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Probabilistic Hydraulic Design of Non-Conventional Breakwaters in Shallow Water Conditions

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Abstract: Probabilistic design analysis is highlighted as a powerful tool during the design/planning phases due to its capability to simulate the hydraulic performance of coastal structures along their lifetime in a context of uncertainty. In this work, a novel methodology for applying a probabilistic approach for non-conventional breakwaters in shallow water conditions following the Monte Carlo simulation method is presented. Because it is based on simulating a large number of realizations, reducing uncertainties related to both the simulation of met-ocean parameters and the hydraulic performance assessment is required. In this regard, the non-linear wave transformation processes play a key role on the wave climate in this kind of breakwaters. To overcome these problems, firstly, a multivariate climate-dependent model is applied to reduce the uncertainties related to the wave climate. Secondly, the uncertainties related to the hydraulic behavior characterization are reduced by means of site-dependent formulae tailored suit built for the analyzed breakwater by combining data-mining algorithms, Computational Fluid Dynamics (CFD) numerical modelling and well-established state-of-the-art theoretical models. Finally, it is integrated together with a scenario of climate change in order to quantify the future evolution in time of its hydraulic performance and the related expected costs from a probabilistic point of view.

Keywords: Probabilistic design, non-conventional breakwaters, CFD modelling, climate change, cost assessment.

1 Introduction

Coastal structures are designed to carry out development activities in a safe and efficient way throughout its lifetime. However, the different sources of uncertainty (such as the future met-ocean conditions, the geometrical/structural properties or how its hydraulic response will evolve) motivate that their lifetime analysis is based on the probability theory (Burcharth, 1993). It allows a better decision-making according to the context of uncertainty. In this regard, some of the most important guidelines have included methodological frameworks to carry out probabilistic analyses of coastal structures. For example, the Spanish recommendation for maritime works ROM 0.0-01 include the need to undertake this approach at the ports of general interest for the country.

Probabilistic approaches are based on solving the integral of the joint probability density function of all the involved stochastic variables (loading and strength variables) with an influence on the failure probability of the breakwater. Because of its high-dimensional behavior, it can generally not be solved analytically. For these reasons, risk-based design methods can be divided into two broad categories: Semi-analytical (Mínguez et al. 2006) and numerical simulation approaches (Suh et al. 2013). However, the current computing power allows to simulate many realizations (synthetic lifetimes) in order to approximate numerically (i.e. Monte Carlo technique) the value of the failure probability based on reliable statistical characterization of all the stochastic variables and failure mechanisms. Besides, these techniques make possible to obtain the total costs associated with the evolution in time of its hydraulic performance (Males et al. 2011).

In connection with the statistical characterization of the involved variables, an adequate multivariate wave climate characterization is necessary to simulate reliable wave-driven events in front of the breakwater. In the last years, copulas methods have undergone a considerable development to describe non-independent multivariate data (Salvadori et al. 2007, De Michele et al. 2007, Wahl et al. 2012, Camus et al. 2016, Rueda et al. 2016) in order to reduce uncertainties in the generation of random wave and sea level parameters. Moreover, these techniques allow to take into account the influence of different climate change scenarios over the wave climate (Lin-Ye et al. 2017, Camus et al. 2017, Camus et al. 2019).

Regarding the non-conventional breakwaters located in shallow water locations, the wave transformation processes such as the refraction-diffraction, the depth-induced wave-breaking and the wave energy transfer to low-frequencies play a fundamental role on the wave climate at the toe of the structure, and consequently, on the breakwater design. However, most of the state-of-the-art semi-empirical formulae are applicable only for conventional breakwater designs and rarely include these non-linear wave effects. To overcome this problem, computational fluid dynamics (CFD) models are likely to be the most cost-effective way to reliably characterize their failure mechanisms. The paper is organized as follows: in Section 2 the objectives are introduced. Section 3 contains detailed information about the proposed methodology. The key findings and conclusions are presented in Section 4.

2 Objectives

The main objective of the work is to perform a probabilistic hydraulic design of a non-conventional breakwater in depth-limited conditions applying the Monte Carlo method. Moreover, a life-cycle cost assessment is also performed from a probabilistic point of view. Because this method is based on simulating a large number of realizations, the secondary objectives are both reducing uncertainties related to the simulation of met-ocean parameters and to hydraulic performance assessment. To do so, a multivariate climate-dependent model is applied following Rueda et al. (2016) and including a probabilistic sea-level rise (SLR) projection by 2050 for the RCP8.5 scenario. Secondly, the fully-validated numerical model IH2VOF (http://ih2vof.ihcantabria.com/) is applied to characterize the hydraulic performance by site-dependent formulae tailored suit built for the analyzed breakwater. Considering all the above, a reliable time-dependent analysis of its future hydraulic performance under a scenario of climate change is performed.

