ADAPTING PORTS TO CLIMATE CHANGE-THE CASE OF EVDILOS PORT, IKARIA ISLAND, GREECE

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Abstract

Along with the unquestionable temperature rise, ocean thermal expansion and glacier melting lead the average sea level to rise at an ever-increasing rate. This increase, in conjunction with the occurrence of more severe storm surges and higher wave heights during extreme weather events, makes the upgrading of existing harbor infrastructure a necessity in order to extend its service life-time. To this end, a case study is considered herein in order to elucidate possible alternatives of reinforcing the existing rubble-mound breakwater at Evdilos Port, Ikaria Island, Greece. The performance of the proposed upgraded structure is investigated under two climate change scenarios, in years 2050 and 2100, which take into consideration sea level rise and maximum wind speed events. It is observed that the armor and toe stability criteria are met under the examined climate change scenarios, however the mean wave overtopping discharge significantly exceeds the tolerable limit in both of them. The finally proposed alternative takes into account the existing structure features, as well as constructability, landscape aesthetics and spatial planning issues.

Keywords: climate change, harbor works, adaptation strategies, wave overtopping, breakwater upgrade

1. INTRODUCTION

Human activity over the past decades has led to climate change. Large-scale storms, floods, fires, unprecedented temperature rise, prolonged drought or heat periods and ocean level rise are only few signs that prove the environmental disturbance and the climate change. Focusing on the impacts of climate change on harbor infrastructure, one can mention the sea level rise caused by ice melting and ocean thermal expansion, the more frequent occurrence of more severe storm surges due to lower sea surface pressure and greater wind velocities, as well as higher waves heights.

Port adaptation to climate change has three components [1]. Protection strategies recommend shielding the works against climate change and include more drastic measures, such as upgrading the breakwaters, protecting the near-water equipment and facilities with artificial barriers [2], elevating the docks [2] or even the entire port [3]. Accommodation strategies allow exposure to the more severe wave climate and the sea level rise, providing measures to manage them without interfering with the design. Such measures include managing the increased rainwater and seawater accumulation in port areas and the increased sediment flow in the harbor and the approach channel, as well as intensively maintaining the infrastructure and restoring possible damages. Finally, retreat strategies are followed in cases where the port location no longer permits its functionality and the satisfaction of the needs it was designed for, and recommend moving the facilities and the operations to another location on higher ground or farther from water.

Regarding breakwaters, armor and toe stability and wave overtopping are the main challenges to be addressed. In the present work, the case of a rubble-mound breakwater is examined, in Evdilos Port, Ikaria Island, drawing our attention due to the serious damage it suffered during the severe storm on January 18th, 2018. In particular, its performance is investigated under the environmental forcing expected by 2050 and 2100, and the proposed upgrading alternatives are also evaluated.

2. METHODOLOGY

2.1. The Impact of Climate Change on the Study Area

When adapting breakwaters to climate change, mainly three parameters should be taken into account: *sea level, storm surges* and *extreme wave heights*. The sea level rise and the more severe storm surges reduce the breakwater's freeboard, leading to higher overtopping discharges. The more intense wave action threatens the armor and toe stability, even though the sea level rise has a positive effect on the latter. In this paper, these parameters are estimated for the 2050 and 2100 time horizons under IPCC's most optimistic and most pessimistic CO_2 emissions scenarios, Representative Concentration Pathway (hereafter RCP) 2.6 and RCP 8.5.

Global mean sea level rise is given an almost steady median projection of 4.5 mm/y according to RCP 2.6, while according to RCP 8.5, it is given a linearly increasing trend, from 4 mm/y in 2015 to 12 mm/y in 2100 [4]. In the case of Evdilos, the sea level change is calculated in relation to the soundings held in the area in 2013.

In the absence of specific data on the *storm surge* maxima around Evdilos under the scenarios studied, the predictions deriving from an intermediate scenario established in the Special Report on Emissions Scenarios (hereafter SRES), the socalled SRES A1B, are used instead. According to SRES A1B, storm surge maxima in the Central Aegean are expected to reach 0.55 m by 2050, then decrease to 0.45 m by 2100 [5].

