PHYSICAL MODEL TESTS OF WAVE OVERTOPPING AND FORCES ON BREAKWATER CROWN WALLS

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This paper describes new physical model tests aiming at measuring both wave overtopping and wave induced forces on rubble mound breakwater crown walls. The physical model and the equipment used for the measurements are described in detail. For the completed tests, a detailed analysis is reported, by evaluating the properties of the incoming waves at the toe of the breakwater and some statistical parameters to describe the wave induced forces and pressures on the crown wall. Careful analysis is also carried out to evaluate how the distribution of the pressures changes with time. It is found that the upper part of the wall is subjected to the first large quasi-impulsive action of the wave; the lower part of the wall is afterwards flooded and a quasi-hydrostatic pressure develops along the height of the wave wall. As far as the pressures on the base of the crown wall are concerned, they develop after a quite large time lag after the maximum of the horizontal force. First attempts to correlate the maximum horizontal force with some explanatory variables such as the ratio of the crest freeboard and of the significant wave height of the incoming waves indicate a promising correlation, also in agreement with the existing literature on the topic. The overtopping rate are also measured and compared with empirical formulas. The correlation between the wave induced forces and the average overtopping discharge on the breakwater is also investigated.

Keywords: Crown wall; rubble-mound breakwater; wave force; wave overtopping

INTRODUCTION

The crown wall, often installed on the crest of rubble mound breakwaters, guarantees safe accessibility of the breakwater and can be used to increase the crest freeboard, avoiding too large use of quarry material. It should however withstand the forces applied by the waves, that may induce sliding and overturning of the whole structure, as it behaves monolithically, and local damages such as the failure of the wave wall or part of it. While a large amount of information, data and design methods are available for other hydraulic responses, like for example the wave reflection coefficient (Zanuttigh *et al.*, 2013) and the average overtopping discharge (EurOtop, 2016), it is widely accepted that design methods for estimation of the wave forces on crown walls can still be improved. Among the recent researches that have considered this important problem it is worth to cite Negro *et al.* (2013), who have presented a careful review of the available existing design methods, and Nørgaard *et al.* (2013), who have updated the method by Pedersen (1996), currently one of the most widely used together with Martin *et al.* (1999). Very recently, Molines *et al.* (2018) have analyzed new experiments on crown wall wave forces and overtopping and have discussed the importance of many possible explanatory variables of the phenomena. They have found that a strong correlation exists between the wave induced forces and the average overtopping discharge on the breakwater.

The aim of this paper is to present the results of new small scale 2D physical model tests on a rubble mound breakwater, with measurements of wave overtopping and wave forces on the crown wall. A detailed analysis of the time development of the wave induced pressures on the wall is carried out, in order to evaluate the effects on the local resistance of the structure, as for example of the upper part of the wave wall. By integration of the point pressure values, the total estimated force on the structure is obtained and it is analyzed how horizontal and vertical maximum values combine in time. The influence of several explanatory variables on the wave forces is investigated, also following the recent conclusions of Molines *et al.* (2018). Finally, the average overtopping discharge is analyzed, considering its correlation with the wave induced forces on the crown wall. The paper is structured as follows. Section 2 describes the physical model. Section 3 and 4 reports the analysis of the experimental data and the main results. Conclusions and future developments of the research are reported in the final Section 5.

DESCRIPTION OF THE PHYSICAL MODEL

The 2D hydraulic model tests are carried out in the new medium scale random wave flume, recently installed at Roma Tre University, Italy. It is 20 m long, 0.605 m wide and 1 m high; it is equipped with

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a 1.35 m stroke piston for the wave generation, controlled by an in-house developed software, capable of 2nd order wave generation and active wave absorption. The considered structure is a rubble mound breakwater in intermediate waters and moderate tidal range, as shown in Figure 1. The structural properties (levels, sizes of the rocks, etc.), have been selected in order to leave the possibility of testing sea states much more severe than the design ones, thus reproducing significant damages to the breakwater in the development of the research.

