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Wave loads on the OBREC device in a real wave climate

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Abstract **This contribution presents the analysis of the structural and of the hydraulic response of the Overtopping Breakwater for Energy Conversion (OBREC hereinafter), developed by the team of the University of Campania. It is a multifunctional device, which can be installed also in existing breakwaters, capable of producing energy from waves and protecting the harbour inshore area. It is composed of a sloping plate, which drives the overtopping waves into a reservoir, linked by means of a pipe with the machine room, where the turbines have to be installed. The difference between the sea water level and the bottom edge of the reservoir is used to produce energy. The presence of the crown wall, provided with a bullnose, reduces the overtopping discharge at the rear side of the structure. The OBREC prototype was recently installed in the port of Naples and has been monitored to analyse its performance under a real wave climate. In the pilot plant, seven pressure transducers were installed along the profile of the device, to assess the wave loadings on the sloping plate, on the crown wall and on the bullnose. Some of the gathered field data are here compared and extended with 2D numerical modelling carried out with the open source software openFOAM. In particular, the statistical pressures acting on the OBREC under an extreme event occurred in the gulf of Naples in 2018 have been experimentally and numerically analysed. Furthermore, the numerical model allowed to have a better understanding of the hydrodynamic inside reservoir and against the crown wall.**

Keywords—Wave energy converter, wave loads, numerical modelling, real wave climate

I. INTRODUCTION

THE OBREC concept was developed by the team of the University of Campania to i) protect the harbour inshore area from flooding, by reducing the overtopping flows at the rear side of the structure; ii) produce energy by capturing the waves flowing inside the reservoir, instead of dissipating them. Figure 1 shows the prototype installed in the port of Naples (Italy). It can be classified as an on-shore Wave Energy Converter (WEC hereafter). Its location simplifies several technical aspects with respect to off-shore devices, such as the installation, the maintenance operations and the energy transfer/local use of energy.

Fig. 1. OBREC prototype installed in the port of Naples (Italy).

Several laboratory campaigns [1], [2], [3] and numerical investigations [4], [5], [6], [7] have been performed to i) assess the reliability of the OBREC concept, ii) to reach a better understanding of the dynamic related to the wave – structure interactions and iii) to define some fundamental guidelines for a proper design of the prototype installed in the port of Naples.

This paper is aimed at contemporarily investigating the hydraulic and structural performance of the OBREC, combining the monitoring activities with the numerical modelling. According to the OBREC concept, the overtopping water flows towards the turbines by means of pipes passing through the crown wall, which links the reservoir and the machine room. Therefore, the analysis of the wave loads acting along the profile of the device is useful not only to define the structural response of the structure, but also to improve its hydraulic performance and eventually its design.

Several studies and laboratory campaigns have been performed to analyse the pressure distributions along simple crown walls placed on rubble–mound breakwaters to improve their stability. The main theories, developed by Pedersen [8] and Martin [9], were based respectively on irregular wave and regular waves generated in

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intermediate/deep water. Nørgaard [10] extended the work of Pedersen [8], with a new set of physical model tests to assess the wave loads on wall superstructures in deep and shallow water conditions.

However, the OBREC cross section is more complex than a rubble-mound with a crown wall. It includes i) the reservoir, which attenuates the intensity of the wave attack against the crown wall, ii) the pipe that lets part of the overtopping waves flowing inside the machine room, iii) the parapet within the crown wall, to reduce the overtopping discharge rate at the rear side of the structure. The effect of the parapet on the structural performance has been recently analysed by Castellino et al. [11], through a numerical investigation. The forces along the seawalls with recurved parapet resulted to be higher with respect to the vertical wall due to the impulsive pressures enhanced by the confined return flow.

Due to the complexity of the structural geometry, it is therefore a good opportunity to combine the monitoring activity with the numerical modelling in order to assess the OBREC performance. The aim of this paper is to apply such an integrated methodology to the investigation of a selected storm, which was monitored at prototype scale and numerically modelled.

In this paper, Section 2 is devoted to the description of the site installation, with specific information about the configurations composing the prototype and about the monitoring system. Section 3 gives an overview of the modelling activity with the openFOAM multiphase numerical model, including the plug – in solver *waves2foam* [12], [13]. Particular attention is paid to the numerical set - up and the measurements made to assess the OBREC structural response. Section 5 presents the numerical results, in terms of statistical values of pressures, compared with the field data. The hydraulic performance is analysed in terms of discharge rate inside the reservoir Q_{in}, and then through the pipe, Q_{pipe}, and at the rear side of the structure Q_{rear}. Section 6 draws the conclusions and recommendations.

