Laboratory Study of the Spatial Distribution of Extreme Overtopping Events at Vertical Structures

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Abstract. Two-dimensional physical model experiments were conducted on a plain vertical seawall with a 1:20 sloping foreshore. Based on previous research, exponential equations were improved to describe spatial measurements for both impulsive and non-impulsive conditions. Comparisons were made between the spatial distributions from previous research studies, and compared to results of this study. It was observed that overtopping water generally distributes closer to seawall than previous predictions. 90% of overtopping was found generally to land within the distance of 0.04 wave-length under impulsive conditions, and similar results were observed in non-impulsive cases. A comparison between the spatial distribution of extreme events and total overtopping volume are discussed. Exponential equations are improved for fitting the distribution of extreme overtopping waves.

1. Introduction

Previous research primarily focuses on accurate predictions of total overtopping volumes passing the parapet of a seawall [1-3], with little or no guidance on the post-overtopping processes, such as where the thrown wave lands. The landward spatial distribution of overtopping is an important indicator which can help estimate the effects of hazards, such as coastal flooding. However, uncertainties still exist in determining the affected hazard area. This not only results in difficulties in predicting the safe distance behind the seawall crest, but also uncertainties exist in horizontal impact forces.

A number of studies have been performed using empirical prediction tools for estimating the spatial distribution of overtopping water [4-6]. Most of these focus on predicting the distribution of total overtopping water, which can help to understand the influence of the mean overtopping over a typical storm duration. However, the spatial distribution characteristics form an extreme individual overtopping wave is less well understood. For rubble mound breakwaters, Andersen and Burcharth [6] and Andersen et al. [7] presented equations involving the wave steepness, based on both field and laboratory data. The distribution for plain vertical structure was described by an exponential function for both laboratory and field studies [8, 9].

Peng and Zou [10] simulated the spatial distribution of overtopping water over both sloping and vertical structures in a numerical model. The results agreed well with predictions recommended by Andersen et al. [7] and Pullen et al. [9]. Peng and Zou [10] observed that the maximum individual overtopping water was thrown further than the mean overtopping distribution, although the profile had similar characteristics. The spatial distribution of extreme individual overtopping volume still requires further investigations.

It has been demonstrated by previous studies that the scale effects for overtopping discharges for impermeable vertical structure configurations can be neglected [11]. It is also reported by Pullen et al. [9], that the scale effects for spatial distribution is negligible. However, the influence of wind in field on both overtopping discharges and spatial distribution should be considered in predictions, as it may increase both indicators [7, 9, 12].

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This paper presents the spatial distribution of overtopping volume at the plain vertical seawall under impulsive and non-impulsive conditions. In particular, the spatial distribution of extreme overtopping events and total overtopping volume are investigated and discussed.

2. Previous Research

2.1. Overtopping Discharges

Overtopping discharge plays a significant role in assessing the hazardous effects of extreme events at coastal structures. Many research studies have been performed to determine mean overtopping discharges, and results are succinctly summarized in EurOtop Ⅱ [13]. The empirical equations for the mean overtopping discharge is given by:

For non-impulsive conditions:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.05\exp\left(-2.78\frac{R_c}{H_{m0}}\right) \quad [1]$$

while for impulsive conditions

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.011\left(\frac{H_{m0}}{\mathrm{hs}_{\mathrm{m-1,0}}}\right)^{0.5}\exp\left(-2.2\frac{R_c}{H_{m0}}\right) \quad \text{for } \frac{R_c}{H_{m0}} < 1.35 \quad [2]$$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0014\left(\frac{H_{mo}}{\mathrm{hs}_{\mathrm{m-1,0}}}\right)^{0.5}\left(\frac{R_c}{H_{mo}}\right)^{-3} \quad \text{for } \frac{R_c}{H_{m0}} > 1.35 \quad [3]$$

The wave conditions are classified as non-impulsive when $h_* = 1.3\frac{h_s}{H_{m0}}\frac{2\pi h_s}{gT_{m-1,0}^2} > 0.23$.

where H_{m0} is the significant wave height and the relative freeboard is described as R_c/H_{m0}. h_s is water depth at the toe of structure, g is gravity acceleration (=9.81 m/s^2), $s_{m-1.0}$, is the wave steepness, and q is the mean overtopping discharge per meter structure width per second.