Wind speed time series, on a daily basis, were produced for 10 deep-sea locations around Evdilos to observe the peaks evolution according to the temperature forcing implied by each of the above scenarios [6-8]. Each time series consists of two parts, the historical one, 1950-2005, and the synthetic one, 2006-2100, which is hereafter divided into two sections, 2006-2050 and 2051-2100. For each of these three time periods, the frequency of high wind speed and the daily wind speed maximum were calculated.

Overall, the occurrence of *wind force* equal to or higher than 8 Beaufort shows a positive trend. According to RCP 2.6, a mean alteration of +4.9% in occurrence is expected by 2050, compared to the historical period, in contrast with the alteration of +3.6% foreseen by RCP 8.5. Subsequently, RCP 2.6 predicts a -2.3% reduction by 2100, compared to the 2006-2050 period, while according to RCP 8.5 this alteration is positive and equal to +2.7%.

This intensification in storminess during the whole future period compared to the historical one is in accordance with the clearly positive trend in wind speed maxima. During the historical period, wind force does not exceed 10.27 Beaufort in the study area. Assuming full wave development [9,10] and taking into account the wave transformation from deep-sea to the breakwater area (shoaling, refraction, diffraction, wave breaking etc.), this wind force corresponds to a maximum *wave height* of 5.45 m at the breakwater area. During the 2006-2050 period, the maximum wind force is found to be equal to 10.4 Bf according to RCP 2.6, whereas it reaches 10.5 Bf according to RCP 8.5. The wave height maxima are 5.57 m and 5.66 m, respectively. Hence, RCP 2.6 and RCP 8.5 give a +2.2% and +3.9% alteration respectively, in wave height maxima by 2050. During the period of 2051-2100, the wind force maxima according to RCP 2.6 and RCP 8.5 are equal to 10.6 Bf and 10.8 Bf respectively, while the corresponding wave heights reach 5.75 m and 5.94 m. This means that RCP 2.6 and RCP 8.5 give a +5.5% and +9% alteration in wave height maxima by 2100, compared to the maximum wave height corresponding to the historical period, respectively.

The above parameters, which have a direct impact on the breakwater of the study area, are summarized in Table 1.

Table 1 Summary of the climate change parameters having an impact on the breakwater

Parameter	2050 Time Horizon		2100 Time Horizon	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Sea Level Rise (m)	0.17 m	0.21 m	0.39 m	0.70 m
Storm Surge (m)	0.55 m	0.55 m	0.45 m	0.45 m
Maximum Wind Force (Bf)	10.40	10.50	10.60	10.80
Maximum Wave Height (m)	5.57	5.66	5.75 m	5.94

2.2. Breakwater Performance Criteria

Pertaining to rubble-mound breakwaters, hydraulic and structural response is of major interest and particularly *armor and toe stability* and *wave overtopping* are the performance criteria that need to be tested.

Hudson's stability coefficient K_D [11] is determined according to the damage rate considered acceptable for the armor layer. Accropodes, constituting a widely adopted armor option, have been used in the breakwater of the present case study. They are designed for a stability coefficient of 15 accounting for non-breaking waves or 11 for breaking waves. In the case of the breakwater under study, as long as K_D does not exceed the value of 15, the performance of the armor is satisfactory [12].

A toe berm supports the main armor layer and protects the structure against scour. Toe berm instability could lead to main armor instability, and thus the toe should be examined in all cases. The number of damage, N_{od}, corresponding to the number of units displaced out of the armor layer within a strip width of one nominal diameter, is the parameter calculated herein. A long as this parameter does not exceed the value of 2, the performance of the toe berm is satisfactory [13].

Wave overtopping occurs when the water level in front of the dike and the waves are high enough, that after the latter break on the outer slope, the wave run up exceeds the crest level. Two quantities related to wave overtopping are to be measured:

the mean overtopping discharge, q_{mean}, and the maximum overtopping volume, V_{max}. For rubble-mound breakwaters, the maximum tolerable limits are 5-10 l/s/m and 10000-20000 l/m, respectively [14].

Given that the perpendicular to the structure wave incidence is the most unfavorable case for both structural and hydraulic response, and bearing in mind the orientation of the windward breakwater of Evdilos Port on the one hand, and that the prevailing wind in the study area comes from the North on the other hand, the analysis was carried out for northern waves.