II. DESCRIPTION OF THE INSTALLATION SITE

The OBREC device can be installed into existing or new coastal structures. The concept of integration represents one of the most reliable solutions to decrease the installation costs, allowing the WEC technologies to be a valuable design option during the construction process.

The first OBREC pilot plant was installed in the gulf of Naples (Italy) in September 2015. Based on the Italian Wave Buoys Network system [14], this area of the Middle Tyrrhenian Sea is characterised by an average wave power flux of about 2 kW/m (the inshore yearly average wave power was found to range between 1.6 and 2.5 KW/m over the last ten years). The low occurrence of extreme events makes this site ideal for a first installation.

Indeed, few WEC technologies have been constructed at a prototype scale, showing a common technical problem, i.e. weak reliability with respect to the extreme events.

Therefore, the pilot plant installation represents a fundamental step for the OBREC design improvement and the achievement of a commercial stage.

A. A. The OBREC device

The OBREC was casted in – situ on the existing San Vincenzo breakwater, which protects the harbour inshore area. It is a traditional rubble–mound breakwater, provided with an armour layer made of Antifers, a filter layer made of rocks and a quarry run core. The freeboard level of the structure is about 4.50 m above the mean water level (i.e. 25 m at the toe of the breakwater), while the offshore slope is approximately 1:2 [15].

The construction process implied the removal of a portion of the layer of Antifers; the installation of the foundation composed by concrete micropiles (to improve the stability against sliding and overturning); the casting in – situ of the main body of the device (i.e. the reservoirs and the machine room) and the location of the prefabricated ramps [15]. This installation substituted a portion of the external layer damaged during several storm events. Therefore, OBREC can be used as an innovative design option during the maintenance operations [16].

The prototype is composed by 2 configurations, i.e. OBREC_RS - Lab (Real Scale Laboratory, in Figure 2) and OBREC_NW - Lab (Natural Waves Laboratory, in Figure 3), which differ only for the height of the sloping plate above the mean low water level, i.e. 1.78 m and 0.98 m, respectively. The selection of this parameter was based on the typical wave climate characterizing the installation site. The NW - Lab configuration is intended to capture the most frequent waves, while the RS - Lab the highest ones. For the prototype installation, a double plate configuration was considered, according also to the results obtained from the numerical investigations performed by Palma et al. [7]. Furthermore, a submerged quasi – vertical part of the ramp was introduced to i) improve its resistance to bending and fatigue, and to ii) enhance the interlocking between the rocks of the armour layer and the device.

The longitudinal dimension of the installation is the same in both cases, having in common the crown wall and the machine room, where the turbines should be installed (see the prototype in Figure 1, and the OBREC sections in Figure 2 and Figure 3). This spatial constraint results in a different dimension of the reservoir width for the 2 configurations, i.e. 2.56 m in Figure 2 and 3.7 m in Figure 3. The wider reservoir is associated to the lower sloping plate, which is the more frequently overtopped; and vice versa. The sensitivity of the reservoir width with respect to the hydraulic and structural performance, as demonstrated by the experimental and numerical investigations [2], [7], can be neglected. Therefore, its definition, during the design procedure, can be subordinated to the height of the sloping plate.

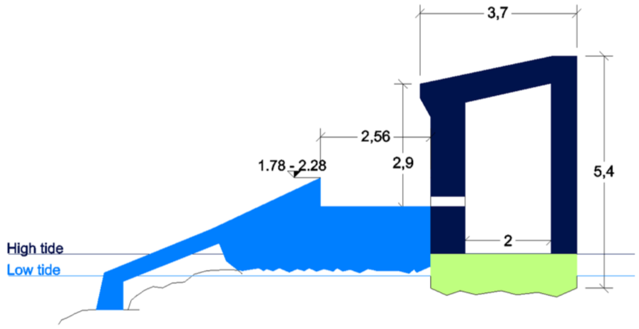

Fig. 2. OBREC Real Scale Laboratory configuration.

