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Prediction of Wave Reflection from Berm Breakwaters, Part A: Presenting a New Formula

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Abstract

Wave reflection is an important hydrodynamic parameter in the design procedure of berm breakwaters. The existing formulae for predicting wave reflection from berm breakwaters are mainly based on regression models derived from available experimental data. Recently, applications of soft computing and data mining techniques to coastal engineering problems have received considerable attention. In this paper, the accuracy of existing berm reflection formulae was evaluated using statistical measures, and the M5′ model tree algorithm was employed to predict wave reflection with high precision. M5′ model trees are trained and tested with the available experimental data. Both hydrodynamic and structural factors, including wave steepness, berm permeability, and structure slope, have been considered in developing the prediction models. The performance of the developed models is tested against the experimental data using statistical error metrics. The results show that the proposed formulae by the M5′ model tree algorithm yield more accurate predictions of wave reflection from berm breakwaters than existing formulae.

1. Introduction

Berm breakwaters are widely used in the construction of fishery ports. Berm breakwaters are rubble-mound structures with a large porous berm above or at SWL at the seaward side. The greater stability of berm breakwaters compared with conventional rubble-mound breakwaters, the optimal use of quarry material, and relatively simple, cost-effective construction processes have drawn engineers’ attention to these coastal structures. Due to the higher sustainability and simplicity of the construction method, several berm breakwaters have been built in Iran over the last decade. Figure 1 shows the image of the Bahal berm breakwater in the Oman Sea.

Figure 1. Bahal berm breakwater in the Oman Sea.

The wave reflection coefficient is the ratio of reflected wave height to the incident wave height and plays an important role in the

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hydraulic design of rubble-mound breakwaters. When the reflected waves from a sloped breakwater interact with the incident waves, they produce partial standing waves and surface-generated turbulence in front of the breakwater. Additionally, the wave reflection could intensify the local scour at the breakwater trunk and lead to the structure's destabilization (Zanuttigh et al., 2008). There are a few experimental studies available on the wave reflection from a berm breakwater. Postma et al. (Postma, 1989) examined the wave reflection from a conventional rubble-mound breakwater under random wave attack. They found a clear correlation between the wave reflection coefficient (C_r) with the wave steepness (S_{op}) and permeability (P) as:

$$C_r = 0.071P^{-0.082}Cotg\alpha^{-0.62}S_{op}^{-0.46} \tag{1}$$

where the wave steepness (S_{op}) is calculated based on the deep water wave length and α the bed slope.

Alikhani (Alikhani,2000) performed laboratory measurements to study the wave reflection from berm breakwaters and proposed the reflection coefficient solely based on wave steepness (Eq.2)

$$C_r = 0.044{S_{op}}^{-0.46} \tag{2}$$

Andersen (Lykke Andersen, 2006) Investigated the wave reflection from a reshaping berm breakwater by testing different slopes, and found a strong correlation between the surf similarity parameter and the reflection coefficient. The surf similarity parameter was calculated based on the spectrum peak frequency and wave period. Andersen (Lykke Andersen, 2006) The berm slope was estimated as the average slope between Still Water Level (SWL) and 1.5H_{mo} below the SWL, and the berm presence was not considered when the berm surface was located at SWL or more than 1.5H_{mo} below SWL.

Zanuttigh et al. (2008) (Zanuttigh et al., 2008), hereinafter referred to as ZVd, explored wave reflection from both permeable and impermeable structures with a berm and argued that wave breaking and run-up on the breakwater should be considered crucial factors that significantly affect wave reflection from a berm. The results showed that for the composed slopes, the effect of the average slope could be incorporated into the surf similarity parameter (Eq. 3).

$$\xi_0 = \xi_{ZVd} = \frac{[\tan\alpha_d \cdot (d - 1.5H_{mo}) + 1.5H_{mo} \cdot \tan\alpha_{inc}]}{d \cdot (\sqrt{H_{mo}/L_0})} \quad d > 1.5H_{mo}$$

$$\xi_0 = \xi_{ZVd} = \frac{\tan\alpha_{inc}}{\sqrt{H_{mo}/L_0}} \quad d \le 1.5H_{mo} \tag{3}$$

where ξ_0 (hereafter referred to as ξ_{ZVd}) is the surf similarity parameter, $\tan\alpha_{inc}$ is the average slope in the run-up/down area, $\tan\alpha_d$ Is the slope of the berm lower part, d is the water depth, H_{mo} is the significant wave height based on frequency domain analysis, and L_0 is the deep water wave length. Zanuttigh and Van der Meer (Zanuttigh and van der Meer, 2006) Employed the weighted average slope, and proposed a relation for the wave reflection coefficient (Eq. 4).

$$C_r = tanh(a\xi_0^b) \tag{4}$$

Where a and b are coefficients that depend on the armor roughness factor (γ_s), and ξ_0 It is determined based on Eq. (3).

Batmanghelichi and Vafai (Batmanghelichi and Vafai, 2010) Studied the wave reflection coefficient from a dynamically stable reshaping berm breakwater and proposed a modified version of the surf similarity parameter (Eq. 3) as:

Surging collapsing	$\xi_0 > 3.3$	$\xi_b > 2.0$	
Plunging	$0.5 < \xi_0 < 3.3$	$0.4 < \xi_b < 2.0$	
Spilling	$\xi_0 < 0.5$	$\xi_b < 0.4$	(5)

Sigurdson and Van der Meer (Sigurdarson and Van der Meer, 2013) presented a modified classification of berm breakwaters (Burcharth et al., 2003), including hard, partly, and fully reshaped berm breakwaters. Eq. (6) summarizes the Sigurdson and Van der Meer. (Sigurdarson and Van der Meer, 2013)

Proposed relations for the reflection coefficient.

$$C_r = 1.3 - 1.7 S_{op}^{0.15}\ HR\ \&\ PR\ \left(\frac{H_s}{\Delta D_{n50}} < 2.5\ \ or\ \ \frac{Re\ c}{D_{n50}} < 4-5\right)$$
$$CapC_r = 1.8 - 2.65 S_{op}^{0.15}\ \ FR\ \ \left(\frac{H_s}{\Delta D_{n50}} > 2.5\ \ \ or\ \ \ \frac{Re\ c}{D_{n50}} > 4-5\right) \quad (6)$$

Where *HR*, *PR*, and *FR* represent the hardly reshaped, partly reshaped, and fully reshaped berm breakwaters, respectively. H_s is the significant wave height, Δ is the relative mas density $(\rho_\alpha - \rho)/\rho$, ρ_a is the mass density of armor stone, ρ is the mass density of water, and D_{n50} is the nominal diameter of armor units.

