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Prediction of wave overtopping at vertical structures

Amir Etemad-Shahidi [a,*], Saeed Shaeri [a], Ebrahim Jafari [b]

[a] *Griffith School of Engineering, Gold Coast Campus, Griffith University, QLD 4222, Australia*
[b] *School of Civil Engineering, Faculty of Engineering, University of Tehran, Iran*

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ABSTRACT

Prediction of wave overtopping rate is an important step in the functional design of vertical coastal structures. In this study, scaling arguments and data mining approaches were used to derive formulae for the prediction of wave overtopping rate at fully vertical and nearly vertical impermeable solid smooth structures. An extensive database mainly selected from the CLASH including impulsive and non-impulsive waves, low and high freeboard and composite structures were used for formulae development. The obtained dimensionless overtopping rates were compared with those of existing formulae. The performances of formulae were first assessed quantitatively using laboratory tests mainly within the CLASH database; and it was shown that the developed formulae are more accurate than the previous ones. In addition, the developed formulae were applied to the field measurements. Results indicated that the developed formulae which consider the effects of all governing parameters, perform better than the previous empirical formulae with at least 18% and 31% *RMSE* improvement in predicting the overtopping rate in laboratory and field experiments, respectively.

1. Introduction

Vertical and nearly vertical coastal structures such as seawalls are designed and constructed to protect coastal regions against storm waves and high water levels during storm surges. The overtopping rates must be lower than the allowable rate both in normal operating and extreme conditions to guarantee the safety of both people and assets on and behind the structures (Goda, 2009). Therefore, an accurate prediction of wave overtopping rate is very important in the design and safety assessment of structures. In addition, consequences of climate change such as sea level rise and its effects on wave climate make the existing coastal defense structures more vulnerable to overtopping (Chini and Stansby, 2012).

Different approaches such as empirical, process-based and data mining approaches have been used for the prediction of overtopping rate in the last decade. Dimensional analysis and regression methods are commonly applied to data obtained from laboratory experiments to derive overtopping rate formulae. However, there is a large scatter (up to two orders of magnitude) between results obtained from different approaches and the measurements, especially for small overtopping rates (Lykke Andersen, 2006). De Gerloni et al. (1991), using random wave flume test, studied different configurations of vertical and composite breakwaters. They noticed that the ratio between maximum and mean wave overtopping values depends on the geometry of the structure. Franco and Franco (1999), using extensive laboratory experiments, studied the effects of wave obliquity, multi-directionality and shortcrestedness on non-breaking wave overtopping. They derived an exponential formula for the overtopping rate and reported that multi-directionality and wave obliquity reduce the overtopping rate.

A major improvement in providing an insight into the process of overtopping was the CLASH project (De Rouck et al., 2009). Analysis of dataset collected in this project has resulted in different formulae such as those of EurOtop (Pullen et al., 2007), Goda (2009), and Van der Meer and Bruce (2014). However, there is still some level of divergence in the existing formulae (Van der Meer and Bruce, 2014). To resolve these issues, Van der Meer and Bruce (2014) reanalyzed the existing formulae and suggested a decision tree approach with six different power and exponential formulae for the prediction of wave overtopping rate. Recently Troch et al. (2014) studied the wave overtopping at low crested structures and noticed the low performance of existing formulae for steep slopes.

Due to the complexity of overtopping process, data mining approaches such as artificial neural network (ANN) have been used to predict mean wave overtopping rate for a wide range of coastal structures as a part of the CLASH project. In EurOtop, an ANN model (Van Gent et al., 2007) was proposed for different types of coastal structures. In order to improve the prediction accuracy, Verhaeghe et al. (2008) developed a 2-phase neural prediction model to classify and quantify the overtopping rate. However, by contrast to empirical approaches, ANN models lack transparency and do not provide physical insight (Jafari and Etemad-Shahidi, 2012).

