

ASSESSMENT OF THE FAILURE PROBABILITY OF UPGRADED RUBBLE-MOUND BREAKWATERS

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Nowadays, the existence of a huge number of aging harbor defense structures and climate change-induced forcing variability highlight the need for a methodology able to deal with uncertainties which arise during the design of new and above all upgraded structures. In the present work, a probabilistic design methodology based on the Monte Carlo simulation technique for the assessment of the failure probability due to independent failure modes and on the factor of change method for the inclusion of the effects of climate change is described, together with its application to the emblematic case study of the Catania harbor breakwater (Italy). The performances of the rubble-mound breakwater under present and future climate scenarios are assessed considering the existing structure and different upgrading options, which include both the raising of the wave wall and the addition of extra armor blocks. Three novel indexes describing the acceptability level of the structure performances (r) as well as the rate of growth (s) and the coefficient of variation (v) of the failure probability along lifetime are employed to quantitatively assess the performances of the existing and upgraded breakwater under present and future climate, considering the ultimate limit state due to the collapse of the outer armor layer and the serviceability limit state due to excessive mean wave overtopping discharge. The obtained results demonstrate that such indexes may give useful indication to designers and decision makers who deal with the upgrade of existing harbor defense structures under the effects of climate change.

Keywords: harbor defense structures; probabilistic design; Monte Carlo technique; climate variability

INTRODUCTION

Nowadays, existing harbor defense structures need maintenance and upgrade works, in view of the increasing demand of port service due to enhanced maritime traffic (Marino et al., 2023) and of the possible future intensification of climate forcing. Indeed, hydraulic performances of harbor defense structures are directly influenced by the effects of climate change (Sanchez-Arcilla et al., 2016; Camus et al., 2019; Izaguirre et al., 2021). The risk of global warming in port operations is even more high when harbor breakwaters are aging and deteriorated (Li et al., 2015). As a consequence, the design of upgrading solutions for historical harbor breakwaters in the face of climate change is one of the most urgent issue for coastal engineers (Hughes, 2014; Foti et al. 2020; Toimil et al., 2020), and it represents a challenge because of the necessity to deal with the uncertainty typical of climate projections (Morim et al., 2018) and the non-conventional nature of most of historical breakwaters (Lara et al., 2019).

Traditional design methods, which are based on the assumption of stationary forcing, do not consider uncertainties due to the stochastic nature of external forcing, the lack of knowledge on the breakwater material and geometry and to the complex wave-structure interaction. On the contrary, reliability-based design methods, which assess the performances of the structure through the calculation of the failure probability, are able to take into account the uncertainty of the design variables (Burcharth, 1987, 1993). While the theoretical basis of the probabilistic design dates back to the 80's-90's (CIAD project group, 1985; van der Meer, 1988a; Burcharth, 1993; PROVERBS, 1999), only recently it has started to be included into some recommendations and guidelines (e.g. US Army Corps of Engineers, 2002; TECH-JAPAN, 2009; Puertos del Estado, 2010), thanks to the diffusion of relatively cheap and high-performing computers that enable complex probabilistic calculations.

Despite several studies define the failure probability of vertical (e.g. Goda and Takagi, 2000), rubble-mound (e.g. Castillo et al., 2004) and composite (e.g. Campos et al., 2010) breakwaters, only few investigations consider the effects of climate change, frequently in a simplistic way. Indeed, expected mean sea level rise and projections of wind speed and significant wave height are often used to adjust the present wave climate conditions, ignoring possible modifications of storm surge, frequency, and duration of extreme storms (Takagi et al., 2011; Kim and Suh, 2014; Galiatsatou et al., 2018). Moreover, most of the existing studies does not provide methodologies to quantitatively compare the performances of existing and upgraded structures under different climate scenarios.

In this context, the present work describes a probabilistic methodology based on the Monte Carlo simulation technique and the factor of change method (Peres and Cancelliere, 2018) for assessment of the performances of existing and upgraded rubble-mound harbor breakwaters in the presence of climate

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change, which allows the quantitative comparison between different structure configurations and climate scenarios. The proposed methodology was applied to an emblematic case study considering the independent failure modes due to the collapse of the outer armor layer and to excessive mean wave overtopping discharge, in order to demonstrate that it can provide useful indications for the selection and design of upgrading solutions for existing structures.

