Assessing failure probabilities of rubble mound breakwaters for extreme conditions under climate change

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Abstract

In the present work, the performance of a selected conventional rubble mound breakwater to different failure mechanisms under extreme conditions associated with climate change, is investigated. The nonstationary Generalized Extreme Value distribution (GEV) is fitted to annual extremes of offshore significant wave heights and sea surface heights due to storm surges at the site of the defence. Extracted distributions for extreme waves are transferred to the breakwater site by means of a statistical approach. Time-dependent future failure probabilities of the structure are assessed for different failure mechanisms within the general framework of nonstationary reliability analysis. Failure probability estimates are used to determine future periods of increased vulnerability of the studied structure to different ultimate limit states. The analysis defines critical failure mechanisms and proves that the assumption of stationarity underestimates the total failure probability of the structure under extreme marine conditions.

Keywords Reliability, Rubble mound breakwater, Climate change, Extreme value theory.

1 INTRODUCTION

Global climate change is expected to cause significant long-term changes in mean sea level (MSL), wave height and storm variability (IPCC 2007, 2012). The general inception of a changing climate with extreme marine events of higher intensity and frequency and MSL rise increases vulnerability and exposure of port and harbour structures to different failure modes, resulting in their inability to fulfill their requirements. Increased future hydraulic loadings, combined with the limited residual service lifetime of many of them, and the fact that economic activity is assembled in these areas, creates a need for a reliable estimation of failure probabilities of such defences under future extreme marine conditions.

Although the majority of scientific studies examining climate change effects in the Mediterranean has focused on the variability and long-term trends in MSL (*i.e.* Adloff et al. 2015), changes in extreme storm surges and waves under climate change started to gain interest quite recently (*i.e.* Benetazzo et al. 2012, Galiatsatou et al. 2016, Makris et al. 2016). The effects of climate change on coastal and port or harbour structures received considerable attention only during the last decade (*i.e.* Suh et al. 2013, Isobe 2013, Burcharth et al. 2014).

Risk-based approaches are currently gaining ground in the process of evaluating safety of coastal structures subject to increased marine conditions. Reliability analysis, corresponding to assessing failure probabilities of such defences, forms an inherent part of a risk-based approach to designing new or evaluating the performance of existing coastal structures (*i.e.* Dai Viet et al. 2008, Kim and Suh 2010, Naulin et al. 2015, Galiatsatou et al. 2018). The vast majority of these studies focus on specific variables of the marine climate (*i.e.* MSL rise or wave climate) and do not consider nonstationarities of marine climate variables under future climate conditions.

In the present work, the performance of a selected conventional rubble mound breakwater to different failure mechanisms under extreme marine conditions associated with climate change, is investigated. Failure probabilities of the structure are assessed for different failure mechanisms, considering variations in MSL, wave climate and storm surge, within the general framework of nonstationary reliability analysis.

2 METHODOLOGY

2.1 *Extraction and analysis of extreme sea states at port or harbour sites*

The boundary conditions for designing or evaluating the safety of port or harbour protection structures mainly include the hydraulic conditions at the site of the defence. Collapse of the defence is associated with Ultimate Limit States (ULS) happening under extreme marine conditions. To capture nonstationarity in the univariate marine extremes, a time-dependent Generalized Extreme Value (GEV) distribution (Galiatsatou et al. 2019) is fitted to deepwater significant wave height (H_s) annual maximum events. To estimate the parameters of the nonstationary distributions a 50-years length moving time window with an annual time step is used. The derived parameter estimates correspond to the last year of each 50-years period. Appropriate nonstationary distribution functions are also fitted to extreme sea level heights due to storm surge (*SLH*) at the site of the structure (Makris et al. 2018).

The abovementioned nonstationary univariate distributions for extreme H_s are then transferred to the site of the breakwater following an approach proposed by Suh et al. (2013). The latter is based on the assumption that H_s distributions in coastal water reduce in the mean and in the standard deviation compared with the deepwater waves, so that their coefficient of variation remains constant. However, the shape of their distribution does not undergo any significant changes. This procedure, which also considers design quantities of the existing structure, is implemented for each moving window to extract time-dependent estimates of all GEV parameters in the study area.

