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On the mean overtopping rate of rubble mound structures

Amir Etemad-Shahidi [a,b,*], Ali Koosheh [a], Marcel R.A. van Gent [c,d]

[a] School of Engineering and Built Environment, Griffith University, QLD, 4222, Australia
[b] School of Engineering, Edith Cowan University, WA, 6027, Australia
[c] Department of Coastal Structures & Waves, Deltares, Delft, the Netherlands
[d] Department of Hydraulic Engineering, TU Delft, Delft, the Netherlands

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ABSTRACT

Estimation of the mean overtopping discharge is a major task in the design and assessment of the crest level of rubble mound structures such as breakwaters and seawalls. The tolerable mean overtopping rates are given based on the associated risk and wave characteristics. Several empirical formulas have been developed for the prediction of mean overtopping discharge at coastal structures. These formulas can be applied to a wide variety of coastal structures, but have limited accuracy and/or do not reflect the physics of the phenomena. The main aim of this study is to overcome these issues for rubble mound structures by considering the physics of the process in the formula development. To achieve this, first, the references used in the extended CLASH database (also called the EurOtop-2018 database), were scrutinized, the reported wave characteristics were corrected (if required) and the rubble mound structure subset was extended using a recent study. Then noting that overtopping occurs when the wave runup exceeds the freeboard, the difference between the maximum wave runup and crest freeboard was considered as the governing parameter in the mean overtopping discharge formula. In the developed formula, a semi-empirical relationship between the mean overtopping and wave runup has been established. The performances of the developed formulas and existing ones were evaluated both qualitatively and quantitatively. Accuracy metrics such as RMSE and BIAS indicated the superiority of the developed simple formula. Finally, a design formula to consider uncertainty and some guidelines are provided for practitioners.

1. Introduction

The safety of coastal structures is generally determined by their hydraulic responses, and mainly mean overtopping rate. In practice, the crest level is usually determined based on the allowable mean overtopping rate and excessive overtopping is unsafe and may result in erosion, instability of the rear and crest of structures, or threat to activities and facilities behind the crest of coastal structures. Different approaches have been used to provide a robust prediction tool for this purpose. These approaches are mostly based on laboratory experiments and scaling arguments. The existing datasets were first collated in the CLASH project (Steendam et al., 2004; De Rouck et al., 2009) and later extended in EurOtop (2018). To develop physically sound and accurate formulas, different dimensionless parameters (inputs and outputs) and functional forms (power, exponential, …) have been used in the literature. Commonly a conventional data mining approach such as curve fitting has been invoked (e.g. Owen, 1980; TAW, 2002) for this purpose. However, with the progress in the computational power, more sophisticated approaches Such as ANN (e.g. Van Gent et al., 2004; Kazeminezhad et al., 2010; Formentin et al., 2018), M5 (e.g. Bhattacharya et al., 2007; Etemad-Shahidi and Bali, 2012), Evolutionary Polynomial (Altomare et al., 2020), Gaussian Process Regression (Hosseinzadeh et al., 2021), XGBoost (Den Bieman et al., 2021) and Genetic Algorithm (e.g. Bonakdar et al., 2015; Koosheh et al., 2022), have been implemented in this field. However, the main shortcomings of the ANN approach are its opacity and complexity. The mean overtopping formula suggested by EurOtop (2018) for rubble mound structures is simple and transparent but inaccurate, as it could underestimate the mean overtopping discharge by more than 100 times (See Fig. 1) which is unsafe.

The objectives of this research are: (a) to validate and/or modify the existing database and incorporate the new data set into it, in order to provide a more comprehensive and reliable database and (b) to develop an improved and more physically sound formula for the estimation of mean overtopping rate at rubble mound structures. To achieve these, first, the existing data sets have been scrutinized, corrected, and extended (see data set section below). Then using physical reasoning

* Corresponding author. School of Engineering and Built Environment, Griffith University, QLD, 4222, Australia.
E-mail address: a.etemadshahidi@griffith.edu.au (A. Etemad-Shahidi).

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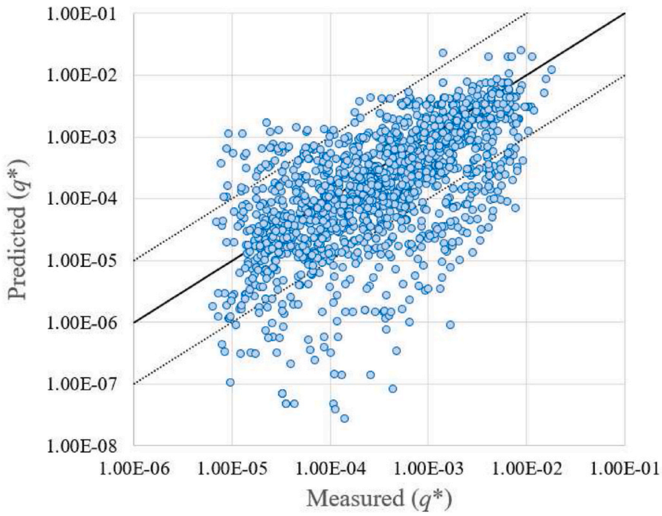

Fig. 1. Qualitative comparison of the measured and predicted mean overtopping discharges. using EurOtop (2018) formula, small-scale head on tests Dashed lines indicate 10 time under/overestimation.

and scaling argument a compact formula is suggested for simple slope rubble mound structures which considers both the effects of wave obliquity and wave walls. The developed formula has been validated with small-scale experiments as well as prototype tests. It is worth noting that this study complements previous ones (Etemad-Shahidi et al., 2020, 2021) to provide a suite of tool for the design of rubble mound structures that can be used by the end-users, i.e. coastal engineers.

2. Background

In a pioneering study, Owen (1980) conducted experiments on relatively simple seawalls (without wave wall), and derived the following formula for mean overtopping rate:

$$Q^* = \frac{q}{gH_{m0}T_z} = a\exp\left(-b\frac{R_c}{H_{m0}}\sqrt{\frac{s_{oz}}{2\pi}}\frac{1}{\gamma_f}\right) \tag{1}$$

where T_z is the mean zero crossing wave period, g is gravity acceleration, and q is the mean overtopping rate. The parameter H_{m0} represents the (significant) spectral wave height, and R_c is the crest freeboard (see Fig. 2).

s_{oz} is the fictitious wave steepness (based on $L_{0z}= g\,T_{zz}^2/2\,\pi$) defined as:

$$s_{oz} = \frac{H_{m0}}{L_{oz}} \tag{2}$$

The roughness (and permeability) reduction factor (γ_f) accounts for the roughness and percolation of different structures' slope. Here, a and b are empirical coefficients that depend on the seaward slope of the structure and wave angle.