METHODOLOGY

The assessment of the failure probability of new, existing or upgraded rubble-mound breakwaters requires the definition of the fault tree representing the relationships between the possible failure mechanisms, which for such a kind of structures are usually related according to a series system (US Army Corps of Engineers, 2002). Each independent failure mechanism, which can refer to an ultimate limit state (ULS) or serviceability limit state (SLS), is described by a state-of-art or site-specific governing equation, which is re-written as a reliability function (US Army Corps of Engineers, 2002):

$$Z = R - S \quad (1)$$

where R includes all the variables contributing to the structure resistance (e.g. geometry of the structure and the characteristics of the component materials) and S represents the external solicitations (e.g. significant wave height, mean wave period, storm surge height). If $Z < 0$, the structure reaches the considered ULS or SLS, and the failure occurs. Since both R and S are stochastic variables, the failure probability during the structure lifetime made up by L years is calculated through the Monte Carlo (MC) simulation technique. According to the indications of Puertos del Estado (2010), each realization of the MC simulation is a life cycle of the structure, which consists of L meteorological years. During each meteorological year, a certain number of sea storms is randomly generated from the probability distributions of the wave climate parameters for the considered site.

In the present work, a marine climate emulator has been employed to generate random sea storms and sea levels, also considering the effects of climate change (Stagnitti et al., 2022). Present (i.e. measured or modeled) and future (i.e. projected) time series of wave climate descriptors are employed for the evaluation of the probability density function of extreme offshore significant wave height (H_{s0}) through the peak over threshold (POT) technique, with threshold equal to 1.50 m and minimum distance between independent events equal to 12 hours (Boccotti, 2004), and the method of moments estimation (MME). Since climate projections are affected by high uncertainty, the calculation of the future climate moments is not performed using directly the raw time series, but by means of the factor of change method (Peres and Cancelliere, 2018). Such a method consists in the calculation of each statistical moment of the projected time series through the multiplication of the corresponding one calculated for the present period by the following correction factor:

$$FOC = \frac{M_{m,f}}{M_{m,c}} \quad (2)$$

where $M_{m,f}$ and $M_{m,c}$ are the statistical moment calculated using the time series of the climate projection model corresponding to the future and the historical control period, respectively. Other climate descriptors, such as mean wave period ($T_{m,0}$), sea storm duration (d_s) and storm surge height (h_{SS}), are correlated to $H_{s,0}$ through site-specific empirical formulas. Therefore, for each random $H_{s,0}$ generated from the extreme value distribution, the corresponding values of the other climate descriptors are calculated using the site-specific empirical formulas, taking into account their uncertainty. Only the mean water depth is assumed independent from the other climate descriptors, and randomly generated from a Normal distribution. Finally, site-specific formulations are employed for wave propagation towards the breakwater site, also including breaking criteria for depth-limited and steepness-limited waves. It should be noted that the use of the factor of change method implies that the projected time series are analyzed using a yearly moving time window, which covers the same number of years of the data corresponding to the present period. Therefore, for each future scenario the marine climate generation and the calculation of the failure probability are performed with reference to several sub-periods.

The number of sea storms to generate during each simulated life cycle is given by the product between L and the mean number of sea storms per year derived from the POT analysis of the $H_{s,0}$ time series. The generated sea storms may cause or not the achievement of the considered limit state. Therefore, the failure probability during the structure lifetime is calculated as follows:

$$P_{f,L} = \frac{N_f}{N_r} \quad (3)$$

where N_f is the number of life cycles with at least one failure (i.e. $Z < 0$), and N_r is the number of simulated life cycles (i.e. realizations of the MC simulation). The number of life cycles to simulate is fixed on the basis of the results of the preliminary analysis of the stabilization process of $P_{f,L}$ and of its coefficient of variation (CV) by varying N_r . In the present work, a maximum acceptable CV equal to 0.35 is considered.

The failure probability is calculated through the above-described procedure for the existing breakwater and for each possible upgrading solution. The quantitative comparison between the performances of different configurations of the structure under present and future scenarios in terms of failure probability requires the definition of easy-to-use indexes. Here, the following indexes are proposed:

- the ratio r between the calculated and the maximum acceptable failure probability during lifetime, which is lower than one when the performances of the structure are sufficient to satisfy the design requirements:

$$r = P_{f,L} / P_{f,L \max} \quad (4)$$

- the rate of the growth s of the failure probability during lifetime, which is the slope of the linear regression model describing the variation of the failure probability as a function of the duration of the lifetime;
- the ratio between the standard deviation and the mean of the failure probability during lifetime calculated with reference to the sub-periods of the considered future scenario, which measures the uncertainty of $P_{f,L}$ due to the variability of the input climate:

