WAVE PRESSURE DISTRIBUTIONS ON A U-OWC BREAKWATER: EXPERIMENTAL DATA VS CFD MODEL

Filianoti P.[1], Gurnari L.[1]

U-OWCs are Wave Energy Converters belongin to the family of Oscillating Water Column. The interaction between waves and a U-OWC breakwater produces an unknown pressure distribution on the breakwater wall, due to the motion inside the plant. In order to evaluate the force acting on a U-OWC breakwater produced by regual waves, we carried out an experiment in a 2D numerical flume. The computational domain is equipped by a piston-type wavemaker, in the left extremity side and a U-OWC breakwater on the opposite side. The water-air interaction is taken into account by means of the Volume Of Fluid (VOF) model implemented in the commercial CFD code Ansys Fluent. Both air and water flow fields are assumed to be unsteady and are computed by solving the Reynolds-Averaged Navier-Stokes (RANS) equations. In the numerical model, air is considered as an ideal gas, in order to take into account the compressibility inside the plenum chamber. Results were compared with a theoretical model on a traditional vertical breakwater and experimental results obtained through an experiment directly at sea, off the beach of Reggio Calabria, in the eastern coast of the Straits of Messina (Southern Italy). As observed in the physical experiment at sea, the pressure distribution are strongly influenced by the absorption of the plant. Indeed, in case of high performace of the U-OWC, we found a deformation of the pressure distribution in respect to the theoretical one, expecially near the outer opening of the plant. This deformation produces a lower in line force on the structure.

Keywords: Oscillating Water Column; breakwater; pressure distributions; CFD; absorption coefficient.

INTRODUCTION

OWCs are a major class of wave energy converters, probably the class with the largest number of prototypes so far deployed into the sea (Falcao and Henriques, 2016). An Oscillating Water Column device consists of a chamber with an opening below the sea water level. The working principle is based on the compressibility of the air in the chamber. In particular, water is forced into the chamber, applying pressure on the air that works as a spring, and goes out to atmosphere through a turbine. The main advantage of the OWC devices is their simplicity at working and at maintaining. Indeed, the only moving part of the energy conversion mechanism is the rotor of a turbine located above water level and then there are no moving parts in the water. The U-OWC is a particular kind of OWC with an additional vertical duct, on the wave-beaten side of the wall. The external opening is at the upper end of the vertical duct, which extends along the whole wave-beaten-wall. Under the wave action, the pressure acting on the upper opening of the vertical duct fluctuates, producing a water discharge alternatively entering the plant throw the U-duct, formed by the duct and the chamber (Boccotti, 2007). The interaction between incoming waves and the water discharge alters the wave pressure distribution on the wave-beaten-wall of the breakwater, in respect to the well-known pressure distribution in front of a vertical pure reflective wall (Boccotti et al, 2012). As a consequence, also the horizontal wave forces produced on the breakwater are different.

Many studies over the past decade have been conduit on scale model experiments to investigate the effect of several parameters that influence the hydrodynamic performance of OWC (Boccoti et al. 2007, Crema et al., 2015, Lopez et al., 2015). For what concern forces on OWC devices many authors observed that under particular settings (e.g, resonant condition, wave conditions, shape parameters), the force on the OWC structure is much smaller than on conventional caisson. Ashlin et al., (2015) attribuited this reduction to the high energy absorption by the OWC, when it works near the natural frequency of system. Thiruvenkatasamy et al. (2005) have ranged hydrodynamic parameters with different damping of the OWC chamber and linked the reduction of damping of the OWC air chamber to the reduction of the force on the array of caissons in respect to a vertical wall. Liu Y. et al. (2011) carried out a random wave experiment in laboratory, simulating several sets of wave parameters and founding the wave force on the OWC caisson is much smaller than conventional caisson.

In this work we carried out a numerical experiment in a 2D wave flume, equipped by a wavemaker and the U-OWC breakwater described in (Boccotti, 2007, Boccotti et al., 2007). We aim to analyse the difference between the force acting on a conventional vertical breakwater and U-OWC breakwater. the knowledge of the pressure distribution represents the first step in evaluating the stability and survivability of the structures.