Despite the efforts that have been made in the past decade to study the wave reflection coefficient, the existing formulae are not capable of predicting the wave reflection from a berm breakwater with high precision. The literature indicates that the wave reflection coefficient (C_r) relations are solely based on wave steepness (S_{op}), Irribaren number (ξ_0) or permeability (P), and do not consider the contribution of major hydrodynamic and structural parameters such as the energy dissipation rate of waves in front of the breakwater, wave interactions with the bottom slope, armor type, and berm permeability. Hence, it is necessary to develop a comprehensive formula capable of predicting the reflection coefficient from all influential parameters.

Numerical and analytical modeling of wave reflection is complex and computationally expensive; therefore, the application of numerical approaches is very limited. (Suh et al., 2001; Sulisz, 1985). Recently, the capabilities of soft computing methods, such as Artificial Neural Networks (ANNs) and Model Trees (MTs), have been explored for coastal engineering problems. (Bonakdar and Etemad-Shahidi, 2011; Etemad-Shahidi et al., 2011; Kambekar and Deo, 2003; Kazeminezhad and Etemad-Shahidi, 2010; Mahjoobi et al., 2008). Soft computing approaches are valuable tools for extracting knowledge and making predictions from existing datasets. Zanuttigh et al. (Zanuttigh et al., 2013; Zanuttigh et al., 2014) Applied neural networks for predicting the wave reflection from coastal structures and wave-structure interactions.

Quinlan first introduced the M5 model tree algorithm. (Quinlan, 1992), and further developed to so-called M5′ algorithm by Wang and Witten (Wang and Witten, 1996). Unlike common soft-computing techniques such as ANNs, the M5′ MT algorithm can produce meaningful relationships between input and output parameters. Therefore, the prediction procedure with the M5′ algorithm is transparent and yields a set of formulae; however, the ANN's output is just a single number. Another advantage of the M5′ MT algorithm over conventional methods, such as ANNs, is its simpler model development and computational efficiency.

In this paper, the capabilities of the M5′ MT algorithm in predicting the wave reflection coefficient from berm breakwater, with a specific focus on reshaping berm breakwaters, have been examined. For developing M5′ MTs, three sets of experimental data are included from Andersen. (Lykke Andersen, 2006), Allsop and Channel (Allsop and Channell, 1989), and Shirian et al. (Shirian et al.) Was employed. Both hydraulic and structural parameters are used in developing the MTs. The performance of existing empirical wave reflection coefficient formulae and the M5′ proposed relations is evaluated and compared using statistical error measures.

2. Materials and Methods

2.1. Model Tree

Presenting a practical formula for intricate, multifaceted phenomena such as wave reflection from a berm breakwater is very difficult. Data mining techniques can learn relationships among dataset parameters without knowing the underlying physical properties of the phenomena, and therefore can be very helpful in solving complex problems.

Model trees are an efficient non-parametric method that can be used for both classification and regression problems (Witten and Frank, 2005). In fact, the model tree is a combination of the decision tree with linear regression functions at the leaves. Model trees are robust to missing data (Barros et al., 2010). Training the MTs is a relatively easy task and, unlike ANN models, does not require time-consuming trial-and-error procedures. M5′ MT algorithm [Wang and Witten (1996)] is one of the most popular algorithms for making a prediction based on a set of data. Developing model trees with the M5′ algorithm involves three stages: tree-building, pruning, and smoothing (Wang and Witten, 1996).

The model tree is formed by using the splitting criterion. M5′ algorithm treats the standard deviation of the class values that reach a node as a measure of the error at that node, and calculates the expected reduction in error as a result of testing each attribute at that node. The attribute that maximizes the expected reduction in error is then selected (Eq. 7).

$$SDR = sd(T) - \sum_i \frac{|T_i|}{|T|} \times sd(T_i) \quad (7)$$

where *sd* is the standard deviation of the set of examples *T* that reach the node, and T_i is the set that results from splitting the node according to the chosen attribute. The splitting process stops when the class values of all the instances that reach a node vary by less than 5% of the *SD* of the original instance, or when only a few instances remain (Wang and Witten, 1996).

An overfitting problem may occur during MT construction when the training dataset's accuracy increases monotonically with the tree's growth. To address overfitting, a "Pruning" technique is employed in this research. The pruning procedures occur if the estimated error for the linear model at the root of a sub-tree is smaller than or equal to the expected error for the sub-tree (Witten and Frank, 2005). Following pruning, sharp discontinuities may occur in the adjacent leaves. To compensate for the discontinuities between adjacent linear models at the leaves, a smoothing method proposed by Quinlan (Quinlan, 1992) It is implemented in this study. The smoothing process uses the linear model at the leaf to compute the predicted value. The predicted value is then filtered along the path back to the root and smoothed at each node by combining it with the linear model's prediction for that node. This involves the following calculation:

$$p' = (np + kq)/(n + k) \quad (8)$$

where p' is the prediction passed up to the next higher node, p is the prediction passed to the current node from below, q is the value predicted by the model at this node, n is the number of training instances that reach the lower node, and k is a constant. In general, smoothing substantially increases the prediction accuracy (Bonakdar and Etemad-Shahidi, 2011; Etemad-Shahidi and Bonakdar, 2009; Etemad-Shahidi et al., 2011; Quinlan, 1992; Wang and Witten, 1996; Witten and Frank, 2005).

2.2. Available Experimental Data

In this work, three sets of experimental data have been employed to develop M5′ model trees and predict the wave reflection from berm breakwaters. The data set is obtained from Andersen. (Lykke Andersen, 2006), Allsop and Channel (Allsop and Channell, 1989), and Shirian et al. (2007) (Shirian et al.) Experimental tests. In the foregoing, the experimental data utilized in this study are summarized.

Andersen experiments have been carried out in a laboratory flume with a bed slope of 1:20. The irregular wave terrain was generated using the JONSWAP spectrum and a peak enhancement factor. $\gamma = 3.3$. The breakwater was constructed in two layers, including a core and an armor layer. Four types of armor stone have been used to construct the berm breakwater profiles. The largest armor size was used to construct a non-reshaping berm breakwater. Several tests were conducted to investigate the effect of reshaping on reflection by fixing the front of the breakwater with a net and steel bars.

Allsop and Channel (Allsop and Channell, 1989) Conducted a series of laboratory tests at the Department of Hydraulic Research, Wallingford, to investigate wave reflection from rock-armored slopes under random wave attack. All the tests were performed using the JONSWAP spectrum. Four different berm sections were tested with different slopes and berm lengths.

Shirian et al. (Shirian et al.) Studied wave reflection from reshaping berm breakwaters in a laboratory flume at Iran Soil Conservation and Watershed Management Research Institute. The random wave terrain was generated according to the JONSWAP spectrum. Table 1 summarizes the experimental data used for this study and the range of tested parameters.

