GREEN PORTS: AN ITALIAN EXPERIENCE

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ABSTRACT

This paper deals with a new U-OWC (*Oscillating Water Column*) device, called REWEC3 (*Resonant Wave Energy Converter – Realization 3*), which is able to easily obtain a natural resonance with random wind-generated waves, allowing to absorb a large amount of wave energy.

A prototype of this kind of breakwater has been planned to be realized in the Salerno's harbor (Italy) in Tyrrhenian Sea for the enlargement of the pre-existent breakwater (for a total length of 200m).

In the paper the peculiarities of the REWEC3 devices, which are able to increase the hydrodynamics performances of the system with respect to traditional OWC plants, will be discussed. Then, the configuration of REWEC3 caisson breakwaters designed for the Salerno's harbor will be analyzed, giving the performance of the plant in terms both of wave absorption and electrical production.

INTRODUCTION

In the last decades, the research has directed its efforts and resources towards the possibility to incorporate wave energy converters, into traditional maritime breakwaters in order to combine classical use with new opportunities and developments (for example, the Green Ports).

Since the nineties, several OWC (Oscillating Water Column) plants were developed at full scale to produce electrical power from ocean waves (see ; Falcao, 2010 for a re-

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sume). A prototype was built into a caisson breakwater of the Sakata Port (Japan); other plants were built in India at Trivandrum (Raju and Neelamani, 1992), in Scotland at Islay (Heath *et al.,* 2000), in Portugal at the Azores (Falcao, 2000), and, recently, in a breakwater at Mutriku in Spain (see Torre Enciso *et al.,* 2009) . Table 1 reports some OWC devices that were build in the world.

In the past decade, a new device has been patented, in Italy and in Europe, called REWEC3 (or U-OWC). This new device is able to absorb a high percentage of energy of the incident waves, always higher than in the classical OWC. A small-scale field experiment has confirmed the excellent performances of REWEC3 caissons (Boccotti et al, 2007) and has shown that the theoretical model proposed by Boccotti (2007) is able to describe the hydrodynamic of the REWEC3.

Some examples of production of electrical power from REWEC3 devices are shown in Table 2 (values taken from Boccotti, 2004), both for locations in the Central Mediterranean Sea as well as off the West coast of USA (California-Oregon).

At present the Port Authority of Salerno (Italy) has planned to build a new 200*m* breakwater with REWEC3 caissons. In the paper the results of the preliminary study for the conceptual design of the breakwater are shown. This study was made by limited company Wavenergy.it, which is a Spin-Off company of the '*Mediterranea*' University of Reggio Calabria (Italy).

Installed power	Localition, Country	Typology of OWC	Dimensions Water depth	Period
500 kW	Toftestalen, Norway	OWC (coastline with steep slope)	diameter: 10 m, d: 70 m	1985-1988
150 kW	Trivandrum, India	OWC embodied into a breakwater	width: 8 m, d: 10 m	from 1990
75 kW	Isle of Islay, Scotland	OWC (coastline with steep slope)	width: 17 m, d: 3 m	from 1988
60 kW	Sakata, Japan	OWC embodied into a breakwater	width: 20 m, d: 18 m	from 1988
40 kW	Sanze, Japan	OWC (coastline with steep slope)	width: 17 m, d: 3 m	1983-1984
40 kW	Niigata, Japan	OWC embodied into a breakwater	width: 13 m, d: 6,5 m	1986-1988
30 kW	Kujukuri, Japan	OWC with a chamber with compressed air	10 cylinders with diameter: 2 m, d: 2 m	from 1987
3 kW	Dawanshan Island, China	OWC (coastline with steep slope)	width: 4 m, d: 10 m	from 1990
300kW	Mutriku, Spain	OWC embodied into a breakwater	width: 4 m, d =4,5m	from 2011

Table1. Partial list of worldwide applications of OWC devices.

	MWh/Km/year
Central Mediterranean Sea: Tyrrhenian Sea	6.000÷9.000
North-East Pacific coast: California-Oregon, USA	85.000÷100.000

Table 2. The mean production (in 1 year) for a REWEC3 plant with a length of 1 kilometer.

GENERAL OVERVIEW

An OWC plant could be embodied into an upright breakwater (see Figure 1*a*). It consists of a chamber (1) with an opening in the wave-beaten side, which is always kept under water surface, so that sea waves can go into the box (1). The upper chamber is connected to the atmosphere by an air-duct (3), where a turbine (4) is lodged. Under wave motion the air in the chamber (1) is alternately compressed (under wave crests) and decompressed (under wave troughs), so that the air produces a flow in the duct (3) in two opposite directions, which drives a self-rectifying turbine connected to a generator for the production of electrical power.

The eigenperiod of oscillations inside OWCs is typically smaller than the period of incident waves, and it is not possible suitably modify this eigenperiod. Therefore, some complex devices (Budal & Falnes, 1980; Jefferys and Whittaker, 1986; Sarmento *et al.,* 1990; Falcao & Justino, 1999) were proposed for phase control in each individual wave to reach the resonance condition, necessary for the wave energy absorption. For the OWCs working with random wind-generated waves it was suggested to use feedback control to build a characteristic "imitating" resonance related to the velocity response of the system (Korde, 1991).

