Numerical Modelling for Coastal Structures Design and Planning. A Case Study of the Venetian Harbour of Chania, Greece

Spyros Foteinis, *Environmental Engineer PhD, School of Environmental Engineering, Technical University of Crete, Greece; email: sfoteinis@gmail.com*
Theocharis Tsoutsos, *Professor, School of Environmental Engineering, Technical University of Crete, Greece; email: Theocharis.Tsoutsos@enveng.tuc.gr*
Costas Synolakis, *Professor, School of Environmental Engineering, Technical University of Crete, Greece and Viterbi School of Engineering, University of Southern California, USA; email: costas@usc.edu*

ABSTRACT*: Wave energy harnessing is associated with high cost, compared to established renewables such as wind and solar. In order to make the technology commercially attractive, electricity production could be coupled with secondary functions, such as coastal defence. An innovative concept is the integration of wave energy converters (WECs) in caisson breakwaters, offsetting the initial high cost of WECs with coastal defence. Here, the functionality of Chania's Venetian harbour offshore breakwater was assessed under typical wave conditions. We used measurements from a Nortek AWAC ADCP, deployed in the nearshore, to numerically simulate the wave conditions induced by a typical low energy storm (M_{dir}=360º, H_{m0}=1 m and T_p=5.5 s) inside the Venetian harbour. We employed the Boussinesq-type wave model MIKE 21 BW and simulated cases with and without the breakwater. In both cases, H_{m0} reached 0.4 m, just inside the harbour's entrance and, in general, similar wave conditions were observed. Therefore, results indicate that the existing offshore breakwater provides little protection to the entrance and the south part of the harbour from waves coming from the north, which are the vast majority of the winter waves according to the field measurements. Thus, an extension or other modifications are required, so as to provide adequate protection to the entrance and the south part of the harbour. We also used the ADCP measured data for a preliminary analysis of the local wave power potential. During winter 2011-2012, the maximum significant wave height (H_{m0}) recorded by the AWAC was 3.85 m, whilst peak periods (T_p) higher than 10 s were observed. These wave characteristics yielded mean (P_{mean}) and maximum (P_{max}) wave power values close to 4.8 kW/m and 72 kW/m, respectively. Therefore, integrating a WEC in future breakwater designs might be a feasible alternative, given also the minimal tidal range of a few cm. Apart from offsetting the WEC's high initial capital expenditure to coastal defence, the electricity from the waves could power the harbour's lighthouse. Coupled with interpretive displays of the wave energy technology, this could also stimulate additional (eco)tourism opportunities.*

KEYWORDS*:* coastal engineering, wave energy converter (WEC), acoustic Doppler current profiler (ADCP), Nortek AWAC, MIKE 21 BW, Hydrodynamic modeling, port, breakwater

SITE LOCATION: Geo-Database

INTRODUCTION

Wave energy is a valuable renewable energy source (RES) with vast potential that remains largely unexploited. Wave energy is nascent and characterized by high capital costs, which impede technological development and industry expansion (Kim et al., 2012; Musial, 2008). Many different technologies and devices for wave-energy harnessing are currently available. In general, wave energy converters (WECs) may include an i) attenuator, ii) point absorber, iii) oscillating wave surge converter, iv) oscillating water column, v) overtopping/terminator, vi) submerged pressure differential device, vii) bulge wave device and viii) rotating mass device (Foteinis and Tsoutsos, 2017). These WECs are at different levels of research and development, yet their large-scale commercialization is decades away at current fossil fuel prices (Foteinis et al., 2017). The viability of wave-energy harnessing depends on the WEC type and design, the level of wave resource, installation size, capital cost and

Submitted: 22 July 2017; Published: 26 October 2018
Reference: Foteinis, S., Tsoutsos, T. and Synolakis, C. (2018). *Numerical Modelling for Coastal Structures Design and Planning. A Case Study of the Venetian Harbour of Chania, Greece*. International Journal of Geoengineering Case Histories, Vol.4, Issue 4, p.232-241. doi: 10.4417/IJGCH-04-04-01

capacity factor (Cf), among others. The latter (Cf) is one of the most important performance indices for renewable energy technologies, since it indicates the energy delivered by the device compared to the maximum possible energy, had it been working at the rated power, or equivalently, the percentage of the time the device is operating at maximum power, for a given time period (Bozzi et al., 2018). Furthermore, WECs must also comply with national power grid codes and withstand, in the long-term, the corrosive/abrasive marine environment, issues that also hamper wave energy's commercialisation (Foteinis and Tsoutsos, 2017).

To make wave energy commercially attractive, multi-function schemes could be considered, where electricity production is coupled with secondary functions. Growing pressure from beach erosion has recently brought attention to sustainable coastal defence plans, with nearshore WECs and offshore WEC arrays emerging as innovative ways to defend the coast, with low environmental and aesthetic impact (Zanuttigh and Angelelli, 2013). Thus, it appears that integrating WECs in coastal defence is promising (Abanades et al., 2014; Jones et al., 2014) and helps offset/reduce WECs initial high capital expenditure.
In this paper, we examine the historic Venetian harbour in Chania, Greece, a potential locale for deploying a dual functionality WEC for electricity generation and coastal defence (Figure 1). Integrating a WEC with a breakwater is not new. As early as 1987, field verification experiments of a wave power-extracting caisson breakwater took place in Japan, and a test breakwater was constructed in 1989 in Sakata Port, Yamagata Prefecture (Takahashi et al., 1992). Today, integrating WECs with other marine facilities is common, especially for nearshore applications, since cost sharing in construction, installation, maintenance and operation provides an overall better economic viability, while it also limits the negative environmental impact and improves WEC reliability and higher lifespan (Mustapa et al., 2017). Also, in breakwater-WEC schemes, the cost of submarine electrical cables is reduced, while access for operation and maintenance is easier, compared to offshore WECs (Henriques et al., 2013).