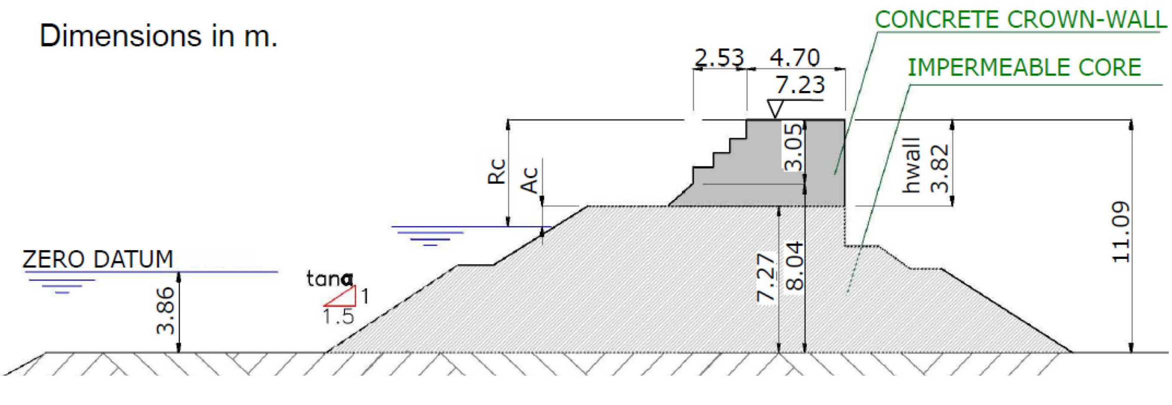

Fig. 1. Studied breakwater: Canouco breakwater (Fishing port of Luarca (Spain)).

3 Methodology

The proposed methodology aims to obtain a probabilistic hydraulic design of a non-conventional breakwater which is in shallow water area where the non-linear wave transformation processes are very relevant on its hydraulic response. This methodology is applied to the Canouco Breakwater (fishing port of Luarca (Spain), Fig. 1). Its cross-section is characterized by its impermeable core and a non-conventional cyclopean concrete crown wall, which means that there are not uplift pressures at the core-wall contact. In this case, the hydraulic design is carried out from two levels of damage: Ultimate Limit State (ULS) and Serviceability Limit State (SLS). Regarding the ULS, it is analyzed by the sliding of the crown-wall failure mode due to an excess of horizontal force. Furthermore, the SLS is analyzed by the overtopping failure modes (excess of mean overtopping discharge and excess of maximum overtopping volume).

The proposed methodology is organized into four main steps (Fig. 2). The first and the second steps deal with the main sources of uncertainty: The wave climate characterization and the hydraulic behavior characterization. Thirdly, a probabilistic lifetime analysis of the studied coastal structure is performed based on the previous steps in order to verify the safety and functionality requirements in its design. This time-dependent analysis allows to take into account the evolution in time of future sea-level rise pathways for the worst-case climate change scenario. Finally, the results obtained in the previous step are transformed into economic consequences.

