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ON DESIGN AND BUILDING OF A U-OWC WAVE ENERGY CONVERTER IN THE MEDITERRANEAN SEA: A CASE STUDY

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ABSTRACT

Since the nineties, the OWC (Oscillating Water Column) plants were developed at full scale to produce electrical power from ocean waves [1]. A prototype was built into a caisson breakwater of the Sakata Port, in Japan; other plants were built in India, in Scotland at Islay, in Portugal at the Azores. A new plant was built in Mutriku (Spain) recently. A new kind of OWC caisson, named U-OWC or REWEC3, was proposed by Boccotti [2]. With respect to a traditional OWC, a U-OWC plant includes an additional vertical duct, which enables to tune the eigenperiod of the plant to the peak period of the wave pressures acting on the converter-breakwater. In this way, resonance conditions can be reached without phase control devices and the wave pressures into the air pocket are increased in amplitude, amplifying the performance of the plant. In 2012, a full scale U-OWC (REWEC3) breakwater has been designed in Italy, for the harbour of Civitavecchia (the port of Rome – Port Authority of Civitavecchia). Such a breakwater embodies 19 caissons, each including 8 cells, 34m long. The paper disseminates the key issues pertaining the design stage. Further, it describes the main phases of the construction stage. The building of the caisson started in October 2012. The first caisson has been completed at the end of 2012. It is the first device for wave energy in the Mediterranean Sea and one of the biggest in the world.

Keywords: Wave energy converter, U-OWC, REWEC, Civitavecchia, green port.

INTRODUCTION

The Resonant Wave Energy Converter 3 (REWEC3) is an Oscillating Water Column (OWC) device. As traditional OWCs, it is composed by an inner chamber with an air pocket alternatively compressed and expanded by the water surface. However, it is differently connected to the open wave field. Indeed, the inner chamber of the REWEC3 is connected to the open wave field by a small vertical duct (because of this configuration the device is also called U-OWC). This solution radically changes the physics of the plant, as the waves do not propagate to the inner chamber, but the oscillations of the inner water surface are induced by the wave pressure fluctuation at the opening of the vertical duct.

The modelling of the U-OWC is different from the one of the OWCs, as the equation of motion of the water column includes nonlinear terms associated to the head losses in the vertical duct. An holistic view on the design process has been given by Boccotti [3], while the modelling and the experimental validation have been discussed by Boccotti [4] and by Boccotti *et al.* [5].

The first prototype of ReWEC3 is under construction in Civitavecchia (Rome, Italy). The device is embodied in a vertical breakwater, so that the plant can be employed both for protection purposes and for energy harvesting. The objective of this paper is present the case study of the Civitavecchia REWEC3 plant. The first part of the paper gives an account of the design issues pertaining to the design stage of the plant.

The design process has been conducted by Monte Carlo simulations. The air/wave pressures acting on the walls of the caissons are estimated. Further, the inner free surface is monitored for checking the safety of the turbine ducts at the design stage. Next, the crucial features of the construction stage are discussed.

MONITORING OF THE INNER FREE SURFACE AND OF THE WAVE PRESSURES

Equations governing the plant

The equations of motion of the water column and of the air pocket were derived by Boccotti [4], based on the reference frame shown in figure 1. The oscillations of the water column are described by the equation

$$\frac{l'}{g}\frac{s''}{s'}\frac{d^2\xi}{dt^2}+\frac{(l''-\xi)}{g}\frac{d^2\xi}{dt^2}=h'-h''-\Delta h_w, \tag{1}$$

where

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

$$h''=\frac{\Delta p}{\rho g}, \tag{3}$$

$$\Delta h_w=K_w\frac{u\,|u\,|}{2g}, \tag{4}$$

and

$$u=\frac{s''}{s'}\frac{d\xi}{dt}. \tag{5}$$

The symbols in the eq.s (1)-(5) denote: g = acceleration due to gravity; ξ = air pocket height measured from the top of the air chamber; ξ_0 = distance from the top of the air chamber to the mean water level; s' = vertical duct width; s'' = inner chamber width; l' = water column length; l'' = vertical duct length; p_a = air pocket pressure; p_{atm} = atmospheric pressure; ρ = water density; Δp = wave pressure at the top of the vertical duct; and K_w = head loss coefficient.