2.2. Spatial Distribution

Bruce et al. [8] and Pullen et al. [9] described the spatial distribution of mean overtopping water (equation (4)):

$$q^* = e^{(-k(x/L_o))} \quad [4]$$

where q^* is a percentage of the discharge at the relative distance of x/L_o after seawall crest in total discharge, and L_o is the offshore wave length. The constant k determines the shape of distribution, which also incorporated the wind effects.

3. Experimental Setup

The schematic design of the flume in the School of Engineering at the University of Warwick is shown in Figure 1. The flume is 22.0m long, 0.6m wide and 1.0m high with a 1:20 beach slope. A piston-type wave generator was applied with an active absorption system, and approximately 1000 pseudo-random waves are generated based on the JONSWAP wave spectrum (γ= 3.3), at a scale of 1:50. Due to the limited size of overtopping collecting system and the accuracy of measurements, a small number of tests with large overtopping discharges or long wave period were conducted with approximately 500 - 600 waves. The model vertical seawall was fixed at 12.21m away from wave paddle.

Experiments were undertaken to cover as large relative freeboard range as possible for both impulsive and non-impulsive conditions. **Table 1** presents wave conditions for both impulsive and non-impulsive conditions. The significant wave height ranged between 0.041m and 0.095m, and various wave periods were generated ranging from 1.03s – 1.75s were generated. As a result,

generated wave steepness ranged between 0.016 – 0.039, and relative freeboard from 1 to 3.2 were covered in these series of tests. Both total overtopping volume and spatial distributions of overtopping water were measured with a multi-chamber container.

Table 1. Nominal wave conditions used for the physical tests (1:50 scale)

Vertical seawall condition								
Water depth (m)	0.07	0.09	0.11	0.09	0.16	0.15	0.18	0.21
Input wave period (s)	1.07 - 1.75		1.07 - 1.50		1.03 - 1.20	1.04 - 1.60		
Significant wave height (m)	0.055 - 0.095		0.068 - 0.085		0.041 - 0.052	0.048 - 0.075		
	Impulsive conditions				Non-impulsive conditions			
Relative freeboard	1.05 - 2.54		2.59 - 3.22		0.97 - 1.22	1.35 - 3.24		

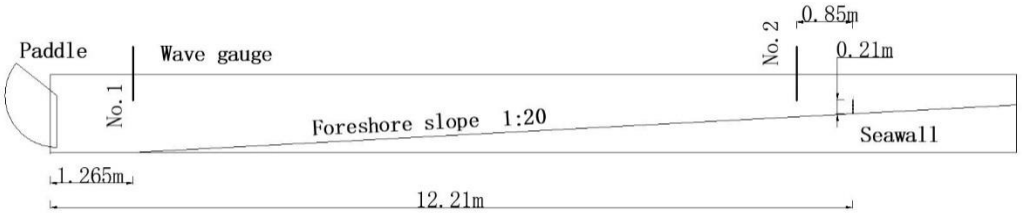


Figure 1. Cross-section of flume

3.1. Spatial Measurements

In order to measure both overtopping discharges and spatial distribution of overtopping water, a multi-chamber container was fixed behind the vertical seawall. Figure 2 shows the cross-section of the whole container. Among the 11 chambers, the relatively smaller ones were placed close to seawall while larger ones were located further. This design was selected in order to measure the spatial distribution with a high resolution especially in the area close to the seawall crest. The top of each chamber wall was made into a slope with a sharp edge in order to minimise the overtopping volumes jumping into adjacent chambers. The overtopping volumes were measured with calibrated wave gauges and pressure transducers fixed in chambers.