Table 1. Data range for reviewed experimental studies, (Allsop and Channell, 1989; Lykke Andersen, 2006; Shirian et al.).

parameter	Dataset		
	Andersen	Allsop and channel	Shirian
Wave steepness S_{op}	0.01-0.054	0.003-0.04	0.01-0.07
Wave height at the toe H_{mo} [m]	0.064-0.164	0.06-0.72	0.048-0.13
Water depth at the toe of d [m]	0.24-0.44	0.38	0.24
Berm width B [m]	0-0.65	0.2, 0.4, 0.8	0
Berm elevation relative to SWL h_b [m]	-0.04-0.12	0	-
Front slope below berm	1:1.25	1:1.5, 1:2.5	1:1.25
Front slope above berm	1:1.25	1:1.5, 1:2.5	1:1.25
Stability number $N_s = H_0$	0.96-4.86	0.17-2.11	1.86-5.03
Armour diameter $D_{n50armour}$ [m]	0.0388, 0.0323, 0.0198, 0.0103	0.056	0.017
Core and filter diameter $D_{n50Core}$ [m]	0.0137	0.01, 0.02, 0.03	0.0079

2.3. Evaluation of existing formula

The performance of existing well-recognized empirical relations for the reflection coefficient is evaluated using the Andersen dataset and statistical error measures. Sigurdson and Van der Meer (Sigurdarson and Van der Meer, 2013) The methodology was applied to classify berm breakwaters.

The correlation coefficients (*R*), bias, Root-Mean-Square-Error (RMSE), and Scattering Index (SI) were used to quantitatively evaluate the performance of the reviewed empirical formulae and proposed relations from this study. Eqs. (9–12) present the formulae used for the statistical analysis.

$$R = \frac{\sum_{i=1}^{n}[(y_i-\bar{y})(x_i-\bar{x})]}{\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2 \sum_{i=1}^{n}(x_i-\bar{x})^2}} \quad (9)$$

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \quad (11)$$

$$\text{SI} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-x_i)^2}}{\bar{x}} \quad (12)$$

Where n is the number of data, x_i is the predicted, $\bar{x}$ Is the averaged value, y_i is the measured, and $\bar{y}$ Is the averaged value.

Figs. 2 and 3 compare measured and predicted reflection coefficient values for Anderson data, obtained using the Alikhani and ZVd formulae, respectively. Fig. 2 shows significant scattering between the measured reflection coefficients from the Andersen data and the predicted values from the Alikhani formula. Fig. 2 indicates that the formula proposed by Alikhani is not capable of providing a reasonable prediction for the wave reflection from the berm breakwater. Figure 3 illustrates that the ZVd formula significantly overestimates wave reflection compared with Andersen measurements and does not provide a good estimate for *FR* and *HR-PR* breakwater types.

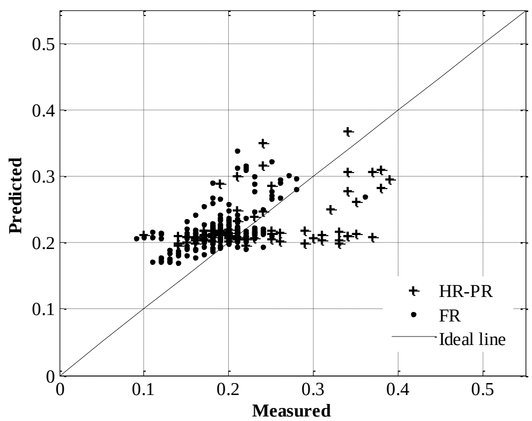


Figure 2. Comparison between the Andersen measured wave reflection coefficient and the predicted values by the Alikhani formula.

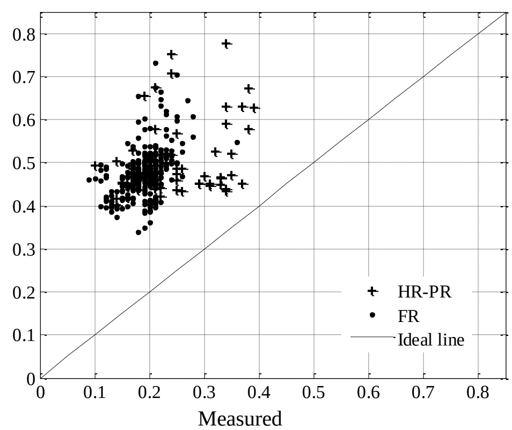


Figure 3. Comparison between the Andersen measured wave reflection coefficient and the predicted values by the ZVd formula.

Furthermore, the performance of the wave reflection formulae proposed by Batmanghelichi and Vafai and Sigurdson and Van der Meer was tested against the Andersen dataset and presented in Figures 4 and 5, respectively.

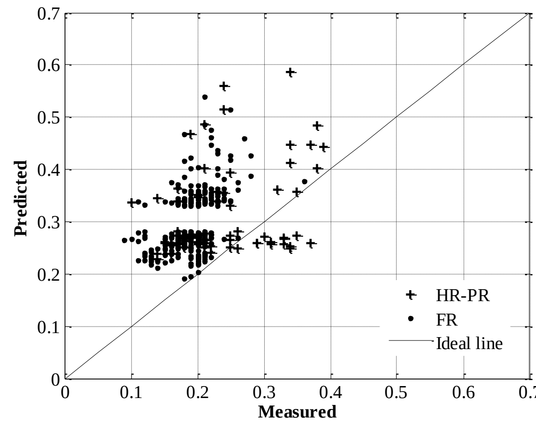


Figure 4. Comparison between the Andersen measured wave reflection coefficient and the predicted values by Batmanghelichi and Vafai's formula.

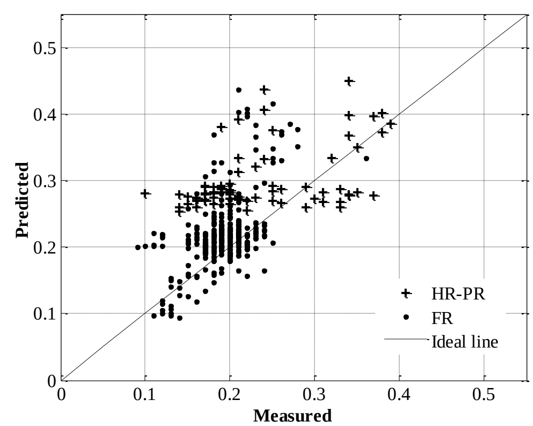


Figure 5. Comparison between the Andersen measured wave reflection coefficient and the predicted

The reflection coefficient proposed by Batmanghelichi and Vafai, based on modified $\xi 0$ (Eq. 5), showed slightly better performance in predicting the wave reflection (Figure 4) in comparison with ZVd and Alikhani formulae. Statistical analysis demonstrates that the Sigurdson and Van der Meer formula yields relatively better predictions for FR data than for *HR-PR* data (Fig. 5).