Eq. (1) is coupled to the equation of motion of the air pocket. Specifically, the equation of state is

$$\frac{p_a}{\rho_a^k}=\frac{p_{atm}}{\rho_{atm}^k}, \tag{6}$$

being k the exponent of the equation of state, ρ_{atm} the atmospheric density and ρ_a the air pocket density.

The density ρ_a is calculated given the air mass M_a, by

$$\rho_a=\frac{M_a}{bs''\xi}, \tag{7}$$

in which b is the width of one cell of the plant.

The air mass variation is related to the air flow velocity u_a in the air tube. Indeed,

$$\frac{dM_a}{dt}=-\frac{1}{2}(\rho_a+\rho_{atm})\frac{\pi D^2}{4}u_a, \tag{8}$$

and u_a is related to the air pressure p_a of the air pocket:

$$K_a\frac{u_a\,|u_a\,|}{2}=\frac{p_{atm}}{\rho_{atm}}\frac{k}{k-1}\left[\left(\frac{p_a}{p_{atm}}\right)^{1-1/k}-1\right], \tag{9}$$

where K_a is a head loss coefficient.

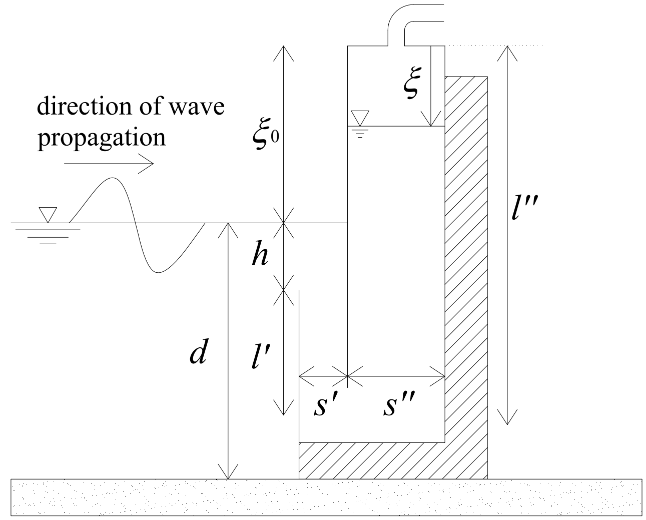

Figure 1. Reference sketch of the REWEC3 plant.

Eq. (1)–(9) are integrated numerically by a finite difference scheme given the initial conditions, at t = 0,

$$\xi=\xi_0;\ \frac{d\xi}{dt}=0;\ M_a=\rho_{atm}bs''\xi_0, \tag{10}$$

and the time history of $\Delta p(t)$.

The time history $\Delta p(t)$ is calculated given the wave pressure of the incident wave field $\Delta p_i(t)$. Specifically, it is estimated as

$$\Delta p=C_d\Delta p_i, \tag{11}$$

being C_d a diffraction coefficient dependent on the absorption coefficient of the plant C_a. That is,

$$C_d=2-C_a. \tag{12}$$

The absorption coefficient C_a is the ratio of the energy absorbed by the plant over the incident wave energy. Obviously, C_a depends on the Δp. Thus, the calculation involves an iteration on the diffraction coefficient C_d. The procedure converges rapidly by assuming C_d = 2 at the first iteration.

Monte Carlo simulation

Monte Carlo simulations are exploited for analysing the behaviour of the plant in a random wave field. In this regard, the wave pressure is considered as a random stationary process of a given power spectral density. The input of the system, Δp_i, is generated by the spectral method via a Fast Fourier Transform algorithm [6], so that Δp_i is compatible with a power spectral density function $S_{\Delta p}(\omega)$. The power spectrum $S_{\Delta p}(\omega)$ is calculated by [7],

$$S_{\Delta p}(\omega)=S(\omega)\frac{\cosh^2[k_0(d-q)]}{\cosh^2(k_0 d)}, \tag{13}$$

where d is the water depth, q is the submergence of the U-duct opening, k_0 is the wavelength estimated by the linear dispersion relation

$$k_0\tanh(k_0 d)=\frac{\omega^2}{g}, \tag{14}$$

and $S(\omega)$ is the spectrum of the free surface displacement.

