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Effects of submerged berms on the stability of conventional rubble mound breakwaters

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A R T I C L E I N F O

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A B S T R A C T

Berms deployed at the toe of conventional breakwaters may be needed to reduce bottom settlements and to limit scour in front of the structure due to coastal currents. In the mean time, they may be effective in increasing the stability of the armor layer and also in minimizing the wave overtopping discharge compared to straight sloped conventional breakwaters without a berm. This research aims to provide a new design criterion for the armor layer of conventional breakwaters with submerged berms marked by small thickness compared to water depth. Indeed, past researches focused on the influence of relatively high berms on the stability of the armor layer. The design of the berm itself is not tackled herein. The effects of submerged berms on the incident waves transformation have been evaluated by means of a numerical model, validated by using experimental data. Then, a parametric correction factor of the incident significant wave height at the toe of the structure is provided and included in well established design criteria. The experimental comparison confirms the reliability of the proposed method by highlighting the importance to use design criteria within their validity ranges, in order to avoid an unsafe dimensioning of the armor elements.

1. Introduction

The main function of conventional rubble mound breakwaters is to provide protection for coastal areas (e.g. Lamberti et al., 2005; Di Risio et al., 2010) and harbors (e.g Van Der Meer, 1988) from wave action. Usually, in front of these breakwaters, scour protection and armor layer support are obtained by using a structure toe (e.g. van Gent and van der Werf, 2014), in particular when the armor layer is made up of concrete units or when it is necessary to protect the toe of conventional rubble mound breakwater from wave breaking (i.e. when the water depth over the toe is low). Often, the toes are rather short (e.g. CIRIA/CUR/CETMEF, 2007). Nevertheless, it could be necessary to extend the toe (e.g. Herrera et al., 2016), in order to limit the scour related to coastal currents and storm surge (e.g. Pasquali et al., 2015), then by increasing the stability of the rock in armor layer, or to solve geotechnical issues related to the foundation settlements due to poor mechanical characteristics of the bottom soil (e.g. Pasquali et al., 2014). In such cases, it may be appropriate to modify the straight slopes of conventional breakwaters, by deploying a submerged berm marked by higher length than usual. The presence of submerged berms could be valuable even in reducing wave overtopping, at least for relative high berms, i.e. when the water depth on the berm is small enough and the berm is wide enough to induce a significant wave height decrease (e.g. see Fig. 1 of van Gent, 2013). Nevertheless, it should be underlined that the research described herein is not aimed to describe the role of submerged berms on the wave overtopping.

Many empirical methods for the design of the armor unit size, required for the stability of conventional rubble mound breakwaters, are available in literature (e.g. Iribarren, 1938, 1965; Hudson, 1959; Van der Meer, 1987; Van Der Meer, 1988; Melby and Kobayashi, 1998; Van Gent et al., 2004; Herrera et al., 2017). An in depth literature review is out of the scope of the present paper, then the readers are referred to the useful literature review of Herrera et al. (2017). Since the loads due to the incident water wave action are reduced in presence of a berm with low water depths (e.g. Van Der Meer, 2011), the use of previous methods may lead to an overestimation of the rock size required for the stability. Then, it is necessary to refer to ad-hoc methods that take into account the influence of submerged berms upon the stability of the armor of

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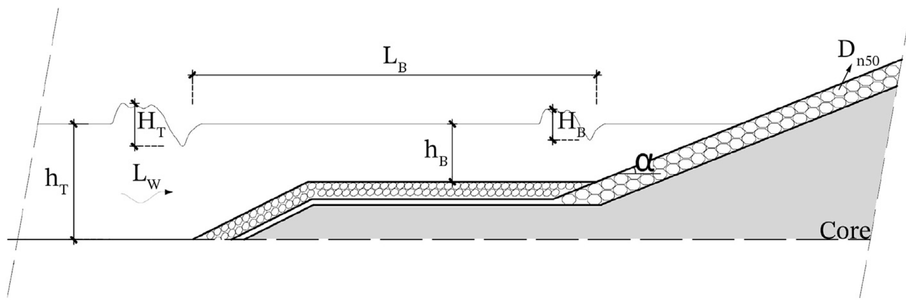

Fig. 1. Geometric parameters definition of conventional rubble mound breakwaters with a berm. The core runs below the berm only for considerable values of berm height.

conventional breakwaters.

Recently, van Gent (2013) provided empirical relationships aimed to evaluate correction factors to be applied to existing design criterion (Van Gent et al., 2004) in order to consider the berm influence on the armor stability. Nevertheless, the experimental range investigated by van Gent (2013) is limited to rather high berms, i.e. characterized by small values of water depth over the berm compared with the water depth at the toe. For submerged berm marked by small thickness compared to water depth, the use of previous methods may lead to underestimations of the rock size of the armor layer.

This research aims to provide a design criterion for the armor layer elements of conventional breakwater with submerged berm, extending the validity range of the method suggested by van Gent (2013). The proposed method herein is based on the use of numerical and experimental tools and on a rationale aimed to continue using well established stability formulas, properly modified to be employed as a reliable design criterion when a submerged berm is foreseen. It has to be stressed that the stability of the berm itself is not tackled herein.

The paper is structured as follows. Section 2 describes the methodology of the research. Then, sections 3 and 4 illustrate the experimental and numerical investigations respectively. Section 5 details and discusses the proposed design criterion. Concluding remarks close the paper.

