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WAVE OVERTOPPING OF ROCK AND STEPPED COASTAL REVETMENTS WITH VERY SHALLOW FORESHORES

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ABSTRACT

Coastal revetments are commonly constructed at the land-sea boundary to control shoreline retreat and protect infrastructure from coastal hazards, such as wave overtopping and coastal flooding. An innovative approach to enhance existing rock revetments involves incorporating steps, which can improve coastal amenities by providing seating and viewing areas. However, current empirical wave overtopping formulations do not consider hybrid configurations combining rock and stepped elements.

This study investigates overtopping performance for both conventional and hybrid rock revetment solutions. To address the lack of empirical data for such hybrid structures - commonly found along the Portuguese coast - physical modelling tests have been conducted with two revetment cross-sections: (i) a conventional double layer rock armour slope and (ii) a hybrid one where the upper layer of rock was replaced with concrete steps. Existing semi-empirical formulations provided in the EurOtop Manual were compared with measured values of the relative mean wave overtopping discharge. Results showed that semi-empirical formulations underpredict the relative mean wave overtopping discharge values by up to a factor of 33 for rock-only revetments and up to 23 for hybrid rock and stepped revetments.

Keywords: *Physical modelling; Hybrid solutions; Stepped revetments, Overtopping*

1. Introduction

Coastal revetments are a durable and effective solution for protecting infrastructures located at the sea-land interface. These coastal defence structures can dissipate or partially reflect incident wave energy, further sustaining shoreline retreat. Minimizing wave overtopping hazard is essential for the design, management, and adaptation of these structures, especially when existing infrastructure is assessed for future resilience. Additionally, protective measures and early-warnings are crucial to safeguard individuals from overtopping waves on coastal revetments and promenades.

Currently available empirical equations to calculate the mean wave overtopping discharge of coastal defence structures are presented in the EurOtop Manual 2018 (Pullen *et al*., 2018). The foreshore – the sloping bottom seaward the structure toe – starts to have an effect on the wave overtopping when the still water depth at the structure toe is less than about two times the significant wave height at the toe. In this case, depth-induced breaking can occur. Under heavy breaking conditions, the spectral mean wave energy period ($T_{m-1,0}$) at the toe can increase up to eight times its offshore value (Pullen *et al*., 2018). This increase is mainly associated with the prominence of infragravity waves (e.g. Lashley et al., 2020). Moreover, and following EurOtop, the ratio between the still water depth at the structure toe and the offshore incident wave height ($d_{TOE}/H_{m0,DEEP}$) is used to classify foreshores. These are classified as *shallow* when $1 < d_{TOE}/H_{m0,DEEP} < 4$ and as *very shallow* when $0.3 < d_{TOE}/H_{m0,DEEP} < 1$. Specifically for these situations, EurOtop 2018 provides the following *mean value approach* formula for the mean wave overtopping discharge per unit width (q) over impermeable structures:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 10^{-0.79}\exp\left[-\frac{R_c}{\gamma_f\gamma_\beta H_{m0}(0.33+0.022\xi_{m-1,0})}\right] \quad (1)$$

where g is the acceleration due to gravity, H_{m0} is the spectral significant wave height at the toe of the structure, R_c is the crest freeboard of the structure, γ_f is the roughness influence factor, γ_β is the influence factor for oblique wave attack. The EurOtop 2018 tabulates values of γ_f for permeable and impermeable rubble mound structures with slope of 1:1.5, for breaker parameters, $\xi_{m-1,0}$, in the range 2.8 to 4.5 (with $\xi_{m-1,0} = tan\,\alpha\,/\sqrt{H_{mo}/L_{m-1,0}}$, α the angle between the structure slope and the horizontal and $L_{m-1,0} = gT_{m-1,0}^2/2\pi$ the spectral wave length in deep water obtained using the spectral mean wave period, $T_{m-1,0}$, at the toe.

Regarding the structure slope in Eq. (1), which is incorporated in the breaker parameter, Altomare *et al.* (2016) have shown that an equivalent slope reduces the scatter between predicted and measured wave overtopping discharges. Unlike the structure slope, that was previously used by van Gent (1999), the equivalent slope considers both the foreshore slope and the structure slope.

