



Title	Spatial Distribution of Wave-by-Wave Overtopping at Vertical Seawalls
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Publication date	2020-12-28
Publication information	Dong, Shudi, Soroush Abolfathi, Md Salauddin, and Jonathan M. Pearson. "Spatial Distribution of Wave-by-Wave Overtopping at Vertical Seawalls." Coastal Engineering Research Council, December 28, 2020. https://doi.org/10.9753/icce.v36v.structures.17 .
Publisher	Coastal Engineering Research Council
Item record/more information	http://hdl.handle.net/10197/12534
Publisher's version (DOI)	10.9753/icce.v36v.structures.17

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SPATIAL DISTRIBUTION OF WAVE-BY-WAVE OVERTOPPING AT VERTICAL SEAWALLS

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INTRODUCTION

Over the years, many physical and numerical modelling research has been carried out to investigate the wave-structure interactions and the resulting mean overtopping characteristics at sea defences (e.g., Franco et al., 1994; Van der Meer and Bruce, 2014; Abolfathi et al., 2016 and 2018; Dong et al., 2018 and 2020; Yeganeh-Bakhtiari et al., 2017 and 2020; Fitri et al., 2019; Salauddin and Pearson, 2019 and 2020). The most reliable empirical predication formulae for prediction of mean overtopping rates have been reported in the overtopping manual, EurOtop (2018). In addition to average overtopping rates, in recent years, the spatial distribution of overtopped water has become an important topic of research to understand the safe zone behind coastal defences. The existing empirical formulae for spatial distribution of overtopping provide conservative predictions, as it has been derived from the mean overtopping volumes. The extreme wave overtopping hazards in generally originate from individual overtopping events rather than the mean overtopping volumes.

Bruce et al. (2005) described the spatial distribution of overtopping water behind vertical structures as an exponential function of distance from seawall, with use of a spatial parameter k , to determine the shape of the spatial distributions (Eq. 1).

$$q^* = e^{-k\left(\frac{x}{L_0}\right)} \quad \text{Eq. 1}$$

$$q^* = \frac{q_{x/L_0}}{q_{total}} \quad \text{Eq. 2}$$

where q_{x/L_0} denotes the overtopping discharge lands after the distance x , q_{total} presents the total overtopping discharge, L_0 is the offshore wavelength, k is an empirical coefficient controlling the shape of spatial distribution and is set to 29 when no wind effects are considered (Pullen et al., 2006; Pullen et al., 2009).

Dong and Pearson (2018) reported that the k increases with the relative freeboard (R_d/H_{m0}), indicating shorter travel distance of overtopping water behind vertical seawalls. The wind effects, in reality, would influence the wave overtopping processes and its spatial distribution (de Waal et al., 1997; Ward et al., 1996). Pullen et al. (2009) improved the predictions by adding the contribution of wind effects on the spatial distribution of overtopping water behind vertical structures. However, their predictions did not include extreme large overtopping which are essential for assessing safety level of coastal defences. Andersen et al. (2009), based on physical modelling experiments, concluded that the characteristics of the maximum overtopping event should be

considered for safety assessment of coastal regions. Peng and Zou (2011) using numerical simulations, showed that overtopping water travels further for the case of maximum overtopping event in comparison to the total overtopping volume. Data from both Andersen et al. (2009) and Peng and Zou (2011) mainly focus on sloping structures, with limited discussions on the spatial distribution of wave-by-wave and mean overtopping events.

This study presents comprehensive laboratory investigations on the spatial distribution of wave-by-wave overtopping at vertical seawalls, which is an extension of the earlier work carried out on the mean overtopping characteristics at vertical walls reported in Dong et al. (2018). The largest five overtopping events are further analysed to understand the spatial distributions wave-by-wave overtopping.

KEYWORDS

Vertical seawall, spatial distribution, wave-by-wave overtopping, hazard zone, coastal resilience

EXPERIMENTAL SETUP

The physical modelling tests were carried out on a 1:50 scaled prototype in two-dimensional wave flume at the University of Warwick, UK. The flume is 22.0m long, 0.6m wide and 1.0m high with a uniform 1:20 smooth beach slope. A piston-type wave generator with an active absorption system were used to generate random sea waves. Both impulsive and non-impulsive waves under swell and storm conditions were tested to investigate spatial distribution of overtopping water behind vertical seawall. For each test case, approximately 1000 pseudo-random waves were generated based on the JONSWAP wave spectrum with γ factor taken as 3.3.