The bottom in the flume is horizontal and the water depth is of 56-57 cm, depending on the selected tidal level (see Table 1). The two-layer armour rocks have a range of 50-100 g and a slope of 2:3 (vertical:horizontal). The filter layer has a range of 5-10 g. The crown wall has a horizontal length of 14.5 cm and a wave wall 11 cm high, measured from the base of the structure. It was built in Perspex, allowing easy mounting of the pressure sensors, as detailed later. Steel reinforcement structures are used to ensure that the crown wall does not vibrate or deform under the wave action. The crest level of the wall is of 14.0-15 cm above the still water level. The breakwater was built assuming a scale reduction factor of 1/20; the model would thus represent a breakwater in a water depth of about 10 m and a wave wall with crest at about 3 m. The significant wave height of the design sea state, according to Hudson's formula, is of 9 cm, i.e. about 1.8 m at prototype. The breakwater is then attacked by moderately severe design sea states, hence justifying the low level of the wave wall crest.

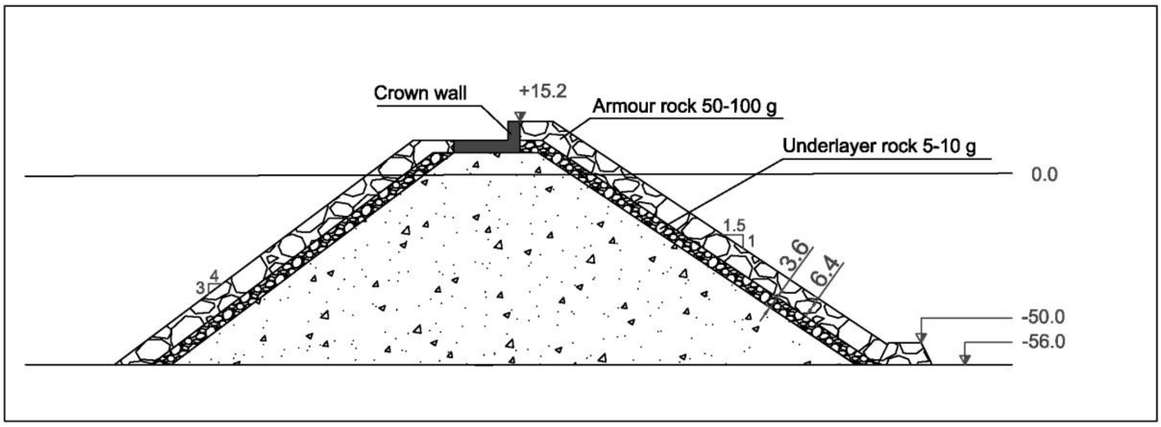

Figure 1. Breakwater cross section with model values relative to tests 1-6 (lengths in cm).

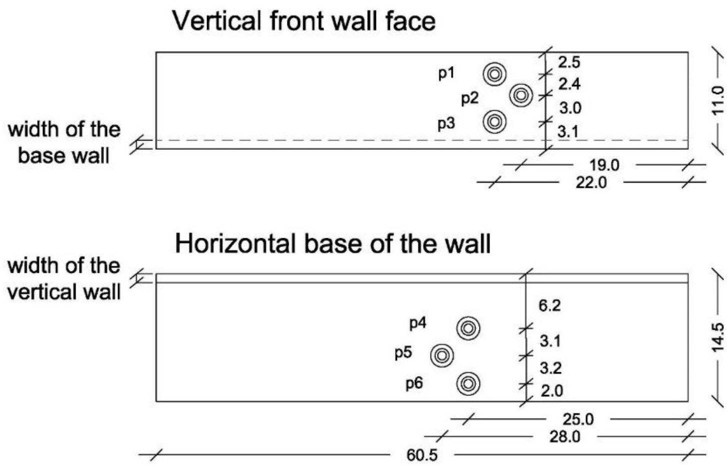

Figure 2. Position of the pressure transducers on the front face and on the base of the modeled crown wall (values are in cm).