$$v = \sigma_c / \mu_c \quad (5)$$

CASE STUDY

The proposed methodology was applied to assess the failure probability during lifetime of different upgraded configurations of the cube-armored Catania harbor breakwater (Italy, see Fig. 1), considering the present scenario and RCP4.5 end-century (2071-2100) and RCP8.5 mid-century (2041-2070) future scenarios. As showed in Fig. 2a, the existing structure and five upgrading solutions were studied, which include the heightening of the wave wall and the addition of extra armor blocks equal or to or smaller than the existing ones (i.e. 62 t cubes and 30 t Antifer units, respectively), placed according to different patterns and with a quarry stone toe berm. If the laying surface is not reshaped, the geometry of the toe of the additional armor layer strongly depends on the waviness of the existing one. For instance, Fig. 2b shows the detail of the toe of the additional armor layer for cross-sections no.10 and no. 40 indicated in Fig. 1. At cross-section no. 10, the extra armor units are not directly in contact with the internal slope of the toe berm, contrary to the case of cross-section no. 40.

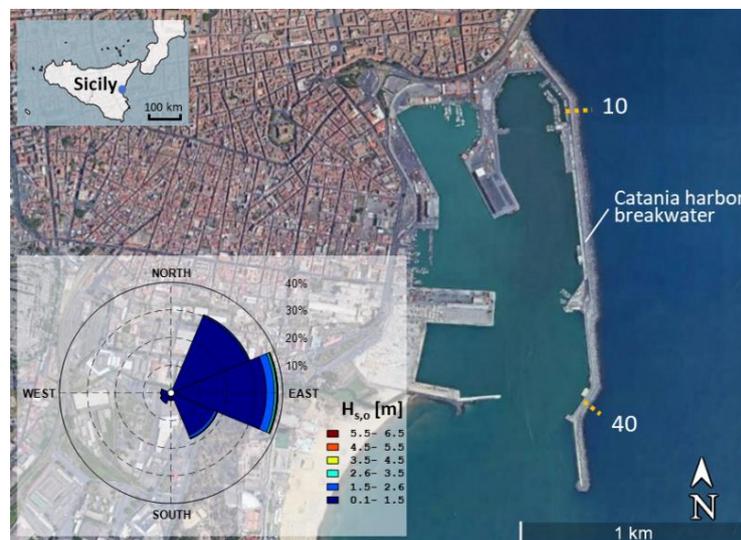


Figure 1. Location and layout of the Port of Catania (Google Earth, 2022) and wave rose representative of the site. Two representative cross-section of the breakwaters are indicated.

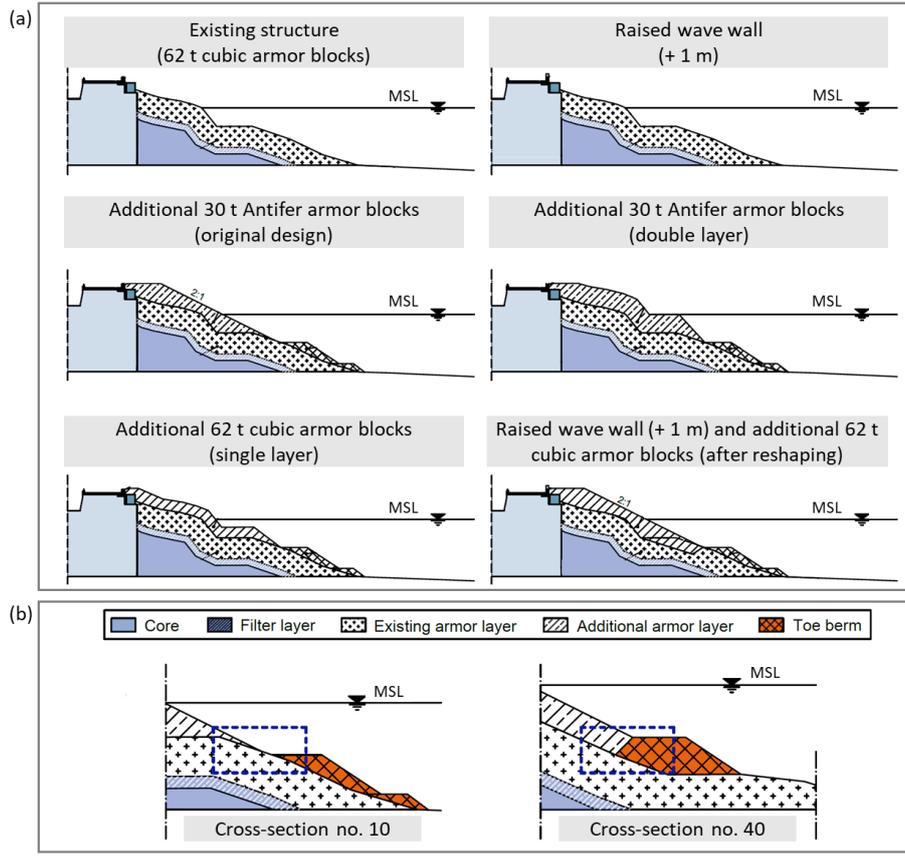


Figure 2. (a) Configurations of the Catania harbor breakwater at cross-section no. 10 and (b) detail of the geometry of the toe of the additional armor layer.