A mean JONSWAP spectrum [8] $S(\omega)$ is employed for representing the free surface displacement of a wind-generated sea state. Such a spectrum is chosen as the simulations pertain to severe sea states. Specifically, sea states with significant wave heights H_S = 5m (peak period T_p=9.5s) and H_S = 6m (T_p=10.4s) have been considered.

The Monte Carlo simulation is employed for monitoring the water level into the inner chamber and the pressures on the walls of the caisson. These quantities play a crucial role in the design process of a REWEC3. Indeed, the water level relates to the operational condition of the plant. Specifically, the monitoring allows checking that the inner free surface does not reach the level of the air duct and that the opening between the U-duct and the inner chamber is never uncovered. The former case is unsafe for the turbine, because it can be damaged. The latter check is needed for avoiding that the air escapes from the air pocked, as it leads to a reduced efficiency of the plant [9]. The pressure calculation on the walls of the chamber are involved in the structural design stage. In this regard, the pressures are estimated for obtaining the maximum load exciting each wall. The quantities of interest are estimated from one adequately long time history of the response (ξ, p_a). Specifically, as the input is stationary, 10^6 samples of the response are utilized [10].

Numerical results

The probability density function (pdf) of the inner free surface displacement is calculated from the time history of $\xi(t)$. Figure 2 shows the pfds obtained from both simulations. It is seen that the safety of the plant is guaranteed in both sea states. Indeed, the pdf of the inner free surface shows that the free surface oscillates in the interval (-3m, 6m), so that the turbine can properly work. Obviously, a more energetic sea state relates to a broader pdf. However, the plant is safe even for quite severe sea states.

The maximum loads are shown in Fig. 3. The figure shows the load distribution on each wall of the caisson. The wall 1 is the wall on the sea side of the U-duct, the wall 2 is the sea side wall of the air pocket, the wall 3 is the port side wall on the inner chamber and wall 4 is the upper wall of the inner chamber. It is worth-mentioning that the figures show maxima that are not necessarily simultaneous. That is, the load distributions are given by the maxima calculated from the whole time history of the pressures. In this context, it is seen that the most excited wall section is at the bottom, as the loads involve also the calculation of the hydrostatic pressure. The upper wall is excited by the air pocket pressure and it is space-wise constant, as the free surface does not reach the top.

CONSTRUCTION STAGE

The works

The contract on the extension of the Port of Civitavecchia was awarded in the spring of 2012. The time schedule has been planned for completing the works at the beginning of 2015. The construction has been started in July 2012.

Several works have been planned for improving the services of the port and the quality of the infrastructure. Specifically, it is mentioned the construction of two new basins, of about 50 ha, devoted to ferries and cruises (extension of quays of about 1.4 km), to naval services (extension of quays of about 1.7 km) and the extension of the breakwater “C. Colombo” (the main breakwater of the port) to a total length of 400 m. The new structures will be built by utilizing reinforced concrete cellular caissons (over 120 reinforced concrete caissons of different sizes). An overall view is given in figure 4, which shows the layout of the port.

In the outlined context, the embodiment of 15 REWEC caissons was proposed by the Constructor for reducing the reflection coefficient in front of the structure. Indeed, in a first instance, the caissons were designed for absorbing wave energy, without employing devices for exploiting wave energy. Then, the use of the REWEC3 technology was conducted by Wavenergy.it (www.wavenergy.it).

Obviously, the novel configuration of the plant has been designed for harvesting as much energy as possible (figure 5). In this context, the crucial change pertains to inclusion of the pneumatic chamber, which has been utilized into all the REWEC3 caissons, for a total length of 510m, at a water depth of 15m.

Each REWEC3 caisson is 33.94 m long and includes 8 independent absorbing cells (vertical duct and pneumatic chamber) 3.87m wide. The vertical duct is 1.60 m wide and the U-duct opening is located at -2.00 m below MWL, so that the opening is not always below the free surface, while the pneumatic chamber is 3.20 m wide.

