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Laboratory Tests on the Reflection Coefficient of a Perforated Caisson

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Abstract: This paper presents new tests on a perforated vertical wall caisson. The tests aim at evaluating the reduction of the reflection coefficient caused by different perforations. The reflection coefficient is estimated using the novel nonlinear methods proposed by Lykke Andersen et al. (2017) and Eldrup and Lykke Andersen (2019). The structure under investigation is, at prototype scale, 21.50 m high, 35.55 m long and 13.90 m wide, divided into 3 rows of 8 cells. The caisson has a recurved 'nose' and air vents on the parapet wall. An identical plain wall caisson without absorbing chambers is also tested for comparison. Two-dimensional laboratory tests have been carried out at Department of Engineering of Roma Tre University with both irregular and regular waves, reproducing mild wave conditions and design wave conditions. Two water levels have been used, reproducing the mean water level and a set-up condition of +0.5 m. Four structural layouts are tested in order to study various perforation types. Furthermore, the effect of the wave obliquity and of the short crestedness on the reflection coefficient is discussed using some 3D laboratory data obtained back in the 1995 but not published before.

Keywords: perforated caisson, wave reflection, hydraulic model, vertical breakwater, AWASYS, wave flume, wave generation, active wave absorption

1 Introduction

It is well known that a useful reduction of wave reflection coefficient $C_r = H_r/H_i$ at vertical walls can be achieved by perforated structures, such as slit screens and more typically cellular reinforced concrete caissons, both at external breakwaters and internal quay walls (Altomare & Gironella, 2014; Fugazza & Natale, 1992; Huang et al., 2011; Noli et al., 2008; Liu et al., 2008).

The modern principle of wave energy dissipating chambers was introduced by Jarlan in 1961: the energy transmitted through the openings is partially dissipated due to resonance phenomena within the chambers (with offset water levels inside and outside), viscous friction losses, flow separation, eddies, vortex shedding and turbulence; such hydraulic dissipations are mainly governed by the porosity of the perforated walls and by the "chamber width/wavelength" ratio (B/L). Typically, the wall porosity varies between 15% and 40% with best response at about 30% and the most effective "relative chamber width" B/L is around 0.1-0.2. Besides One Chamber Systems (OCS) also Multiple Chamber Systems (MCS) have been developed to increase the effective width in the usual case of relatively long incident waves. In this case the interference of secondary reflections from the inner perforated walls are significant. An important role is also played by the volume of free air inside the chamber and its possibility to escape easily when pushed by the water: air vents can thus be helpful. The shape and location of the holes also play a (minor) role. Moreover, further holes in the internal cross walls can be also effective in energy absorption, especially for oblique waves.

There is a very extensive literature about the hydraulic response of perforated structures, also devoted to the related aspect of wave forces, which is relevant for the caisson design. For a recent review see Huang et al. (2011). Most studies are based on 2D model tests. 3D model tests and field studies, as well as analytical and numerical studies have also been carried out (Fugazza and Natale, 1992). An early study by Tanimoto et al. (1976) on an OCS is reported in the classical book of Goda, showing a minimum of C_r around 0.3 for $B/L = 0.15$. A systematic study was performed for the Porto Torres Industrial Port breakwater design (De Gerloni et al. 1989, Noli et al.1995) where either 1-2-3 chambers with variable diameters of the circular holes (0.6-0.8-1.0 m) were tested and the reflection coefficient reduced down to about 0.4 for the 3-chamber system with an outer porosity of 39%. Further analysis of such data and those from the model of Dieppe caisson breakwater during the UE-PROVERBS project (Belorgey et al. 2000) led to a tentative formula. The above analysis also included some unique unpublished results of advanced 3D tests (Franco C., 1996), within a LIP EU-funded overtopping project (Franco & Franco 1999), which showed the further reduction of C_r with wave obliquity and short-crestedness and a slightly better performance of vertical rectangular holes than circular holes (with same overall porosity), as reported in the chapter below.

The present work is indeed related to the study of the reflection performance of a perforated caisson designed for the extension of the Civic Port of Porto Torres, Sardinia (Italy), as compared to a plain wall caisson. The paper presents new tests on a perforated vertical wall caisson and a reference caisson. The tests aim at evaluating the reduction in reflection coefficient caused by the perforation. The reflection coefficient is estimated using the novel nonlinear methods proposed by Lykke Andersen et al. (2017) and Eldrup and Lykke Andersen (2019b). Results are compared against tests carried out more than 25 years ago on a very similar structure by Noli et al. (1995) and against the standard design method by Tanimoto et al. (1976). Furthermore, analysis of the tests carried out by Franco (1996) are reported to evaluate the effects of the oblique wave incidence and of the short-crestedness.

2 The caisson for the extension of the Civic Port of Porto Torres

The structure under investigation is shown in Figure 1 and Figure 2. It has been designed for the extension of the outer breakwater of the Civic Port of Porto Torres, in the north of the Sardinia Island, Italy. The tideless site is partially protected from the North-West sector by the Asinara island and is therefore attacked by moderate waves, with a 100-yr design significant wave height H_{m0}=4.5 m.

