DISTRIBUTION OF INDIVIDUAL WAVE OVERTOPPING VOLUMES ON A SLOPING STRUCTURE WITH A PERMEABLE FORESHORE

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Maximum wave overtopping volumes on sea defences are an indicator for identifying risks to people and properties from wave hazards. The probability distribution of individual overtopping volumes can generally be described by a two-parameter Weibull distribution function (shape and scale parameters). Therefore, the reliable prediction of maximum individual wave overtopping volumes at coastal structures relies on an accurate estimation of the shape factor in the Weibull distribution. This study contributes to an improved understanding of the distribution of individual wave overtopping volumes at sloping structures by analysing the wave-by-wave overtopping volumes obtained from physical model experiments on a 1V:2H sloped impermeable structure with a permeable shingle foreshore of slope 1V:20H. Measurements of the permeable shingle foreshore were benchmarked against those from an identical experimental set-up with a smooth impermeable foreshore (1V:20H) of the same geometry. Results from both experimental set-ups were compared to commonly used empirical formulations, underpinned by the assumption that an impermeable foreshore exists in front of the sea structure. The effect on the shape factor in the Weibull distribution of incident wave steepness, relative crest freeboard, probability of overtopping waves and discharge are examined to determine the variation of individual overtopping volumes with respect to these key parameters. A key finding from the study is that no major differences in Weibull distribution shape parameter were observed for the tested impermeable and permeable sloped foreshores. Existing empirical formulae were also shown to predict reasonably well the Weibull distribution shape parameter, b, at sloping structures with both impermeable and permeable slopes.

Keywords: individual overtopping volumes; shingle foreshore; sloping structure; Weibull distribution; wave overtopping; climate resilience

INTRODUCTION

Reliable predictions of wave hazards from overtopping of sea defences are critical to the functional stability of the defence structure, the safety of pedestrians and other foreshore users and for mitigating the damage and loss in surrounding properties in the event of defence levels being exceeded. Many physical and numerical modelling studies that investigate complex wave-structure interactions, together with the hydrodynamic and wave overtopping processes on coastal protection structures are reported in scientific literature (see for example, Abolfathi et al., 2018; Dong et al., 2018 and 2020; Formentin et al., 2017; Fitri et al., 2019; Yeganeh-Bakhtiary et al., 2017 and 2020). The largest individual overtopping volumes during a storm have the potential to cause damage to both the structure and properties in the surrounding area. Recent research in the prediction of wave overtopping hazards have demonstrated that maximum individual overtopping volumes, rather than mean overtopping discharges, are better indicators of direct, wave induced hazards (EurOtop, 2018). While a significant amount of research investigating mean overtopping discharges at sloping structures (Van der Meer and Janssen, 1995; Van Gent, 2002; Victor and Troch, 2012; Victor et al., 2012; Van der Meer and Bruce, 2014; Salauddin et al., 2017) has contributed to the development of robust empirical prediction tools (e.g. EurOtop, 2018), studies of individual wave overtopping volumes, particularly for structures with permeable shingle foreshores, are considerably more limited. It is this knowledge gap that is being contributed to in this paper.

As originally proposed by Franco et al. (1994) and Van der Meer and Janssen (1995), and later confirmed in physical and numerical investigations of wave overtopping (see for example, Victor et al. (2012); Hughes et al. (2012); Zanuttigh et al. (2013); Abolfathi et al. (2018); Salauddin and Pearson (2018); Dong et al. (2018, 2020); Salauddin and Pearson (2019a, 2020)), the distribution of individual overtopping volumes at conventional sea defences follow a two-parameter Weibull distribution function, as follows:

$$P_v = 1 - exp\left[-\left(\frac{V}{a}\right)^b\right] \quad (1)$$

where, V is the overtopping volume per wave [m^3 per m width], P_v is the probability that an individual overtopping volume will not exceed V, and a and b are the scale and shape parameters of the distribution, respectively.

In Eq. 1, the Weibull scale parameter, a, can be determined from the following relationship proposed in EurOtop (2018):

$$a = \left(\frac{1}{\Gamma\left(1+\frac{1}{b}\right)}\right)\left(\frac{qT_m}{P_{ov}}\right) \quad (2)$$

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where, q is the mean overtopping discharge per meter width of the structure [m^3/s per m width], T_m is the mean wave period [s], P_{ov} $(= \frac{N_{ow}}{N_w})$ is the probability of overtopping waves, Γ is the mathematical gamma function, N_{ow} is the number of overtopping waves, and N_w is the total number of overtopping waves during a storm.

To estimate values of the Weibull distribution shape parameter at smooth sloping structures, Hughes et al. (2012) established the following correlation between shape factor b and relative freeboard:

$$b = \left[\exp\left(-0.6\frac{R_c}{H_{m0}}\right)\right]^{1.8} + 0.64 \qquad (3)$$

where, Eq. 3 is valid for $-2 < \frac{R_c}{H_{m0}} < 4.0$

For relatively steep, low crested sloping structures, Victor et al. (2012) proposed the following formulation for estimating the shape factor as a function of relative freeboard and seaward slope:

$$b = \exp\left[-2.0\frac{R_c}{H_{m0}}\right] + (0.56 + 0.15\cot\alpha) \qquad (4)$$

where, R_c is the crest freeboard of the structure [m], H_{m0} is the significant wave height [m], and α is the slope of the structure [radians].

