Feaseability study of a wec integrated in the port of giardini naxos, italy

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This paper presents the feasibility study for a green touristic infrastructure by the installation of a WEC system in the port of Giardini Naxos, in the Mediterranean Sea. The area is characterized by a low amount of annual wave energy. The WEC system chosen is the OWC and its geometry has been tested by means of a small scale physical model. The surface elevation and the pressure on the structure have been recorder in such tests in order to evaluate, respectively, loadings and reflection at the front wall. The eigenperiod of the water column inside the device is also obtained. Finally, the economic return is estimated.

*Keywords: Wave Energy Converters, Oscillating Water Column, Feasibility study, Green Port*

# INTRODUCTION

The European interest in renewable energy has the aim of reducing the noxious emissions for the human beings and for the environment. The interest in renewable energy is increasing and many solutions are adopted all over the world.

In particular, the interest in wave energy associated with the motion of the waves is growing in the last years (Clement et al. 2002).

The wave energy is produced by the energy transfer of the wind to the sea surface. The weak point of this form of energy is its irregular distribution in the globe (Mork et al. 2010). In close seas, the wave energy is scarcely used for exploitation since the amount of available energy is very low. The annual wave energy in Mediterranean sea is between 2 and 12 kW/m (Arena et al 2015, Monteforte et al. 2015 and Vicinanza et al. 2011), with a most energetic areas along the western coast of Sardinia (Buccino et al. 2015).

The present study focuses the attention on the Sicilian coast (Italy). The energy around the coast of Sicily has been studied in deep by Iuppa et al. (2015, a), by means of a third-generation model. The most energetic areas are located in western side of Sicily and in the Strait of Sicily.

For Iuppa et al. (2015, b), the offshore values of the energy flux are close to 8 kW/m on the western side, such values decrease in the Strait of Sicily to 4 – 6 kW/m. Instead, the minimum values of the energy flux is reached in the north and east sides of Sicily, with values of 2 – 3 kW/m.

Consequently with the increasing interest in wave energy, the study of Wave Energy Converters (WEC) system has increased. The WECs are the system used for the conversion of wave energy in electrical energy. There are more than 1000 devices (Buccino et al. 2015), each of them having different working principle. Moreover, many WEC systems can be installed in harbors, in vertical or in rubble mound breakwater.

In this work, the WEC system chosen to be installed in the site of interest is the OWC, below described in detail. Few prototypes of OWC were installed in Europe and the most important was located in Mutriku, Spain (Torre Enciso et al. 2009; Torre Enciso et al. 2010; Torre Enciso et al. 2012). Such a device was located inside a vertical breakwater for al length of about 100 m; it was formed by 16 OWC caissons, arranged to a curvature of 220 m. The caissons had trapezoidal shape of about 6 x 12 m and 16 turbo-generators were install inside the chambers. The expected production of electric energy was   
600 MWh/year. The system now does not convert energy anymore, since the structure was damage by a violent storm.

The aim of this work is to carry out the feasibility study of the installation of a WEC system in a low energy area. The optimized geometric configuration of the device is carried out by means of physical model tests. The structural and economic feasibility is performed on the basis of such information. Finally the results are discussed in the conclusions.

# PELIMINARY ANALYSIS OF WEC SYSTEMS FOR THE CASE STUDY

In the present study, a WEC system is considered to be installed in a harbor, with the aim of achieving a green infrastructure by using renewable energies for the lighting of the port.

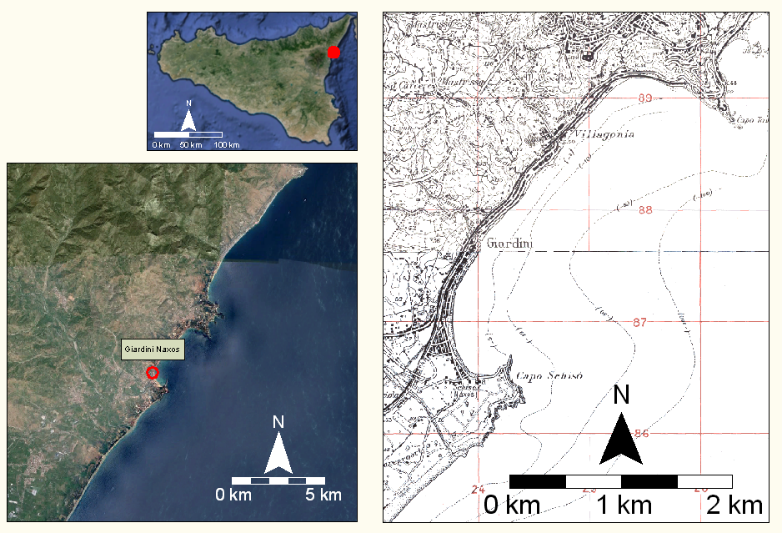
The case study is the Giardini Naxos summer seasonal port, which is located on the East coast of the island of Sicily (in Italy), as shown in Figure 1 (a). In such an infrastructure, maintenance and extension interventions are planned. The widening of the port includes the construction of new lee breakwater and the extension of the existing main breakwater. In this way, the berths and the docking of yachts and cruise ships will be expanded.