A new kind of OWC caisson named REWEC3 or U-OWC, has the advantage to obtain an impressive natural resonance without any device for phase control.

Figure 1*b* shows an example of REWEC3 plant embodied into an upright breakwater (Boccotti, 2003, 2004, 2007). Firstly, it is worth-mentioning that this modified caisson, which is able to absorb wave energy (and to converting it into electrical power), is structurally very close to traditional caisson breakwaters. The plant is defined, on the wave-beaten side, by a vertical duct (2), which is connected both to the sea through an outer opening (1) and to an inner room (4-5) through a lower opening (3). This inner room contains water mass (4) in its lower part and an air pocket (5) in its upper part. An air-duct (6), which connects the air pocket (5) to the atmosphere, contains a self-rectifying turbine (7). When waves produce pressure fluctuations at the outer opening (1), water oscillates up and down into the duct (2) and, thus, into the inner room (4). Consequently, the air pocket (5), inside the inner room, is alternately compressed and expanded and an alternate air flow is obtained in the air duct which drives the self-rectifying turbine (3). A comparison between Figures 1*a* and 1*b* shows as, with respect to a traditional OWC, in a U-OWC plant, the additional vertical duct connected to the inner room [elements (1,2,3,4,5) in Figure 1*b*] defines a U duct in the sea-beaten side of the modified caisson breakwater.

Main properties of the new U-OWC

Even if the U duct does not determine important structural modifications in the U-OWC with respect to the classical OWC, it is able to produce important differences on the hydrodynamics inside the U-OWC plant, which are responsible of its performances and of its energy efficiency. In fact, in the U-OWC (REWEC3), with respect to the OWC, waves do not get into the structure, but they act as strength to establish the motion of compression and decompression of the air pocket inside the plant.

The introduction of the U duct, between the air pocket and the open sea, is responsible of the following main results:

- The U-OWCs are able to absorb an amount of wave energy greater than that one absorbed by the conventional OWC in every feature, in the heavy sea states and in the lowest ones (Boccotti, 2007b) and under wind waves and swells. This is, mainly, due the following reason: a U-OWC has an eigenperiod greater than that one of a conventional OWC, and close to the period of waves with the large percentage of wave energy (note that the eigenperiod of OWCs is small with respect to the period of ocean waves). Two small-scale field experiments on two different kind of REWEC plants were carried out in the Natural Ocean Engineering Laboratory, NOEL, of Reggio Calabria off the eastern coast of the Straits of Messina (Boccotti, 2003; Boccotti et al 2007; Arena & Filianoti, 2003, 2007). The results validated the theoretical model for the plant hydrodynamic.

- Most of all, the additional element in the new U-OWC caisson enables us to regulate the eigenperiod of the plant during the design. Therefore the plant can be designed to have an eigenperiod very close to the peak period of the incident wave pressures to which the greater amount of wave energy is associated. The eigenperiod of the plant is regulated by designing suitably their active parts [elements (1,2,3,4,5) in Figure 1*b*]. That allows for achieving strong amplifications of the performances of the REWEC3 plant with respect to classical OWC.

- The structural resistance of a conventional OWC is reduced because of the large opening at the sea-beaten side. The U-OWC exceeds this limit, being characterized by a high structural resistance guaranteed by the two vertical walls (that one of the vertical duct and that one of the inner room) partially superimposed on each other on the seaward side.

GENERAL DESCRIPTION OF THE BEHAVIOUR OF A REWEC3 (U-OWC) PLANT

Hydrodynamics inside the Plant

Referring to the scheme of Figure 1*b*, the equation of the flow inside the plant is

$$h' - h'' - \Delta h_w = \frac{I'}{g}\frac{du}{dt} + \frac{(I'' - \xi)}{g}\frac{d^2\xi}{dt^2}, \qquad (1)$$

where h' and h'' are the energies per unit weight referred, respectively, to the air-water interface in the inner room [(4-5) of Figure 1*b*] of the caisson and to the upper opening of the vertical duct [(1) of Figure 1*b*]. Here *u* is the water velocity in the vertical duct (2), positive if upward; $\xi=\xi(\tau)$ is the instantaneous level of the air-water in the inner room, positive if downward. These two quantities are related each other by the continuity equation Δh_w are the head losses.

The energy per unit weight *h*′ and *h*″ are, respectively, defined as

$$h' = (\xi_0 - \xi) + \frac{1}{2g}\left(\frac{d\xi}{dt}\right)^2 + \frac{(p_a - p_{atm})}{\rho_w g}, \quad (2)$$

$$h'' = \frac{\Delta p}{\rho_w g}, \quad (3)$$

where *g* is the acceleration due to gravity, $\rho\omega$ the water density, p_{atm} the atmospheric pressure, p_a the air pressure inside the inner room, ξ_0 the water level in the inner room at rest and, finally, Δp is the wave pressure on the upper opening of the vertical duct [(1) of Figure 1*b*].