2. Methodology

The aim of this paper is to propose a new stability formula to be used when relative low berms are foreseen at the toe of conventional rubble mound breakwaters.

The strategy is to include the physical phenomena occurring when incident waves propagate on the berm, thus affecting the wave loads on the upper slope armor, into well established design criteria (e.g. Van der Meer, 1987; Van Der Meer, 1988). As an example, the same methodology has been adopted by van Gent (2013), that proposed to apply two coefficients to the formulation of Van Gent et al. (2004), in order to take into account the role of relative high berms upon the damage suffered by the upper slope of conventional rubble mound breakwaters.

As far as deep water conditions are concerned, the formulations proposed by Van der Meer (1987) may be employed. They read as follows:

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_p}\xi_m^{0.5}\frac{H_s^T}{\Delta D_{n50}}P^{-0.18}\right)^5 \quad \text{if } (\xi_m \le \xi_c) \tag{1a}$$

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_s}\xi_m^{-P}\sqrt{\cot\alpha}\ \frac{H_s^T}{\Delta D_{n50}}P^{0.13}\right)^5 \quad \text{if } (\xi_m > \xi_c) \tag{1b}$$

Equations (1a) and (1b) are valid for plunging waves ($\xi_m \le \xi_c$) and surging waves ($\xi_m > \xi_c$) respectively. Indeed, ξ_m is the value of surf parameter (e.g. Battjes, 1974) of the incident waves ($= \tan\alpha/\sqrt{2\pi H/g/T^2}$) estimated by using significant wave height ($H = H_s$), wave length computed on the basis of the mean wave period ($T = T_m$) and the slope of the breakwater armor (α). The critical value ξ_c affects the breaking characteristics on the armor:

$$\xi_c = \left[\frac{c_p}{c_s}P^{0.31}\sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}}. \tag{2}$$

Equations (1) provide the damage parameter (S_d, e.g. CIRIA/CUR/CETMEF, 2007) as a function of the number of individual incident waves (N_w), of the surf parameter of the incident waves (ξ_m), of the stability number ($N_s = H_s^T/\Delta D_{n50}$, being H_s^T the significant wave height at the toe of the armor, Δ the relative density evaluated as $\rho_s/\rho_w - 1$, with ρ_s and ρ_w the bulk density of armor elements and water density respectively, and D_{n50} the mean dimension of the armor elements), of the slope of the armor (α), of the permeability factor (P, e.g. Van der Meer, 1987) and of an empirical coefficient (either $c_p = 6.2$ or $c_s = 1.0$ for plunging and surging waves respectively).

In shallow water, the distribution of individual wave heights may significantly deviate from theoretical Rayleigh distribution and lower wave heights are likely to occur (Battjes and Groenendijk, 2000; Goda, 2010). Therefore, if the same offshore conditions are considered, the stability will increase (e.g. Van Der Meer, 2011; van Gent, 2013), i.e. the wave load will decrease. Then, Van Der Meer (1988) suggested to use the 2% exceedance individual wave height ($H_{2\%}$) instead of the significant wave height in equations (1):

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_p^*}\xi_m^{0.5}\frac{H_{2\%}^T}{\Delta D_{n50}}P^{-0.18}\right)^5 \quad \text{if } (\xi_m \le \xi_c) \tag{3a}$$

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_s^*}\xi_m^{-P}\sqrt{\cot\alpha}\ \frac{H_{2\%}^T}{\Delta D_{n50}}P^{0.13}\right)^5 \quad \text{if } (\xi_m > \xi_c) \tag{3b}$$

where, again, the suffix 'T' indicates that the 2% exceedance individual wave height has to be computed at the toe of the breakwater and the empirical parameters c_p^* and c_s^* are equal to 8.7 and 1.4 respectively. It should be noted that equations (3) have been further modified by Van Gent et al. (2004) by slightly changing the parameters c_p^* and c_s^* (to 8.4 and 1.3 respectively) and by making use of surf parameter $\xi_{m-1,0}$ defined on the basis of spectral period $T_{m-1,0}$.

It has to be stressed that the use of equations (3) requires the knowledge of $H_{2\%}$, in general difficult to estimate. In the practice, it is usual to make use of spectral wave propagation models (e.g. CIRIA/CUR/CETMEF, 2007) to estimate the significant wave height (H_s^T) at the toe of the breakwater. Then, equations (3) read:

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_p^*}\xi_m^{0.5}\frac{H_s^T}{\Delta D_{n50}}P^{-0.18}\frac{H_{2\%}^T}{H_s^T}\right)^5 \quad \text{if } (\xi_m \le \xi_c) \tag{4a}$$

$$\frac{S_d}{\sqrt{N_w}} = \left(\frac{1}{c_s^*}\xi_m^{-P}\sqrt{\cot\alpha}\ \frac{H_s^T}{\Delta D_{n50}}P^{0.13}\frac{H_{2\%}^T}{H_s^T}\right)^5 \quad \text{if } (\xi_m > \xi_c) \tag{4b}$$

where the dependence of damage parameter S_d on the individual waves height probability distribution is expressed by the ratio of the 2% exceedance wave height to the significant wave height (i.e. $H_{2\%}^T/H_s^T$). It has to be stressed that in deep water, equations (4) are equivalent to