2.3. Rubble-mound Breakwater Upgrade Alternatives

Upgrading alternatives applicable specifically for rubble-mound breakwaters, include adding an armor layer or a berm, making the seaward slope milder, increasing the crown width and/or the crown wall height, or constructing a submerged breakwater on the foreshore.

However, not all of the above alternatives are applicable to the breakwater of Evdilos Port. For instance, adding an armor layer is not an option, since Accropodes have been designed for a single layer. The placement of the units is thorough and their interlocking is critical to the operation of the layer. Adding a berm is also not considered, since it is subject to the same constraints and has the additional risk of causing armor units instability due to the transition from double to single layer in the middle of the slope. Furthermore, despite the fact that making the seaward slope milder results to reduced overtopping volumes, in single armor layers, gravity plays a significant role in the interlocking of the units and the stability of the layer. Slopes milder than 1:1.5, which is the case here, are unfavorable to stability and thus not recommended [12,15].

Consequently, the upgrading alternatives to be further assessed herein are narrowed down to *increasing the crown width and/or the crown wall height*, and *constructing a submerged breakwater on the foreshore*.

3. RESULTS AND DISCUSSION

The results of investigating the existing breakwater performance over the aforementioned criteria are given in Table 2. Cells highlighted with bold indicate that the corresponding quantities exceed the tolerable limit.

Table 2 Performance of the existing cross-section

Criterion	Acceptable Range	2050 Time Horizon RCP 2.6	2050 Time Horizon RCP 8.5	2100 Time Horizon RCP 2.6	2100 Time Horizon RCP 8.5
Hudson's Armor Stability Coefficient, K_D	≤15	10.67	11.19	11.73	12.94
Number of Toe Damage, N_{od}	≤2	1.26	1.38	1.48	1.6
Mean Overtopping Discharge, q_{mean} (l/s/m)	5÷10	**35.37**	**42.19**	**52.01**	**89.88**
Maximum Overtopping Volume, V_{max} (l/m)	10000÷20000	1540.44	1724.23	1960.15	2712.76

In the light of the above results, it can be observed that the armor and toe stability meet the required criteria, and the maximum overtopping volume remains lower than the tolerable limit. However, the mean overtopping discharge significantly exceeds the acceptable limit in both time horizons and under both scenarios, which means that the breakwater is vulnerable to wave overtopping in the cases examined.

This observation implies that the existing structure must be enhanced. The upgrading alternatives studied are *increasing the crown width [14] and/or the crown wall height* [16], and *constructing a submerged breakwater on the foreshore* [13,17,18]. Each upgrading alternative takes into consideration the critical criterion, namely the mean overtopping discharge, not exceeding 7.5 l/s/m. The proposed changes in the cross-section envisaged by each alternative are given in Table 3. The corresponding preliminary cost was calculated for the 155.6 m long main part of the breakwater, where the damage was identified, taking into account the harbor works descriptive invoice [19].

Table 3 Changes to the cross-section envisaged by each upgrading alternative and corresponding costs

No	Upgrade Alternative	2050 Time Horizon RCP 2.6 (m)	2050 Time Horizon RCP 8.5 (m)	2100 Time Horizon RCP 2.6 (m)	2100 Time Horizon RCP 8.5 (m)	Cost Estimation
1	Increasing the crest width	6.05	6.84	7.80	10.30	957,428.58 €
2	Increasing the crown wall height	1.75	1.90	2.06	2.40	37,344 €
3	Increasing the crest width and the crown wall height	1.62 & 1.10 respectively	1.84 & 1.23 respectively	2.10 & 1.40 respectively	2.80 & l.90 respectively	1,041,807.35 €
4	Constructing a submerged breakwater on the foreshore	2.86 freeboard	2.90 freeboard	2.92 freeboard	3.00 freeboard	731,251.54 €

Following the original cross-section, depicted in Figure 1, the modified cross-sections for each alternative under the most unfavorable conditions, namely the 2100-time horizon and the RCP 8.5 scenario, are illustrated in Figures 2-5. The alterations in the crest width can be identified by following the corresponding dimension, while the proposed crown wall reinforcement and the submerged breakwater are depicted with hatching.