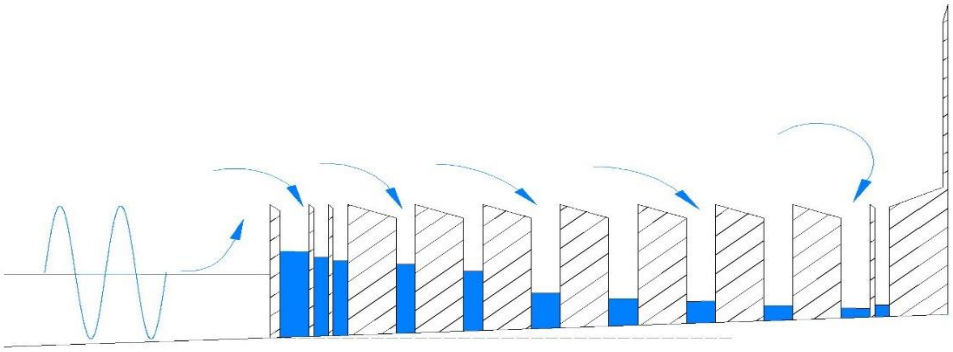


Figure 2. Schematic of the multi-chamber collection container

4. Results

4.1. Overtopping Observations

The overtopping water was collected by the multi-chamber container behind the seawall, and overtopping discharges were obtained by volume data converted from water level changes in each container. The measurements of mean overtopping discharges were compared with EurOtop Ⅱ [13] predictions from equations (1)-(3). The dimensionless overtopping discharges are plotted against relative freeboard in **Figure 3**.

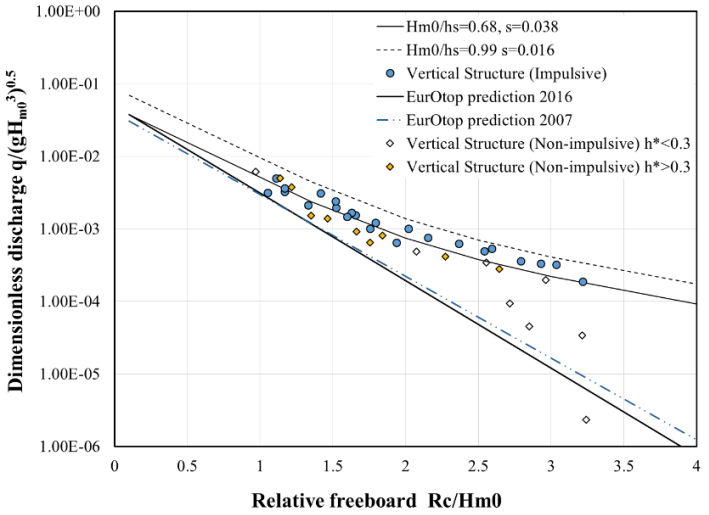


Figure 3. Mean overtopping discharges at plain vertical seawall

Figure 3 shows that the measured mean overtopping discharges from impulsive conditions fit predictions well, however the results from the non-impulsive overtopping events show that the measurements are under predicted. As the relative freeboard increases, the deviation appears to increase. A similar phenomenon was reported by Besley et al. [1], namely that the underestimation in non-impulsive overtopping discharge is noticeable, when the impulsiveness parameter h_* is over 0.3. In addition, the overtopping proportion under non-impulsive conditions was also found be under-predicted, especially in the cases with relative freeboard $R_c/H_{m0} > 1.8$.

A further aim of the study was to elucidate the difference between the spatial distributions of extreme individual overtopping events compared to the mean overtopping distribution. The measured maximum individual overtopping discharges were compared to the equations from EurOtop Ⅱ [13] (see **Figure 4**). Although there was some scatter for extremely low overtopping events, acceptable agreement was observed between laboratory data and empirical predictions.

4.2. Spatial Distribution of Total Overtopping Volume

The spatial distribution of total overtopping volumes can be predicted by an exponential function of relative distance to seawall (equation (4)). The best fit equation was obtained by the constant k fixed to 29 when there is no wind speed involved in tests [9]. Four examples of the measured spatial distribution are given in **Figure 5**. It is noticeable that the prediction equation from Pullen et al. [9] overestimates the distribution of total overtopping water. According to the predicted distribution curve, 90% of water lands in a distance of 0.08 wave length, however, in terms of measurements from this study, 90% of overtopping water lands in a distance of 0.04 wave length. This over prediction becomes more significant in the cases of extremely low overtopping discharges, while acceptable agreement are observed in tests with larger overtopping volumes. It is therefore assumed that the constant k in the exponent of equation (4) can be related with relative freeboard R_c/H_{m0} when no wind speed is involved. Larger R_c/H_{m0} values are assumed to give a larger k value, and overtopping water lands closer to the crest of seawall.