The external walls of the absorbing part of the REWEC3 are 0.50-0.60 m thick while the inner walls are 0.35m thick.

Some cells of the caissons are filled with concrete in order to ensure both the global stability and a monolithic behavior of the structure. The remaining part are filled by using dredged materials.

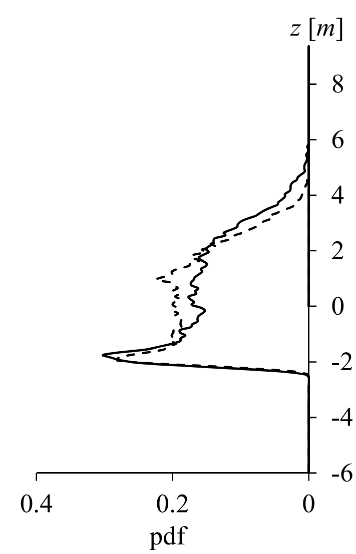

Figure 2. Pdf of the free surface displacement. It has been assumed: H_S = 5m (dotted line); H_S = 6m (continuous line).

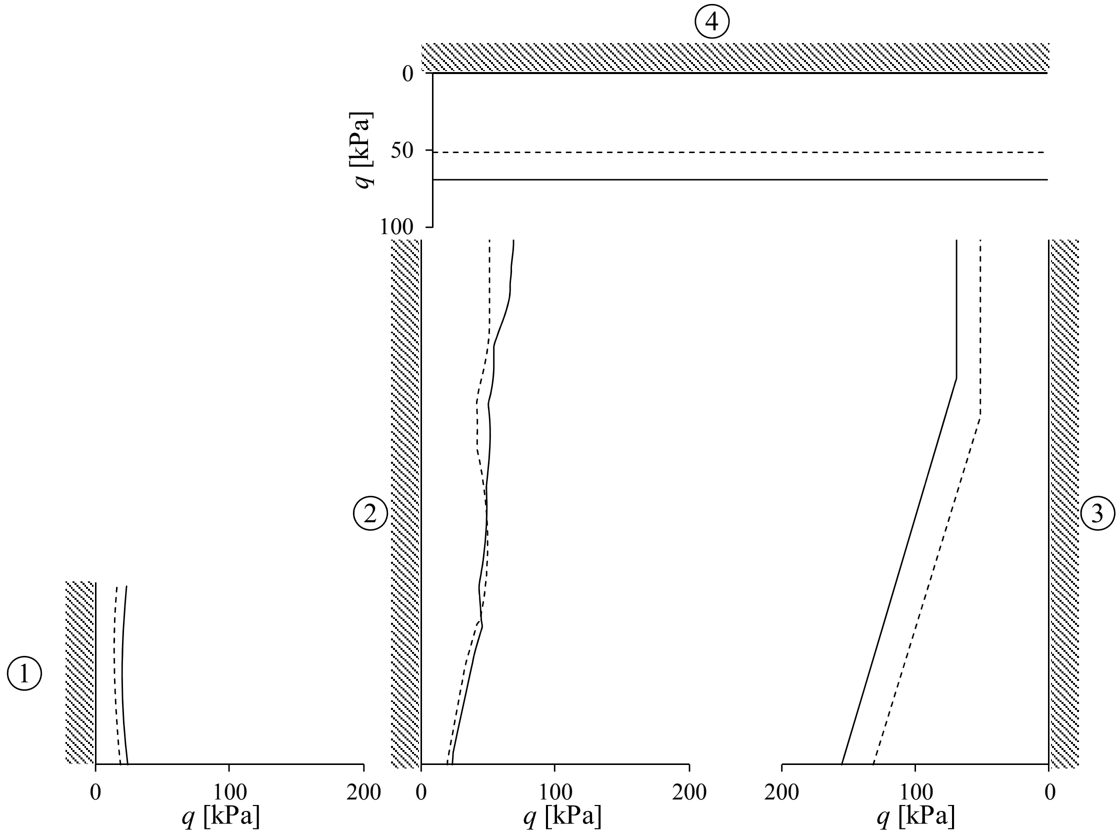

Figure 3. Loads on the walls of the REWEC3. The numbering denotes: sea side wall of the U-duct (1); sea side wall of the inner chamber (2); land side wall of the inner chamber (3); upper wall (4). It has been assumed: H_S = 5m (dotted line); H_S = 6m (continuous line).