The data used by Altomare *et al*. (2016) included smooth coastal revetments with cot(α) between 2 and 6 and with foreshore cot(θ) between 35 and 50. Van Gent (1999) used data with smooth coastal revetments but with cot(α) between 2.5 and 4 and with foreshore cot(θ) between 100 and 250. Moreover, Eq. (1) includes the γ_f parameter despite the previous datasets only included smooth slopes. Therefore, Eq. (1) has not been previously tested on coastal revetments composed by rocks and with a foreshore cot(θ) of 20. This constitutes a typical case of many coastal revetments located along the western coast of mainland Portugal. Additionally, the use of a hybrid coastal revetment where the upper part is composed by steps has not been addressed in the available literature. The later constitutes an important research gap since stepped revetments can improve coastal amenities, by providing seating and viewing areas.

This paper presents a comprehensive comparison of mean wave overtopping discharges obtained from two-dimensional (2D) physical model tests of two coastal revetment cross-sections: i) a revetment consisting of a double rock layer armour slope, and ii) a hybrid revetment, where the double rock layer was removed from the upper section of the structure and replaced with concrete steps.

2. Wave Overtopping

Wave overtopping occurs when the maximum wave run-up surpasses the crest elevation of coastal defence structures, allowing water to flow onto the landward side. This phenomenon can challenge the effectiveness of these structures and cause injury to people and damage to infrastructure, particularly in areas exposed to extreme wave conditions or rising sea levels. The reduction of overtopping impact can be achieved through careful design, maintenance, and implementation of protective measures, enhancing safety in vulnerable regions (EurOtop, 2007). The quantification of wave overtopping is typically expressed as the average discharge per linear meter of width, q, which is measured in either m^3/s or l/s per meter (EurOtop, 2018).

According to the EurOtop classification system, the foreshore is classified through the ratio $d_{TOE}/H_{m0,DEEP}$, where d_{TOE} is the still water depth at the structure toe and $H_{m0,DEEP}$ is the offshore incident wave height. If $d_{TOE}/H_{m0,DEEP} > 4$, the foreshore is classified as deep. A ratio of $1 < d_{TOE}/H_{m0,DEEP} < 4$ indicates a shallow foreshore, $0.3 < d_{TOE}/H_{m0,DEEP} < 1$ defines a very shallow foreshore, and $d_{TOE}/H_{m0,DEEP} < 0.3$ corresponds to an extremely shallow foreshore.

For very shallow foreshores, the EurOtop 2018 equation (Eq. 1) provides a mean value approach to estimating q, considering the equivalent slope in the breaker parameter (Fig. 1).

Altomare et al. (2016), defined it similarly to the average slope reported in EurOtop (2007), thus enabling evaluation of the effect of composite slopes on wave overtopping discharges. The principal distinction is the extent of the average slope, which includes very gentle, long, and shallow foreshores. However, the wave heights and periods are calculated at the toe of the structure. Consequently, the equivalent slope considers both the foreshore (tan (β)) and the structure slope (tan(α)).

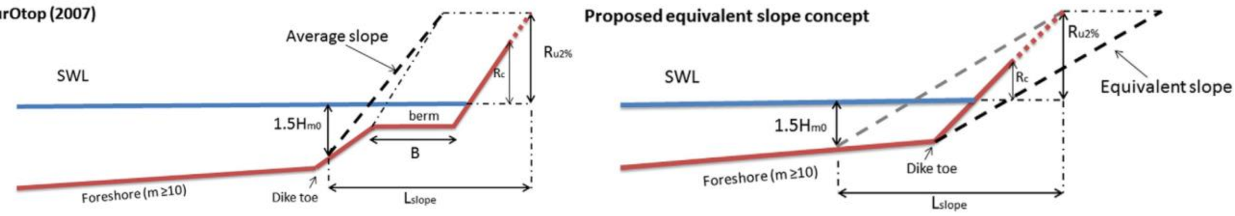

Fig. 1. Parameter definition to calculate the equivalent slope and comparison with scheme of the average slope. Source: EurOtop, 2007.

The iterative nature of the calculation ensures convergence of wave run-up estimates ($R_{u2\%}$), where the final equivalent slope ($\tan(\delta)$) is applied once successive $R_{u2\%}$ values stabilize within a 1% margin.