The hydrodynamics inside the plant can be solved (Boccotti 2003, 2004, 2007*a*-*b*) to give the behaviour of the plant under the action:

- of extreme waves, for the estimation of overall stability and structural safety of the plant;
- of sea waves to which the greater amount of wave energy is associated during the year, for evaluation of the wave energy absorption.

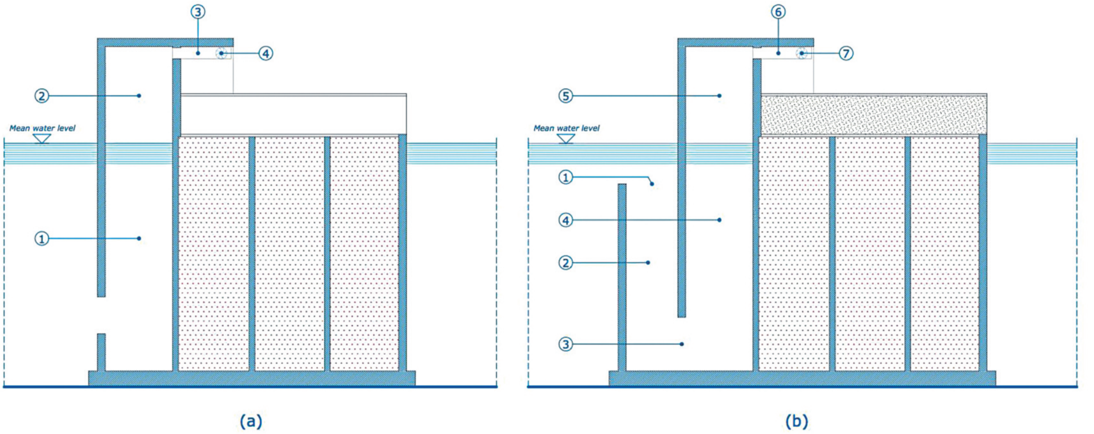


Figure 1. Schematic cross-section and plan: (a) of an OWC plant embodied into an upright caisson breakwater; (b) of a REWEC3 (or U- OWC) plant embodied into an upright caisson breakwater.

Hydrodynamic of the plant under the action of extreme waves

Such a verification is made on applying the Quasi Determinism theory of sea waves (Boccotti 2000). With this theory we can evaluate the pressure fluctuations on the opening of the vertical duct (in Eq. (3)), under the action of the wave group including the largest expected wave during the lifetime of the structure, in order to estimate all the critical parameters of interest: the largest elevation reached by the water in the absorption chamber, the largest and the lowest pressures in the air pocket, the pressure distribution on the various walls of the absorption chamber and of the vertical duct.

Under the action of extreme waves, the overall stability of a U-OWC breakwater can be evaluated. The calculation is made with the most suitable methods considered in the international community (for eg. Goda's model, 1974, 1999) for conventional caisson breakwaters. It will be considered for the U-OWC also the dynamic force produced by the water flow inside the system vertical-duct/absorption-chamber.

Estimation of wave energy absorption in a given sea state (of given conditions): performance of the plant

As aforesaid, it has been proved (Boccotti, 2007) that the performances of a REWEC3 plant are strongly optimized with respect to a classical OWC device for every wave conditions. This is essentially due to the possibility to obtain the resonance conditions without phase control in individual waves by regulating the eigenperiod of the plant such that it results very close to the period of the wave pressures on the vertical breakwater. The eigenperiod is related to the geometry of the plant and it is increased by increasing either the length of the vertical duct or the height of the inner room or the ratio between the cross width of the inner room and the cross width of the vertical duct. Thus, the active part of the REWEC3 plant has to be designed in order to optimize the absorption of the incident wave energy.

Starting from this feature, the evaluation of the wave energy absorption proceeds through numerical simulations of pressure fluctuations produced by waves interacting with U-OWCs and by evaluating the hydrodynamic behavior of the plant under these actions. The numerical simulations of the pressure fluctuations (in Eq. (3)) are carried out by applying classical linear solution to modeling Gaussian sea states (Phillips, 1967; Borgman, 1969) or by considering most accurate solution, which takes into account non-linear contributions (Arena, 2005; Arena et al, 2008; Arena & Guedes Soares, 2009; Romolo & Arena, 2008). The results of numerical simulations are also tested with the analytical solution proposed by Boccotti (2007b), who solved in a closed-form the problem of interaction of the incident wave motion with the plant.