Several types of WEC concepts have been adapted for breakwater-integration purposes, such as overtopping, piston-type and oscillating water column (OWC) (Henriques et al., 2013; Mustapa et al., 2017). A breakwater-OWC WEC was recently constructed in the port of Mutriku, Spain, with 16 chambers and 16 Wells turbines rated 18.5 kW each. A field experiment was carried out off the eastern coast of the straits of Messina, using a geometry for an OWC embedded into a breakwater, named U-OWC (Henriques et al., 2013). A U-OWC has a characteristic period greater than that of a conventional OWC, and hence is expected to perform better than a conventional OWC with waves of large periods, such as swells or sea storm waves, and also, it has been claimed, will perform well with small wind waves (Boccotti, 2012). Also, an OWC embodied into a breakwater in the mouth of the Douro River at Porto, Portugal has been proposed (Henriques et al., 2013). Moreover, in January 2016 at Naples, Italy, a pilot unit of an innovative rubble mound breakwater for overtopping wave energy conversion (a.k.a. Overtopping BReakwater for Energy Conversion -OBREC) was installed. It is the first overtopping WEC totally embedded in a traditional rubble mound breakwater (Contestabile et al., 2017). Therefore, the Venetian harbour (Figure 1) appears as a promising location for a dual functionality WEC, since the area is exposed to large fetch lengths, by Greek standards, and a minimal tidal range of a few cm.

The Venetian harbour, in addition to being a highly visited historic landmark, plays also an important role in the local economy, being the only available port for cruise and sailboats in Chania (Kazolea et al., 2015). The harbour was built in the 14^{th} century (Maravelakis et al., 2014), it is facing north and has a maximum length and width of about 650 m and 320 m, respectively (Figure 2). It is exposed to north winds and from its early construction could not provide safe anchorage, at least from December till April (Playfair, 1882). To tackle this problem, a low crested offshore breakwater, ~150 m in length, was constructed during the early 1990s (for a detailed description see Maravelakis et al. 2014) at about 200 m N-NW of the harbour entrance, to shield it from storms (Figure 2). Nonetheless, even after its construction the problem persist, with severe overtopping and flooding of the western dock and damage to the quay being reported in highly energetic seas (Kazolea et al., 2015; Maravelakis et al., 2014). Moreover, according to anecdotal evidence, even in mild wave conditions, the harbour is not fully functional, since waves coming from the north induce significant wave motions in its outer basin (Figure 2 inset).

Therefore, as the existing breakwater does not provide adequate protection even in mild wave conditions, reparation, modifications or the construction of a new breakwater have been considered by local authorities at different times. To quantitatively assess the functionality of the existing offshore breakwater or of a proposed new one, measurements of the local wave climate are required and then modeling to simulate the wave disturbances inside the harbour, a procedure that is currently not a standard practice in Greece. Hence, here we used as a case study the Venetian harbour and collected actual wave measurements in order to assess its functionality under typical wave conditions. To this end, we used bathymetric data for the area, obtained from Maralevakis et al. (2014), and applied the numerical model MIKE 21 BW. We also explored on a preliminary basis the benefits of integrating a WEC in the new or improved caisson offshore breakwater as an innovative concept for the Venetian harbour.

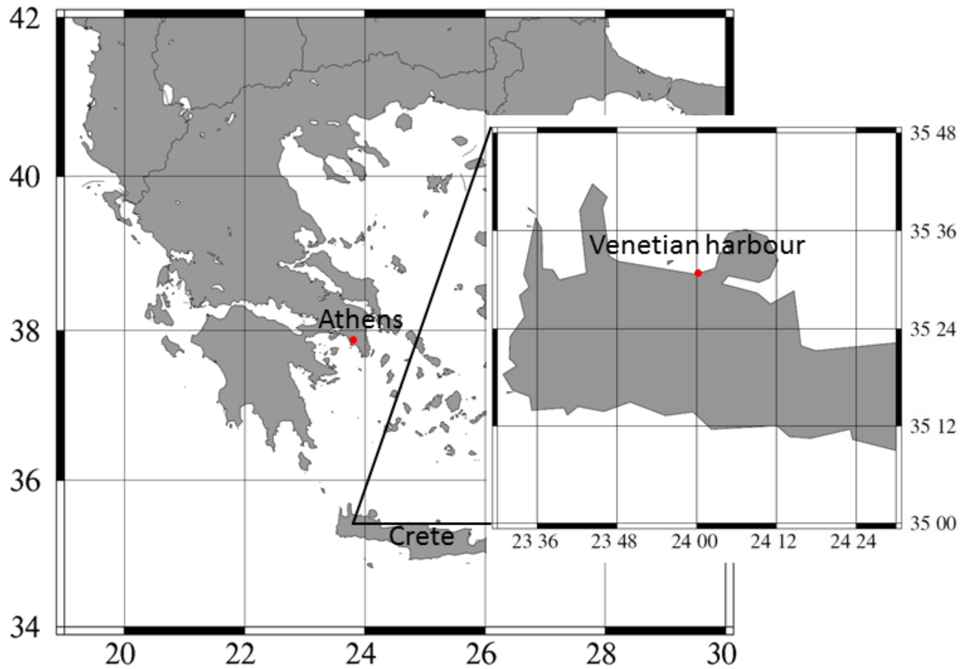

Figure 1. The area of study (maps produced using the Generic Mapping Tools (GMT)).