Later on, the mean overtopping rate has been nondimensionalized using the square root of $g\,H_{m0}^3$ called q^* where $q^* \sim Q^*\,s_o^{-1/2}$. Using this approach, Van der Meer and Janssen (1994) developed the following formula set for low ("breaking waves") and high ("non-breaking waves") Iribarren numbers:

$$\text{If}\;\; Ir_{op} < 2 \text{ then }\;\; q^* = \frac{q}{\sqrt{g\cdot H_{m0}^3}} = \sqrt{\frac{\tan\alpha}{S_{op}}}0.06\exp\left(-5.2\frac{R_C}{H_{m0}}\frac{\sqrt{S_{op}}}{\tan\alpha}\frac{1}{\gamma_f\cdot\gamma_h\cdot\gamma_\beta}\right) \tag{3a}$$

$$\text{If}\;\; Ir_{op} \geq 2 \text{ then }\;\; q^* = \frac{q}{\sqrt{g\cdot H_{m0}^3}} = 0.2\exp\left(-2.6\frac{R_C}{H_{m0}}\frac{1}{\gamma_f\cdot\gamma_b\cdot\gamma_h\cdot\gamma_\beta}\right) \tag{3b}$$

where $Ir_{op} = \tan\alpha/s_{op}{}^{1/2}$ is the Iribarren number (based on peak period). γ_h accounts for shallow water effects for which in fact $H_{m0}/1.4H_{2\%}$ is used (unity in deep water with Rayleigh distribution). The effect of oblique wave attack has been accounted for by using γ_β and the product of reductions factors should be more than 0.5.

In a more recent study, Jafari and Etemad-Shahidi (2012) improved the existing formulas using the CLASH database (Steendam et al., 2004) and M5 approach and ended up to the following formula set:

$$\begin{cases} if\;\frac{R_C}{H_{m0}} > 2.08\; and\; \frac{G_C}{H_{m0}} > 1.51\; then \\ q^* = \exp(-0.64R^* - 0.71\tan\alpha - 11.49) \\ if R^* \leq 0.86\; then\; q^* = \exp(-6.18R^* - 3.21) \\ if R^* > 0.86\; then\; q^* = \exp(-3.1R^* - 6.05\tan\alpha - 2.63) \end{cases} \tag{4}$$

where G_c is the crest width and

$$R^* = \frac{R_C}{H_{m0}\cdot\gamma_\beta\cdot\gamma_f}\times\frac{\sqrt{S_{op}}}{\tan\alpha} \tag{5}$$

They showed that their formula set is more accurate than the previous formulas.

In EurOtop (2018), it was stated that the formula in the previous version of this manual is not performing well for very low crest structures and the following modified formula was presented:

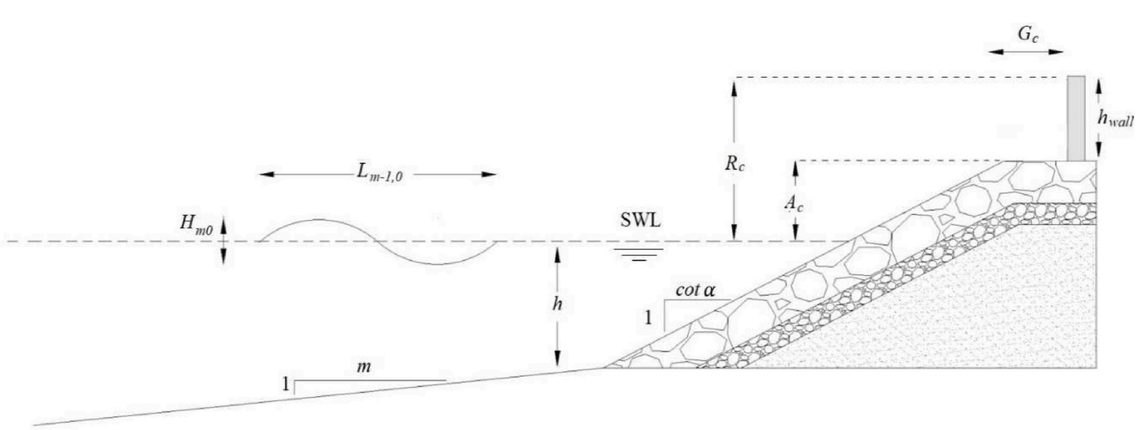

Fig. 2. Schematic cross section of rubble mound structures.

$$q^* = 0.09.\ \exp\left[-\left(1.5\frac{R_c}{H_{m0}\cdot\gamma_f\cdot\gamma_\beta}\right)^{1.3}\right] \quad (6)$$

The main differences of this formula with previous versions (TAW, 2002; Pullen et al., 2007) is that the power of argument has changed from 1 to 1.3 in order to incorporate structures with $R_c/H_{m0} < 0.5$ (EurOtop, 2018). Note that the power of reduction factors for roughness and oblique waves have also changed to 1.3. The recommended roughness factors are valid for $2.5 < Ir_{m-1,0} < 4.5$. EurOtop (2018) proposes the following modification for very steep slopes and/or very long waves with $Ir_{m-1,0} > 5$:

$$\gamma_{fmod} = \gamma_f + \frac{(Ir_{m-1,0} - 5)(1-\gamma_f)}{5} \quad (7)$$

The mean overtopping rate has a spatial distribution and decaying along the crest of the rubble mound structures. Hence, following Besley (1999), the below reduction factor has been suggested in EurOtop (2018):

$$C_r = 3.06\ \exp\ (-1.5\ G_c/H_{m0}) < 1 \text{ for } G_c > 3\ D_{n50} \quad (8)$$

It is noteworthy that neither Owen (1980) nor Van der Meer and Janssen (1994) considered effects of a permeable crest in their formulas (Lykke Andersen and Burcharth, 2004).

Recently, Koosheh et al. (2022), extended the existing database by conducting 2D experiments on steep seawalls within the design range and developed the following formula for the mean overtopping rate at rubble mound seawalls with an impermeable core:

$$q^* = 0.034\ exp\left[-4.97\left(\frac{R_c}{H_{m0}\cdot\gamma_f}\right)^{1.12}(s_{m-1,0})^{0.35}\right] \quad (9)$$

The main difference between their formula and that of EurOtop (2018) is including the effect of the wave period (in terms of wave steepness) which improved the prediction accuracy.

De Waal and Van der Meer (1992) noticed that the Owen (1980) approach is not suitable for all wave breaking conditions and suggested a mean overtopping formula based on the shortage in the crest height (Ru_{max}- R_c), which is physically sound and justifiable (see also Medina et al. (2001). Hence, this parameter has been used by some other researchers (e.g. Hedges and Reis, 2004; Ibrahim and Baldock, 2020; Altomare et al., 2020) to predict the overtopping rate. In addition, Chen et al. (2020) using the conventional approach for overtopping formula development defined a γ_f which in fact depends on $R_{u2\%}$ -R_c. Schüttrumpf and Van Gent (2003) also suggested that both overtopping flow thickness and velocity over the crest depend on the $(R_{u2\%} - R_c)/H_{m0}$.

