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Wave Forces on Recurved Parapet Wall: The Influence of the Wave Period

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Abstract: The aim of the present paper is to give some preliminary guidelines for the design of recurved parapet wall.The results of the work are carried out by menas of numerical simulations, carried out with OpenFOAM®. The goal is to describe the influence of the wave period on the confined-crest impact (Castellino et al., 2018). The confined-crest impact is an impulsive phenomenon that occur when a recurved parapet wall, used to reduce the wave overtopping at vertical breakwaters, is subjected to non-breaking wave conditions. Composite vertical breakwaters are commonly used when the water depth is larger than 15 m, consequently subjected to non-breaking wave conditions. A dimensional analysis is carried out to identy the non-dimensional ratio on which the confined-crest impact depends on.

Keywords: vertical breakwaters, recurved parapet wall, non-breaking waves, impulsive forces, wave period, numerical simulations.

1 Introduction and state of the art

To limit the wave overtopping, aiming at protecting the inner side of the harbor, parapet walls are often used. Moreover, to further reduce the wave overtopping, different shape for the parapet can be considered. An example is represented by recurved crown wall, which are a widespread technical solution. As a matter of fact, their effectiveness in wave overtopping reduction has been tested and confirmed by Kortenhaus et al. (2002, 2004) and by Martinelli et al. (2018). A typical example of this kind of hydraulic device is reported in Fig. 1. The picture represents the Civitavecchia harbor (Italy), cited located in the central Tyrrhenian Sea, built in deep-water conditions.
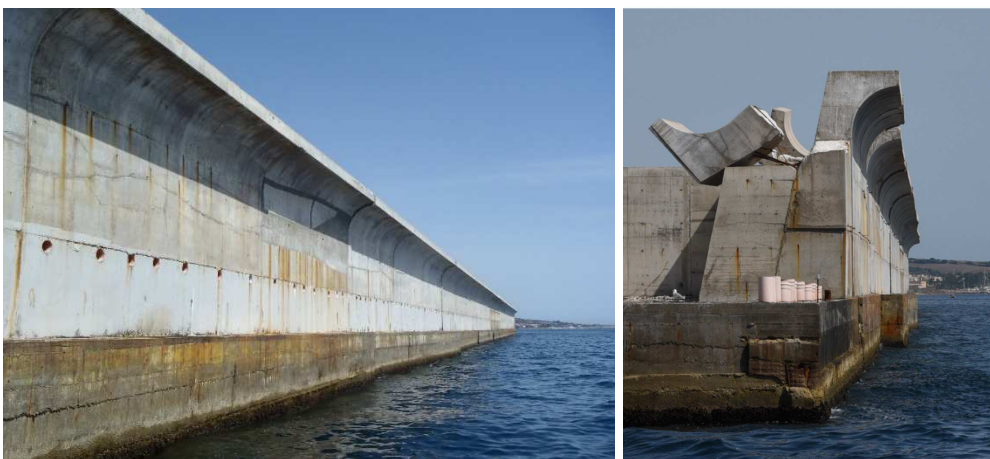

Fig. 1.   Left panel: picture of the main breakwater of Antemurale Cristoforo Colombo, Civitavecchia, Lazio (Italy) made by r.c. precast caissons with a recurved parapet wall. Right panel: part of the damaged recurved parapet in the Civitavecchia harbor.

Although this kind of shaped wall exhibits an excellent hydraulic performance, the non-breaking wave-induced load is higher than those acting on a traditional vertical parapet. In this case, a bad designed wall can suffer dangerous damages, like those shown in the right panel of Fig. 1.

The state of the art on the design of vertical breakwater, is mainly focused on the impact induced by breaking wave conditions (Goda, 2010) and not by the interaction of the waves with non-traditional wall configuraitons (as underlined by Castellino et al., 2018a, 2018b).

Castellino et al. (2018), describing for the first time the physical features of the so-called confined-crest impact, have shown the trade-off between wave overtopping and total force increase due to the presence of the recuerved parapet. The results show the variation of the non-dimensional force varying, at the same time, wave height (H) and wave period (T). The combination of the wave parameters (H and T) have been chosen such that maximizing the wave steepness, always ensuring non-breaking wave conditions.

