the most important phenomena concerning both the functional efficiency and the structural safety of coastal and port structures, such as breakwaters. However, wave overtopping is a very complex phenomenon influenced by a large number of factors, in addition to the inherent random nature of wind-generated waves impacting against the coastal structures. Thus, overtopping is affected by processes governing the mean sea level over which wave trains propagate and by the sea bottom geomorphology, as well as by the characteristics of the defence structure. Due to its complexity, wave

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overtopping has been studied from different perspectives and using various methods for estimating the wave overtopping rate at distinct structures.

The most-widely used tools for predicting wave overtopping of coastal and harbour structures are empirical/semi-empirical formulae based on physical model tests (e.g. Owen [1], Besley [2], Reis et al. [3], EurOtop [4]). However, direct application of these formulae is limited to simple structural configurations and to specific wave/water-level conditions.

Physical model tests remain the most reliable method for determining overtopping. They are used for prototype studies, as well as providing data for the development, calibration and validation of other prediction methods. Results from field measurements or from large-scale laboratory tests are still rather rare (Franco et al. [5], Geeraerts and Boone [6], Hordijk [7], Pullen and Allsop [8], Carrasco et al. [9]). Most studies have been performed under the CLASH European project to fill this gap and allow investigation of both the model and scale effects (Kortenhaus et al. [10], De Rouck et al. [11]).

In recent years, due to the continuous increase in computer power, numerical models of wave overtopping have been developed further and their use is becoming increasingly attractive (Hu et al. [12], Losada et al. [13], Didier et al. [14]). They are more flexible than both formulae and physical models; and the more complex models, once calibrated and validated, can be configured and applied reliably to a large range of alternative geometries and wave conditions. However, their use in practical engineering applications still has limitations, related to computational cost and to their own limitations. For flood warning purposes, where the computation of many wave overtopping scenarios is needed, models that solve the non-linear shallow water (NLSW) equation models (Hu et al. [12], Reis et al. [15], Zijlema et al. [16]) have been used due to their low computational cost. Nowadays, new forecast models suggest the implementation of more complex models, namely volume of fluid (VOF) models (Zou et al. [17]). The use of artificial neural networks is also proving to be a way forward in view of solid results obtained in recent studies (Medina et al. [18], Wedge et al. [19], Coeveld et al. [20], Verhaeghe [21]).

The objective of this article is to evaluate the wave overtopping rate and its flooding consequences in terms of risk, both for the existing port of Las Nieves (Agaete, Gran Canaria) and for its future configuration due to port expansion. The evaluation is based on a methodology which uses a neural network tool to calculate mean overtopping discharges (Reis et al. [22], Poseiro et al. [23], Fortes et al. [24]), taking into account the sea state conditions (waves and water levels) reaching the structure.

2 STUDY AREA

Las Nieves Port, also known as Puerto de Agaete, is located in Agaete, a town at the northwest coast of Gran Canaria Island, in the Canary Archipelago, Spain (Fig. 1). It is a coastal infrastructure managed by the Canary government with large socioeconomic and cultural importance, mainly due to its role in fishing and transport activities, but also by its role as a coastal defence structure, protecting its two inner beaches and the buildings located at its back (see Figs 2 and 3).

Between years 2004 and 2013, the average number of passengers in the line between Gran Canaria and Tenerife was approximately 680,000 people, ranging from about 550,000 in 2012 to 1,030,000 in 2007. This use, coupled with fishing and nautical sports, entails that the inoperability due to the closure of this port has serious socioeconomic drawbacks.

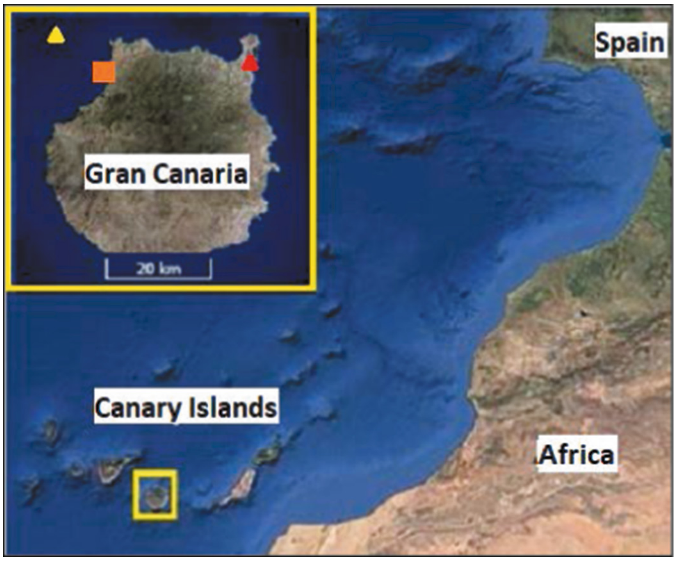

Figure 1: Location of the study area in Canary Islands (orange square), wave buoy (yellow triangle) and tide gauge (red triangle).

