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Distribution of individual wave overtopping volumes in shallow water wave conditions

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ABSTRACT

This paper contributes to a better knowledge on the distribution of individual wave overtopping volumes in shallow-water wave conditions. Results from new two-dimensional physical model tests on typical rubble-mound breakwater geometries indicate that the formulae by Besley (1999) are underestimating the number of individual overtopping waves in non-Rayleigh-distributed, shallow-water wave conditions. Additionally, the proposed shape factors by Franco et al. (1994), Van der Meer and Janssen (1994), Victor et al. (2012) in the two-parameter Weibull-distribution, which is normally used for describing individual wave overtopping volumes, have been seen to over predict the largest overtopping volumes in depth-limited waves. Correction terms based on the incident wave height distributions are introduced in the present paper to modify the existing formulations by Besley (1999), Franco et al. (1994), Van der Meer and Janssen (1994), and Victor et al. (2012). The modifications significantly improve the predictions of the largest overtopping volumes in shallow-water wave conditions.

1. Introduction

Wave overtopping can affect buildings, persons etc. located behind a sea defence structure and is usually specified as a design parameter with a specific return period. Normally, the average wave overtopping rate, q, is used as a design parameter. However, in recent time Franco et al. (1994) suggested instead to use the individual wave overtopping volumes as design criteria, such as the maximum individual wave overtopping volume during a design storm, V_{max}, since this is believed to provide a better design measure than the average overtopping rate. The reason is that the largest overtopping volumes during the storm will most likely cause the damages to buildings etc. in the hinterland. The EurOtop manual by Pullen et al. (2007) provided tolerable individual wave overtopping levels.

Several researchers have suggested probability distribution functions for individual wave overtopping volumes on coastal defence structures; Franco et al. (1994), Van der Meer and Janssen (1994), Besley (1999), Pullen et al. (2007), Lykke Andersen et al. (2009), and Victor et al. (2012). Many studies are, however, based on relatively deep-water wave conditions, and are believed to provide conservative predictions of the largest individual wave overtopping volumes in depth-limited conditions.

It should, however, be mentioned, that the depth-limitation effects have gained an increasing attention in recent time. As an example, Pullen et al. (2007) used the first negative moment of the energy spectrum, $T_{-1,0}$, in many of the design formulae instead of the commonly used peak period, T_p. The reason is that $T_{-1,0}$ is proportional to the wave energy flux and is thus more appropriate than T_p to introduce the effects of changes in the energy spectra in shallow water wave conditions, c.f. Van Gent (2001).

This paper presents a review of the state of art knowledge including an evaluation of the performance of existing formulations in depth-limited wave conditions by comparing them against new two-dimensional physical model tests in shallow-water wave conditions. Based on this, modifications are suggested to more effectively account for the effects of shallow-water wave conditions in existing distribution functions for individual overtopping wave volumes from previous studies.

2. Existing knowledge

The probability of wave overtopping is defined by (1) in which N_{ow} is the number of individual overtopping waves and N_w is the total number of waves.

$$P_{ow} = \frac{N_{ow}}{N_w} \tag{1}$$

The number of individual overtopping waves can be predicted from (2) given by Besley (1999) where T_m is the mean wave period in the time domain, H_s is the significant wave height in the time domain at the toe of the structure, and q is the average overtopping rate.

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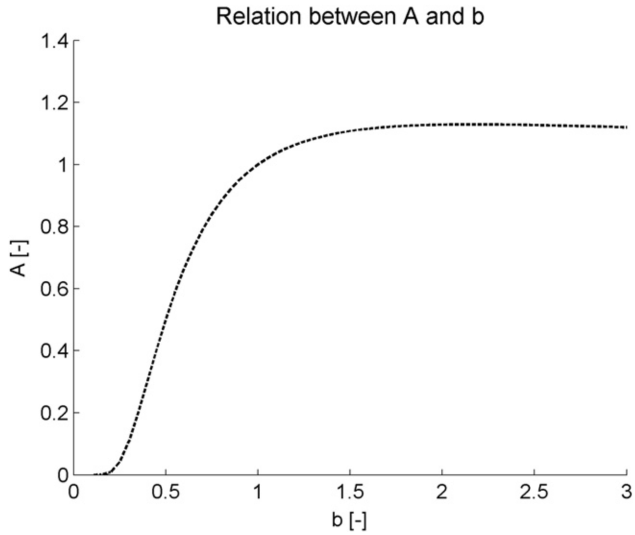

Fig. 1. Relation between *A* and *b*.

$$\frac{N_{ow}^{Besley}}{N_w} = 55.4 \cdot Q_*^{0.634} \qquad \text{for } Q_* < 8 \cdot 10^{-4}$$
$$\frac{N_{ow}^{Besley}}{N_w} = 2.50 \cdot Q_*^{0.199} \qquad \text{for } 8*10^{-4} < Q \le 1*10^{-2}, \qquad Q_* = q/(T_m \cdot g \cdot H_s)$$
$$\frac{N_{ow}^{Besley}}{N_w} = 1 \qquad \text{for } Q_* > 1 \cdot 10^{-2} \tag{2}$$

Other formulations for prediction of N_{ow} are presented in Pullen et al. (2007). However, these exclude the effect of the crest berm B, which is included in q in (2). Thus, since different B are evaluated in the present study, as explained later, solely the formulation in (2) is considered in the present paper.