The purpose of this study was to overcome the shortcomings of the previous approaches by providing physically sound and accurate formulae for estimation of wave overtopping rate at vertical and nearly vertical structures. To achieve this, scaling arguments and model tree

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[*] Corresponding author.
E-mail address: a.etemadshahidi@griffith.edu.au (A. Etemad-Shahidi).

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approaches were used to find explicit relationships between dimensionless governing parameters. Model trees have also been used in civil engineering problems recently (e.g. Bhattacharya et al., 2007; Bonakdar and Etemad-Shahidi, 2011; Bonakdar et al., 2015; Etemad-Shahidi and Bali, 2011; Etemad-Shahidi et al., 2011; Kazeminezhad and Etemad-Shahidi, 2015; Sakhare and Deo, 2009). An extensive database, including small and large scale experiments from CLASH (Van der Meer et al., 2009) and some other experiments were used to develop the formulae; and the results were compared with those of the existing ones such as those given in EurOtop (Pullen et al., 2007), Goda (2009) and Van der Meer and Bruce (2014).

1.1. Database

The laboratory dataset used in this study is a combination of the database created by the EU-financed CLASH project (De Rouck et al., 2009), and Allsop et al. (1995). In addition, full scale measurements of the Samphire Hoe seawall Pullen and Allsop (2004) were used for the validation stage. Within the CLASH project, an extensive database on wave overtopping, consisting of both small and large scale experiments, was collected. The database includes many tests from different experiments conducted worldwide using different measurement tools and precisions. Details of the CLASH database and experiments can be found in Verhaeghe (2005) and Van der Meer et al. (2009). Experiments of Allsop et al. (1995) also consist of both small scale and large scale tests, conducted on vertical walls with a fixed (1:50) foreshore slope.

In total, the used dataset contains 688 data points from 25 laboratory tests. The used field data from Samphire Hoe seawall were 23 full scale measurements at different water levels and storm conditions. In the CLASH database a complexity factor *CF*, ranging from $CF = 1$ for a very simple structure to $CF = 4$ for complex structures has been given to each structure. Similarly, a reliability factor *RF* ranging from $RF = 1$ for a very reliable test to $RF = 4$ for a non-reliable test has been assigned to each test (Van Gent et al., 2007). In order to increase the reliability of the results, only data points with $CF < 4$ and $RF < 4$ were used in this study. Noting that tests with very low overtopping rates may not be accurate due to measurement errors, following Van Gent et al. (2007) and Verhaeghe et al. (2008), only tests with discharge rate per unit width $\geq 1 \times 10^{-6}$ m^3/s/m were used for further processing. Furthermore, tests of incident waves with an incident angle greater than 5°, non-smooth/permeable structures, and inclined structures with $\cot\alpha$ more than 0.1 were excluded.

Scale and model effects are of concern in laboratory experiments. Therefore, large scale data (with wave heights more than 0.5 m) and field measurements were not used during the model development process to evade model confusion (Verhaeghe, 2005; Jafari and Etemad-Shahidi, 2012). Finally a few outliers were removed. In other words, the model was developed based on the small scale laboratory experiments and then validated using field measurements. The ranges of the dimensional parameters used in the current study are shown in Table 1. As seen, the used database has wide ranges of dimensional parameters.

Table 1
Ranges of dimensional parameters of the used dataset.

Parameter	Laboratory experiments	Field measurements
$R_C\,[m]$	0.010–1.46	5.590–8.345
$H_{m0}\,[m]$	0.029–0.498	1.256–2.531
$d\,[m]$	0.050–1.28	1.383–3.425
$h\,[m]$	0.050–1.28	2.295–5.05
$L_{m-1,0}\,[m]$	0.983–23.191	58.903–89.814
$\cot\alpha\,[-]$	0.0–0.10	0.0
$\tan\theta\,[-]$	0.001 (flat)–0.10	0.033
β	0.00–5.00 (0–45 for Eq. (23))	0.78–30.0
$q\,[m^3/s/m]$	1.021×10^{-6}–1.443×10^{-2}	5.0×10^{-5}–3.30×10^{-3}