Several instruments were used to measure the surface elevation along the flume, the wave pressures on the crown wall, as well as the overtopping discharge and individual volumes. The surface elevation along the flume is measured using six Churchill resistive wave gauges. One is located at the middle of the flume, four are close to the structure and are used to calculate the properties of the incoming waves on the basis of reflection analysis. The exact position of the five gauges is of 0.22, 0.30, 0.40, 0.70, and 7.50 m, measured from the toe of the breakwater toward offshore. In Figure 3 is schematized a section view of the wave flume, reporting the position of the dike, the gauges and the wave generator strating from one end of the flume. Six Trafag pressure transducers (0.0-2.0 m of water column pressure range) are mounted on the crown wall as shown in Figure 2. Three of them are installed on the wave wall, at a level from the bottom of 3.1, 6.1 and 8.5 cm respectively. The other three are placed on the base slab respectively at 6.2, 9.3 and 12.5 cm from the wall. A photo of the crown wall with all the instruments is reported in Figure 4. It can be noted that further five pressure transducers are installed. These, however, work in a measurement range of 1.2-10.0 m of water column pressure. The order of magnitude of the wave induced pressures on the structure was about 10 cm of water column, hence these devices have not enough resolution and accuracy to detect the signals of interest in this research. A tank (Figure 4 b) is used to collect the overtopping water. It discharges the flow in a bucket located below the flume and connected to a force transducer that records the weight. It can therefore be calculated the mean overtopping discharge during each test and with a careful analysis of the recorded weight signal the individual overtopping waves volumes can be obtained.

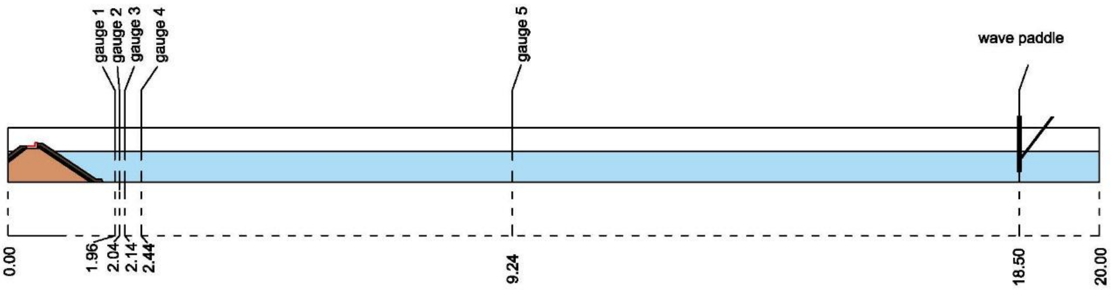

Figure 3. Longitudinal section of the wave flume

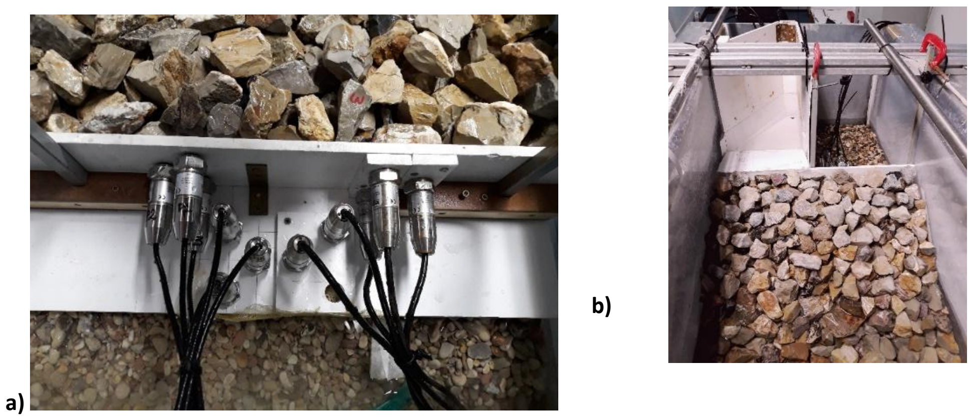

Figure 4. a) Photo of the pressure transducers. The 6 devices used in the present study are those on the left, while the other 5 on the right have a too large measurement range for the present scope. b) Photo of the breakwater, the wall and the overtopping collection tank (front view from the wave generator)