The statistical measures demonstrate poor performance of existing reviewed formulae (Table 2) in predicting wave reflection from the Andersen dataset (Lykke Andersen, 2006). Table 2 indicates that the reviewed formulae perform better for FR berm breakwaters than for HR & PR. The weakness of existing formulae is mainly due to the inconsistency between the input and output.

parameters. Soft computing methods, such as model tree algorithms, can discover relationships between dataset parameters and translate them into a meaningful predictive formula. Hence, applying the M5′ model tree algorithm could address the inconsistency problem in existing formulae and yield an improved wave reflection coefficient formula.

values by Sigurdson and Van der Meer formula (Lykke Andersen, 2006)

Table 2. Performance of empirical approaches in predicting the wave reflection coefficient for Andersen data set

Model	Classification of berm breakwaters	BIAS	RMSE	SI (%)	R
Alikhani	HR-PR	-0.0079	0.0649	27.66	0.4413
	FR	0.0251	0.0382	19.97	0.5118
ZVd	HR-PR	0.2614	0.2749	117.14	0.3531
	FR	0.2871	0.2914	152.33	0.0793
Batmanghelichi and Vafai	HR-PR	0.0718	0.1155	49.22	0.3368
	FR	0.1082	0.1205	62.99	0.4572
Sigurdson and Van der Meer	HR-PR	0.0645	0.0918	39.12	0.4494
	FR	0.0283	0.0528	27.60	0.5381

3. Result and Discussion

3.1. Implementing new Ideas for the accuracy improvement of existing equations

To improve the accuracy of existing empirical formulae, two new approaches for estimating the average breakwater slope and berm permeability were adopted in this work.

The basic concept is to develop a new formula that satisfies all the following requirements:

• its shape can reproduce all different slope types;

• it represents physical bounds;

• it gives a relationship with the roughness factor in the wave overtopping discharge formula.

This particular requirement relates to the overtopping and reflection performance of different armor units or slopes with varying roughness. Since roughness has been measured or determined for many materials and structures, the dependence on this parameter, if confirmed, may allow the new reflection formula to be extended to a wide variety of slopes.

At first, efforts were made to incorporate the average breakwater slope into the wave reflection equations by comparing the reflection from conventional and berm breakwaters. The wave reflection differences are mainly due to the wave-breaking type at the structure. This study suggests two new approaches for breakwater slope design and introduces average breakwater slopes based on ZVd recommendations.

Starting from the work by Lykke Andersen (2006), the main points of the present analysis can be summarized as follows:

• what reflects is the slope below SWL;

• for combined slopes, an average slope has to be included in the evaluation of the Iribarren parameter;

• Reflection is influenced by wave breaking and run-up. The lower the run-up, the greater the reflection; the greater the energy dissipation by breaking on the berm/toe, the lower the reflection. The presence of a toe and/or a berm should thus be accounted for whenever it may affect these processes, more specifically also when the berm is placed in the run-up area $+1.5H_{m0t}$.

Fig. 6 illustrates a schematic of the average breakwater slope in terms of the boldc of average breakwater slope in terms of the $\boldsymbol{tan\,\alpha_{inc}}$. With a simple mathematical calculation and considering that $\boldsymbol{\alpha_{up}}$ and $\boldsymbol{\alpha_d}$ are the same for the Andersen dataset, $\boldsymbol{tan\,\alpha_{inc}}$ is calculated (Eq. 13).

$$\boldsymbol{tan\,\alpha_{inc}} = \frac{\boldsymbol{3H_{m0}\,tan\,\alpha_d}}{\boldsymbol{B\,tan\,\alpha_d + 3H_{m0}}} \qquad (13)$$

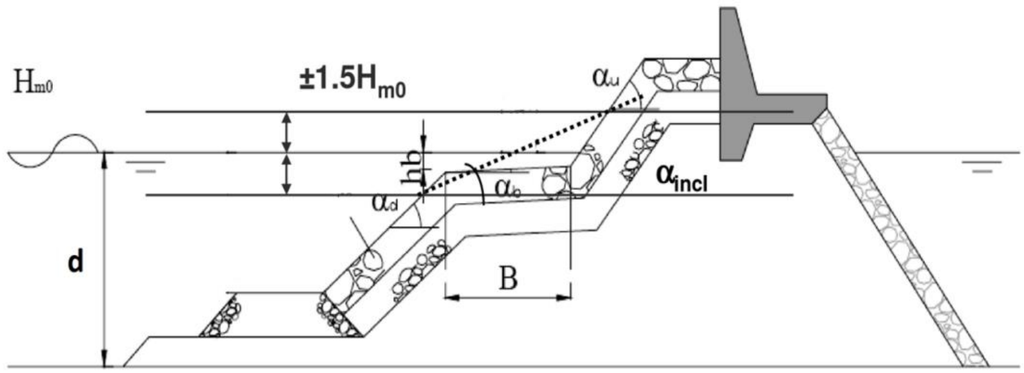


Figure 6. Schematic sketch of the parameters involved in Eq. (13), ZVd (Zanuttigh et al., 2008).

de Waal and van der Meer method was adopted for calculating the average breakwater slope ($tan\,\alpha_{inc}$). Fig. 7 demonstrates the average breakwater slopes for two different berm levels, below and above the SWL. By applying mathematical calculation, de Waal and van der Meer's average breakwater slope ($tan\,\alpha_{deW,Vd}$) can be obtained from Eq. (14) when the berm is located above SWL and Eq. (15) if the berm is located below SWL.

$$tan\,\alpha_{deW,Vd} = \frac{2H_s}{\frac{H_s+h_{br}}{tan\,\alpha_d}+\frac{H_s-h_{br}}{tan\,\alpha_{up}}} \qquad (14)$$

$$tan\,\alpha_{deW,Vd} = \frac{2H_{m0}}{B+\frac{H_{m0}+h_{br}}{tan\,\alpha_d}+\frac{H_{m0}-h_{br}}{tan\,\alpha_{up}}} \qquad (15)$$

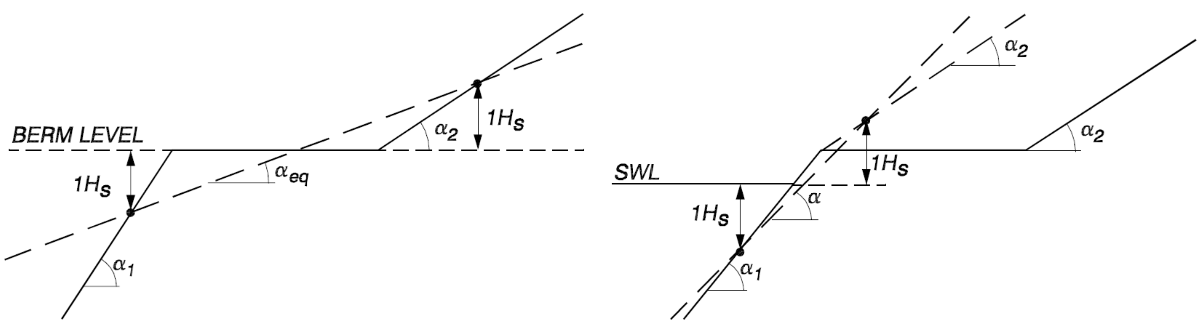


Figure 7. Schematic sketch of the berm location and the parameters involved in deriving the average breakwater slope ($\tan\,\alpha_{deW,Vd}$) from CEM (Coastal Engineering Manual).