2.2 *Assessment of nonstationary failure probabilities under climate change*

Principal failure mechanisms of conventional rubble mound breakwaters include failure or instability of the windward armour layer, failure of the leeward slope, scouring of the toe, excessive overtopping, the slip cycle, sliding and tilting of existing superstructures, and excessive settlement. Three failure modes are considered here as the main types of instability under extreme marine conditions, namely instability of the windward primary armour layer, excessive overtopping, and scouring of the breakwater toe. Reliability analysis hinges on the use of the probability of failure, P_f, as a measure of the structure performance. The reliability function, Z, for a certain limit state is defined as the difference between the resistance of the structure and the load it is exposed to. The failure domain is defined for $Z \leq 0$. Reliability functions contain variables of the marine climate at the windward side of the breakwater, as well as variables describing geometrical and material properties of the studied structure. Level II reliability methods, including the linearization of the reliability function at an appropriately defined design point of the failure space, are used in this work to assess time-dependent P_f for the limit states.

The reliability function for hydraulic stability of a windward primary armour layer composed of accropodes is based on the stability formula of Van der Meer (1998), using a safety factor of 1.5:

$$Z_{stability} = 2.5 \cdot \Delta \cdot D_n - H_{su} \tag{1}$$

where $\Delta = (\rho_{ac}/\rho_w) - 1$ and ρ_{ac} and ρ_w are accropode and water densities [ton/m^3], D_n [m] is the characteristic diameter of armour stone units, and H_{su} [m] is the significant wave height in front of the studied breakwater corresponding to its ULS. The reliability function for excessive wave overtopping is based on the formula of EurOtop (2007):

$$Z_{overtopping} = q - 0.2 \cdot C_r \cdot \exp\left(-\frac{2.3 \cdot R_c}{\gamma_f \cdot H_{su}}\right) \sqrt{g H_{su}{}^3} \; with \, R_c = H_{crest} - MSLR - TR_{max} - SLH \tag{2}$$

where q [m^2/s] is the maximum allowable overtopping discharge, $C_r = 3.06 \cdot exp(-B/H_{su})$ is the reduction factor due to effect of armoured crest berm of width B [m], γ_f is the influence factor for crest armour units, and R_c [m] is the freeboard height resulting when subtracting MSL rise, $MSLR$ [m], maximum tidal range, TR_{max}, and storm surge, SLH [m], from crest level height, H_{crest} [m]. The reliability function for toe stability is based on the formula proposed by Van der Meer et al. (1995):

$$Z_{scouring} = \left(0.24\frac{h_t}{D_{n50}} + 1.6\right) {N_{od}}^{0.15} \varDelta D_{n50} - H_{su} \; with \; h_t = d + MSLR + TR_{mean} + SLH \qquad (3)$$

where h_t [m] is the total water depth at the breakwater toe, D_{n50} [m] is the characteristic diameter of toe elements, N_{od} is the number of displaced units within a strip with width D_{n50}, d [m] is the depth of the water column from MSL to breakwater toe, and TR_{mean} [m] is the mean tidal range of the area.

3 STUDY AREA AND AVAILABLE DATASETS

The selected conventional rubble mound structure is located at the port of Alexandroupolis in the northern Greek coast of the Aegean Sea. The southern windward breakwater protects the port from waves of south and southwestern origin. Its newly constructed part of length 1155m has a primary armour layer made of Accropode blocks with unit volume of $5m^3$. The breakwater has been designed for deepwater H_s=5.25m and peak spectral period T_p=9s, and for a maximum incident H_s=4m locally at the breakwater site. The water depth in front of the breakwater toe is d=5m, its crest level height H_{crest}=5.10m, and its crest width B=7.7m. Its windward and leeward slopes are 3/4. The breakwater toe consists of rocks with maximum weight of 6tons. The necessary wave and SLH data used in this paper cover a period of 150 years (1951-2100) and are derived from 3-hourly simulation results for the Greek Seas, produced by SWAN wave model and the high-resolution two-dimensional, barotropic, storm surge model GreCSS (Makris et al. 2016). Forcing of wind and atmospheric pressure fields are derived from dynamically downscaled simulations with Regional Climate Model RegCM3, and future climate projections are based on IPCC-A1B emissions scenario (IPCC 2007).