We judge the performances of the plant in term of wave absorption through the following parameters:

- The *absorption width*, C_a, defined as the percentage of energy absorbed by the plant with respect to incident wave energy; that is

$$C_a = \frac{\text{energy absorved by the plant}}{\text{energy ot the incident sea waves}} = \frac{P_{pl}}{\Phi_{in}}, \tag{4}$$

  Φ_{in} being the energy flux associated to incident wave field, related to the communicating active cells and P_{pl} the instantaneous power absorbed by the plant, which is evacuate through the relation that

$$P_{pl} = Q_p(t) \cdot \Delta p(t), \tag{5}$$

where Δp is the wave pressure at the upper opening of the vertical duct of the REWEC3 and Q_p the water discharge inside the plant (equal in the vertical duct and in the inner room).

- The *resonance coefficient*, *R*, defined as

$$R = 4\frac{T^*}{T_p}, \tag{6}$$

T_p being the peak period of the spectrum of the wave pressure at the upper opening of the vertical duct and T^* the abscissa of the first maximum of the following cross-correlation function related to the duration of a sea state

$$\Psi(T) \equiv < \Delta p(t) \cdot Q_p(t+T) >. \tag{7}$$

We should like to recall that *R* ranges from –1 to 1. Under a resonance condition, *R* is equal to zero; *R* smaller than zero means that the eigenperiod is smaller than the wave period; *R* greater than zero means that the eigenperiod is greater than the wave period. (Boccotti 2004, 2007*a*-*b*).

AN ITALIAN EXPERIENCE: DESIGN OF THE NEW REWEC3 FOR SALERNO'S HARBOUR

The first applications of a REWEC3 plant embodied into a caisson breakwater of a commercial port has been planned to be realized in Italy, in Salerno's harbour in Tyrrhenian Sea (jointly, a prototype has been designed for the Marina di Cicerone, a marina that will be built in Formia, Italy). The actual breakwater of the port of Salerno will be enlarged by an overall length of 200*m* (see Fig. 2).

For this purpose, the Port Authority of Salerno has already planned a conceptual design of the extension of the main breakwater with the adoption of the new technology of caisson breakwaters modified by embodying the REWEC3 plant in place of traditional upright caissons.

The total enlargement of 200*m* will be realized through ten REWEC3 caissons at a water depth of about 11.5*m*, each with length of 20*m*.

First REWEC3 solution defined through initial configuration of traditional caisson breakwaters

At the first stage, the design of the new REWEC3 caissons has been defined in order to assure the same safety factors for the stability of a traditional caisson breakwaters. A REWEC3 with the same safety coefficients for whole stability of a traditional caisson for the Salerno's harbor is shown in Figure 3. A comparison between the two structures shows as, with respect to the traditional caisson, the REWEC3 caisson is char-

Figure 2a. View of the Salerno's harbor before the project of enlargement of 200m by the adoption of REWEC3 caisson breakwaters (from GoogleEarth).

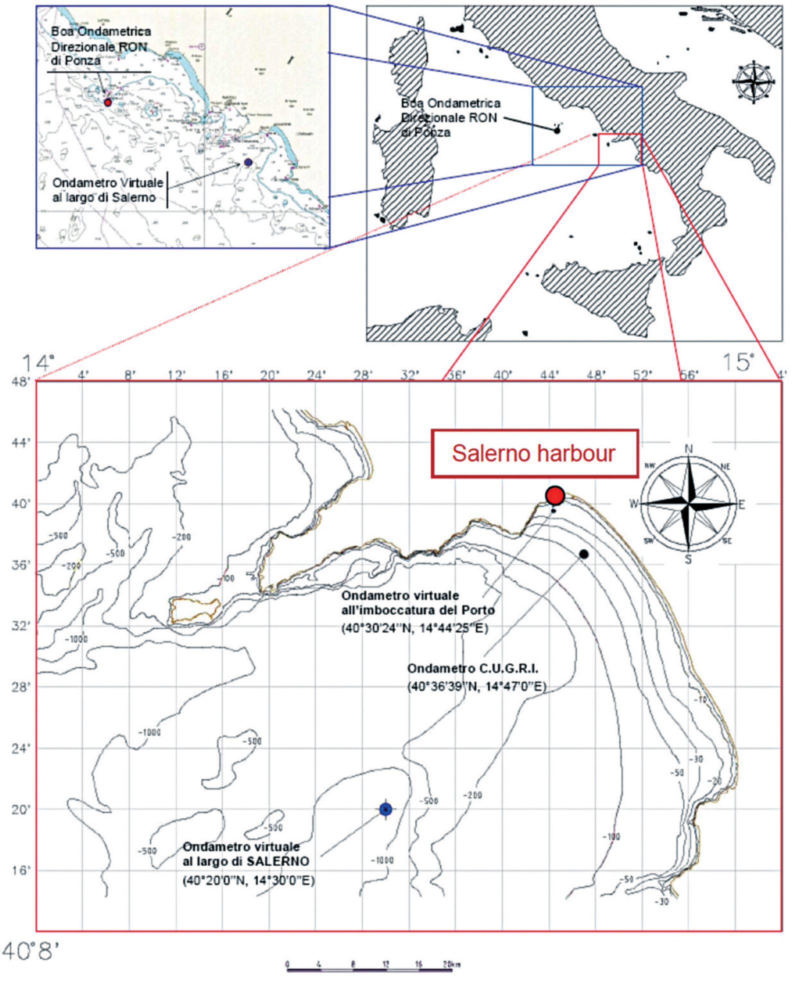


Figure 2b. Location of buoys for the acquisition of the wave climate for the Salerno's project.

acterized, in the cross-section, in the emerged part by a limited extension in width of about 1.6*m* and by a further enlargement in the submerged part given by the width of the vertical duct.

