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THE COMPARISON OF EMPIRICAL FORMULAE FOR THE PREDICTION OF MEAN WAVE OVERTOPPING RATE AT ARMORED SLOPED STRUCTURES

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INTRODUCTION

Armored sloped structures are generally used to provide the safety of their lee side, i. e. harbours and coastal regions against wave attacks and storm surge. Recently, due to the potential impact of climate change, increasing emphasis has been placed on their hydraulic performance (e.g. Pillai et al. 2019). Thus, accurate estimation of wave overtopping rate, as the hydraulic response of coastal structures, has an important role in design. Wave overtopping is a complex phenomenon and depends on structural geometry and wave characteristics. Hence, empirical formulae are generally used for estimation of mean overtopping rate. These formulae have been derived from laboratory measurements in which the dimensionless measured overtopping rates are correlated with the dimensionless structural and hydraulic parameters through physical arguments. The most well-known formulae for wave overtopping prediction can be found in the Coastal Engineering Manual (2012) and European Overtopping Manual (EurOtop, 2018). The CLASH database as one of the most comprehensive datasets, was initially provided by De Rouck and Geeraerts (2005). This data base was recently updated by including more test results (EurOtop, 2018). However, a detailed comparison of formulae proposed for the estimation of overtopping rates at rubble mound sloped structures is not reported. The present paper aims to evaluate the performance of existing empirical formulae namely EurOtop 2018 (hereafter ET18), Owen (1982), van der Meer and Janssen (1995) (hereafter VMJ) and Jafari and Etemad-Shahidi (2012) (hereafter JES) against EurOtop database (updated CLASH database). The analysis includes structures with different armor types (rock, concrete cubes etc.) with both impermeable and permeable cores, to evaluate the capability of used formulae under different conditions.

METHOD AND DATASET

The new EurOtop (2018) database is an extension of the CLASH database and has more than 13,000 wave overtopping tests on a variety of coastal structures. Different filters were applied to the EurOtop database to select reliable and relevant data. First, based on reliability and complexity factors (RF and CF), the records with the lowest reliability and the highest level of complexity were excluded. Then, large-scale tests with H_{m0} > 0.5 m (e.g. Verhaege, 2005; Etemad-Shahidi and Jafari, 2014) were excluded due to possible scale effects. Very low overtopping rates (q < 10^{-6} m^3/s/m) were excluded which are likely to be affected by greater error measurements in small-scale tests (van Gent, 2007). Regarding structural geometry parameters, the records with simple slopes (without a berm) with 0.5 < tan α <0.75, emerged crest (R_c > 0) and no wave wall at the crest were selected. By selecting records with the surface roughness factor (γ_f) between 0.38 and 0.6 which covers the variety of armor layer types with both permeable and impermeable cores, a total number of1339 records were finally selected for the further analysis. The data set included both low crest and high crest structures, with 0.017 < R_c/H_{m0} <2.83. In addition, both sea and swell waves with 0.022 < $S_{m-1,0}$ < 0.079 were covered in the used data. The list of used formulae to predict dimensionless mean overtopping rate ($q^* = q/\sqrt{gH_{m0}^3}$) is given in Table 1. The predicted overtopping rates were then compared with those of measurements. Accuracy metrics such as BIAS (Eq.1) and RMSE (Eq. 2) were calculated to quantify the over/underestimation and scatter of results.

$$\text{BIAS} = \log(q^*_{\text{pred}}) - \log(q^*_{\text{mea}}) \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{(\log(q^*_{\text{pred}}) - \log(q^*_{\text{mea}}))^2}{\text{n}}} \quad (2)$$

Table 1 - Empirical formulae for the prediction of mean overtopping rate at armoured sloped structures

Formula	Equation
Owen	$q^* \frac{1}{T_m}\sqrt{\frac{H_{m0}}{g}} = a\ exp\ (-b \frac{R_c}{H_{m0}} \sqrt{\frac{s_{m0}}{2\pi}} \frac{1}{\gamma_f})$
VMJ	$\xi_p < 2$: $q^* \sqrt{\frac{S_{op}}{\tan\alpha}} = 0.06\ exp\ (-5.2 \frac{R_c}{H_{m0}} \frac{\sqrt{S_{op}}}{\tan\alpha} \frac{1}{\gamma_f\gamma_b\gamma_h\gamma_\beta})$ $\xi_p > 2$: $q^* = 0.2\ exp\ (-2.6 \frac{R_c}{H_s} \frac{1}{\gamma_f\gamma_b\gamma_h\gamma_\beta})$
ET18	$q^* = 0.09\ exp\ (-(1.5 \frac{R_c}{H_{m0}\gamma_f\gamma_b})^{1.3})$
JES	$q^* = \begin{cases} \exp(-0.639R^* - 0.7085\, tan\,\alpha - 11.4897); & \frac{R_c}{H_s} > 2.08\ and\ \frac{G_c}{H_s} > 1.5 \\ exp(-6.18R^* - 3.21); & R^* \leq 0.86 \\ exp(-3.1R^* - 6.05\, tan\,\alpha - 2.63); & R^* > 0.86 \end{cases}$

RESULTS

The predicted and measured values of dimensionless mean overtopping rate (q*) are compared in Fig1. As seen, the scatter of results (nearly for all formulae) becomes more at lower overtopping rates. It can also be inferred that JES formula has less scatter in general as that the predicted values lie between the 10 times over/under estimation lines. The significant underestimation of ET18 and VJM formulae can be easily seen for the low predicted rates. For the high rates of mean overtopping, the Owen formula has good predictions while it clearly overestimated most of the low rates.

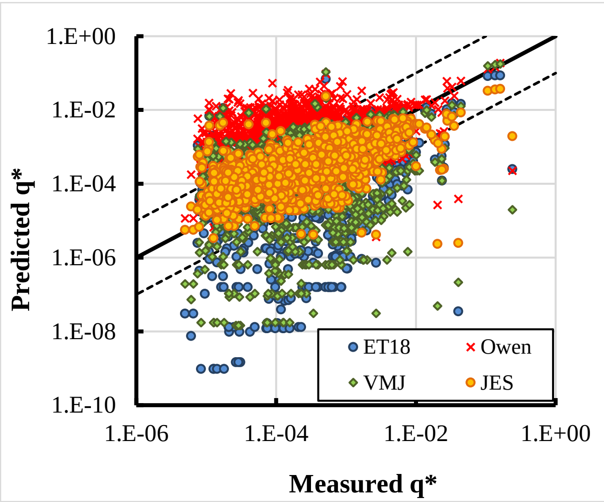

Figure 1 - Predicted vs measured dimensionless wave overtopping rate (q*) using different empirical formulae (the solid line displays perfect agreement and the others demonstrate 10 times, overestimation and underestimation)

Table 2 shows the results of mean overtopping rate prediction by empirical formulae. As can be seen, by having negative BIAS values, both ET18 and VMJ formulae underestimate the dimensionless mean wave overtopping rate at armored sloped structures. On the other hand, a significant overestimation (BIAS = 0.91) can be observed for Owen (1982) formula. Among all formulae, JES with a BIAS of 0.013 and a RMSE of 0.61 has the best performance. Surprisingly, Owen (1980) and VMJ as the classical formulae, give lower RMSE than that of ET18.

Table 2 - The results of prediction of mean overtopping rate

Formula	BIAS	RMSE
ET18	-0.29	1.28
Owen	0.91	1.25
VMJ	-0.30	1.18
JES	0.013	0.61

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