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Research paper

Improved prediction of wave overtopping rates at vertical seawalls with recurve retrofitting

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ABSTRACT

This study investigates the reduction in overtopping discharge along a vertical seawall through the implementation of a recurve retrofitting. A comprehensive set of physical modelling experiments were undertaken in a laboratory-scale wave flume at the University of Warwick, to investigate the wave overtopping processes under both swell and storm wave conditions. The tests measured overtopping discharges for impulsive and non-impulsive wave conditions. The effects of geometrical design of recurve retrofitting on overtopping reduction are examined by four configurations with varying overhang length and recurve hight. The study revealed that the reduction in overtopping is primarily determined by the length of the overhang in the recurve wall, while the influence of the recurve height is limited. A longer overhang length results in a more substantial decrease in overtopping discharges on the seawall crest. The results also highlight the role of incident wave steepness and the crest freeboard on the overtopping mitigation performance of the recurve walls. A new enhanced methodology is proposed to predict the wave overtopping from vertical seawalls with recurve retrofitting., considering the effects of freeboard and wave steepness. The findings of this study provide new important insight in the role of retrofitting as a robust intervention to improve the wave overtopping mitigation performance of seawalls. The predictive empirical formulae proposed by this study facilitate readily and accurate estimation of overtopping rates as a function of retrofitting geometrical design, allowing for wider application of retrofitting solutions.

1. Introduction

According to the data released in recent climate reports, sea levels are rising at an increasingly rapid pace and are projected to continue increasing in the coming decades (IPCC, 2023). Higher wave magnitudes pose an elevated risk to coastal defenses, making them more susceptible to threats such as coastal flooding and erosion (Chini et al., 2010; Dong et al., 2021a; Yeganeh-Bakhtiary et al., 2020; Donnelly et al., 2024). Existing coastal defenses face greater challenges in safeguarding both people and critical infrastructure in coastal areas (Xie et al., 2019; Almar et al., 2021; Salauddin et al., 2022; Fanti et al., 2023; Habib et al., 2023a,b; 2024). Retrofitting is widely recognised as an effective method for enhancing the climate resilience of existing coastal defences. In recent years, there has been a growing focus on enhancing resilience and biodiversity in coastal regions. As such, retrofitting solutions made up with eco-friendly materials (e.g., vegetation, coral reef), also known as 'green infrastructures', has gained significant attention in recent years (Liu et al., 2022; Manousakas et al., 2022; Salauddin et al., 2021). Eco-friendly soft retrofits have demonstrated the ability to reduce wave heights substantially at the toe of coastal defence structures and significantly decrease overtopping discharges (Keith and Jeremy, 2007; Horstman et al., 2014; Luhar et al., 2017; Liu et al., 2020; Salauddin and Pearson, 2020). Alternatively, traditional hard-engineered retrofitting structures such as berm and recurve parapet remain reliable options with predictable performance in reducing overtopping discharges (Bruce et al., 2009; Molines and Medina, 2015; Formentin and Zanuttigh, 2019; Bayle et al., 2020; Van Gent et al., 2022). The recurve wall is considered as effective and efficient hard engineered retrofit with satisfactorily mitigating effect on wave overtopping (Kortenhaus et al., 2003; Martinelli et al., 2018; Dong et al., 2021b; Ravindar et al., 2022).

In recent years, several investigations have been undertaken to quantify the appropriateness and robustness of the recurve walls on