Table 1. Model Test matrix				
	h	H_{m0}	T_p	R_c
	(m)	*(m)*	*(s)*	*(m)*
Test 1	0,56	0,053	1,3	0,15
Test 2	0,56	0,070	1,2	0,15
Test 3	0,56	0,081	1,2	0,15
Test 4	0,56	0,091	1,2	0,15
Test 5	0,56	0,106	1,1	0,15
Test 6	0,56	0,111	1,4	0,15
Test 7	0,57	0,072	1,3	0,14
Test 8	0,57	0,071	1,2	0,14
Test 9	0,57	0,120	1,5	0,14
Test 10	0,56	0,100	1,4	0,15
Test 11	0,56	0,127	1,4	0,15
Test 12	0,56	0,087	1,4	0,15
Test 13	0,56	0,109	1,3	0,15
Test 14	0,56	0,129	1,5	0,15
Test 15	0,56	0,123	1,5	0,15
Test 16	0,56	0,091	1,4	0,15
Test 17	0,56	0,118	1,2	0,15
Test 18	0,56	0,121	1,4	0,15
Test 19	0,56	0,098	1,4	0,15
Test 20	0,56	0,099	1,2	0,15
Test 21	0,56	0,082	1,13	0,15
Test 22	0,56	0,079	1,16	0,15
Test 23	0,56	0,077	1,13	0,15
Test 24	0,56	0,091	1,15	0,15
Test 25	0,56	0,094	1,14	0,15
Test 26	0,56	0,093	1,15	0,15
Test 27	0,56	0,092	1,39	0,15
Test 28	0,56	0,091	1,38	0,15
Test 29	0,56	0,092	1,36	0,15
Test 30	0,56	0,120	1,33	0,15
Test 31	0,56	0,113	1,37	0,15
Test 32	0,56	0,120	1,3	0,15
Test 33	0,56	0,079	1,33	0,15
Test 34	0,56	0,081	1,28	0,15
Test 35	0,56	0,083	1,34	0,15
Test 36	0,56	0,109	1,88	0,15
Test 37	0,56	0,109	2,13	0,15
Test 38	0,56	0,108	2,19	0,15
Test 39	0,56	0,123	2,06	0,15
Test 40	0,56	0,118	1,86	0,15
Test 41	0,56	0,118	1,82	0,15

WAVE PRESSURES AND FORCES ON THE CROWN WALL

The wave and water level conditions of the tests carried out so far are reported in Table 1. The tests differ mainly for the incident sea state parameters. The waves are generated using the Jonswap spectrum from the values of spectral significant wave height, H_{m0} and peak period, T_p. All tests have a duration that reproduces about 1000 waves, which is in the range of 18-25 minutes. For each test, the water surface elevation at the five resistive gages is analyzed, allowing the derivation of the actual incoming sea state on the breakwater.

The pressure recorded at the transducers placed on the vertical face of the crown wall have been used to calculate the total horizontal force acting on the wall, by using a basic integration method. The pressures at p1, p2 and p3 are multiplied for the vertical height of 3.7, 2.7, and 4.6 cm respectively (see Figure 2), considering therefore a unit wide area. Then the total horizontal force over the front face of the wall is obtained by adding the three forces given by the three transducers. A statistical analysis of the horizontal force time series is carried out for the 41 tests, extracting the peak values of the horizontal wave induced force. For each test, a threshold value is assumed in order to identify only the extreme values of the wave impact. The average of the highest four values of the horizontal force has been calculated and used as a significant statistical parameter. This value is referred to as the $F_{1/250}$, since each test reproduces 1000 waves and the highest four represent the 0.4%; the maximum (e.g. 1/1000, or 0.1%) force is also considered, referred as $F_{1/1000}$. Figure 5 shows the dependence of $F_{1/250}$ and $F_{1/1000}$, respectively in red and in grey, with the relative freeboard, R_c/H_{m0}. A promising good negative correlation can be noted. The diamond green markers refer to the horizontal forces predicted following the method suggested by Martin et al. (1999). They suggest two diagrams for the pressure on the crown wall: the dynamic pressure that corresponds to the first impact of the incident wave and the pseudo-hydrostatic pressure that occurs during the water mass descent. Here we applied the formula for the dynamic pressure, in order to obtain the horizontal force on the crown wall induced by the first more severe peak of wave pressure. In the pressure formula we used as design wave $1.6 \cdot H_{m0}$, and we calculate the horizontal force for each the 41 tests reproduced. As can be noted in Figure 5, the experiment results are similar to those predicted by Martin et al. (1999), although a general overestimation of the forces is given by the formula. Further explanatory variables are currently being tested, also following Molines *et al.* (2018).