To sum up, there are different approaches for developing mean overtopping formulae using different inputs and outputs and it seems that there is room for improvement which will be discussed below.

3. The data set

The used data set was the extended CLASH-database (or EurOtop 2018 database) enhanced by recent measurements of Koosheh et al. (2022). First, the references of the database were scrutinized to ensure that appropriate wave characteristics are reported (or estimated properly). In most of the references before 2000, $H_{1/3}$ (significant wave height based on time-domain analysis) and T_p have been reported. Hence, to provide a homogenized database that has the required parameters, $H_{1/3}$ was converted to H_{m0} for those shallow water tests that were not corrected. Then, similarly, $T_{m-1,0}$ was estimated using the method proposed by Hofland et al. (2017) (see Appendix A for details). Finally, the recent data set of Koosheh et al. (2022) was added to the database. This data set includes about 140 small-scale records of relatively steep rock armoured seawalls with an impermeable core.

To develop the formulas, first, small-scale head on tests of conventional rubble mound structures were selected. During scrutinizing of the references, it was also noticed that there are some tests on special cases (stepped seawalls, homogenous structures, …) that need to be excluded. The details of filters used for this purpose are provided in Appendix B. The parameter ranges, as well as the number of the records used for formula development and verification, are shown in Table 1. In this table, A_c is the armour crest level, β is the wave angle and S is the directional wave spreading.

Table 1
Range of parameters used for formula development and verification.

Parameter	Small scale Simple slope head on	Small scale Simple slope oblique	Prototype Simple slope head on + oblique	Small scale Wave wall head on
R_c (m)	0.03–0.30	0.04–0.18	4.06–6.05	0.08–0.37
A_c (m)	0.05–0.35	0.05–0.19	4.06–7.87	0.01–0.25
H_{m0} (m)	0.03–0.32	0.046–0.17	1.74–3.76	0.05–0.22
$T_{m-1,0}$ (s)	0.79–5.47	0.98–2.09	5.93–19.00	0.84–4.60
h (m)	0.08–0.73	0.15–0.54	4.00–9.32	0.11–1.01
G_c (m)	0.00–0.70	0.09–0.94	4.80–5.00	0.00–0.67
q (m^3/s/m)	$1.10 \times 10^{-6} - 1.02 \times 10^{-2}$	$1.06 \times 10^{-6} - 1.65 \times 10^{-3}$	$2.51 \times 10^{-6} - 8.59 \times 10^{-4}$	$1.10 \times 10^{-6} - 1.88 \times 10^{-3}$
β (deg)	0	6–60	0–40	0
S (deg)	0.00–10.00	0–10	0	0
R_c/H_{m0}	0.44–2.59	0.43–1.63	1.72–3.07	0.59–2.70
$tan\ \alpha$	0.25–0.80	0.5–0.75	0.25–0.71	0.25–0.75
$s_{m-1,0}$	0.002–0.07	0.019–0.06	0.004–0.049	0.003–0.067
$Ir_{m-1,0}$	1.32–11.74	2.04–4.64	1.87–4.67	1.27–11.63
G_c/H_{m0}	0.00–6.09	0.79–7.97	1.33–2.75	0.01–6.42
$G_c/L_{m-1,0}$	0.00–0.25	0.02–0.26	0.01–0.09	0.00–0.20
h_{wall}/R_c	–	–	–	0.01–0.95
No of records	1 392	386	88	644

4. Formula development

The mean wave overtopping rate depends on the wave characteristics (at the toe) and structure ones. Hence, for head on waves on single slope rubble mound structures without a crest wall, it can be assumed that:

$$q = f\ (H_{m0},\ T_{m-1,0},\ h,\ m,\ tan\ \alpha,\ R_c,\ G_c,\ \gamma_f) \quad (10)$$

where h is the water depth at the toe and m is the inverse of bed slope. Noting that wave overtopping occurs only when wave run-up exceeds the crest level, the nondimensional functional form of overtopping rate can be written as:

$$q^* = q/(g\ H_{m0}^3)^{1/2} = f\ [(Ru\text{-}\ R_c)/H_{m0},\ s_{m-1,0},\ m,\ Ir_{m-1,0},\ tan\ \alpha,\ G_c/H_{m0}\ (or\ G_c/L_{m-1,0}),\ h/H_{m0}] \quad (11)$$

This is based on the common approach where H_{m0} is used to nondimensionalize all dimensional variables with a length-scale, including the overtopping discharge. It should be mentioned that in some empirical formulas (following Owen, 1980) $Q^*=q/(gH_{m0}T_{m-1,0})$ was used as the dimensionless overtopping rate, which in fact means that an influence of the wave steepness or wavelength is incorporated in the non-dimensional overtopping rate. Our preliminary analysis showed that formulas for q^* perform better and hence it was used for further processing. The reason for choosing the wavelength (as well as the wave height) for scaling crest width is that some recent studies (e.g. Zanuttigh et al., 2016; Pillai et al., 2017) have found it more appropriate.

To obtain the best runup parameter, different runup levels were tested and $Ru_{2\%}$ given by EurOtop (2018) mean approach was applied here. This formula is:

$$R_{u2\%}/H_{m0} = 1.65\ \gamma_f\ \gamma_\beta\ Ir_{m-1,0} \leq 1.0\ \gamma_{f\ surging}\ \gamma_\beta\ (4.0\text{–}1.5/\sqrt{Ir_{m-1,0}}) \quad (12)$$

where

Table 2
Various input and output parameters used for the formula development.

Input parameters	Output parameters
$(Ru_{2\%}\text{-}R_c)/H_{m0}$	Q^*
$(Ru_{0.1\%}\text{-}R_c)/H_{m0}\ s_{m\text{-}1,0}$	q^*
m	
$\tan\alpha$	
$Ir_{m\text{-}1,0}$	
$G_c/L_{m\text{-}1,0}$	
$G_c/H_{m0}\ h/H_{m0}$	

$$\gamma_{f\ surging} = \gamma_f + (Ir_{m-1,0} - 1.8) \times (1 - \gamma_f)/8.2 \tag{13}$$

with a maximum of $R_{u2\%}/H_{m0} = 3.0$ (2.0) for structures with an impermeable (permeable) core.

The final selected dimensionless parameters, for both input and output of modeling, are shown in Table 2.