The available wave energy is quite low at this site of study. However it has been chosen in order to evaluate the feasibility of installing a WEC system in such critical conditions. The offshore annual mean power is equal to 1.75 kW/m at the water depth of -20 m, and its intensity is reduced to 0.76 kW/m for the wave propagation from offshore to near shore, as shown in Figure 1 (b).

The choice of a WEC system and its performance optimization is important for a site with low wave energy. In any case, the system will be installed in that part of the dam most exposed to wave energy: the extension of the main breakwater.

**(b)**

**(a)**



**Figure 1: Site of study: (a) geographic localization (red point); (b) potential energy around the island of Sicily and indication of Giardini Naxos harbor with red point.**

The planned new part of the main breakwater is 176 m long, and it starts from the final part of the existing main breakwater. It is located over a sea bottom of about 14 m and it is designed with vertical caisson filled with inert material and a concrete top. Only the first 80 m of the dam can lodge a WEC, because the final part will accommodate a passenger a terminal for yachts and cruise ships.

Three types of WEC systems was considered to be installed in the breakwater with different work principle: the Oscillating Water Column (OWC), oscillating water column modified (U-OWC) and Overtopping Breakwater for Energy Conversion (OBREC). The OWC has been chosen since it allows the berthing of cruises at the offshore side of the breakwater in calm water conditions.

# LABORATORY SETUP

A set of experiments were projected for the wave channel of Hydraulic Laboratory of Catania. The configuration of Giardini Naxos’ breakwater with an OWC system integrated, was tested at 1:75 scale (see Naty et al. 2016).

In Figure 2 the schematic OWC caisson is shown with indication of geometrical dimension and of the location of the measurement tools.

The OWC model was installed at about 16 m far from the wavemaker. The still water deep is *h* = 0.19 m.

Such a model consists of 11 chambers with transversal length *Bt* = 0.08 m, wide *B* = 0.05 m, height of the chamber *h*t = 0.28 m and air chamber height in still conditions *h*a = *h*t - *h* = 0.09 m. The anterior wall draft *a* is variable from 0.05m and 0.155m, consequently the gap opening *h*i in vertical wall is also variable.

In the vertical conduct at the top of the caissons, an orifice is inserted to simulate the pressure reduction due to the installation of the turbine. Two diameters of orifice are tested: *d*0 = 0.01 m, with a relative air of orifice over the air of chamber *A*0*/A*c = 0.71%, and *d*0 = 0.006 m, with *A*0*/A*c = 1.96%, where *A0* = *π/4•d*0 is the area of the orifice and *Ac* = *B•B*t is the horizontal section of internal chamber.

The wave motion was monitored with six wave gauges and three pressure sensors. In particular, for the evaluation of the reflection coefficient three wave gauges (WG01-03) were installed at the center of channel, at about 2 m far from the structure. The wave gauges were placed with distancebetween the first and the second wave gauge *x12* = 0.185 m and at a distance between the first and the third wave gauge *x13* = 0.345 m. Such distances between the wave gauges are chosen in order to follow the limit of the method for evaluating the reflection coefficient. The interaction of the surface elevation with the structure has been evaluated by means of two wave gauges (WG04-05), installed in front of the structure, and by using one more gauge (WG06) installed in the central chamber of the model. Two pressure sensors (P01-02) were installed in a lateral chamber of the model, for the evaluation of the pressure at the front vertical wall. The reason of installing two pressure sensors in a lateral chamber is due to avoid the influence of the sensor on the measurement, since the sensors and the chamber have similar lengths. Such pressure sensors were located at the lower edge of the front wall and at the mean water level.

