ASSESMENT OF WAVE OVERTOPPING ON REEF-FRONTED SHORES

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INTRODUCTION

Overtopping has been widely studied to design coastal structures, and it is also an important parameter for coastal management in order to evaluate the protection by natural coastal systems against inundation. Most formulations for open coasts have estimated overtopping using the wave runup ($R_{2\%}$), the beach slope (β) and the truncated point (Z_c), with empirical coefficients to account for further details (e.g. EurOtop, 2018). However, for beaches that are naturally protected by fringing reefs, the knowledge of overtopping is limited, and reliable analytical formulations have not been developed. The aim of this research is to evaluate the previous overtopping model and scaling laws and suggest one model applicable to reef-fronted shores.

METHODS AND LITERATURE REVIEW

A set of 144 overtopping experiments were run using regular and random waves, using the idealised fringing reef profile adopted by Gourlay (1996). The basic profile consisted of an offshore area, the forereef, reef flat, and beach face, Figure 1. The physical modeling was performed with 9 different wave conditions, 2 reef flat widths (2.75 m and 4.835 m), 2 water levels above the reef flat (0.031 and 0.062m) and 4 different values of Z_c (0.028 m, 0.075 m, 0.106 m and 0.137 m) with a 1:5 slope. An overtopping box with a water level gauge was used to collect and measure the volume of water that overflowed the truncation point Z_c.

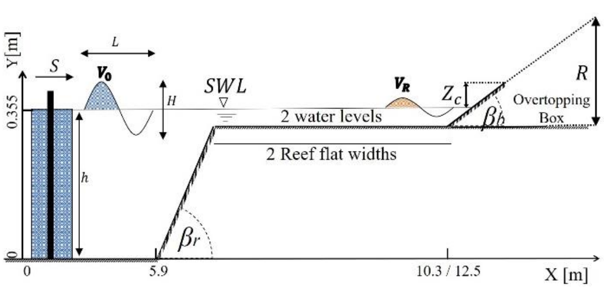

Figure 1 - Definitions and experimental reef profile

The overtopping volume (V^*) can be approximated by scaling the volume flux per unit width. In the laboratory, this scales with the volume flux and the deficit in freeboard $(R_{2\%} - Z_c)/R_{2\%}$ (Baldock et al., 2012). $V_0 = Sh$, which is equivalent to the water displaced by a piston with stroke S (Fig. 1). There are two approaches to relate the wave height and length to the volume flux. The first method can be approximated following Galvin (1964), in which the crest volume of the propagated wave is obtained by integrating the volume under a wave crest. The second approximation to V_0 can be found by integrating the instantaneous volume flux (Eq. 1), as proposed by Svendsen (1984), over the half of the wave period for positive velocities ($u > 0$).

$$\int_{-h}^{\eta} u dz = C\eta \quad (1)$$

$$V_0 = \int_{-T/4}^{T/4} C\eta dx = \frac{HL}{2\pi} \quad (2)$$

Therefore, the relationship between the wavemaker motion and the volume flux can be written as:

$$Sh = \frac{HL}{2\pi} \quad (3)$$

Ibrahim and Baldock (2020) showed that most of the expressions for overtopping can be written in terms of V_0, a scaling factor $f(Z_c/R_{2\%})$, the beach slope and an empirical coefficient m.

$$V^* = mV_0 \tan\beta^{\alpha} f\left(\frac{Z_c}{R_{2\%}}\right) \quad (4)$$

α is the coefficient of the beach slope and can take the value of 1 or 0.5, depending on the model.