Initially, $R_{u2\%}$ is computed using $R_{u2\%}=1.5H_{m0}$. It is then recalculated using Eq. (2), incorporating $\xi_{m-1,0}$, Eq. (3), with the updated $\tan(\delta)$, Eq.(4). In this step, L_{slope}, an adjusted wavelength, accounts for both the structure slope ($\tan(\alpha)$) and the foreshore slope ($\tan(\beta)$), as well as the water depth at run-up, Eq. (5).

$$R_{u2\%} = \left(4.0 - \frac{1.5}{\sqrt{\xi_{m-1,0}}}\right)\gamma_b H_{m0} \quad (2)$$

$$\xi_{m-1,0} = \frac{\tan\delta}{\sqrt{\frac{2\pi H_{mo}}{gT_{m-1,0}^2}}} \quad (3)$$

$$tan\delta = \frac{1.5H_{mo}+R_{u2\%}}{L_{slope}} \quad (4)$$

$$L_{slope} = \frac{R_{u2\%}+d_{toe}}{tan\alpha} + \frac{1.5H_{m0}-d_{toe}}{tan\beta} \quad (5)$$

3. Stepped Revetments

Geometry and hydraulic parameters for step shapes

Stepped revetments address modern coastal protection needs by enhancing surface roughness, allowing for precise, efficient, and aesthetically engaging construction. The use of prefabricated components ensures accurate definition and repeatability of geometries, step shapes, and the hydraulic parameters governing wave interaction, thereby enhancing both performance and constructability (Kerpen et al., 2016), as illustrated in Fig. 2.

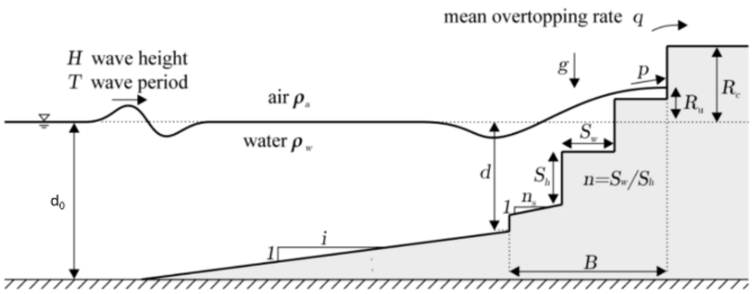

Fig. 2. Definition of geometry and hydraulic parameters related to stepped revetments. Source: Kerpen et al. (2016)

The offshore region is characterized by a deep-water depth, d_0, while within the zone of the structure, B denotes the revetment width, i the shoreface slope, n the revetment slope, and n_s the slope of a single step. Additionally, p indicates the pressure load, and S_h and S_w represent the step height and step width, respectively, as illustrated in Fig. 2 (Kerpen et al., 2016).

Scientific investigations on stepped revetments

Stepped revetments have been studied extensively since the 1950s, with research focusing on their surface roughness and ability to reduce wave overtopping and energy dissipation. Early studies by Saville (1955–1957) analyzed wave run-up and overtopping, showing that wave height, period, and slope influence these processes. Suzuki (2003) conducted flume experiments on gently sloped seawalls, demonstrating that stepped seawalls reduce overtopping more effectively than smooth ones.

Kerpen et al. (2016) provided a comprehensive review of stepped revetments studies, emphasizing key factors such as wave run-up, overtopping, and wave loads. His research indicated that slope, shoreface presence, and wave steepness are crucial for reducing overtopping, while step geometry has a lesser impact. Schoonees et al. (2018) conducted physical model tests, finding that a stepped revetment with a 1:6 slope and 0.05 m steps significantly reduced wave overtopping.

Van Steeg et al. (2018) studied roughness coefficients of stepped revetments using physical model experiments and developed empirical equations linking step height and wave height to overtopping reduction. Kerpen et al. (2019) extended previous studies, proposing a new empirical model for predicting wave overtopping under different wave conditions, confirming that stepped structures dissipate wave energy effectively.

Schoonees et al. (2021) conducted full-scale flume experiments, showing that larger steps (0.50 m) reduced overtopping more than smaller ones (0.17 m). The study refined previous roughness factor estimates, highlighting that SR effectiveness depends on wave steepness, step height, and wave period.

Overall, research confirms that stepped revetments reduce wave overtopping more effectively than smooth slopes, with larger step heights and gentler slopes improving performance. However, under extreme wave conditions, their effectiveness may be limited due to increased wave energy exceeding the designed overtopping thresholds, potential for structural damage, and reduced dissipative capacity of the steps under highly turbulent and forceful wave impacts.