The recently updated overtopping design manual (EurOtop, 2018) is underpinned by the statistical characterisation of extreme overtopping waves of Zanuttigh et al. (2013), where the shape parameter, b, of the Weibull distribution for the overtopping volumes of smooth (Eq. 5) and rubble mound or armoured structures (Eq. 6) is described in terms of relative discharge $q/(gH_{m0}T_{m-1,0})$:

$$b = 0.73 + 55\left(\frac{q}{gH_{m0}T_{m-1,0}}\right)^{0.8} \qquad (5)$$

$$b = 0.85 + 1500\left(\frac{q}{gH_{m0}T_{m-1,0}}\right)^{1.3} \qquad (6)$$

where, $T_{m-1,0}$ is the mean spectral wave period [s], and g is the gravitational acceleration [m/s^2].

The peak individual wave overtopping volume (V_{max}) on coastal structures can be predicted for a given number of overtopping waves during a storm and for known Weibull parameters, from the following:

$$V_{max} = a(\ln N_{ow})^{1/b} \qquad (7)$$

An accurate estimation of the Weibull shape parameter, b, in the distribution of wave-by-wave overtopping volumes leads to a more reliable prediction of maximum overtopping volumes. In a distribution of individual overtopping volumes, a relatively large value of the Weibull shape parameter indicates that most of the overtopping volumes are large, with these volumes being similar in magnitude. Conversely, a small value of the shape parameter in the Weibull distribution implies that most of the overtopping volumes are small.

Th work reported in this paper builds on the recent research of Salauddin and Pearson (2020) that describes the mean overtopping characteristics of sloping structures, where it was observed that the mean overtopping rate at these structures is reduced significantly (up to a factor of 4) by the presence of permeable shingle slopes. Data on individual overtopping volumes however, have until now, not been analysed to estimate the shape parameter in Weibull distribution functions for individual overtopping volumes at sloping structures with permeable slopes. This paper presents a small-scale physical model study of a sloping structure with both a permeable foreshore (control condition) and with two impermeable shingle foreshores of different particle size. Weibull shape parameter values, b, in the distribution of individual overtopping volumes for the three test configurations are compared. These data are then compared with commonly used empirical prediction formulae available in the literature. The influence of wave steepness, crest freeboard, the number of overtopping waves and the discharge of the waves on the shape parameter of the Weibull distribution of wave-by-wave overtopping volumes is also considered.

LABORATORY SET-UP
The physical modelling study was undertaken in a two-dimensional wave flume at the University of Warwick, UK. The flume is equipped with an active absorption paddle-type wavemaker. A smooth, impermeable sloping foreshore with a uniform slope of 1V:20H was constructed in front of a 1V:2H

smooth, sloping defence structure as shown in Fig. 1. Permeable (shingle) foreshores, with slopes of 1:20 were simulated using crushed anthracite (specific gravity of 1.40 T/m^3) following the approach of Powel (1990). For 1:50 geometrical scaling, model anthracite d_{50} values of 2.10 mm and 4.20 mm represented prototype shingles with d_{50} values of 13 mm and 24 mm, respectively. Detailed shingle scaling methods have been reported in Salauddin and Pearson (2019b and 2020).
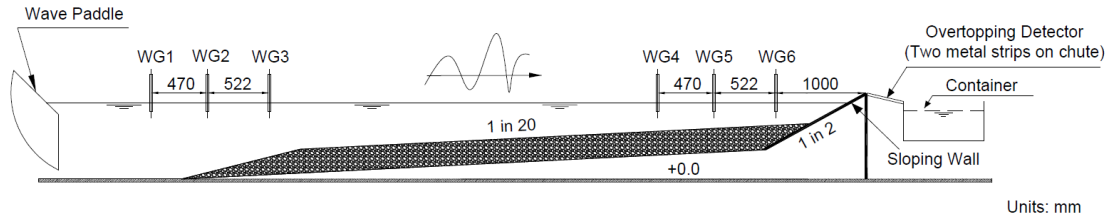
Figure 1. Schematic of the experimental set-up (adapted from Salauddin and Pearson, 2020)

Two constant deep-water wave steepnesses ($s_{0p} = 0.02$ and 0.05) were tested with six different toe water depths. Each test comprised of 1,000 pseudo-random wave sequences with a peak enhancement factor, $\gamma = 3.3$. The test matrix in this study is summarised in Table 1.

