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New Understanding on the Distribution of Individual Wave Overtopping Volumes over a Levee under Negative Freeboard

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ABSTRACT

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This paper presents some new understanding on the distribution of individual wave overtopping volumes under combined wave and surge overtopping conditions. Two-parameter Weibull distribution was utilized to present the distribution of the individual wave overtopping volumes. In different studies, the best-fit values of Weibull factors were fitted with different proportions of the sample values, ***e.g.***, all values, upper 50 % and upper 10 % of the values. In this paper, the performances of the Weibull factors fitted with different proportions of the data were assessed based on an analysis of the data of full-scale flume tests. Comparisons and discussions were made among the best fits with different proportions of the sample values. Mean and maximum values of the individual wave overtopping volumes calculated from the Weibull factors were compared to the measured ones. The results show that the maximum values are underestimated by the Weibull factors fitted with the upper parts of the data. It is suggested to use all proportion in Weibull curve fitting of individual wave overtopping volumes.

ADDITIONAL INDEX WORDS: *Weibull distribution, combined wave and surge overtopping, full-scale tests.*

INTRODUCTION

Combined wave and surge overtopping is the wave overtopping under negative freeboard (Figure 1). It means that the wave overtopping occurs at the same time as storm surge overflow and may cause more severe damage than wave-only overtopping and surge-only overflow (Hughes and Nadal, 2009). Combined wave and surge overtopping has become an issue of concern in coastal engineering since hurricane Katrina, where studies show that it may be responsible for a large part of the levee failures (ASCE Hurricane Katrina External Review Panel, 2007). Studies have been conducted on the overtopping discharge, flow structure, and levee erosion processes of combined wave and surge overtopping (***e.g.***, Hughes and Nadal, 2009; Reeve ***et al.***, 2008; Li *et al*., 2012; Pan ***et al.***, 2013; Pan ***et al.***, 2015; Pullen *et al*., 2007; Schüttrumpf *et al*., 2001).

This paper presents some new discussion on the distribution of individual overtopping volume of combined wave and surge overtopping. The individual wave overtopping volume is one of the most concerned parameters of combined wave and surge overtopping as it is an important factor in design criteria of the sea defense structures, as suggested by Franco *at al*. (1994).

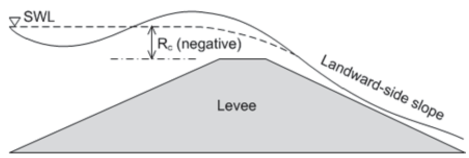

Figure 1. Combined wave and surge overtopping.

Franco ***et al.*** (1994) and van der Meer and Janssen (1994) used the Weibull distribution to represent the distribution of individual overtopping volumes under wave-only overtopping conditions. The research of Hughes ***et al.*** (2012), Nørgaard *et al*. (2014), Pullen *et al*. (2007), Victor *et al*. (2012) extend the understanding on the distribution of individual overtopping volume of wave-only overtopping under different water depth and levee slopes.

The Weibull distribution was also used to represent the distribution of individual overtopping volume of combined wave and surge overtopping (***e.g.***, Hughes and Nadal, 2009; Pan ***et al.***, 2015). Flume experiments were conducted and equations were provided to estimate the shape factor and scale factor of Weibull distribution presenting the individual overtopping volumes.

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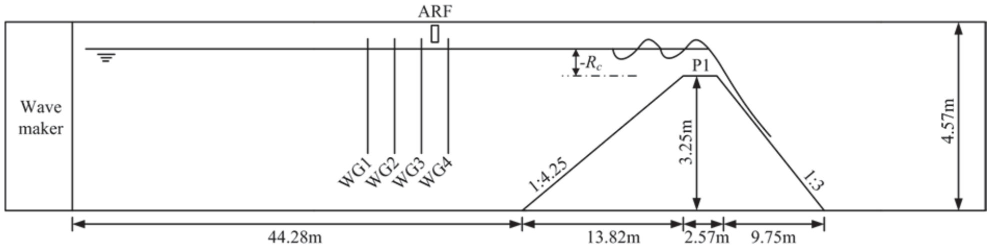


Figure 2. Illustration of the LWF and the full-scale test set-up.