The last pressure sensor (P03) was installed at the top of the central chamber, for the evaluation of the air pressure.

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**(a)**

**(b)**

**Figure 2: Schematic section of the experimental setup of OWC model with the indication of geometrical parameters, wave direction, wave gauges and pressure sensor: (a) longitudinal section of central chamber; (b) longitudinal section of a lateral chamber.**

The data were recorded at a frequency of 1000 Hz, in order to analyze the peak of pressure signal due to impulsive waves.

The irregular waves listed in Table 1 were tested in the laboratory with mean JONSWAP spectrum where *H*m0,i is the incident wave height, *Tp* is the peak period of the wave and *S* is the wave steepness (*H*m0,i over *Lp*) variable between 0.016 and 0.039.

**Table 1. Wave conditions tested at the small scale physical model of the OWC device to be installed in Giardini Naxos.**

|  |  |  |  |
| --- | --- | --- | --- |
| **N** | **Hm0,i [m]** | **Tp [s]** | **S= Hm0,i /Lp** |
| **1** | 0.020 | 0.700 | 0.026 |
| **2** | 0.020 | 0.900 | 0.016 |
| **3** | 0.020 | 1.500 | 0.006 |
| **4** | 0.030 | 0.700 | 0.039 |
| **5** | 0.030 | 0.900 | 0.024 |
| **6** | 0.030 | 1.200 | 0.013 |
| **7** | 0.040 | 0.900 | 0.032 |
| **8** | 0.050 | 1.200 | 0.022 |
| **9** | 0.060 | 1.400 | 0.020 |

# RESULTS

The tests of the physical model was carried out for different configurations in order to perform the optimization of the system and to achieve the minimum of reflection coefficient as a function of the relative submergence *a/h* and of the relative orifice section *A0/Ac*, equal to the ratio between orifice area and chamber area.

The final aim of the experiments is to furnish results for the optimization and the design of the OWC.

## Reflection coefficient

The reflection coefficient *Cr* is defined as the ratio between reflected and incident wave heights. For a harbor and in particular for the summer seasonal port of Giardini Naxos, the low reflection coefficient is important for reducing the pitch of a boat that is entering in the harbor.

The reflection coefficient for random waves is maximum for a vertical structure, for which is always equal to 0.9 (Allsop et al. 1994). For the Jarlan type caisson the reflection coefficient is lower and it is function of the characteristics of the wave and of the structure (Huang et al. 2011; Faraci et al. 2015; Liu and Faraci 2014).

The OWC system can be considered like a vertical breakwater with a gap at the bottom and without Power Take Off (PTO).

In this case, the reflection coefficient is evaluated by the three probes method proposed by Mansard and Funke (1980).Such a method uses the free surface elevation signals registered at three wave gauges (WG01, WG02 and WG03).

The reflection coefficient is shown in Figure 3 as a function of the ratio between the width of internal chamber and the peak wave length (*B/Lp*). Such results are shown for *A0/Ac* =0.71% because the variability of orifice diameter is not very influent on the reflection coefficient, since those tested are both close to the optimum orifice defined in Viviano et al. 2016.

The reflection coefficient is expected to increase with the relative submergence *a/h*. In Figure 3 the values of relative submergence (*a/h)* equal to 0.45 and 0.82 are shown, which give the maximum and the minimum values of the reflection coefficient, respectively.

The reflection coefficient is in the range 0.55 - 0.9. The submergence of front wall becames important on reflection coefficient when *B/Lp* > 0.02. Moreover, independently from the geometry of the OWC caisson, the *Cr* converges to the value 0.7 with decreasing *B/Lp*.

The minimum values of *Cr* are found when the relative submergence *a/h* = 0.45. This value of relative submergence represents an optimum configuration of the device, which can be applied to the design of OWC breakwater for the case study.

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**Figure 3: Reflection coefficient *Cr* as a function of *B/Lp* for tests with orifice relative section *A0/Ac*=0.71%.**

## Eigenperiod

An holistic indication on the OWC behavior can be furnished by means of the eigenperiod of the water column oscillation inside the pneumatic chamber.

Here, the approach defined in Boccotti (2007) has been followed, on the basis of the resonance coefficient which is defined as:

 (1)

where *T\** is the time lag between water flow *Qp(t)* inside the chamber and wave pressure oscillation *Δp(t)* at the opening of the vertical duct. For estimating such a time lag in the presence of random waves, it is necessary to compute a cross-correlation, equal to the mean value of the product between pressures and water flow, as follows:

 (2)

where *T* is the time lag between the two time serires. *T\** is equal to the value of *T* corresponding to the maximum of cross-correlation.