Table 1. Test matrix followed in this study (reported by Salauddin and Pearson, 2020)

| Foreshore bed configurations	Water depth near structure, h_t [mm]	Crest freeboard, R_c [mm]	Significant wave height, H_{m0} [mm]	Nominal wave steepness, s_{op} [-]	Wave Period, T_p [s]
Impermeable	60	190	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Impermeable	75	245	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Impermeable	100	150	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Impermeable	150	100	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Impermeable	180	140	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Impermeable	200	50	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	60	190	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	75	245	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	100	150	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	150	100	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	180	140	50-160	0.02	1.27-2.26
				0.05	0.80-1.43
Shingle ($d_{50} = 13$ mm / $d_{50} = 24$ mm)	200	50	50-160	0.02	1.27-2.26
				0.05	0.80-1.43

Measurement of the incident wave characteristics at deep water (close to wave paddle) as well as at the toe of structure followed the methodology of Mansard and Funke (1980) and involved the placement of six wave gauges (WG1 to WG6 in Fig. 1) along the wave flume. The measured incident wave heights near the wave paddle showed good agreement with the predicted Rayleigh distribution for the tested wave conditions (details in Salauddin and Pearson, 2019b). The wave overtopping volumes were

determined using a calibrated load-cell suspended from a collection container, adopting the approach of Salauddin and Pearson (2019a, 2020). An electrical detector comprising two strips of metal tape positioned along the crest of the structure was used for identifying individual overtopping events in a test sequence – the tapes acting as a switch that was closed with passing water. Wave-by-wave overtopping volumes were determined by identifying the increment in the mass of overtopped water in the container for each overtopping event.

RESULTS AND DISCUSSIONS

Weibull Plots of Wave-by-Wave Overtopping Volumes

In a sequence of overtopping events, coastal engineers and practitioners are generally interested in the largest wave by wave overtopping volumes. Consequently, the Weibull shape parameter, b, is usually calculated from the gradient of the extreme tail of the Weibull distribution where only the largest volumes reside on the Weibull scale (see for example, Pearson et al., (2002); Dong et al., (2018, 2020); Salauddin and Pearson (2018, 2020)). In Fig. 2, the individual overtopping volumes observed for two of the tested conditions are plotted on a Weibull scale by considering only the largest overtopping volumes ($V > V_{bar}$) in a test sequence, where V is the individual wave overtopping volume, $P(V)$ is the probability that an individual event volume equals or exceeds a volume V and V_{bar} is the mean overtopping volume. The general trend of the data points in Fig. 2 is linear for the test conditions being considered, indicating that the measured wave by wave overtopping volumes follow the two-parameter Weibull distribution. Similar trends in overtopping volumes as those in Fig. 2 were observed for the other test conditions in this study.

(a) $H_{m0} = 0.07$ m, $s_{m-1,0} = 0.02$ (b) $H_{m0} = 0.10$ m, $s_{m-1,0} = 0.06$
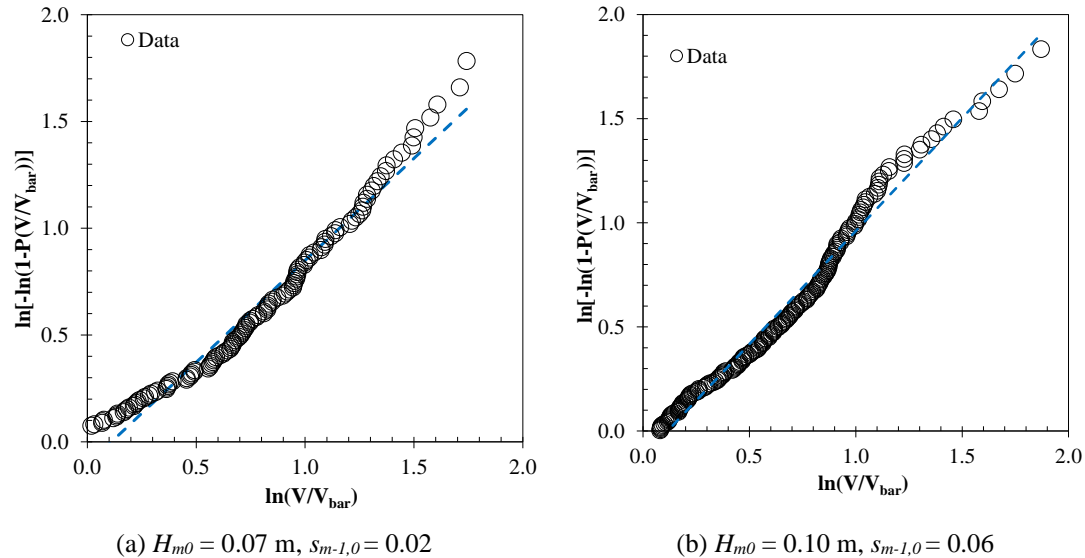
Figure 2. Distribution of wave-by-wave overtopping volumes on a Weibull scale for two tested wave conditions