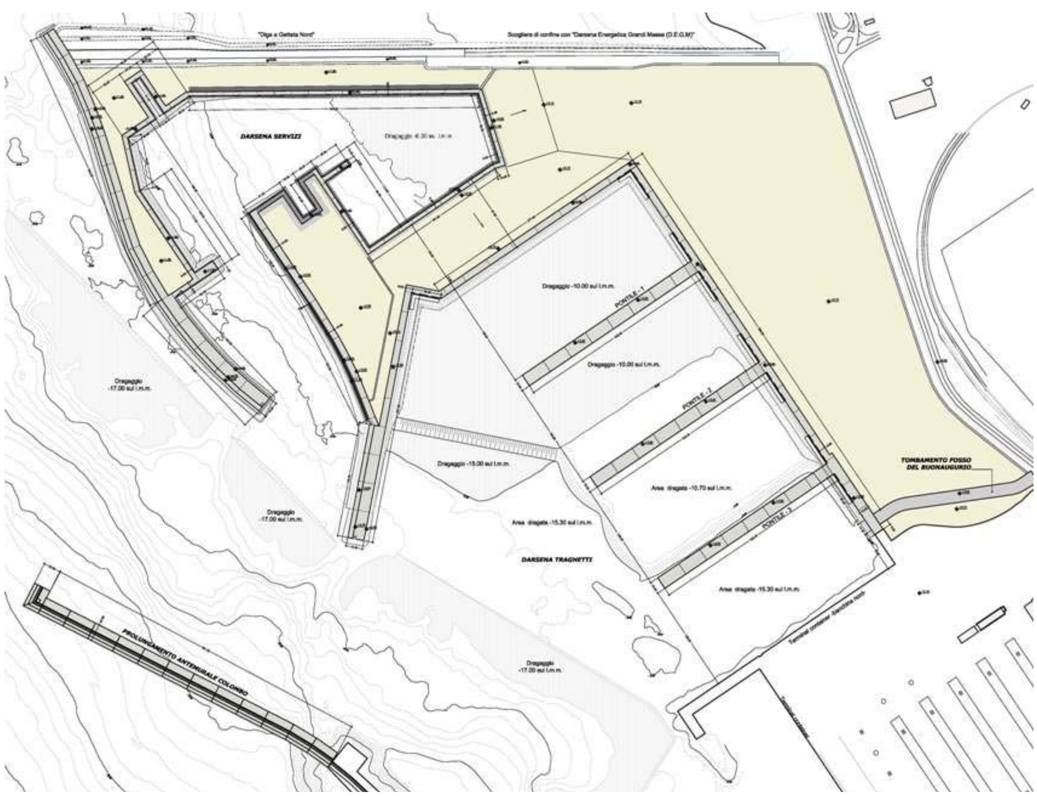

Figure 4. Layout of the Civitavecchia harbour.