[1]University Mediterranea of Reggio Calabria, DICEAM department Via Graziella Feo di Vito, Reggio Calabria,89122, Italy

EXPERIMENTS ON A SMALL SCALE MODEL OF U-OWC

The numerical experiment

The numerical experiment has been carried out considering a wave flume equipped by a wavemaker piston type on the left extremity and an U-OWC device at the other side (see Fig. 1). The plant shown has the same vertical cross section of the plant tested at sea by Boccotti et al. (2007). Due to the two-dimensional scheme, the circular cross section of venting tube is substituted by a slit 4.2 cm width. In order to have the same pressure drop of the circular hole, we put a porous media inside the slit.

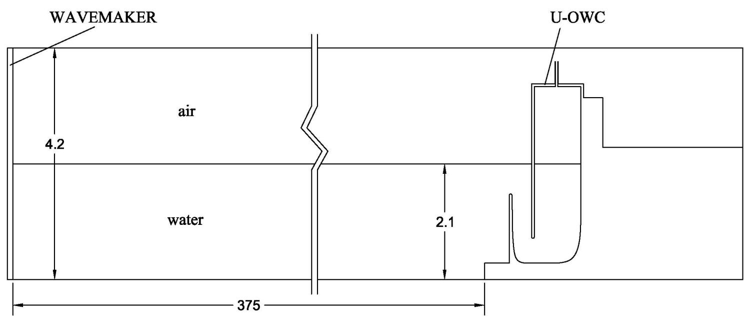

Figure 1: Sketch of the computational domain (measures are in meter).

The computational domain was discretized adopting an ibrid mesh. As we can see in Fig.2, near the air-water interface the mesh adopted is rectangular, and triangular elsewhere. This choice is done to achieve a better resolution of the free surface displacement. In all the computational domains we have used the laminar model, except inside the plant, where a turbulence model has been implemented.

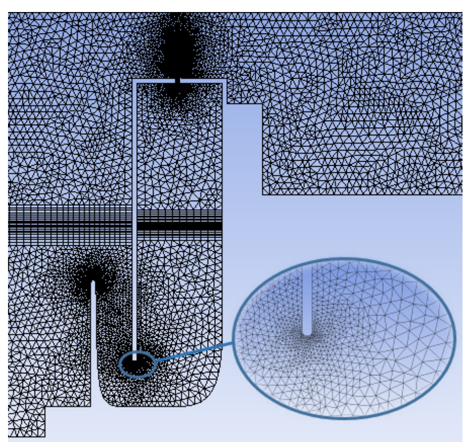

Figure 2: The conformal mesh adopted in the proximity and inside the U-OWC.

In order to match the behaviour of a physical wave flume, we have to set the boundary conditions of the numerical one. Smooth no-slip wall boundary conditions have been assigned to all solid walls, whilst the upper domain boundary is defined as pressure outlet with zero-gauge pressure.

The water-air interaction is taken into account by means of the Volume Of Fluid (VOF) model implemented in the commercial CFD code Ansys Fluent. Both air and water flow fields are assumed to be unsteady and are computed by solving the Reynolds-Averaged Navier-Stokes (RANS) equations. In the numerical model, air is considered as an ideal gas, in order to take into account, the compressibility inside the plenum chamber.

The wave generation process was simulated by means of a moving wall like a piston-type wavemaker that starts from rest and moves sinusoidally for a given time interval *t*. The free surface displacement can be written as (Huges, 1993):

$$\eta(x,t) = \frac{2}{\pi}\int_0^\infty \frac{\tanh kd}{k}\cos kx \int_0^t U_0(\tau)\cos\sigma(t-\tau)d\tau]dl, \tag{1}$$

where d is the flume depth, U_0 is the horizontal velocity of the wave board, and $\sigma^2 = gk\tan(kd)$, where $k = 2\pi/\lambda$, λ being the length of the flume. Assuming the board starts from rest at its extreme backward position, its displacement and velocity are given, respectively, by

$$X(t) = -\frac{S}{2}\cos(\omega t), \tag{2}$$

$$U_0(t) = \frac{S}{2}\omega\sin(\omega t), \tag{3}$$

where S is the total horizontal stroke excursion and ω is the angular frequency of the wave board.