The time evolution of the pressure signals has also been investigated, in order to evaluate the effects on the local resistance of the structure, as for example of the upper part of the wave wall. The time analysis is carried out during the extreme events, looking at the 4 highest horizontal forces measured during each tests. As an example, the 4 largest force events are reported for the test 11 (Figure 6 and Figure 7). The top panels of both figures report the pressure time series of the four events at the six transducers (p1-p3 in the front face, p4-p6 at the horizontal slab of the crown wall). The black dashed horizontal line is the dynamic pressure predicted by the Martin et al. (1999) formula. The vertical black lines indicate 8 time instants considered in the plots at the lower panels. Here the vertical and horizontal distribution of the pressure is plotted in red adjacent to the wall, considering the exact position of the transducers. It can be noted that the upper part of the walls is first subjected to the large quasi-impulsive action of the wave (time instant t_1-t_4); while the lower part of the wall hit afterwards (time instant t_5-t_8) and a quasi-hydrostatic pressure develops along the height of the wave wall. According to this pressure distribution at the front face of the wall, the transducers at the horizontal face measure higher wave induced pressure during the quasi-hydrostatic vertical distribution of the pressure. The time evolution of the wave pressure is similar to that suggested by Martin et al. (1999). Further analysis is underway to evaluate the time lag between the maximum of the horizontal and vertical forces, which is a crucial parameter in evaluating the global stability of the whole crown wall structure.

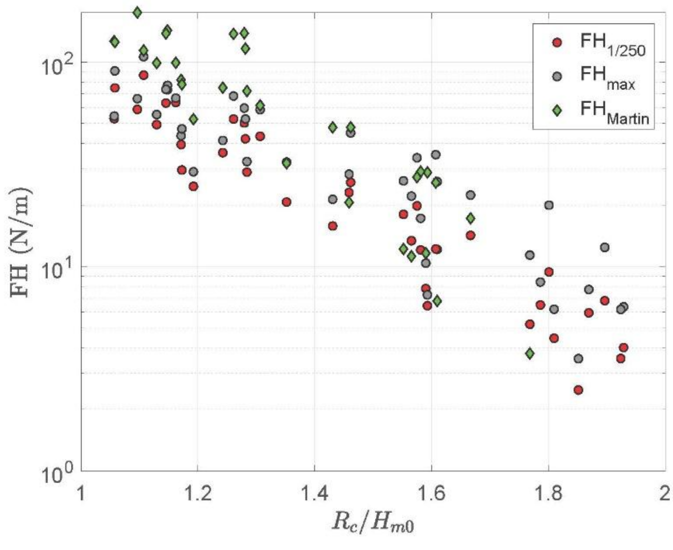

Figure 5. Horizontal forces induced at the front face of the crown wall in the 41 tests carried out. The red dots refer to the statistical value $F_{1/250}$, the grey ones refer to the $F_{1/1000} = F_{max}$, while the diamond markers are obtained from the pressure formula of Martin et al. (1999).