Fig. 3 shows the simplified fault tree considered in the present study. For ULS, the collapse of the outer armor layer was analyzed, considering the case of addition of an extra armor layer over the existing one. Instead, for SLS, the excessive mean wave overtopping discharge was studied for the existing structure and for the solution with both raise of the wave wall and addition of extra 62 t cubic armor units. The structure lifetime and the maximum acceptable failure probability were set equal to 50 years and 0.1, respectively (Puertos del Estado, 2010). The number N_r of generated life cycles for each climate scenario was 2.25×10^4 . The following reliability functions for the selected ULS and SLS were deduced from van der Meer (1988a) and EurOtop (2018), respectively:

$$Z_{ULS} = f \times \left(6.7 \frac{N_{od}^{0.4}}{N_w^{0.3}} + 1 \right) \times \Delta D_{n50} - H_s \times \left(\frac{2\pi H_s}{g T_m^2} \right)^{0.1} \quad (6)$$

$$Z_{SLS} = q^* - \sqrt{g H_s^3} \times a \times \exp \left[- \left(b \times \frac{R_c}{H_s \gamma_f} \right)^{1.3} \right] \quad (7)$$

In Eq. 6, f is the empirical coefficient of the formula, N_{od} is the damage parameter, $N_w = (3600 d_s)/T_m$ is the number of incident waves, Δ and D_{n50} are the relative density and the median nominal diameter of the armor units, H_s and T_m are the significant wave height and the corresponding mean wave period at the toe of the structure. In Eq. 7, q^* is the non-dimensional mean overtopping discharge, g is the gravity acceleration, a and b are the empirical coefficients of the formula, $R_c = h_{wall} - (h + h_{SS})$ is the maximum value between the crest level and the wave wall height referred to mean sea level, with h and h_{SS} being respectively the mean water depth and the storm surge height, h_{wall} is the height of the wave wall measured with respect to the toe of the structure, and γ_f is the roughness factor (equal to 0.47 for double layer of artificial cubes).

The values of H_s , T_m , d_s , h and h_{SS} for each realization of the MC simulations under present climate were generated by the marine climate emulator, whose input were the measured wave time series (APAT, 2004) and modeled storm surge height data (Hersbach et al., 2019) referred to the years 1989-2014. The

wave rose displayed in Fig. 1 indicates that the most energetic sea states come from the angular sector centered in the 90°N direction, which therefore was considered in the present study. Fig. 4 shows the adapted probability distribution function of the extreme offshore significant wave height, which is characterized by a frequency of occurrence of sea storms equal to about 13 events/year, together with the randomly generated H_{s0} for the present scenario. Such random H_{s0} values were used to calculate the corresponding values of mean wave period, sea storm duration and storm surge height through site-specific formulas defined applying the least squares method to available datasets. The water depth at the toe of the structure h was randomly generated from the defined Normal distribution. Then, a site-specific formula is employed to model wave propagation towards the breakwater site, also including the breaking criteria. Instead, the wave and storm surge height projection datasets provided by Copernicus Climate Change Service (2019) were employed for the two considered future scenarios. Since the present time series are shorter than the future ones, a yearly-moving time window having length equal to the number of years covered by the present data (i.e. 17 years) was used to apply the factor of change method and to calculate the extreme value distributions of H_{s0} , which are characterized by a frequency of occurrence of sea storms in the range 12÷14 events/year. Then, random sea storms were generated following the same procedure employed for the present scenario.

N_{od} and q^* represent the considered limit state and were set equal to 2.00 and $5 \times 10^3 \text{ m}^3/\text{s}$, respectively. All the other parameters are normally distributed, similarly to h . Table 1 reports the mean and the standard deviation of the normally distributed variables included in Eq. 6 and Eq. 7. The standard deviations of the Normal distributions of Δ and D_{n50} were set following the indications of van der Meer (1988b) and Burcharth (1992). Moreover, such Normal distribution were truncated to avoid possible unrealistic values during the random generation process. Instead, the standard deviation of the Normal distribution of h_{wall} was set following the indications of Lara et al. (2019). The employed values of f , a and b are not only the ones indicated by van der Meer (1988a) and EurOtop (2018), but also the site-specific ones deduced from the results of the previously carried out composite modeling of the upgraded Catania harbor breakwater (Stagnitti et al., 2020, 2022, 2023). In particular, site-specific values of f were calculated for the cases showed in Fig. 2b of additional armor layer in direct contact with the toe berm (SS) or not (NSS). Instead, values of a and b were calculated for the existing structure and for the configuration with additional armor layer and raised wave wall. In this way, the failure probabilities obtained using state-of-art and site-specific formulas could be compared.