Starting from rest, the wave generation process has been simulated, assigning the horizontal velocity to the left wall of the wave flume, by means of a User Defined Function (UDF). The Fluent dynamic mesh feature has been used for both the wall motion and the deformation of the neighbouring cells.

The physical experiment at sea

A small-scale model of an U-OWC breakwater (also named REWEC3, which stands for REsonant Wave Energy Converter, release 3) has been placed off the beach of Reggio Calabria in the eastern coast of the Straits of Messina (Southern Italy). The location of the experiment is almost unique in the world, in that there is often pure wind generated waves with the characteristics (height and period) of a big wave tank (i.e. $0.2<H_s<0.8$ m; $2<T_p<4$ s). The "active" part of this U-OWC model is in steel, given that the small-scale walls are too small to be made in reinforced concrete. Moreover, in order to simplify manufacturing, the structure has been modified from cellular caisson to wall in reinforced concrete ballasted with concrete blocks. Nine caissons, having the dimensions represented in Fig.3, have been placed close one to each other and parallel to the coast, at the depth of about 2.1 m, to form a breakwater 16.5 m long (Boccoti et al, 2007).

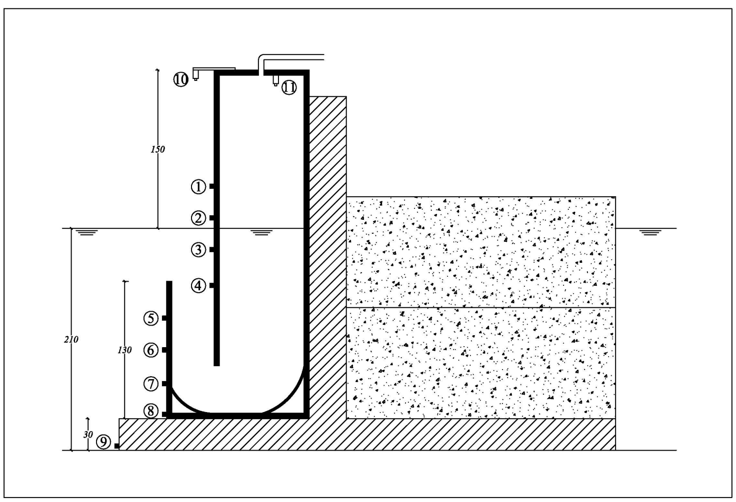

Figure 3: Cross section of the central caisson of the small-scale model of REWEC3 equipped by gauges (①-⑨ pressure transducers; ⑩-⑪ ultrasonic probe).

The wave-beaten-wall of the central caisson was equipped by a vertical row of nine pressure transducers (at 30 cm distance interval) allowing to measure the wave force on the breakwater, and by an ultrasonic probe (gauge N. ⑩ in Fig. 3) for measuring the surface displacement in front of the breakwater. A second ultrasonic probe was installed inside the plenum to measure the vertical displacement of the air-water interface (gauge N. ⑪; in Fig.3). Other four gauges (two ultrasonic probes and two pressure transducers) are placed in the undisturbed wave field for characterizing the incident waves. All the gauges were connected to a DAQ board by submarine wires. The duration of each record was 5 min. The sampling rate was 10 Hz for each gauge.

PRESSION DISTRIBUTIONS ON A U-OWC BREAKWATER

The mathematical model

Boccotti (2000) pointed out that the pressure distributions on a vertical wall are close to distributions obtained from linear wave theory. Moreover, for a very large wave in respect to the average of a given sea state, the positive pressures are typically smaller than the negative pressure. As a consequence, Boccotti suggests the following model for the largest positive pressures and the largest negative pressures:

(a) wave crest:

$$p_w = \begin{cases} \rho g H^+ \frac{\cosh(k\zeta)}{\cosh(kd)} & \text{if } 0 \le \zeta \le d, \\ \rho g(d + H^+ - \zeta) & \text{if } d \le \zeta \le d + H^+, \end{cases} \tag{4}$$

