Distribution of wave by wave overtopping volumes at vertical seawalls

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Abstract

This paper reports results of small scale physical tests on vertical walls describing the probability distribution of wave by wave overtopping volumes at a plain vertical structure with a shingle foreshore slope. The present paper contributes to the existing knowledge on the distribution of overtopping volumes by analyzing the acquired Weibull shape parameter from the experiments consisted of a matrix of 180 test conditions (wave steepnesses, crest freeboards, water depths, shingle sizes) and, by comparing the test results with the empirical prediction. Alongside the outputs of this study, the measured Weibull b values under the VOWS project are also analyzed in the present paper. The results of this study showed that there is no apparent relationship between Weibull shape parameter and incident wave steepness, relative freeboard or, relative discharge.

1 Introduction

Wave overtopping is a dynamic and irregular process because of the random nature of waves, the amount of overtopped water of in an overtopping event varies significantly from the mean overtopping discharge (Van der Meer and Janssen, 1994). Therefore, it is not possible to describe wave overtopping process wholly with the use of mean wave overtopping rate (q), however this 'dynamic and irregular process' can be described satisfactorily with the use of overtopping wave volume distribution (EurOtop, 2016). To assess the tolerable wave overtopping levels and to predict the probable overtopping hazards on individuals or property, the wave by wave overtopping volumes (the distribution of volumes and maximum individual volumes) are often used instead of average overtopping discharge.

Considerable research effort has been made to describe the probability distribution of individual overtopping volume in a sequence of incident waves, see Franco et al. (1994), Van der Meer and Janssen (1994), Besley (1999), Hughes et al. (2012), Victor and Troch (2012), Zanuttigh et al. (2013). For instance, based on physical model studies, Van der Meer and Janssen (1994) described the distribution of individual overtopping volume by a two-parameter Weibull distribution (Equation 1), incorporated in the new overtopping manual (EurOtop, 2016).

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

where, V is the overtopping volume per wave, P_v is the probability that an individual overtopping volume will not exceed V, and a and b are scale and shape parameter respectively for Weibull distribution.

To estimate the probability distribution of wave by wave volumes at plain vertical walls, empirical prediction formulae are available in EurOtop (2016) which are based on the laboratory and field measurements. Since most of the parametric studies were performed with the use of a solid impermeable bed in front of the model structure thus there may be an existence of the uncertainties in the application of these empirical methods for shingle foreshores.

This study is aimed to report the probability distribution of individual overtopping volumes of vertical seawalls in front of a shingle foreshore slope. The present paper contributes to the existing knowledge on the distribution of overtopping volumes by analyzing the acquired Weibull shape parameter from the experiments and by comparing the test results with the empirical prediction. In addition to experiments with shingle beds, experimental studies on overtopping were performed at a plain vertical seawall with the use of an impermeable bed to compare the wave overtopping behavior of permeable shingle foreshore with the solid impermeable foreshore.

2 Literature Studies

To estimate the maximum individual overtopping volume and proportion of overtopping waves, the empirical formuale suggested by EurOtop (2016) are adopted in this work, see Equations 2-7. The maximum individual overtopping volume (V_{max}) at a plain vertical structure can be approximated by estimating the number of overtopped waves (N_{ow}) in a sequence for both non-impulsive and impulsive conditions, see Equation 4 (EurOtop, 2016).

Maximum individual overtopping volume (V_{max}),

$$V_{max} = a(\ln N_{ow})^{1/b} \tag{2}$$

where, N_{ow} is the number of overtopping waves, a is the Weibull scale factor and b is the Weibull shape factor.

For a known relative crest freeboard (R_c/H_{m0}), EurOtop (2016) proposed the following empirical formulas (Equation 8 and 9) for the assessment of proportion of overtopping waves (P_{ov}) at a plain vertical wall under perpendicular wave attack, subjected to non-impulsive and impulsive wave conditions.

For non-impulsive conditions ($h^2/(H_{m0}L_{m-1,0}) > 0.23$), P_{ov}

$$P_{ov} = \frac{N_{ow}}{N_w} = \exp\left[-1.21\left(\frac{R_c}{H_{m0}}\right)^2\right] \tag{3}$$

For impulsive conditions ($h^2/(H_{m0}L_{m-1,0}) \leq 0.23$), P_{ov}

$$P_{ov} = \frac{N_{ow}}{N_w} = 0.024\left[\frac{h^2}{(H_{m0}L_{m-1,0})}\left(\frac{R_c}{H_{m0}}\right)\right]^{-1} \tag{4}$$

with a minimum predicted by Equation 3.