1.2. Evaluation of existing formulae

The CLASH project was conducted to provide a comprehensive dataset of overtopping rate and unified the different European design manuals. One of the outputs of this study was the publication of EurOtop (Pullen et al., 2007) and provision of formulae for different structures. EurOtop recommends different formulae with different forms for breaking (impulsive) and nonbreaking (non-impulsive) waves. The probabilistic formula given for non-impulsive waves ($h_* > 0.3$) is as follows:

$$q^* = \frac{q}{\sqrt{gH^3_{m0}}} = 0.04\exp\left(-2.6\frac{R_C}{H_{m0}}\right) \quad \text{for } 0.1 < R_c/\,H_{m0} < 3.5 \tag{1}$$

where h_* is the discriminating impulsiveness parameter defined as:

$$h_* = 1.35\frac{h}{H_{m0}}\frac{2\pi h}{gT^2_{m-1,0}} = 1.35\frac{h^2}{H_{m0}L_{m-1,0}} \tag{2}$$

where h is the water depth at the toe of the structure, H_{m0} is the wave height at the toe of the structure, q is the mean overtopping discharge per unit width, $T_{m-1,0}$ is the mean deep water wave period, $L_{m-1,0}$ is the fully deep wave length based on $T_{m-1,0}$ ($L_{m-1,0} = gT^2_{m-1,0}/2\pi$), q^* is the dimensionless overtopping rate per unit width, and R_C is the structure crest freeboard. For cases with zero freeboard, an average value of 0.062 is suggested for q^*.

For impulsive condition with $h_* < 0.2$, EurOtop suggests the following formulae:

$$q* = \frac{q}{h_*^{\,2}\sqrt{gH_{m0}^{\,3}}} = 1.5 \times 10^{-4}\left(h_*\frac{R_C}{H_{m0}}\right)^{-3.1} \text{for } 0.03 < h_*R_c/H_{m0} < 1.0 \tag{3}$$

$$q* = \frac{q}{h_*^{\,2}\sqrt{gh^3}} = 2.7 \times 10^{-4}\left(h_*\frac{R_C}{H_{m0}}\right)^{-2.7} for\ h_*R_c/\,H_{m0} < 0.02. \tag{4}$$

For other conditions, it is recommended to use the equation that gives the more conservative rate. In addition, a correction factor of 1.3 is given for 10:1 battered walls.

For composite walls with a berm or toe, h_* in Eq. (1) needs to be replaced by a modified impulsiveness parameter, defined as:

$$d_* = 1.35\frac{d}{H_{m0}}\frac{2\pi h}{gT^2_{m-1,0}} \tag{5}$$

where d is the berm depth. For impulsive conditions, the following formula is recommended for composite walls:

$$q* = \frac{q}{d_*^{\,2}\sqrt{gd^3}} = 4.1 \times 10^{-4}\left(d_*\frac{R_C}{H_{m0}}\right)^{-2.9} \text{for } 0.05 < d_*R_c/H_{m0} < 1.0. \tag{6}$$

Scatter diagram of the measured and predicted overtopping rates by the aforementioned formulae given by EurOtop (Pullen et al., 2007) for the laboratory datasets is shown in Fig. 1. The inclined upper dashed line, solid line and lower dashed line are representative of 10 times over estimated, perfect agreement, and 10 times under estimated limits, respectively. It is clear from Fig. 1 that there is a large scattering which predictions are mostly overestimated for low values of dimensionless discharge rates. This was also noticed by Goda (2009), especially in steep-bed slopes in relatively shallow waters.

In an attempt to provide an improved and unified formula for wave overtopping rate at vertical and inclined walls, Goda (2009) reanalyzed the CLASH dataset. He noticed the inadequacy of EurOtop formulae for shallow water with steep slope condition. Using the exponential function form, Goda (2009) included the effects of seabed slope and relative