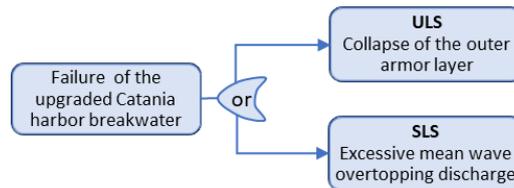


Figure 3. Fault tree for the upgraded Catania harbor breakwater.

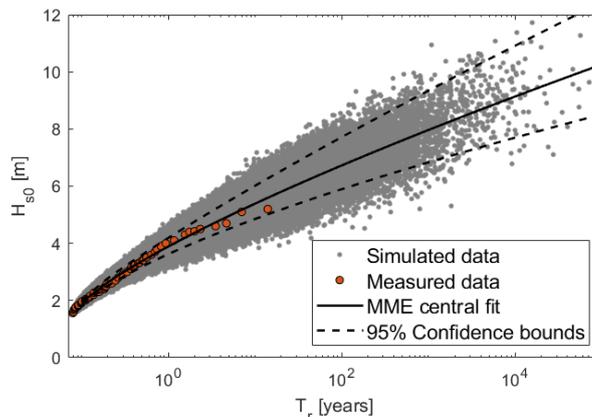


Figure 4. Central fit and 95% confidence bounds of the Weibull distribution of extreme H_{s0} for the site of Catania under present climate.

Variable	Formulation	Mean	Standard deviation
f [-]	van der Meer (1988a)	1.00	0.10
	Experimental - SS	1.72	0.29
	Experimental - NSS	1.35	0.20
	EurOtop Manual (2018)	0.09	0.01
a [-]	Numerical - existing	0.30	0.14
	Numerical - upgraded	0.06	0.05
	EurOtop Manual (2018)	1.50	0.15
b [-]	Numerical - existing	1.50	0.10
	Numerical - upgraded	1.50	0.15
	Present	19.00	0.10
h [m]	RCP4.5	19.36 ÷ 19.42	0.10
	RCP8.5	19.24 ÷ 19.33	0.10
	30 t Antifer	2.35	0.03
D_{n50} [m]	30 t Cubes	3.00	0.03
Δ [-]	-	1.23	0.05
h_{wall} [m]	Existing wave wall	27.5	0.03
	Raised wave wall	28.5	0.03

RESULTS

The index r calculated with the traditional and site-specific reliability functions for ULS and SLS is smaller than one under both present and future scenarios, thus indicating acceptable structural and hydraulic performances for all the tested configurations (see Fig. 5a and Fig. 6a).

The state-of-art reliability function employed for the ULS of the upgraded configurations is far more conservative than the site-specific ones. Figure 5a shows that the first one produces values of r up to 34 and 8 times higher than the SS and NSS reliability functions, respectively. Moreover, Figure 5b reveals that the ULS state-of-art reliability function gives s greater by 49 and 9 times than the SS and NSS formulations. Instead, the site-specific reliability function used for the SLS is the most conservative for the existing structure, but not for the upgrading solution with additional 62 t cubes and raised wave wall. In particular, as shown in Fig. 6a-b, the SLS site-specific formula produces r and s 0.66 times higher than the state-of-art one for the existing configuration. On the contrary, the SLS site-specific reliability function gives r and s about 0.37 times smaller than the state-of-art one for the upgraded configuration.

The comparison between present and future performances of the existing and upgraded structure revealed a reduction of r and s , for both the considered limit states. Fig. 7 shows that the percentage reduction of future r and s calculated for all the upgrading options with additional armor units considering the ULS is about 40% under both future scenarios. Instead, Fig. 8 shows the percentage reduction of future r and s calculated for the existing structure and the upgrading solution with additional 62 t cubes and heightened wave wall considering the SLS. The two indexes experience a 42% and 19% reduction on average, under RCP4.5 and RCP8.5 scenarios, respectively. Such results are in accordance with the expected reduction of future H_{50} found for the site of Catania. In this regard, it is worth to point out that the effects of the expected reduction of H_{50} on wave overtopping phenomena are more significant than the effects of the projected mean sea level rise.