(b) wave trough:

$$p_w = \begin{cases} \rho g H^- \frac{\cosh(k\zeta)}{\cosh(kd)} & \text{if } p_w > -p_{st}, \\ -p_{st} & \text{otherwise.} \end{cases} \tag{5}$$

where ζ is the vertical coordinate with origin at the lowest point of the front wall, p_{st} is the hydrostatic pressure and H^+ and H^- are the virtual wave height, respectively under a crest and under a trough, evaluated by means of

$$H^+ = \frac{1}{\rho g} p^+_{wb} \cosh(kd), \tag{6}$$

$$H^- = \frac{1}{\rho g} p^-_{wb} \cosh(kd). \tag{7}$$

Pressure p^+_{wb} and p^-_{wb} are measured at the lowest point of the front wall, respectively at the time instant of the wave crest and at the time instant of the wave trough. Starting from these values, the virtual wave heights at the wall are evaluated and, using the linear theory of waves, the pressure distributions followed straightforwardly.

The experimental pressure distributions

By integrating the instantaneous values of wave pressure recorded every 0.1 s along the wave beaten wall, the time history of the horizontal wave force is calculated for each of the nearly 1600 recorded sea states (each lasting five minutes). The pressure distribution of the highest 1/100 peaks (both positive and negative) have been analyzed. The actual distributions on the front wall of the U-OWC are compared with those obtained with Eqs. (4) - (7).

To evaluate the effects of the energy absorption of the plant, we have classified the set of records falling in the range $0.15 < d/L_{p0} < 0.20$ in four interval of absorption coefficient (=mean captured energy / mean incident wave energy), and we have represented in Fig. 4 the average of the pressure distributions produced by the n /100 highest crests and deepest troughs of the force process, for four different range of absorption coefficient [0-25%], [25-50%], [50-75%], [75-100%]. As we can see, the linear wave theory is valid to predict the pressure distributions in all different intervals of absorption coefficient values, especially in that concerns the positive wave forces. In particular, it appears that the maximum value of p_w is slightly overestimated by theory, the more the captured energy increases.

The CFD pressure distributions

The incident waves generated in the flume have 0.2 m of height H, and wave periods T, ranging in the interval [2.5s, 9.0s]. The fluid dynamics coefficients of the porous media inside the vent tube were varied, in order to simulate different diameters and, consequently, different level of absorbed energy.

In order to validate the numerical experiment, we carried out some preliminary tests on the numerical wave flume. The wave generated numerically in the flume has been compared with the analytical solution. In detail, Fig. 5 shows this comparison: dashed line is the numerical surface displacement η and the continuous line is the η obtained through eq (1).

As a preliminary test, we have compared the teoretical pressure distribution on a vertical reflecting wall with the numerical pressure distibution obtained along the front shape of the U-OWC breakwater considering the outer opening of the vertical duct closed. In other words, we aimed to investigate the effects produced by an L-shaped impermeable wall on the pressure distribution. The continous line in Fig 6 represents the pressure distribution obtained by means of Eqs. (4) - (7) (valid for a straight impermeable

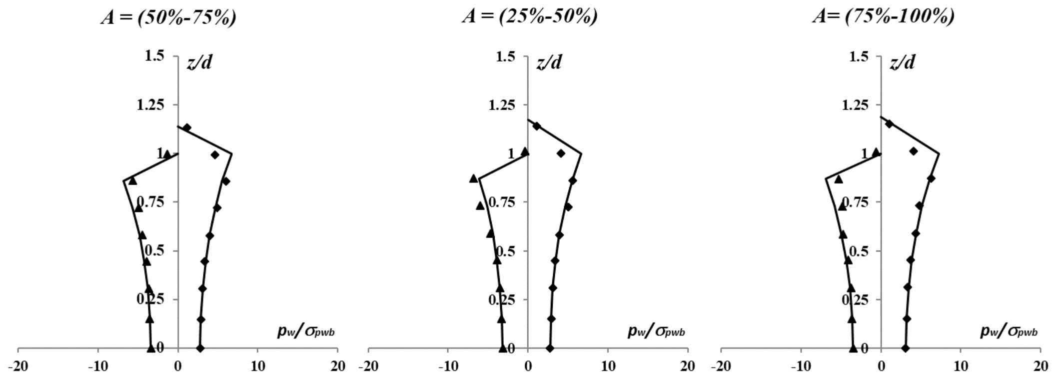

Figure 4: Average of the highest 1/100 wave pressure distribution (crests and troughs) of sea states constituted by wind waves in a fixed interval of d/L_{p0} [0.15-0.20], and for different range of absorption coefficient [0-25%], [25-50%], [50-75%], [75-100%]. Points are obtained by means the experimental measures on the front wall of the REWEC3. The continuous lines are obtained by means of the linear wave theory.