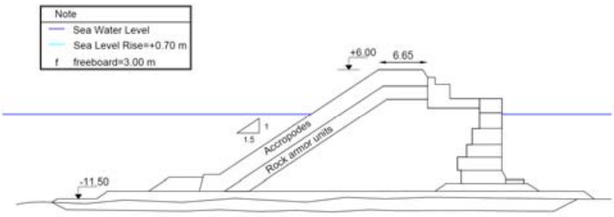

Fig. 1 The original cross-section

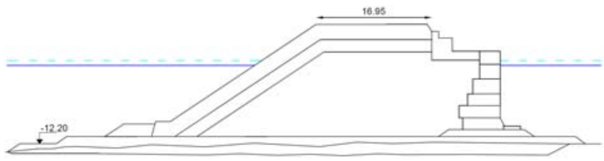

Fig. 2 Alternative No 1: Increasing the crest width

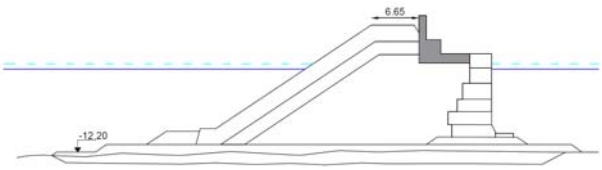

Fig. 3 Alternative No 2: Increasing the crown wall height

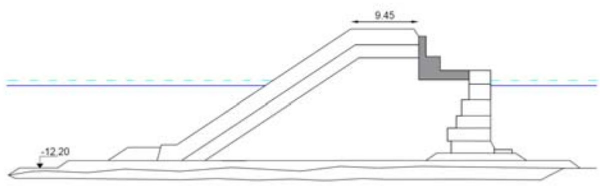

Fig. 4 Alternative No 3: Increasing both the crest width and the crown wall height

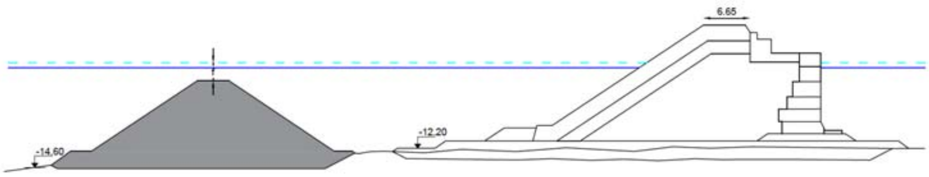

Fig. 5 Alternative No 4: Constructing a submerged breakwater on the foreshore

Among the aforementioned alternatives, the finally chosen one herein is to *increase both the crest width and the crown wall height*. Increasing the crest width or constructing a submerged breakwater on the foreshore both require the occupation of a large sea area. Additionally, increasing the crest width by 10 m would have a significant impact on the aesthetics of the landscape, whereas the submerged breakwater could possibly cause problems to navigation. Finally, increasing the crown wall height by 2.4 m could lead to significant wave forcing loads on the wall, thereby threatening the stability of the structure. Thus, despite the fact that increasing both the crest width and the crown wall height is the most expensive solution, it is the only one that complies with safety in navigation, preservation of landscape aesthetics, and stability requirements.

4. CONCLUSIONS

Sea level rise in conjunction with the more severe wave climate directly threaten port infrastructure, which is not initially designed for such environmental conditions. The present work aims to examining whether the existing infrastructure can adapt to future possible extreme conditions foreseen by climate change scenarios. Investigating the existing works performance under such conditions is of utmost importance to identify any reinforcement and/or upgrade needed.

As a first step of the current research, the effects of climate change in the vicinity of Evdilos Port in Ikaria Island, Greece, were investigated. A careful analysis of the evolution of maximum wind velocities and frequencies of occurrence, yielded a positive trend in both quantities for the years to come, and specifically for the period 2006-2100, in comparison to the past time period 1950-2005. This intensification in storminess implies that higher waves are to be expected in the study area.

Inspection of the existing breakwater performance under sea level rise and more severe wave action pointed out that armor and toe stability were not affected, whereas hydraulic response and particularly wave overtopping was affected. More specifically, the mean wave overtopping discharge remarkably exceeded the tolerable limits in both IPCC's scenarios.