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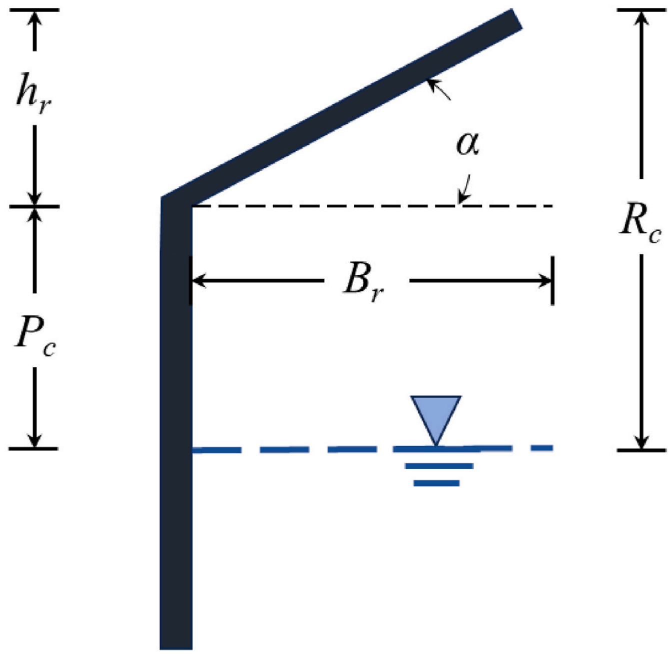

Fig. 1. Definitions of the key design parameters for recurve walls (Adopted from Pearson et al., 2004).

mitigating the mean overtopping discharge (Kortenhaus et al., 2003; Pearson et al., 2004; Dong et al., 2018, 2022; Abolfathi et al., 2018). Franco et al. (1994) assessed the performance of a recurved crown wall (nose) and rubble mound protection on a vertical breakwater under low overtopping conditions. They showed that the recurved crown wall provides improved reduction of the mean overtopping discharge compared to rubble mound breakwater. Kortenhaus et al. (2003) elucidated the performance of recurve wall with introduction of a reduction factor k in the mean overtopping discharge formula. The proposed reduction factor was determined using some of the key design parameters, including the freeboard height of recurved seawall (R_c), the height of recurved structure (h_r), the overhang length (B_r), the freeboard height of vertical seawall (P_c), and the recurve angle (α) (see Fig. 1).

Several studies proposed that overtopping mitigation performance of a recurve wall can be quantified and predicted as a function of its dimensions (Kortenhaus et al., 2003; Pearson et al., 2004). Despite noticeable improvement in the existing prediction formulae, there exist considerable discrepancies between the measured and predicted values of overtopping discharge from recurve walls. For example, deviations up to two orders of magnitudes were reported by Pearson et al. (2004). This signifies the necessity of enhanced predictive formulae for assessing the climate resilience of retrofitted seawalls in the face of climate change and more extreme climatic events.

While the overhang length has been identified as a significant parameter in determining the effectiveness of a recurve wall, there has been limited research on the relative importance of recurve height. The impact of changes in recurve height on the performance of recurve walls remains not well understood. This study aims to investigate and quantify the influence of recurve geometrical design and wave characteristics on the wave overtopping mitigation performance of recurve walls.

The relative importance of the recurve dimensions on overtopping mitigation is studied. Several tests are conducted to quantify the effects of overhang length in wave attenuation and reducing the volume of overtopping water at vertical seawalls. Previous research observed that up to a certain length threshold for recurve's overhang, a longer overhang results in a larger reduction in overtopping water volume from the vertical structure (Swart, 2016). It is also illustrated that the length threshold of overhang can be determined by wave periods, water level, and the relative freeboard. Swart (2016) showed that despite the increased overhang length with high freeboard can provide robust overtopping protection performance, for the case of very low relative freeboard, this configuration performs worse than plain vertical structure.

In addition to the dimensions of recurve wall, wave period also influence the performance of recurve wall in mitigating wave overtopping (Swart, 2016). For the case of relatively high-water levels at the defence structure, larger wave periods are more likely to increase wave overtopping rates. Van Doorslaer and De Rouck (2011) found the angle between recurve and vertical structure influence the overtopping discharge over the crest. It was suggested that a recurve wall with 45-degree angle can provide the best performance in mitigating overtopping waves.