However, in some cases the Weibull distribution could not fit all of the individual overtopping volumes well, and therefore in some studies only large individual wave volumes were used to achieve a best fit, ***e.g.***, in Victor ***et al***. (2012) only the individual volumes that larger than the average wave volume V_{mean} were used, and in Hughes ***et al***. (2012) only the upper 10 % of the wave volumes were used. In this paper, different proportions of the individual wave overtopping volumes, ***i.e.***, all values, upper 50 % and upper 10 % of the values, were used to get the best-fit Weibull factors, and new empirical relationships for the Weibull factors were proposed. The performances of different sets of Weibull factors were assessed by comparisons between the measured mean and maximum individual overtopping volumes and the estimated ones with different Weibull factors. The results suggest that the Weibull factors fitted with all values performs better in estimation of the characteristic individual overtopping volumes.

METHODS

The two-parameter Weibull distribution was used to present the individual wave overtopping volume of combined wave and surge overtopping. The measurements of full-scale flume tests of Li ***et al***. (2012) and Pan ***et al***. (2013) were used for analysis.

Laboratory experiments

The laboratory tests were conducted in the Large Wave Flume (LWF) of the O.H. Hinsdale Wave Research Laboratory (HWRL) at Oregon State University. A definition sketch of the test set-up is shown in Figure 2. The LWF is a 104 m × 3.66 m × 4.57 m (length × width × height) flume equipped with a unidirectional piston wave maker. The levee model was built with a sand core and a concrete cap. A test section was reserved in the landward-side slope to test the anti-erosion performances of different levee strengthening system; however, in this paper the erosion aspect is not discussed.

Irregular wave time series realization was generated conforming to the idealized TMA (Texel-Marsen-Arsloe) wave spectrum, which is a modified JONSWAP spectrum for better performance in shallow water. A total of 24 different conditions were designed with different upstream heads and incident wave conditions. Four surface-piercing wave gauges were placed near the seaward-side toe of the levee to record the time series of water level and separate the incident and reflected waves. The Acoustic Range Finder, ARF, placed between WG 3 and WG 4 was used to calibrate the wave gauges. The flow depths and flow velocities at P1 were recorded by ARF sensor and Acoustic Doppler Velocimetry (ADV) sensors, respectively. One ARF sensor and two ADV sensors at different elevations are installed. A pump system was used to provide return flow to counterbalance the overtopping discharge.

Weibull distribution

Weibull distribution is widely used to present the distribution of individual overtopping volumes under wave-only overtopping and combined wave and surge overtopping condition. The probability distribution function is given by

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

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

The scale factor a and the shape factor b are the two factors that control the shape of the Weibull distribution. Based on the 25-to-1 laboratory tests, Hughes and Nadal (2009) gives equations to estimate the factors as

$$a = 0.79 q_{ws} T_p \tag{2}$$

$$b = 15.7\left(\frac{q_s}{gT_pH_{m0}}\right)^{0.35} - 2.3\left(\frac{q_s}{\sqrt{gH_{m0}^3}}\right)^{0.79} \tag{3}$$

where q_{ws} is the average discharge of combined wave and surge overtopping, T_p is the peak wave period, q_s is the surge-only overflow discharge under the same freeboard, H_{m0} is the energy-based significant wave height, g is the gravity.

It should be noted that the hydraulic parameters (***e.g.***, the average overtopping discharge q_{ws}) of the combined wave and surge overtopping show different behaviors in different ranges of the relative freeboard R_c/H_{m0} (***i.e.***, R_c/H_{m0} < -0.3 and -0.3 ≤R_c/H_{m0} < 0), Pan ***et al***. (2015) classified the cases with R_c/H_{m0} < -0.3 as surge dominated cases (SD hereafter) and the cases with -0.3 ≤R_c/H_{m0} < 0 as wave dominated cases (WD hereinafter). For SD cases and WD cases, modified equations were proposed separately to provide better estimations of the shape parameter b. The equations are given as

$$b = 73.55\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.76} \quad \text{for} \quad R_c / H_{m0} \le \text{-0.3} \tag{3}$$

$$b = 54.58\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.63} \quad \text{for} \quad \text{-0.3} < R_c / H_{m0} < 0 \tag{4}$$

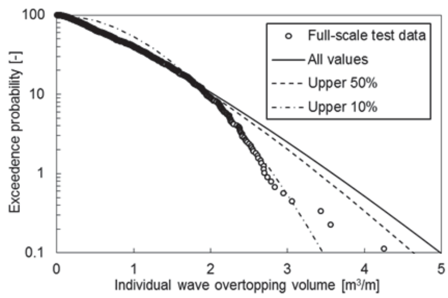


Figure 3. Example of the best fits of Weibull distribution to individual wave overtopping volume to different part of the data.