In prototype the caisson is 21.50 m high, 35.55 m long and 13.90 m wide, divided into 3 rows of 8 cells. The absorbing chambers have plan dimensions of 4.00 m x 4.00 m and different height depending on the chamber row (see Fig. 2). The seaside row of cells is connected to the sea by 4 rows of 16 rectangular windows, two for each cell, the window dimensions being 1.07 m x 1.90 m. At the port-side there is one row of windows (1.07 m x 2.65m) to absorb the waves inside the harbor. It is noted that the second wall has two rows of windows of small size. Moreover, the transversal inner wall is perforated too. The caisson has a recurved ‘nose’ and air vents on the parapet wall.

To compare it with a standard vertical wall structure, the same caisson has been tested closing the seaside windows, still including the recurved nose parapet wall. For all the tests the caisson is placed at a water depth of about -20.0 m, on a rock foundation with crest level at -17.50 m. Armour rock layers protect the toe of the structure.

Four structural layouts are tested in this study: i) the caisson without perforation, ii) 4 rows of windows connecting the inner chamber to the sea, iii) 3 rows of windows open (row 1 of Figure 1 closed), iv) 2 rows of windows open (rows 1 and 2 closed). The layout i) is tested in order to produce some reference data to quantify the energy dissipations (and therefore the reduction of C_r) due to the rocks at the toe, friction along the wall and at the flume sides. In addition, the wave transmission under the caisson contributes to the reduction of reflection.

The porosity of the outer wall in the four layouts is analyzed based on the basic data reported in Tab. 1, where only the part of the caisson reproduced in the wave flume (see next section), 21.5 m long, thus including 10 columns of windows, is considered. Note that each window has an area of 2.03 m^2 and that the reference area of the wall, calculated from the upper row of windows (+2.20 m) is of (2.20+12.80)x21.50=322.50 m^2 (down to the crest of the rock berm).

Tab. 1. Porosity parameters

Parameter	i) Plain wall caisson	ii) 4-rows of perforations	iii) 3-rows of perforations	iv) 2-rows of perforations
Area of the open windows over 21.5 m width (m^2)	0.00	81.2	60.9	40.6
Porosity of external wall	-	0.25	0.19	0.13