Furthermore, in Fig. 3, the distribution of measured individual overtopping volumes for the three different bed configurations are compared for a specific tested wave condition (incident wave height, H_{m0}, of 0.10 m and wave steepness, $s_{m-1,0}$, of 0.06). The data in Fig. 3 confirms that no significant differences are observed between the Weibull distribution of individual overtopping volumes for tests with the impermeable and permeable foreshores at the sloping structure.
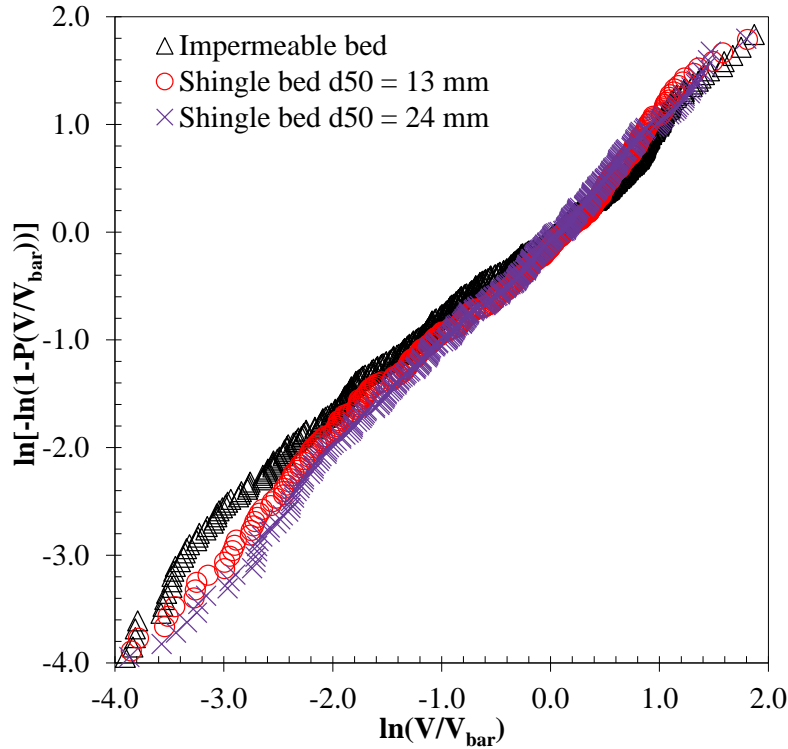
Figure 3. Distribution of wave-by-wave overtopping volumes on a Weibull scale for three tested bed configurations for $H_{m0} = 0.10$ m, $s_{m-1,0} = 0.06$

Effect of Probability of Overtopping Waves on Weibull Shape Parameter

Fig. 4 illustrates the correlation between Weibull b values determined from observations and probability of overtopping waves. For the conditions tested in this study, the b values determined from experimental measurements generally varied from 0.50 to 1.40, albeit a small number of higher b values were determined for relatively low overtopping waves (below 5% P_{ow}). Similar trends for the shape parameter of the Weibull distribution of individual wave overtopping volumes were reported by Zanuttigh et al. (2013) for low overtopping waves on rubble mound and smooth sloping structures. Furthermore, Fig. 4 suggests that the distribution of wave-by-wave overtopping volumes is not significantly influenced by the presence of the permeable foreshore.
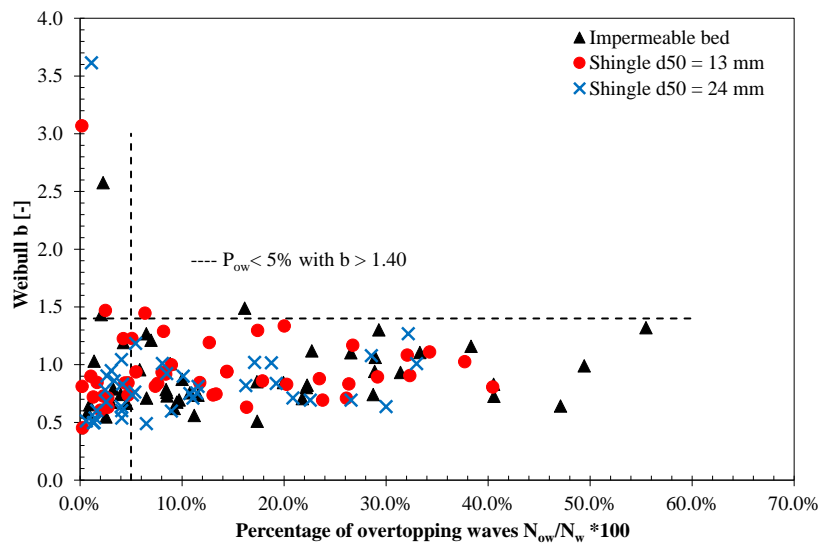
Figure 4. Variation of Weibull b shape parameter with percentage of overtopping waves at sloping structures

