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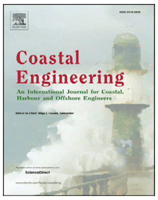

Large impulsive forces on recurved parapets under non-breaking waves. A numerical study

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ABSTRACT

This paper describes 2-D numerical simulations of velocity and pressure fields generated by non-breaking waves on a vertical breakwater with a recurved parapet wall. The influence of the geometrical characteristics of the parapet is investigated. An impulsive pressure force is identified and discussed with respect to the pure vertical wall case. This force is generated by the seaward flow confinement induced by the surging wave crest. We refer to this impulsive impact as "confined-crest impact".

A large part of the vertical wall is affected by an impulsive increase in pressure caused by pulsating wave, compared to the case where the parapet is completely vertical. The maximum values of the impulsive pressures are localized under the recurved parapet. The total force increase on the entire structure may be significant when compared to the pure vertical wall case.

1. Introduction and state of the art

Composite vertical breakwaters are a type of coastal structure often used in deep water conditions to protect harbours from incoming waves (typically non-breaking). In order to safely use the port-side of these breakwaters, it is crucial to limit wave overtopping. To this purpose, a high vertical crown parapet wall is a very efficient and economical design solution. To improve the hydraulic efficiency of the crownwall, the seaward side of the top profile may be shaped to form an overhang (*recurved parapet/wave return wall/bullnose*) aimed at further reducing wave overtopping by deflecting back seaward the uprushing water (Fig. 1 illustrates the parameters definition from EurOtop, 2016).

Curved parapets at breakwater crownwalls and quay walls have been efficiently used since the ancient Roman times (see Fig. 2).

An overhang or a curved parapet located in the upper part of a crownwall yields two effects: (i) reduces wave overtopping if compared to a pure vertical wall characterized by the same value of the crest freeboard R_c (see Fig. 1); (ii) generates a wave impact on the underside part of the overhang. This wave impact produces impulsive pressures acting both on the overhang and on the vertical wall.

These two effects have been largely considered by the technical and scientific literature, which however has mainly dealt with the use of curved parapets or overhangs for seawalls. Seawalls are characterized by shallow water conditions at the toe of the structure and therefore the incoming waves are generally broken or nearly breaking. In these conditions the wave impact contribution of the overhang is not easily detectable.

The aim of the present work is to analyze the wave impact on a recurved parapet of a vertical breakwater placed at a large water depth. Therefore, in these conditions the presence of broken or breaking waves can be excluded.

The scientific literature dealing with impulsive pressures and forces on vertical or inclined walls with or without recurved parapets or overhangs is very extensive.

A first review concerning wave impacts on bodies and coastal structures is provided by Ramkema (1978) who highlighted that the development of mathematical wave impact and slamming models was originated by Von Karman (1929) and Wagner (1932). They were interested in the impact of seaplane floats during landing and taking off. Ramkema (1978) developed the so-called Bagnold's piston model (Bagnold, 1939). The model was used to describe the wave impact caused by standing waves against protruding structural elements inserted in the

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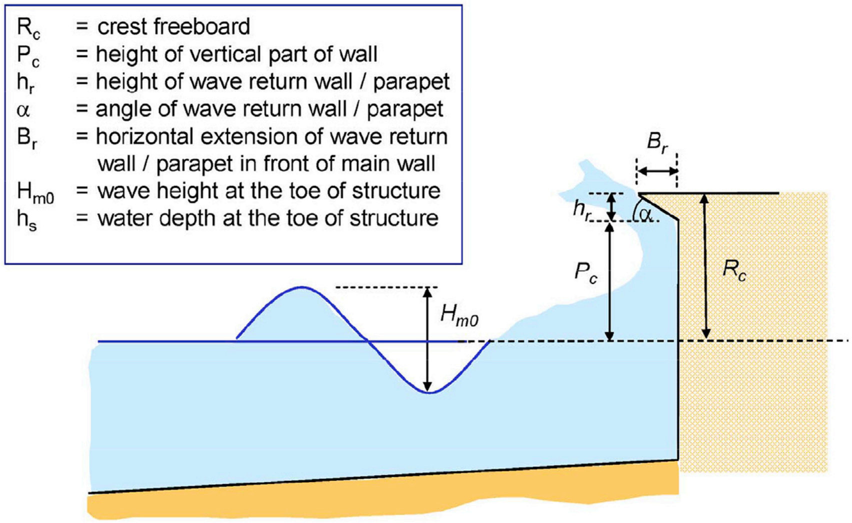

Fig. 1. Parameters definition for assessment of overtopping at structures with parapet/wave return wall (EurOtop, 2016).