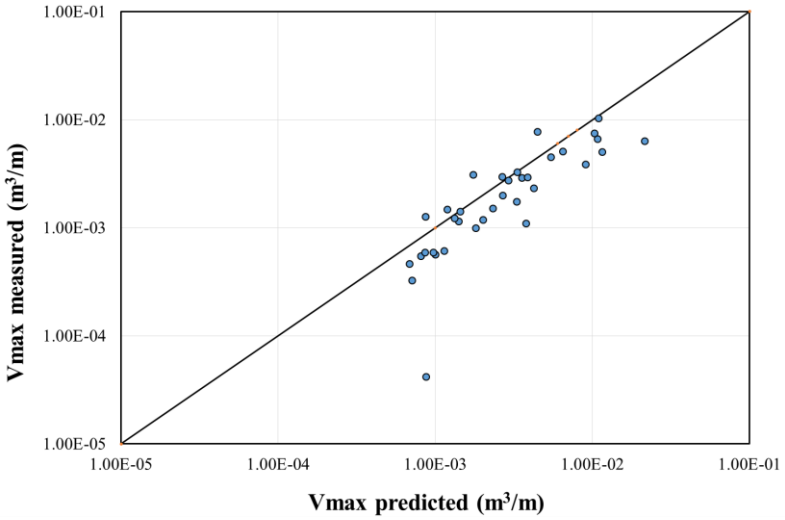
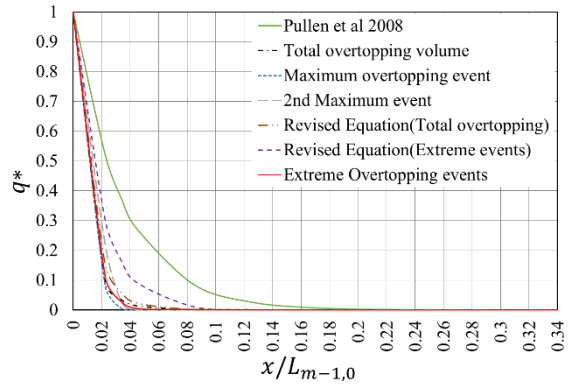
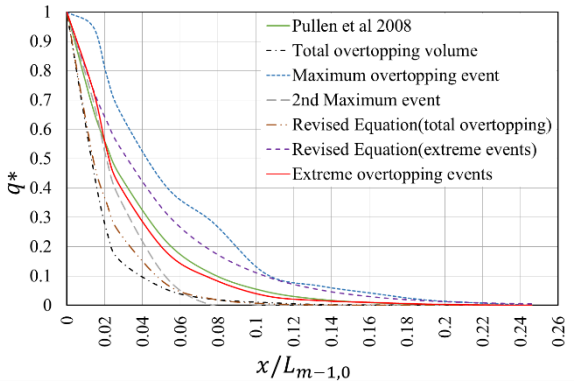


Figure 4. Maximum individual overtopping discharges over plain vertical structure

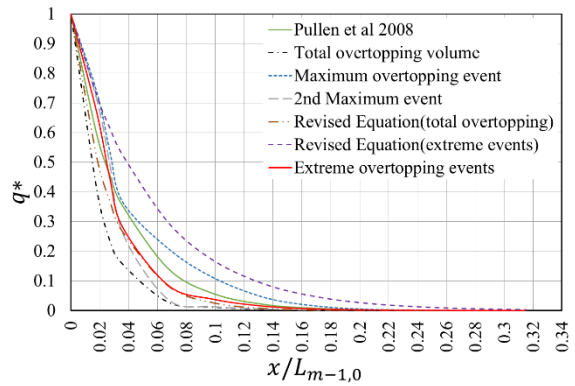
The spatial distributions given in **Figure 5** (a) and (d) are close to the seawall, which presents difficulties in distinguishing the distribution of total overtopping volume and extreme overtopping events. Thus, the square root of $x/L_{m-1,0}$ was applied to x-axis to improve the results. **Figure 6** gives the new spatial distribution of the four cases shown in **Figure 5**. The new distributions show a clear trend within a distance of 0.14 wave length, while the distributions in further landward of this region from the seawall are less important. Less than 5% of overtopping water landed beyond a distance of 0.14 wave length.