In order to upgrade the said breakwater, various alternatives were examined, such as adding an armor layer, making the seaward slope milder, increasing the crest width and/or the crown wall height and constructing a submerged breakwater on the foreshore. The optimal solution turned out to be the increase of both the crest width and the crown wall height.

REFERENCES

1. Mills-Knapp, S., Bourdeau, E., Falco, G., Resler, C., Tovar, H., Zoegall, S.: Climate Change Adaptation and Sustainable Design at the Port Authority of New York & New Jersey. In. USA, (2011)
2. Port of Long Beach, A.E.C.O.M.: Port of Long Beach: Climate Adaptation and Coastal Resiliency Plan. In. USA, (2016)
3. Becker, A., Hippe, A., Mclean, E.: Cost and Materials Required to Retrofit US Seaports in Response to Sea Level Rise: A Thought Exercise for Climate Response. Journal of Marine Science and Engineering **5**(3), 44-65 (2017).
4. Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S.Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, N.Y., U.S.A. (2013)
5. Krestenitis, Y., Androulidakis, Y., Kombiadou, K., Makris, C., Baltikas, V.: Extreme values of storm surges in the Mediterranean Sea and the Aegean Sea due to climate change. https://www.academia.edu/9542497/ (2014). Accessed April 2019

6. Department of Meteorology and Climatology of the A.U.Th., National Observatory of Athens: DEAR-Clima Application. http://meteo3.geo.auth.gr:3838 (**2016**). Accessed May 2019
7. Max Planck Institute for Meteorology: MPI-ESM Model. https://www.mpimet.mpg.de/en/science/models/mpi-esm/. Accessed May 2019
8. Climate Service Center of Germany: The Regional Climate Model REMO. https://www.remo-rcm.de/. Accessed May 2019
9. Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E.: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). In. Deutches Hydrographisches Institut, Hamburg, Germany, (1973)
10. Sverdrup, H.U., Munk, W.H.: Wind, sea and swell: Theory of relations for forecasting. In. U.S. Navy Department, Hydrographic Office, Washington, D.C., (1947)
11. U.S. Army Corps of Engineers, U.S. Coastal Engineering Research Center: Chapter 7: Structural Design: Physical Factors. In: Shore Protection Manual Volume II. pp. 16-67. Vicksburg, Mississippi (1984)
12. Concrete Layer Innovations: Accropode™ Design Guide Table. www.concretelayer.com/sites/default-/files/ACCRO-PODE%E2%84%A2_Design_Table_2012_0.pdf (2012). Accessed January 2019
13. U.S. Army Corps of Engineers: Part VI Chapter 5: Fundamentals of Design. In: Coastal Engineering Manual (C.E.M.). pp. 22-38. Washington, DC (2011)
14. Pullen, T., Allsop, N.W., Bruce, T., Kortenhaus, A., Schüttrumpf, H., Van der Meer, J.W.: Eurotop: Manual on wave overtopping of sea defences and related structures, second edition. Boyens Medien GmbH& Co, Heide i. Holstein (2007)
15. Concrete Layer Innovations: Accropode™ Basic Specifications. www.concretelayer.com/sites/default/files/ACCRO-PODE%E2%84%A2_Basic%20Specifications_Version%20D_0.pdf (2015). Accessed January 2019
16. Bradbury, A.P., Allsop, N.W.H., Stephens, R.V.: Hydraulic Performance of Breakwater Crown Walls. In. HR Wallingford, Wallingford, Oxfordshire, U.K., (1988)
17. Chen, H.-B., Tsai, C.-P., Jeng, C.-C.: Wave Transformation between Submerged Breakwater and Seawall. In: International Continence Society Australia 2007, pp. 1069-1074. Journal of Coastal Research
18. Van der Meer, J.W., Daemen, I.F.R.: Stability and Wave Transmission at Low-Crested Rubble-Mound Structures. Journal of Waterway, Port, Coastal, and Ocean Engineering **120**(1), 1-19 (1994).
19. Hellenic Parliament: Harbor Works Descriptive Invoice. Official Government Gazette **363**(B) (2013).