To estimate, the scale factor, a, EurOtop (2016) proposed the following empirical formula (Equation 7) in together with an empirical relationship between $\Gamma(1 + 1/b)$ and shape factor b, see EurOtop (2016) for details.

$$a = \left(\frac{1}{\Gamma\left(1 + \frac{1}{b}\right)}\right)\left(\frac{qT_m}{P_{ov}}\right) \tag{5}$$

where, Γ is the mathematical gamma function, q is the mean overtopping discharge per m width and P_{ov} is the probability of overtopping waves (N_{ow}/N_w).

For sloping structures, Van der Meer and Jansen (1994) reported that the probability distribution function of individual overtopping volume can be described with Weibull b value of 0.75. Afterwards, Franco et. al. (1994) described the probability distribution of wave be wave volumes of vertical breakwaters with a Weibull b value of 0.75. Further in 1999, Besely concluded that incident wave steepness has an influence on the shape of the Weibull distribution and proposed to increase the value of shape factor b with the increase of wave steepness for both vertical walls and smooth sloping structures. These findings by Besely (1999) were incorporated in the overtopping manual EurOtop (2007) and EurOtop (2016), see Equation 6 and 7 as formulated by EurOtop (2016).

For non-impulsive conditions, shape factor b

$$b = \begin{cases} 0.66 & \text{for } s_{m-1,0} = 0.02 \\ 0.88 & \text{for } s_{m-1,0} = 0.04 \end{cases} \quad h^2/(H_{m0}L_{m-1,0}) > 0.23 \tag{6}$$

For impulsive conditions, shape factor b

$$b = 0.85 \qquad h^2/(H_{m0}L_{m-1,0}) \leq 0.23 \tag{7}$$

However, recent investigations by Victor 2012 on steep low crested sloping structures and by Bruce et al. 2009 on rubble mound structures showed that there is no apparent effect of wave steepness on the distribution parameter b.

3 Laboratory description

The physical model experiments were undertaken in the wave flume within the School of Engineering at the University of Warwick, with flume dimensions of 22.0 (l) X 0.60 (w) X 1.0 (h) m and with a uniform 1:20 beach slope. An absorbing piston-type wavemaker was attached to the flume for generating regular and irregular waves. In this study, the shingle beaches were scaled adopting the methodology described by Powell (1990), which consisted of anthracite crushed coal with a quoted specific gravity of 1.39. At a 1:50 scaling, model beach materials (anthracite crushed coal) d_{50} of 2.10 mm and 4.20 mm were designed to represent prototype grain diameter d_{50} of 13 mm and 24 mm respectively with a specific gravity of 2.65. Within this manuscript, any reference to the sediment has been quoted as prototype values only.

A matrix of 180 test conditions (wave steepnesses, crest freeboards, water depths, shingle sizes) was covered to study overtopping characteristics at plain vertical walls with a shingle foreshore. Two constant nominal wave steepnesses ($s_{m-1,0}$ = 0.02 and 0.06) in relatively deep water were tested to represent both wind and swell sea wave conditions. Each experiment consisted of a sequence of approximately 1000 incoming irregular waves of a JONSWAP energy spectrum with a peak enhancement factor of $\gamma = 3.3$ ($\sigma_a = 0.07$ and $\sigma_b = 0.09$). Table 1 presents the incident wave conditions applied in this study.