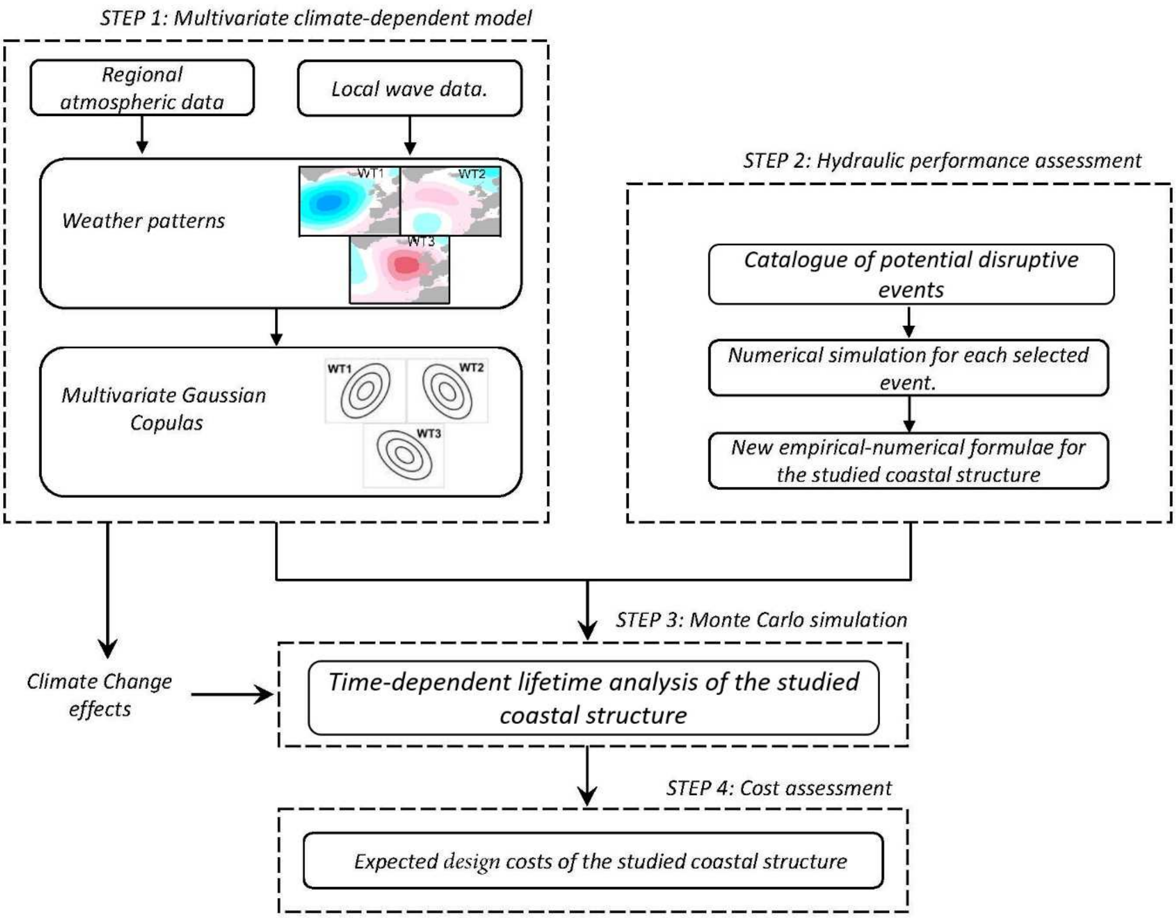

Fig. 2. Proposed methodology for probabilistic hydraulic design of non-conventional breakwaters.

3.1 Multivariate climate-dependent model

The climate-dependent model proposed by Rueda et al. (2016) is applied to reduce the uncertainties related the wave climate and, consequently, reliably simulate many loading cycles over the breakwater. Because the wave climate in a certain location results from the wave generation and propagation at regional scale, similar regional atmospheric situations also produce similar wave conditions (Camus et al. 2014). Therefore, the applied climate emulator is based on the relationship between the predictor (regional atmospheric data in the wave generation and propagation area) and the predictand (the local wave data). A detailed explanation of the methodology can be found in Camus et al. (2014), Camus et al. (2016) and Rueda et al. (2016).

In this case, the regional atmospheric data is defined by the regional sea-level pressure fields (SLP) and sea-level pressure gradients (SLPG) of CFSR and CFSRv2 (Climate Forecast System Reanalysis, Saha et al. 2014) database which spans from 1979 to 2013 with hourly time resolution. The local wave data (Significant wave height, *Hs*; peak wave period, *Tp*; mean wave direction, *Dir*; storm surge, *SS*) is described by the DOW (Downscaled Ocean Waves, Camus et al. 2013) and GOS (Global Ocean

Surges, Cid et al. 2014) reanalysis databases, with the same temporal coverage and time resolution as the atmospheric database.

Then, a regression-guided clustering (Camus et al. 2016) between the predictor and predictand is carried out. The predictor is defined as the daily SLP and SLPG averaged over the 3 previous days to properly consider the wave generation and propagation processes in its influence area (Fig. 3). The predictand is characterized by the daily maximum values of *Hs*; *Tp*; *SS* and the daily mean *Dir*. This classification technique isolate climate-related events with similar ocean conditions, so-called Weather types *WTs*. The main advantage of this technique is grouping the wave data with similar dependences structures (such as the correlation between the main sea-state variables) according the meteorological processes. At this location, and following the above-mentioned works, 100 *WTs* are obtained (Fig. 4).

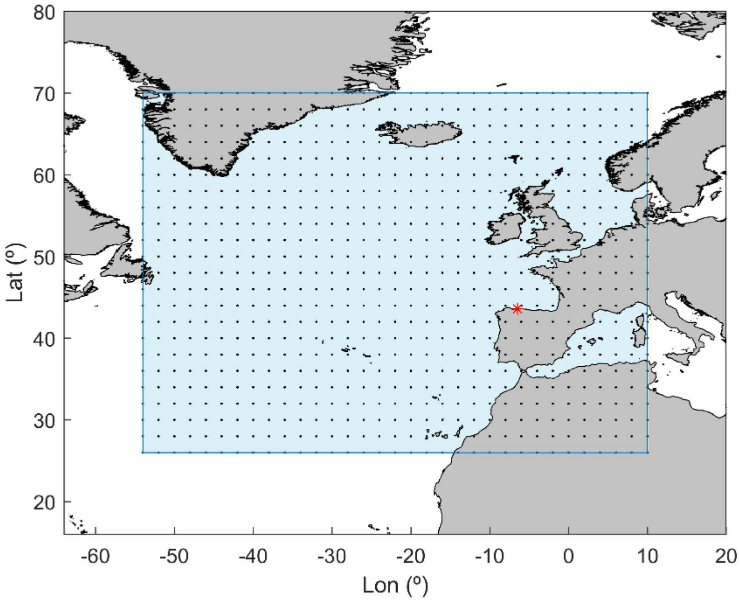

Fig. 3. Spatial domain of predictor (black dots) and study location (red point).