4. Physical Modelling Experiments

4.1. Model Setup

The experiments were developed at the National Laboratory for Civil Engineering (LNEC) at the Ports and Maritime Structures Unit (NPE) of the Hydraulics and Environment Department. The wave flume (COI 1) is approximately 50 m long, with an operating width of 0.80 m and an operating water depth of 0.80 m. The flume is equipped with a piston-type wave-maker, capable of generating irregular waves using 1st order wave theory and of effectively minimizing re-reflected waves due to an active wave absorption system (AWASYS). The AWASYS uses two wave gauges (AWA1 and AWA2) located in front of the paddle (Fig. 3).

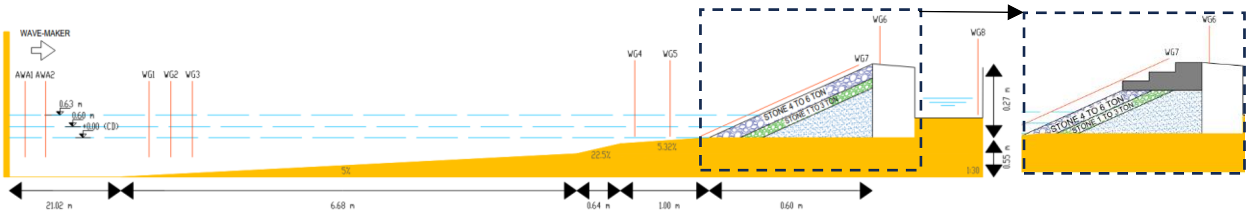

Fig. 3. Sketch of the experimental setup in the wave flume (dimensions for a 1:30 scale and for the tested water levels): left: two-layer rock armour slope revetment, right: modified revetment.

Two structures were tested (see Fig. 3 and Fig. 4): i) a typical rock coastal revetment with a slope of 1:2.2, a trapezoidal core covered by two rock layers and a rock nominal diameter, D_n, between 0.023 m to 0.069 m for the filter and 0.093 m to 0.139 m for the armour (model scale); ii) a hybrid coastal revetment, where the two-layer rock filter was removed from the upper section of the structure and replaced with concrete steps. As hydraulic stability was beyond the scope of this study, a thin layer of mortar (i.e. a mixture of water and cement) was applied on the rock armour of both cross-sections to prevent damage.

The models were built and operated according to Froude's similarity law, with a geometrical scale of 1:30 to ensure reduced scale effects. Seven resistive-type wave gauges were deployed along the flume and an extra gauge was placed on the model armor layer slope to measure wave run-up (Fig. 3), with a sampling frequency of 128 Hz.

The equipment used to collect the overtopping water consisted of a tank located at the back of the structure. The water was directed to the tank via a chute that was 0.40 m wide. A wave gauge was positioned in the tank to measure the water level and water volume (Fig. 3). In addition, the overtopping water was transferred to a graduated container outside the flume using a pump, where it was then measured.

Fig. 4. Left: Rock armour revetment; right: hybrid revetment composed by rock armour and steps

4.2. Testing Conditions

Two-dimensional wave run-up and wave overtopping tests for the rock armour slope and the hybrid structure were performed. Irregular wave tests conformed to a JONSWAP spectrum, with a peak enhancement factor of 3.3. Test durations were approximately 2200 s long, which represented about 1200 waves for a peak period of 1.83 s and about 670 waves for a peak wave period of 2.39 s. All tests were repeated at least three times to ensure reliability and, in some cases, several repetitions to guarantee the accuracy of the results. Ten repetitions were carried out for the two extremes of the wave steepness at the lower tidal height, and the average, μ, the standard deviation, σ, and variance, σ^2, were calculated for each test, with the mean σ^2 being about 30%.

Overall, the wave overtopping tests included very shallow foreshores ($0.3 < d_{TOE}/H_{m0,DEEP} < 0.7$) with relative crest freeboards R_c/H_{m0} between 1.0 and 1.8, breaker parameters, $\xi_{m-1,0}$, calculated with the structure slope, between 4.0 and 7.9 and wave steepness $s_{m-1,0,toe}$ between 0.003 and 0.014 (Table 1). The measured relative mean wave overtopping discharge - $q/\sqrt{gH_{m0}^3}$, ranged between 0 to 8.3x10^{-2}.