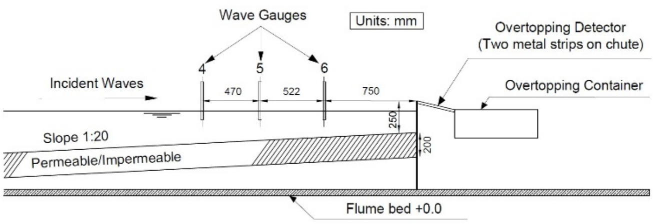


Figure 1. Cross-section of the test setup

Table 1. Incident wave conditions near wave paddle

T_p [sec]						
s_{op} [-] /H_{m0} [m]	0.05	0.07	0.09	0.12	0.14	0.16
0.02	1.27	1.50	1.70	1.96	2.12	2.26
0.05	0.80	0.95	1.07	1.24	1.34	1.43

The incident wave conditions at the structure as well as at deep water (near wave paddle) were determined with the use of 3-gauge method adopting the procedure suggested by Mansard and Funke (1980). The overtopping volumes were measured using a calibrated load-cell attached to a measuring container. To detect an overtopping event, an overtopping detector consisted of two parallel strips of metal tape was set along the crest of structure, worked as a switch closed by the water. The individual overtopping volumes were measured by determining the increment in the mass of water in the container for each overtopping event.

4 Results and discussions

4.1 System accuracy

The accuracy of the overtopping measurement system was inspected prior to carrying out any experiments, adapting the technique followed by Pearson et al. (2001). A series of overtopping events were simulated by throwing known volumes of water into the overtopping measuring container. The observed data from overtopping detector and load-cell were then processed by using an algorithm to find the number of overtopping waves and resulting individual overtopping volumes. Afterwards, the actual volume of each simulated overtopping event was compared with the measured value, see Figure 2. The data points clearly indicate that measured overtopping volumes were almost identical to actual (given) values. The variation of total measured volumes and actual volumes were found satisfactory around 0.6%, indicating that any errors induced by the measurement system were negligible.

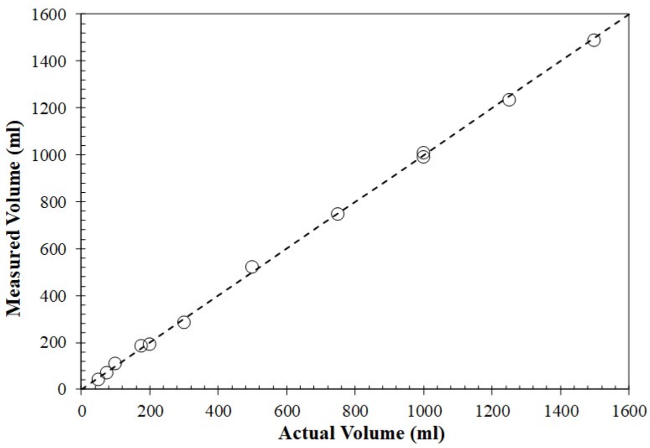


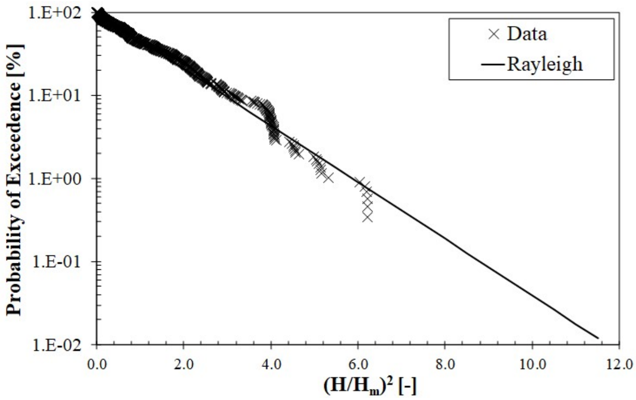
Figure 2: Actual (known) volume of simulated overtopping events compared with the measured values

4.2 Incident wave conditions

To compensate reflected waves originated from the structure, the wave paddle was equipped with an active absorption system. However, due to the presence of high reflection induced by structure, there may be an existence of uncertainties in the determination of incident wave conditions, especially at the toe of the structure. Therefore, to reduce probable uncertainties in the measurement of inshore wave conditions, the incident wave conditions were calibrated by repeating the test sequence without the presence of the structure. The calibration of incident wave conditions allows neglecting the effect of structure induced reflection in further analysis.