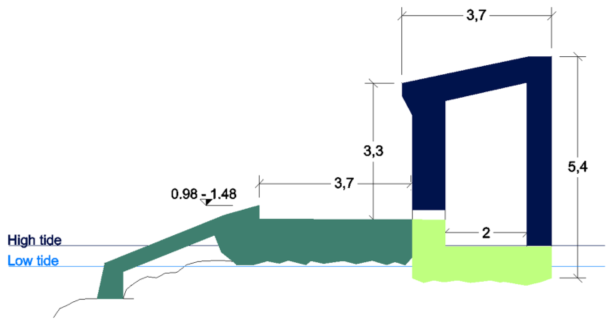

Fig. 3. OBREC Natural Waves Laboratory configuration.

B. *Monitoring system*

The installation site and the OBREC device were provided with several instruments during these last 2 years. The wave conditions are measured by means of a wave buoy named *Directional Wave Spectra Drifter* (DWSD) and developed by the Scripps Institution of Oceanography (San Diego, US), using the Global Positioning System (GPS) technology [17]. The buoy is located 100 m far from the OBREC device and in 26 m water depth, with a bottom mounted Acoustic Doppler current profiler (ADCP), one directional radar and one moored waverider buoy [17]. The main information recorded are the significant incident wave height H_s and the associated wave period named T_a.

The structural response of the device has been analysed by means of 7 pressure transducers installed along the OBREC profile, here listed going from the lower part of the sloping plate going towards the bullnose. The transducers F, G and H were placed on the sloping plate of the RS - LAB configuration (Figure 2); while A, B and C on the crown wall and N on the bullnose of the NW – LAB configuration (Figure 3). Their characteristics have been selected based on the hydrodynamic loads theoretically expected and on the results obtained during the laboratory campaigns [1], [3], [4], and numerical simulations [5], [7]. They are capable of measuring i) the fluid temperature from - 40° to 125°, and ii) the pressures ranging from 0 to 100 bar, with a full scale F.S. precision at 25° of 0.4%. The output signals vary between 4 and 20 mA.

The assessment of the hydraulic performance of the device is slightly more difficult. The OBREC principle of operation consists of using the potential energy of the water. Indeed, the OBREC design is aimed to maximize the difference between the still water level and the reservoir bottom edge. The available head is then exploited by means of turbines, which resulted to be the most reliable power take – off (PTO) system for this kind of WEC [18]. To maximize the energy exploitation, the water flowing towards the turbines has to be as constant as possible. To this purpose, a shunt tank is located just after the pipe, linking the reservoir with the machine room. The hydraulic head in the shunt tank has been measured by means of a resistive gauge, characterized by an acquisition frequency of 10 Hz. From a preliminary analysis, the precision of the instrument was enough for a good description of the phenomenon.

III. FIELD MEASUREMENTS DURING A CHARACTERISTIC STORM

Several storm events have been recorded during the first months of the 2018. For this paper, a single storm event, occurred on the 6th January 2018 and lasted for 4 days, has been selected. The information acquired consisted of a value of the significant wave height H_s associated to a mean wave period T_a for each hour of the field monitoring. This specific storm event has been chosen because it was clear to distinguish a i) rising phase, which occupied the first 2 days; ii) a peak phase, when the highest wave height related to the storm event occurred; and iii) a decay phase that lasted up to the 10th of January.

The field measurements analysed in this work belong to the peak phase, which is characterized by a significant wave height H_s = 2.13 m and a peak period T_p = 8.37 s. Specifically, the pressures signals are related to 6 hours of monitoring, in which the characteristics of the wave condition did not vary from their representative values.

The aforementioned pressure transducers allowed the analysis of the loads on the RS – LAB sloping plate and the NW – LAB crown wall and bullnose. In the first case, the transducers are installed in correspondence of the middle section of the sloping plate. In the latter case, A and C are located in correspondence of the same section of the pipe, while B and N not. The pressures measured at the transducers are affected by the presence of the pipe, which reduces the wave run – up and the wave reflection.

IV. 2D NUMERICAL MODEL SET – UP

C. *Wave attack*

The temporal window of the storm event selected (Section III) is characterized by a significant wave height H_s = 2.13 m and a peak period T_p = 8.37 s.

The wave spectrum was implemented as a JONSWAP spectrum characterized by a peak enhancement factor γ = 3.3. The simulations contained at least 200 waves, in order to obtain a reliable statistic of the forces.

D. *Numerical model*

The 2D numerical simulations have been carried out by means of the open source code openFOAM [13] (www.openfoam.org).