Effect of Wave Steepness on Weibull Shape Parameter

Besely (1999) has previously suggested that the shape parameter of the Weibull distribution of individual wave overtopping volumes on sloping seawalls is dependent on the incident wave steepness and recommended a Weibull b value of 0.76 for a wave steepness of 0.02, and 0.92 for a wave steepness of 0.04. More recently however, Bruce et al. (2009) reported no discernible relationship between Weibull shape parameter values and incident wave steepness for armoured rubble mound breakwaters, a finding also observed by Victor et al. (2012) for steep low crested sloping structures. To investigate the influence of incident deep water steepness, b values determined from measured data for the test conditions in this study are plotted against wave steepness in Fig. 5. Shown in Fig. 5 (dashed line) is the shape parameter of 0.76 and 0.92 for incident wave steepness values of 2% and 4%, respectively, as suggested by Besely (1999).
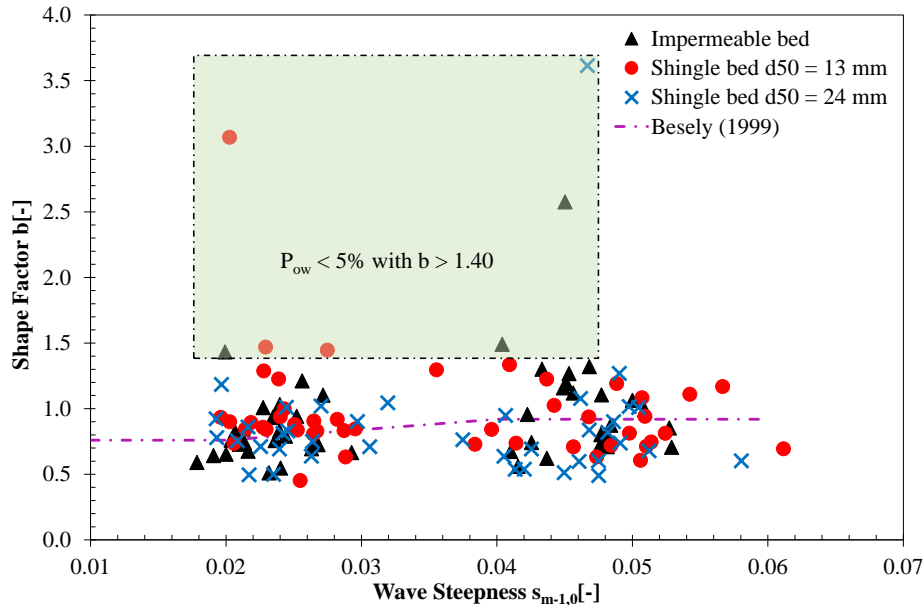
Figure 5. Variation of Weibull b parameter with incident wave steepness at sloping structures

The data in Fig. 5 shows that b values determined from measured data do not appreciably vary with wave steepness. This suggests that for conditions tested in this study, incident wave steepness does not significantly influence the value of the Weibull distribution shape parameter.

Effect of Relative Toe Water Depth on Weibull Shape Parameter

Fig. 6 portrays the variation of shape parameter, b, with relative toe water depth, h_t/L_m, in which h_t refers to the water depth at the toe of the structure, while L_m is the deep-water wavelength based on mean wave period, T_m. Data in Fig. 6 suggests that for the permeable and impermeable foreshores tested, no clear relationship between the value of the Weibull shape parameters and relative toe water depth, confirming that there is no apparent influence of relative toe water depth in the distribution of wave-by-wave overtopping volumes.
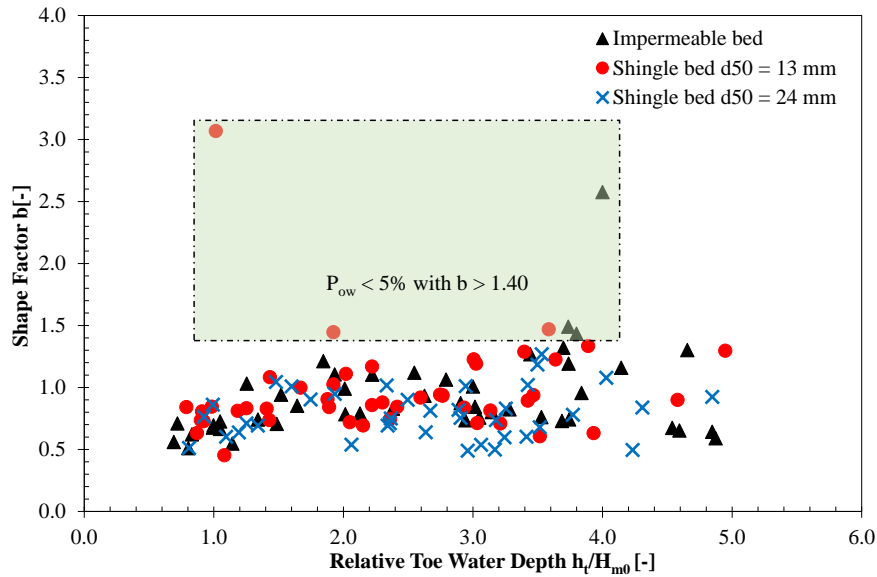
Figure 6. Variation of Weibull *b* parameter with relative water depth at sloping structures