The system works in the resonance condition, ideal for maximizing wave energy conversion, when the resonance coefficient *R* is near to the unit. If the resonance coefficient is greater than unit, the eigenperiod of the plant is greater than the wave period. On the contrary, if the value is smaller than unit, the eigenperiod of the system is smaller than the wave period.

The eigeenperiod is important to find the optimum geometric configuration of the system. For the small scale tests carried out in the laboratory, the resulting time lag *T\** is shown in Figure 4 as a function of the Froude number defined in Sheng et al. (2014):

 (3)

where *g* is the gravity acceleration and *L* is characteristic length, in this case equal to the width of the chamber *B*.

For the configurations having relative submergence equal to 0.45 and 0.82, the mean value of *T\** is about 0.15 s and 0.22 s, respectively. As a consequence, the increase of submergence causes higher values of *T\**.

Such results, obtained for the eigenperiod of the water column inside the chamber, provide further information to be used in the design of the OWC embedded in the port of Giardini Naxos.

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**Figure 4: Time lag *T\** as function of Froude number *Fr*.**

## Loadings

The pressure on the front vertical wall is recorded by the sensors P01 and P02, placed at the lowest edge of the wall and at the steel water level, respectively. In this way, the relative submergence *a/h* and the relative orifice diameter area *A0/Ac* are investigated. The values of measured pressures are compared with Sainflou formulation for vertical wall breakwaters (Sainflou 1928).

The chosen high frequency of acquisition (1000 Hz) allows to evaluate the impulsiveness of waves. The signal was cut at its initial part and was filtered out of the negative values.

The forces on the vertical wall are obtained from the filtered signal integrated on the front wall, and the surface elevation is considered in the area of integration. In particular, the surface elevation at the front wall is estimated by an extrapolation of the signal recorded at the wave gauges WG04 and WG05, near the front wall.

From signals covering 1000 waves, only four peaks of the pressure and of the loading are used the analysis. In this way, the forces are representative of the 1/250 maximum value of the signal (Cuomo et al. 2010; Goda 2010, Contestabile et al. 2017). Furthermore, the wave impact point on the vertical wall is extrapolated from the 1/250 maximum surface elevation, corresponding to the four values of the free surface that give the peaks of the loading.

In Figure 5 and Figure 6 the pressure diagrams are shown for two tests (N. 3 and 4 of Table 1), with minimum and maximum steepness *S* respectively, different orifice relative section *A0/Ac* and submergences *a/h.* The pressure is made dimensionless by dividing for *ρgHm0,i* and the elevations *z* are divided for the water depth *h*. The measured pressures are compared with those obtained by Sainflou formulation.

The tested condition are far from the breaking limit and they do not cause impulsive loadings. For such a reason, the predicted and measured pressures have similar hydrodynamic trend.

The pressure increases with the submergence. The predicted pressure is small underestimate near the maximum free surface elevation, on the contrary, it is overestimated at the edge of the front vertical wall. At the water level, the predicted pressure is less that measured.

Furthermore, the measured forces are compared with the Sainflou predicted forces, shown in Figure 7 for the tests with *A0/Ac* =0.71%, as a function of relative width of the caisson *B/Lp* and of the relative height *H\*=H*m0,i*/h.* In particular, the ratio Fmeasured/Fpredicted shows that the optimum submergence *a/h*=0.45, having minimum reflection coefficient, causes an underestimation of 15% of the measured forces. The increasing wall submergence gives a safe predicted value for *B/Lp* near to 0.02 and *H\** greater than 0.25. The mean value of the ratio Fmeasured/Fpredicted is equal to 1.05 and it can be multiplied for the predicted forces values to obtain more realistic values of force acting on the OWC.