The dependence between predictand variables is modelled by Gaussian Copulas within each *WT*. By coupling clustering techniques (previous *WT* classification) and Gaussian copulas, non-independent multivariate data conditions are characterized. Moreover, this grouping at *WT*-scale enables to use the most flexible copula technique (Gaussian copulas). Each of the 4-dimensional Gaussian copulas are defined by the marginal distributions and the correlation coefficients between the predictand variables (Fig. 5).

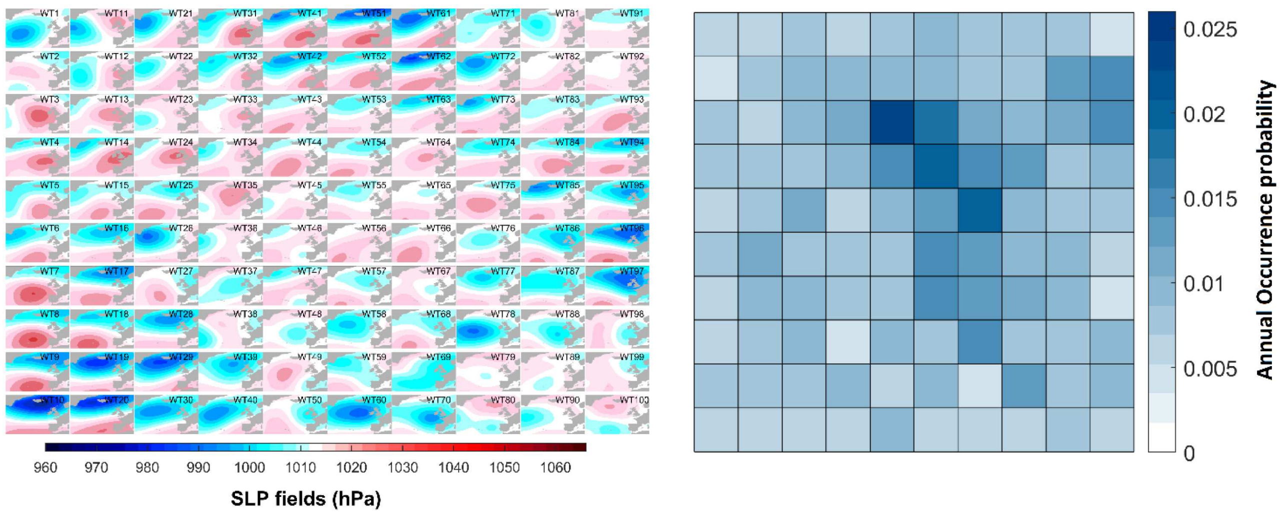

Fig. 4. Left panel: Regression-guided classification at the study location, 100 Weather Types represented by SLP fields. Right panel: Annual Occurrence probability of each Weather Type.

As can be noted in Figs. 4 and 5, low pressure systems centered over the British Isles (WT96 and WT97) produce the largest significant wave heights, although both have a low occurrence probability.

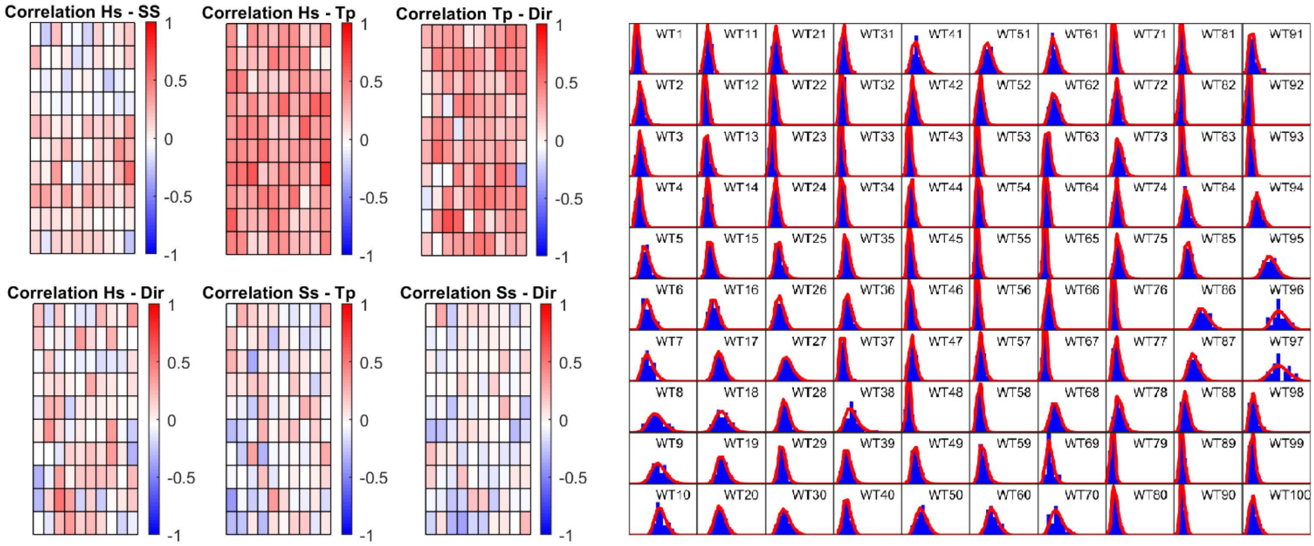

Fig. 5. Left panel: Correlation coefficients matrix. Right panel: Histogram and GEV marginal distribution for the predictand variable Hs. X-axis [0 9.15] meters, Y-axis [0 0.5].