Table 3 shows the statistical performance of the improved ZVd and Postma et al. formulae, incorporating the average slope definition (Eqs. 13, 14, & 15). The results indicate that including $tan\,\alpha_{inc}$ In ZVd and Postma et al., the formula increases the performance of wave reflection predictions. Also $\tan\alpha_{inc}$ shows a better performance in comparison with $tan\,\alpha_{deW,Vd}$ and$tan\,\alpha_d$. Fig. 8 presents the measured wave reflections from the Andersen dataset against the predicted values from Postma et al. revised formula. Despite Postma et al.'s formula, developed for rubble-mound breakwaters, it shows better predictive accuracy for berm breakwaters than the ZVd formula, mainly because it includes a permeability parameter.

Table 3. Performance of empirical relations by adopting new average slope relations for Andersen (Lykke Andersen, 2006) dataset.

Model	Formula	Structure slope	R	RMSE	SI
ZVd	$C_r = \tanh(a\xi_0{}^b)$	$\tan\alpha_d$	0.49	0.24	120.50
		$\tan\alpha_{deW,Vd}$	0.32	0.22	108.83
		$\tan\alpha_{inc}$	0.52	0.065	32.83
Postma	$C_r = 0.071P^{-0.082\cot\alpha--0.62Sop}$	$\tan\alpha_d$	0.44	0.088	44.18
		$\tan\alpha_{deW,Vd}$	0.29	0.078	39.16
		$tan\,\alpha_{inc}$	*0.44*	*0.043*	*21.60*

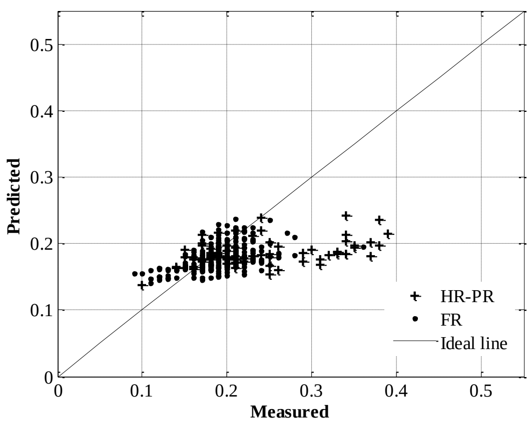


Figure 8. Comparison between the Andersen measured wave reflection coefficient and the predicted values by the Postma formula

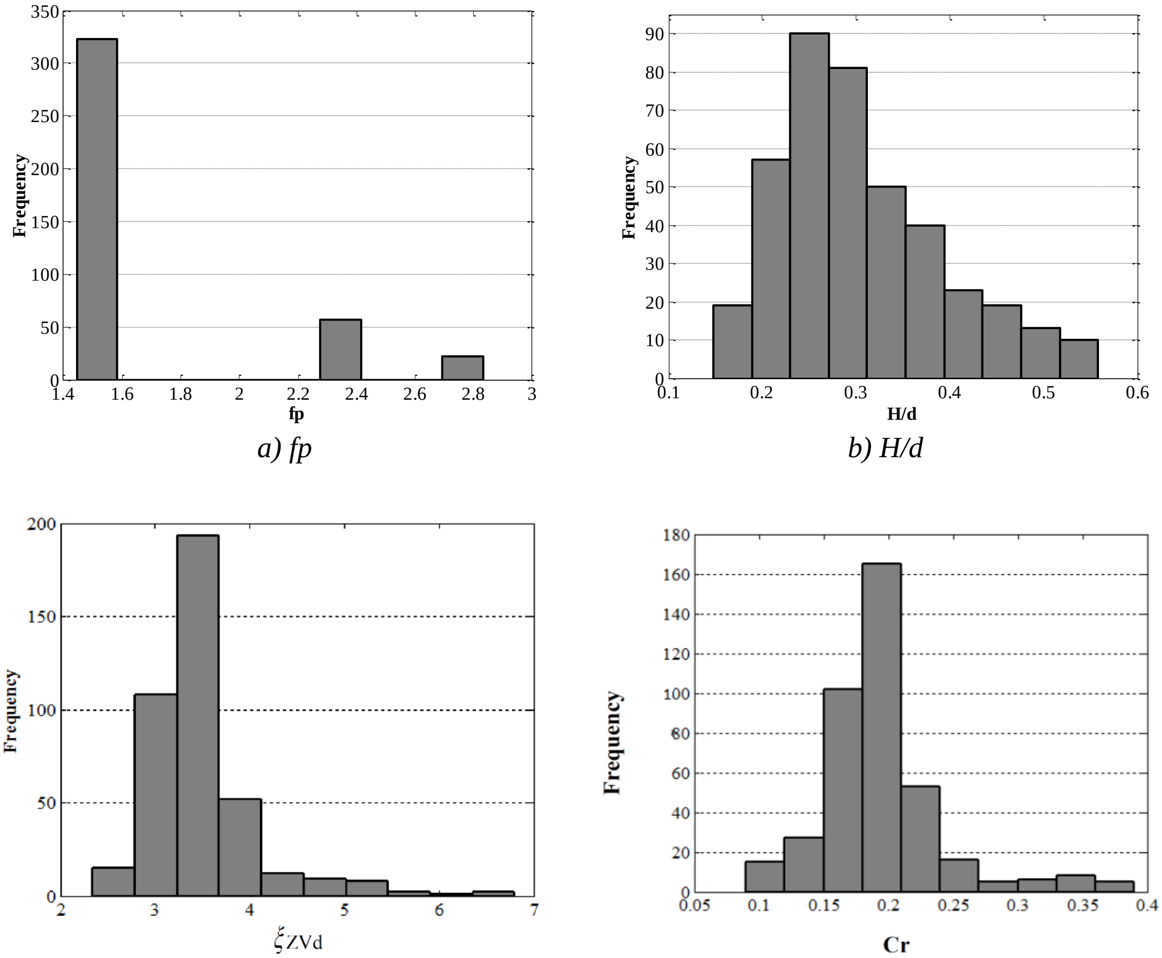
The second approach proposed in this paper is the permeability factor. In previous studies, the conventional rubble-mound breakwaters consisted of three layers (Postma, 1989; Van der Meer, 1992) and the permeability was estimated with Van der Meer (Van Der Meer, 1988) methodology. The berm breakwaters are mainly comprised of two layers, the armour and the core layer; however, the diameters of these layers are not consistent with Van der Meer (Van Der Meer, 1988) Proposed range. Therefore, in this paper, a new permeability concept is developed based on van Gent et al.'s stability formula and core permeability calculated according to Eq. (16).

$$f_{pCore} = \frac{D_{n50Armour}}{D_{n50Core}} \tag{16}$$

where $D_{n50Armour}$ and $D_{n50Core}$ are defined as the ratio of the median armour to the median core stone diameter. For conventional three-layer berm breakwaters, $D_{n50Core}$ should be substituted by$D_{n50filter}$.

