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Full-scale laboratory study on distribution of individual wave overtopping volumes over a levee under negative freeboard

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ABSTRACT

Wave overtopping parameters are key parameters in the design of levees and the management of coastal protection. This paper presents the distribution of wave overtopping volume and instantaneous overtopping discharge under negative freeboard. The analysis and discussions are based on the results of full-scale flume tests for a levee section in the combined wave and surge overtopping. Four wave overtopping patterns under negative freeboard were observed. Weibull distribution was used to represent the distribution of individual overtopping volumes and the distribution of instantaneous overtopping discharge. Based on the hydraulic characteristics of wave overtopping under negative freeboard, empirical equations for Weibull factors were developed in the two different ranges of relative freeboard. The new equation gives better estimates of Weibull factors for the low discharge condition.

1. Introduction

Wave overtopping on levees is one of the important issues in coastal engineering field. The wave overtopping parameters are key parameters in the design of levees and the management of coastal protection. The most representative overtopping parameter is the average overtopping discharge q_w, which is used in the design of the crest elevation of levees. Several studies have been conducted on the distribution of the individual wave overtopping volumes under positive freeboard (e.g., Besley, 1999; Franco et al., 1994; Lykke Andersen et al., 2011; Nørgaard et al., 2014; Pullen et al., 2007; Van der Meer and Janssen, 1994; Victor et al., 2012). The freeboard is defined as vertical distance between the still water elevation and crest elevation. A positive freeboard means incoming still water elevation below crest elevation. Fig. 1 illustrates the wave overtopping under positive, zero and negative freeboard and surge overflow.

During storm surge, wave overtopping is more dangerous under negative freeboard than under positive freeboard. Analysis showed that during overtopping, the landward-side slope of levees was exposed to significantly higher velocities and much greater erosive forces than the flood-side slope (Hughes and Nadal, 2009). The climate changes lead to the sea level rising at an increased rate and storms increasing in intensity and duration (IPCC, 2007), which increases the risk of wave overtopping under negative freeboard. Since hurricane Katrina, wave overtopping under negative freeboard has been studied by several researchers (Li et al., 2012, 2014; Pan et al., 2013a, 2013b; Rao et al., 2012; Yuan et al., 2014a, 2014b). Hughes and Nadal (2009) initially investigated distribution of individual wave overtopping volumes for levees under negative freeboards via a series of 25-to-1 flume tests. Pan et al. (2013a, 2013b) conducted a series of full-scale tests to investigate the hydraulic characteristics of wave overtopping under negative freeboard and the erosion resistant performance of three different levee strengthening system, including Roller Compacted Concrete (RCC), Articulated Concrete Block (ACB), and High Performance Turf Reinforcement Mat (HPTRM).

The analysis and discussions in this paper are based on the measurements and observations of full-scale flume tests (Pan et al., 2013a). Four observed wave overtopping patterns are divided into two categories. In each category, empirical equations were given to estimate the probabilities of occurrence. Results of the full-scale tests indicate that, under negative freeboard, some of the overtopping parameters show distinctly different behaviors over the range of negative relative freeboard R_c/H_{m0} [−] (e.g., $R_c/H_{m0} < -0.3$ and $-0.3 \leq R_c/H_{m0} < 0$) as illustrated by the variation of dimensionless discharge shown in Fig. 2. The goal of this paper is to study the distribution of wave overtopping volume and instantaneous overtopping discharge under negative freeboard in the ranges of $R_c/H_{m0} < -0.3$ and $-0.3 \leq R_c/H_{m0} < 0$ separately. Weibull distribution is used to represent both individual wave overtopping volume and instantaneous overtopping discharge. The distribution parameters of the full-scale tests are compared to

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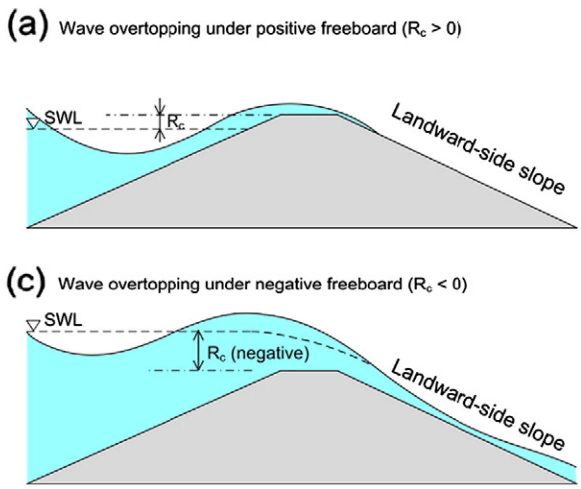

Fig. 1. Wave overtopping under positive, zero and negative freeboard and surge overflow.