For this study, the distribution of measured incident wave heights at deep water is plotted for each experiment and compared with expected Rayleigh distribution. In Figure 3, two examples of observed wave height distributions near wave paddle are presented along with predicted Rayleigh distribution of wave heights for deep water.

a)



b)

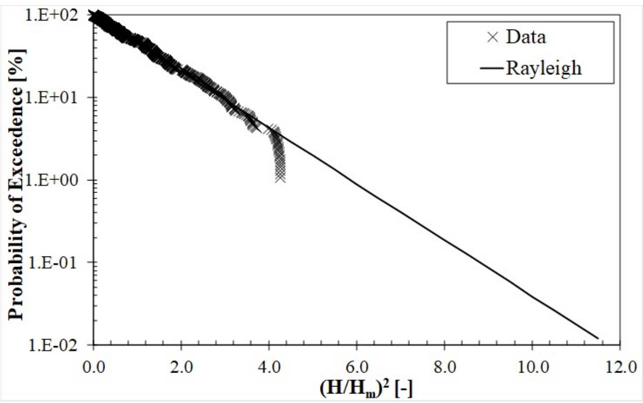


Figure 3: Distributions of measured incident wave heights- a) $s_{m-1,0}$ = 0.02, H_{m0} = 0.085 m and b) $s_{m-1,0}$ = 0.06, H_{m0} = 0.12 m

Overall, the results clearly demonstrate that the measured wave heights in deep water follow the Rayleigh distribution. Nevertheless, a slight variation of measured wave heights from the predicted Rayleigh distribution is observed for high waves. For instance, the data points corresponding to the example in Figure 3 (a) show that resulting wave heights clearly follow the trend estimated by Rayleigh distribution with only the larger waves being smaller than the prediction. This variation of largest wave heights may be happened due to the wave breaking phenomenon near the wave paddle for depth-limited conditions.

4.3 Overtopping observations

4.3.1 *Mean overtopping rate*

The mean overtopping rate for a plain vertical wall on a solid bed, are compared with the empirical predictions prescribed by EurOtop (2016), see Figure 4 for both impulsive conditions and non-impulsive conditions. For both breaking (impulsive) and non-breaking (non-impulsive) conditions, the graph shows an overall good agreement between the physical model results and empirical predictions.

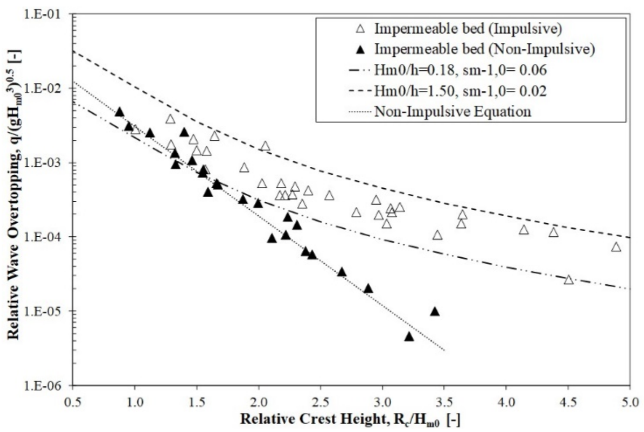


Figure 4: Mean overtopping rate at a plain vertical wall, subjected to both impulsive and non-impulsive conditions

4.3.2 *Maximum individual overtopping volume*

Figure 7 compares measured maximum individual overtopping wave volumes at plain vertical walls on the shingle beds with the empirical predictions suggested by EurOtop (2016) for both impulsive and non-impulsive conditions. The results from benchmark tests (solid bed) are plotted in Figure 7 as the reference case. For both shingle and solid beds, maximum individual overtopping wave volumes predicted using the empirical formulae (Equation 2-7) for vertical walls given by new overtopping manual EurOtop (2016).

For the tested conditions within this study, the graph demonstrates that the measured individual overtopping wave volumes correlates reasonably well (within a factor 2) with the estimated values under both impulsive and non-impulsive wave conditions. However, some scatter values of measured individual overtopping wave volumes were also reported for experiments under non-breaking conditions especially with low overtopping waves.