3.2. Model development

In this study, the M5′ MT algorithm was used to predict the wave reflection coefficient by reshaping the berm breakwater. 402 data records from Andersen's experimental tests were used to develop model trees. The dataset was randomly split into training (300 records) and test (102 records). Data parameters and range are presented in Table 1. The data frequency histograms (Fig. 9) show that the distributions of input and output variables are not uniform; hence, the M5′ MTs could provide better predictions for cases with higher variable densities.The M5′ MT algorithm is only capable of providing a linear association between input and output parameters; however, the relation between the wave reflection and input parameters is non-linear. To overcome this limitation, models were developed using ln(*input*) and ln(*output*).



a) fp *b) H/d*

c) ξ_{zvd} *d) Cr*

Figure 9. Data frequency histogram for modelling parameters

Fig. 10 shows the results of the developed M5′MTs for predicting the reflection coefficient. The proposed MT results in three prediction rules for the wave reflection coefficient. Eq. (17) summarizes the rules recommended by the M5′ algorithm:

$$
\begin{aligned}
&if \quad \xi_{ZVd} \le 3.67, f_{pCore} \le 1.85 \quad C_r = 0.073\xi_{ZVd}^{1.2}\left(\frac{H_{m0}}{d}\right)^{0.43} \\
&if \quad \xi_{ZVd} \le 3.67, f_{pCore} > 1.85 \quad C_r = 0.01\xi_{ZVd}{f_{pCore}}^{2.09}\left(\frac{H_{m0}}{d}\right)^{0.08} \\
&if \quad \xi_{ZVd} > 3.67 \quad C_r = 0.11\xi_{ZVd}^{0.49}{f_{pCore}}^{0.58}\left(\frac{H_{m0}}{d}\right)^{0.16}
\end{aligned}
\tag{17}
$$

where ξ_{ZVd} The surf similarity parameter is calculated according to Eqs. (3) and (13).

3.3. Model Assessment

The performance of the proposed wave reflection formulae (Eq. 17) is explored and assessed against Andersen's experimental data. The formulae were classified based on ξ_{ZVd} and f_{pCore}, the significance of sthe urf similarity parameter (ξ_{ZVd}) in predicting the wave reflection coefficient is evident. The splitting range based on surf similarity ($\xi_{ZVd} \le 3.67$&$\xi_{ZVd} \ge 3.67$) indicates the transition from plunging breaker to surging or collapsing breaker type, and M5′ MTs recognize that the contribution of surf similarity parameters changes for different breaker types. In the proposed formulae (Eq. 17), the contribution of the surf similarity parameter decreases for the surging/collapsing breaker type. Considering the greater wave period of collapsing/surging breaking waves, higher wave energy dissipation occurs in front of the berm breakwater (Kik, 2011). Therefore, the proposed M5′ relations are shown to follow physical laws without understanding the complex nature of the phenomena.

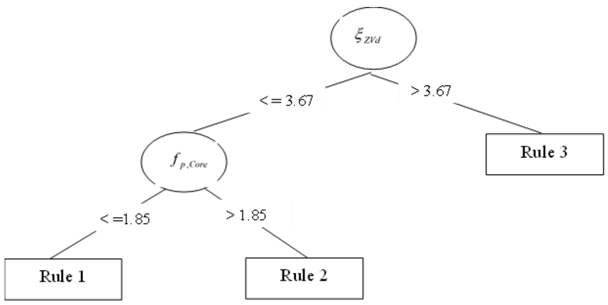


Figure 10. The developed M5′ model tree

The results showed that wave reflection increases with increasing f_{pCore} value. Hence, if the armor diameter is equal to the stone diameter used in the core layer,$f_{pCore} = 1$The permeability increases, and a larger portion of the incoming water body infiltrates into the breakwater layers; consequently, higher wave energy dissipates in front of the berm breakwater. In other words, the larger f_{pCore} results in lower permeability, and the results confirm Van der Meer's recommendations for the permeability parameter. Using larger stone sizes tends to increase breakwater stability, leading to less recession and, in turn, increased wave reflection. M5′ MT algorithm proposed that relative wave height *H/d* is also important in the prediction of wave reflections from berm breakwaters (Eq.17). In this study, the relative depth *d/L* for the Andersen dataset is in the range of 0.08 to 0.23, which means the incident wave transforms into a so-called transition condition and the wave does not break. In the transition condition, higher wave reflection may occur due to the shoaling effect; therefore, the relative wave height can be selected as an appropriate parameter for expressing the wave-bed interactions.

Fig. 11 presents the comparison between the measured C_r from Andersen data and the predicted C_r using the proposed formula by the M5′ MT algorithm (Eq. 17). The statistical error measures confirm the high accuracy of the proposed wave reflection formula for berm breakwaters (Table 4). The formula marginally under-predicts (*bias* = -0.002) the wave reflection coefficient for Andersen data. The performance of the proposed wave reflection relation shows a remarkable improvement compared with the existing reviewed formulae. Statistical indices show higher accuracy of the M5′ MTs formula for fully reshaped berm breakwaters (*SI* = 12.81%).

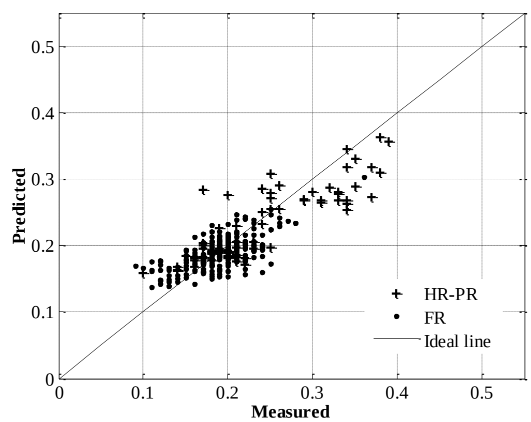


Figure 11. Comparison between the Andersen measured wave reflection coefficient and predicted values by the M5′ MT algorithm

To evaluate the reliability of the empirical and proposed models, this study uses a box plot of the Discrepancy Ratio (DR). This ratio is calculated as:

$$DR = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i}{O_i} \tag{18}$$

where P_i and O_i represent the predicted and the observed values, and N is the number of observations.