Overall, the mitigating performance of recurve retrofitting on the seawall crest is mainly influenced by the hydrodynamics of the incident wave attacks, and geometrical design of the recurve i.e., height and width. Understanding the optimal design configurations for recurve retrofitting is crucial to the effectiveness and efficiency of the solution under extreme climatic conditions. A predictive methodology has been derived and developed for overtopping discharge reductions (Kortenhaus et al., 2003). Although some agreements are reached between the measured and predicted overtopping discharge on recurve wall, up to 3 orders of magnitude scatters are noticeable in the existing predictive relations. These scatters can be interpreted as indications of the influences of wave steepness on the overtopping mitigating effects of recurve walls. However, limited data is currently available to accurately quantify the influences of wave steepness on overtopping discharges. This study presents a comprehensive laboratory-scale physical modelling investigation on the wave overtopping at a vertical seawall with a recurve retrofitting. The data obtained from the physical modelling experiments were adopted to analyse the overtopping behaviour and develop enhanced empirical-based predictive formulae for estimating wave overtopping from recurved walls considering the geometrical design of the recurve and wave steepness.

2. Previous works

2.1. Mean overtopping rates at vertical seawalls

Overtopping discharge is a main indicator for assessing the efficiency of coastal protections in reducing the risk of coastal flooding. Previous research proposed predictive formulae to assess the wave overtopping from vertical seawalls (Allsop et al., 2015; Liu et al., 2020; Salauddin and Pearson, 2018; Mase et al., 2013; Lashley et al., 2021, 2023; Cao et al., 2022; Buccino et al., 2023). Based on analyses of various datasets, van der Meer and Bruce (2014) and Van der Meer et al. (2018) proposed the wave impulsiveness parameter as h_* $\left(= \frac{h_s}{H_{m0}} \frac{2\pi h_s}{gT^2_{m-1,0}}\right)$, which describes the degree of variability or sudden changes in wave height and steepness. Conditions with $h^* < 0.23$ are defined as impulsive conditions, and those with $h^* > 0.23$ as non-impulsive conditions. Highly impulsive waves with rapid fluctuations in wave height and steepness can potentially increase the likelihood of wave overtopping events. The rapid changes in wave characteristics can lead to larger wave run-up and higher water levels on coastal structures, increasing the chances of waves breaching or exceeding the design limits of the structure. Empirical-based formulae are proposed for predicting overtopping discharge at vertical seawalls under both conditions (Eqs. (1)–(3)): For non-impulsive conditions,

$$\frac{q}{\sqrt{gH^3_{m0}}} = 0.05 \exp\left(-2.78 \frac{R_c}{H_{m0}}\right) \tag{1}$$

while for impulsive conditions:

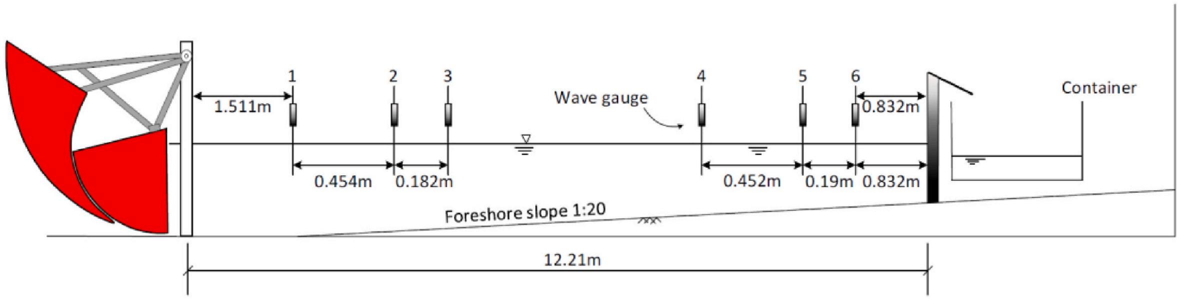

Fig. 2. Schematic of wave flume experiments (adopted from Abolfathi et al. (2018)).

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

and

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

where R_c is the crest freeboard of structure, h_s is the water depth at the toe of structure, g is gravity acceleration (=9.81 m/s^2), q is the mean overtopping discharger per meter structure width and $s_{m\text{-}1,0}$ is statistical wave steepness.

2.2. Overtopping reductions with recurve wall

The reduction in overtopping discharges is often used to describe the mitigating effects of retrofitting structures. The reduction factor in mean overtopping discharge for recurve walls was proposed by Kortenhaus et al. (2003):

$$K=\frac{q_{with\ recurve}}{q_{without\ recurve}} \tag{4}$$

where $q_{with\ recurve}$ is the mean overtopping volumes with recurve wall and $q_{without\ recurve}$ is the mean overtopping volumes without recurve wall.