Effect of Relative Crest Freeboard on Weibull Shape Parameter

To better understand the influence of relative freeboard on the shape parameter of the Weibull distribution for individual wave overtopping volumes, shape parameters determined from measurement are shown as a function of relative freeboard in Fig. 7. Empirical predictions of *b* using the empirical relations of Hughes et al. (2012) and Victor et al. (2012) in Eq. 3 and Eq. 4, respectively are also shown in Fig. 7 for the tested conditions.
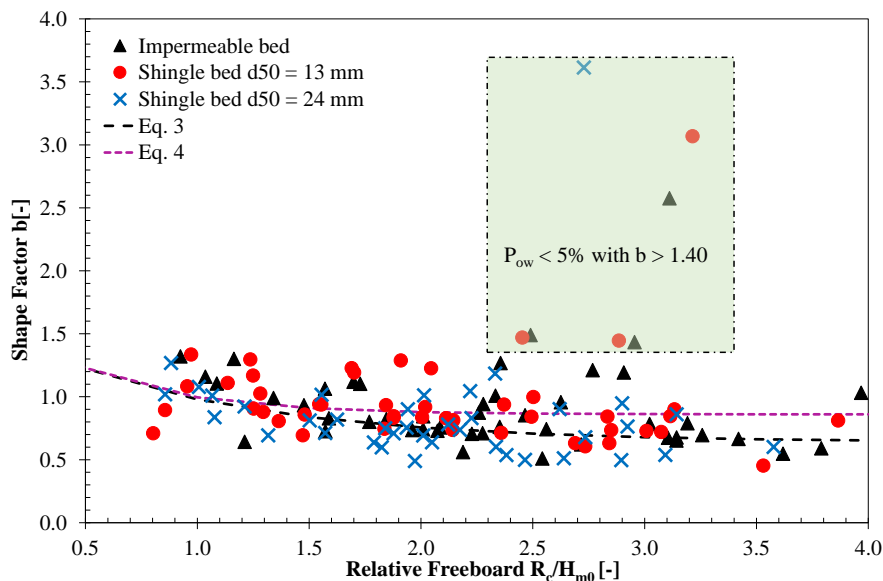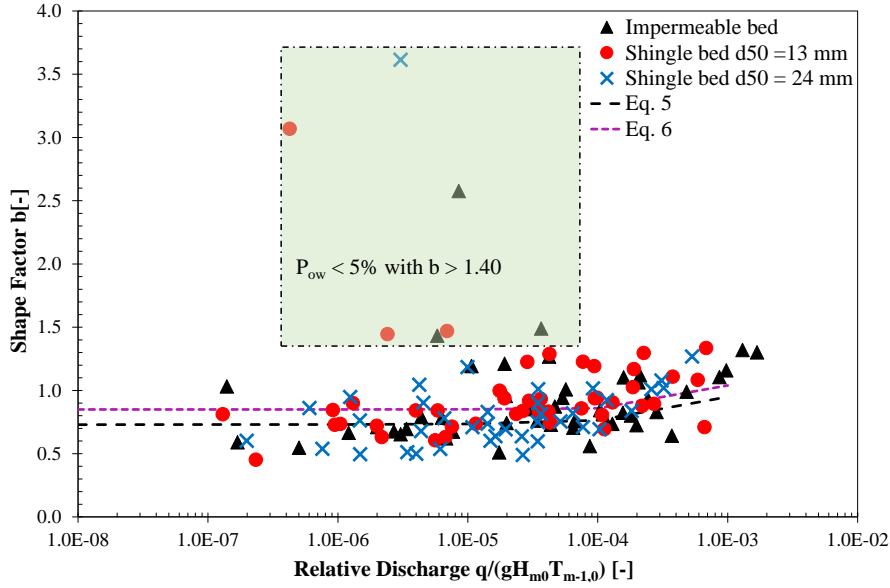

Figure 7. Variation of Weibull *b* parameter with relative crest freeboard at sloping structures

Data in Fig. 7 suggests that shape parameter values determined from measurement increase with decreases of relative freeboard. Similar trends in Weibull distribution shape parameter values with relative freeboard have been reported by Hughes et al. (2012) and Victor et al. (2012). For both impermeable and permeable foreshore configurations that were tested, the measured data show good agreement with the empirical predictions using Eq. 3 and Eq. 4.

Effect of Relative Wave Overtopping Discharge on Weibull Shape Parameter

In Fig. 8, shape parameters from measured data are shown as a function of the relative discharge. The dashed lines represent the empirical shape parameter predictions for smooth and rubble mound structures from (Zanuttigh et al., 2013) using Eq. 5 and Eq. 6, respectively.

Figure 8. Variation of Weibull *b* parameter with relative wave overtopping discharge at sloping structures

The data in Fig. 8 show that the measured data are consistent with the empirical predictions of Zanuttigh et al. (2013) for rubble mound and smooth structures and validate the findings of the latter with high confidence. Nonetheless, the predictions given by Zanuttigh et al. (2013) for sloping structures (Eq. 5) were mainly based on measurements on a 1 in 1.5 sloping structure on an impermeable foreshore. As perhaps may therefore be expected, Fig. 8 indicates that Eq. 5 performs slightly better for impermeable, as opposed to permeable foreshore configurations.