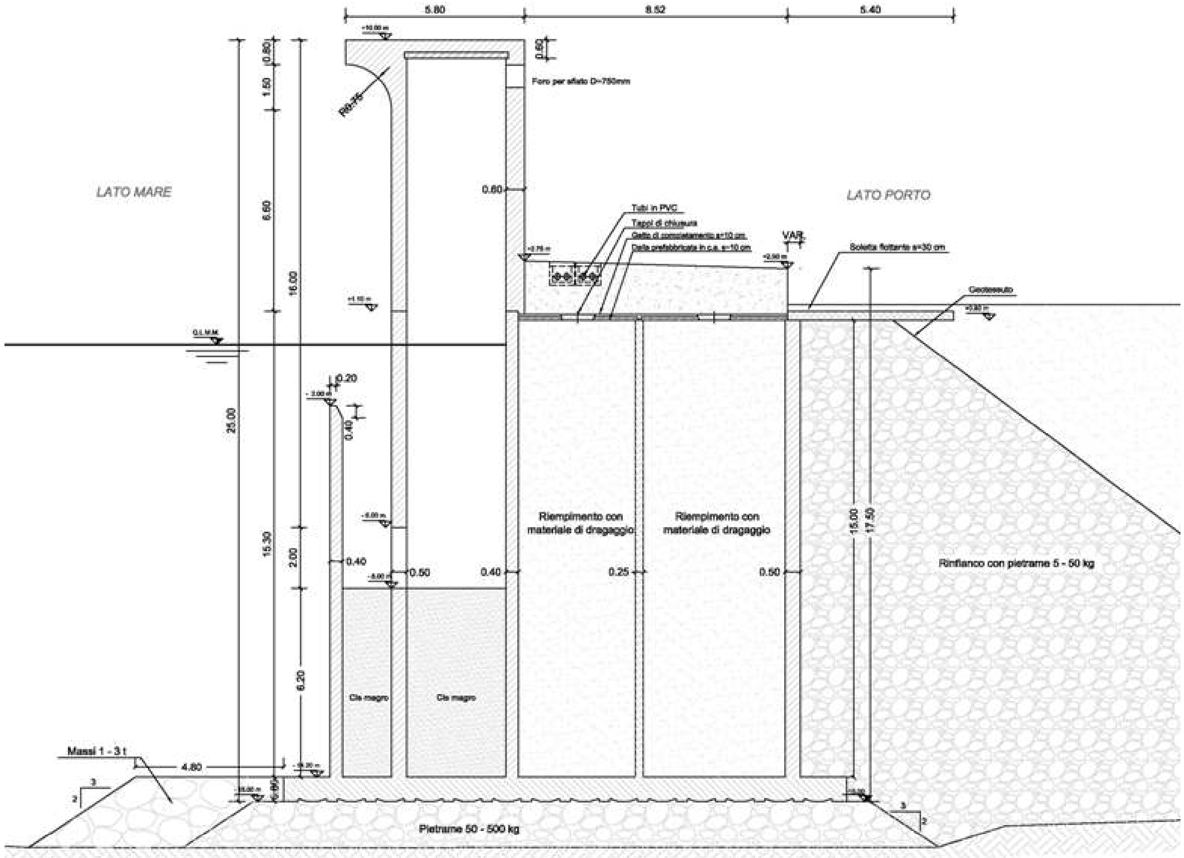

Figure 5. Cross-section of the REWEC3 wave energy converter in the Civitavecchia harbour.

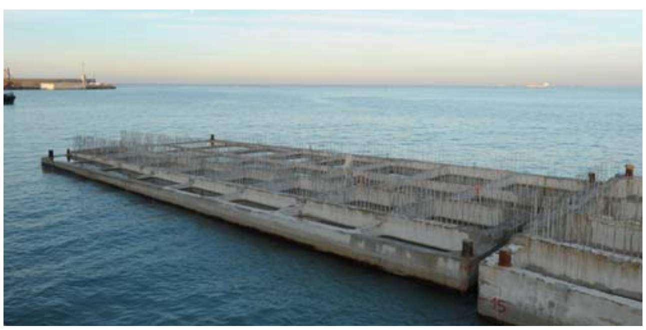

Figure 6. REWEC3 at the preliminary stage, before placing in situ.

The caissons casting

The construction of the reinforced concrete REWEC caissons consist of the following main steps:

- Rubble layer foundation placement;
- Caissons' casting up to 0,80m SWL on a floating plant and launching ;
- Caissons' towing to preliminary site and sinking with water;
- Caissons' towing to final site;
- Caissons' filling with concrete and dredged material;
- Caissons' backfilling ;
- Caissons' completion up to 10,00m SWL on site;

The rubble mound foundation consists of a quarry rock layer 50-500kg about 1 m thick placed on the seabed and topped with a final levelling/blinding layer of finer aggregate. The quarry material is placed and levelled by means of a crane pontoon which discharges by means of a hydraulic grab on site.

Owing to its dimensions and weight, the caissons are cast in two different main phases. The former considers the construction of the REWEC caissons for a total height of 15,80m (until the quote of +0.80 m under MSL) on a floating casting plant.