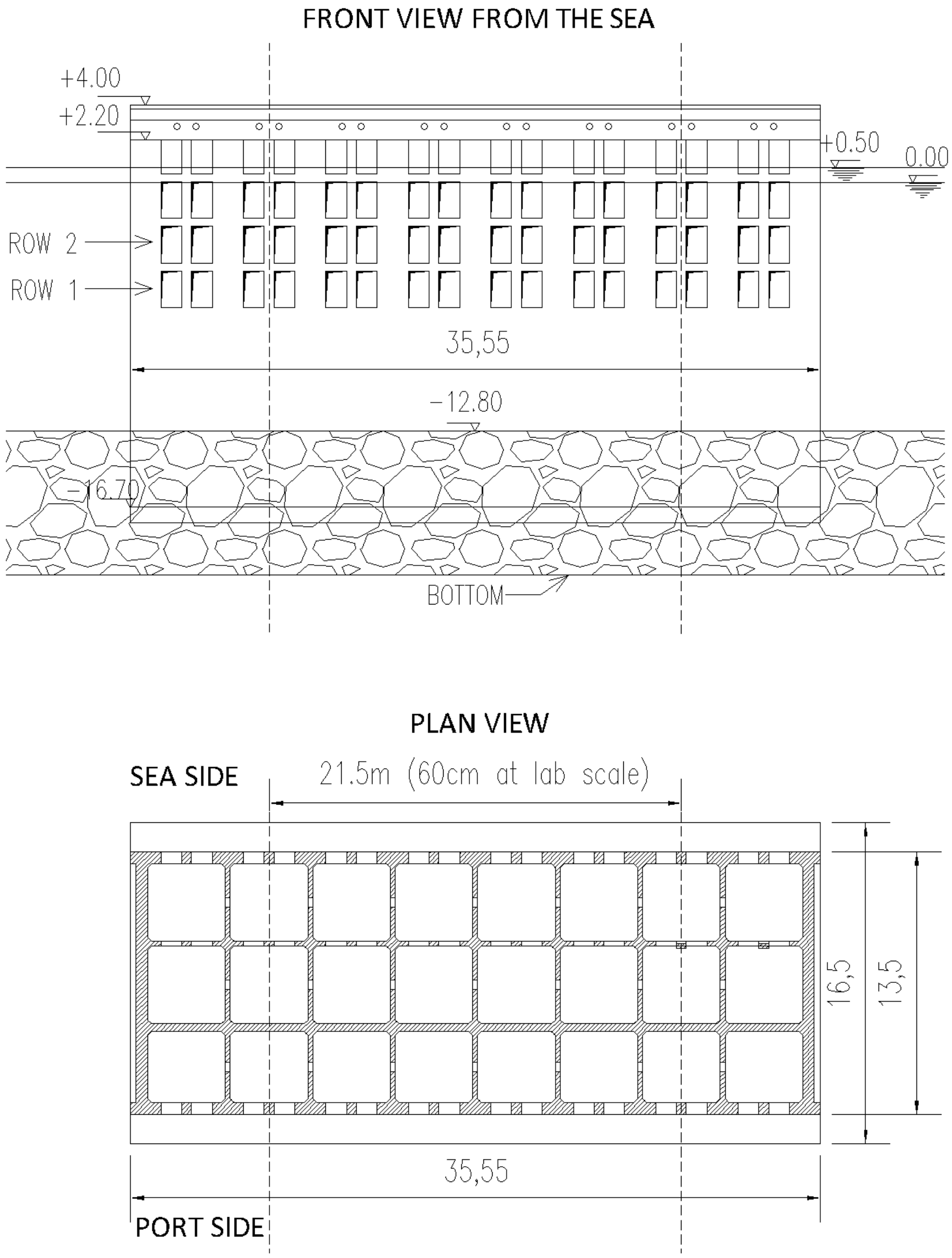

Fig. 1. Front and plan view of the caisson. The vertical dashed lines indicate the inner sides of the wave flume. All the dimensions and levels are in meters at prototype scale.

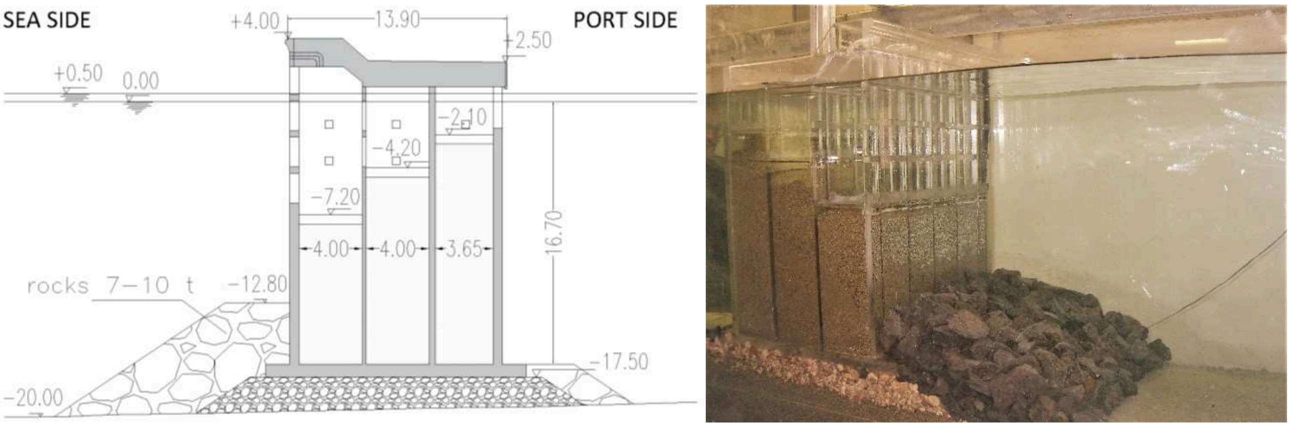

Fig. 2. Section of the caisson (left) and photo of the experimental set-up (right). All dimensions and levels are in meters at prototype scale.

3 Description of the laboratory model set-up and methodology

The 2D laboratory tests have been carried out at the Department of Engineering of Roma Tre University in the new medium scale random wave flume. The wave channel is 20 m long, 0.605 m wide and 1 m high (see Figure 3). The wave flume is equipped with a 1.35 m stroke piston for the wave generation, controlled by the software AWASYS, capable of 2nd order wave generation using Schäffer and Steenberg (2003) with modification by Eldrup and Lykke Andersen (2019a). Active wave absorption is obtained using the method by Lykke Andersen et al. (2016), which provides excellent performances with regular and irregular waves even for nonlinear waves, cf. Lykke Andersen et al. (2018). Two wave gauges are mounted on the wave generator, at 6 cm from the paddle, in order to provide the feedback to the active absorption system. The water depth at the wave paddle is of 0.7 m. The bottom is flat for 11 m, then a 1:20 concrete ramp followed by a 1:125 sloping seabed that reproduces prototype conditions (see Fig. 3). The structure is placed at a water depth of 0.55 m. Five wave gauges are located close to the structure and their position is shown in Fig. 3. These wave gauges are used to determine the incident and reflected wave trains using the methods of Lykke Andersen et al. (2017) and Eldrup and Lykke Andersen (2019b).

A length scale of 35.33 (in Froude similarity) has been chosen. The selected reduction factor allows to reproduce in the available flume width a longitudinal length of the caisson of 21.50 m, as shown in the Fig. 1. The flume walls, therefore, cut the cells exactly at the middle, ensuring that two symmetry axes are modelled at the walls.