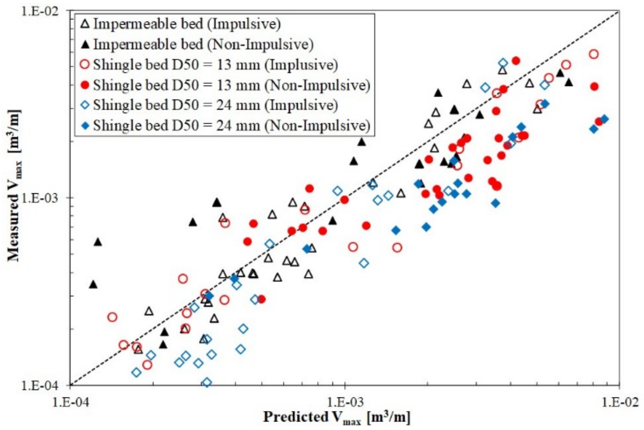


Figure 5: A comparison between predicted and measured maximum individual overtopping volume at a plain vertical wall

4.3.3 *Distribution of wave by wave volumes*

In the empirical prediction of overtopping volumes, it is generally considered that the wave by wave overtopping volumes in a sequence follow a two parameter Weibull distribution (Van der Meer and Janssen, 1994, Besley, 1999, EurOtop, 2016). For this study, wave by wave overtopping volumes were measured and plotted on a Weibull scale for each experiment to identify the distribution of these volumes.

For two different tested conditions, distributions of wave by wave volumes on a Weibull scale are presented in Figure 6, where V is the individual overtopping volume, P(V) is the probability of exceedance and V_{bar} is the mean overtopping volume. Overall, a linear trend of data points is noticeable from graphs, which denotes that measured individual overtopping volumes fit a two-parameter Weibull distribution for the tested conditions within this study.

In the Weibull distribution of wave by wave volumes, distributions of the small overtopping volumes (lower part) in many cases deviate from the inclination of the upper part of the distribution (Victor and Troch, 2012, Zanuttigh et al., 2013). Many researchers reported that higher wave by wave volumes give a good fit to Weibull distribution and provide a reliable estimation of extreme individual overtopping wave volumes, see Van der Meer and Janssen (1994), Besley (1999). For the design of coastal defences designers are interested mainly in the largest wave overtopping volumes, hence Zanuttigh et al. (2013) suggested to use the upper part of the distribution to get a good fit at the extreme overtopping wave volumes. Adopting the procedure of Zanuttigh et al. (2013), the best-fit linear trend line in Figure 6 is plotted by considering only the upper part of the resulting distribution of wave by wave volumes.