The total width of each REWEC3 caisson is 19.5*m*, with a width of the emerged part of about 17*m*.

The absorption chamber of the REWEC3 device was designed to have the maximum height, with respect to the mean water level, equal to that one of the traditional upright breakwater (+6m with respect to the mean water level).

Final optimized design of the REWEC3 plants for the absorption of wave energy

As aforesaid, the behavior of the REWEC3 plant and the related performance of wave energy absorption is strongly influenced by the geometry of their active parts. For fixed incident wave energy conditions, an optimized configuration of the REWEC3, which maximizes the amount of wave energy absorption by the plant for the production of electrical power, can be defined.

From the data of wave climate of Salerno (see Fig. 2), with an iterative procedure of optimization a final configuration for the REWEC3 devices has been achieved. This final solution considers 10 REWEC3 caissons, each with 5 active cells along the sea-beaten side with a total length of 20*m* (see Fig. 4).

An efficient configuration for each caisson breakwater embodying a REWEC plant, for the examined location in the Tyrrhenian Sea for the Salerno's harbour (Central Mediterranean Sea), could be that shown in Figure 5, which is defined by:

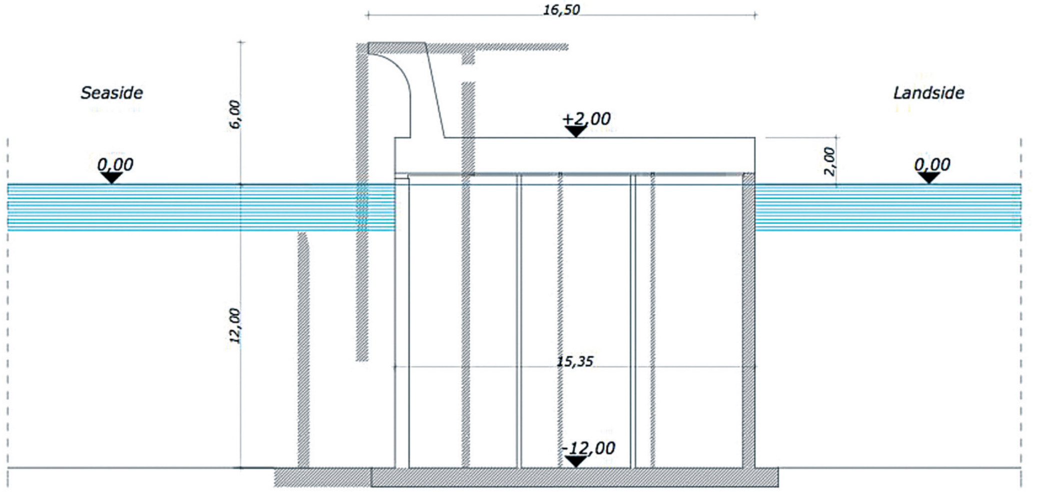


Figure 3. General comparison between a section of a REWEC3 caisson and an upright traditional one, for a breakwater.

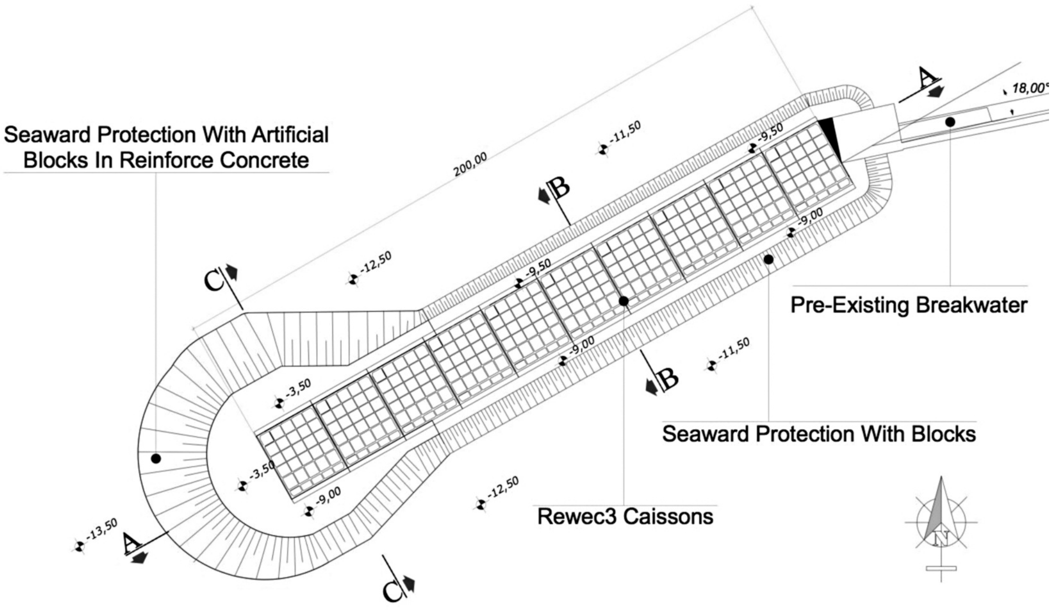


Figure 4. Plan Plant of the enlargement of 200m the existing breakwater in the Salerno's harbor with the adoption of ten REWEC3 caissons.