Regular and random waves tests with prototype periods between 4 and 15 s (for the random waves the peak period is considered) are reproduced for two reference water levels (+0.00 and +0.50 m). For the irregular waves tests about 1000 waves have been reproduced. The tests presented in the following have been carried out using waves with H=H_{m0}=1.5 m and H_{m0}=4.5m. The formers represent mild and relatively frequent conditions for which is important to ensure a low reflection, in order to avoid disturbance to the navigation of ships approaching the harbor entrance. The latter are design waves tested in order to check that the reflection coefficient used for the evaluation of the wave conditions at the caisson for the calculation of the wave forces had been properly selected.

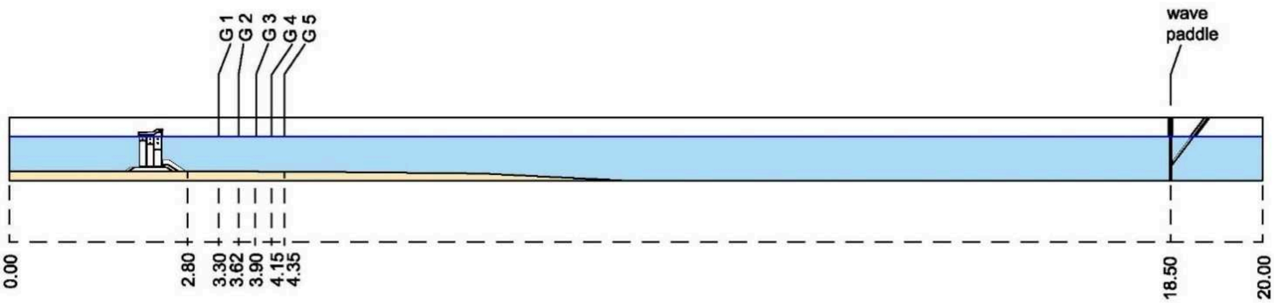

Fig. 3. Position of the structure and of the wave gauges (distances in meters).

4 Presentation and discussion of the results

4.1 Test results

The results of the experimental campaign are reported in Tab. 2. For each tested layouts, waves and water level conditions, the reflection coefficient C_r is reported. As far as the fully plain solid caisson is concerned, the C_r is of the order of 0.92-0.94. While in laboratory experiments, due to friction losses, the reflection coefficient is always a bit less than 1, here the wave reflection is also attenuated by the rocks at the toe of the caisson. The further reduction of reflection by means of the perforated cells should therefore be evaluated by comparison with this reference value.

As far as mild wave conditions are concerned, the reflection coefficient depends strongly on the wave period for the structures with absorbing cells. For the level +0.0 m the C_r varies between 0.34 (T_p=5 s) and 0.79 (T_p=12 s). It is not surprising that for the higher water level (+0.5 m) the reflection coefficient increases significantly, on average of about 0.13. In these conditions, the waves are more reflected by the outer wall strip and by the inclined roof of the first cell, thus making the second (inner) cell less effective.

It is on the contrary partially surprising that by reducing the porosity of the outer wall, i.e. by closing the lower rows of windows, the reflection coefficient is lower than for the configuration with maximum porosity. For the layout iii) C_r reduces of approximately 10%, while for layout iv) 7% reduction is found with respect to the layout ii). This is likely to be due to the larger dissipating fall of the water flow within the first cell (with constant air volume) in the case of closed lower windows.

The reflection coefficient for regular waves, as reported in Figure 5 is in general smaller than that for irregular waves, thus confirming the findings of Huang et al. (2011).

In Fig.5 (left panel) it is noted that C_r shows a remarkable minimum of about 0.2 for the wave periods of 4 to 6 s. The energy dissipation due to resonance is more effective for regular waves with a constant (short) length (L=40 m prototype) as related to the chamber width (B=8m), i.e. B/L= 0.2.

As far as the design waves (H_{m0}=4.5m) are concerned, it is to be noted that the reflection coefficient is about 15-20% smaller than that observed for the same periods but for milder wave conditions. Larger dissipation of energy, as well as relevant overtopping over the structure is the main causes for this difference.

Tab. 2. Reflection coefficients obtained from the tests (JS indicates tests with random waves, JONSWAP spectrum, RW regular waves)

H_{m0}/H (m)	T_p/T (s)	i) Plain caisson (level +0.0 m, JS)	ii) 4-rows perforated (level +0.0 m, JS)	ii) 4-rows perforated (level +0.5 m, JS)	iii) 3-rows perforated (level +0.0 m, JS)	iv) 2-rows perforated (level +0.0 m, JS)	ii) 4-rows perforated (level +0.0 m, RW)	ii) 4-rows perforated (level +0.5 m, RW)
1.5	4		0.43	0.50		0.36	0.18	0.32
1.5	5	0.92	0.34	0.54			0.25	
1.5	6		0.40	0.59	0.36	0.36	0.18	0.48
1.5	7	0.92	0.46	0.62			0.27	0.56
1.5	8		0.54	0.69	0.44	0.45	0.42	0.62
1.5	9	0.94	0.63	0.73	0.53	0.63	0.57	0.70
1.5	10		0.69	0.78	0.58	0.57	0.63	0.79
1.5	11		0.74	0.81	0.62	0.70	0.69	0.81
1.5	12		0.79		0.68	0.65	0.75	0.83
1.5	13						0.79	0.89
1.5	14						0.93	0.84
4.5	9		0.52	0.57				
4.5	11	0.91	0.61	0.65				