After dividing the data set to train (70%) and test (30%) subsets, different functional forms were tested. Considering the advantages of M5 data mining approach, such as transparency and its successful application for the prediction of mean overtopping rate (e.g. Etemad-Shahidi et al., 2016), it was used for formula derivation. The algorithm provided different formulas for different crest characteristics. However, detailed analysis showed that they can be merged to a single formula with a marginal loss of accuracy. Hence, considering the simplicity and accuracy, the following formulas were selected for further processing.

$$q^* = 9.51 \times 10^{-5} \ \exp\left[3.47\left(\frac{Ru_{2\%} - R_c}{H_{m0}}\right) - 13.16\left(\frac{G_C}{L_{m-1,0}}\right)\right] \tag{14a}$$

$$q^* = 1.22 \times 10^{-4} \ \exp\left[3.50\left(\frac{Ru_{2\%} - R_c}{H_{m0}}\right) - 0.64\left(\frac{G_C}{H_{m0}}\right)\right] \tag{14b}$$

where $\sigma\,(1.22 \times 10^{-4}) = 1.30 \times 10^{-5}$, $\sigma\,(3.50) = 0.13$ and $\sigma\,(0.64) = 0.07$.

As seen, the obtained formulas are very simple and compact and clearly show the role of different parameters such as shortage in the crest height and crest width in a physically sound and justifiable way. Simply saying, they indicate that the dimensionless mean overtopping rate is an exponential and direct function of the dimensionless difference between wave runup and crest level, a result in line with previous studies (e.g. Schüttrumpf and Van Gent, 2003; Hedges and Reis, 2004; Altomare et al., 2020). The second term of the formulas also shows that the mean overtopping rate is inversely and exponentially related to the crest width, which is in line with the findings of Besley (1999) and Mares-Nasarre et al. (2020). Simply saying, the percolation and trapping of overtopped water on the crest of rubble mound structures result in the reduction of mean overtopping rate and the longer the crest, the more the reduction.

The performance of the obtained formulas, as well as existing ones, are evaluated both qualitatively and quantitively in the next section. For this purpose, the following common accuracy metrics were used:

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(\log P_i - \log M_i) \tag{15}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\log P_i - \log M_i)^2} \tag{16}$$

where M_i and P_i are the dimensionless measured and predicted values, respectively; and n is the number of the records.

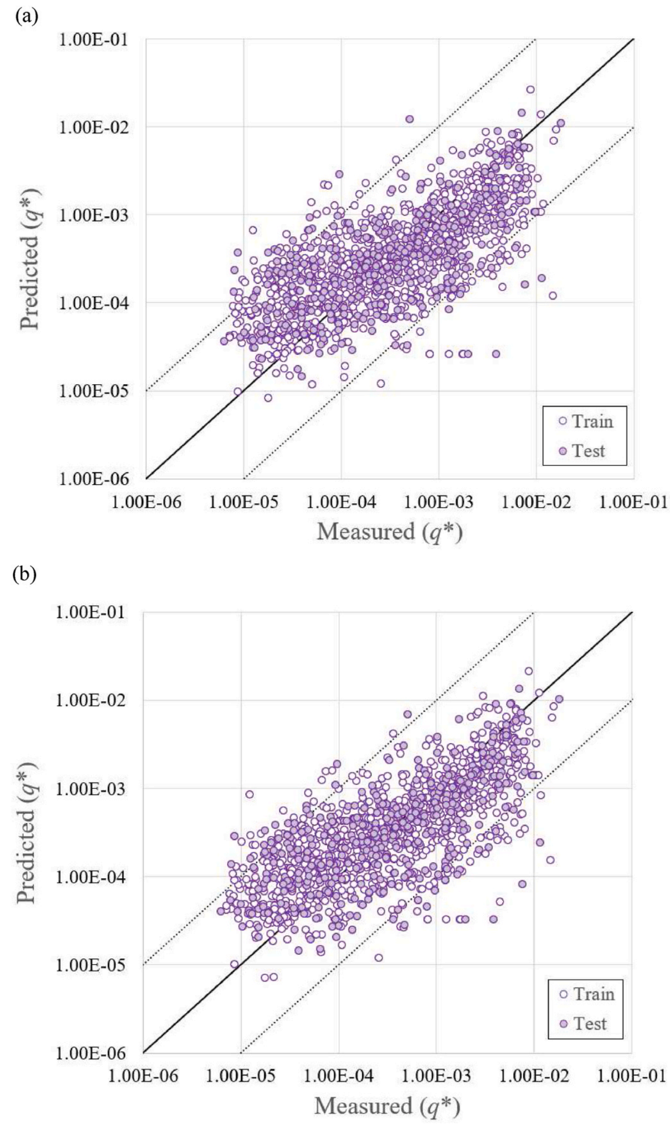

Fig. 3. Qualitative comparison of the measured and predicted mean overtopping discharges, small-scale head on tests (a): Eq. 14a, (b): Eq. (14) b. Dashed lines indicate 10 times under/overestimation and solid line shows perfect agreement.

Table 3
Accuracy metrics of different formulas, small-scale head on tests.

Formula	*BIAS*	*RMSE*
Owen (1980)	0.26	0.74
Van der Meer and Janssen (1994)	−0.30	0.80
Jafari and Etemad-Shahidi (2012)	−0.22	0.59
EurOtop (2018)	−0.60	0.98
Koosheh et al. (2022)	−0.20	0.62
Eq. 14a	0.00	0.55
Eq. 14b	**0.00**	**0.54**

5. Results and discussion

The scatter diagrams of measured and estimated dimensionless mean overtopping rates using the developed formulas (for small-scale head on tests) are shown in Fig. 3. As seen the spreading of the data is much less than that of EurOtop (2018) shown in Fig. 1 and generally speaking, the data points are closer to the optimal line, even though there are still some records which have been overestimated or underestimated by

Table 4
Summary of formulas used in the literature to account for wave obliquity in the prediction of mean overtopping.