3.2 Hydraulic performance assessment

The hydraulic behavior is characterized by site-dependent empirical-numerical formulae. As explained in the introduction, two are the main features of this kind of breakwaters: their non-conventional designs and the non-linear wave-structure interaction. It means that the state-of-the-art semi-empirical formulae are not valid for characterizing their hydraulic response. It motivates the use of a fully-validated numerical model based on the computational fluid dynamics (CFD).
Because the aim is to reduce the uncertainties related the hydraulic response in the Monte Carlo simulation, applying CFD models must be accompanied by a highly-efficient procedure as data-mining algorithms. It consists of applying the numerical model in a limited number of met-ocean conditions. Based on these numerical results, any sea-state which may trigger the failure of the system can be properly evaluated.

The following briefly explain how to include CFD models in the Monte Carlo simulation procedure. For more details, see Lara et al. (2019) in which the entire procedure for the hydraulic performance assessment of the same breakwater is developed. It can be summarized in three following steps:

Firstly, potential disruptive events are identified based on the wave climate provided by the reanalysis databases at this location. A potential disruptive event is defined as the met-ocean conditions which causes hydrodynamic forces on the crown-wall or overtopping ratios higher than the “zero overtopping criterium”. A pre-analysis using semi-empirical formulae (EurOtop 2016 and Martin et al. 1999) is applied to identify potential disruptive events during the reanalysis time-period. Then, the catalogue of $N=20$ representative potential events are obtained applying the Max-Diss selection method (Camus et al. 2011) on the subset previously derived. Therefore, this catalogue is the reduced data subset which properly represent the wave climate diversity which may trigger the sliding of the crown-wall or produce an excess of wave overtopping (analyzed failure modes).

Secondly, the $N=20$ sea-states are simulated using the IH2VOF numerical model (Losada et al. 2008 and Lara et al. 2011), which has been extensively validated for wave-structure interaction including non-conventional breakwaters (Di Lauro et al. 2019) and for solving the surf zone hydrodynamic (Ruju et al. 2012). Because the aim is to obtain site-dependent formulae tailored suit built for the analyzed failure modes (Sliding of the crown wall, excess of mean overtopping discharge and excess of maximum overtopping volume), the wave climate parameters at the toe of the structure are also required. In this regard, each of the selected sea-states are numerically simulated twice (without structure to assess the wave conditions at the toe of the structure and with structure to assess the hydraulic performance). It ensures that wave transformation processes and the hydraulic response of any sea-state is properly evaluated. Each of the hourly sea-states of 3600 s are simulated at prototype scale and using a peak enhancement factor γ=3.3.

Finally, the site-dependent formulae tailored suit built for the analyzed breakwater are obtained. These are based on the results obtained numerically and well-established state-of-the-art theoretical models. Please, see Lara et al. (2019) for more information related the fitting procedure for this breakwater. Eq. (1) models the maximum horizontal forces in a sea-state to verify the sliding of the crown wall; Eq. (2) models the maximum wave overtopping discharge in a sea-state to verify the excess of mean overtopping discharge; Eq. (3) models the maximum wave overtopping volume in a sea-state to verify the excess of maximum overtopping volume. These models depend on the spectral significant wave height H_{m0} *(m);* the spectral wave period $Tm_{-1,0}$ *(s);* the zero up-crossing mean wave period T_z *(s) time of the sea-state (s),* and the geometrical variables shown in Fig. 1.

$$F_H = a_f\ \rho\ g\ h_{wall}\ (Ru_{max} - A_c) \qquad \text{(1) [Maximum horizontal forces model, KN/m]}$$

$$\frac{q}{\sqrt{gH_{m0}^3}} = a_q exp\left[-\left(b_q \frac{R_c}{H_{m0}\ \xi_{-1,0}}\right)^{c_q}\right] \qquad \text{(2) [Maximum wave overtopping discharge model, -]}$$

$$V_{max} = a_v\ \left(\frac{q\ T_z}{P_{ov}}\right)[log(N_{ow})]^{-1/b_v} \qquad \text{(3) [Maximum wave overtopping volume model, m}^3\text{/m]}$$