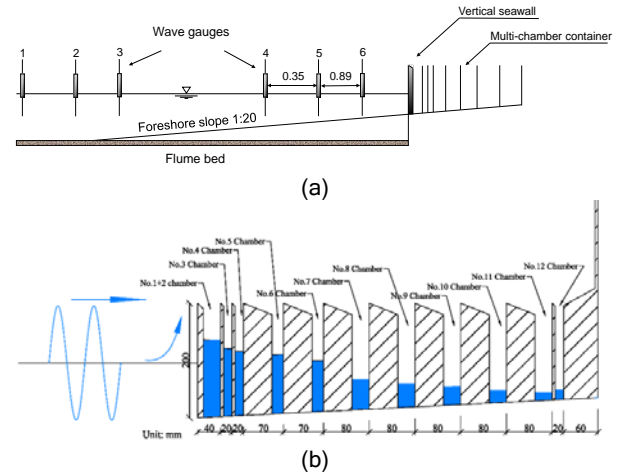


Figure 1 - Schematic design of (a) wave flume and experimental setup (b) multi-chamber container designed to capture overtopping spatial distribution (adopted from Dong and Pearson, 2018)

The incident wave characteristics at deep and shallow water were measured by two sets of wave gauges (3 probs in each set) placed close to the wave paddle and seawall, respectively. The spatial distribution of overtopping water was measured using a container with 0.7m length, consisted of 11 chambers. The container's length was set longer than the possible maximum travel distance, described by Pullen et al. (2009). To capture the spatial distribution of overtopping with high resolution, immediately after the seawall, the

container was designed with relatively smaller chambers close to the seawall, while larger chambers were located further from the wall (see Figure 1b). The top of each chamber wall was designed sloped with a sharp edge to minimize the overtopping volumes jumping into the adjacent chambers.

RESULTS AND DISCUSSION

The comparison between the measured overtopping travel distance and the predictions of Pullen et al. (2009) formulae for the case of no wind, shows over-estimations of the existing empirical-based formulae. The over-estimation from empirical formulae becomes more significant as freeboard increases (Dong and Pearson, 2018). Figure 2 illustrates the travel distance measured for 85% mean and extreme overtopping discharge with changing freeboard. Within tested wave conditions, the travel distance ($x/L_{m-1,0}$) decreases sharply as dimensionless freeboard (R_c/H_{m0}) increases. Reductions up to 84% and 91% are observed in the mean and extreme overtopping discharge, respectively, when R_c/H_{m0} rises from 0.85 to 2.5.

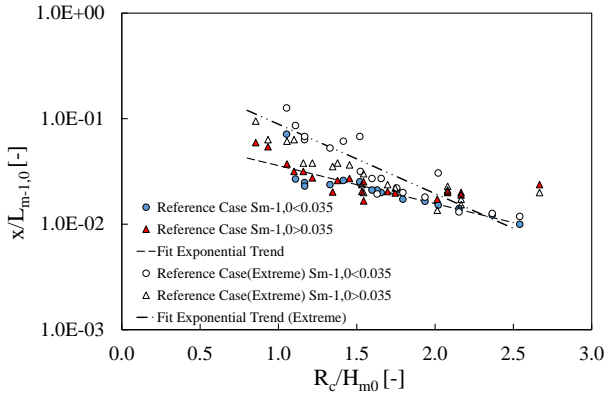


Figure 2 - The travel distance ($x/L_{m-1,0}$) of 85% mean and extreme overtopping discharges influenced by dimensionless freeboard (R_c/H_{m0})

Figure 3 presents the spatial parameter k measured for both impulsive and non-impulsive wave conditions tested within this study. The figure shows measured k increases with R_c/H_{m0} , and the relationship can be described as an exponential function. Hence, Pullen et al (2006) empirical formulae for k on plain vertical seawall are further improved in this study, using physical modelling data for both swell and storm waves as Eq. 3 and 4:

$$k = 23e^{\frac{0.82R_c}{H_{m0}}} \quad (\text{Impulsive}) \quad \text{Eq. 3}$$

$$k = 21e^{\frac{0.63R_c}{H_{m0}}} \quad (\text{Non - impulsive}) \quad \text{Eq. 4}$$

Figure 4 plots the spatial parameter k for the mean and wave-by-wave overtopping discharge. It is evident that the k from the wave-by-wave overtopping event is significantly smaller than the measurements of the mean overtopping discharges, indicating that the wave-by-wave overtopping discharges travel further than the mean overtopping discharges.

Figure 4 also compares the spatial parameter k from swell and storm waves. The figure shows slight deviations in the spatial parameter k from swell and storm waves under impulsive conditions when $R_c/H_{m0} < 2.0$. Parameter k from swell waves is observed to be smaller than values from

storm waves. This deviation becomes insignificant as R_c/H_{m0} decreases.