At the toe of the structure, spectral significant wave heights ranging from 0.13 to 0.22 m were tested for spectral wave periods between 2.64 s and 4.96 s, for still water depths of 0.60 cm and 0.63 cm, respectively.

The relationship between S_h/H_{m0} and $\xi_{m-1,0}$ has been previously analysed in the literature (Kerpen et al., 2016), covering a broad spectrum of wave breaking conditions, including plunging, collapsing, and surging. According to Kerpen et al. (2016), most data fall within the intervals of $2 < \xi_{m-1,0} < 6$ and $0.2 < S_h/H_{m0} < 0.45$, Fig. 5. The data obtained in this study (hybrid structure), represented with light blue and orange rhombus, as illustrated in Fig. 5, reside within the surging regime, with intervals of $3.85 < \xi_{m-1,0} < 6.28$ and $0.16 < S_h/H_{m0} < 0.26$.

Table 1. Test conditions

Parameter	Symbol	Value	Unit
Step height	S_h	0.035	m
Step length	S_l	0.11	m
Slope rock structure	$cot\, \alpha$	2.2	–
Slope hybrid structure	$cot\, \beta$	2.5	–
Slope foreshore	$cot\, \beta$	18.7	–
Spectral significant wave height toe	$H_{m0\ toe}$	0.13 – 0.22	m
Peak wave period toe	$T_{p\ toe}$	1.79 – 3.48	s
Spectral wave period toe	$T_{m-1,0\ toe}$	2.64 – 4.96	s
Water depth	d	0.60 – 0.63	m
Freeboard	R_c	0.20 – 0.23	m
Water depth and offshore incident wave height ratio	$d_{TOE}/H_{m0,DEEP}$	0.30-0.72	
Wave steepness toe	$s_{m-1,0\ toe}$	0.003 – 0.014	–
Surf similarity parameter toe	$\xi_{m-1,0\ toe}$	3.85 – 7.89	–
Surf similarity parameter equivalent	$\xi_{m-1,0\ equivalent}$	1.25 – 2.83	–
Step ratio	$H_{m0\ toe}/S_h$	3.91 – 6.32	–
Relative freeboard	R_c/H_{m0}	0.95 – 1.80	–

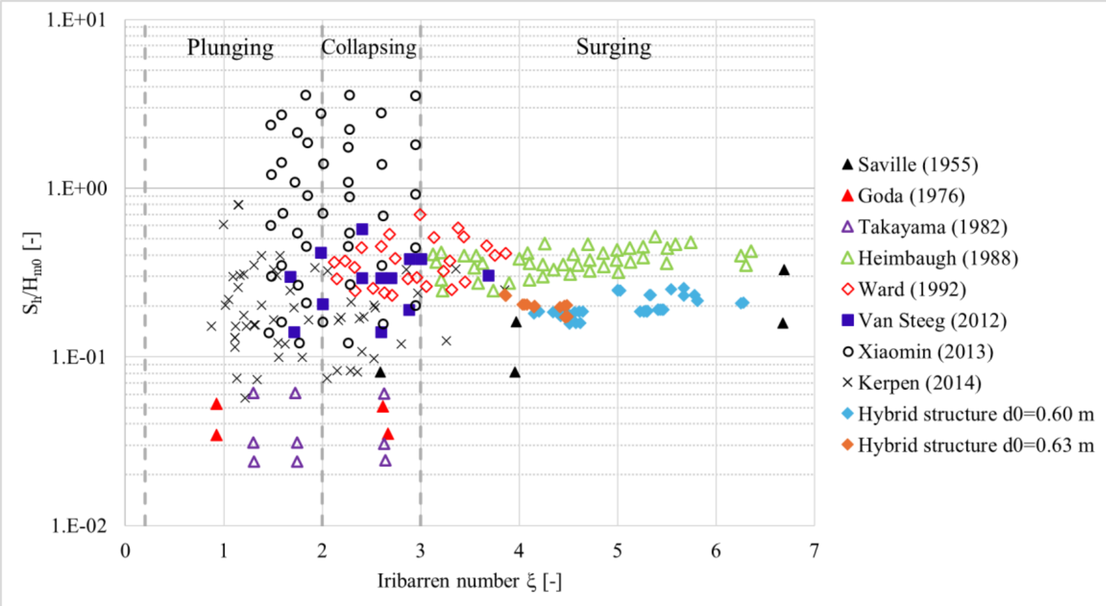

Fig. 5. Relationship between S_h/H_{m0} and $\xi_{m-1,0}$ for stepped revetments and hybrid structure. Adapted from Kerpen et al. (2016)