The wave generation/absorption was performed with the library *waves2foam*, developed by Jacobsen [12]. It is a toolbox that applies the relaxation zone technique (active sponge layers), supporting a large range of wave theories. Specifically, it is capable of solving 2 incompressible, isothermal immiscible fluids, i.e. water and air, using the VOF method (Volume Of Fraction) to track the free surface. For the simulations here analysed the LES turbulence model [21] was introduced. The governing equations of the model are the Volume Average Reynolds Average Navier Stokes equations (VARANS).

E. *Set – up of the domain*

The numerical domain was drawn and meshed by means of Gmsh [22], a free 3D finite element mesh generator with a built – in CAD engine and post – processor. The OBREC is reproduced at 1:1 scale. The number of the cells is indicatively 30’000, and slightly change according to the characteristics of each test.

The total length of the domain is equal to 334 m, i.e. slightly more than 3 times the estimated wavelength *L*. The inlet relaxation zone, where the wave generation occurs, has been set equal to 0.5*L*. The bottom of the San Vincenzo breakwater occupies 65 m. The presence of the outer relaxation zone (10 m) allows the representation of the off-shore structure only, without compromising the dynamic of the wave – structure interactions.

The selected wave height affects the vertical dimension of the domain. To minimize the computational effort, i.e. the number of the cells, the domain has been divided in 2 parts, which differ for their vertical dimension and for the mesh adopted. The first part is 31 m high, i.e. 26 m of water depth (SWL) plus 5 m to allow the correct representation of the waveform. It is characterized by a structured and graded mesh, with greater refinement in correspondence of the water surface elevation. In the second part, where the wave – structure interaction occurs, the vertical dimension has been extended up to 35 m. It is characterized by an unstructured mesh, which is more flexible and suitable for such peculiar geometries. The grid reaches its minimum dimension, i.e. 0.02 m, in correspondence of the reservoir and of the pipe.

The boundaries of the domain have been characterized as follow:

- the bottom edge has been set as an impermeable wall;
- the top edge has been defined as atmosphere, allowing the fluids to freely flow out;
- the inlet and the outlet edges are characterized by the presence of the relaxation zones. In the first case, allowed to i) generate the waves and ii) absorb the by the reflected ones; while in the second one, let the water to freely flow out.

F. *Structure characteristics*

The characteristics of the San Vincenzo breakwater are summarized in Table 1, where the porosity *n*, the added mass coefficient c_A, the nominal diameter D_{50}, and linear and non – linear friction coefficient α and β, necessary to characterize a porous media, have been reported. These parameters have been defined according to the numerical investigations performed by Jensen et al. [23], trying to represent as closest as possible the real characteristics of the structure. The off – shore armour slope composed by the Antifer layer has been represented as a straight line. In the reality, the random placement of the concrete blocks produced a curved edge, which acts like a berm. This simplification has to be taken into account during the analysis of the data, and so the performance.

TABLE I

Characteristics of the layers in terms of n, KC number, c_a, D_{50}, α and β

Layer	n [/]	KC	C_A	D_{50} [m]	α [/]	β [/]
Antifer	0.50	128	0.34	2	500	2
Armour	0.45	128	0.34	1.4	500	2
Filter	0.45	128	0.34	0.75	500	2
Core	0.45	128	0.34	0.5	500	2

The OBREC prototype, in the installation site, is composed by 2 configurations, which are adjacent and divided by a wall septum, as shown in Figure 1. In the numerical simulations, the 2 cross sections have been tested separately. Furthermore, for each configuration 2 test cases have been proposed: the first provided a pipe linking the reservoir with the machine room (i.e. open configurations), while the second characterized by a closed reservoir (i.e. closed configurations). The verification of these 2 last cross sections, i.e. NW – LAB and RS – LAB cases, has been carried out since it was observed that during severe storms the reservoir usually works in saturated conditions, and so the water level inside it acts as a “water bag” against the incoming flows.

Therefore, the tests performed under the same storm wave condition result to be 4.

V. OBREC PERFORMANCE IN STORM CONDITIONS

G. *Integrated hydro-structural dynamics of the OBREC device*

The run – up process occurs along the sloping plate, leading the water to flow inside the reservoir. During an intense storm event, the water partially saturates the pipe and partially creates a "water bag" that attenuates the loads both on the reservoir and on the lower part of the crown wall. The sliding above such water bag allows the overtopping waves to impact directly the central part of the crown wall and the bullnose, to be then reflected towards the sea and so the sloping plate.