For the EurOtop (2018) model, the general expression (q) can be multiplied by the wave period to obtain $V^* = qT_0$, as shown in Ibrahim and Baldock (2020). The final expression can be written as Eq. 5 in which the scaling factor $f(Z_c/R_{2\%})$ is very similar to that given by Eq. 6.

$$V^* = 0.36\, V_0\sqrt{\tan\beta}\, \exp\left(-\left(2.7\frac{Z_c}{R_{2\%}}\right)^{1.3}\right) \quad (5)$$

Battjes (1974) model can be rewritten as Eq. 7. For this expression the $f(Z_c/R_{2\%})$

$$f\left(\frac{Z_c}{R_{2\%}}\right) = \left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (6)$$

yielding the expression:

$$V^* = \frac{2\pi}{10} V_0\sqrt{\tan\beta}\left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (7)$$

Ibrahim and Baldock (2021) presented a couple of models in which the major difference is the exponent of the slope, which is compensated by the empirical coefficient m.

$$V^* = 0.17\, V_0 \sqrt{\tan\beta} \left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (8)$$

$$V^* = 0.50\, V_0 \tan\beta \left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (9)$$

The Peregrine and Williams (2001) formulation for monochromatic waves can be expressed as Equation 10. For this model, the scaling function $V(E)$ is a non-dimensional volume which depends $E = 2Z_c/R$.

$$V^* = \frac{\pi}{2} V_0 \tan\beta\, V(E) \quad (10)$$

Where $V(E) = 1/27\left(4 - 12E + 8E\sqrt{2E} - 3E^2\right)$.

The scaling using the volume flux and deficit in freeboard works for open sandy shores or plane beaches. However, it is expected to differ with reef-fronted beaches. In these natural protected shorelines, the reef crest and the reef flat promote wave dissipation, leading to different wave and water level conditions at the beach toe. However, Astorga-Moar and Baldock (2022) showed that runup on reef-fronted beaches still scales according to the classical Hunt (1959) model when using wave and water level conditions at the beach toe. In this work, we propose that the overtopping scaling laws for open beaches will still hold, providing the new volume flux V_R at the beach toe is used, together with the appropriate deficit in freeboard.

$$V^* = m V_R \tan\beta^{\alpha} f\left(\frac{Z_c}{R_{2\%}}\right) \quad (11)$$

RESULTS

Random wave conditions were extracted at the beach toe, which includes the setup over the reef flat as the new vertical datum. These nearshore conditions were then applied to the EurOtop (2018) scaling factor (Equation 2). Figure 2 shows the relationship between this scale and the non-dimensional mean overtopping discharge, which gives a linear regression goodness-fit (R^2) value of 0.80. Some differences still occur for different wave periods. Overtopping showed an increase with period and wave height but a reduction with greater reef width, as expected (Figure 2).

Following the scale of Ibrahim and Baldock (2020), two empirical coefficients were obtained using the structure of Equation 11. The results are given in Figure 3 as the non-dimensional overtopping volume ($V^*/V_R \tan\beta$). As expected, the ratio increases with the deficit of freeboard. However, for larger waves the non-dimensional overtopping is reduced. The results show scatter above the linear fit, this corresponds to cases in which the wave did not dissipate enough energy to induce the wave setup, allowing larger momentum over the beach. The resulting scaling factors were $m_1 = 0.22$ for $\tan\beta$ and $m_2 = 0.10$ for $\sqrt{\tan\beta}$, Therefore, Equation 10 can be rewritten as;

$$V^* = 0.10\, V_R \tan\beta \left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (12)$$

$$V^* = 0.22\, V_R \sqrt{\tan\beta} \left[\frac{R_{2\%} - Z_c}{R_{2\%}}\right]^2 \quad (13)$$

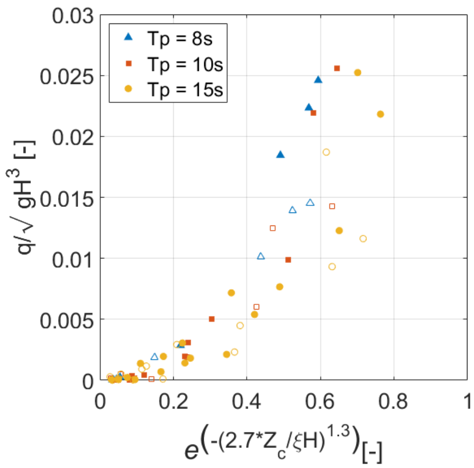

Figure 2 - Non-dimensional mean overtopping discharge variation using the EurOtop formulation and beach toe wave conditions. The filled marks correspond to the cases from the short reef width and the open marks to the long reef width cases.