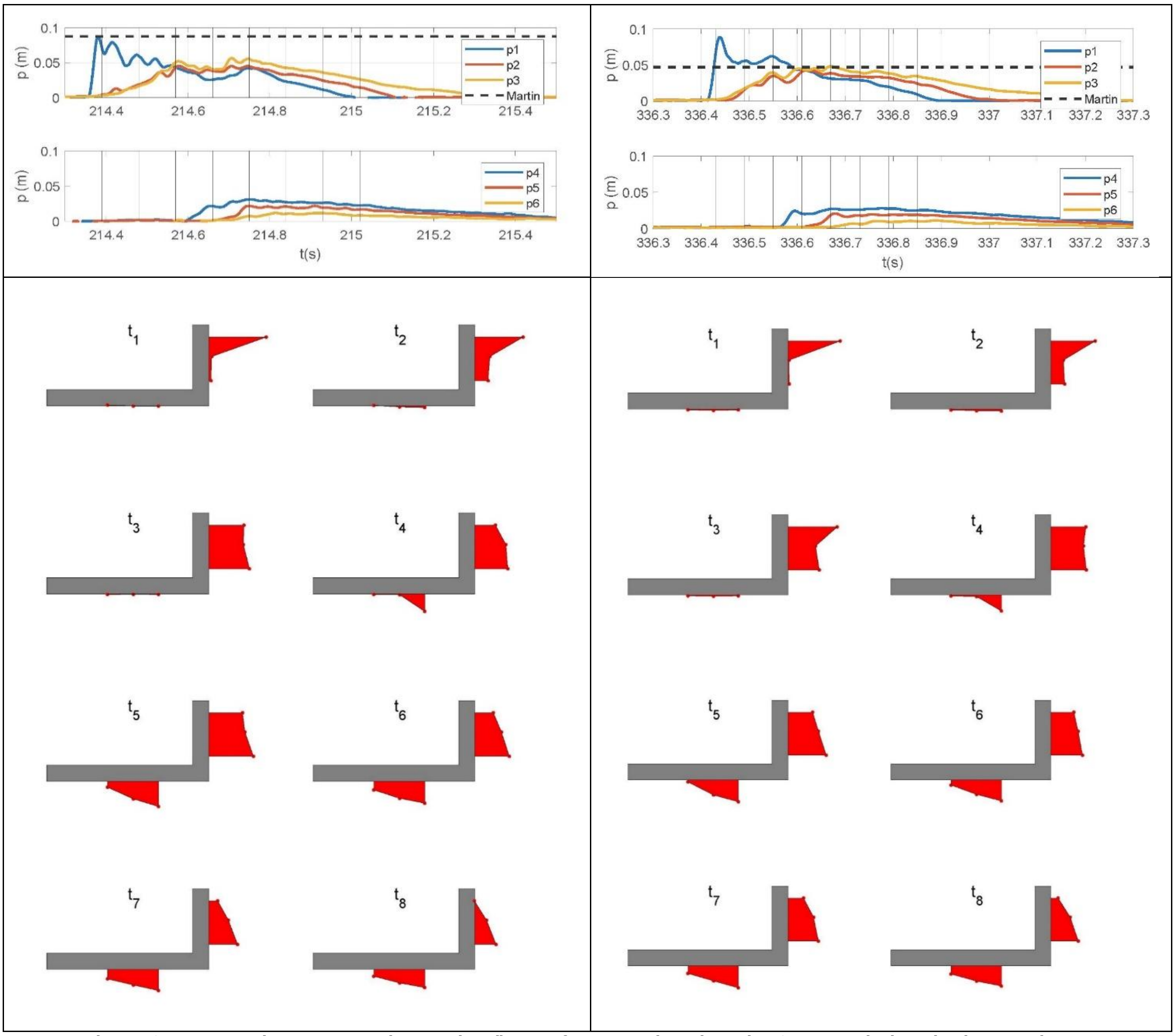

Figure 6. Top panels: Pressure time series (in m of water column) at the 6 gages during the impact that produces the first (left plot) and the second (right plot) highest horizontal force on the wall. Lower panels: Snapshots at 8 instants (reported by the vertical lines in the upper plots) of the pressure values.