Figure 2. Satellite images of the Venetian harbour during calm (June 2013) and mild wave conditions (inset, January 2010). Imagery from Google Earth®.

WAVE CLIMATE ASSESSMENT

To estimate the local wave climate, one 600 kHz Nortek AWAC bottom-mounted upward-facing acoustic Doppler current profiler (ADCP) was deployed at ~24.5m depth, just offshore the Harbour's breakwater (Figure 2), over various time periods and intervals, starting from 2011 and onward (Maravelakis et al., 2014). Assessments of the local wave climate and the wave direction have been conducted by Kazolea et al. (2015); Maravelakis et al. (2014). Here, we used AWAC measurements obtained from (Maravelakis et al. 2014), as inputs in the DHI's hydrodynamic wave model MIKE 21 BW to numerically study the harbour's response to a typical wave storm. As a case study, we used a typical mild storm recorded in January 2013. The wave parameters were estimated by Nortek's wave and current profile data processing software "Storm" (Figure 3). The modelled wave storm's mean wave direction (M_{dir}) was 360°, the significant wave height (H_{m0}) was 1 m, and the peak wave period (T_p) was 5.5 s, at 20 m depth. Moreover, the winter's 2011-2012 nearshore wave power resource was estimated using the AWAC's data.

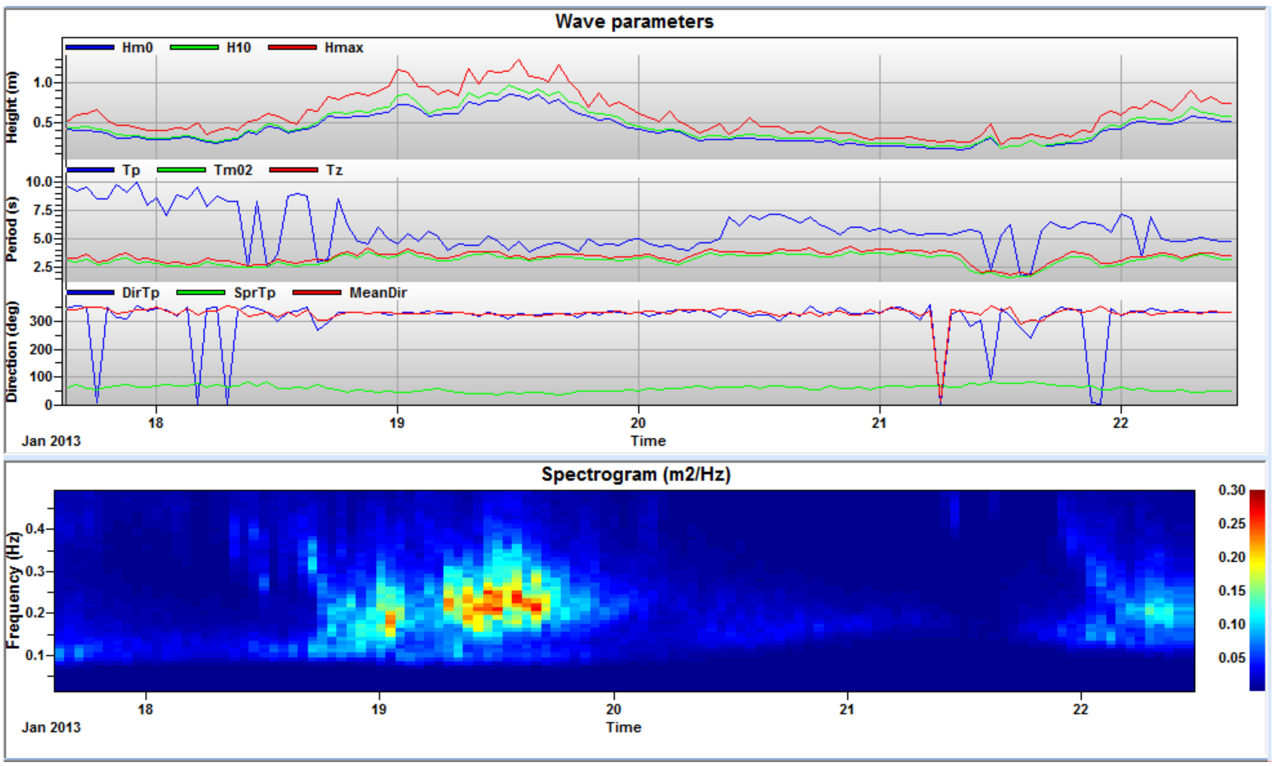

Figure 3. Main wave characteristics of a typical mild wave storm as recorded by the AWAC and processed by Storm (reference period 01/17/2013 to 01/22/2013).