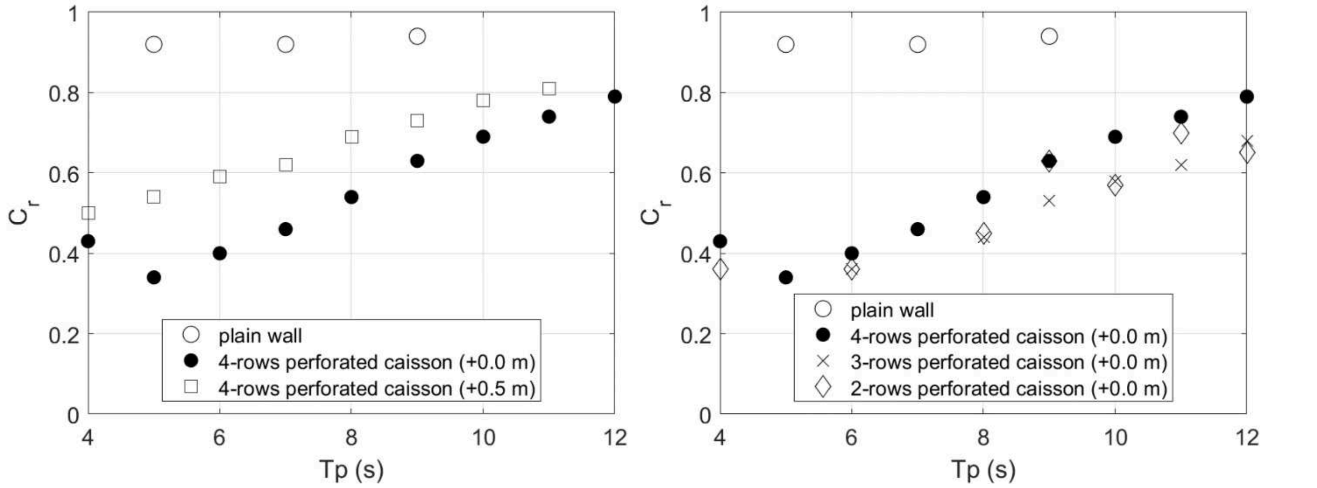

Fig. 4. Reflection coefficient plotted against the peak wave period for the different levels (left) and for different perforation layouts (right) for H_{m0}=1.5 m tests.

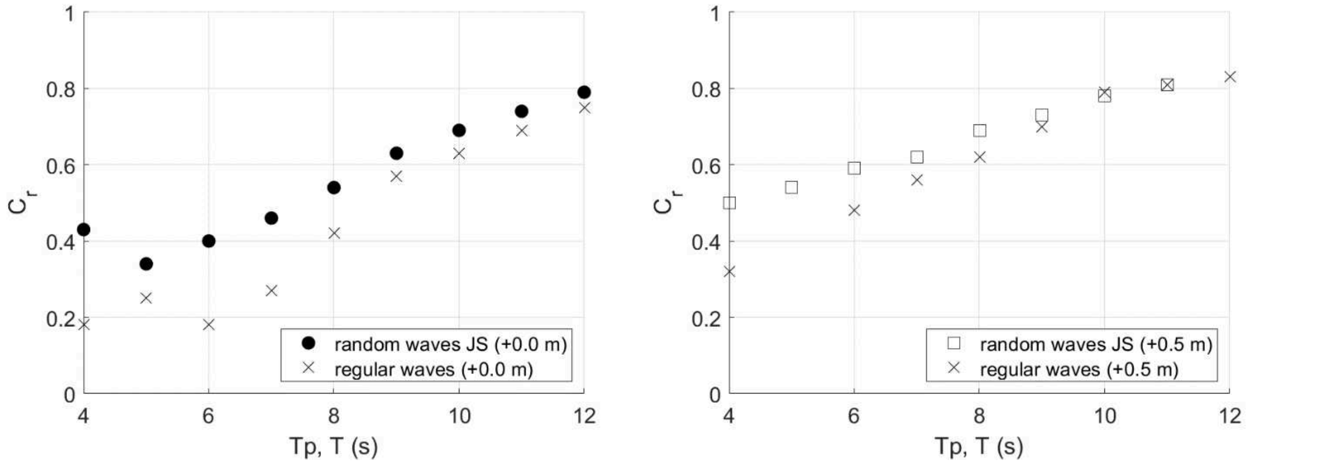

Fig. 5. Comparison between the reflection coefficient calculated using random waves with JONSWAP spectra (H_{m0}=1.5 m) and regular waves (H=1.5 m) for the 4-rows perforated caisson. For both cases the wave height is 1.5 m. Left: reference water level. Right: +0.5 m water level.