A study on the probability distribution of individual wave overtopping volumes was carried out by Franco et al. (1994) for vertical wall breakwaters. They found that the distribution of the individual wave overtopping volumes is well fitted by a two-parameter Weibull distribution. The non-exceedance probability is thus given by (3) where $\overline{V}$ is the mean volume per individual overtopping wave. A and b are the scale factor and the shape factor, respectively. V_i is the individual wave overtopping volume.

$$F(V \ge V_i) = 1 - \exp\left[-\left(\frac{V_i/\overline{V}}{A}\right)^b\right] \tag{3}$$

By using the Weibull plotting position formula, $F(V_i) = 1 - i/(N_{ow}+1)$, the distribution function can be expressed by (4), cf. Lykke Andersen et al. (2009).

$$\frac{V_i}{\overline{V}} = A \cdot \left[-Ln\left(\frac{i}{N_{ow}+1}\right)\right]^{1/b} = A \cdot [Ln(N_{ow}+1) - Ln(i)]^{1/b} \tag{4}$$

The maximum individual wave overtopping volume per meter width, V_{max}, can be determined by setting the rank i to 1 which leads to the expression (5). This is similar to the formulation for V_{max} presented in Pullen et al. (2007) except that they used N_{ow} instead of $N_{ow} + 1$. Lykke Andersen et al. (2009) noted that the formulation in Pullen et al. (2007) would predict $V_{max}/\overline{V} = 0$ for $N_{ow} = 1$ and thus their formulation is only valid for $N_{ow} > 5$–10. However, since many coastal protection structures are designed to obtain small N_{ow} solely the formulation in (5) is considered in this paper.

$$V_{max} = A \cdot [Ln(N_{ow}+1)]^{1/b}\, \overline{V} \tag{5}$$

The mean individual wave overtopping volume $\overline{V}$ is given by (6) which introduce a new expression for V_{max}. V_{total} is the total overtopping wave volume per meter width during a storm.

$$\overline{V} = \frac{V_{total}}{N_{ow}}$$
$$V_{max} = \frac{A}{N_{ow}} \cdot [Ln(N_{ow}+1)]^{1/b} \cdot V_{total} \tag{6}$$

The mean value of a Weibull distribution, μ_V, given by (7), has to be equal to the mean individual wave overtopping volume and thus sets a relationship between for A and b. Γ is the mathematical gamma function.

$$\mu_V = A\Gamma\left(1 + \frac{1}{b}\right) = \overline{V} \tag{7}$$

From this, the relation between A and b is obtained given by (8) which is illustrated in Fig. 1.

$$A = \frac{1}{\Gamma\left(1 + \frac{1}{b}\right)} \tag{8}$$

b was found by Franco et al. (1994) and Van der Meer and Janssen (1994) to be approximately 0.75 for respectively caisson breakwaters and dikes in relatively deep water. The shape factor was assumed to be constant for geometrical changes of the structures. However, according to Pullen et al. (2007), b is likely to increase in shallow-water wave conditions.

Victor et al. (2012) did a more detailed analysis on the values of b, based on two-dimensional physical model tests, in which the shape factor was fitted to the distribution of measured individual wave overtopping volumes in each dataset. The aim was to improve the knowledge on the probability distribution of individual wave overtopping volumes on steep, low-crested smooth structures such as floating wave energy converters. The effect of slope angle, non-Rayleigh-distributed incident waves, relative crest freeboard, and wave steepness was evaluated. A prediction formula for b was suggested based on the trends in the findings, and was concluded to fit relatively well to the b-values obtained from the different tests, although with some scatter. The tests by Victor et al. (2012) indicated an exponential decreasing trend of the shape factor b for increasing relative crest freeboard in the range $0.1 \le R_c/H_{m0} \le 1.69$ (i.e. for relative small freeboards), where H_{m0} is the significant wave height based on frequency domain analysis and R_c is the crest height. Additionally, a linear increase in b was observed for an increasing slope angle in the range $0.36 \le \cot\alpha \le 2.75$ (i.e. for relatively steep slopes). The non-Rayleigh-distributed waves

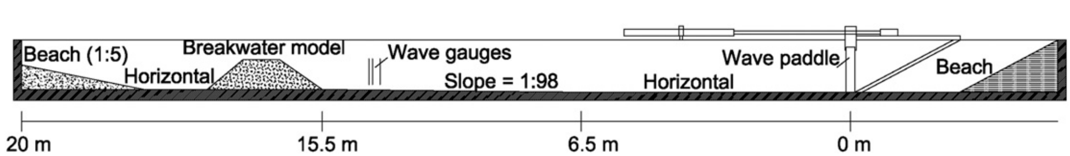

Fig. 2. Layout of model test in 2D wave flume.