ESTIMATION OF THE NEARSHORE WAVE POWER RESOURCE

Equations (1) – (2) (Foteinis et al., 2017) were used to estimate the wave power at this site. The wave power P is the wave energy per metre of wave crest and is calculated from:

$$P \approx \frac{1}{16}\rho g C_g H_{\mathrm{m0}}^2 \tag{1}$$

where ρ is the water density, g is the acceleration of gravity, H_{m0} is the significant wave height, and C_g is the group velocity, calculated from

$$C_g = \left[1 + \frac{4\pi d}{\lambda \sinh\left(\frac{4\pi d}{\lambda}\right)}\right]\frac{gT_{\mathrm{e}}}{4\pi}\tanh\left[\frac{2\pi d}{\lambda}\right] \tag{2}$$

where d is water depth, T_e is the so called energy period, and λ is wavelength. The latter is determined using the classic linear wave dispersion equation.

Values for the significant wave height (H_{m0}) and the energy period (T_e) are required to estimate the wave power potential. Herein, H_{m0} was determined by the Nortek Storm software used to process raw wave measurements from the AWAC (Figure 2). T_e was approximated by multiplying the peak period, T_p, also calculated using Storm, with a coefficient equal to 0.9, which is equivalent to assuming a standard JONSWAP spectrum with a peak enhancement factor of γ=3.3 (Cornett, 2008; Foteinis et al., 2017; Vögler and Morrison, 2013). Equations (1) – (2) were then solved in MATLAB® to estimate the nearshore wave power resource.

MIKE 21 HYDRODYNAMIC WAVE MODELLING

We used the Boussinesq Wave (BW) module of MIKE 21, i.e. MIKE 21 BW, which is a state-of-the-art numerical modelling tool for studies and analysis of wave disturbances in ports and harbours (DHI, 2015). Then, we applied MIKE Animator Plus to turn MIKE 21 BW model results into 2D and 3D visualisations, as to facilitate a clear communication of the modelling results. Two different scenarios were examined; one under the existing conditions and another hypothetical one, where the harbour operates without the offshore breakwater, i.e. the breakwater is omitted and seafloor bathymetry is smoothed to match the bathymetry just west of the breakwater. By comparing the wave motions of the two scenarios inside the harbour it is possible to assess the degree of protection that the breakwater provides. Typical wave conditions (i.e. M_{dir}=360º, H_{m0}=1 m, T_p=5.5 s at 20 m depth) estimated by the AWAC, were used in both scenarios.

RESULTS AND DISCUSSION

Numerical Modelling

Previous works by Kazolea et al. (2015); Maravelakis et al. (2014) concluded that the existing low crested offshore breakwater, sheltering the harbour's entrance, provides little protection during the most intense storms (i.e. H_{m0}>3.5 m and T_p>8.5 s). This is consistent with eyewitness accounts (Figure 4). According to the AWAC measurements, the apparent reason is that the incoming winter waves are largely coming from the north, while a smaller percentage of the lower energy waves comes from the NW, which is the wave direction for which the breakwater appears to provide some protection. One reason is that the offshore breakwater was designed without the guidance of long-term field measurements; another is that the armouring units began failing almost immediately after construction and it is probably due to substandard design.

Figure 4. The wave disturbances inside the old Venetian harbour during a winter storm in 2011. Photos provided by the Natural Disasters and Coastal Engineering Laboratory (NDCEL), TU-Crete, Greece.

It is quite clear that breakwater modifications need to be considered to improve protection during the most intense storms. Here we further assessed the harbour's functionality during a typical, low energy, storm. For the numerical study bathymetric data were collected using a single beam echo sounder (Sonar Mite, Ohmex Instruments) coupled with a differential GPS (Hiper Pro, Topcon) (Maravelakis et al., 2014). A 2 m cell-sized seamless grid, referenced at mean water level (MWL), was created and further smoothed, using a cut-off at 20 m depth. (Figure 5).

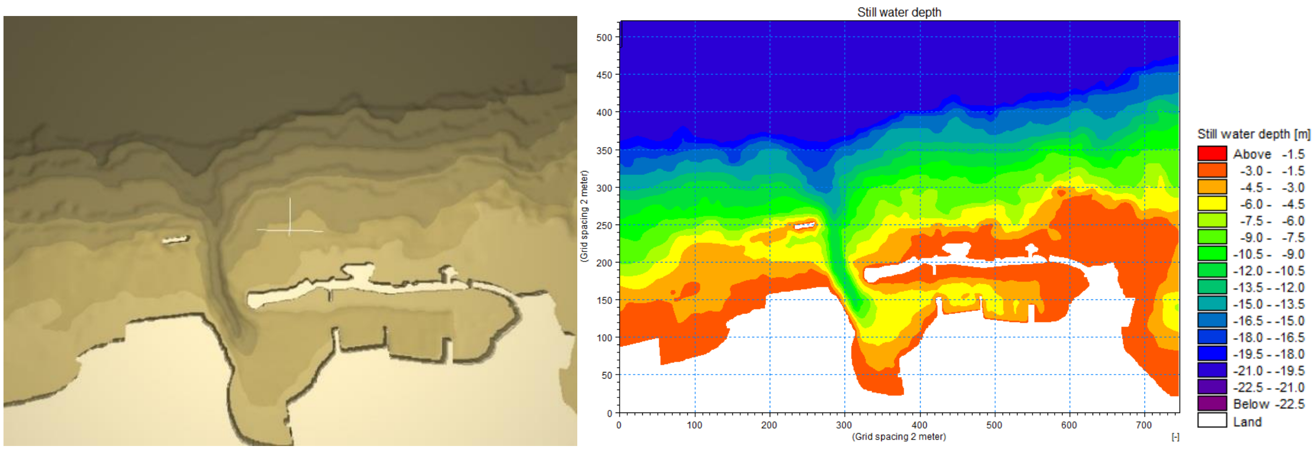

Figure 5. Chania's Venetian harbour bathymetry, using a cut-off of 20 m depth and above, by MIKE Animator Plus (left) and MIKE zero (right) software programs.