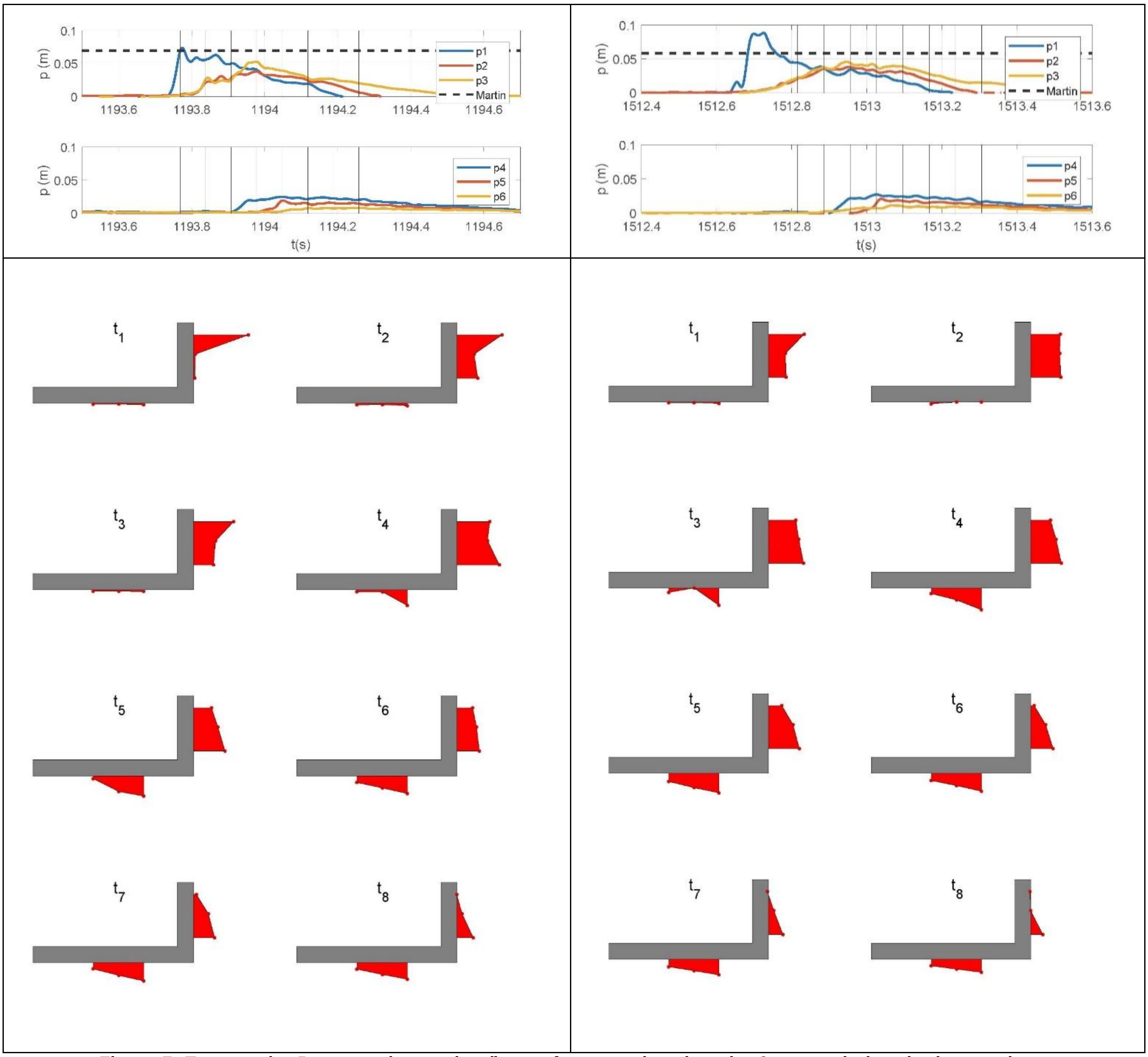

Figure 7. Top panels: Pressure time series (in m of water column) at the 6 gages during the impact that produces the third (left plot) and the fourth (right plot) highest horizontal force on the wall. Lower panels: Snapshots at 8 instants (reported by the vertical lines in the upper plots) of the pressure values.

WAVE OVERTOPPING

For the 41 test, the average overtopping discharge has been measured. As shown in Figure 4, a water collection tank is positioned behind the crown wall, and connected to it with a slide 27 cm wide. The overtopping water is convoyed into a tank placed outside the flume, connected to a load cell able to measure the overtopped water volume in time.

The total water volume overtopping the crest of the breakwater during the 1000 waves, is transformed into mean overtopping discharge over one meter of breakwater. Therefore, 41 measurements of mean overtopping rate are obtained and its values are correlated with the relative freeboard, R_c/H_{m0}. Figure 8 presents this correlation showing the dimensionless overtopping discharge, $Q=\boldsymbol{q}/\sqrt{\boldsymbol{g}\boldsymbol{H}_{\boldsymbol{m0}}^{\boldsymbol{3}}}$, in a semi-logarithmic plot. The grey dots indicate the physical model measurements, while the black line represents the empirical formula for the overtopping rate, given by:

$$Q = \frac{q}{\sqrt{gH_{m0}^3}} = 0.09 \cdot exp\left[-\left(1.5\frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)^{1.3}\right] \tag{1}$$

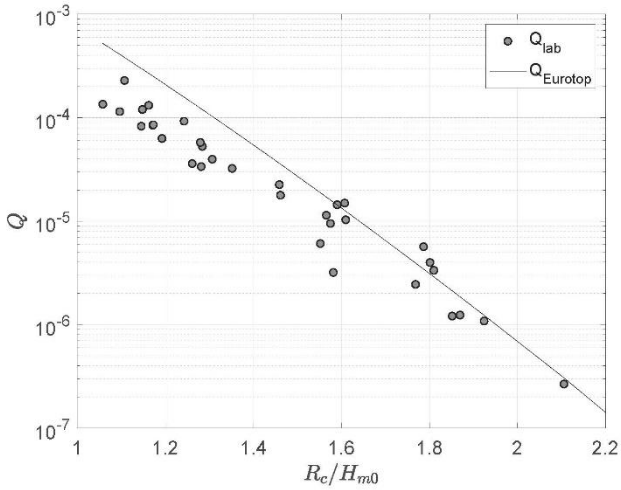

Figure 8. Correlation between the dimensionless mean overtopping discharge, *Q=q/√gH$_{m0}$* with the relative freeboard, *R$_c$/H$_{m0}$*. The dots represent the physical model measurements while the black line represents the Eurotop mean approach empirical formula.