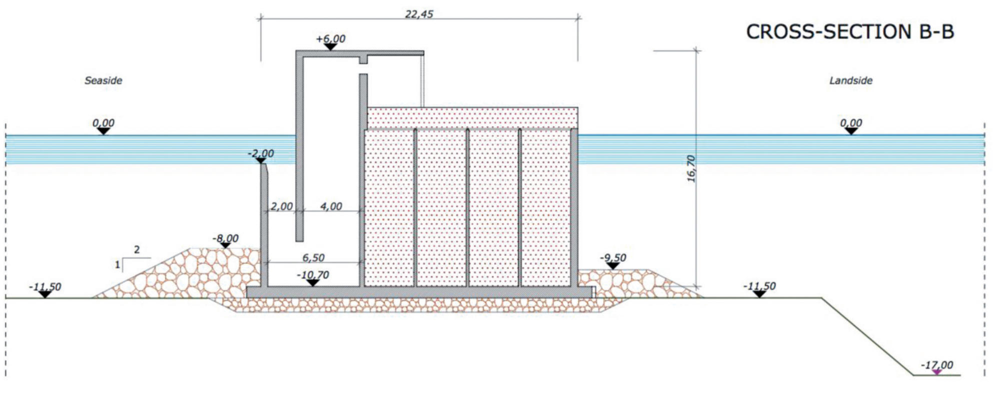


Figure 5. Cross-section B-B of a REWEC3 caisson in the Salerno's project, in the middle of the total breakwater.

- a cross-sectional width of the vertical duct equal to 2.0*m*;
- depth of the vertical duct, with respect to the mean level water, equal to 2.0*m*;
- a length of the vertical duct equal to 8.7*m*;
- a cross-sectional width of the inner room equal to 4.0*m*;
- a height of the inner room, with respect to the mean level water, equal to 6.0*m*;
- height of the opening connecting the vertical duct to the inner room equal to 2.5*m.*

In this final configuration the REWEC3 caissons are defined, on one hand, by a total width in the cross dimension of about 22.5*m*, on the other hand, they are not modified in height with respect to the initial dimension.

Figure 6 shows a detail, of the caisson at the head of the breakwater of the Salerno's project. The plant of the REWEC3 caissons is then given in figure 7.

The increase in width of the new REWEC3 caissons determines an increment of the cost of the structure with respect to traditional breakwater of Figure 6, which is about 5%. The realization of the new REWEC3 caissons for the enlargement of the Salerno's harbour, might be financed through the EU fund "POR-FESR 2007-2013" (at present, the request of financing is under evaluation).

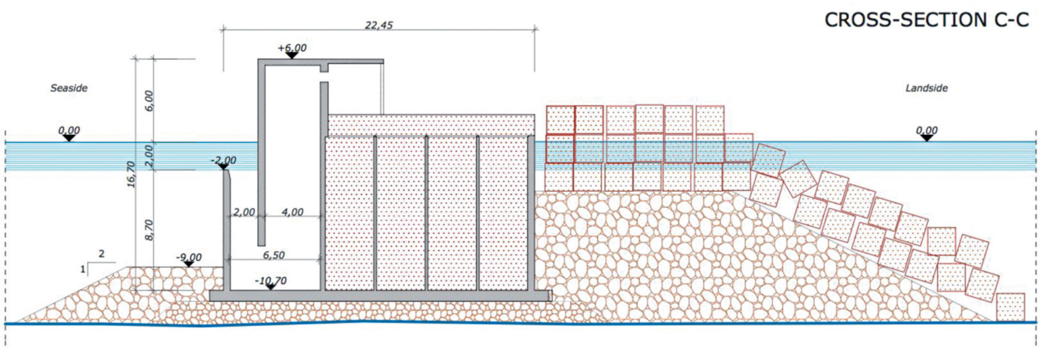


Figure 6. Cross-section C-C of a REWEC3 caisson in the Salerno's project, at the head position seaward of the total breakwater.