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**Figure 5: Dimensionless pressure profiles of the test with minimum steepness (*S*=0.006), measured and predicted on the frontal vertical wall: (a) relative submerged *a/h* = 0.45; (b) *a/h* = 0.82. Effect of orifice relative section A*0*/A*c* is also shown in each graph.**

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**Figure 6: Dimensionless pressure profiles of the test with maximum steepness (*S*=0.039), measured and predicted on the frontal vertical wall: (a) relative submerged *a/h* = 0.45; (b) *a/h* = 0.82. Effect of orifice relative section A*0*/A*c* is also shown in each graph.**

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**Figure 7: Ratio of forces measured and predicted for the tests with *A0/Ac* =0.71%: (a) the x axes shows the relative wide caisson *B/Lp*; (b) the x axes shows the relative height *H\*=Hm0,i/h*.**

# ECONOMIC ANALYSIS

The structural stability and economic estimations are evaluated for an OWC system embedded in the breakwater of the port of Giardini Naxos, having geometry similar to the optimum configuration chosen by means of physical modelling results. Such configuration provides the minimum reflection coefficient and consequently the maximum energy conversion between those tested.

The vertical breakwaters are usually composed of concrete caissons, filled with dredging inert material and a concrete top. The presence of an embedded OWC inside the breakwater section needs some modification to the classic vertical wall caisson: the first chamber of the caisson, in front of the open sea, becomes the pneumatic chamber.

Since the configuration chosen by means of physical model results is that having relative submergence of *a/h* = 0.45, the submergence *a* in the prototype is 6.50 m (see Figure 8).

The stability of such a breakwater with embedded OWC system is evaluated by means of Sainflou formulation, with the forces incremented by the factor of 1.05, in accordance with the experiments.

The sliding and overturning are verified for such a structure. The sliding is verified with vertical forces *FV* greater than 1.2 times of the horizontal forces *FH*; the overturning is verified with stabilizing moment *MS* greater than 1.5 times of the not stabilizing moment *MI*.

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dredging inert material

reinforced concrete

offshore plane wall

concrete

internal wave absorbing cells

**Figure 8: Schematic section of the configuration of the OWC system embedded in the vertical breakwater for the case of study.**

The structural changes to the classic vertical wall caisson for the embedding the OWC system cause an increase of the costs of about 3%.

Furthermore, the OWC needs for a power take off (PTO) system, composed of a generator and   
self-rectifying Wells turbines. It is found that the presence of PTO further increases the cost of the work of about 0.8%.

Another cost is due to electrical connection at the local net, which is evaluated to be equal to 0.2% of the total cost of the structure. Therefore, the total increment of the cost is about 4%, if the OWC is installed in the first part of the new extension of the main breakwater, for a length of 80 m. The greatest influence on cost is due to the turbines that are not yet commercial.

The energy exploited in a year by the system installed with an estimated efficiency of 0.18 (Naty et al. 2016) is about 100 MWh, where the available mean power is 0.76 kW/m in the site of study. This can be considered a good result for a low energy area, which is achieved thanks to the optimization of the system for the incident wave conditions representative of the local wave climate.

The renewable electricity extracted from waves is paid 300 €/MWh in Italy. The total profit in one year is about 30,000 €. Therefore, the payback is achieved in 19 years, which is comparable with the life of a turbine (i.e. 20 years).

Finally, it is possible to estimate that the cost of mechanical components will reduce if they become commercial systems.

# CONCLUSION

The installation of an OWC system in a small harbor is here proposed, after a choice among three systems. The site of study is placed in Giardini Naxos, Italy, where the energy level available is quite low. The focus of the work is the optimization of the system to be installed inside the breakwater for maximizing the amount of wave energy converted in electricity.

The OWC system is found to be the best solution to be installed inside the breakwater since it allows to maintain the planned functionality of the harbor. The air chamber connected to the sea is obtained from the first chamber of the caisson breakwater and the structural stability of the system is verified. The change on the structure is not expensive, since it causes an increase of 3% of the costs for constructing a classic vertical wall caisson breakwater.

The optimum geometric configuration was obtained through physical model results, where the submergence of the front wall was varied. Such a configuration gives the minimum wave reflection.

The wave loadings on the front wall are compared with the predicted forces by Sainflou formulation, obtaining a mean underestimation of about 5%, which has been taken into account in the structural design of the prototype.

The eigenperiod of the water column oscillations inside the chamber is found to increase with submergence of front wall.

The economic feasibility shows that the OWC breakwater and its PTO causes an increase of costs of about 4%, if compared with a classic caisson vertical wall structure. On the basis of the gain resulting from the selling of electricity, such a WEC system has a payback period of 19 years. This time can be reduced if the Wells turbines here adopted becomes commercial. Nevertheless, such an application is an interesting investment since the main goal is to make the harbor a green infrastructure.

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