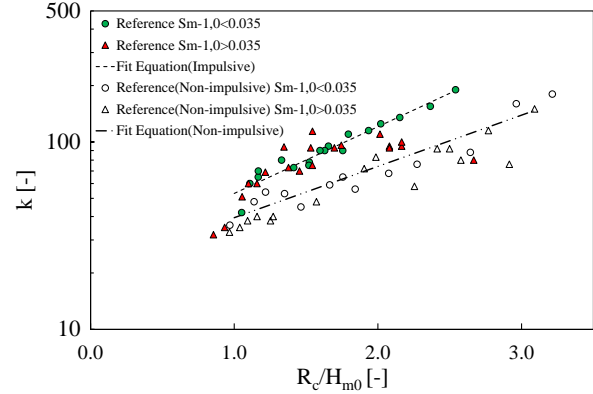


Figure 3 - Relationship between k and R_c/H_{m0} for the spatial distribution of mean overtopping discharge under swell and storm waves

Figure 5 compares the travel distance of the mean and wave-by-wave overtopping discharges with the increase ratio of the travel distance of 85% the mean and wave-by-wave overtopping discharges. It is seen from the graph that the increase ratio ($x_{mean}/x_{extreme}$) rises with decreasing $R_c/L_{m-1,0}$, at a maximum of three folds. As $R_c/L_{m-1,0}$ increases over 0.10, the travel distance of wave-by-wave and mean overtopping discharges becomes identical.

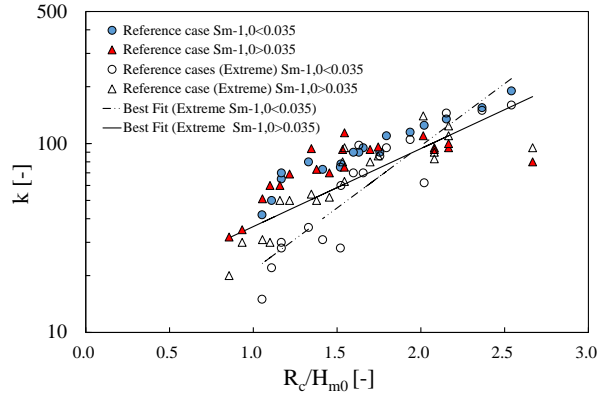


Figure 4 - Comparison of spatial parameter k , for mean and extreme overtopping events under swell and storm waves

CONCLUSIONS

This paper aims to understand the hazard zone behind the coastal defence structures. Physical modelling experiments were undertaken to investigate the shape of spatial distribution of the mean and extreme overtopping discharge behind the plain vertical seawall. The wave conditions were designed to include both swell and storm waves. For the wave conditions tested within this study, it was observed that existing empirical prediction formulae of Pullen et al. (2009) overpredicts the spatial distribution of overtopping water, particularly for the case of $R_c/H_{m0} < 1.5$. The parameter k measured in this study, increases with R_c/H_{m0} under both swell and storm wave conditions. Using extensive laboratory measurements, this study provides improved empirical equations for k on plain vertical seawall (Eq. 3 and 4).

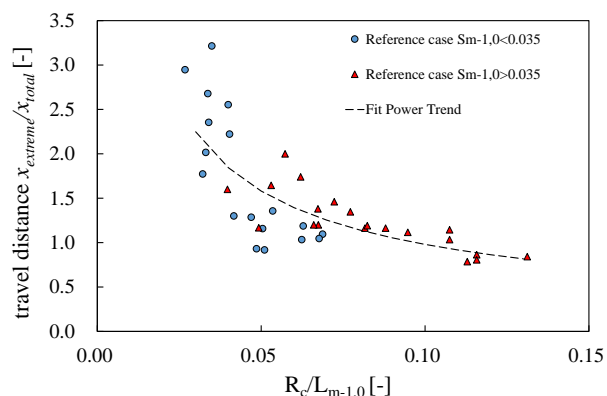


Figure 5 - Increases in travel distance for 85% of the mean and wave-by-wave overtopping volume ($X_{mean}/X_{extreme}$).

It was found that, for the cases with small freeboard ($R_c/H_{m0} < 2.0$), the wave steepness plays a key role in determining the spatial parameter k . Lower wave steepness (longer wave period in general), resulted in more significant increases of spatial parameter k . However, the effects of wave steepness become insignificant for the cases with $R_c/H_{m0} > 2.0$.

Comparisons are also made between the parameter k from the mean and wave-by-wave overtopping discharges. Measurements indicate that the maximum overtopping events are usually travel further than averaged distribution of the mean overtopping discharges, at a maximum of three folds. As freeboard increases and wave steepness decreases, the parameter k from mean and wave-by-wave overtopping discharges becomes gradually identical.

The analysis of experimental data presented in this paper provides important new knowledge on the variation of travel distance between the maximum overtopping and the mean overtopping events. The new predictive formulae suggested in this study improve the safety assessment of critical coastal infrastructures during extreme climatic events.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support by the China Scholarship Council and the University of Warwick Global Challenges Research grant for EMBRACES project.

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