In this paper we present the effect of the wave period on the total force acting along a recurved parapet wall placed on the top of a vertical breakwater. The study has been carried out by means of numerical simulations, carried out by using the toolbox OpenFOAM®. The wave period has been parametrically varied for each considered wave height, in order to highlight the effect of the wave period only. The interFOAM is the considered solver, which solves the RANS equations for multiphase flow. Both the phases (air and water) are considered as incompressible. This hypothesis, in non-breaking wave conditions, where the role of the air is limited, can be accepted.

This paper is structured as follows: after this Introduction the Section 2 describes the geometrical setup and the numerical simulations. Then, the dimensional analysis of the problem at hand (Section 3) and results and discussions (Section 4) follows. Finally, few concluding remarks (Section 5) close the paper.

2   The geometrical setup and numerical simulations

2.1   The geometrical setup

In Fig. 2, the geometrical setup is shown. The represented structure typically falls into the vertical breakwater category. A fixed water depth h has been considered ($h = 20.0$ m), as well as the freeboard R_c equal to 6.5 m. The geometrical parameter, radius r and exit angle a, are both considered constant and equal to 1.0 m and 90° respectively.
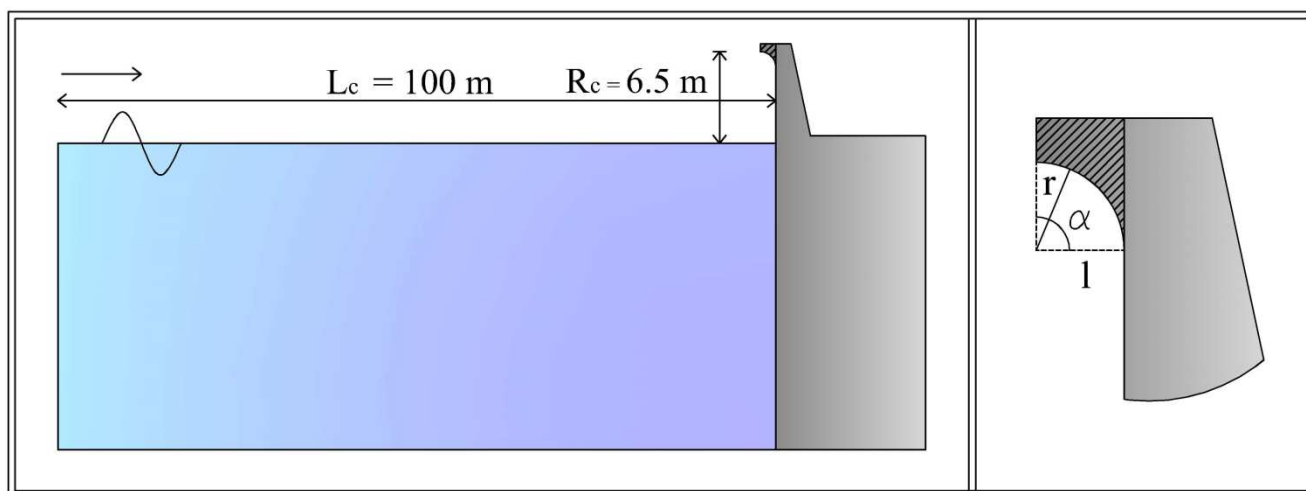

Fig. 2.   Geometrical configuration of the recurved parapet wall. On the left panel, the overall configuration is represented. On the right, panel the magnified recurve is considered. R_c, r, aa nd l represent the freeboard, radius, exit angle and overhang respectively.

2.2 The numerical simulations

As previously stated, the study has been conducted by means of numerical simulations, carried out with OpenFOAM®. The chosen solver is interFOAM, which solves the 3D RANS equations (shown in the equations 1 and 2) for a multiphase flow (air and water). Both the phases are considered incompressible. Furthermore, the solver IHFOAM (Higuera et al., 2013a; Higuera et al., 2013b) for the wave generation and absorption boundary condition has been used. These solvers have been validated and employed in the coastal engineering field. The 3D RANS equations, coupled to the VOF equation, reads as follows:

$$\frac{\partial u_i}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} - \frac{\partial}{\partial x_j}\left[\mu_{eff}\frac{\partial u_i}{\partial x_j}\right] = -\frac{\partial p^*}{\partial x_i} + F_{b,i} + F_{\sigma,i} \tag{2}$$

$$\frac{\partial \alpha}{\partial t} + \frac{\partial(\alpha u_j)}{\partial x_j} = 0 \tag{3}$$

where u represents the velocity, p the pressure and $F_{b,i}$ the viscose and turbulence stresses. $f_{s,i}$ is the surface tension.