With input wave conditions M_{dir}=360º, H_{m0}=1 m, T_p=5.5 s and γ =3.3 at 20 m depth, MIKE 21 BW simulated the waves until fully-developed sea state conditions were achieved (see "video 1-surface elevation with the breakwater" in supplementary files). Then, the model was re-run using the same input, but with a hypothetical bathymetry, where the breakwater is removed and the bathymetry in this area is assumed to be similar to the bathymetry just west of the breakwater (see "video 2-surface elevation without the breakwater" in supplementary files). By comparing both scenarios it was possible to assess the functionality and the degree of protection that the existing offshore breakwater provides.

Our computational methodology can store the surface elevation and relevant time series, e.g. water level, significant (H_{m0}) and maximum (H_{max}) wave height, on a 2m-spaced 2D array. Moreover, various wave gauges, inside and outside the harbour, were used to compare both scenarios, i.e. with and without the breakwater.

Figure 6. The study area and the wave conditions inside and outside the old Venetian harbour as simulated with MIKE 21 BW wave model and animated using MIKE Animator Plus software program.

As a preamble, the breakwater provides little protection from waves coming from the north, which comprise the vast majority of the winter waves according to the ADCP measurements (for more details see Maravelakis et al. (2014)). As shown in Figure 6, waves appear to enter the harbour relative unchanged, then diffract and head towards the west quay. When incoming waves hit the quay they are reflected, leading to wave amplification. Thus, the south part of the harbour is not fully functional, even in mild wave conditions. The modelling was repeated with the offshore breakwater removed (Figure 7), to evaluate its effectiveness during northerly wave storms. Again, during the simulations, the surface elevation and relevant time series were recorded using numerical wave gauges. Similar to the case with the breakwater, it appears that in this case waves also enter the harbour relative unchanged, then diffract and head towards the west quay.

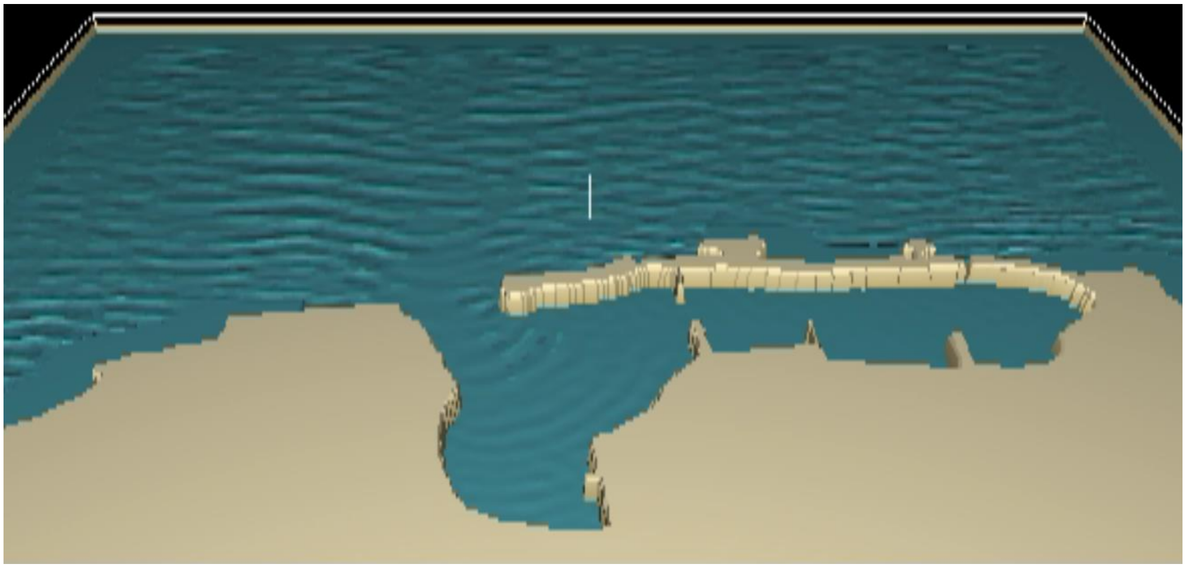

Figure 7. The study area with the omission of the offshore breakwater from the bathymetry, as simulated with MIKE 21 BW wave model and animated using MIKE Animator Plus software program.

Figure 8 presents a comparative analysis of the harbour's response, as induced by a typical mild storm (M_{dir}=360°, H_{m0}=1 m, T_p=5.5 s at 20 m depth), with (Figure 8a) and without (Figure 8b) the breakwater. As shown in Figure 8, in both scenarios the wave disturbances are quite similar. Specifically, in the current situation with the offshore breakwater in place, and under the simulated wave conditions, the H_{m0} is 0.79 m outside the harbour (point with coordinates 300, 250 in the structured grid) and 0.38m just after the harbour's entrance (point with coordinates 330, 150 in the structured grid) at a fully developed sea state. Without the breakwater and at a fully developed sea state the same values were observed at the same grid points. This indicates that breakwater makes no difference at north coming waves. At the east basin of the harbour, calm conditions were observed in both scenarios, with H_{m0} well below 0.1m (in general of the order of 0.05 m) (Figure 6-8). Therefore, additional breakwater construction or improvement works are required, so as to provide adequate protection to the entrance and the south part of the harbour from north coming waves, which is the predominant wave direction according to the AWAC measurements.