5. Results

Fig. 6 and Fig. 7 depict the comparison between measured values of relative mean wave overtopping discharge (markers) and predicted values following Eq. (1). For the coastal revetment, the predictions employed a γ_f value of 0.55, consistent with the value recommended in the EurOtop Manual for a double rock layer with an impermeable core. In the case of the hybrid structure, a γ_f value of 0.7 was adopted, selected from within the range identified by previous studies (e.g., van Steeg, 2018; Schoonees et al., 2021) as yielding good performance for stepped configurations. Additionally, the measured values used the breaker parameter with the structure slope, as well as the equivalent slope, as proposed by Altomare et al. (2016).

The figures highlight three aspects: 1) the underprediction of the relative wave overtopping values by Eq. (1) for both rock and hybrid coastal revetments; 2) the overtopping discharge generally decreases exponentially with increasing relative freeboard; and 3) the use of equivalent slope consistently reduces correlation and increases spread, for the tested cases.

Regarding the first aspect, the underprediction is larger for water depths of 0.63 m (orange markers) than for water depths of 0.60 m (blue markers). The equivalent slope and structure slope graphs, show that the ratio between measured and predicted relative wave overtopping discharge has an average value of about 14 (Fig. 6a and Fig. 7a) and 6 (Fig. 6b and Fig. 7b), respectively. The largest ratio with the equivalent slope is 75 for the coastal revetment (Fig. 6a) and 41 for the hybrid coastal revetment (Fig. 7a), and for the structure slope 33 for the coastal revetment (Fig. 6b) and 23 for the hybrid coastal revetment (Fig. 7b).

These results indicate that the semi-empirical formulas analyzed for shallow foreshores tend to underpredict the relative wave overtopping discharge by approximately one order of magnitude under the tested conditions. This discrepancy may be attributed to the comparatively steep foreshore slope in this case study (1:20), which lies outside the range of foreshore slopes (1:30 to 1:250) used to develop Eq. (1).

Regarding the second aspect, the overtopping discharge, for both configurations, decreases exponentially with increasing relative freeboard, confirming the effectiveness of increasing crest height (or wave steepness reduction) as a design strategy to minimize overtopping, aligning with the expected trend of the established EurOtop prediction model.

Regarding the third aspect, the measured overtopping values shown in Fig. 6a and Fig. 7a exhibit greater scatter, with a significant number of data points falling outside the 90% confidence band. This indicates that the use of the equivalent slope in the calculation leads to reduced predictive accuracy. In contrast, a closer agreement with the predicted overtopping trend is observed when the structure slope is used, as evidenced in Fig. 6b and Fig. 7b, for both the coastal revetment and the hybrid structure.

For the coastal revetment (Fig. 6a and Fig. 6b), when calculating the breaker parameter with the structure slope instead of using the equivalent slope, the geometric mean improves from 0.19 to 0.22 and the geometric standard deviation improves from 2.70 to 2.66. Similarly, for the hybrid revetment (Fig. 7a and Fig. 7b), when the structure slope is used, the geometric mean improves from 0.27 to 0.49, and the geometric standard deviation shows a reduction from 3.71 to 3.21.

These results contrasts with some findings in literature (e.g., Altomare et al., 2016), highlighting that the performance of equivalent slope methods may vary depending on specific structural configurations or wave conditions.