The parametric simulations have been carried out in a numerical wave flume which is 100.0 m long and 40.0 m high, therefore prototype scale has been considered to avoid scale effects.The structure is placed at the East side of the numerical wave flume and the wave generation on the Westside. Furthermore, an active wave absorption condition (present in the solver IHFOAM) has been applied on the Westside. Regular waves have been reproduced to save computational time costs. Due to the non-breaking wave conditions, no trained or entrained air occurs during the development of the processes. This makes the incompressible conditions of the phases acceptable. The wave heights ranges between 5.0 and 7.0 m, while the wave periods vary, for each wave condition, between 8.0 and 14.0 s, always ensuring non-breaking wave conditions. All the wave conditions and the related parameters (wave height H, wave period T and wave steepness s) are shown in Tab. 1. For what concerns the wave steepness, it has been calculated considering the linear wave theory in deep water conditions.

Tab. 1.   Simulated regular non-breaking wave conditions.

Wave Conditions	H (m)	T (s)	s (-)
WH5_1	5.0	8.0	0.05
WH5_2	5.0	9.0	0.04
WH5_3	5.0	10.0	0.03
WH5_4	5.0	11.0	0.03
WH6_1	6.0	8.0	0.06
WH6_1	6.0	9.0	0.05
WH6_1	6.0	10.0	0.04
WH6_1	6.0	11.0	0.03
WH6_1	8.0	11.0	0.05
WH6_1	8.0	12.0	0.05
WH6_1	8.0	13.0	0.04
WH6_1	8.0	14.0	0.04

3 Dimensional analysis

In order to explore the influence of wave and geometrical parameters (with a particular focus on the wave period) on the phenomenon at hand (i.e. crest-confined impact) a dimensional analysis has been carried out. Any physical variable of a physical phenomenon can be expressed as a function of all the involved parameters. Concerning the study presented in this work, a general variable A can be expressed as:

$$A = f(r, \alpha, R_c, h, H, T, \rho_w, g, \mu) \tag{4}$$

where r_w is the water density, g the gravity acceleration and μ the water viscosity.

The vertical force component can be represented as the one induced by the water volume under the recurve, which is travelling upward with the velocity v, as reported in Fig. 3. Defining the vertical force component as:

$$F_R^v = m \times a \tag{5}$$

where $m = \rho_w \times l \times H$ and $a = \omega^2 \times H$ (w is the wave frequency), the horizontal force component can be identified as the sum of the force on the vertical (traditional) parapet and a part of the vertical force component on the recurved:

$$F_R^h = F_V + \alpha F_R^v = H \frac{\omega^2}{k^2} + \alpha l H^2 \omega^2 \tag{6}$$
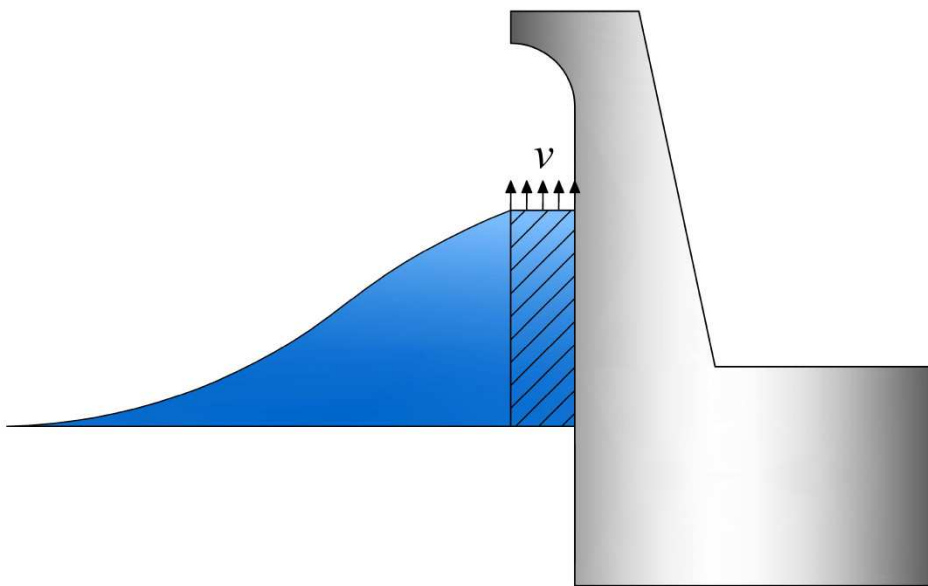