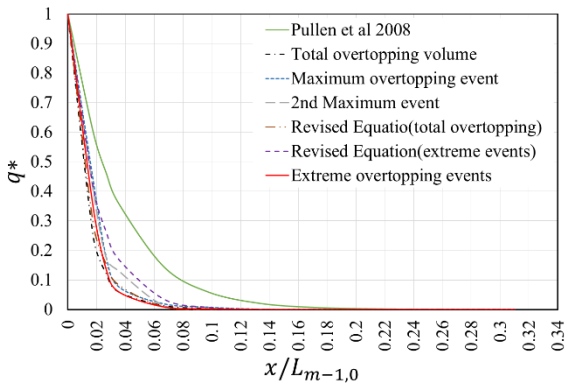
(a)



(b)



(c)



(d)

Figure 5. Spatial distribution behind plain vertical seawall. (a) Case R_c/H_{m0}=1.755 (Impulsive) (b) Case R_c/H_{m0}=1.109 (Impulsive) (c) Case R_c/H_{m0}= 1.138 (Non-impulsive) (d) Case R_c/H_{m0}= 2.273 (Non-impulsive).

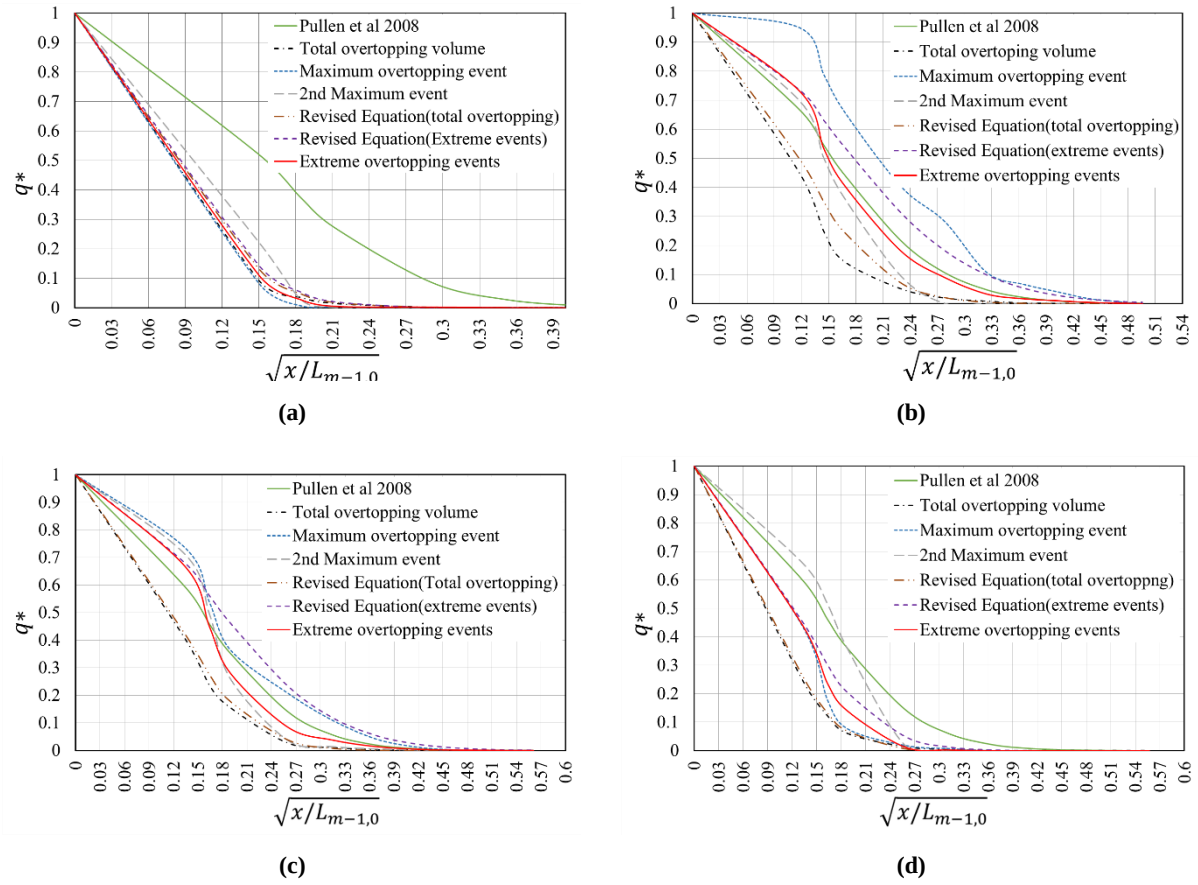


Figure 6. Improved spatial distribution behind plain vertical seawall. (a) Case R_c/H_{m0}=1.755 (Impulsive) (b) Case R_c/H_{m0}=1.109 (Impulsive) (c) Case R_c/H_{m0}= 1.138 (Non-impulsive) (d) Case R_c/H_{m0}= 2.273 (Non-impulsive)

Based on the exponential equation given by Pullen et al. [9], efforts were made to find the best fit equation of spatial distribution in each test case. As no wind speed applied in model tests, constant k was initially fixed to 29, and the distribution of overtopping water close to the seawall crest was given priority [8]. As assumed earlier, the value k is observed to increase with the relative freeboard R_c/H_{m0} . By quantifying the relationship between constant k and relative freeboard (R_c/H_{m0}), it is found that an exponential function is able to predict the value of k with a correlation of approximately R^2=0.93 (see **Figure 7**(a)). When no wind speed is involved, k in exponent for impulsive conditions can be predicted by the expression given as equation (5):

$$k = 22e^{0.85R_c/H_{m0}} \quad [5]$$

For green overtopping events, it is also found that the overtopping volume will influence the landward area behind the crest of structure within a distance of 0.12 of the maximum wave length maximum. The spatial distribution of the overtopping water can also be described by a similar exponential function with a correlation of around R^2=0.91(see **Figure 7** (b)). The k value can be derived from equation (6).