The bottom slab (0,80m thickness) is cast in one single operation, during this phase the sliding formwork is hung up from the floating plant. Once the base slab is completed the sliding formwork is lowered to start with the caisson body casting.

The concrete is cast in layers and in the meantime the horizontal reinforcement is positioned. Concrete is carried to the upper frame and distributed by means of a pump. The self-climbing formwork is raised by hydraulic jacks acting simultaneously on steel vertical bars, which stand on the caisson's base slab and cause the formwork to rise slowly until the final level.

A series of mix designs were set at the beginning of the work, so the caissons are made with concrete respecting the following requirements:

Figure 7. Construction of the caisson.

- cubic compressive strength 45MPa
- exposure class XS3
- workability S4/S5
- cement CEM III or CEMIV
- w/cm 0.40-0.44
- maximum diameter of aggregates 25-32mm
- concrete cover thickness value of 5 cm.

When the caisson body casting and concrete ballasting, needed to ensure the caisson nautical stability, are completed the mobile upper frame with the formwork hung up is raised to allow the caisson launch. At the same time the plant is brought down to the depth necessary for allowing the caisson floatation. Once floating, the caisson is moved out of the plant and is towed waiting for the final positioning .

The placing phase consists in the towing of the caisson, by means a tugboat, at the placing site, where it is maintained in the right position by means of winches connected with some eyebolts on the caisson's top at one end, and with other eyebolts on a crane pontoon or on the nearest caisson already sunk at the other end. Pumps are put on the caisson's top slab and the seawater is pumped into the cells.

The caisson's position is constantly kept under observation by topographic surveyor during the final step of the operation. A final check of the rubble mound levelling is made by divers, just before a complete sinking is reached. If it is acceptable, the caisson is completely sunk and filled with seawater to assure it is stable until filling.

The caisson's filling is made of concrete and dredged material. The filling material will be unloaded on the caissons directly by lorries and then it is pushed into the cells by an excavator (from the placing of the first caisson a terrestrial connection has been realized).

Backfilling operation (when necessary) is started behind caisson once it has been filled. The backfill material placed just behind the caisson consists of selected quarry material (5-50kg).

The latter phase of REWEC3 caissons casting considers the completion of the caissons with the construction of the upper part of the pneumatic chamber ("the seawall") by using a sliding formwork in situ in order to align the pneumatic chamber from the +0,80m SWL up to +10,00 m SWL.

The final step of the construction involves the concrete demolition of the upper part of the vertical duct from -+2,00m SWL up to +0,80 m SWL (the sea side row of cells) by cutting.

Behind the active part of the REWEC3, a superstructure of reinforced concrete will be built in situ including configurations for water, electricity and telecommunications services (see Figure 8). The current design doesn't include the mechanical and the electrical parts to transmit energy into the port grid.

The different phases have been designed in order to simplify and optimize the casting process, avoid settlements, guarantee work safety conditions and merge the structures into the final layout of the basin.

CONCLUDING REMARKS

The paper has dealt with the first caisson breakwater plant embodying an U-OWC device: the REWEC3. The plant is located in Civitavecchia (Rome, Italy).

The issues related to the design stage of the plant have been disseminated. It has been shown that two crucial quantities to be monitored are the inner free surface displacement and the maximum load on the caisson walls. In this regard, a Monte Carlo simulation has been performed from a spectrum compatible realization of the exciting wave pressure. The simulation has allowed to determine the pdf of the inner free surface displacement and the maximum load exciting the walls. These quantities have been utilized for evaluating the turbine working condition and the safety of the caisson. Specifically, it has been shown that the turbine duct must be protected during severe sea states, as the impact of the inner free surface with the turbine can damage the device. In this regard, the plant is safe even in severe sea states and the inner free surface oscillates in the interval (-3m,6m). The maximum loads acting on the caisson walls have been calculated. It has been shown that the most excited section of the walls is located at the bottom, as the contribution of the hydrostatic pressure is remarkable. Further, as the plant works in safe operational conditions, the upper wall is excited only by the air pocket pressure and the shock impact due to extremely large fluctuations of the inner free surface is not accounted for, because it does not occur even in the most severe sea states pertaining to the location of Civitavecchia.