Fig. 3.   Schematization of the water column that causes the confined-crest impact after impinging the overhang of the wall. v represents the vertical velocity of the wave.

The force on the vertical parapet has been calculated starting from the definition of the dynamic pressure by means of the linear wave theory, that reads as follows:

$$p^+ = \rho g \frac{\cosh[k(h+z)]}{\cosh(kh)} 2a \cos(kx) \cos(\omega t) \tag{7}$$

where k is the wavenumber. After simple mathematical steps, the following relation has been obtained:

$$\frac{F_V}{\rho L} = H \frac{\omega^2}{k^2} \tag{8}$$

Finally, the total force on the recurved parapet can be expressed as:

$$F_R = lH^2\omega^2(1 + \alpha) + H\frac{\omega^2}{k^2} \qquad (9)$$

With reference to the Eq. 4, the non-dimensional product that can be taken into account for the non-dimensional total force acting on the recurved parapet are:

$$\frac{F_R}{F_V} = f\left(\frac{H}{L}, \frac{R_c}{H}, \frac{l}{gT^2}\right) \qquad (10)$$

4   Results and discussions

The numerical results are represented through the non-dimensional force F^*, which has been calculated as the ratio of the total force on the recurved parapet (as the one of Fig. 2) and the force acting on the traditional vertical parapet (with an exit angle $a = 0°$).

In Fig. 5 the non-dimensional force F^* is represented as a function of the dimensionless ratio R_c/H. Every group of points (starting from the right, circles, squares and diamonds), refers to a group of wave conditions characterized by fixed wave height and different wave periods.

The worst load increase is always induced by the wave with the maximum steepness. The circles refer to the group of waves with $H = 5.0$ m and $T = [8.0\ 11.0]$ s, squares refer instead to the group with $H = 6.0$ m and $T = [8.0\ 11.0]$ s. The last group (with the diamond marker), refers to the group characterized by a wave height $H = 7.0$ m and $T = [11.0\ 14.0]$ s.
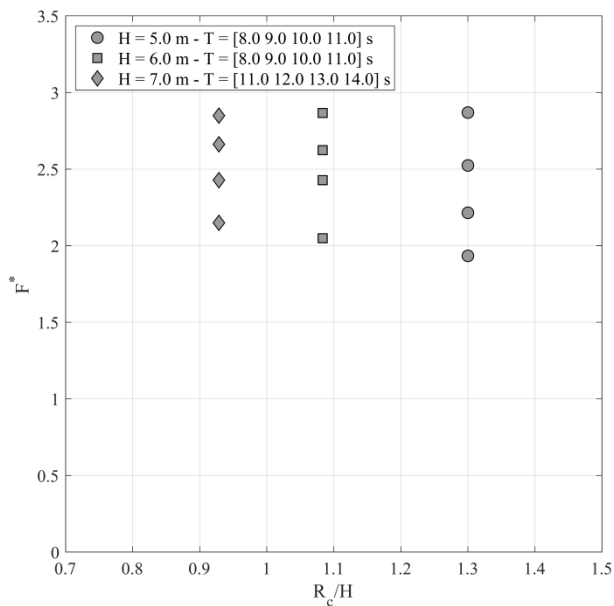

Fig. 4.   Representation of the dependence of the non-dimensional force F^* on the dimensionless product Rc/H. Circles refer to the conditions $H = 5.0$ m and $T = [8.0\ 11.0]$ s. Squares refers to $H = 6.0$ m and $T = [8.0\ 11.0]$ s and diamonds to $H = 7.0$ m and $T = [11.0\ 14.0]$ s.