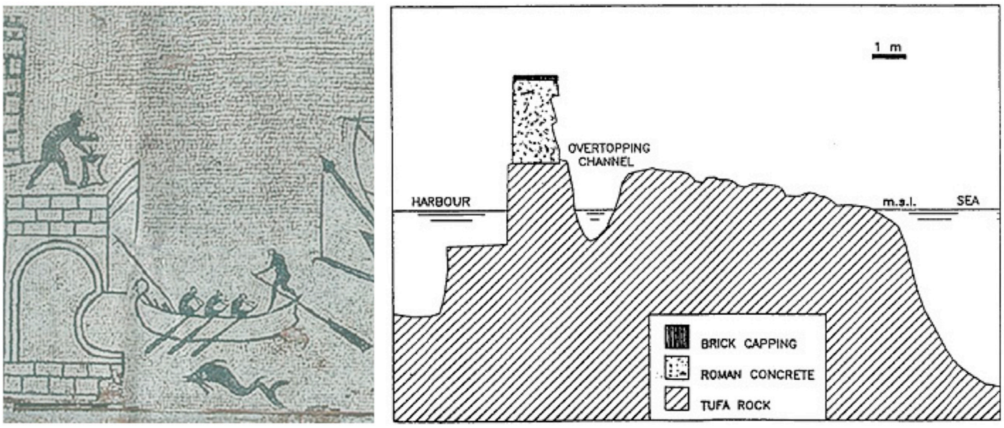

Fig. 2. Left panel: curved seawall in a Roman mosaic of 2^{nd} century AD in Rimini (Italy). Right panel: cross section of the rock carved breakwater of the Roman port of Ventotene built under Augustus on 14 BCE and still operational (from Franco, 1996).

caissons of the storm surge barrier of the Eastern Scheldt. In the geometry considered by Ramkema (1978) a layer of air between the protruding element and the water mass was present.

The basic concepts of wave impact beneath a horizontal surface are given by Wood and Peregrine (1999). They considered the wave impact on the underside of a projecting surface, e.g. a flat deck, close to the mean water level. The horizontal surface of finite length is confined on at one side by a vertical wall. Wood and Peregrine (1999) showed that the pressure-impulse (e.g. the integral of pressure over the duration of the impact) generated by the wave action under the horizontal surface affects also the vertical wall.

Most of research concerning pressures and forces have addressed the violent breaking wave impacts on vertical sea walls placed in shallow water, where breaking of wind waves is induced by bottom effects (Bagnold, 1939; Cooker and Peregrine, 1990, 1992; Peregrine, 2003). Hattori et al. (1994) observed that pressure waves generated by the wave impacts, propagate away from the impact zone at the speed of sound, i.e. as acoustic waves in the fluid. Other findings regarding the characteristics of violent breaking wave impacts may be found in the works of Wood et al. (2000), Bullock et al. (2007), Bredmose et al. (2009), Plumerault et al. (2012) and Bredmose et al. (2015). These works (see Bredmose et al., 2015, for a comprehensive state of art) deal with the strong sensitivity of the impact pressures on the wave shape and the oscillatory temporal pressure variations due to compression and expansion of trapped and entrained air. In these situations, compressibility effects need to be taken into account. The effect of air bubbles on the speed of sound in water is addressed by Gibson (1970) while the influence of salinity in the bubble size in water is studied by Scott (1975a, b). The importance of scale effects and aeration in simulating violent breaking impacts are considered by Blenkinsopp and Chaplin (2011) and Bredmose et al. (2015).

Recent applied research concerning breaking wave loads and their effects at vertical seawalls and at caisson breakwaters may be found in Cuomo et al. (2010a, b) and Elsafti and Oumeraci (2017). Chen (2011); Chen et al. (2015) and Van Doorslaer et al. (2017) considered the impact on stormwalls induced by overtopping flow.

An extensive review of curved seawall shapes can be found in Anand et al. (2010). Such curved shapes have been extensively used for onshore seawalls under breaking and broken wave attack.

One of the earliest studies on the application of curved crownwalls on composite vertical breakwaters was conducted by De Gerloni et al. (1989) for the deep water perforated caissons at Porto Torres, testing three different recurve shapes with excellent overtopping reduction. Even field measurements of pressures acting on the Porto Torres caissons (see Fig. 3) were then carried out by De Girolamo et al. (1996), but no large events were recorded in the limited measurement period. General formulations for overtopping reduction factors, as compared to the pure vertical wall, were then proposed by Franco et al. (1995), while recent effective applications were described by Di Risio et al. (2007, 2009) and Franco et al. (2013). A systematic investigation on chamfered parapets was conducted by Cornett et al. (1999). Early work for curved seawalls was reported by Owen and Steele (1993). An extreme Flaring Shaped