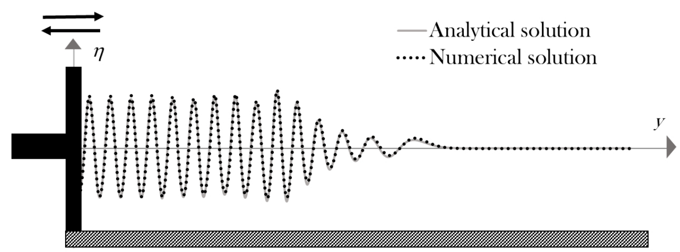

Figure 5: Comparison between the analytical solution for transient waves in a flume (Huges, 1993) and numerical solution.

wall). Triangles represent the numerical results. As we can see, there is a good agrement between the two pressure distribution, except near the (closed) outer opening, where the numerical pressure are larger than pressures obtained with linear theory.

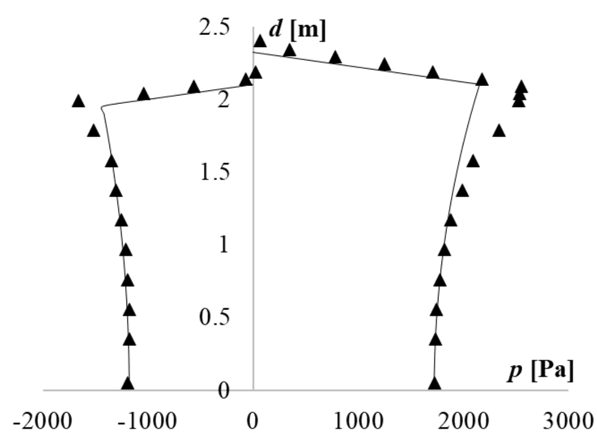

Figure 6: Wave pressure distribution (crests and troughs) obtained numerically on the U-OWC devise with the outer opening closed.

Fig. 7 shows pressure distributions relevant to four different values of the absorption coefficient A. As in the previuos figure, symbols represent numerical values while continuous lines, the linear wave theory.

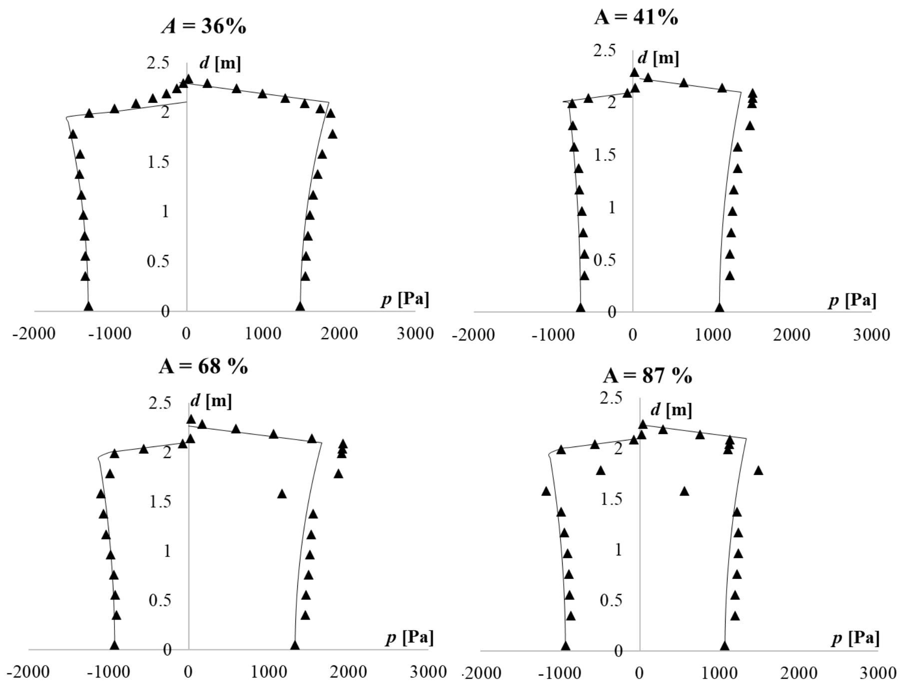

Figure 7: Wave pressure distribution (crests and troughs) obtained numerically on varying the ratio between the energy captured by the plant and the incident wave energy.