Table 4. Comparison between the performance of M5′ MT formula and empirical relations for Andersen data (Lykke Andersen, 2006)

Model	Formula	Dataset	Bias	RMSE	SI	R
ZVd	$C_r = \tanh(a\xi_{ZVd}{}^{b})$	All Andersen data	0.158	0.165	82.67	0.40
Alikhani	$C_r = 0.044S_{op}^{-0.46}$	All Andersen data	0.019	0.044	22.33	0.49
Model Tree	$C_r = f\{\xi_{ZVd}, f_{pCore}, (H/d)\}$	All Andersen data	-0.002	0.027	13.8	0.80
		HR-PR	-0.006	0.038	16.19	0.86
		FR	-0.001	0.024	12.81	0.65

Reviewing the statistical measures for the empirical relations and the proposed M5′ MTs formula shows uncertainty associated with the available wave reflection formulae. Determining the exact degree of uncertainty is difficult. Hence, to overcome this limitation, a safety factor based on the acceptable risk level is considered for each model. Fig. 12 shows the box plots and the safety factors for the empirical formulae and the M5′ model tree. The plot indicates that empirical models have higher uncertainty than the model tree, which provides a reasonable prediction. Also, the acceptable safety factors for the proposed model tree are generally smaller than those for empirical models; e.g., if 10% risk is desired, the prediction of the M5′ model should be multiplied by only 1.19, whereas this factor is higher than 3 in the equation of Zanuttigh et al. Despite the high accuracy of the M5′ model tree and the capability of producing meaningful relations for wave reflection predictions, the proposed M5′ MT formula is only valid for reshaping berm breakwater and for the data range presented in Table 1.

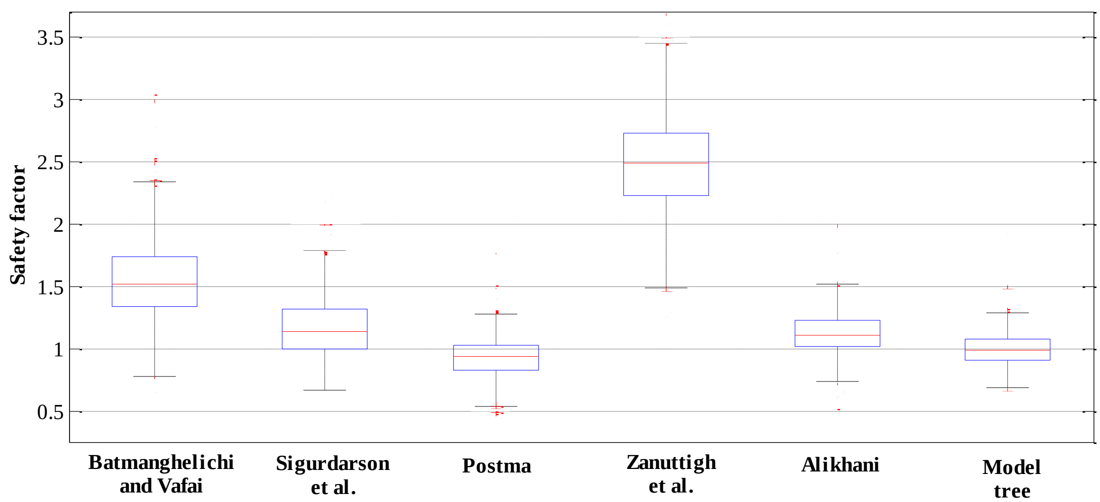


Figure 12. Reliability of all formulae using box plots.

3.4. Evaluation of the proposed formula for different data sets

This section explores the performance of the proposed formula (Eq. 17) for both Allsop & Channel (Allsop and Channell, 1989) and Shirian et al. (Shirian et al.) experimental data (§2.2). The range of recorded parameters and number of tests (Table 1) for Allsop and Channel (Allsop and Channell, 1989) data are within the range of the training data set (Andersen) used to develop model trees;

however, a remarkable difference in data range was observed between Andersen and the records of Shirian et al.

The wave reflection coefficient is predicted for the Allsop & Channel (Allsop and Channell, 1989) dataset using the proposed M5′ MT formula. The result is compared with the empirical formulae proposed by Alikhani 2000), Batmanghelichi & Vafai, Sigurdson et al. (Sigurdarson and Van der Meer, 2013), and Zanuttigh et al. (. The statistical error measures (Table 5) indicate that the formula proposed by the model tree (Eq. 17) predicts wave reflection much more closely to Allsop & Channel (Allsop and Channell, 1989) measurements than other empirical relations. Fig. 13 shows the predicted reflection coefficient against the measured reflection coefficient. The figure demonstrates the higher accuracy of the model tree formula and the overestimation of empirical approaches.

Table 5. Comparison between the performance of the M5′ MT formula and empirical relations for Allsop and the channel (Allsop and Channell, 1989) dataset

Model	BIAS	RMSE	SI(%)	R
Alikhani	0.3398	0.3841	150.63	0.6283
Zanuttigh et al.	0.3645	0.3915	153.53	0.6359
Batmanghelichi and Vafai	0.1919	0.2367	92.82	0.6819
Sigurdson et al.	0.1331	0.1607	63.02	0.5319
Model tree	0.0323	0.0701	27.49	0.7361

The performance of the proposed model tree relations (Eq. 17) and existing reviewed formulae is tested against Shirian et al. (Shirian et al.) data. The statistical measures confirm the model tree's good performance. Despite the lower correlation coefficient, the model tree performs better than empirical relations overall (Table 6).

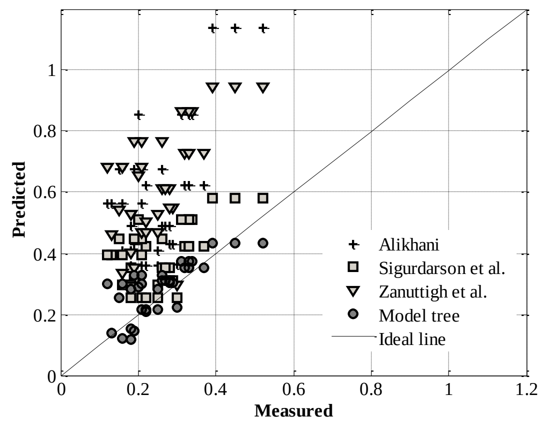


Figure 13. Comparison between Allsop and Channel measured wave reflection coefficient and predicted values by M5′ MT algorithm.