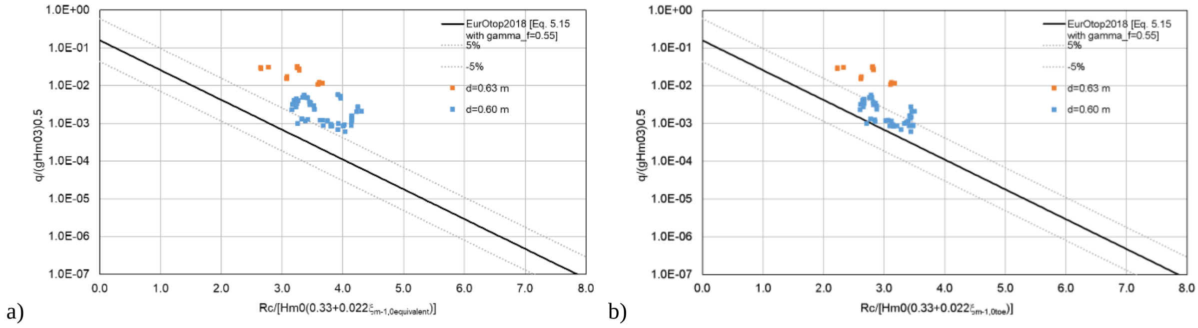

Fig. 6. Computed (Eq. 1 obtained with $\gamma_f = 0.55$ and 90%-confidence band; EurOtop, 2018) and measured relative mean overtopping discharges, $q/(gH_{m0}^3)^{0.5}$, versus relative freeboards, $R_c/[H_{m0}(0.33+0.022\xi_{m-1,0})]$ for a rock coastal revetment. a) $\xi_{m-1,0}$ calculated with the equivalent slope, b) $\xi_{m-1,0}$ calculated with the structure slope.

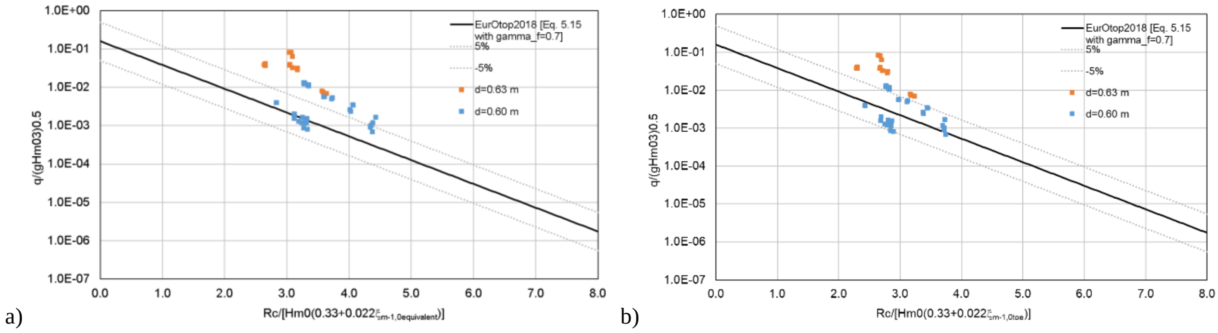

Fig. 7. Computed (Eq. 1 obtained with $\gamma_f = 0.70$ and 90%-confidence band; EurOtop, 2018) and measured relative mean overtopping discharges, $q/(gH_{m0}^3)^{0.5}$, versus relative freeboards, $R_c/[H_{m0}(0.33+0.022\xi_{m-1,0})]$ for a hybrid coastal revetment composed by rocks and concrete steps. a): $\xi_{m-1,0}$ calculated with the equivalent slope, b) $\xi_{m-1,0}$ calculated with the structure slope.

6. Discussion and conclusions

This study compared relative wave overtopping discharges for two coastal revetment designs—a standard two-layer rock armour revetment and a hybrid revetment incorporating concrete steps in place of rock armour on the upper section. Empirical formulae from EurOtop (2018) were compared against measured values in a physical model to assess their applicability under varying wave conditions.

The tested empirical formula consistently underestimates the relative wave overtopping discharge by approximately one order of magnitude. The underprediction is more pronounced at higher water levels (0.63 m) and when the breaker parameter is calculated using the equivalent slope.

For both structure types, overtopping discharge was observed to decrease exponentially with increasing relative freeboard, in agreement with expectations from the EurOtop formulation. This trend reinforces the importance of freeboard elevation as an effective overtopping mitigation strategy.

Using the equivalent slope to compute the breaker parameter led to greater scatter and reduced correlation with the predicted trend, with numerous measured values falling outside the 90% confidence band. In contrast, using the actual structure slope yielded significantly improved agreement with predictions, particularly for the hybrid revetment. This is reflected in improved geometric mean and geometric standard deviation metrics for both structure types.