Figure 2: Actual aerial view of the Port of Las Nieves in Agaete, Gran Canaria Island.

The shelter of the current port is provided almost exclusively by the dyke that closes the port from the west sector. There have been many cases of overtopping over this infrastructure during its operation period, which have been documented in photographs and press articles. An example is shown in Fig. 4. It is expected that, when port is expanded, the separation of the new commercial dock, prepared for 2–3 berths (one currently), will allow greater port functionality in manoeuvres, shelter and berths.

Figure 3: Rendering view of the future enlargement of the Port.

Figure 4: Overtopping event in study area. Date: 15 January 2014 (wave characteristics during the event were as follows: mean direction, NNW; significant wave height, 2 m; maximum wave height, 4 m; peak period, 12 s; mean period, 8 s).

Wave conditions at the study area are generally mild or moderate with episodic events storms, mainly during winter. Analysis of the wave buoy data reveals that the percentage of occurrence of sea states with significant wave height, Hs, higher than 2 m is close to 20%, but reduces to about 3% for Hs>3 m, and to less than 1% for Hs>4 m. In terms of Hs and peak period, Tp, the most frequent wave conditions correspond to sea states with Hs close to 2 m and Tp around 8 s. The prevailing wave directional sector is NNW-NE, with more than 90% of the observations. The more frequent direction is always NNE, mainly during summer, veering slightly towards the N-NNW sector in winter.

The tide on the island is semi-diurnal, with two high tides and two low tides slightly different each day. Tidal wave in this zone propagates from south to north and produces almost the same sea level at two points located in the same latitude. Las Palmas and Agaete are located in a quiet similar latitude (see Fig. 1), and is therefore acceptable to assume that records obtained at Las Palmas are representative of the sea level behaviour in the study area (Martinez et al. [25]). Accordingly, sea level data have been obtained from two tide gauges installed by Puertos del Estado [26, 27] in the port of Las Palmas for successive periods of time, 1992–2009 and 2009–2015, located 38 km from the wave buoy, approximately (see Fig. 1). Tidal range in the study area is close to 3 m and storm surge in the range ±20 cm.

3 DATA AND METHODOLOGY

The experimental databases, including waves, tides and bathymetry conditions, as well as the approaches used to assess wave overtopping and flooding risk, are briefly described in the following subsections.

3.1 Datasets

Offshore wave climate has been characterized by considering the significant wave height, peak period and mean wave direction associated to every sea state recorded, by using a directional wave buoy located at 780 m depth site, during the period from 2003 to 2013 (see Fig. 1). This dataset has been complemented and enlarged with the characteristic wave parameters resulting from hindcasting (1958–2001, set of SIMAR-44 database) [28] and predictions (1995–2015, set of WANA database) [28], at two points (1017013 SIMAR-44 and 1016012 WANA) located close to the study zone, as depicted in Fig. 5.

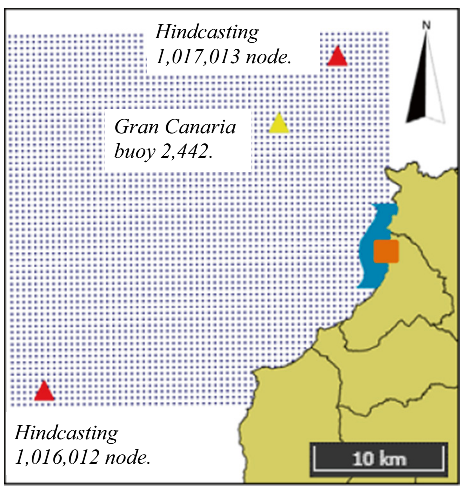

Figure 5: Location of wave buoy (in yellow), hindcasting/prediction points (in red), BOCD [2] bathymetry (blue dots), nearshore bathymetry (blue shaded area) and study area (orange).