Ref	Formula	Notes
Van der Meer and Janssen (1994)	$1 - 0.0033\beta$ *if* $\vert\beta\vert \leq 10^{\circ}$ 1 $cos^2(\beta - 10) > 0.6$ if $50 > \vert\beta\vert > 10^{\circ}$ if $\vert\beta\vert \leq 10$	Short crested waves Long crested waves
EurOtop (2018)	$1 - 0.0063\vert\beta\vert > 0.496$ 1 if $\vert\beta\vert \leq 10$ $\cos^2\vert\beta - 10\vert > 0.60$ if $\vert\beta\vert > 10$	Short crested Long crested
Lykke Andersen and Burcharth (2004)	1-(0.0077–0.000046 S) $\vert\beta\vert$	
Goda (2009)	1–0.0096 $\vert\beta\vert$ +0.000054$\vert\beta\vert^2$ $\vert\beta\vert \leq 80^{o}$	smooth structures
Van Gent and Van der Werf (2019)	$\gamma_\beta = (1 - c_\beta)\cos^2\beta + c_\beta$ with $c_\beta = 0.35$	Rubble mound breakwaters with a crest element
Van Gent (2020)	$\gamma_\beta = (1 - c_\beta)\cos^2\beta + c_\beta$ with $c_\beta = 0.35\left(1 + \frac{B}{H_{m0}}\right)^{-1}$	Dikes
Van Gent (2021)	$\gamma_\beta = (1 - c_\beta)\cos^2\beta + c_\beta$ with $c_\beta = 0.75/\gamma_p$	Vertical structures
Etemad-Shahidi and Jafari (2014)	$\gamma_\beta = 1 - 0.33\sin(\beta)$ $0^{o} \leq \vert\beta\vert \leq 80^{o}$	smooth sloped structures
Shaeri and Etemad-Shahidi (2021)	1–0.377 sin β + 0.054 sin^2 β	Vertical and battered structures
Eq. 14a	$\cos^2(\beta - 0.8\ S)$ $6 \leq \beta \leq 60^{o}$, $0 < S < 10$	Rubble mound structures
Eq. 14b	$\cos^2(\beta - 0.6\ S)$ $6 \leq \beta \leq 60^{o}$, $0 < S < 10$	Rubble mound structures

more than 10 times. In addition, the underestimation observed in the previous figure for low values of q^* has been rectified.

The qualitative comparisons of different formulas are shown in Table 3. In line with the scatter plots, the bias, as well as RMSE of developed formulas are minimum and less than those of other formulas. Nearly all existing formulas (except Owen, 1980), underestimate the measurements; similar to the results reported for the seawalls (Koosheh et al., 2022). Among the existing formulas, Jafari and Etemad-Shahidi (2012) shows the lowest value for the RMSE, which is comparable to those of the new ones.

5.1. Effect of wave obliquity

In real cases, incident waves are usually oblique and short crested which result in lower overtopping rates than those of perpendicular (head on) cases with the same characteristics. Hence, researchers have developed different reduction factors based on 3D experiments. A summary of the developed formulas is given in Table 4. Note that the expression for the influence of oblique waves depends on the wave overtopping expression in which it is applied. For instance, if for instance a reduction factor that is developed for Eq. (1) or 3, applying the same expression in Eq. (6) would lead to an overestimation of the effect of oblique waves. This is because in Eq. (6), the influence factor is raised to the power 1.3. Here, the influence factor for oblique waves is applied in the prediction of the wave run-up level, $R_{u2\%}$ (Eq. (12)).

The reduction factor for wave obliquity and spreading was obtained by curve fitting to the existing data, using Eq. (14). For this purpose, different function forms and wave angle information were tested and finally considering both the accuracy and physical justification, cos^2 ones given in Table 4 were selected for applications with wave angles between 0 and 60°. The new expressions show the dependency on the amount of energy reaching the structure under oblique waves. In addition, the formulas clearly quantify the effect of spreading and indicate that directional spreading will reduce the effect of wave obliquity on wave overtopping, in line with the existing knowledge. More importantly, they perform better than the oblique formulas from the literature. As shown in Fig. 4, nearly all predictions are within the range of 10 times over/underestimation and there is no bias in the predicted values.

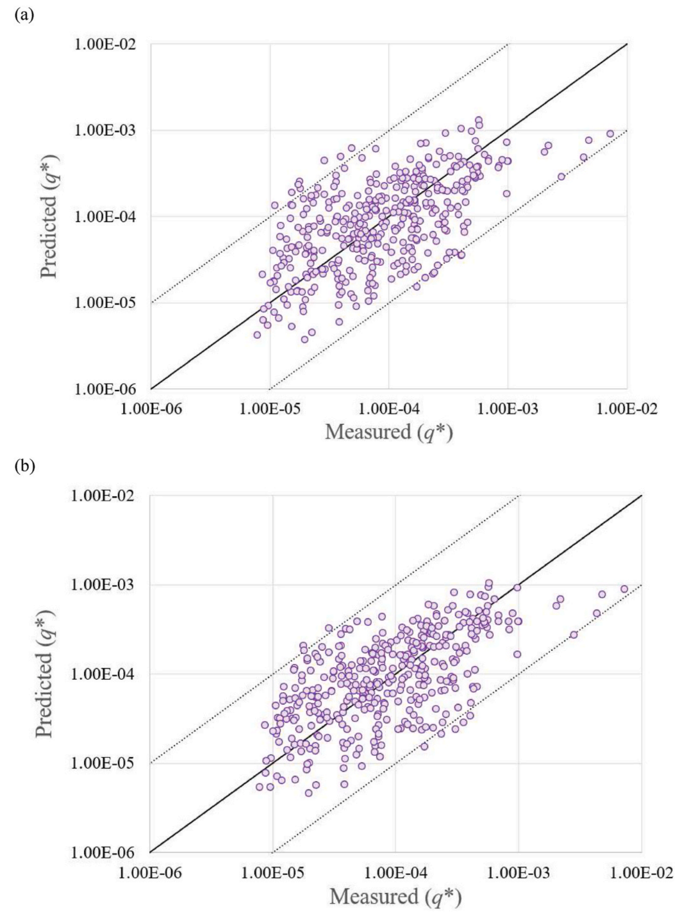

Fig. 4. Qualitative comparison of the measured and predicted mean overtopping discharges small-scale oblique tests (a) Eq. 14a, (b) Eq. (14b). Dashed lines indicate 10 times under/overestimation.

Table 5
Accuracy metrics of different formulas, small scale, oblique tests.

Formula	*BIAS*	*RMSE*
Owen (1980)	1.03	1.16
Van der Meer and Janssen (1994)	0.84	1.07
Jafari and Etemad-Shahidi (2012)	0.41	0.46
EurOtop (2018)	−0.10	0.64
Koosheh et al. (2022)	0.11	0.47
Eq. 14a	0.00	0.46
Eq. 14b	**0.00**	**0.44**

In this table, β is the angle of wave incidence and S is the directional spreading. Generally, these expressions show that the reduction factor is lower as the spreading decreases (long crested waves) and or obliquity increases.

Table 5 displays the quantitative comparison of different prediction formulas for oblique cases where the expressions have been applied in Eq. (12). As seen and in agreement with the scatter plots, both formulas are superior to others, with zero bias and minimum RMSE and Eq. (14b) is the best. Among the existing formulas, the formula of Koosheh et al. (2022) which has been corrected by EurOtop (2018) reduction factor, performs the best but is slightly conservative, while Owen (1980) performs the worst with the highest bias and RMSE.