The Aegean Sea is a semi-enclosed water basin labelled as a marginal sea, with rather low maxima of storm surge-induced sea levels in the coastal zone, identifying H_s extremes as the primary cause of port downtime (stoppage of operations within the basins due to malfunction of the protection system). Wave height events of directions affecting the port of Alexandroupolis, exceeding a threshold of 1.5m for durations more than six hours, were initially selected at a representative point of the SWAN model grid in the offshore area of the study site. Waves have been corrected for bias (Makris et al. 2016) and annual maxima were extracted to be fitted by the nonstationary GEV distribution (see Sect. 2.1). Nearshore storm-driven SLH corresponding to the respective annual maxima of H_s was also used in the analysis. A five-day window of SLH data was used, covering the time of corresponding records of H_s maxima by 2.5 days bilaterally, and extracted data was fitted by the nonstationary GEV distribution. To assess the MSL rise in the Aegean Sea (used in Eqs. 2-3), both a steric and a component of mass addition due to ice melting were considered, resulting to a total value of 25cm by 2100 (Galiatsatou et al. 2019). The maximum tidal range near the port of Alexandroupolis is considered to be TR_{max}=0.66m while the respective mean tidal range is TR_{mean}=0.24m (HNHS 2011).

4 RESULTS

The nonstationary GEV distribution was first fitted to extreme deepwater H_s and nearshore SLH and parameters of the fitted 50-year windows were estimated using L-moments. Figure 1 presents time-dependent estimates of 100-years return levels of H_s and SLH for the selected study site, together with their associated 95% confidence intervals estimated using a parametric bootstrap approach.

H_s return level estimates present an increasing trend in the first half of the 21st century, with their maximum values in the interval 2040-2055. A second peak in H_s extremes appears around 2065-2070, while H_s decreases rapidly at the end of the century. Most probable estimates of H_s vary more than 33% within the 21st century, while predictions in the mid-century appear highly uncertain (very wide 95% confidence intervals). GEV distributions of deepwater H_s extremes have been then transferred to the studied breakwater site (see Sect. 2.1). SLH extremes at the breakwater site show quite similar variation to the respective deepwater H_s estimates. They present an evident increasing trend in the interval 2020-2040, and a decreasing one in 2070-2100. Two peaks in SLH extremes can be distinguished, around 2040 and 2065, while predictions in the interval 2040-2070 are characterized by increased uncertainty.

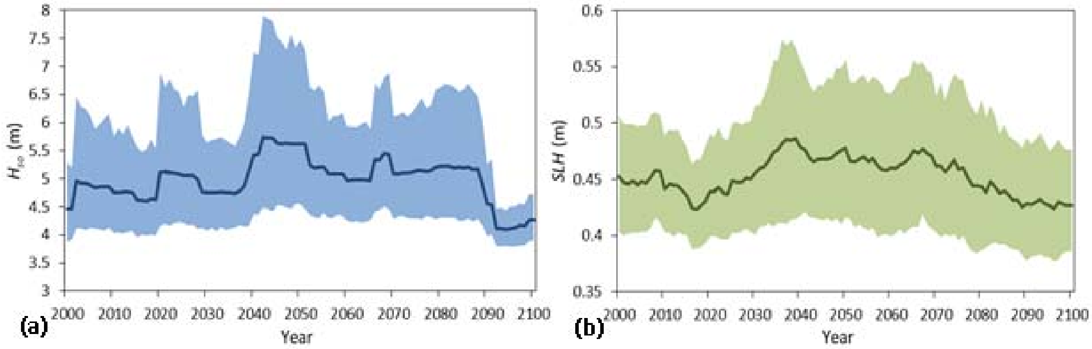

Figure 1 Time-dependent 100-years return level estimates with 95% confidence intervals for: a) H_s in the offshore area, b) Nearshore SLH at the port of Alexandroupolis