The reduction in mean overtopping discharge due to recurve wall can be estimated following Eqs. (5)–(7):

$$k=\begin{cases}1.0 & \mathrm{R_c/H_s}\leq \mathrm{R_0}^*\\ 1-\frac{1}{m}\left(\frac{R_c}{H_s}-R_0{}^*\right) & \mathrm{R_0}^*<\mathrm{R_c}\Big/\mathrm{H_s}\leq \mathrm{R_0}^*+\mathrm{m}^*\\ k_{23}-0.01\left(\frac{R_c}{H_s}-R_0{}^*-m^*\right) & \mathrm{R_c}\Big/\mathrm{H_s}\geq \mathrm{R_0}^*+\mathrm{m}^*\end{cases} \tag{5}$$

$$R_0{}^*\equiv 0.25\frac{h_r}{B_r}+0.05\frac{P_c}{R_c} \tag{6}$$

$$\mathrm{m}\equiv 1.1\sqrt{\frac{h_r}{B_r}}+0.2\frac{P_c}{R_c}\quad m^*\equiv m(1-k_{23}) \tag{7}$$

where P_c and hr presents the distance from the bottom of recurve to SWL and the height of recurve, respectively, B_r is the overhang length of recurve and k_{23} is the lowest k-factor, which was set to. k_{23} = 0.20. Overestimations were observed between the predictions made by Kortenhaus et al. (2003) and the experimental measurements. Pearson et al. (2004) described the dependency of overtopping discharge on recurve wall on the relative water depth and proposed a revised predictive formulae based on Kortenhaus et al. (2003)'s methodology as follows:

Table 1
Nominal wave conditions used for the physical modelling tests.

Height of seawall [mm]	Toe water depth [mm]	Nominal wave period [s]	Significant wave height measured at the toe of structure [mm]
210	70	0.80	52
		0.90	65
		0.95	70
		1.20	55,59
		1.50	65
		2.00	69
	90	0.80	66
		0.90	78
		0.95	79
		1.00	62,68,92
		1.10	80
		1.25	67,74
		1.35	75
	110	0.85	73
		0.90	76
		0.95	80
		1.00	95
		1.10	105
		1.35	77
		1.42	79
		1.80	79,85
310	150	0.90	58,61,64,72,76
		1.00	43
		1.20	50,54
		0.95	78
		1.00	49,83
	180	1.10	71
		1.20	57
		1.35	63,71
		1.50	48,51
	210	0.90	71
		0.95	72
		1.00	87
		1.10	85
		1.20	60,74
		1.25	54
		1.35	68
		1.50	57

$$k=\begin{cases}k\ R_c/h_s\leq 0.6\\ k\times 180\exp\left(-8.5\frac{R_c}{h_s}\right)\ 0.6<R_c\Big/h_s\leq 1.1\\ k\times 0.02\ 1.1<R_c/h_s\end{cases} \tag{8}$$

3. Experimental set-up

The experimental study was undertaken in the wave flume (22 m long, 0.6 m wide and 1.0 m deep) within the School of Engineering at the University of Warwick, with a 1:20 impermeable foreshore slope. A schematic design of the flume is shown in Fig. 2. The flume was