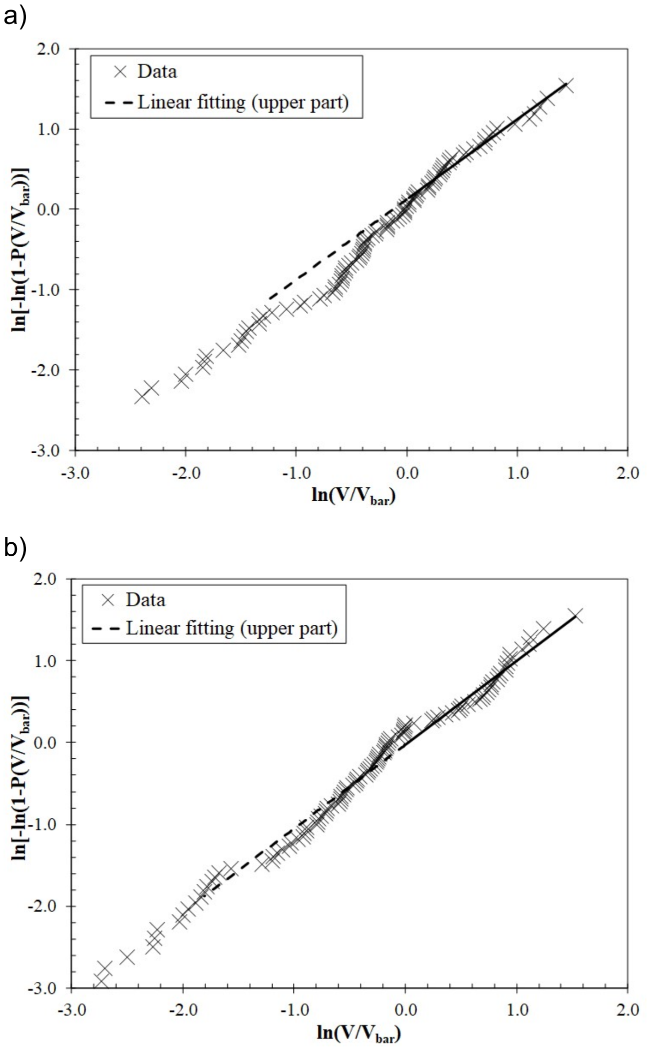


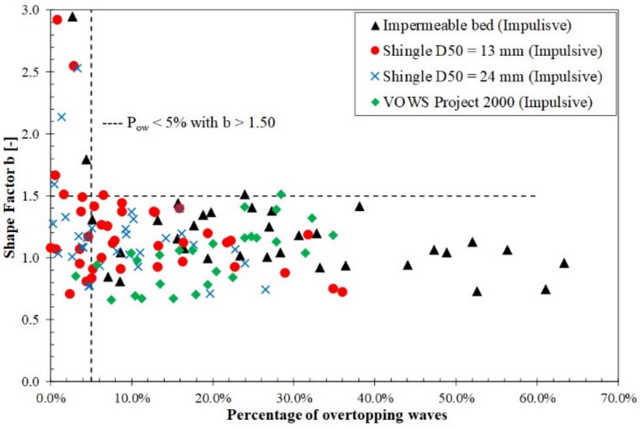
Figure 6: Distribution of wave by wave overtopping volumes- a) $s_{m-1,0}$ = 0.02, H_{m0} = 0.085 m and b) $s_{m-1,0}$ = 0.06, H_{m0} = 0.12 m

The Weibull b parameter can be determined from the inclination of the best fitting line. From the resulting Weibull distribution of overtopping volumes, the shape factor b of the distribution was also determined for each test. Alongside the test results of this study, the measured Weibull b values under VOWS project are also analyzed in the present paper. In VOWS project, specific tests were carried out to investigate wave by wave overtopping volumes at plain vertical walls, see Pearson et al. (2001), Pearson et al. (2002).

4.3.3.1 Variation of Weibull b with probability of overtopping waves:

The variation of Weibull shape parameter b with the percentage of overtopping waves is shown in Figure 4, subjected to both impulsive and non-impulsive conditions. The results of this study showed that the measured Weibull b values were within the range of 0.65-1.50 for most of the tested conditions. However, for some cases, higher values of (b > 1.5) Weibull shape parameter can be noticed in Figure 7.

a)



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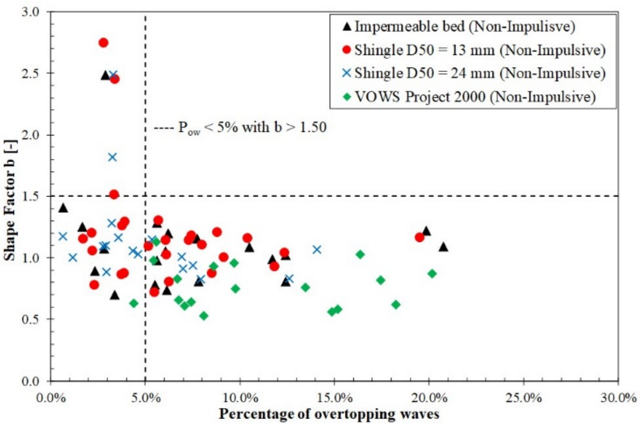


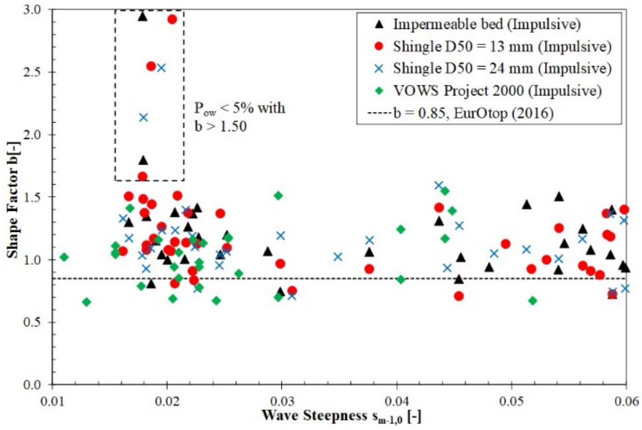
Figure 7: Variation of Weibull b with percentage of overtopping waves

Based on Figure 7, it is clearly noticeable that the tests with very low overtopping waves give the higher Weibull b values (b > 1.5). Similar characteristics of Weibull shape parameter with respect to low overtopping waves (less than 5% of overtopping waves) were also reported by Zanuttigh et al. (2013) for rubble mound breakwaters.