The analysis of the indexes r and s allowed the quantitative comparison between the performances of the tested configurations. As regards the ULS due to the collapse of the outer armor layer, the results confirmed that the use of 62 t additional cubic blocks ensures the lowest r and s . Moreover, for the SLS due to the excessive mean wave overtopping discharge, the addition of similar armor units to the existing ones together with the heightening of the wave wall by one meter produced a reduction of r and s by 0.86 times on average.

Finally, the analysis of v showed that its highest values correspond to those configurations with the lowest failure probability, and hence with the lowest r . Such a result is in accordance with the fact that the lower $P_{f,L}$ is, the higher the CV of the corresponding MC simulation is. As regards the uncertainty component due to climate variability, it is higher than one only for the mid-century period under RCP8.5 scenario. When v is higher than one, highly flexible maintenance interventions should be planned to avoid excessive cost of being wrong about future climate change.

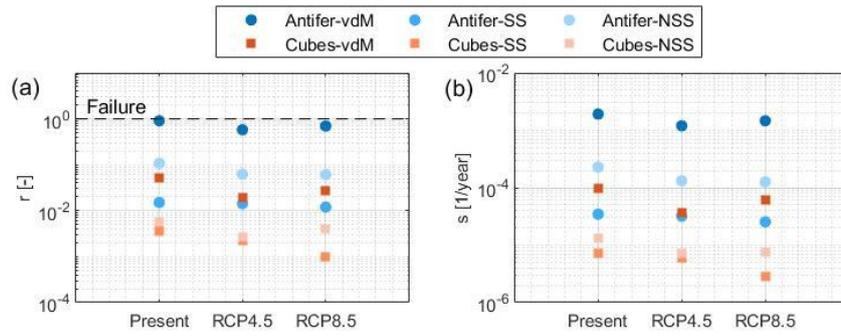


Figure 5. Indexes of the failure probability during lifetime due to the collapse of the outer armor layer (ULS), calculated for the present period (1989-2005) and the future sub-periods 2084-2100 under RCP4.5 and 2053-2069 under RCP8.5: (a) ratio between $P_{f,L}$ and the acceptance limit; (b) rate of the growth of the failure probability during lifetime.

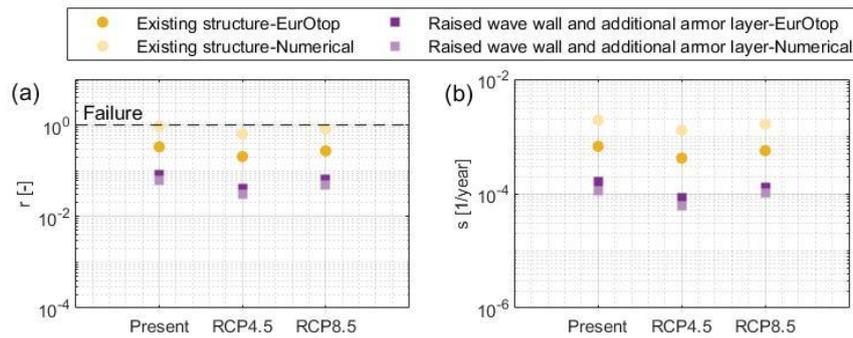


Figure 6. Indexes of the failure probability during lifetime due to excessive mean wave overtopping discharge (SLS), calculated for the present period (1989-2005) and the future sub-periods 2084-2100 under RCP4.5 and 2053-2069 under RCP8.5: (a) ratio between $P_{f,L}$ and the acceptance limit; (b) rate of the growth of the failure probability during lifetime.

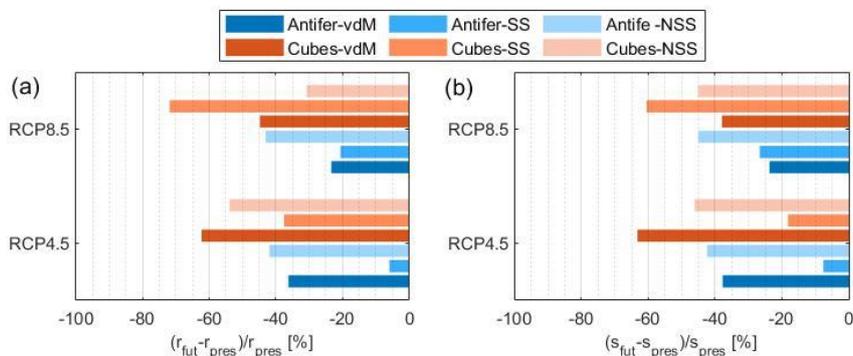


Figure 7. Percentage difference between the future and present (a) r and (b) s calculated considering the failure probability due to the collapse of the outer armor layer (ULS).