Validation of Empirical Formulae for Prediction of Weibull *b* at Sloping Structures

The values of the Weibull distribution shape parameters determined in this study from measured data were compared with estimates from commonly used empirical prediction formulae (Eqs 3–6) reported in the literature. The reliability of the empirical predictions of *b* for sloping structures were assessed using a suite of statistical indicators that included Scatter Index (SI), Bias, and root mean square errors (RMSE) as described in Eq. 8 to Eq. 10 - the SI reflects the relative scatter of the measured data points, the Bias describes the difference between the estimates of b from measurement and formulae and the RMSE defines the accuracy of the prediction formulae.

$$SI = \frac{1}{|\overline{X}|} \sqrt{\frac{1}{N_{test}} \sum_{n=1}^{N_{test}} [(b_{estimated})_n - (b_{measured})_n]^2} \times 100 \qquad (8)$$

$$Bias = \frac{1}{N_{test}} \sum_{n=1}^{N_{test}} [(b_{estimated})_n - (b_{measured})_n] \qquad (9)$$

$$RMSE = \sqrt{\frac{1}{N_{test}} \sum_{n=1}^{N_{test}} [(b_{measured})_n - (b_{estimated})_n]^2} \qquad (10)$$

where, N_{test} is the number of experimental data, $b_{measured}$ and $b_{estimated}$ are the measured and estimated Weibull b values respectively, and $\overline{X}$ is the mean of $b_{measured}$ values.

The summary statistics using Eq. 8 to Eq. 10 are in Table 2. It is evident from Table 2 that the overall values of the statistical indicators are relatively low for the tested conditions in this study. The values in Table 2 therefore confirm that the empirical prediction formulae used in this study were in general agreement with measured data for both permeable and impermeable bed configurations, indicating the applicability of those formulae in the prediction of shape factor b values for permeable foreshores. The results for the impermeable foreshore configuration also show that the predictions by Zanuttigh et al. (2013) using Eq. 5 and Eq. 6 provide marginally improved estimates of the Weibull distribution shape parameter for individual wave overtopping volumes compared to corresponding estimates of *b* using the Hughes et al. (2012) and Victor et al. (2012) relations.

Table 2. Summary of the statistical indicators for empirical formulae in predicting Weibull *b* values at sloping structures

Error Indicator	Foreshore	Hughes et al. (2012) – Eq. 3	Victor et al. (2012) – Eq. 4	Zanuttigh et al. (2013) – Eq. 5	Zanuttigh et al. (2013) – Eq. 6
SI (%)	Impermeable	25.03	21.72	20.45	20.39
	d_{50} = 13 mm	20.56	18.60	21.85	18.81
	d_{50} = 24 mm	17.90	22.20	19.80	21.52
BIAS	Impermeable	-0.110	0.010	-0.070	0.009
	d_{50} = 13 mm	-0.068	-0.002	-0.089	-0.026
	d_{50} = 24 mm	-0.005	0.093	-0.030	0.060
RMSE	Impermeable	0.22	0.19	0.18	0.18
	d_{50} = 13 mm	0.18	0.17	0.20	0.17
	d_{50} = 24 mm	0.15	0.19	0.17	0.18

CONCLUSIONS

The shape parameter, *b,* in the Weibull distribution of individual wave overtopping volumes plays a key role in the estimation of maximum individual wave overtopping volume for coastal structures. This study investigated the influence of the presence of permeable shingle foreshores on shape parameters in the distribution of wave-by-wave overtopping volumes at sloping structures. The Weibull *b* values based on experimental measurement for the permeable, shingle bed configurations were benchmarked against measurements with an impermeable foreshore configuration. Results show that there is no significant variation in Weibull *b* values for the permeable and impermeable foreshore at sloping structures. For the tested conditions, it was also evident that the incident wave steepness had only limited influence on the shape parameter of the Weibull distribution. Overall, for low overtopping waves (less than 5%), a higher Weibull value of *b* was observed for both impermeable and permeable slopes.

Despite the varied structural and test configurations, the shape parameter values determined from experimental measurement were in good agreement with the empirical predictions for both permeable and impermeable foreshores. These findings confirm that existing empirical formulae can be applied with reasonable accuracy to predict Weibull distribution shape parameters at sloping structures for both permeable and impermeable slopes.

REFERENCES

Abolfathi, S., S. Dong, S. Borzooei, A. Yeganeh-Bakhtiari, and J.M. Pearson. 2018. Application of Smoothed Particle Hydrodynamics in Evaluating the Performance of Coastal Retrofits Structures, *Coastal Engineering Proceedings*, 1(36). https://doi.org/10.9753/icce.v36.papers.109

Besley, P. 1999. Overtopping of seawalls – design and assessment manual. R&D Technical Report W 178, Environment Agency, UK. ISBN 185705069X.

Dong, S., M. Salauddin, S. Abolfathi, Z.H. Tan, and J.M. Pearson. 2018. The Influence of Geometrical Shape Changes on Wave Overtopping: a Laboratory and SPH Numerical Study, *Proceedings of Coasts, Marine Structures and Breakwaters Conference 2017*, pp. 1217-1226. https://doi.org/10.1680/cmsb.63174.1217

Dong, S., S. Abolfathi, M. Salauddin, Z.H. Tan, and J.M. Pearson. 2020. Enhancing Climate Resilience of Vertical Seawall with Retrofitting - A Physical Modelling Study. Applied Ocean Research, *Applied Ocean Research*, 103, 102331. https://doi.org/10.1016/j.apor.2020.102331

EurOtop (2018): Manual on wave overtopping of sea defences and related structures. Second Edition.