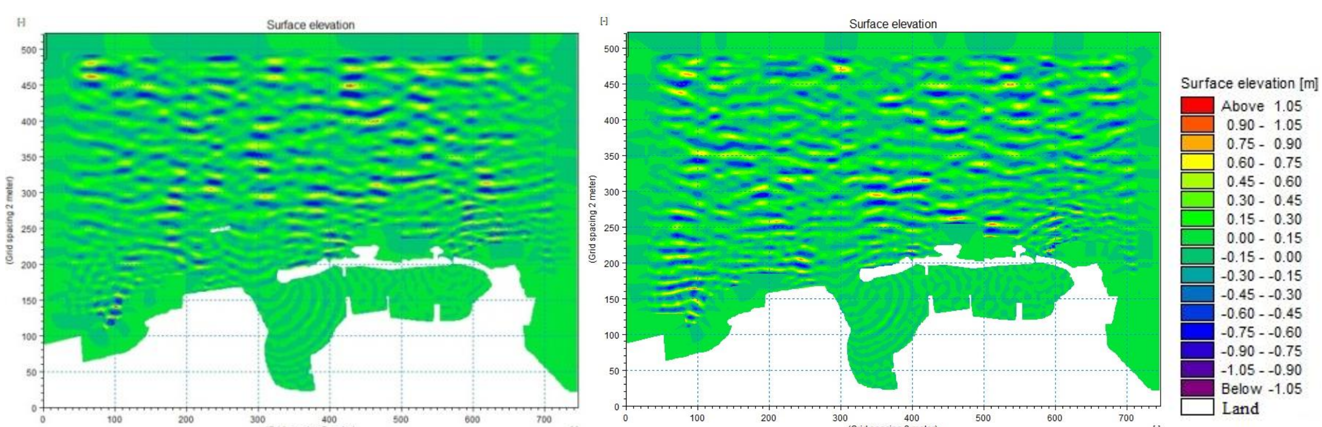

Figure 8. The surface elevation in Chania's Venetian harbour, (a) with and (b) without the offshore breakwater, as simulated by MIKE 21 BW.

We also conducted a preliminary analysis of the AWAC measurements to assess the Venetian harbour's wave power potential. Due to technical difficulties, only data for the reference period 06/10/2011 to 31/01/2012 were available at the time of this study, and the maximum significant wave height (H_{m0}) recorded by the AWAC was 3.85 m, while peak periods (T_p) higher than 10 s were observed (Figure 9). Specifically, seven storms had a H_{m0} > 2 m, whilst three had a H_{m0} > 3.5 m. The maximum T_p recorded by the AWAC was ~11 s, while the three storms with the highest wave power potential (with H_{m0} > 3.5 m) had T_p close to 8.5 s (Figure 9). Subsequently, equations (1) to (3) were applied, using the H_{m0}, as recorded by the AWAC, while the energy period (T_e) was approximated by multiplying the T_p with a 0.9 (Foteinis et al., 2017; Vögler and Morrison, 2013). The preliminary analysis indicates a mean wave power (P_{mean}) potential of 4.77 kW/m for the above reference period, with a maximum wave power (P_{max}) potential of 71.57 kW/m. A more detailed assessment of the local wave regime, extending for a 2-years period, can be found in Maravelakis et al. (2014). Specifically, it appears that in the area the joint occurrence of the significant period (T_s) with H_{m0} mainly occurs in the region of H_{m0} < 1.5 m and T_s < 6s, while events with H_{m0}> 3m have periods between 7s < T_s < 9s and a mainly northerly direction (Maravelakis et al., 2014).