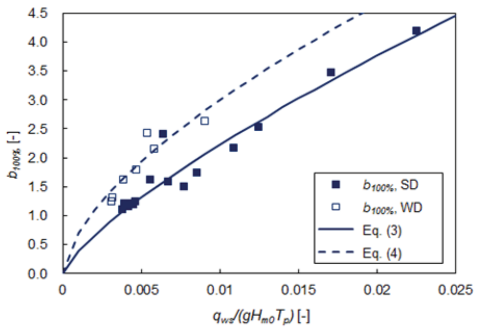
Pan *et al.* (2015) also proposed an equation for the scale parameter a based on the full-scale test data as

$$a = 1.017 q_{ws} T_{m-1,0} \tag{5}$$

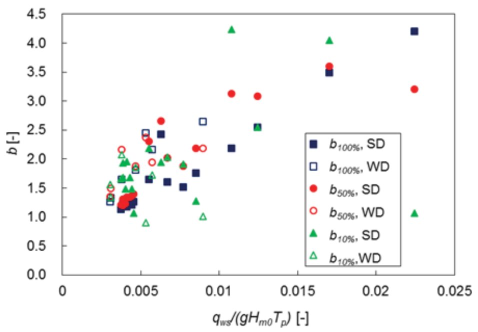
where $T_{m-1,0}$ is the mean (energy) wave period.

Using both wave-only overtopping data and combined wave and surge overtopping data of van der Meer and Janssen (1994), Hughes and Nadal (2009) and Victor *et al*. (2012), Hughes and Nadal gives a general equation for both cases by

$$b = \left(\exp\left(-0.6 \frac{R_c}{H_{m0}} \right) \right)^{1.8} + 0.64 \tag{6}$$



(a) $b_{100\%}$, Eqs. (3) and (4)



(b) $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$

Figure 4. The Weibull shape parameters $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$ versus dimensionless overtopping discharge.

RESULTS

All values, upper 50 % and upper 10 % of the values, were used separately to get the best fits of the individual overtopping volumes measured in the full-scale test data. Figure 3 shows an example of best-fits of Weibull distribution to different parts of the data. Different scale factors and shape factors were obtained with different parts of the data. For convenience, we used a subscript to denote the part of data used in the fitting, ***e.g.***, $b_{50\%}$ denotes the shape factor *b* obtained with upper 50 % of the data.

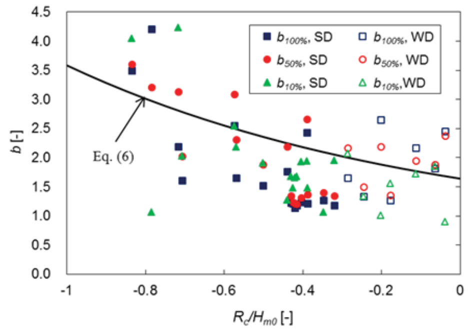


Figure 5. The Weibull shape parameters $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$ versus relative freeboard.

The Weibull shape parameter *b*

The $b_{100\%}$ for SW cases and WD cases were plotted versus dimensionless overtopping discharge $q_{ws}/(gH_{m0}T_p)$ together with Eqs. (3) and (4) in Figure 4(a). The $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$ for all the full-scale tests were plotted versus dimensionless overtopping discharge $q_{ws}/(gH_{m0}T_p)$ in Figure 4(b). As seen, the data spots of $b_{100\%}$ for SW and WD cases have good trends with the increase of the dimensionless parameter $q_{ws}/(gH_{m0}T_p)$, while the $b_{50\%}$ and $b_{10\%}$ show more scattered distributions. The general trends of the three sets of shape parameter *b* are similar, but the exclusive using of the upper parts of the data yields more scattered data. However, it should be mentioned that the scattered data might be induced by the limited numbers of samples after the removal of the small values.