4.2 Comparison against previous researches

As stated before, a structure very similar to that under investigation had been studied using laboratory tests about 25 years ago, when the main breakwater of the nearby industrial port of Porto Torres was partially built using wave-absorbing caisson walls. An overview of the project is described by Noli et al. (1995), while a detailed report on the experimental tests is given by De Gerloni et al. (1989) and by Franco et al. (1998), the latter also reporting comparison against field measurements. The caisson had a prototype width of about 14 m and was tested in several configurations: plain vertical wall, 1 cell open to the sea with circular holes of 0.6 m diameter, 2 cells open and 3 cells open. It should be noted that while the width of the cells of the caisson under investigation here is of 4 m, smaller cells were used at the time, being of about 3.2 m each. Then, as far as the total size of the open cells is concerned, it might be assumed that the present layout is somewhat in the middle of the 2 cells and 3 cells open of the Noli et al. (1995) structure. Parametric tests were carried out by varying the wave period between about 5.5 and 16 s, and the wave height between about 4.2 m and 4.9 m, thus making them comparable to those here performed with design waves. The results of the original tests are reported in the Fig. 6. The tests carried out in this research with H_{m0}=4.5 m are reported for comparison. It appears that the reflection coefficients obtained in the present research are in very good agreement with those obtained by Noli et al. (1995).

Comparison is also carried out against the design method by Tanimoto et al. (1976). It is reported by Goda (2000) as a diagram, from which the reflection coefficient can be evaluated once the ratio B/L is specified. The results of the present research for the water level of 0.0 m and the parametric tests with H_{m0}=1.5 m are plotted on the diagram in the right panel of Fig. 6. The wave length L is calculated using the peak period and the water depth of 20 m, while B=8 m, thus considering the full width of the two open cells system. It appears that there exists a very reasonable agreement between the results of the tests and the method, thus once again confirming the solidity of the experimental procedure and confirming the minimum of C_r for B/L = 0.10-0.25. It should however be emphasized that it is not easy to adapt the results of Tanimoto (1976) to the present structural configuration. By applying it without the support of physical model tests, an uncertainty of about 20% would result, thus confirming the great importance of the laboratory modelling activities for the design of vertical wall caissons.

Finally Fig.6 also reports for comparison the equation given by Belorgey et al.2000, within the UE project PROVERBS: $C_r=18.6*(B/L)^2-7.3(B/L)+0.98$. The general trend is similar with minor differences due to the variable geometries.

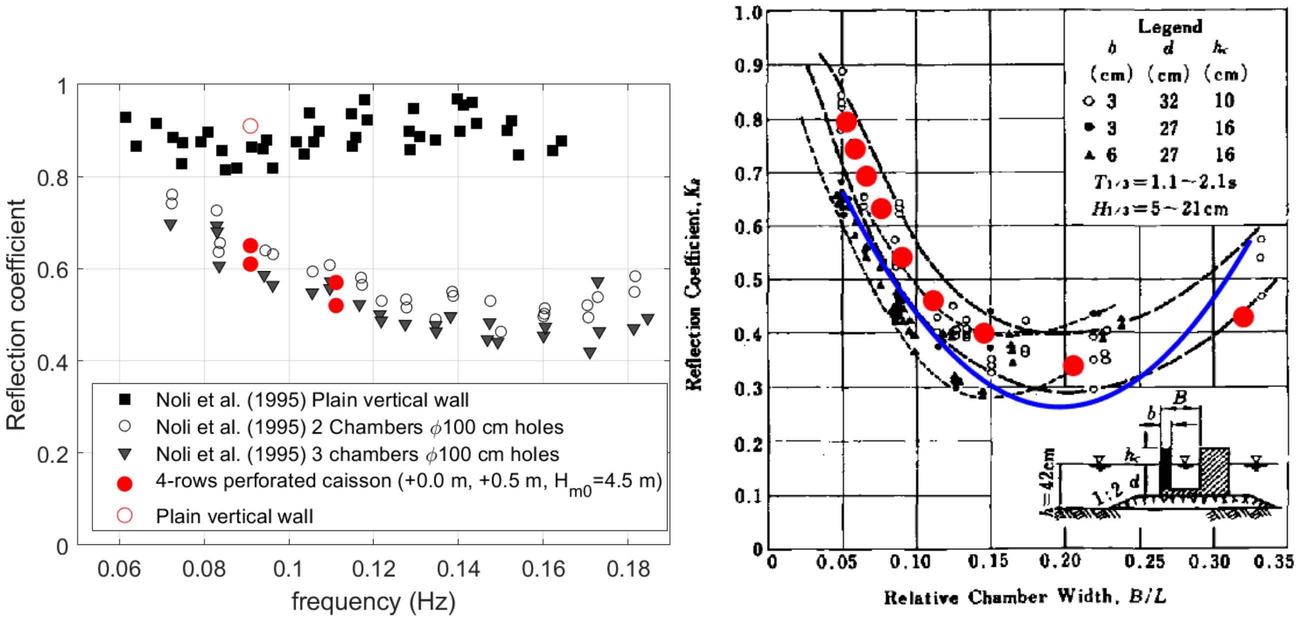

Fig. 6. Left: Comparison of the results of the design waves tests (H_{m0}=4.5m) against Noli et al. (1995), as reflection coefficient were obtained for a very similar caisson. Right: comparison of mild random wave test results (H_{m0}=1.5 m, see black dots in Fig. 5 left) against the results of Tanimoto et al. (1976) plot adapted from Goda (2000) and the curve proposed by Belorgey et al. 2000 (blue thick line).