It is evident, at the depth of the entrance of the plant, the deviation from the linear curve, the more the A increases. This behavior was observed also at sea, as we can see in Fig. 8, which shows pressure measured on the wall during a record of wind waves, characterized by a large value of A. CFD helped us to understand why it happens. The reason appears clear at a first sight to Fig. 9, which shows the streamlines of the velocity field around the U-OWC. As we can see, the streamlines focus close to the opening of the vertical duct to originate the water discharge entering/exiting the plant. Therefore, the pressure drops so as to provide the energy necessary to accelerate the flow.

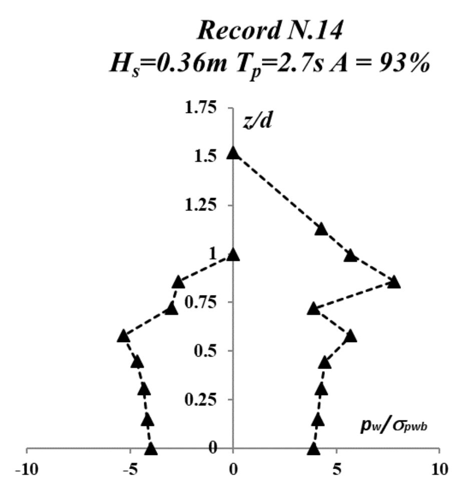

Figure 8: Wave pressure distribution measured at sea during the largest wave height occurring during record N. 14.

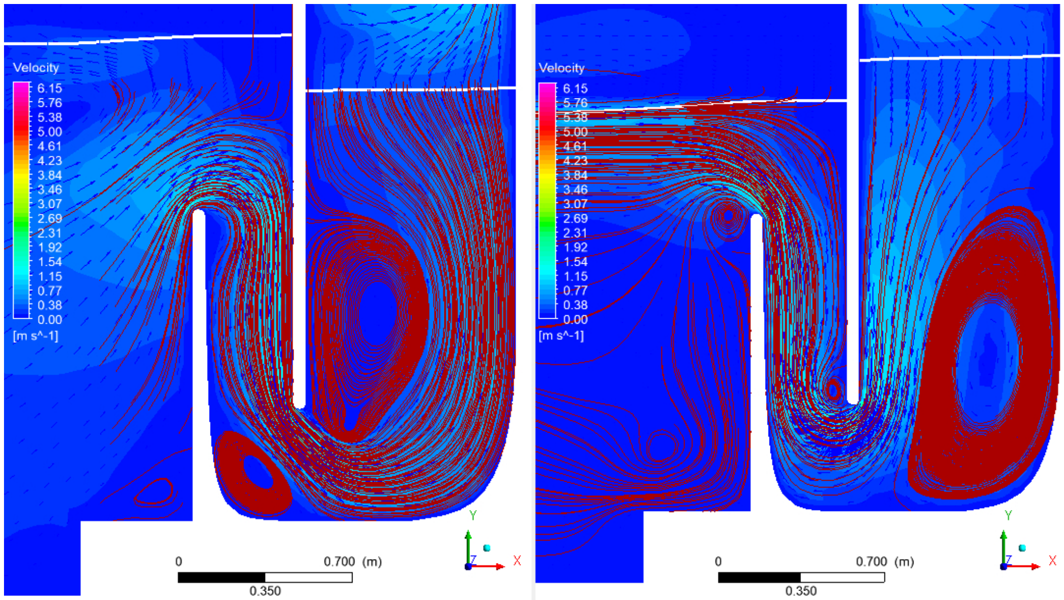

Figure 9: Streamlines of velocity field at the time instant of a crest distribution (on the left) and a trough distribution (on the right). The white line represents the water free surface.