4.3.3.2 Variation of Weibull b with wave steepness:

To investigate the influence of wave steepness on the Weibull distribution of the individual volumes, the measured shape factor b is plotted as a function of the wave steepness $s_{m-1,0}$ for both impulsive and non-impulsive conditions, see Figure 8.

a)



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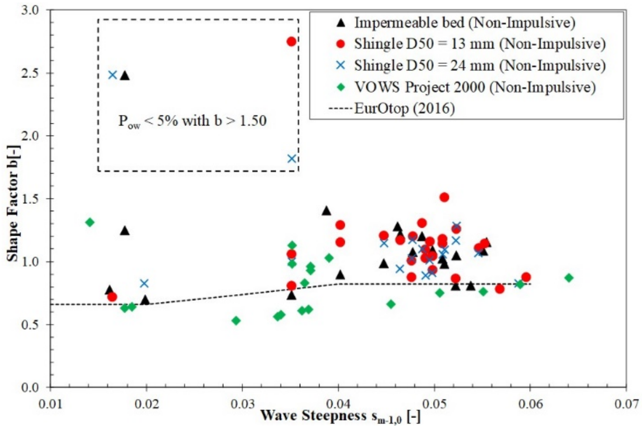


Figure 8: Variation of Weibull b with wave steepness

The solid lines in Figure 8 represent the b values (b = 0.66 for $s_{m-1,0}$ = 0.02 and b = 0.82 for $s_{m-1,0}$ = 0.04 under non-impulsive conditions, and b = 0.85 for all $s_{m-1,0}$ under impulsive conditions) recommended by Besley (1999). From Figure 8, it is noticeable that the data points have some scatter, demonstrating that there is no clear influence of wave steepness on the shape of the Weibull distribution. Based on the graph, it can be also observed that overall the measured values of shape parameter are higher than the values suggested by EurOtop (2016).

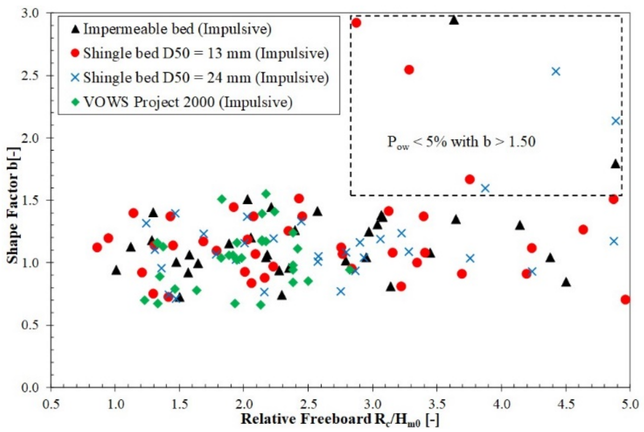
4.3.3.3 Variation of Weibull b with relative freeboard:

Recent advancements on the distribution of wave by wave overtopping volumes show that there is an influence of relative crest freeboard on the Weibull shape factor b for rubble mound and smooth sloping structures, see Victor 2012, Hughes 2012. To cite an example, for relatively steep low crested sloping structures, Victor 2012 proposed an empirical formula (Equation 8) for the estimation of shape factor as a function of relative freeboard and seaward slope.

$$b = \exp\left[-2.0\frac{R_c}{H_{m0}}\right] + (0.56 + 0.15\cot\alpha) \qquad (8)$$

For vertical walls with relatively high freeboard under non-impulsive conditions, Equation 8 gives b value equals to 0.56.

a)