5 Effect of wave obliquity and short-crestedness on the reflection coefficient

It is important for practical design applications also to remind that a further reduction of the reflection coefficient of perforated caissons is achieved when the incident waves are oblique and/or with directional spreading. Indeed the vast majority of studies have been performed in unidirectional head-on 2D conditions and rather few available studies about 3D wave reflection are just addressed to rubble mounds (Zanuttigh and Lykke Andersen, 2010) or to analytical solutions of schematic perforated walls (Liu et al.2007). Even though the data are limited in quantity a final comparison has thus also been made with some old unpublished results obtained in a pioneering 3D study within the EU MAST-LIP project (Franco, 1996), The old 3-D model study was carried out in 1995 in the Vinjè multidirectional basin at Delft Hydraulics (Figs. 7-8-9), by a research team from Politecnico di Milano and Aalborg University. This model (scale about 1:25) consisted of 13 caissons (see section in Fig. 7), each 0.9 m long, linked through a permeable two-layer rock basement to a flat concrete bottom with a constant water depth of 0.61 m. The significant wave height was kept nearly constant (H_s = 0.12-0.14 m). Peak periods T_p of standard JONSWAP spectra were 1.50 s and 2.12 s (peak wave steepness s_{0p} = 0.017 to 0.04). Even a few bimodal directional spectra were simulated. The angle of attack β varied between 0° (normal to the structure) and 60° in steps of 10°, while three groups of directional spreading values were simulated (σ = 0°; 20°-25°; 26°-30°). Wave conditions in front of the model have been analyzed through a set of 20 gauges placed in two rows of ten at 1.0 m distance offshore of the structure (see Fig. 8). Methods of analysis, that were able to separate incident and reflected wave energy, are the Maximum Likelihood and the Bayesian approach as explained by Frigaard and Petersen (1994).

An extensive number of tests were performed for the simplest case of a straight vertical plain wall, whereas a reduced number of tests were conducted for the alternative geometries, which included the curved parapet and both fully perforated front walls with either circular and rectangular openings (Fig. 7), having an equal area porosity of 20% and overall wet perimeter (10x5 round holes of 51 mm diameter and 7x5 rectangular holes of 38x76 mm for each caisson). The absorbing chamber width B was reduced to 0.40 m, simulating ratios to the peak wave length B/L= 0.057 and 0.114. In the final layout with rectangular perforations, an air intake of 150x850 mm was opened in the top deck (ceiling) to simulate the full effect of air vents favoring energy absorption ("Open Deck").

Fig. 7. Photos of the two types of perforated caissons tested in 3D (from Franco C. 1996) .

The main goal of the study was the measurement of overtopping volumes and horizontal and uplift pressures and forces in 3D conditions (Franco et al. 1996, Franco and Franco 1999). Analysis of wave reflection was performed only for a few wave conditions and the results are shown in Fig. 10.

First it is noted that the largest value of C_r = 0.53 obtained for the case of long-crested head-on wave attack corresponds well with the value obtained here for the period of 8 s with B/L around 0.1. It is then shown that indeed C_r reduces significantly with increasing angle of wave attack and to a less extent with spreading. Even a perpendicular short-crested wave attack yields a C_r reduced to around 0.4. The effect of the hole shape (circular or rectangular) is marginal. The few data have been fitted with a simple linear equation to provide an "obliquity factor" γ_b similar to that given in the EurOtop Manual 2018 (since reflection and overtopping are somewhat correlated). The reduction due to obliquity for typical real shortcrested waves (for either circular and rectangular perforation) can then be expressed by the following simple equation, where the angle is specified in degrees and the results are expected to be valid for $\beta \leq 60°$:

$$C_r(\beta) = C_r(\beta = 0°) * (1 - 0.0055\,\beta) \quad (1)$$

The highest efficiency is achieved when the caisson ceiling is removed (Open Deck), thus allowing easy air escape. The influence of perforation shape is modest, but it seems that long vertical rectangular holes with increased wet perimeter may be more efficient in dissipating the energy of oblique waves. It may be noted that the chamber volume was relatively large, but no perforations were present in the transverse walls between adjacent chambers (which were then spaced by 2.25 B instead of about 1.0 B as in our present case, as in most practical caisson designs).