Figure 2a presents nonstationary P_f estimates for the three selected failure mechanisms (see Sect. 2.2). In Eq. 2 the maximum allowable overtopping discharge q=5 l/sm (EurOtop 2007), while the number of displaced units in Eq. 3 is N_{od}=0.5, corresponding to negligible damages at the breakwater toe. Estimated probabilities for all failure mechanisms present a bimodal behavior, showing discrete peaks in the intervals of maximum H_s. Therefore, P_f of all three mechanisms vary considerably within the 21st century. Excessive overtopping seems to be the governing failure mechanisms for the entire study period, followed by scouring of the breakwater toe and by instability of primary armour layer of the structure. The highest P_f correspond to return periods of 81, 104, and 140 years, for overtopping, scouring of the breakwater toe and instability of its primary armour layer, respectively. It should be noted that even if the structure can be considered quite safe for present marine conditions (P_f for all failure mechanisms are very low, corresponding to return periods of less than 1000 years), it seems to be exposed to severe marine conditions in the future. Considering the excessive overtopping ULS, P_f in the interval 2065-2070 are estimated higher compared to the respective ones in the middle of the century, identifying the significant contribution of $MSLR$ and SLH in determining failure conditions.

Figure 2b presents estimates of total failure probability P_{ftotal} considering the three ULS as independent or perfectly dependent. It also includes P_{ftotal} estimates from the series of 150 (1951-2100) and 100 (2001-2100) years, considering stationarity of marine conditions. Lower and upper bounds of these intervals correspond to perfect dependence or independence of ULS. The highest failure probabilities correspond to return periods of 36 and 81 years, for independent or perfectly dependent ULS, respectively. The stationarity assumption significantly underestimates P_{ftotal} reaching 82% and 64% when failure probabilities are estimated from 150 and 100 years, respectively.

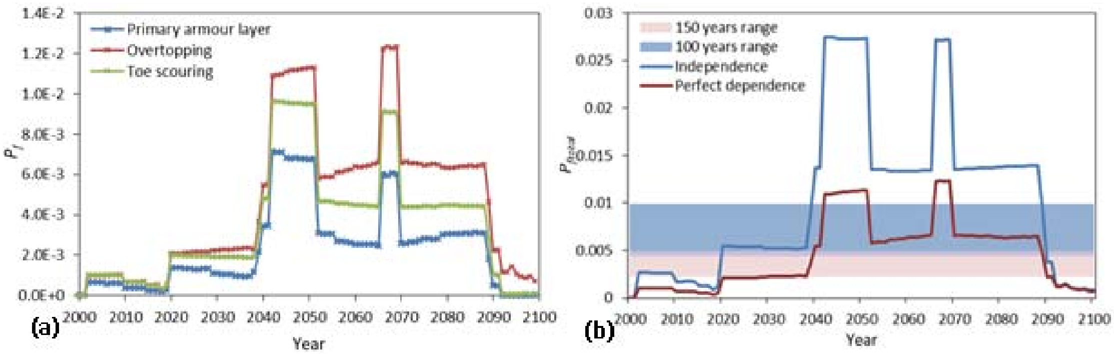

Figure 2 Time-dependent estimates of: a) Failure probabilities for three failure mechanisms (ULS), b) Total failure probability for independent and perfectly dependent failure mechanisms

5 CONCLUSIONS

In the present work failure probabilities of an indicative rubble mound breakwater protecting a Greek port against increasing future marine hazards and related escalating exposure to downtime risks are estimated within a nonstationary extreme value analysis framework. The results concern time-dependent P_f estimates for three main ULS, which are intercompared and used to determine future periods of increased vulnerability of the studied structure to extreme marine hazards. Excessive overtopping ULS seems to be the most critical for the collapse of the studied defence. This failure mechanism identifies a period around 1965-1970, with the highest P_f, where all variables of the marine climate ($H_s,\ MSLR$ and SLH) have a significant contribution to port downtime. Total failure probabilities are quite high for the future periods 2040-2055 and 2065-2070, with the highest values corresponding to a return period of 36 years for independent ULS. Estimating P_{fotal} within a nonstationary reliability framework assists in avoiding underestimation of future marine hazard effects on port and harbour structures. It should be noted that only selected ULS are considered in the present work. Excessive wave height inside the port/harbour basin during normal weather conditions causes port downtime without severe collapse of defence structures, and can be regarded as Serviceability Limit State (SLS). Such limit states can significantly affect P_{fotal} of Greek ports and harbours.