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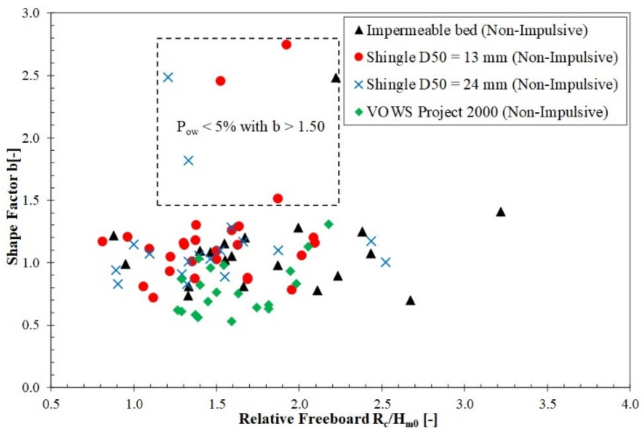


Figure 9: Variation of Weibull b with relative crest freeboard

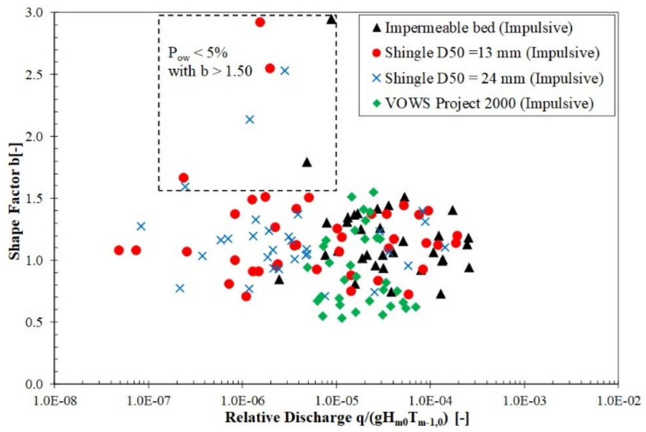
Figure 9 shows the effect of relative crest freeboard on the Weibull shape factor b under both impulsive and non-impulsive conditions tested within this study. The results illustrate that there is no apparent relationship between the relative freeboard and Weibull shape parameter b.

4.3.3.4 Variation of Weibull b with relative discharge:

Recently, to estimate Weibull shape factor b at rubble mound and smooth structures, Zanuttigh et al. (2013) suggested new prediction formulae by establishing a relationship between shape factor and relative discharge ($q/(gH_{m0}T_{m-1,0})$), see Equation 9 for smooth structures.

$$b = 0.73 + 55\left(\frac{q}{gH_{m0}T_{m-1,0}}\right)^{0.8} \qquad (9)$$

a)



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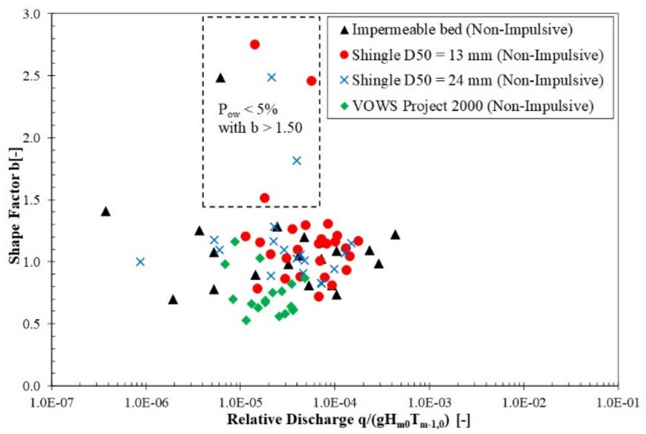

Figure 10: Variation of Weibull b with relative discharge

In Figure 10, the measured Weibull shape parameter b is expressed as a function of relative discharge ($q/(gH_{m0}T_{m-1,0})$). For the tested conditions within this study under impulsive conditions, the resulting data points demonstrate that shape parameter b does not vary with relative discharge, which concludes that there is no influence of relative discharge on the shape parameter b for vertical walls.

5 Conclusions

The Weibull shape parameter b for vertical walls has been investigated experimentally by performing an extensive laboratory study and by analyzing existing Weibull b values under VOWS project. The results of this study showed that there is no apparent relationship between Weibull shape parameter and incident wave steepness, relative freeboard and relative discharge. Overall, the measured Weibull b values were moderately higher than the predicted values by EurOtop (2016) both for impulsive and non-impulsive conditions. It was observed that low overtopping waves (less than 5% of overtopping waves) give higher Weibull b values, similar characteristics were reported by Zanuttigh et al. (2013) for rubble mound breakwaters.

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