The first row of the points, with the maximum force increase, refers to the wave conditions:
1. H = 5.0 m T = 8.0 s
2. H = 6.0 m T = 8.0 s
3. H = 7.0 m T = 11.0 s

while the last row of points refers to the conditions:
1. H = 5.0 m T = 11.0 s
2. H = 6.0 m T = 11.0 s
3. H = 7.0 m T = 14.0 s

Although a visible decrease of the force with the increase of the wave period appears. It is clear that the confined-crest impact is always present, giving a minimum increase of two times the force on the vertical parapet and a maximum increase equal to three times the force on a traditional vertical configuration.

Indirectly, the results of Fig. 4 suggest a strict dependence of the confined-crest impact on the wave period indeed, passing from a lower to a higher steepness value, it has been found an increase of the total force acting on the emerged part of the vertical breakwater. The influence of the wave steepness on the confined-crest impact is stressed by the results shown in Fig. 5, where the total force is represented as a function of the non-dimensional parameter *H/L*, where L is the wavelength (calculated with the linear theory) in deep water conditions. The plot refers to all the wave conditions reported in Tab. 1.
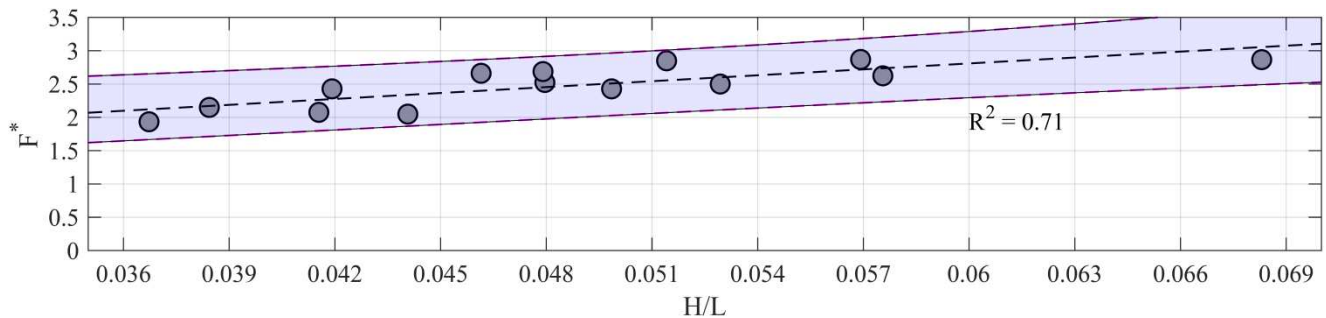

Fig. 5.   Representation of the non-dimensional total force on the recurved parapet *F** as a function of the wave steepness *H/L*.

In Fig. 5, the results have been also fitted by means of an interpolation line, together with the 95% confidence interval. The interpolation line is represented by the following equation:

$$\frac{F_R}{F_V} = 29.60\frac{H}{L} + 1.03 \tag{11}$$

which gives lower *F** values increasing the wave period.

5   Concluding remarks

The role of the wave period on the confined-crest impact (Castellino et al., 2018) has been studied by means of numerical simulations (OpenFOAM[®]). The structure studied is characterized by a recurved parapet and only non-breaking wave conditions has been taken into account.

The first step of the present work has been the dimensional analysis conducted to identify the most important non-dimensional products on which the confined-crest impact depends on.

Then, the results have been presented by means of the non-dimensional total force acting on the recurve ($F*=F_R/F_V$). The figures show the influence of the wave period on the load increase. Indeed a steeper wave induce an higher load. Nevertheless, the minimum force increase is two times the force obtained on a traditional vertical parapet in which the force is calculated by means of the empirilcal Goda's formulae.

A possible devolpment of the work, concern the study on how the confied-crest impact, associated with the standing wave that realize in front of the revurved vertical breakwater, can significantly increase the seabed pressure potentially triggering soil instability such as momentary liquefaction phenomenon (e.g. Celli et al., 2019)

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