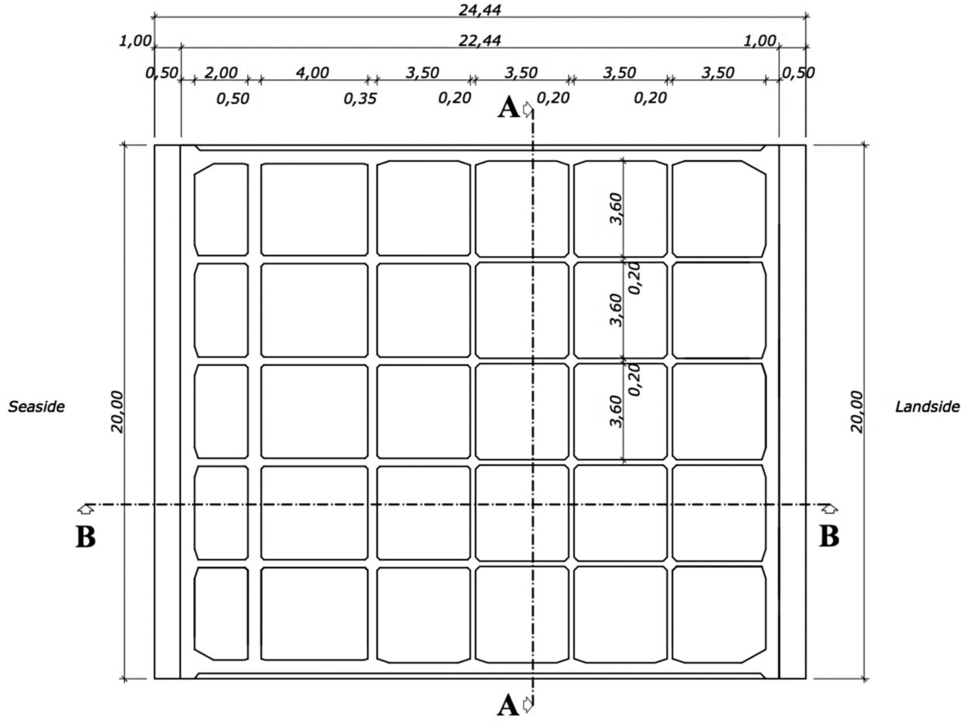


Figure 7. Plant of a REWEC3 caisson in the Salerno's project.

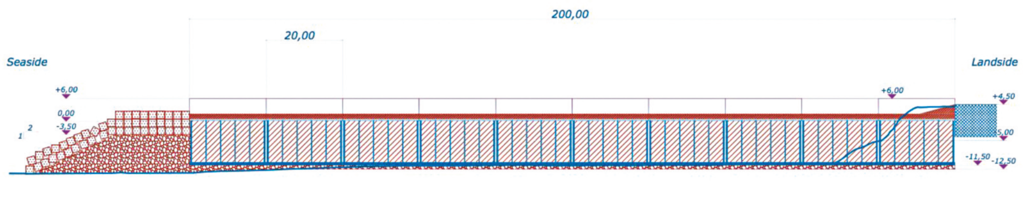


Figure 8. Longitudinal-section A-A of a REWEC3 caisson in the Salerno's project.

Hydrodynamic Controls and Stability

The final configuration of the REWEC3 has to be verified under the whole stability and under the extreme hydrodynamic conditions of the plant.

For both verifications, we have analysed the behaviour of the plant, when it is attacked by a characteristic group of very high waves. Of course, we mean a characteristic group of very high waves for the design sea state, and we shall resort to the Quasi-Determinism theory (Boccotti 1989, 1997, 2000) to describe this group. Doing so, we can check the stability of the plant under the most severe condition, and we can test its safety during the wave energy absorption. For simplicity we shall consider long-crested waves (no directional spread) and we shall assume an orthogonal wave attack. Moreover we assume that the location y_0 where the largest wave height (H) occurs is above the centre of the plant (we mean that H is the largest wave height during the evolution of the wave group).

Under the extreme H_S value, to avoid that the water column hits the roof in the inner room and yields some shock pressures, the surface of the water column has to be kept at least 1m beneath the roof. For this reason, a valve has to be predisposed.

As regards to the analysis of stability, the Goda's formula (1974, 2000) has been considered, which gives the maximum expected wave force in a sea state of given characteristics.

For a REWEC3 device embodied into a caisson breakwater the vertical force varies with time, that is since the the air volume within the plant varies with time under the action of the incident wave motion. Therefore, by taking into account all the hydrodynamic forces acting on the plant, a variation, ΔR_V, on the resultant of the vertical forces is produced, which produces an increase of stability of the structure. To advantage of safety this additional force has been neglected for the stability; therefore, the following safety factors have been obtained:

- safety factor against sliding equal to 1.4;
- safety factor against overturning equal to 1.8.

Energy performances: estimation of wave energy absorption and of electrical power production

The final project of the enlargement of the breakwater in Salerno by the REWEC3 devices for 200m is characterized by 50 cells for the wave energy absorption, each one provided with a turbine (see Fig. 8).