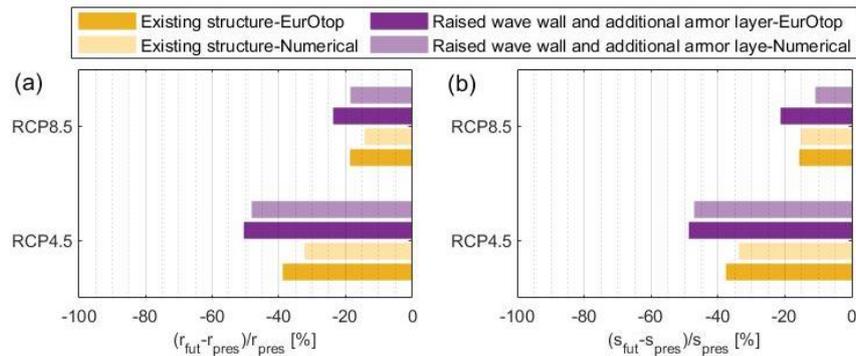


Figure 8. Percentage difference between the future and present (a) r and (b) s calculated considering the failure probability due to excessive mean wave overtopping discharge (SLS).

CONCLUSIONS

The present work describes a probabilistic methodology for the assessment performances of existing and upgraded harbor breakwaters under the effects of climate change. Such a methodology is based on the MC simulation technique for the calculation of the failure probability along lifetime due to independent failure modes of the breakwater. Moreover, the factor of change method is employed to include climate projections and assess the expected structure future performances. In order to make the results of the application of the probabilistic methodology usable for designers and decision makers involved in upgrading processes of existing harbor breakwaters, three quantitative indexes were defined: i) the ratio between the calculated and the maximum acceptable failure probability during lifetime (r); ii) the rate of the growth of the failure probability along the lifetime (s); iii) the coefficient of variation of the failure probability along the lifetime due to uncertainty of both MC simulation and climate variability (v).

The proposed methodology was applied to the existing and upgraded configurations of the cube-armored rubble-mound breakwater of the Port of Catania (Italy). The obtained results revealed that the use of traditional formulas for the description of failure mechanisms may cause significant underestimation of the failure probability when applied to non-conventional existing or upgraded structures, thus highlighting the importance of physical and numerical modelling. Concerning the defined quantitative indexes of performance, r appeared as an easy-to-use measure of the adequacy of different configurations of the structure to withstand both present and future external forcing, whereas s gives useful indications for planning maintenance interventions during the structure lifetime including the effects of climate change. Moreover, v quantifies the level of uncertainty of the structure performance estimates, thus enabling the identification of those configurations that, under certain climate conditions, requires the design of highly flexible maintenance plan able to ensure an economically optimal adaptation to highly variable climate conditions.

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REFERENCES

- APAT-University of Roma TRE 2004. Italian Wave Atlas. APAT.
- Boccotti, P. 2004. *Idraulica marittima* (Turin, Italy: UTET Università).
- Burcharth, H. F. 1987. The lessons from recent breakwater failures. Developments in breakwater design (Vancouver: World Federation of Engineering Organizations Technical Congress).
- Burcharth, H. F. 1992. "Introduction of partial coefficients in the design of rubble mound breakwaters," in *Coastal structures and breakwaters* (London, England: Thomas Telford), 543–566.
- Burcharth, H. F. 1993. Reliability evaluation and probabilistic design of coastal structures, *International Seminar on Hydro-Technical Engineering for Future Development of Ports and Harbors*.
- Campos, A., Castillo, C., and Molina, R. 2010. Optimizing breakwater design considering the system of failure modes. *Proc. 32nd Int. Conf. Coastal Eng.*, Shanghai, China (Vol. 30).