It could also be noticed that in $b_{50\%}$ and $b_{10\%}$ cases (especially for $b_{10\%}$), the deviations between the distributions of surge dominated cases and wave dominated cases are not as significant as that of $b_{100\%}$. One possible explanation is that the upper parts of the data, ***i.e.***, the individual overtopping volumes of the large waves, are more controlled by the wave breaking rather than the relative proportion of wave and surge.

Since the distributions of the $b_{50\%}$ and $b_{10\%}$ along the dimensionless overtopping discharge are relatively scattered, we also plot the $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$ versus relative freeboard together with Eq. (6) in Figure 5. As it can be seen, the data spots of $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$ distribute around Eq. (6), but the data spots are also scattered and no significant deviation are found among the general trends of the distributions of $b_{100\%}$, $b_{50\%}$ and $b_{10\%}$. After several attempts based on Figure 4(b) and Figure 5, we tentatively used different dimensionless parameters to estimate the $b_{50\%}$ and $b_{10\%}$, as plotted in Figure 6. The best-fit curves in Figure 6 are given as

$$b_{50\%} = 25.05\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.5} \quad (7)$$

$$b_{10\%} = 5.004\left(\frac{R_c}{H_{m0}}\right)^{3.261} + 1.418 \quad (8)$$

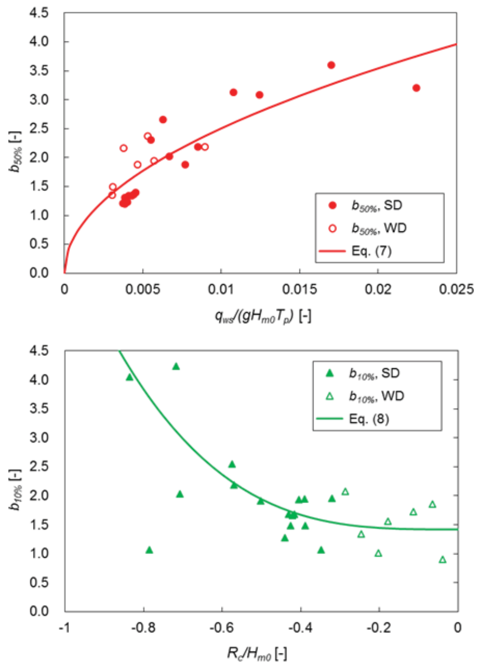


Figure 6. Estimations of the Weibull shape parameters $b_{50\%}$ and $b_{10\%}$ with dimensionless parameters.

The Weibull scale parameter *a*

The Weibull scale parameters $a_{100\%}$, $a_{50\%}$ and $a_{10\%}$ are plotted versus overtopping parameter $q_{ws}T_{m-1,0}$ in Figure 7. According to previous studies, the Weibull scale factor a has a linear relationship with the product of the overtopping discharge and the characteristic wave period of the incident wave, which confirms Figure 7. It can be seen that the distributions of $a_{100\%}$, $a_{50\%}$ and $a_{10\%}$ are close to each other, so we use a general form of equation to estimate Weibull scale factor a by

$$a = k_a q_{ws} T_{m-1,0} \quad (9)$$

where k_a is an empirical parameter, which could be taken as 1.017 for $a_{100\%}$, 1.041 for $a_{50\%}$ and 1.037 for $a_{10\%}$.

DISCUSSION

Now we have the $b_{100\%}$, $b_{50\%}$, $b_{10\%}$, $a_{100\%}$, $a_{50\%}$ and $a_{10\%}$, both best-fit values from the time series of overtopping discharge and estimations based on the overtopping parameters. However, the question is which ones are better, or which parts of the data should be used in the Weibull curve fitting?

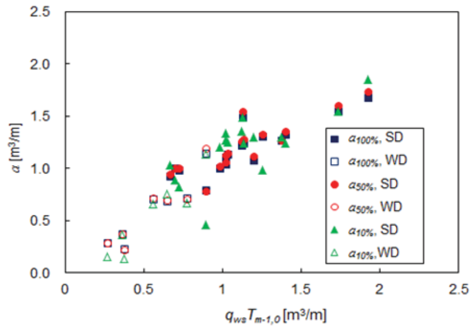


Figure 7. The Weibull scale parameter *a* versus overtopping parameter $q_{ws}T_{m-1,0}$.