The complex hydrodynamics, above described, affects the structural response of the device, which is here assessed by means of the pressure transducers installed in the prototype, then compared with the numerical results.

A qualitative analysis of the field measurements highlights an impulsive nature of the loads for both the crown wall and the sloping plate. The signals are characterized by a strong noise (Figure 4) due to the complex interactions occurring between the waves and the device under a real sea state. Furthermore, the monitored pressure signals include a significant number of negative values (as shown in Figure 4) that can be explained with the high – aeration effect, which produces sub – atmospheric pressures after the impact takes place, as already observed in large – scale experiments [20].

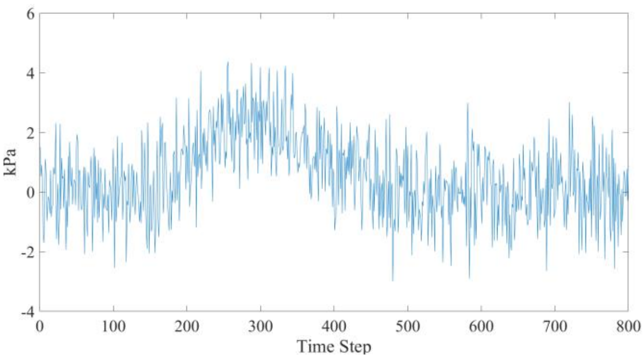

Fig. 4. Pressure signal of the pressure transducer F (on the sloping plate).

According to Kortenhaus and Oumeraci [19], the wave loads can be split in quasi – static, slightly breaking, impulsive and broken waves. This classification depends on the characteristics of the structure and on the wave condition.

For the OBREC case, during the small – scale experiments [1], [3], it was observed that over the sloping plate, the wave loading slowly varies in time with relatively mild gradient. Thus, a quasi – static loading time history was recognizable, while a different behaviour was observed from the time history analysis of the crown wall loadings. The signal showed evident rapid variations in time, with a high force peak typically described as impact wave load [1], [3]. For the full – scale prototype this is not completely true, at least for the sloping plate. In this latter case, the monitored pressure signals can be classified as slightly breaking and broken wave loads, due to the presence of the berm, which anticipates the breaking process. The difference between the small and full – scale dynamics points out the importance of a prototype installation for such a peculiar geometry.

H. *Structural performance*

Some of the pressures recorded during the selected storm event are here compared, and then extended, with the 2D numerical simulations carried out with the openFOAM software (Figure 5). Specifically, the 2 OBREC configurations have been tested both with and without the pipe, to assess its effects on the structural performance.

Figure 6 shows the comparison between the field and the numerical dimensionless pressure values on the sloping plate and along crown. The results are proposed in terms of maximum p_{max} and statistical values p_{250}, which correspond to the non – exceedance level of about 99.7% (i.e. the average of the highest 4% of values). According to the stochastic nature of the wave impact phenomenon, the values of p_{250} are more representative but the values of p_{max} are here reported to prove that the numerical model is capable of giving a cautious estimate of the maximum loads, even if the solver does not take into account of the compressibility of the fluids.

Both in the field and in the numerical model (Figure 5), the crown and the bullnose are subjected to higher pressures than the sloping plate (Figure 6). This result is coherent with the hydrodynamic explained in the previous Section.

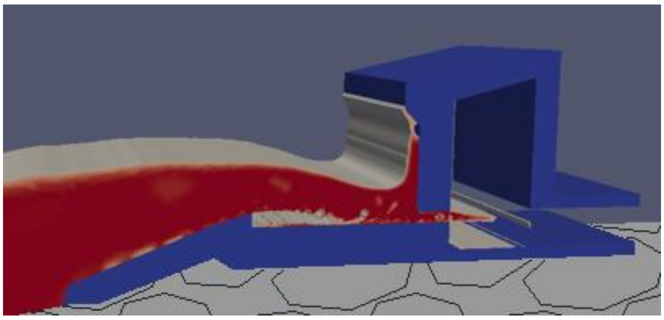

Fig. 5. Snapshot of the simulation of the NW – LAB open configuration, in which the wave impacts the crown wall and then goes towards the bullnose

Figure 6 highlights that the numerical model tends to generally overestimate the field data.

The closed reservoir leads to more stressed OBREC cross sections, with respect to the open ones. Indeed, all the overtopping waves impact the crown wall and then are totally reflected towards the sea, and so affect also the sloping plate, increasing the magnitude of the measured values.