As can be noted, the previous prediction models need to characterize the maximum run-up level Ru_{max}, the Iribarren number $\xi_{-1,0}$ and number of overtopping waves N_{ow}. Following the same procedure, these are modelled as follow:

$$Ru_{max} = a_{ru}\ \xi_{-1,0}H_{m0} \qquad \text{(4) [Maximum run-up level model, m]}$$

$$\xi_{-1,0} = \frac{\tan\alpha}{\sqrt{\frac{2\pi}{g\ Tm_{-1,0}^2}}} \qquad \text{(5) [Iribarren number model, -]}$$

$$N_{ow} = P_{ov}N_w = exp\left[-a_{Pov}\left(\frac{Rc}{Ru_{max.}}\right)^2\right]\frac{time_{sea-state}}{T_z} \qquad \text{(6) [Number of overtopping waves model, -]}$$

The statistical characterization of the previous empirical-numerical models is shown in Tab. 1 (Taken from Lara et al. 2019). It is important to highlight the probabilistic behavior of these models in order to introduce the uncertainty related the hydraulic response of the analyzed coastal structure in the Monte Carlo simulation.

Tab. 1. Statistical characterization of the empirical-numerical coefficients

Empirical-numerical coefficient	Normal probability distribution [μ, σ]
a_f	[0.0619, 0.014]
a_q	[0.0342, 0.0111]
b_q	[5.37, 0.82]
c_q	[2.1, 0]
a_v	[2.972, 0.345]
b_v	[5.55, 0]
a_{ru}	[0.3555, 0.020]
a_{pov}	[3.404, 0.529]

3.3 *Monte Carlo simulation*

The probabilistic hydraulic design is carried out by simulating 1,000 realizations of its lifetime (from 2000 to 2050) at daily time-scale according to proposed methodology to generate synthetic wave-driven events (see subsection 3.1). The Monte Carlo procedure can be summarized as follows:

1. Simulation of the met-ocean conditions within each realization: based on the occurrence probability matrix (Fig. 4, right panel), 365x50 daily *WTs* are randomly simulated within each realization. Then, the daily wave (Hs, Tp, Dir) and storm surge (SS) parameters are obtained using the Gaussian copulas and GEV marginal distributions. It allows to simulate multivariate daily events. As can be seen in Fig. 6, an adequate simulation of the extreme regimes is achieved. The remaining sea-state parameters are derived from well-established relationships ($T_z = T_p / 1.3$; $Tm_{-1,0} = Tp / 1.1$). The astronomical tide (AT) is independently simulated at daily time-scale from the harmonic analyses of the global model of ocean tides TPXO7.2. The last sea-level component to be randomly generated is the sea-level rise. Following Camus et al. (2019), a lognormal distribution characterizes the uncertainty related to the sea-level rise projection by 2050 for the RCP8.5 scenario (0.257±0.069 m at the study location). Therefore, a linear trend from 2000 to 2050 is randomly simulated within each realization based on the distribution previously defined.

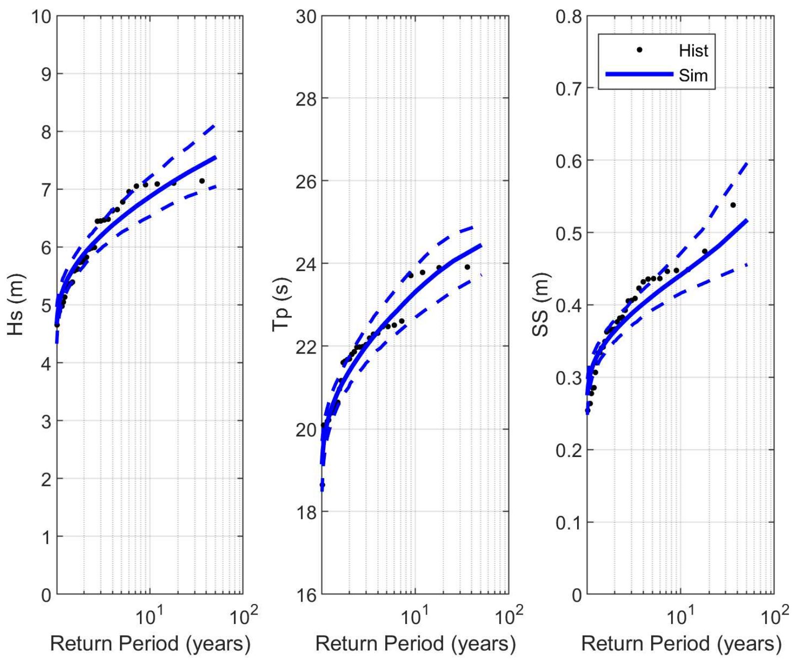

Fig. 6. Extreme significant wave height distribution (left panel); extreme peak wave period distribution (central panel) and extreme storm surge distribution (right panel); based on the climate-dependent model simulation with 90 % confidence interval. Black dots are the reanalysis data at the study location.

2. Simulation of the hydraulic performance: based on the met-ocean conditions previously simulated and the empirical-numerical prediction models (see subsection 3.2), the hydraulic performance assessment is carried out. In this regard, the uncertainties related the geometrical and structural properties are also taken into account following the statistical characterization of the strength variables described in Lara et al. (2019). Fig. 7 shows the evolution in time of each of the three hydraulic behavior models, which are characterized by the maximum values from the beginning of the analysis to any time *t*.