Due to the small fetch – less than 20 km – between the points where information is available and the port being studied, the generation of wind waves between both zones has not been considered.

Bathymetric information near the port has been provided by Puertos Canarios and obtained by the Spanish Ministry of Environment [29]. This information does not include the locations of the wave buoy and hindcasting/prediction points. So, it has been complemented with a deep water bathymetry provided by the British Oceanographic Data Centre, BODC [30] (Fig. 5).

3.2 Wave propagation and overtopping evaluation

The SWAN model 40.72a [31] has been used for modelling the transformation of offshore wave conditions during their propagation towards the coastal zone of interest. The directional spectrum has been characterized with a JONSWAP model, considering 30 frequency intervals between 0.02 and 0.3 Hz and a directional discretization of 2°.

Wave overtopping evaluation has been performed by means of the artificial neuronal network tool NN_OVERTOPPING2, developed in the context of the European project CLASH [20]. This tool is built on a database of about 8,400 test conditions, which originated from many different international laboratories. It employs measurements from physical model tests covering a wide range of coastal structure types (such as dikes, rubble mound breakwaters and caisson structures) and different wave conditions (Van der Meer et al. [32]). This variability is imposed by the input parameters that produce Froude scaled mean wave overtopping discharges and the associated confidence intervals. In addition, prototype mean overtopping estimates, allowing for scale and model effects, are provided. Nevertheless, Coeveld et al. [20] suggest that the reliability of the predictions should be verified using dedicated physical model tests for the particular wave conditions and structure geometry under consideration.

3.3 Definition of study cross-sections

Any change in the geometrical section type of the infrastructure implies differences in the overtopping probability of occurrence, while variations in its use entail differences in the consequences of the flood. With this in mind, both the existing infrastructure and its future expansion have been divided into sections according to their structural typology and the use given to the protected areas. Cross-sections used to assess flood risk due to wave overtopping are depicted in Fig. 6 and indicated as E1–E7 and N1–N7 for the existing (left) and planned expansion (right), respectively. It is important to remark that the location of the initial sections (E1, E2 and N1, N2) coincide. Then, according to their geographical location and the use of the space, initial sections are likely to experience inland inundation while the rest could be affected by quayside overtopping.

3.4 Flood risk

The overtopping thresholds used in this work have been chosen on the basis of the recommendations given by Pullen et al. [33], who set limit values for mean overtopping discharge according to the type of structure and its uses for people, vehicles, boats, buildings and equipment.

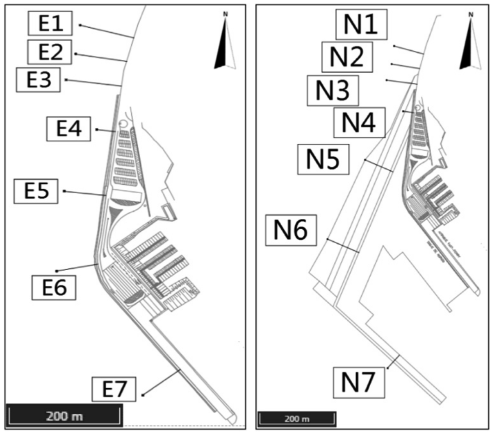

Figure 6: Study sections. Existing port (left); Planned expansion (right).

The flood risk is evaluated qualitatively by combining the probability of occurrence of mean overtopping discharges above a given threshold and the consequences of such threshold being surpassed.

For simplicity, probability and consequences scales are assigned to the probability of occurrence and the associated consequences, instead of using the probability of occurrence of the event and the damage associated with it. The risk, R, is then given by

$$R = P \cdot C \tag{1}$$

where P is the probability level and C represents the consequences level. The process of qualitative evaluation of the flooding risk due to wave overtopping is carried out by using the methodology proposed by Santos et al. [34] (and used in Neves et al. [35], [36], Silva et al. [37], Reis et al. [22], Rocha et al. [38], Poseiro et al. [23, 39]). This methodology allows carrying out a qualitative assessment of overtopping risk, using the risk level concept, by applying the following five-step procedure:

- Definition of acceptable thresholds for mean overtopping values with the guidance of Pullen et al. [33] according to structure characteristics and use;
- Establishment of the probability level for the different overtopping thresholds considering a linear scale of five levels of probability (from 'Unlikely' to 'Frequent'): (1) Unlikely, less than 1%; (2) Unusual, 1–10%; (3) Occasional, 10–25%; (4) Probable, 25–50%; and (5) Frequent, more than 50%;
- Selection of the consequence level for each threshold, based upon the recommendations by Pullen et al. [32], site characteristics and information obtained from the responsible authorities, with five levels of consequences (from 'insignificant' to 'catastrophic'): insignificant – 1; limited – 2; serious – 5; very serious – 10; and catastrophic – 25;
- Computation of the risk level associated with the different pre-set thresholds, considering four levels of risk, R (from 'insignificant' to 'unacceptable'): (1) insignificant (R=1–3); (2) limited (R=4–10); (3) undesirable (R=15–30); and (4) unacceptable (R=40–125);
- Production of risk level maps and analysis of risk level acceptability.

4 RESULTS

The probability (in percentage) of conditions in which the threshold values established for each cross-section are exceeded and the corresponding probability level are presented in Table 1, where cells corresponding to sections without a given use were marked with a script (-). The levels of consequences associated with flooding are given in Table 2, while Table 3 shows the flood risk levels resulting from the product of the level of probability by the level of consequences.

As shown in Table 1, the thresholds that are more likely to be exceeded are those established for areas where pedestrians are present. This is particularly true for sections located in the port access. The exceedance probability reduces significantly for the sections forming integral part of the protection structure. This fact is even more pronounced for the new structure sections, except for the last section (N7) where the exceedance probability is considerably large, due to the change of structural typology, as indicated in Section 3.3. Regarding the presence of vehicles, the probability of threshold exceedance is null for all the sections but the last one (N7) where overtopping events exist with an unlikely level.

Furthermore, concerning the existence of buildings and boats, the probability of exceeding the corresponding thresholds is null along all the structure. In relation to the equipment use, there are two sections (E4, E7) with unlikely level, which reduces in the case of the future structure (N4, N7).

Consequences associated with overtopping of the structure (Table 2) are serious in all the sections regarding the presence of pedestrians. However, environmental consequences of wave overtopping events are insignificant in the sections of the port access (E1, E2, E3) and limited in the rest. Port Management is very seriously hampered if overtopping affects port access sections and seriously hampered if flooding exists in the areas designated for passengers transport activity (E7, N6, N7). Concerning buildings, overtopping consequences

Table 1: Probability (%) of exceeding the overtopping thresholds and corresponding probability levels.

	Pedestrians		Vehicles		Equipment		Buildings		Boats	
Section	%	Level	%	Level	%	Level	%	Level	%	Level
E1=N1	2.00	(2)	0	(1)	-	-	-	-	-	-
E2=N2	2.55	(2)	0	(1)	-	-	0	(1)	-	-
E3	2.57	(2)	0	(1)	-	-	0	(1)	-	-
E4	0.70	(1)	0	(1)	0.14	(1)	0	(1)	-	-
E5	0.44	(1)	0	(1)	-	-	0	(1)	0	(1)
E6	0.37	(1)	0	(1)	-	-	-	-	0	(1)
E7	0.41	(1)	0	(1)	0.33	(1)	-	-	0	(1)
N3	0.86	(1)	0	(1)	-	-	0	(1)	-	-
N4	0.01	(1)	0	(1)	0.01	(1)	0	(1)	-	-
N5	0.08	(1)	0	(1)	-	-	0	(1)	0	(1)
N6	0.09	(1)	0	(1)	-	-	0	(1)	0	(1)
N7	0.87	(1)	0.53	(1)	0.12	(1)	-	-	0	(1)

Table 2: Associated consequences for pedestrians (P), environment (Env), Port Management (PM), buildings (B), equipment (Eq), structure (S) and vehicles (V).