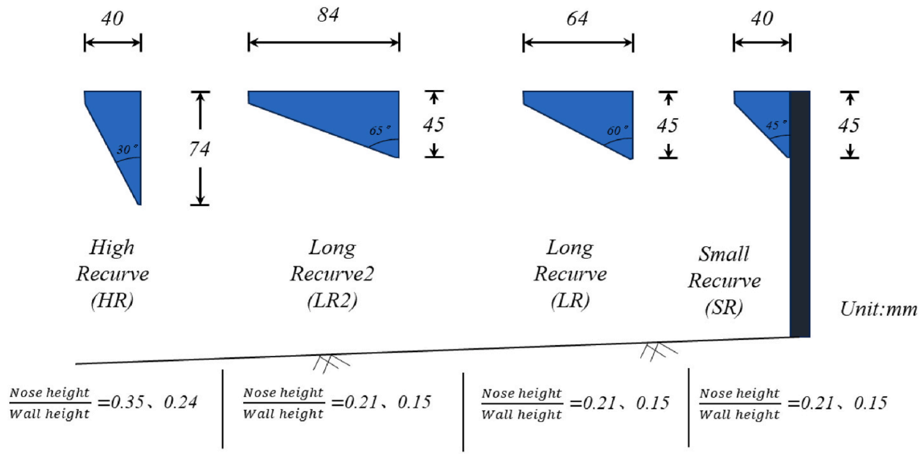

Fig. 3. Schematic designs of four tested recurve walls.

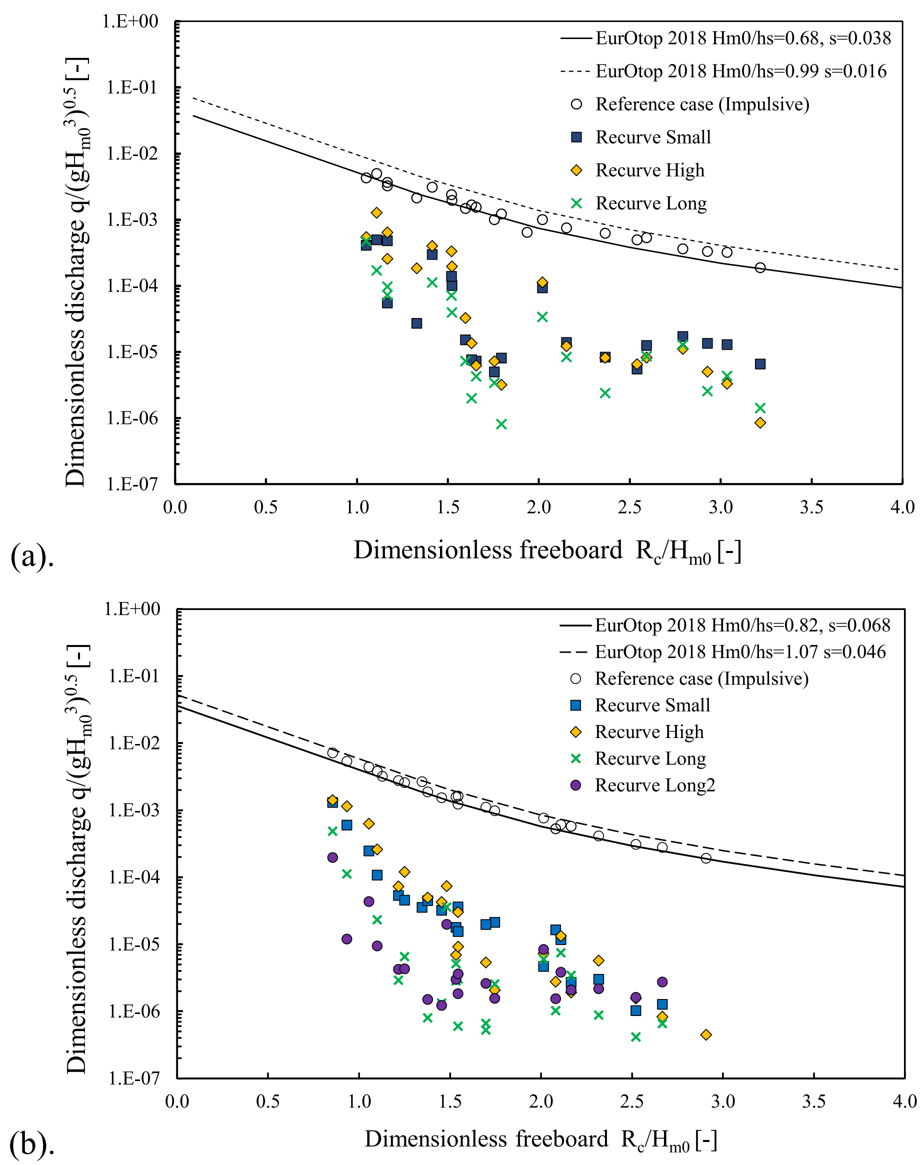

Fig. 4. Mean overtopping discharge (impulsive) from recurve wall – (a) wave conditions with $s_{m-1,0}$ around 0.02 and (b) wave conditions with $s_{m-1,0}$ around 0.05.