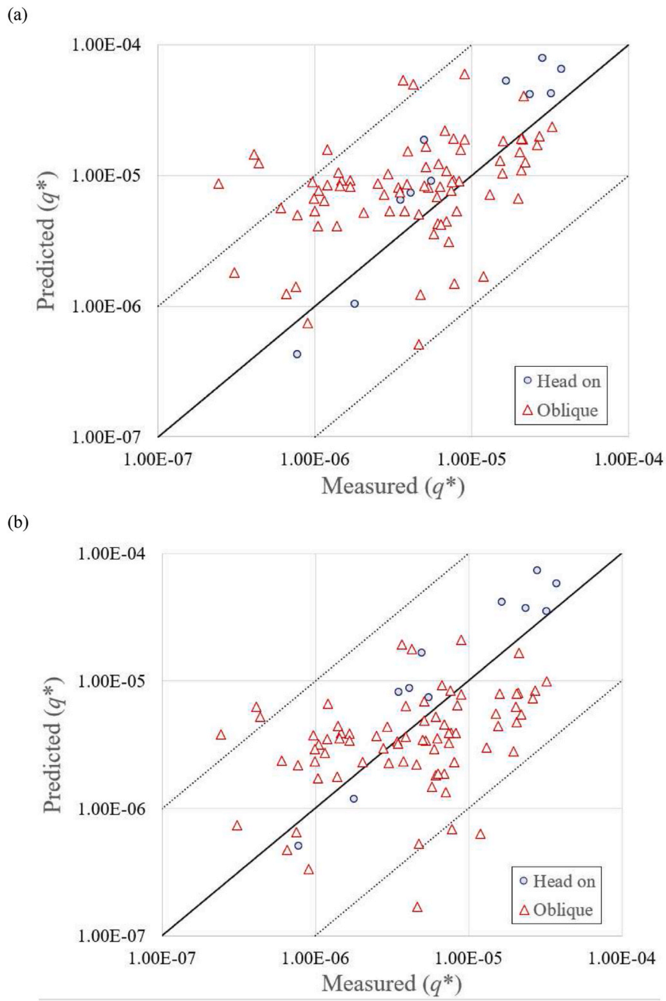

Fig. 5. Qualitative comparison of the measured and predicted mean overtopping discharges, prototype (head on and oblique) tests (a) Eq. 14a, (b) Eq. (14b). Dashed lines indicate 10 times under/overestimation.

Table 6
Accuracy metrics of different formulas, prototype tests.

Formula	*BIAS*	*RMSE*
Owen (1980)	−1.69	1.94
Van der Meer and Janssen (1994)	−0.73	0.90
Jafari and Etemad-Shahidi (2012)	−0.53	0.83
EurOtop (2018)	−2.31	2.44
Koosheh et al. (2022)	0.35	0.69
Eq. 14a (using γ_β Eq. 14a)	0.29	0.57
Eq. 14b (using γ_β Eq. 14b)	**−0.04**	**0.50**

5.2. Prototype tests

As the main purpose of design formula is the application to the real world, the formulas were also applied to the reported prototype cases ($H_{m0} > 0.5$ m) with both head on and oblique waves to evaluate their skills in those cases. Fig. 5 is given for a qualitative assessment of the developed formulas and to distinguish between head on and oblique wave cases, different symbols have been used in it. Both panels show that the head on measurements were predicted much better than oblique wave cases. As discussed by Etemad-Shahidi and Jafari (2014), this type of discrepancy could be because the measurements (e.g. wave direction and spreading) in the field is more challenging (compared to the lab conditions) as they may even change during the observations (see also Shaeri and Etemad-Shahidi, 2021).

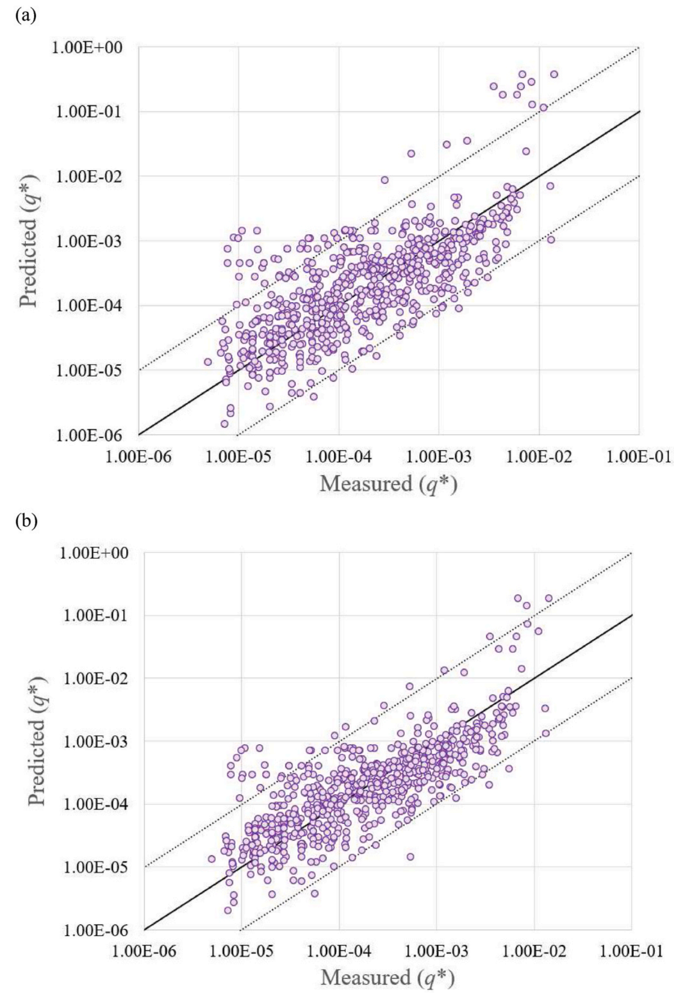

Fig. 6. Qualitative comparison of the measured and predicted mean overtopping discharges, small scale tests with wave wall (a): Eq. (14a) (b): Eq. (14b). Dashed lines indicate 10 times under/overestimation.

Table 6 shows the accuracy metrics and as seen both developed formulas outperform existing ones and Eq. (14b) is the best with nearly zero bias and the lowest value for the RMSE. Most of the existing formulas underestimate the measured values. This could be due to scale and model effects. Verhaeghe et al. (2008) suggested to use an enhancement factor to overcome this issue. Again, within the existing formulas, Owen (1980) performs the worst but underestimates the measured values this time; while Koosheh et al. (2022) has an acceptable performance, even though it has been developed for impermeable rubble mound structures.

5.3. Wave wall effects

Finally, the formula was modified to account for wave walls (without bull nose) on the crest. EurOtop (2018) suggests using the height of the wave wall rather than height of the armour crest when predicting the mean overtopping rate at rubble mound structures. In other words, no correction is introduced for rubble mound structures with a crest wall. However, for smooth dikes EurOtop (2018) suggests using the correction factor developed by Van DoorslaerDe Rouck and Van der Meer (2017) which depends on the ratio of the wall height (above the crest) to R_c. Applying the recommendation by EurOtop (2018) for a rubble mound structure with a crest wall yielded in inaccurate results when using the developed formulas. Hence, to account for effects of (vertical) wave

Table 7
Accuracy metrics of different formulas, small-scale head on waves with wave wall on the crest.