One of the usages of the Weibull factors is the calculation of the mean and maximum values. In this paper comparisons between the measured mean/maximum individual overtopping volumes and the estimated ones with Weibull factors were conducted to study the performances of different sets of Weibull factors. The mean and maximum value of the Weibull distribution can be calculated in terms of the scale factor *a* and shape factor *b* as (*e.g.*, Victor *et al.*, 2012)

$$V_{mean} = a \cdot \Gamma\left(1+\frac{1}{b}\right) \quad (10)$$

$$V_{\max} = a \cdot \left(\ln\left(N+1\right)\right)^{1/b} \quad (11)$$

where Γ is the gamma function and *N* is the overtopping wave number.

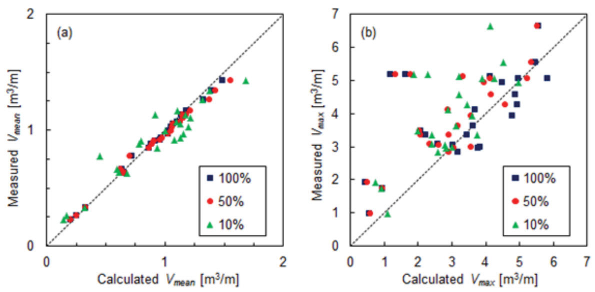


Figure 8. Comparison of measured characteristic overtopping volumes and calculated characteristic overtopping volumes with fitted *a* and *b*: (a) V_{mean}, (b) V_{max}.

Firstly the V_{mean} and V_{max} were calculated with the best-fit Weibull factors from the time series of overtopping discharge. The measured values versus calculated values were plotted in Figure 8. The estimation of the V_{mean} was good and the estimation of V_{max} was mediocre but reasonable. The root-mean-square errors (RMSE) of the calculations of V_{mean} with $a_{100\%}$ and $b_{100\%}$, $a_{50\%}$ and $b_{50\%}$, and $a_{10\%}$ and $b_{10\%}$ are 0.035, 0.053, and 0.133 respectively. The root-mean-square errors (RMSE) of the calculations of V_{max} with $a_{100\%}$ and $b_{100\%}$, $a_{50\%}$ and $b_{50\%}$, and $a_{10\%}$ and $b_{10\%}$ are 1.303, 1.330, and 1.332 respectively. It can be seen that for the calculation of both V_{mean} and V_{max}, the fitted $a_{100\%}$ and $b_{100\%}$ perform better.

Then the V_{mean} and V_{max} were calculated with the estimations of Weibull factors based on the overtopping parameters. The measured value versus calculated value was plotted in Figure 9. The estimation of the V_{mean} was good and the estimation of V_{max} was mediocre but reasonable. The root-mean-square errors (RMSE) of the calculations of V_{mean} with $a_{100\%}$ and $b_{100\%}$, $a_{50\%}$ and $b_{50\%}$, and $a_{10\%}$ and $b_{10\%}$ are 0.142, 0.149, and 0.151 respectively. The root-mean-square errors (RMSE) of the calculations of V_{max} with $a_{100\%}$ and $b_{100\%}$, $a_{50\%}$ and $b_{50\%}$, and $a_{10\%}$ and $b_{10\%}$ are 1.389, 1.625, and 1.638 respectively. It can be seen that for the calculation of both V_{mean} and V_{max}, the estimated $a_{100\%}$ and $b_{100\%}$ perform better. Another noticeable thing is that the calculated $a_{50\%}$ and $b_{50\%}$ and $a_{10\%}$ and $b_{10\%}$ tend to underestimate the large waves.

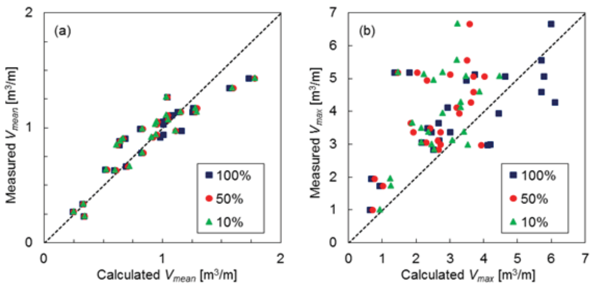


Figure 9. Comparison of measured characteristic overtopping volumes and calculated characteristic overtopping volumes with estimated *a* and *b*: (a) V_{mean}, (b) V_{max}.