Equation (1) has been developed for rubble mound steep slopes (1:2 to 1:4/3), (EurOtop, 2016).

Molines et al. 2018 used NN models to detect relationships between input variables and wave forces and overturning moments on crown walls to develop new formulas. In details, they defined seven input variables to estimate wave forces; among these variables, wave overtopping (log Q) was the most relevant to estimate horizontal wave forces and overturning moments.
We verified the formula proposed by Molines et al., 2018 (equation 2), with the results of the physical tests (Figure 9)

$$FH = \frac{FH_{0.1\%}}{0.5\rho g C_h^2} = \left(\left(0.27 \cdot ln(\xi_{0p}) + 0.1\right)(logQ + 6) + 0.23\right)\left(0.5 \cdot \frac{R_c - A_c}{C_h} + 1\right) - 0.15 \tag{2}$$

In Figure 9 the physical model forces are dimensionless, as proposed in equation (2), where C_h is the crown wall height.

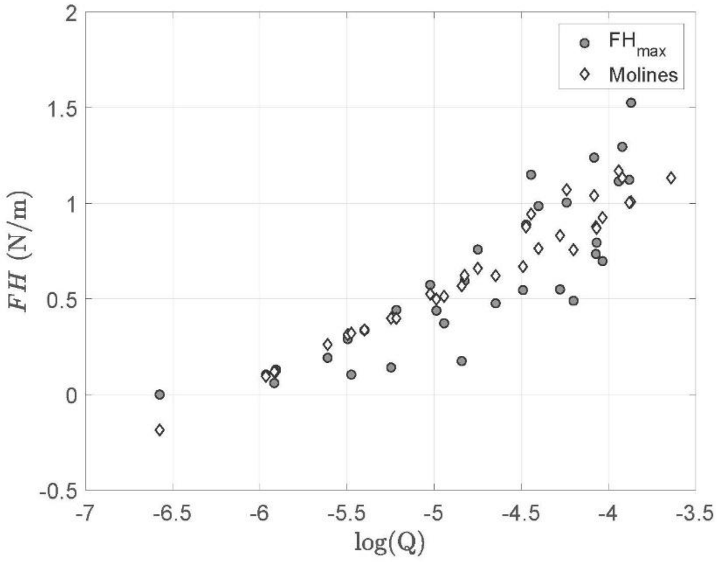

Figure 9. Horizontal forces vs Overtopping: comparison with Molines et al (2018) formula.

CONCLUSIONS

The preliminary results of a 2D experimental investigation on wave induced forces and mean overtopping discharge on a rubble mound breakwater have been presented in this paper. Detailed analysis of the time evolution of the pressures on the crown wall has been reported. Coherently with the existing literature it shows that the upper part of the wall undergoes a large, quasi-impulsive wave action. Subsequently the whole wave wall is loaded by the wave according to a quasi-hydrostatic distribution of the pressures. At the bottom of the crown wall the pressures are smaller, as expected. Pressure peaks at the six transducers occur with relevant time lags. The maximum values at the sensors p2 and p3, installed in the lower part of the wall, occur about 0.2 s later than the peak at p1, installed at the top of the wall. The peak of the pressure at the bottom of the crown wall occurs about 0.5 s after the maximum at p1. A good correlation has finally been found between the $F_{1/250}$ peak force and the ratio between the wall crest freeboard and the significant wave height, also considering the Irribarren number. The measurements are in good agreement with the prediction formulas suggested by Martin et al. (1999).

The mean overtopping discharges are in good agreement with the prediction formula available in the Eurotop Manual (2016), and as proposed by Molines et al. (2018) are correlated with the dimensionless horizontal force induced on the crown wall.

Future developments of this research will be aimed at evaluating the uncertainties given by the specific wave series on wave forces and overtopping, as also discussed by Romano et al. (2015).

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