$$k = 21e^{0.63R_c/H_{m0}} \quad [6]$$

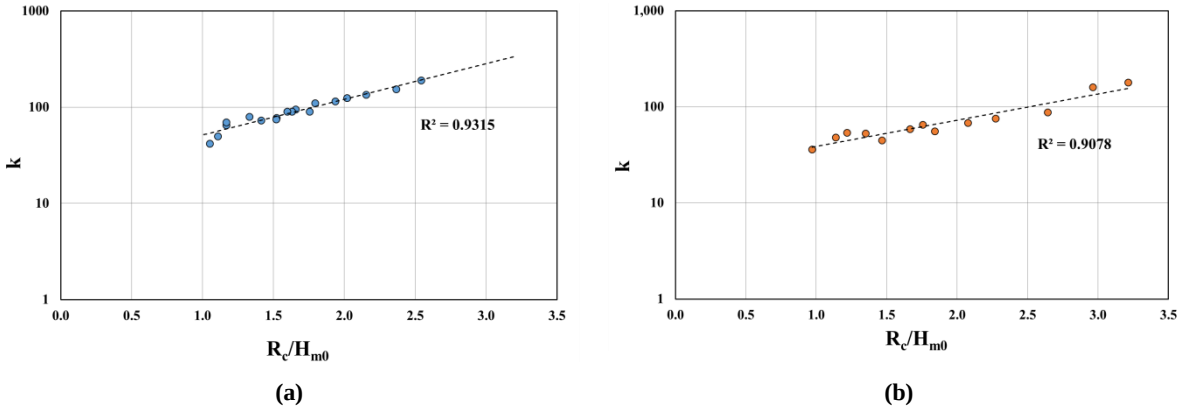


Figure 7. Relationship between k and R_c/H_{m0}. (a) From Impulsive test conditions; (b) From Non-impulsive test conditions

4.3. Spatial Distribution of Extreme Events

In previous studies, measurements have been conducted on both individual and total spatial distribution on the smooth sloping structures. It is reported that the spatial distribution of maximum and average overtopping volume are similar [7]. Peng and Zou [10] obtained similar results by comparing the distribution of maximum individual overtopping event with the distribution of time average overtopping in numerical simulations. **Figure 5** illustrates that the exponential equation of total distribution is still able to describe the individual overtopping events (purple dotted line). The k value can still be determined by a similar exponential function as total distribution, with correlations of R^2=0.82 and R^2=0.91 for impulsive and non-impulsive conditions respectively (see **Figure 8**). The difference between individual and total spatial distribution is not always significant in all tested configurations. With the increase in relative freeboard, R_c/H_{m0}, the gap between two distributions tends to decrease, as a result of decreasing overtopping events. When the relative freeboard R_c/H_{m0} reaches 2.0, the spatial distribution of maximum individual overtopping events and mean overtopping discharges show similar results, and overtopping water lands immediately after seawall crest.