CONCLUSIONS

In this work we present new understanding on distribution of individual wave overtopping volumes under combined wave and surge overtopping condition. The analysis was based on full-scale flume tests. Two-parameter Weibull distribution was used to present the distribution of the individual wave overtopping volumes. Different proportions of the sample values, ***e.g.***, all values, upper 50 % and upper 10 % of the values, were used to get the best fit and calculate the corresponding Weibull factors. New empirical relationships for the Weibull factors $b_{50\%}$, $b_{10\%}$, $a_{50\%}$ and $a_{10\%}$ were proposed.

Mean and maximum values of the individual overtopping volume were calculated with both the fitted and estimated values of Weibull factors $b_{100\%}$, $b_{50\%}$, $b_{10\%}$, $a_{100\%}$, $a_{50\%}$ and $a_{10\%}$. Calculated values were compared to the measured ones. The comparisons show that for the calculation of the mean and maximum individual overtopping volume, the Weibull factors $a_{100\%}$ and $b_{100\%}$ perform better than then Weibull factors obtained from the upper parts of the data. Hence, it is suggested to use all proportion in Weibull curve fitting of individual wave overtopping volumes to have better performance in estimation of characteristic individual overtopping volumes.

However, it is noticeable that the poor performances of the Weibull factors fitted from the upper parts of the data may result from the limited numbers of samples after the removal of the small values. Future research is needed on this regard.

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LITERATURE CITED

ASCE Hurricane Katrina External Review Panel, 2007. *The New Orleans Hurricane Protection System: What Went Wrong and Why?* Reston, Virginia: American Society of Civil Engineers, 92p.

Franco, L.; de Gerloni, M., and van der Meer, J.W., 1994. Wave overtopping on vertical and composite breakwaters. *Coastal Engineering Proceedings*, 24, 1030-1044.

Hughes, S.A. and Nadal, N.C., 2009. Laboratory study of combined wave overtopping and storm surge overflow of a levee. *Coastal Engineering*, 56(3), 244-259.

Hughes, S.A.; Thornton, C.I.; van der Meer, J.W., and Scholl, B.N., 2012. Improvements in describing wave overtopping processes. *Coastal Engineering Proceedings*, 33, waves-35.

Li, L.; Pan, Y.; Amini, F., and Kuang, C.P., 2012. Full Scale Laboratory Study of Combined Wave and Surge Overtopping of a Levee with RCC Strengthening System. *Ocean Engineering*, 54(1), 70 – 86.

Reeve, D.E.; Soliman, A., and Lin, P.Z., 2008. Numerical study of combined overflow and wave overtopping over a smooth impermeable seawall. *Coastal Engineering*, 55, 155-166.

Pan, Y.; Kuang, C.P.; Li, L., and Amini, F., 2015. Full-scale laboratory study on distribution of individual wave overtopping volumes over a levee under negative freeboard. *Coastal Engineering*, 97, 11–20.

Pan, Y.; Li, L.; Amini, F., and Kuang, C. P., 2013. Full Scale HPTRM Strengthened Levee Testing under Combined Wave and Surge Overtopping Conditions: Overtopping Hydraulics, Shear Stress and Erosion Analysis. *Journal of Coastal Research*, 29(1), 182-200.

Pullen, T.; Allsop, N.W.H.; Bruce, T.; Kortenhaus, A.; Schüttrumpf, H., and van der Meer, J.W., 2007. *EurOtop: Wave Overtopping of Sea Defences and Related Structures: Assessment Manual*. http:// www.overtopping-manual.com

Schüttrumpf, H.; Möller, J.; Oumeraci, H.; Grüne, J., and Weissmann, R., 2001. Effects of natural sea states on wave overtopping of seadikes. *Proceedings of the 4th International Symposium Waves 2001, Ocean Wave Measurement and Analysis* (San Francisco, California, ASCE), pp. 1565-1574.

van der Meer, J.W. and Janssen, J.P.F.M., 1994. *Wave run-up and wave overtopping at dikes and revetments*. Delft, Netherlands: Delft Hydraulics, 22p.

Victor, L.; van der Meer, J.W., and Troch, P., 2012. Probability distribution of individual wave overtopping volumes for smooth impermeable steep slopes with low crest freeboards. *Coastal Engineering*, 64, 87–101.