Finally, the construction stage of the REWEC has been described. Different phases have been described for highlighting the crucial steps involved in the construction of the structure. The details of the layout and of the cross-section of the plant have been shown, as well.

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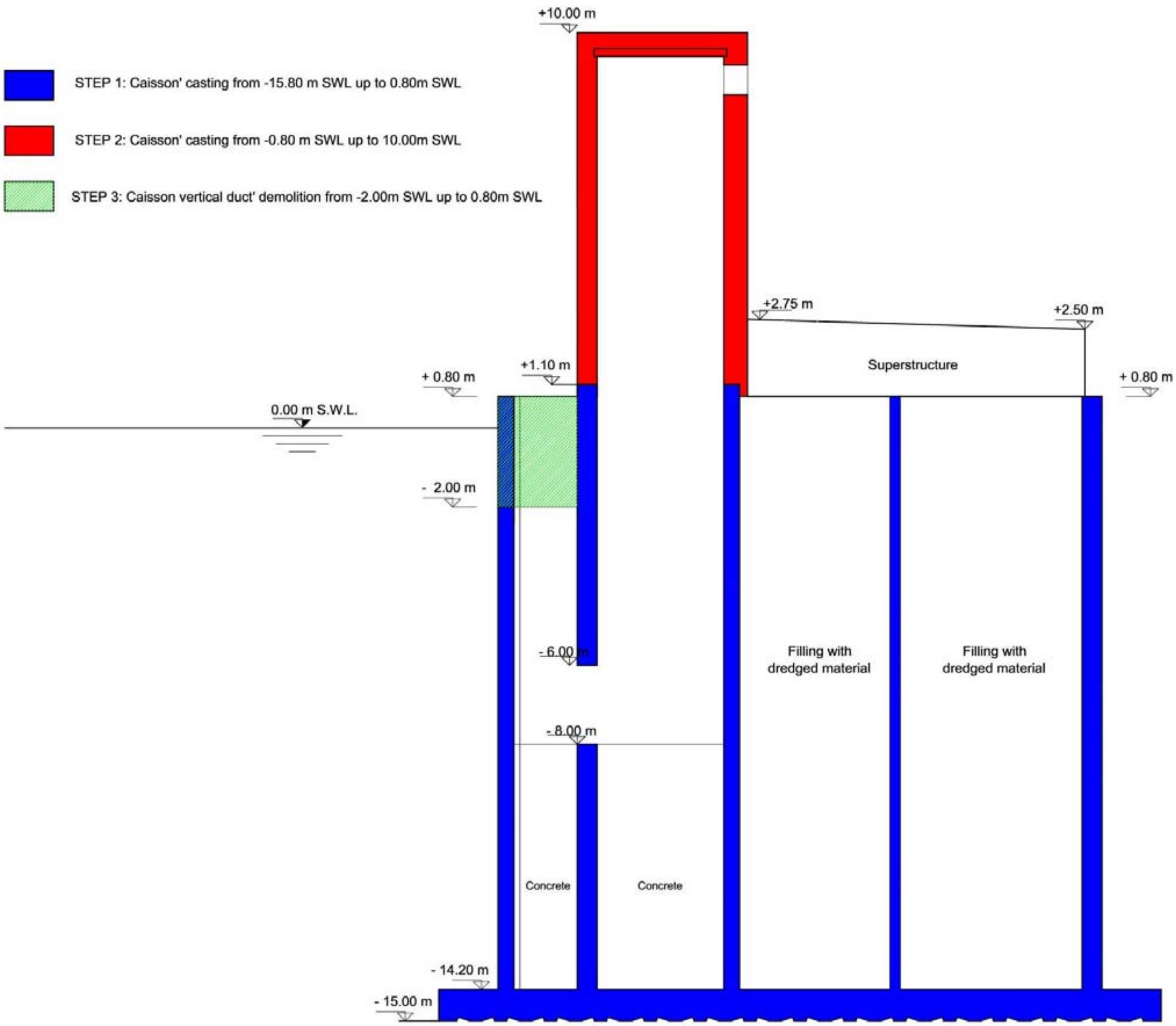

Figure 8. Reference frame of the REWEC3 caisson.