References

Adloff F et al. (2015) Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. Clim Dynam 45(9-10): 2775-2802. doi:10.1007/s00382-015-2507-3

Benetazzo A et al. (2012) Wave climate of the Adriatic Sea: a future scenario simulation. Nat Hazard Earth Sys Sci 12(6): 2065-2076. doi:10.5194/nhess-12-2065-2012

Burcharth H F, Andersen T L, Lara J L (2014) Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach. Coast Eng 87: 112–121.

Dai Viet N, Verhagen H J, van Gelder P, Vrijling J K (2008) Conceptual Design for the Breakwater System of the South of Doson Naval Base: Optimization versus Deterministic Design. Paper presented at PIANC-COPEDEC VII, Dubai, United Arab Emirates.

EurOtop (2007) Wave Overtopping of Sea Defences and Related Structures: Assessment Manual. EA, Bristol, UK, ENW,Utrecht, The Netherlands, KFKI, Hamburg, Germany.

Galiatsatou P et al. (2016) Modelling nonstationary extreme wave heights in present and future climates of Greek Seas. Water Sci Eng 9(1): 21-32. doi:10.1016/j.wse.2016. 03.001

Galiatsatou P, Makris C Prinos P (2018) Optimized Reliability Based Upgrading of Rubble Mound Breakwaters in a Changing Climate. J Mar Sci Eng 6(3): 92. doi:10.3390/jmse6030092

Galiatsatou P, Makris C, Prinos P Kokkinos D (2019) Nonstationary joint probability analysis of extreme marine variables to assess design water levels at the shoreline in a changing climate. Nat Haz (accepted, under revision).

HNHS (2011) Statistical data of sea level in Hellenic Ports. Hellenic Navy Hydrographic Service, Athens, Greece. (in Greek) https://www.hnhs.gr/en/online-2/2015-05-16-18-51-00

IPCC (2007) Climate change 2007: The Scientific Basis, Contribution of Working Group I to the Fourth Assessment Report of IPCC. Cambridge University Press, USA.

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate change Adaptation. A Special Report of Working Groups I & II of IPCC. Cambridge University Press, USA.

Isobe M (2013) Impact of global warming on coastal structures in shallow water. Ocean Eng 71: 51–57. doi:10.1016/j.oceaneng.2012.12.032

Kim TM, Suh KD (2010) Reliability analysis of breakwater armor blocks: Case study in Korea. Coast Eng J 52: 331–350. doi:10.1142/S0578563410002208

Makris C et al. (2016) Climate change effects on the marine characteristics of the Aegean and Ionian Seas. Ocean Dyn 66(12): 1603-1635. doi:10.1007/s10236-016-008-1

Makris C et al. (2018) Climate change impacts on the coastal sea level extremes of the east-central Mediterranean Sea. Paper presented at the XIV PRE Conference, Thessaloniki, Greece.

Naulin M, Kortenhaus A, Oumeraci H (2015) Reliability-based flood defense analysis in an integrated risk assessment. Coast Eng J 57: 1540005. doi:10.1142/S0578563415400057

Suh KD, Kim SW, Kim S, Cheon S (2013) Effects of climate change on stability of caisson breakwaters in different water depths. Ocean Eng 71: 103–112.

Van der Meer J W (1988) Deterministic and probabilistic design of breakwater armor layers. J Waterw Port Coast Ocean Eng 114: 66–80. doi:10.1061/(ASCE)0733-950X (1988)114:1(66)

Van der Meer JW, D’Angremond K, Gerding E (1995) Toe structure stability of rubble mound breakwaters. Adv Coast Struct Brkwtr, 308–321. doi:10.1680/aicsab.25097.0029