Formula	*BIAS*	*RMSE*
Owen (1980)	−0.13	0.69
Van der Meer and Janssen (1994)	−0.55	0.93
Jafari and Etemad-Shahidi (2012)	0.00	0.60
EurOtop (2018)	−1.10	1.43
Koosheh et al. (2022)	−0.55	0.92
Eq. 14a (using γ_w)	0.05	0.59
Eq. 14b (using γ_w)	**0.00**	**0.51**

walls, the following wall correction factor, needs to be applied in the estimate of the wave run up level, i.e. Eq. (12):

$$\gamma_w = \exp\,(0.10\ h_{wall}/\ R_c) \text{ for } h_{wall} > 0 \tag{17}$$

where h_{wall} $=R_c$-A_c is the height of the wall (above the crest). This correction factor varies between one in the absence of wave wall ($R_c = A_c$) to 1.10 for very high walls. This increase is because replacing an armour slope (or a part of it) with a vertical wall will result in more run-up. Fig. 6 compares the measured values of q^* at structures with wave wall against the.

estimations using the developed formulas. Even though there exist some scatter, especially at high values, still the performances of both formulas are acceptable and Eq. (14b) outperforms Eq. (14a) in this case.

Here, we also quantified the performance of the developed formulas for head on tests with vertical wave wall on the crest (Table 7). It should be mentioned that in all existing formulas, the correction suggested by Besley (1999) has been used.

Again, both developed formulas are superior to others and Eq. (14) b has the minimum bias and RMSE. Among the existing formulas, Jafari and Etemad-Shahidi (2012) shows the lowest value for the RMSE, which is comparable to those of the new ones. This can be due having a more complex configuration compared to other formulas. Noting the better performance of Eq. (14b) in all cases, it is suggested as the optimum one (for the mean approach).

5.4. *Design (semi-probabilistic) formula*

The adopted design approach is a semi-probabilistic approach with a partial safety factor. In this approach the uncertainty in the prediction is accounted for by adding one standard deviation of each fitted parameter (EurOtop 2018). Assuming a normal distribution, this leads to about 16% risk of having larger discharges (to account for uncertainties). The suggested design (probabilistic) formula, assuming a Gaussian distribution for parameters of eq. (14) b i.e. $\sigma\,(1.22\times10^{-4}) = 1.30\times10^{-5}$, $\sigma\,(3.50) = 0.13$ and $\sigma\,(0.64) = 0.07$ is.

$$q^* = 1.35\times10^{-4}\ \exp\left[3.63\left(\frac{Ru_{2\%}-R_c}{H_{m0}}\right) - 0.57\left(\frac{G_C}{H_{m0}}\right)\right] \tag{18}$$

Box 1
Summary of derived formulae and range of application

Deterministic formula (mean approach):

$q^* = 1.22\times10^{-4}\exp\left[3.50\left(\frac{Ru_{2\%}-R_c}{H_{m0}}\right) - 0.64\left(\frac{G_C}{H_{m0}}\right)\right]$ (14 b)

where $\sigma\,(1.22\times10^{-4}) = 1.30\times10^{-5}$, $\sigma\,(3.50) = 0.13$ and $\sigma\,(0.64) = 0.07$.

Design formula (including one standard deviation):

$q^* = 1.35\times10^{-4}\exp\left[3.63\left(\frac{Ru_{2\%}-R_c}{H_{m0}}\right) - 0.57\left(\frac{G_C}{H_{m0}}\right)\right]$ (18)

Runup estimation:

$R_{u2\%}/H_{m0} = 1.65\ \gamma_f\,\gamma_\beta\,\gamma_w\,Ir_{m\text{-}1,0} \le 1.0\ \gamma_{f\ surging}\,\gamma_\beta\,\gamma_w\,(4.0\text{–}1.5/\sqrt{Ir_{m\text{-}1,0}})$ (12)

where

$\gamma_{f\ surging} = \gamma_f + (Ir_{m\text{-}1,0} - 1.8)\times(1-\gamma_f)/8.2 \ge \gamma_f$ (13)

with a maximum of $R_{u2\%}/H_{m0} = 3$ (2) for impermeable (permeable) structures

reduction factor for oblique wave attack:

$\gamma_\beta = \cos^2(\beta - 0.6\ S)$ for $S < \beta$.

Correction factors for wave wall on the armour crest:

$\gamma_w = \exp\,(0.10\ h_{wall}/R_c)$ with a minimum of $\gamma_w = 1.0$ (17)

Range of applicability:

Parameter	Range
γ_f	0.38–0.6
R_c/H_{m0}	0.43–2.70
h/H_{m0}	0.9–13.8
$\tan a$	0.25–0.80
$s_{m\text{-}1,0}$	0.002–0.07
$Ir_{m\text{-}1,0}$	1.27–11.74
G_c/H_{m0}	0.0–7.97
β	0–60
S	0–10
h_{wall}/R_c	0.0–0.95

6. Limitation of the study

In this study, similar to most studies, it has been assumed that γ_f only depends on armour type and layer composition. However, there is some dispute about the (mean) values of γ_f given in design manuals (e.g. Molines and Medina, 2015). More importantly, in some studies (e.g. Bruce et al., 2009) it has been stated that γ_f may depend on the Iribarren number. We also speculate that γ_f is not constant and depends on both the overflow layer thickness and velocity, and hence overtopping flow rate. This is mainly because the thicker and/or the faster the overtopping flow, the less the role of roughness and percolation in the armour layer (see also Capel, 2015).

It is worth mentioning that about 20% of the records did not have any reference, and they were confidential. Hence, it was not possible to scrutinize and check the quality of relevant data sets. We think that those records need to be modified as the accuracy of the developed formulas was lower for them. In addition, it was noticed that there are about 35 records with wave steepness lower than 0.01 (out of the design range) where the mean overtopping rate was significantly underestimated by the developed formula. The developed formula does not cover structures with a berm or bullnose wave walls.

Noting the limited number of oblique tests on wave wall, it is recommended that future studies focus on this case to cover the white spots of the existing data sets.