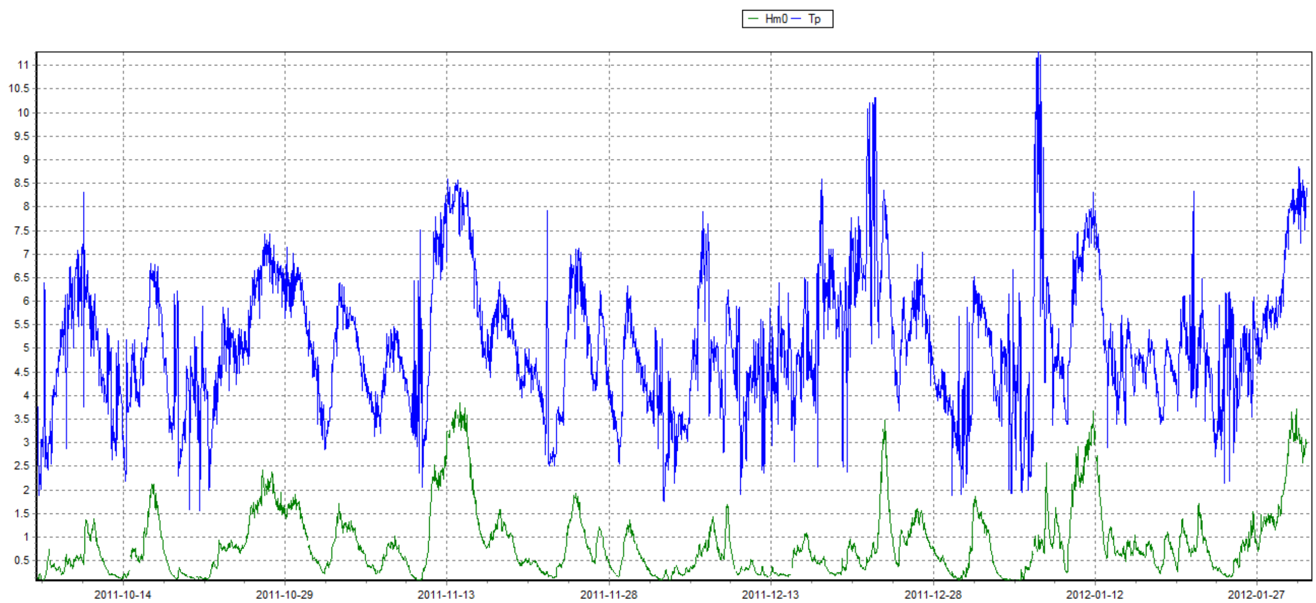

Figure 9. The significant wave height (H_{m0}) and peak periods (T_p) in the Venetian harbour, as measured by the AWAC. Reference period 06/10/2011 to 31/01/2012 (units in meters).

The initial assessment of Venetian harbour wave power potential suggests that it might be possible to install a WEC, but one that could operate in moderate wave climates. Specifically, using the wave data (joint occurrence of T_s with H_{m0}) presented in Maravelakis et al. (2014), it is inferred that the wave regime in the Venetian harbour is not as energetic as areas exposed to ocean waves, where P_{mean} is well over 60 kW/m. Thus, a WEC that could efficiently operate in mild wave climates should be employed. Currently, wave energy technology is designed for the ocean waves and therefore cannot capture the energy of moderate sea states, which prevail in the Mediterranean Sea. As a result, there is a need to downscale existing technology in order to shift the power bins corresponding to their rated capacity to lower values of wave height and period, allowing WEC devices to reach the highest performance for moderate sea states (Bozzi et al., 2018).

As far as WECs integrated into a caisson breakwater are concerned, such as in our case study, Schoolderman et al. (2011) proposed one such device that could operate in moderate wave climates (Schoolderman et al., 2011). The primary function of this structure is the protection of the harbour, while electricity generation is a secondary function. The WEC-breakwater structure is intended to be used in regions with normal daily H_{m0} = 0.5 –1.5 m and T_p = 5 – 10 s (Schoolderman et al., 2011). Moreover, Stagonas et al. (2010) examined theoretically the application of a modified composite seawall for wave energy conversion in Chania's Venetian harbour, but more research is needed. Given all the above it appears that an innovative concept for the Venetian harbour could be the integration of a WEC in the new or improved caisson offshore breakwater.

Nonetheless, more studies are needed towards the long-term local wave regime as well as other important parameters, such as the direction of the incoming wave, tidal range, wave reflection direction and bathymetry (Mustapa et al., 2017), as well as the identification of WEC technology that best fits the specific location (Bozzi et al., 2018).
By allocating WEC costs to the protection of the Venetian harbour, wave energy harnessing could be rendered commercially attractive, since the combined scheme could add a revenue generation stream, Here, wave energy could be used to power the harbour's lighthouse, which coupled with educational and interpretive displays of the wave energy technology could generate additional tourism and ecotourism opportunities (Foteinis and Tsoutsos, 2017).

CONCLUSIONS

The functionality of Chania's Venetian harbour was evaluated with hydrodynamic modeling and field measurements. The local wave climate was recorded by a Nortek AWAC bottom mounted ADCP. The wave conditions induced by a typical low energy storm (M_{dir}=0, H_{m0}=1 m, T_p = 5.5 s and γ=3.3) were simulated with MIKE 21 BW. In order to assess the functionality of the existing offshore breakwater or of a proposed new one, two scenarios were examined; one under the existing situation (i.e. with the offshore breakwater in place) and one without the breakwater. In both scenarios examined, similar wave motions were observed inside the harbour. Moreover, in both scenarios, H_{m0} of about 0.8 m and 0.4 m were observed just outside and just inside the harbour's entrance. Results indicate that the harbour is not functional during northerly storms, which is the predominant wave direction. Therefore, modifications or an additional breakwater construction might be required, as to provide adequate protection to the entrance and the south part of the harbour.
Additional breakwater works could be possibly tailored to accommodate a wave energy converter (WEC), if long-term wave data support the feasibility of this venture and a WEC technology that best fits the specific location is developed/identified. A preliminary analysis for winter 2011-2012 indicates a P_{mean} and a P_{max} of 4.77 kW/m and 71.57 kW/m, respectively (for a reference period from 06/10/2011 to 31/01/2012). By integrating a WEC in the modified or in an additional breakwater, which is required for the harbour's protection, wave energy harnessing could be made commercially attractive in the area, since the WEC's high capital cost would be offset by coastal defence. Furthermore, this innovative stream of electricity could be used to power the harbour's lighthouse, which coupled with educational and interpretive displays of the wave energy technology could generate additional tourism and ecotourism opportunities.

ACKNOWLEDGMENTS

We would like to thank the State Scholarships Foundation (IKY) of Greece for providing funding through the Postdoc Fellowship of Excellence IKY – Siemens. Moreover, we would like to thank DHI for providing a free academic thesis license for the MIKE 21 BW model and especially Mr Elias Moussoulis, DHI's Greek representative, along with the Danish office for all their help during model set up and validation. We thank Nikos Kalligeris, Vassilis Skanavis, Nikos Maravelakis and Constantine Papadogiannis for their contributions in data collection.