These findings suggest that the equivalent slope method, while proposed in prior studies (e.g., Altomare et al., 2016), shows reduced reliability for both tested configurations - especially under steeper foreshore conditions or hybrid structural configurations. Instead, the use of the actual structure slope appears to yield more reliable overtopping estimates in such contexts.

These results highlight a significant gap in the used overtopping prediction model for both configurations tested, particularly under conditions of shallow foreshores and high wave energy/water levels.

While hybrid revetments offer functional and amenity-related benefits, such as increased usability and aesthetic value, their hydraulic performance must be carefully evaluated using updated methods. Further research is under development to improve current design guidance and with the numerical model SWASH. The later has it focus on additional stepped configurations and wave conditions for hybrid revetments under various environmental conditions.

Acknowledgements

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References

Altomare C, Suzuki T, Chen X, Verwaest T, Kortenhaus A (2016) Wave overtopping of sea dikes with very shallow foreshores. Coastal Engineering, Volume 116, 2016, Pages 236-257, ISSN 0378-3839, https://doi.org/10.1016/j.coastaleng.2016.07.002.

Bruce T, Pullen T, van Der Meer JW, Allsop, W (2008) Direct hazards from wave overtopping - the forgotten aspect of coastal flood risk assessment? pages 1–11, 2008.

EurOtop 2007, van der Meer JW, Allsop NWH, Bruce T, De Rouck J, Kortenhaus A, Pullen T, Schüttrumpf H, Troch P (2007). EurOtop: Wave overtopping of sea defences and related structures – Assessment manual. UK: Environment Agency, NL: Rijkswaterstaat, DE: Kuratorium für Forschung im Küsteningenieurwesen.

Kerpen N, Schlurmann T (2016) Stepped Revetments - Revisited. Proceeding of the 6 th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16). At: Ottawa, Canada. 10.5281/zenodo.4028357.

Kerpen NB, Schlurmann T, Schoonees T (2018) Wave overtopping prediction of a gentle sloped stepped revetment. Coastal Engineering Proceedings, 1(36):papers.99, Dec. 2018. doi: 10.9753/icce.v36.papers.99. URL https://icce-ojs-tamu.tdl.org/icce/article/view/8792.

Lashley C, Bricker J, van der Meer J, Altomare C, Suzuki T (2020) Relative Magnitude of Infragravity Waves at Coastal Dikes with Shallow Foreshores: A Prediction Tool. Journal of Waterway, Port, Coastal and Ocean Engineering. 146. 10.1061/(ASCE)WW.1943-5460.0000576.

Pullen T, Allsop W, Bruce T, Kortenhaus A, Schuttrumpf H, van der Meer JW (2018) EurOtop manual on wave overtopping of sea defences and related structures: An overtopping manual largely based on European research, but for worldwide application (2nd ed.).

Saville T (1955) Laboratory data on wave run-up and overtopping on shore structures, volume 64. Technical memorandum - Beach Erosion Board.

Saville T (1957) Wave run-up on composite slopes. Coastal Engineering Proceedings, 1(6):41, Jan. 1957. doi: 10.9753/icce.v6.41. URL https://icce-ojs-tamu.tdl.org/icce/article/view/2050.

Schlurmann T, Kerpen N.B (2016) Stepped revetments – revisited. Coastlab16, page 10, 2016.

Schoonees T, Schlurmann T, Kerpen NB (2019) Wave overtopping of stepped revetments. Water, page 17.

Schoonees T, Kerpen NB, Schlurmann T (2021) Full-scale experimental study on wave overtopping at stepped revetments. Coastal Engineering, 167:103887, 2021. ISSN 0378-3839. doi: https://doi.org/10.1016/j.coastaleng.2021.103887. URL https://www.sciencedirect.com/science/article/pii/S0378383921000478.

Tanaka M, Okayasu A, Suzuki T (2003) Laboratory experiments on wave overtopping over smooth and stepped gentle slope seawalls. pages 154–155, 02 2003. ISBN 9789812385581. doi: 10.1142/9789812703040 0078.

Van Gent MRA (1999) Physical model investigations on coastal structures with shallow foreshores; 2D model tests with single and double-peaked wave energy spectra, WL | Delft hydraulics Report H3608.

Van Steeg P, Joosten R, Steendam G (2018) Physical model tests to determine the roughness of stair shaped revetments.