Fitri, A., R. Hashim, S. Abolfathi, and K. N. Abdul Maulud. 2019. Dynamics of Sediment Transport and Erosion-Deposition Patterns in the Locality of a Detached Low-Crested Breakwater on a Cohesive Coast. Water 2019, 11, 1721. https://doi.org/10.3390/w11081721

Formentin, S.M., B. Zanuttigh, and J.W. van der Meer. A neural network tool for predicting wave reflection, overtopping and transmission. Coastal Engineering Journal, Vol. 59, No. 1 (2017) 1750006. https://doi.org/10.1142/S0578563417500061

Franco, L., M. De Gerloni, and J.W. Van Der Meer. 1994. Wave overtopping on vertical and composite breakwaters, *Proceedings of the 24th ICCE*, ASCE, Kobe, Japan, pp. 1030-1045.

Hughes, S. A., Thornton, C. I., Van der Meer, J.W., Scholl, B. N. 2012. Improvements in describing wave overtopping processes. In: Proceedings of ICCE 2012, ASCE, Santander, Spain. https://doi.org/10.9753/icce.v33.waves.35

Mansard, E. P. D., and E.R. Funke. 1980. The measurement of incident and reflected spectra using a least squares method, *Coastal Engineering*, 154–172.

Powell, K.A. 1990. Predicting short term profile response for shingle beaches, HR Wallingford, Report SR 219.

Salauddin, M., A. Broere, J.W. Van der Meer, H.J. Verhagen, E. Bijl. 2017. First Tests on the Symmetrical Breakwater Armor Unit Crablock. *Coastal Engineering Journal*, 59 (4), 1-33. https://doi.org/10.1142/S0578563417500206

Salauddin, M. and J.M. Pearson. 2018. A laboratory study on wave overtopping at vertical seawalls with a shingle foreshore. *Coastal Engineering Proceedings*, 1(36), waves.56. https://doi.org/10.9753/icce.v36.waves.56

Salauddin, M. and J.M. Pearson. 2019a. Wave overtopping and toe scouring at a plain vertical seawall with shingle foreshore: A Physical model study. *Ocean Engineering*, 171, 286-299. https://doi.org/10.1016/j.oceaneng.2018.11.011

Salauddin, M. and J.M. Pearson. 2019b. Experimental Study on Toe Scouring at Sloping Walls with Gravel Foreshores. *Journal of Marine Science and Engineering*, 7, 198. https://doi.org/10.3390/jmse7070198

Salauddin, M. and J.M. Pearson. 2020. Laboratory investigation of overtopping at a sloping structure with permeable shingle foreshore. *Ocean Engineering*, 197 (1), 1-13. https://doi.org/10.1016/j.oceaneng.2019.106866

Salauddin, M. J.J. O'Sullivan, S. Abolfathi, and J.M. Pearson. 2020. Extreme wave overtopping at ecologically modified sea defences. *22nd EGU General Assembly*, 6162, https://doi.org/10.5194/egusphere-egu2020-6162

Van der Meer, J. W., and W. Janssen. 1995. Wave run-up and wave overtopping at dikes, In: Kabayashi and Demirbilek (Eds.), Wave Forces on Inclined and Vertical Wall Structures, American Society of Civil Engineers, pp 1-27.

Van der Meer, J. W., and T. Bruce. 2014. New physical insights and design formulas on wave overtopping at sloping and vertical structures. Journal of Waterway, Port, Coastal, and Ocean Engineering 140(6), 04014025.

Van Gent M.R. 2002. Wave overtopping events at dikes. Proceedings of the 28th International Coastal Engineering Conference, vol. 2. World Scientific, 2203-2215.

Victor, L. and P. Troch. 2012. Wave overtopping at smooth impermeable steep slopes with low crest freeboards. Journal of Waterway, Port, Coastal, and Ocean Engineering, 372–385. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000141

Victor, L., J.W. Van der Meer, and P. Troch. 2012. Probability distribution of individual wave overtopping volumes for smooth impermeable steep slopes with low crest freeboards. *Coastal Engineering*, 64, 87–101. https://doi.org/10.1016/j.coastaleng.2012.01.003

Yeganeh-Bakhtiary, A., H. Houshangi, F. Hajivalie, and S. Abolfathi. 2017. A Numerical Study on Hydrodynamics of Standing Waves in Front of Caisson Breakwaters with WCSPH Model, Coastal Engineering Journal, 59:1, 1750005-1-1750005-31, DOI: 10.1142/S057856341750005X

Yeganeh-Bakhtiary, A., H. Houshangi, and S. Abolfathi. 2020. Lagrangian two-phase flow modeling of scour in front of vertical breakwater. Coastal Engineering Journal, 62:2, 252 - 266, DOI: 10.1080/21664250.2020.1747140

Zanuttigh, B., J.W. Van Der Meer, T. Bruce, and S. Hughes. 2013. Statistical characterisation of extreme overtopping wave volumes. *Proceedings of ICE, Coasts, Marine Structures and Breakwaters*, ICE, Edinburgh, UK.