SUPPLEMENTARY DATA

Two animations of models with and without a breakwater can be found in the journal's webpage for this paper.

REFERENCES

Abanades, J., Greaves, D., and Iglesias, G., (2014). "Coastal defence through wave farms." *Coastal Engineering*, 91, 299-307.

Boccotti, P., (2012). "Design of breakwater for conversion of wave energy into electrical energy." *Ocean Engineering*, 51, 106-118.

Bozzi, S., Besio, G., and Passoni, G., (2018). "Wave power technologies for the Mediterranean offshore: Scaling and performance analysis." *Coastal Engineering*, 136, 130-146.

Contestabile, P., Iuppa, C., Di Lauro, E., Cavallaro, L., Andersen, T.L., and Vicinanza, D., (2017). "Wave loadings acting on innovative rubble mound breakwater for overtopping wave energy conversion." *Coastal Engineering*, 122, 60-74.

Cornett, A.M., (2008). "A Global Wave Energy Resource Assessment." *Proc., The Eighteenth International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers, Vancouver, Canada.

DHI, (2015). *MIKE 21 Wave Modelling*. MIKE 21 Boussinesq Wave Module Short Description, DHI, Hørsholm, Denmark, 18.

Foteinis, S., Hancock, J., Mazarakis, N., Tsoutsos, T., and Synolakis, C.E., (2017). "A comparative analysis of wave power in the nearshore by WAM estimates and in-situ (AWAC) measurements. The case study of Varkiza, Athens, Greece." *Energy*, 138, 500-508.

Foteinis, S., and Tsoutsos, T., (2017). "Strategies to improve sustainability and offset the initial high capital expenditure of wave energy converters (WECs)." *Renewable and Sustainable Energy Reviews*, 70, 775-785.

Henriques, J.C.C., Cândido, J.J., Pontes, M.T., and Falcão, A.F.O., (2013). "Wave energy resource assessment for a breakwater-integrated oscillating water column plant at Porto, Portugal." *Energy*, 63, 52-60.

Jones, C., Magalen, J., and Roberts, J., (2014). *Wave Energy Converter (WEC) Array Effects on Wave, Current, and Sediment Circulation: Monterey Bay, CA*. Sandia National Laboratories, Albuquerque, New Mexico.

Kazolea, M., Kalligeris, N., Maravelakis, N., Synolakis, C. E., Delis, A. I., and Lynett, P. L., (2015). "Numerical study of wave conditions for the old Venetian harbor of Chania in Crete, Greece." *Proc., 36th IAHR World Congress*, The Hague, Netherlands.

Kim, C.K., Toft, J.E., Papenfus, M., Verutes, G., Guerry, A.D., Ruckelshaus, M.H., Arkema, K.K., Guannel, G., Wood, S.A., Bernhardt, J.R., Tallis, H., Plummer, M.L., Halpern, B.S., Pinsky, M.L., Beck, M.W., Chan, F., Chan, K.M., Levin, P.S., and Polasky, S., (2012). "Catching the right wave: evaluating wave energy resources and potential compatibility with existing marine and coastal uses." *PLOS ONE*, 7(11), e47598.

Maravelakis, N., Kalligeris, N., Lynett, P.J., Skanavis, V., and Synolakis, C.E., (2014). "A Study of Wave Amplification in the Venetian Harbor of Chania, Crete." *Proc., 34th Conference on Coastal Engineering*, Seoul, Korea.

Musial, W., (2008). *Status of Wave and Tidal Power Technologies for the United States, Innovation for our energy future*. National Renewable Energy Laboratory, Golden, Colorado.

Mustapa, M.A., Yaakob, O.B., Ahmed, Y.M., Rheem, C.-K., Koh, K.K., and Adnan, F.A., (2017). "Wave energy device and breakwater integration: A review." *Renewable and Sustainable Energy Reviews*, 77, 43-58.

Playfair, R.L., (1882). *Handbook to the Mediterranean: its cities, coasts, and islands*.

Schoolderman, J., Reedijk, B., Vrijling, H., Molenaar, W., ten Oever, E., and Zijlema, M., (2010). "Generating Electricity at a Breakwater in a Moderate Wave Climate." *Proc., 32nd Conference on Coastal Engineering*, Shanghai, China.

Stagonas, D., Müller, G., Maravelakis, N., Magagna, D., and Warbrick, D., (2010). "Composite seawalls for wave energy conversion: 2D experimental results." *Proc., 3rd International Conference on Ocean Energy*. ICOE, Bilbao

Takahashi, S., Nakada, H., Ohneda, H., and Shikamori, M., (1992). "Wave Power Conversion by a Prototype Wave Power Extracting Caisson in Sakata Port." *Proc., 23rd Conference on Coastal Engineering*, ASCE, Venice, Italy.

Vögler, A., and Morrison, J., (2013). "Assessment of the grid capacity sharing potential for wave and wind energy conversion systems in the outer Hebrides of Scotland." *Proc., European Wave and Tidal Energy Conference (EWTEC),* Aalborg, Denmark.

Zanuttigh, B., and Angelelli, E., (2013). "Experimental investigation of floating wave energy converters for coastal protection purpose." *Coastal Engineering*, 80, 148-159.