Section	P	Env	PM	B	Eq	S	V
E1=N1	S (5)	I (1)	VS (10)	I (1)	-	L (2)	L (2)
E2=N2	S (5)	I (1)	VS (10)	L (2)	-	L (2)	L (2)
E3	S (5)	I (1)	VS (10)	L (2)	-	L (2)	L (2)
E4	S (5)	L (2)	L (2)	S (5)	S (5)	L (2)	S (5)
E5	S (5)	L (2)	L (2)	S (5)	S (5)	L (2)	S (5)
E6	S (5)	L (2)	L (2)	L (2)	-	L (2)	S (5)
E7	S (5)	L (2)	S (5)	-	VS (10)	L (2)	S (5)
N3	S (5)	L (2)	VS (10)	L (2)	-	L (2)	L (2)
N4	S (5)	L (2)	L (2)	S (5)	S (5)	L (2)	S (5)
N5	S (5)	L (2)	L (2)	S (5)	S (5)	L (2)	S (5)
N6	S (5)	L (2)	S (5)	L (2)	-	L (2)	S (5)
N7	S (5)	L (2)	S (5)	I (1)	VS (10)	L (2)	S (5)

vary among insignificant, limited and serious according to the building use (private properties, entrance checkpoint and port terminal). If overtopping affects lifting equipment, consequences are catalogued as serious (E4, E5, N4, N5) and has very serious implications if it affects passenger's gangway (E7, N7). Overtopping effects on the structure stability are limited.

Based on the above, the estimated risk level for the different sections of the structure (Table 3), both for the existing port and for its future expansion, is classified as 'Undesirable' in the sections corresponding to the port access road and as 'Limited' in the remaining zones. However, among those sections classified with 'Limited' risk, the final section of both structures (E7, N7) has associated a significantly higher risk value (10) than the remaining sections (5), because of the change in structural section.

It has to be mentioned that for sections E1=N1, E2=N2, E3 and N3, with a natural volcanic platform seaward of the structural section, those sea states whose parameters are not encompassed by the neural network ranges could not be considered for further analysis. This limitation can be partially eliminated by using a more detailed wave propagation model that includes propagation on the shallow natural volcanic platform. Furthermore, the breakwater has an unusual structural section, including a stilling basin, something that was not considered in the development of the used neural network tool.

In the absence of wave overtopping experimental measures, a particular effort has been carried out to contrast the results provided by the procedure used to predict the occurrence of such events. This has been accomplished through review of the local and national daily press, covering the whole study period. In this respect, it is worth mentioning that in general extreme events resulting in more severe impacts were reported by the press, but information on moderate and work events was seldom, especially during the first 20–30 years of the study period. In any case, most extreme predicted overtopping events were reported by the press, particularly those causing the stop of part activities.

Table 3: Levels of risk (*R*) obtained as the product of the highest probability level per section (*P*) and the highest consequences level per section (*C*).

Section	*P*	*C*	*R*		Risk control
E1=N1	2	10	20	Undesirable	Consider the possibility of risk elimination. Monitoring is essential.
E2=N2	2	10	20	Undesirable	Consider the possibility of risk elimination. Monitoring is essential.
E3	2	10	20	Undesirable	Consider the possibility of risk elimination. Monitoring is essential.
E4	1	5	5	Limited	Some control actions are necessary.
E5	1	5	5	Limited	Some control actions are necessary.
E6	1	5	5	Limited	Some control actions are necessary.
E7	1	10	10	Limited	Some control actions are necessary.
N3	1	10	10	Limited	Some control actions are necessary.
N4	1	5	5	Limited	Some control actions are necessary.
N5	1	5	5	Limited	Some control actions are necessary.
N6	1	5	5	Limited	Some control actions are necessary.
N7	1	10	10	Limited	Some control actions are necessary.

5 CONCLUSIONS

Wave overtopping probability of occurrence and the resulting flood risk at the Port of Las Nieves in Agaete and its planned expansion has been explored by using large databases of offshore wave climate and associated tidal conditions, as well as bathymetric characteristics to obtain nearshore wave conditions by means of a wave propagation model, while mean overtopping discharges have been evaluated using a neural network-based model.

The frequency of occurrence of wave overtopping events, as well as the associated risk level in the initial sections (port access area) of the Port of Las Nieves, is substantially higher than that associated with the cross-sections located in the main body, for both the existing breakwater and its future expansion, leading during extreme or even moderate overtopping events to the suspension of port activities. Naturally, the construction of a new breakwater will virtually eliminate wave overtopping in the inner zone of the existing port for the main part of the infrastructure, but the risk will remain fairly high in the access area for the existing and the planned expansion. These findings highlight the need to undertake proper actions against wave overtopping in the area of the access road to the Port of Las Nieves. This fact would become even more important in the case of the future expansion of the harbour, due to the expected increase of socioeconomic implications regarding the infrastructure downtime.

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