The open configurations slightly underestimate the pressures along the crown wall because of the presence of the pipe, which collects in the machine room a portion of the overtopping waves.

The field results fall in the middle of these 2 cases, i.e. open and closed reservoirs. It is clear that the right dynamic may be represented only with a fully 3D simulation, in which the pipe can be correctly represented.

The numerical model allows the comparison between the 2 cross sections, composing the prototype, giving information also where field data are not available. Figure 7 and Figure 8 show the values of p_{max} and p_{250} along the crown wall (with and without the pipe) of the RS – LAB and NW – LAB configurations, respectively. The number of the pressure transducers is slightly different for the 2 configurations, because in the case of the higher sloping plate the crown wall is shorter, and vice versa. The numbering order goes from the top of the bullnose (9 in both cases), towards the reservoir (19 and 21, respectively).

As it possible to note, the NW –LAB configuration results to be generally more stressed with respect the RS – LAB. In case of the lower sloping plate, more overtopping waves go inside the reservoir and therefore against the crown wall. These dynamics could represent a weakness from the structural point of view, but a strength point for the hydraulic performance. These 2 technical aspects have to be combined to improve the design of the device.

I. Hydraulic performance

The hydraulic performance of the device has been analysed only numerically, for both the upper and lower plates provided with the pipe.

The average values of Q_{in}, Q_{pipe} and Q_{rear} (Table 2) have been computed by integrating along the vertical direction the horizontal velocity component. The velocity profiles have been measured at the offshore edge of the reservoir (discretisation of 0.01 m), inside the pipe (discretisation of 0.005 m) and at the inshore edge of the machine room (discretisation of 0.01 m), respectively. The difference in the discretisation accuracy accounts for the different dynamics related to these 3 parts of the structure. Considering that the numerical model treats 2 fluids, i.e. air and water, the velocity has been previously combined with the VOF values, to isolate the water contribution.

As shown in Table 2, the NW – LAB gives a higher discharge rates, i.e. Q_{in} and Q_{pipe}, with respect to the RS – LAB configuration, due to the higher overtopping at the lower sloping plate. As anticipated in the Section related to the monitoring system, these measurements could be useful to assess the dimension of the shunt tank linked to the turbines. However, the general hydraulic performance have to be analysed considering all the wave conditions characterizing the typical climate of a specific site.

In both the configurations, the percentage of time in which the pipe works as a full section is circa the 5%. However, it is worthy to remark that the 2D domain forces the pipe to be a rectangular section crossing the whole structure.

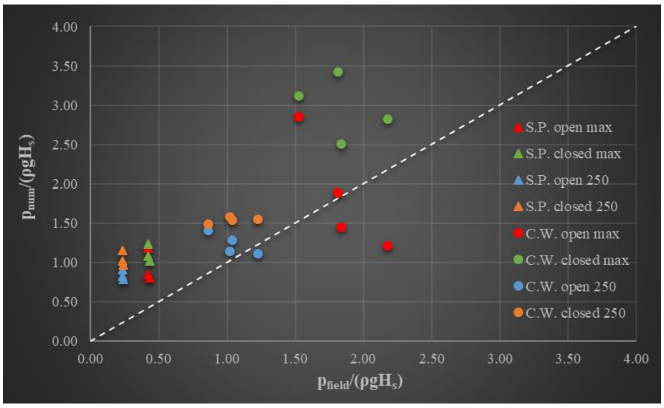

Fig . 6. Comparison between the field and the numerical dimensionless pressure values, on the sloping plate S.P. (triangles) and the crown wall with the bullnose C.W. (circles). In red and green are reported the values of p_{max}, while in blue and orange the values of p_{250}. The pressure values are divided by the density ρ, the gravitational acceleration g and the significant wave height H_s.

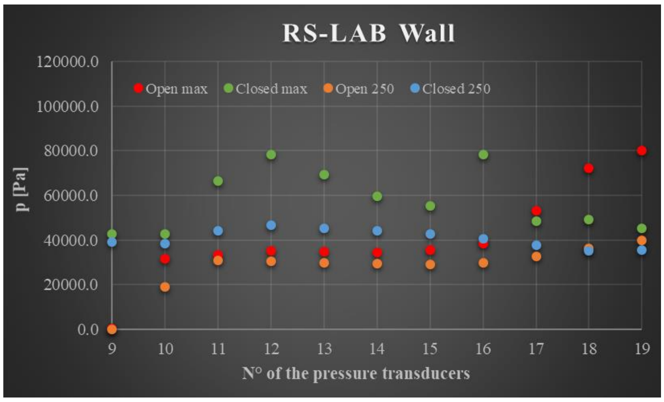

Fig. 7. Comparison between the maximum and the statistical values of pressure [Pa], both in the open and closed RS – LAB configuration.