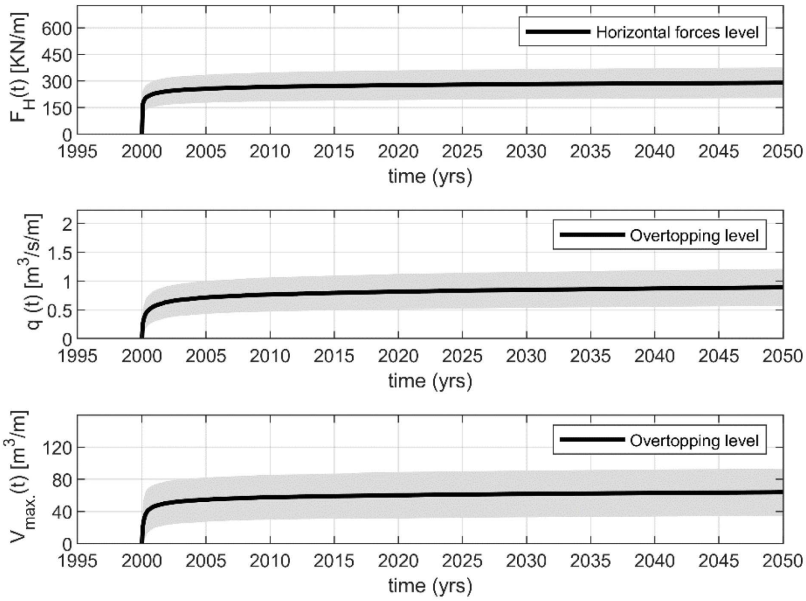

Fig. 7. Hydraulic performance assessment of the maximum horizontal forces, mean wave overtopping discharge and maximum overtopping volume. Evolution in time of the mean values (solid lines) and one standard deviation away from the mean (shaded areas).

Finally, the failure probabilities of each failure mode are evaluated at any time t as the number of realizations in which the limit-state equation is less than zero in relation to the total number of realizations (Eq. (7), Fig. 8). Limit-state equations are used to characterize when a failure mechanism takes place (Eq.(8) to Eq.(10)). Threshold for the sliding failure mode is defined as the resistance force due to the weight of the crown wall over the core-wall contact. It is calculated as the weight of the crown-wall multiplied by the friction coefficient, randomly simulated within each realization according to Lara et al. (2019). Thresholds for SLS failure modes are defined following EurOTop (2016), ($Threshold_{ov.Discharge} = 0.005\ m^3/s/m$ and $Threshold_{ov.Volume} = 5\ m^3/m$).

$$P_f \approx \frac{\#realizations\ :g<0}{\#realizations}$$ (7) [Failure probability solved by numerical approximation]

$$g_{sliding} = Threshold_{sliding} - F_H$$ (8) [Sliding failure mode]

$$g_{ov.Discharge} = Threshold_{ov.Discharge} - q$$ (9) [Mean wave overtopping discharge failure mode]

$$g_{ov.Volume} = Threshold_{ov.Volume} - V_{max}$$ (10) [Maximum wave overtopping volume failure mode]

Considering the analyzed coastal structure as a series system which may fail or not operate for safety-related causes (ULS failure modes) or serviceability-related causes (SLS failure modes), the failure probability of the whole breakwater can also be obtained (Tab. 2, Fig. 7).

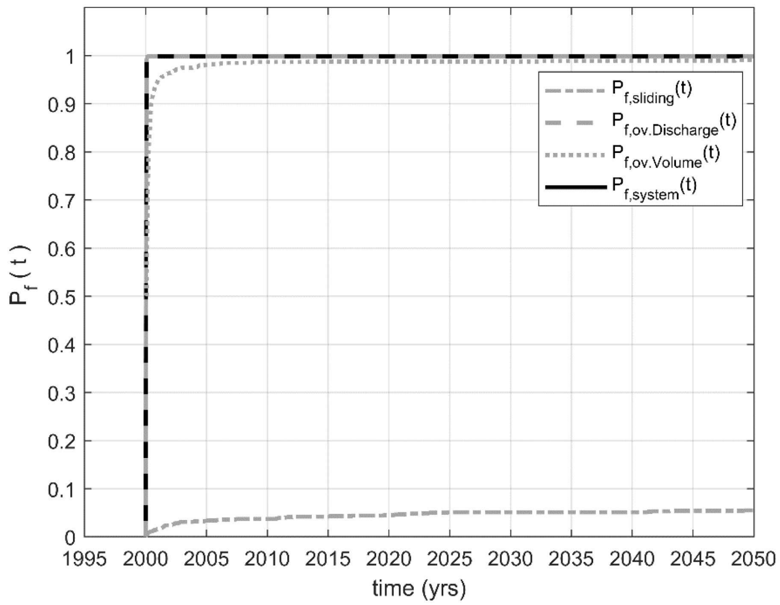

Fig. 8. Evolution in time of the failure probability of each failure mode and for the whole system.