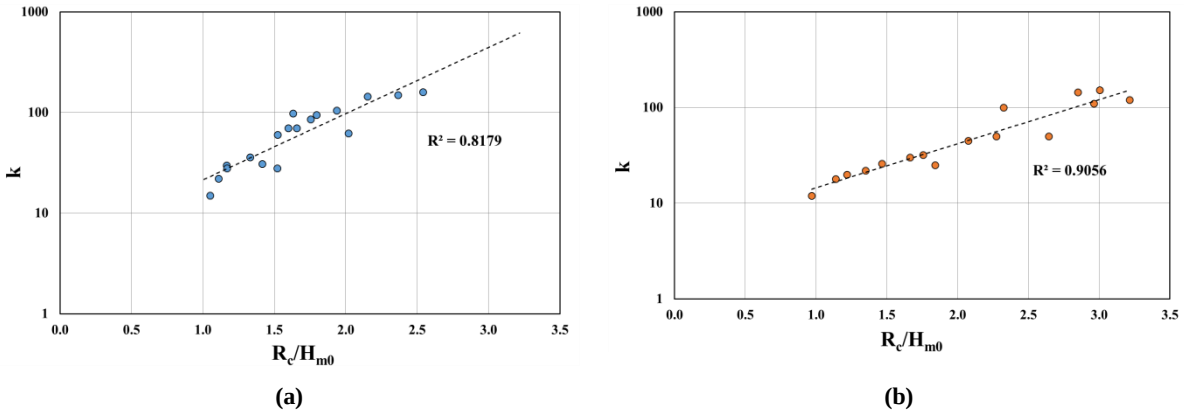


Figure 8. Relationship between k and R_c/H_{m0} for largest 5 individual overtopping events. (a) From Impulsive test conditions; (b) From Non-impulsive test conditions.

5. Conclusion

This paper presents a series of laboratory experiments on the landwards distribution of overtopping water behind the crest of the plain vertical structure. The spatial distribution of both total and individual overtopping water are analysed, and described by exponential functions. An improved method for the prediction of constant k in exponent is recommended when no wind speed involved, based on research conducted by Pullen et al. [9] and Bruce et al. [8]. This method is also expanded for the predictions of spatial distribution of green overtopping events, as well as the individual overtopping events in the tested cases.

Irrespective of the wind effects, 90% of overtopping was observed generally to land in the distances of 0.04 wave length under impulsive conditions. Similar spatial distribution was found in non-impulsive overtopping events, and overtopping volume is distributed further with increase of relative freeboard. The exponential function of relative distance $x/L_{m-1,0}$ published by Bruce et al. [8] and Pullen et al. [9] can be adopted to predict spatial distribution of overtopping volumes. However, the value of constant k in exponent was underestimated in most cases. Better predictions may be achieved by the application of equation (5) and (6) with reasonable good correlations of R^2=0.93 and R^2=0.91. However, further validation with field data is desirable.

In addition, the individual overtopping distributions are found usually a bit further than the distribution of total overtopping discharge. However, the distribution of extreme and total overtopping volumes do not vary significantly when freeboard increases to over 2.0, while more scatter is observed on the distribution of extreme overtopping volume. No noticeable differences were observed between extreme and total overtopping events for high relative freeboard conditions ($R_c/H_{m0} > 2.7$).

6. References

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Acknowledgements
Shudi Dong sincerely acknowledge the financial support for his PhD studies, from the School of Engineering, University of Warwick and Chinese Scholarship Council. Jonathan Pearson sincerely acknowledges the financial support by the Royal Academy of Engineering (RAEng/The Leverhulme Trust Senior Research Fellowships scheme).