The performance of the proposed model tree relations (Eq. 17) and existing reviewed formulae is tested against Shirian et al. (Shirian et al.) data. The statistical measures confirm the model tree's good performance. Despite the lower correlation coefficient, the model tree performs better than empirical relations overall (Table 6). Among the empirical relations, the Alikhani formula predicts wave reflections with higher accuracy than Shirian et al. (Shirian et al.) data. Fig. 14 compares the measured and predicted values for Shirian et al. (Shirian et al.). The performance of the proposed model tree formulae in predicting wave reflection coefficients across different ranges of hydrodynamic and structural parameters demonstrates the strength of the presented approach.

3.5. Sensitivity Analysis

It is important to determine the contribution of the model tree’s input parameters in predicting the wave reflection coefficient. Therefore, a sensitivity analysis was conducted, and the relative importance of independent parameters was determined by excluding them (one at a time) from the model’s input. Then, the performance of each model was examined (Table 7).

Table 6. Comparison between the performance of M5′ MT and empirical relations for Shirian (Shirian et al.) dataset.

Model	BIAS	RMSE	SI(%)	R
Alikhani	0.0722	0.0750	23.60	0.9631
Zanuttigh et al.	0.2591	0.2602	82.11	0.9667
Batmanghelichi and Vafai	0.0791	0.0829	26.16	0.9638
Sigurdson et al.	-0.1186	0.1223	38.60	0.9685
Model tree	-0.0447	0.0622	19.63	0.8200

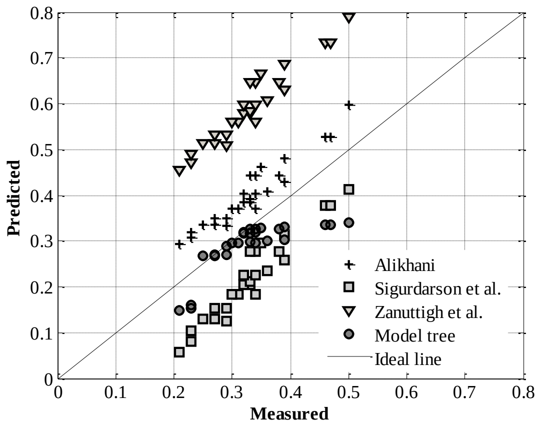


Figure 14. Comparison between the wave reflection coefficient measured by Shirian et al. and the predicted values from the M5′ MT algorithm.

Table 7. Sensitivity analysis for the developed model tree.

model	BIAS	RMSE	SI(%)	R
Model tree	-0.0031	0.0276	13.83	0.8028
Model tree without ξ_{zvd}	-0.0045	0.0424	21.24	0.4005
Model tree without f_p	-0.0031	0.0381	19.09	0.5616
Model tree without H/d	-0.0034	0.0370	18.84	0.6012

The result indicates that the surf similarity parameter ξzvd dominated the prediction of the wave reflection coefficient, followed by fp and H/d.

4. Conclusions

This paper presents a comprehensive study of wave reflections from reshaping berm breakwaters. Two new approaches were adopted to increase the performance of existing empirical relations by proposing a new formula for the average breakwater slope ($tan\ \alpha_{inc}$) and a modified permeability factor (f_p). A new formula was introduced for predicting wave reflection from reshaping berm breakwaters using the M5′ model tree algorithm (Eq. 17). The Andersen comprehensive dataset included various hydrodynamic and structural conditions used to develop the model trees. The performance of the model tree's proposed formula is evaluated using statistical error measures. The statistical parameters indicate greater accuracy in wave reflection prediction for the model tree formula than for the existing empirical relations. The proposed model tree relations demonstrate the strength of the M5′ MT algorithm in understanding the relationships between dataset parameters without understanding the underlying physics of the phenomena. The sensitivity analysis indicates that modified surf similarity is the principal contributor to the proposed wave reflection coefficient formula; however, permeability and relative wave height also make significant contributions. The validity of proposed wave reflection formula is further tested for Allsop & Channel and Shirian et al. data. The statistical measures confirm that the M5′ MT algorithm outperforms the existing empirical relations.

A new simple formula has been proposed to predict *K*r for rock-permeable, rock-impermeable, armor-unit, and smooth slopes. This formula, given by Eq. (5), relates *K*r to _0, has a physical limit, and depends on two parameters, which can be expressed as functions only of the roughness factor _f, as found in overtopping research. This formula has been validated against reflection data for slopes characterized by various roughness factors. Reflection and overtopping performance of coastal structures are strongly related: large roughness and permeability lead to lower overtopping and reflection, due to greater dissipation. And vice versa, smooth slopes give more overtopping and higher reflection.

To extend the formula developed for straight slopes to combined slopes, the method for computing the slope used to estimate the breaker parameter has been analyzed.

Reflection occurs along the entire slope below SWL and is strictly related to the run-up and breaking processes.
It should be highlighted that since the effect of water depth and berm elevation are both included in the present formula, it would perform more appropriately compared to other existing ones, at least for hardly/partly reshaping breakwaters. The conclusions from this equation indicate a more precise estimation rather than the other formula for predicting the wave reflection coefficient, at least for the experimental data.

Notations

g	Acceleration due to gravity
$H_{m_0 t}$	Significant incident wave height at the structure toe
h	Water depth at the structure toe
h_b	Berm position with respect to SWL (positive if submerged)
h_t	Water depth above the structure toe
K_r	Reflection coefficient, i.e. the reflected to incident significant wave height ratio at the structure toe $H_{m_0 r}/H_{m_0 t}$
L_0	Wave length based on spectral wave period at the structure toe
R_c	Structure freeboard (negative if the structure is submerged) SWL still water level
s_0	Wave steepness based on spectral wave at the structure toe
$T_{m-1,0}$	Spectral wave period at the structure toe
α	Off-shore slope for structures with a single slope
α_b	Berm slope with respect to the horizontal
α_d	Structure slope below the berm
α_{incl}	Average structure slope including the berm in the run- down/up area, i.e. $\pm 1.5 H_{m_0 t}$
α_t	Toe slope
γ_f	Roughness factor as found in overtopping research
ξ_0	Breaker parameter based on spectral wave period at the structure toe

Acknowledgment

The present research is part of an analytical-experimental project (and, in the future, numerical) on berm breakwaters that is being planned and carried out. In this project, we aim to provide more accurate relationships and formulas based on the laboratory results. In this regard, the first part of the work, which is deriving a new formula to express the reflection coefficient of the breakwater, is presented in the current text as part A.; In the next sections, new formulas for the width of the platform, the top and bottom slope of the berm, etc. will be presented. We are so grateful for the past and future financial and technical support of the NIMALA (National Iranian Marine Laboratory, Tehran, Iran).

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