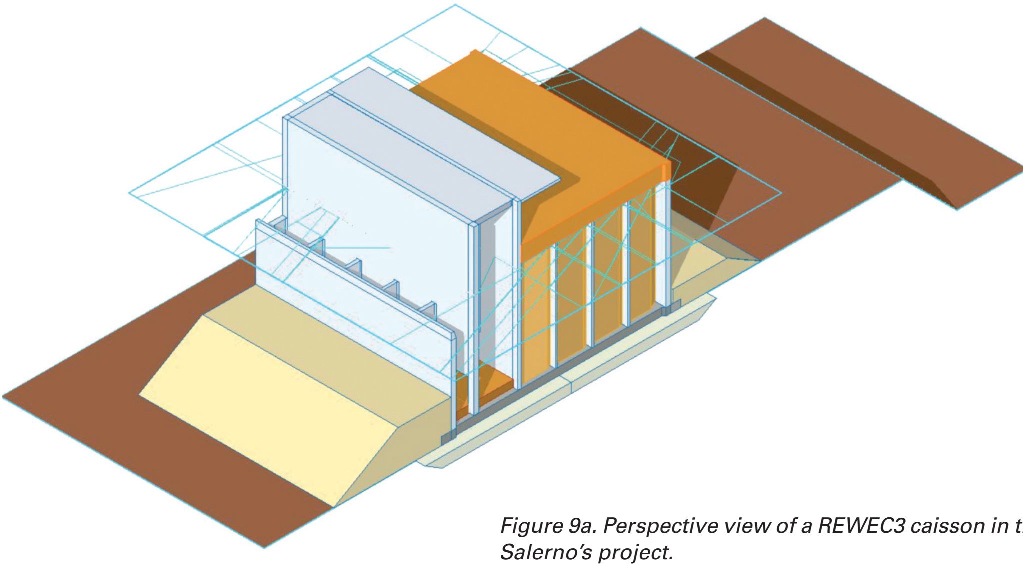
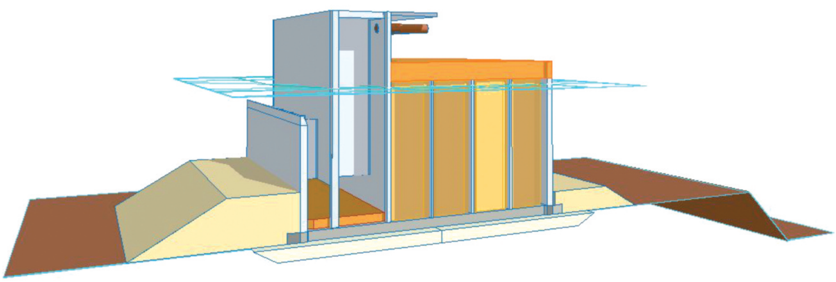


Figure 9a. Perspective view of a REWEC3 caisson in the Salerno's project.



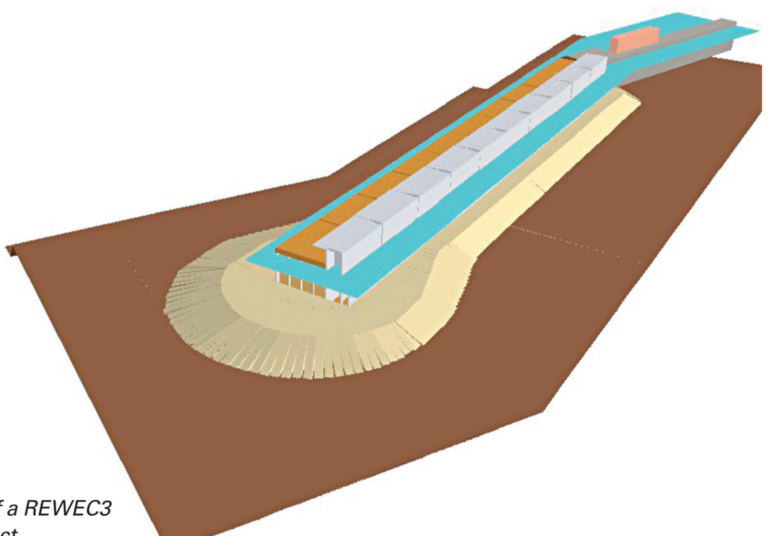


Figure 9b. Perspective view of a REWEC3 caisson in the Salerno's project.

For this designed configuration, in term of wave absorption, the plant will have the maximum value of the absorption coefficient C_a [Eq. (4)] for significant wave heights between 2*m* and 3*m*. In this range the plant will absorb more than 80% of the incident waves.

As for the conversion of wave energy into electrical power, the ten REWEC3 caissons are able to give more than 400,000 kWh of the average wave energy converted in electrical power in a year. This estimation takes into account also the periods during which the production of the plant is zero. For the final design, a new report on the wave climate will be prepared, by considering the values of significant wave height which are more important for production, including swells.

In our idea the breakwater should be able to product more than 250 kWh, when significant wave height is close to 1*m*. By increasing H_s up to 2*m*, we expect that the electrical power that will be produced is close to 800kWh. With 3*m* of significant wave height, or more, we will have the maximum power, which is limited by the turbine and current generators at a value close to 1MWh.

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