The empirical coefficients are smaller than those obtained by Ibrahim and Baldock (2020) for random waves (0.17 and 0.50, respectively). The differences might be related to the transfer of momentum of the waves to the setup over the reef flat due the wave dissipation, resulting in a reduction of the momentum flux behind breaking waves.

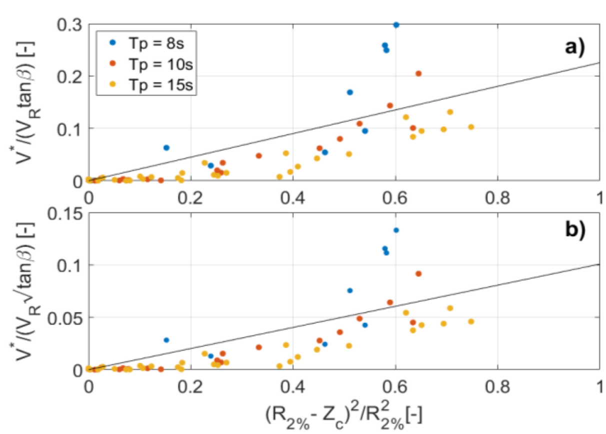

Figure 3 - Non-dimensional overtopping volume scaled by the volume flux and the slope versus the deficit of freeboard. In both subplots the solid lines are the resulting empirical coefficients m_1 in a) and m_2 in b) with $R^2 = 61.4\%$ for both parameters.

The shorter period waves do not scale so well with this scaling, again perhaps due to greater loss of momentum across the reef flat.

Figure 4 shows the comparison of the models developed for random waves. The runup applied in $f(Z_c/R_{2\%})$ was calculated as $R_{2\%} = 1.09\xi H_s$, which is based on the parametrization for reef protected shores developed by Astorga-Moar and Baldock (2022). As expected, EurOtop (2018) and Ibrahim and Baldock (2020) are overpredicting V^*, whereas the Peregrine and Williams (2001) analytical model clearly underestimates the swash overtopping volume, consistent with Baldock et al., (2005) observations.

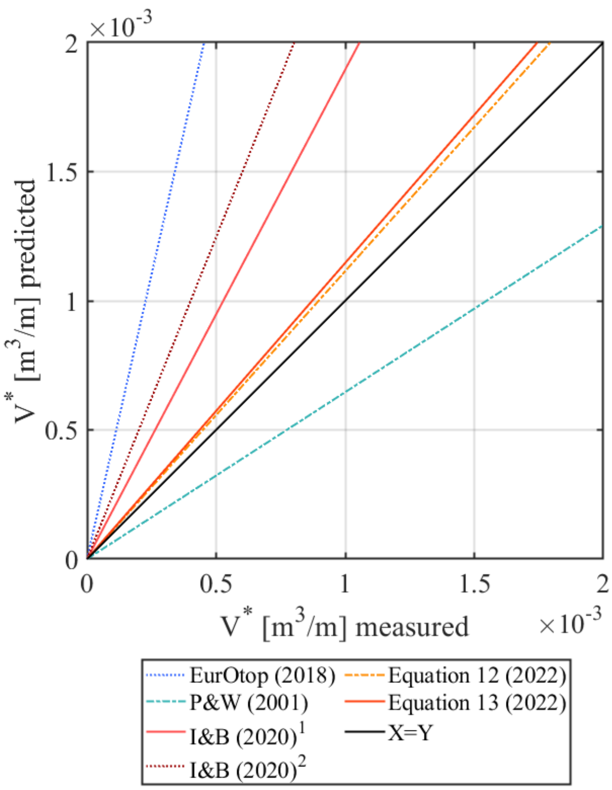

Figure 4 - Linear fit of the overtopping volumes obtained with the physical experiments compared with previous models. P&W (2001) is Peregrine and Williams (2001) and I&B (2020) are Ibrahim and Baldock (2020) models.

Hence, the present results suggest the conventional overtopping expressions remain valid for reef-fronted beaches provided that the wave and water level conditions at the beach toe are adopted. This will enable rapid assessment of overtopping of natural systems using results from wave transformation models applied across fringing reefs to the beach toe.

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