6 Conclusions

New 2d model tests on a perforated caisson breakwater have demonstrated the good efficiency of the new random wave flume with the active absorption system. The test results have been compared with previous studies and confirmed that multichamber perforated caisson can achieve quite low reflection coefficient (even as low as 0.2-0.3, especially under regular waves), clearly dependent upon the incident wave period or length, as related to the open chamber width (B/L). The retrieval and reanalysis of some old unpublished 3D wave reflection data provides further design guidance for real projects under oblique and shortcrested wave attacks. A tentative simple formula for the reduction factor due to wave obliquity is given, while the influence of wave spreading and hole shape seems marginal.

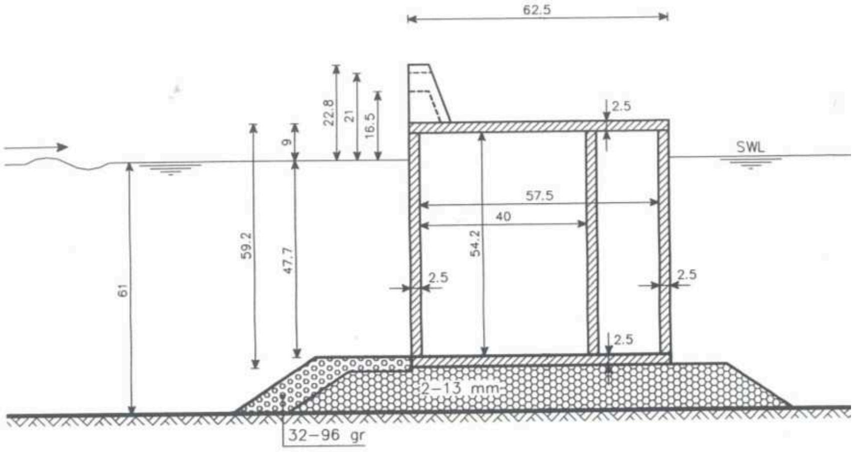

Fig. 8. Section of model caisson in the 3D model of Franco et al. (1996, measures in cm, at lab scale):

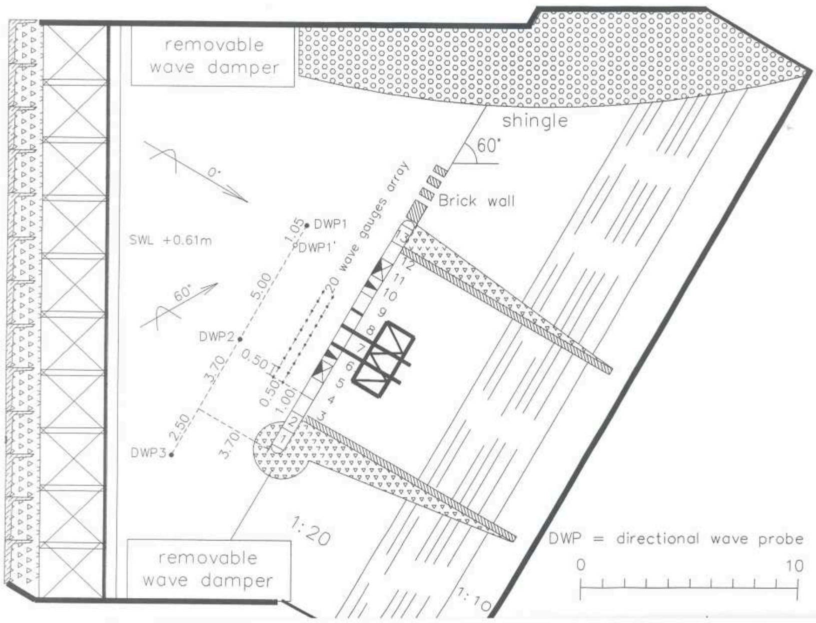

Fig. 9. Setup of the 3D caisson breakwater model in Vinjè basin (from Franco et al. 1996).

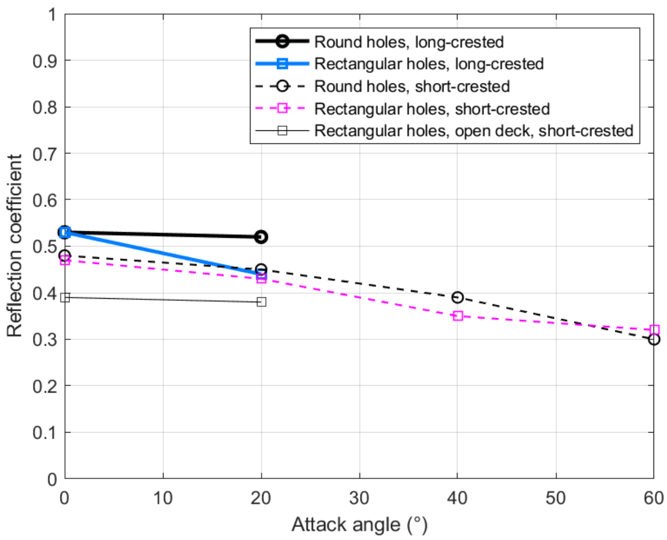

Fig. 10. Effect of wave obliquity, shortcrestedness and perforation shape on reflection coefficient (adapted from Franco, 1996).

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