- Camus, P., Tomás, A., Díaz-Hernández, G., Rodríguez, B., Izaguirre, C., and Losada, I. 2019. Probabilistic assessment of port operation downtimes under climate change. *Coastal Engineering* 147, 12–24.
- Castillo, E., Losada, M. A., Mínguez, R., Castillo, C., and Baquerizo, A. 2004. Optimal engineering design method that combines safety factors and failure probabilities: Application to rubble-mound breakwaters. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 130, 77–88.
- Copernicus Climate Change Service 2019. ECMWF Copernicus Report. Product user guide for sea level and ocean wave products - time series and indicators.
- EurOtop 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.
- Foti, E., Musumeci, R. E., and Stagnitti, M. 2020. Coastal defence techniques and climate change: A review. *Rendiconti Lincei. Scienze Fisiche e Naturali* 31, 123–138.
- Galiatsatou, P., Makris, C., and Prinos, P. 2018. Optimized reliability-based upgrading of rubble mound breakwaters in a changing climate, *Journal of Marine Science and Engineering* 6, 92.
- Goda, Y., and Takagi, H. 2000. A reliability design method of caisson breakwaters with optimal wave heights. *Coastal Engineering Journal*, 42(4), 357-387.
- Hersbach, H., Bell, B., Berrisford, P., Horányi, A., Sabater, J. M., Nicolas, J., Radu, R., Schepers, D., Simmons, A., Soci, C., and Dee, D. 2019. Global reanalysis: goodbye ERA-Interim, hello ERA5. *ECMWF Newsletter* 159, pp. 17–24.
- Hughes, S. A. 2014. Coastal engineering challenges in a changing world. *Journal of Applied Water Engineering and Research*, 2(2), 72-80.
- Izaguirre, C., Losada, I. J., Camus, P., Vigh, J. L., and Stenek, V. 2021. Climate change risk to global port operations. *Nature Climate Change*, 11(1), 14-20.
- Lara, J. L., Lucio, D., Tomas, A., Di Paolo, B., and Losada, I. J. 2019. High resolution time-dependent probabilistic assessment of the hydraulic performance for historic coastal structures: Application to Luarda breakwater. *Philosophical Transactions of the Royal Society A* 377, 20190016.
- Marino, M., Cavallaro, L., Castro, E., Musumeci, R. E., Martignoni, M., Roman, F. and Foti, E. 2023. New frontiers in the risk assessment of ship collision. *Ocean Engineering*. In press.
- Morim, J., Hemer, M., Cartwright, N., Strauss, D., and Andutta, F. 2018. On the concordance of 21st century wind-wave climate projections. *Global planetary Change* 167, 160–171.
- Kim, S. W., and Suh, K. D. 2014. Determining the stability of vertical breakwaters against sliding based on individual sliding distances during a storm. *Coastal Engineering*, 94, 90-101.
- Peres, D. J., and Cancelliere, A. 2018. Modeling impacts of climate change on return period of landslide triggering. *Journal of Hydrology*, 567, 420-434.
- Puertos del Estado 2010. ROM-1.0-09 Recommendation for the Project Design and Construction of Breakwater. Part I: Calculation and Project Factors. Climate Agents.
- Sánchez-Arcilla, A., Sierra, J. P., Brown, S., Casas-Prat, M., Nicholls, R. J., Lionello, P., and Conte, D. 2016. A review of potential physical impacts on harbours in the mediterranean sea under climate change. *Regional Environmental Change* 16, 2471–2484.
- Stagnitti, M., Iuppa, C., Musumeci, R. E., and Foti, E. 2020. Catania harbor breakwater: Physical modelling of the upgraded structure. *Coastal Engineering Proceedings*, 2–2
- Stagnitti, M., Lara, J. L., Musumeci, R. E., and Foti, E. 2022. Assessment of the variation of failure probability of upgraded rubble-mound breakwaters due to climate change. *Frontiers in Marine Science*, 9:986993.
- Stagnitti, M., Musumeci, R. E., and Foti, E. 2023. Surface roughness measurement for the assessment of damage dynamics of existing and upgraded cube-armored breakwaters. *Coastal Engineering*, 179, 104226.
- Suh, K. D., Kim, S. W., Mori, N., and Mase, H. 2012. Effect of climate change on performance-based design of caisson breakwaters. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 138, 215–225.
- Takagi, H., Kashihara, H., Esteban, M., and Shibayama, T. 2011. Assessment of future stability of breakwaters under climate change. *Coastal Engineering Journal*, 53(01), 21-39.
- TECH-JAPAN 2009. Technical standards and commentaries on port and harbour facilities in Japan. Ports and Harbours Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), National Institute for Land and Infrastructure Management, MLIT, and Port and Airport Research Institute. Tokyo, Japan: The Overseas Coastal Area and Development Institute of Japan.

- Toimil, A, Losada, I. J., Nicholls, R. J., Dalrymple, R. A., and Stive, M. J. F. 2020. Addressing the challenges of climate change risks and adaptation in coastal areas: A review. *Coastal Engineering*, 156, p. 103611.
- US Army Corps of Engineers 2002. Coastal engineering manual. US Army Engineering Research and Development Center Vicksburg, Mississippi.
- van der Meer, J. W. 1988a. Stability of cubes, tetrapods and accropode. *Breakwaters '88* (American Society of Civil Engineers), 59–68.
- van der Meer, J. W. 1988b. Deterministic and probabilistic design of breakwater armor layers. *Journal of Waterway, Port, Coastal and Ocean Engineering* 114, 66–80. doi: 10.1061/(ASCE)0733-950X(1988)114:1(66)