7. Summary and conclusions

The aim of this study was to develop a robust, i.e. accurate and compact, formula for the estimation of the mean overtopping rate at simple slope rubble mound structures; as the most common one. Hence, first, the existing data sets were scrutinized, corrected, and extended to cover a wide range of parameters. Then using the physical arguments and scaling analysis, a formula was developed for mean overtopping rate as a function of the difference between the runup and crest levels, as well as the crest width. The obtained formula (Eq. (14b)) was validated using small-scale head on tests first. Next, it was modified for oblique wave attack for both long and short crested waves. The formula was also validated successfully for the large-scale data. Then, it was tested for cases with wave wall and a correction factor was suggested for it. Finally, the uncertainty of the formula was estimated, and a design formula (Eq. (18)) was suggested to account for uncertainties. This formula can be used for the (conceptual) design of rubble mound structures and for the assessment of existing structures with respect to wave overtopping. A summary of the developed formulas and the application ranges are shown in Box 1.

Some hints and a real world example are provided for practicing engineers in Appendix A.

CRediT authorship contribution statement

Amir Etemad-Shahidi: Conceptualization, Writing – original draft, Methodology, modeling. **Ali Koosheh:** conducted validation, Formal analysis, Visualization. **Marcel R.A. van Gent:** Methodology, performed review, Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Wave characteristics conversion and worked example

In shallow waters, H_{m0} could be less than $H_{1/3}$, especially for swell conditions. In that case, tables provided by Battjes and Groenendijk (2000) can be used to convert H_s to H_{m0} noting that the power of wave height in the formula developed for the inside of the surf zone should be 1.5 (personal communications). Similarly, Hofland et al. (2017) method can be used to estimate the spectral mean wave period at the toe, as a function of the offshore peak wave period.

In shallow waters, the wave distribution is not Rayleigh and the ratios between $H_{2\%}$ and $H_{33\%}$ (and $H_{0.1\%}/H_{2\%}$) is not constant. Battjes and Groenendijk (2000), using Laboratory data, provided a table for these ratios as a function of spectral wave height, water depth and bottom slope. For the ease of use, the following simple functions are obtained based on curve fitting to the values of their table:

$H_{0.1\%}/H_{2\%} = 1.117 \leq 0.702 + 0.2385\, H^*_{tr} \leq 1.33$ ($R^2 = 0.99$)
where $H^*_{tr} = H_{tr}/H_{rms}$, $H_{tr} = (0.35 + 5.8/m)\, h$, $H_{rms} = 0.25\,(0.167 + 0.203\, H_{m0}/h)\, H_{m0}$. This approximation can be used (instead of the table) to convert $Ru_{2\%}$ to $Ru_{0.1\%}$.

Worked example

Noshahr's breakwater information is used in this example to estimate mean overtopping rate at the lee side of the crest. The design conditions are (see Fig. 1):

$H_{m0} = 3.7$ m, $T_p = 11$ s $T_m = 10$ s, $T_{m-1,0} = 11.8$ s, $h = 7$ m, $m = 100$, rock two-layer, permeable core, $D_{50} = 1.23$ m, $\beta = 15^o$, $S = 0.5^o$, $\cot\alpha = 2$, $G_c = 13$ m, and $R_c = A_c = 4$ m

$$R_{u2\%}/H_{m0} = 1.65\, \gamma_f\, \gamma_\beta\, \gamma_w\, Ir_{m-1,0} \leq 1.0\, \gamma_{f\ surging}\, \gamma_\beta\, \gamma_w\, (4.0 – 1.5/\sqrt{Ir_{m-1,0}}) < 2$$

$\gamma_f = 0.4$ (rock two-layer, permeable core)

$$L_{m-1,0} = g/2\pi\, T^2_{m-1,0} = 1.56 \times 11.8^2 = 217.2 \text{ m}$$

$s_{m-1,0} = H_{m0} / L_{m-1,0} = 3.7/217.2 = 0.017$

$Ir_{m-1,0} = \tan\alpha / \sqrt{s_{m-1,0}} = 0.5/\sqrt{0.017} = 3.83 > 1.8$

$\gamma_{f\ surging} = \gamma_f + (Ir_{m-1,0} - 1.8) \times (1 - \gamma_f)/8.2 \geq \gamma_f$

$\gamma_{f\ surging} = 0.4 + (3.83–1.8)) \times (1–0.4)/8.2 = 0.55$

$\gamma_\beta = \cos^2(\beta - 0.6\,S) = \cos^2(15–0.6 \times 5) = 0.96$

$\gamma_w = 1$ (no wave wall)

$R_{u2\%}/H_{m0} = 1.65 \times 0.4 \times 0.96 \times 1 \times 3.83 \leq 1.0 \times 0.55 \times 0.96 \times 1\ (4.0–1.5/\sqrt{3.83}) < 2$

$R_{u2\%}/H_{m0} = \min(2.42, 1.70, 2) = 1.70$

$R_c/H_{m0} = = 4/3.7 = 1.08$

$(R_{u2\%} - R_c)/H_{m0} = 0.62$

$G_c/H_{m0} = 13/3.7 = 3.51$

$q^* = 1.22 \times 10^{-4} \exp\,[3.50\,(R_{u2\%} - R_c)/H_{m0} - 0.64\,G_c/H_{m0}]$

$q^* = 1.22 \times 10^{-4} \exp\,(3.5 \times 0.62–0.64 \times 3.51) = 1.12 \times 10^{-4}$

$q = 1.12 \times 10^{-4} \times (9.8 \times 3.7^3)^{1/2} = 2.5 \times 10^{-3} = 2.5$ L/s/m

The comparison of (mean approach) formulas are given below:

Formula	q (L/s/m)
Owen (1980)	115.0
Van der Meer and Janssen (1994)	4.56
Jafari and Etemad-Shahidi (2012)	0.10
EurOtop (2018)	0.03
Koosheh et al. (2022)	0.20
Eq. 14a	8.23
Eq. 14b	**2.5**

Appendix B

Summary of initial filters applied to the records of the collated databases.

Filter	Rationale
$q \geq 10^{-6}$ m^3/s/m	to disregard very small, unreliable, insignificant records, which could perhaps be affected by measurement errors
$RF \neq 4$	to disregard structures with the least reliable input/output parameters
$CF \neq 4$	to disregard records related to complex structures
$0.38 \leq \gamma_{f,u} \leq 0.6$	to select records of rubble mound structures
Non-conventional cases	To excluded stepped seawall, homogenous structure, highly compact armour layer, no filter layer
$B = 0$	to select records without structural berm on the structure slope (while there might still be a small toe berm in front of the structure toe)
$\cot\alpha_u = \cot\alpha_d$	to select records of single sloped structures
Bull nose (BN)	to excluded tests with bull nosed- wave wall
$Rc \leq A_c$	to remove structures with wave wall
$H_{m0,toe} < 0.5$ m	to select only small-scale data
$\beta = 0$	to select head-on (perpendicular) waves
$Ru_{0.1\%} - R_c > 0$	To select tests where structure was overtopped

It should be mentioned that a couple of outliers were excluded, and the last filters were removed (accordingly) later to include oblique waves, prototype and head wall records.

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