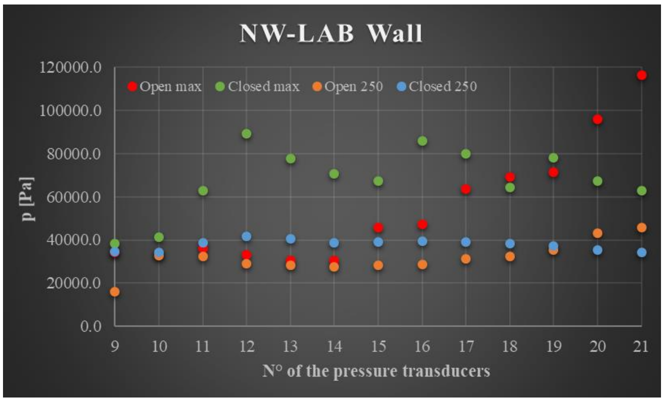

Fig. 8. Comparison between the maximum and the statistical values of pressure [Pa], both in the open and closed NW – LAB configuration.

The analysis of a fully 3D configuration would be therefore needed to verify the design of the pipe and of the position of the hole with respect to the ramp.

Table 2 shows also that under the storm event here analysed there is no overtopping at the rear side of the structure, according to the standard safety level which have to characterize the inshore areas.

The wave reflection coefficient K_r was derived by applying A 3 – point method [24] to 3 gauges placed at 155 m, 156.1 m and 157.8 m from the beginning of the domain, far more than a wavelength L from the breakwater. The value of K_r results to be 0.46 for both the RS – LAB and NW – LAB configurations. The effect of the wave reflection is more visible in front of the structure, where destructive groups do occur. However, the resulting K_r is not significantly different from the values expected from a traditional breakwater.

TABLE II
HYDRAULIC PERFORMANCE IN TERMS OF I) OVERTOPPING DISCHARGE RATE INSIDE THE RESERVOIR Q_{IN}, FLOWING INSIDE THE PIPE Q_{PIPE}, PERCENTAGE OF SIMULATION IN WHICH THE PIPE WORKS AS A FULL SECTION $T_{\%FULL}$, DISCHARGE RATE AT THE REAR SIDE OF THE STRUCTURE Q_{REAR} AND WAVE REFLECTION COEFFICIENT K_R.

Configuration	Q_{in} [m³/s]	Q_{pipe} [m³/s]	$T_{\%,full}$ [/]	Q_{rear} [m³/s]	K_r [/]
NW LAB	0.221	0.170	0.05	0	0.46
RS LAB	0.107	0.093	0.0583	0	0.46

VI. CONCLUSIONS

In the present work, the hydraulic and the structural performance of the OBREC device, for a single storm event, have been analysed by combining the analysis of the field data with the numerical results.

Specifically, the pressures measured at the full – scale prototype, installed in the port of Naples, have been compared and extended with 2D numerical modelling carried – out with the openFOAM software for the case of a single storm event. To better represent the hydrodynamics related to this peculiar device, the 2 configurations composing the prototype have been tested both with and without the pipe, that links the reservoir with the machine room. This because it was observed that the pipe during storms is not capable of collecting all the incoming water, allowing the creation of a "water bag" inside the reservoir.

The numerical model tends to generally overestimate the measured pressures. The closed reservoir leads to more stressed OBREC cross sections, with respect to the open ones, because all the overtopping waves impact the crown wall and then are totally reflected towards the sloping plate. The crown walls of the open configurations are subjected to smaller loads, because of the presence of the pipe, which absorb part of the incoming waves. The field results fall in the middle of these 2 cases, considering that the right dynamics can be represented only with a 3D simulation.

The 2D model allows also to compare the performance of the 2 cross sections, composing the prototype, giving information also where the field data are not available.

The configuration with the lower sloping plate is capable of capturing more water, leading to higher pressures on the OBREC profile, and specifically on the crown wall.

The extension of this integrated hydro and structural analysis of the device performance to the typical wave climate would allow to optimise the design taking into account both the effective energy capture and the extreme loads.

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