Hughes and Nadal (2009), and the differences between the results are discussed. New equations are presented for individual wave overtopping volume and instantaneous overtopping discharge to obtain better estimations. Because the tested levee strengthening systems are installed only on levee crest and land-side slope, the levee strengthening systems have little influence on the overtopping pattern, the distribution of wave overtopping volume, and the distribution of instantaneous overtopping discharge. The effects of levee strengthening systems are not discussed herein.

2. Background

The probability of overtopping P_{ow} is defined by the ratio of overtopping number of waves N_{ow} and incoming number of waves N_w as

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

Besley (1999) gives the formulae for prediction of probability of overtopping in design and assessment manual of seawalls:

$$P_{ow}^{\text{Besley}} = \begin{cases} 55.41 Q_*^{0.634} & \text{for} \quad 0 < Q_* < 0.008 \\ 2.502 Q_*^{0.199} & \text{for} \quad 0.008 \le Q_* < 0.01 \\ 1 & \text{for} \quad Q_* \ge 0.01 \end{cases} \tag{2}$$

where Q_* [−] is the dimensionless average overtopping discharge:

$$Q_* = \frac{q_w}{T_m g H_s} \tag{3}$$

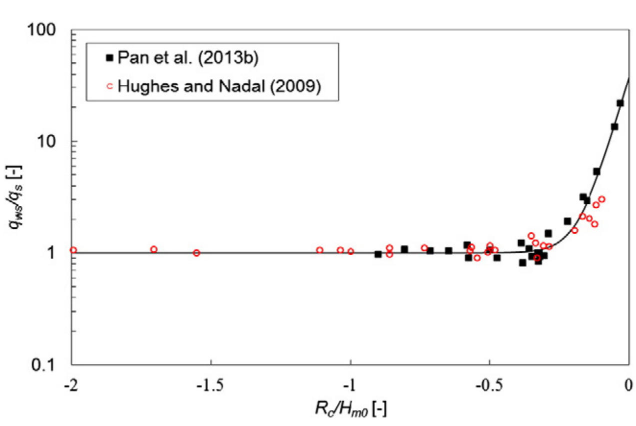

Fig. 2. Ratio of average overtopping discharge to the steady overflow discharge (q_{ws}/q_s) versus relative freeboard (R_c/H_{m0}).

where q_w is the average overtopping discharge, T_m is the mean wave period of incoming wave, H_s is the significant wave height of incoming wave.

Nørgaard et al. (2014) conducted a series of two-dimensional physical model tests on typical rubble mound breakwater geometries and provided a modification of Besley (1999) formula, to get better estimations in shallow water wave conditions. Based on the distribution of incident waves, they obtained a better prediction of probability of wave overtopping under shallow water condition:

$$P_{ow} = P_{ow}^{\text{Besley}} \cdot C1 \tag{4}$$

with

$$C1 = \begin{cases} 1 & \text{for} \quad H_{m0}/H_{1/10} \le 0.848 \quad \text{or} \quad H_{m0}/h \le 0.2 \\ -6.65 + 9.02 \cdot \dfrac{H_{m0}}{H_{1/10}} & \text{for} \quad H_{m0}/H_{1/10} > 0.848 \quad \text{and} \quad H_{m0}/h > 0.2 \end{cases} \tag{5}$$

where H_{m0} is the energy-based significant wave height, $H_{1/10}$ is the characteristic wave height, h is the water depth.

In the EurOtop Manual (Pullen et al., 2007), another equation for prediction of probability of overtopping is given based on the run-up height by

$$P_{ow} = \exp\left[-\left(\sqrt{-\ln 0.02}\,\frac{R_c}{R_{u2\%}}\right)^2\right] \tag{6}$$

where R_c is the freeboard and $R_{u2\%}$ is the 2% run-up height (where run-up height is the vertical run-up elevation above still water level).

Franco et al. (1994) and Van der Meer and Janssen (1994) used the Weibull distribution with a shape factor of 0.75 and a scale factor a, which is dependent of the average overtopping discharge per wave and the overtopping probability, to represent the distribution of water volume in individual overtopping waves under positive freeboard condition ($R_c > 0$). The probability distribution function is given by

$$P_V = P(V_i \le V) = 1 - \exp\left[\left(-\frac{V}{a}\right)^b\right] \tag{7}$$

with

$$a = 0.84 \frac{T_m q_w}{P_{ow}} \tag{8}$$

where P_V is the probability of the overtopping volume per wave V_i being less than or equal to V, and $b = 0.75$ is the shape factor.