CONCLUSIONS

The U-OWC is a caisson breakwater for port defence which embodies a wave energy converter (WEC) belonging to the family of Oscillating Water column (OWC). The dynamic behaviour of U-OWCs under wave action were deeply investigated both analitically and experimentally. The latter approach was carried out using both physical and numerical model. A small scale model was put at sea, and the performance of the plant were measured under the action of irregular sea waves. Also the pressure distribution acting on the front wall of the breakwater were measured. In the present work, an experiment on a numerical 2D wave flume has carried out, to investigate the reason of some differences emerged between theoretical and experimental pressure distribution. The plant investigated has the same size of the plant put at sea. Numerical simulations aimed to measure the pressure fluctuations on the front wall of the breakwater, whose knowledge is crucial for the structural design of the breakwater.

We obtained pressure distributions which deviates from the well-known theoretical distribution in front of a vertical reflective wall, the more the share of the incident wave energy captured increases. CFD analysis revealed the reason: pressure near the plant opening drops to accelerate the fluid which have to enter the plant. Anyway, theoretical distribution based on linear wave theory proposed by Boccotti et al (2012) can be used for design purposes, in that the design wave generally occurs during extreme sea states, when the plant is off, or the energy absorbed is very low because the working conditions are far from resonance.

ACKNOWLEDGEMENTS

The computing resources and the related technical support used for this work have been provided by CRESCO/ENEAGRID High Performance Computing infrastructure and its staff (G. Ponti et al., 2014). CRESCO/ENEAGRID High Performance Computing infrastructure is funded by ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development and by Italian and European research programmes, see http://www.cresco.enea.it/english for information'. International Conference on High Performance Computing and Simulation, HPCS 2014, art. no. 6903807, 1030-1033.

REFERENCES

Ashlin J. A. , Sannasiraj. S. A., Sundar. V *Wave forces on an Oscillating Water Column Device* 8th International Conference on Asian and Pacific Coasts (APAC 2015) Procedia Engineering 116 (2015) 1019-1026

Boccotti P. (2007). *Caisson breakwaters embodying an OWC with a small opening - Part I: Theory*, Ocean Engineering 34 (5-6), 806-819.

Boccotti, P., Arena, F., Fiamma, V., Romolo, A., and Barbaro, G. (2012). *Small-Scale Field Experiment on Wave Forces on Upright Breakwaters.* J. Waterway, Port, Coastal, Ocean Eng., 138(2), 97-114.

Boccotti, P. Filianoti, V. Fiamma, F. Arena, (2007) *Caisson breakwaters embodying an OWC with a small opening - Part II: A small-scale field experiment*, Ocean Engineering 34 (5-6), 820-841.

Boccotti P, *Wave Mechanics for Ocean Engineering*, Elsevier Science, Oxford, UK, 2000.

Crema I., Simonetti S., Cappietti L., Oumeraci H. *Laboratory Experiments on Oscillating Water Column Wave Energy Converters Integrated in a Very Large Floating Structure* Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), September 6â€“11, Nantes, France (2015)

Falcao Antonio F.O. and Joao C.C Henriques, (2016). *Oscillating-water-column wave energy converters and air turbines: A review*, Renewable Energy 85 (2016) 1391e1424.

Hughes, S.A., 1993, *Physical Models and Laboratory Techniques in Coastal Engineering*, Advanced Series on Ocean Engineering, Vol. 7. World Scientific, London, 568 pp

Liu Y.; H. Shi; Z. Liu ; Zhe Ma *Experiment Study on a New Designed OWC Caisson Breakwater* Proceedings of 2011 Asia-Pacific Power and Energy Engineering Conference

Ponti G. et al., *The role of medium size facilities in the HPC ecosystem: the case of the new CRESCO4 cluster integrated in the ENEAGRID infrastructure*, Proceedings of the 2014 International Conference on High Performance Computing and Simulation, HPCS 2014, art. no. 6903807, 1030-1033.

Lopez L., B. Pereiras, F. Castro, G. Iglesias *Performance of OWC wave energy converters: influence of turbine damping and tidal variability* Int. J. Energy Res., 39 (4) (2015), pp. 472-483

Thiruvenkatasamy K., S. Neelamani, M. Sato *Nonbreaking wave forces on multiresonant oscillating water column wave power caisson breakwater* J. Waterw. Port Coast. Ocean Eng., 131 (2) (2005), pp. 77-84 .