Because the failure probability is numerically approximated using a limited number of realizations, the uncertainty of the results depends on the number of future lifetimes simulated. In this regard, the number of realizations in which the failure is reached can be described by a binomial distribution (see Lara et al. 2019). Then, the uncertainty related to the failure probabilities resulting from Monte Carlo simulation can be calculated (Tab. 2).

Tab. 2. Failure probabilities at the end of its lifetime (2050).

Failure probability	Lower bound (90 % CI)	P_f	Upper bound (90 % CI)
$P_{f,\ sliding}$	0.041	0.055	0.069
$P_{f,\ ov.Discharge}$	0.997	0.999	1.000
$P_{f,\ ov.Volume}$	0.985	0.991	0.997
$P_{f,\ System}$	0.997	0.999	1.000

As can be seen, the analyzed breakwater meets the safety requirements but not the serviceability requirements ($P_{f,max.ULS} = 0.1$, $P_{f,max.SLS} = 0.1$; see ROM 1.0-09) due to its low-crested design. It is worth emphasizing that the failure probability of the sliding failure mode has risen from 4.84 % for the period between 1948 and 1993 (Lara et al. 2019) to 5.5 % for the RCP8.5 scenario between 2000 and 2050.

3.4 Cost assessment

The last step is to obtain the economic consequences related to the simulated hydraulic performance undertook in subsection 3.3. This probabilistic cost assessment ensures better decision-making according to the context of uncertainty throughout its lifetime.

The total costs C_T include initial costs (construction costs, C_0), cost of repair of major damage (repairing costs associated with ULS failure modes, C_{r1}) and costs of repair of minor damage (repairing costs associated with SLS failure modes, C_{r2}). Because of the stochastic nature of the hydraulic performance, these costs are also random processes evolving with time (Fig. 9).

Costs related to minor damages are evaluated annually assuming to be a 0.2 per cent of the initial costs. Cost related to a major damage are evaluated every time the failure takes place assuming to be a 20 per cent of the initial costs. At the end of the lifetime, the total expected costs are 1.22±0.18 times the initial costs.

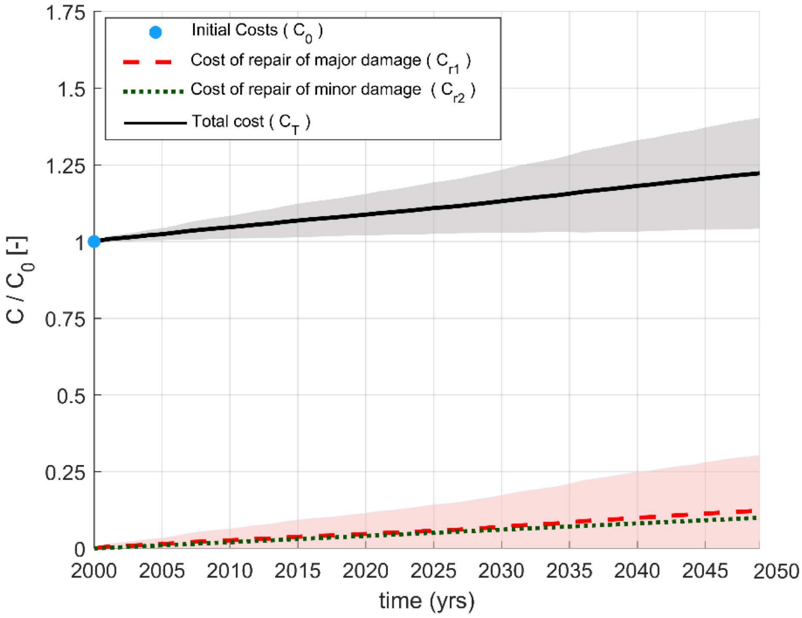

Fig. 9. Costs related to the future hydraulic performance. Evolution in time of the mean values (solid lines) and one standard deviation away from the mean (shaded areas).

4 Conclusions

The proposed work is focused on showing a complete probabilistic design of a non-conventional breakwater with the particularity that is located in shallow water conditions. Along the work, the following outputs are highlighted:

Regarding the simulation of wave-driven events, a multivariate-climate dependent model allows to reduce uncertainties related to wave climate. Hence, sea-level rise is also considered as a stochastic variable.

Accordingly the hydraulic behavior characterization, new location-based empirical formulae are tailored suit built for the analyzed breakwater applying an advanced CFD numerical model. These allow to take into account the complex configuration of the studied breakwater and its depth-limited wave conditions.

In accordance to the probabilistic methodology, it enables to manage the uncertainties related to the future met-ocean conditions and the hydraulic response. Moreover, the total lifetime costs are evaluated from a time-dependent and probabilistic point of view, which could be of a great benefit for the stakeholders to efficiently manage the coastal structure.

5 Acknowledgments

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