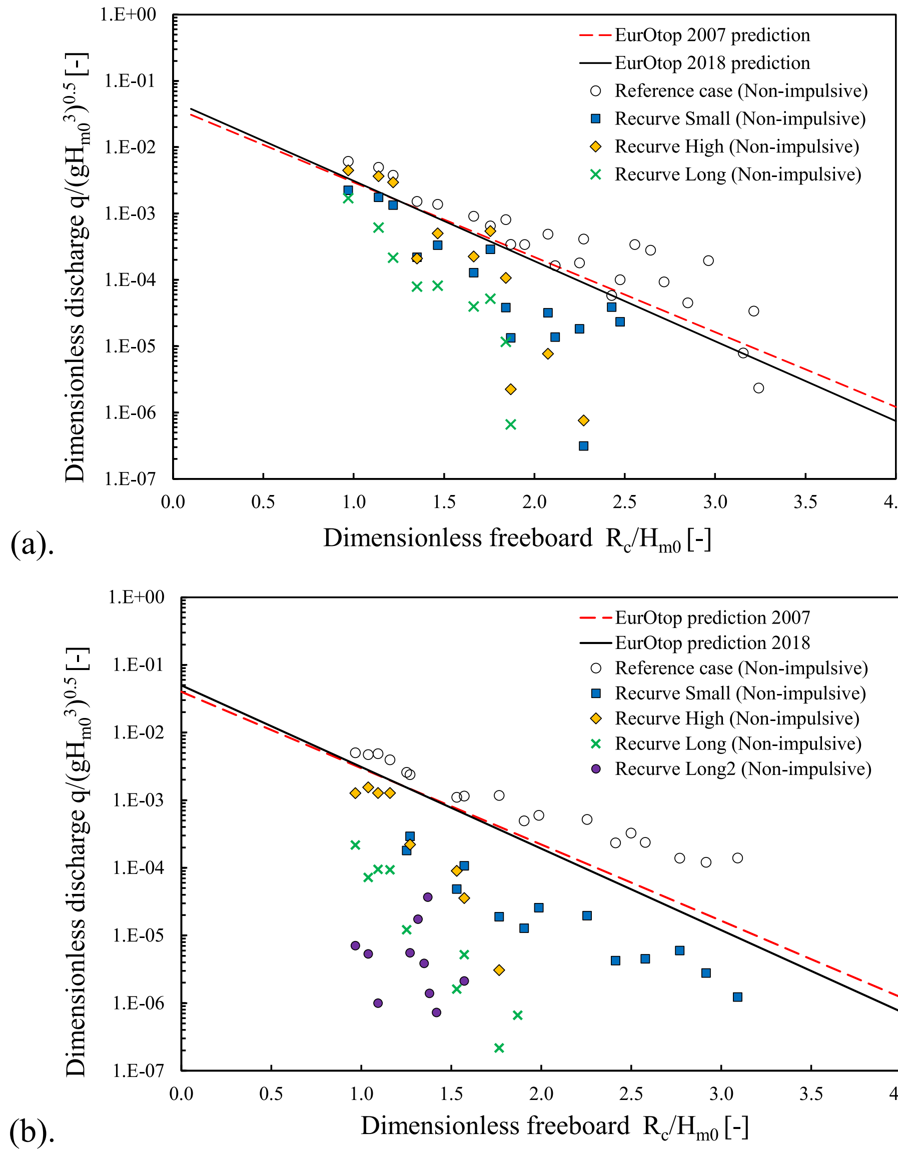

Fig. 5. Mean overtopping discharge (non-impulsive) from recurve wall – (a) wave conditions with $s_{m-1,0}$ around 0.02 and (b) wave conditions with $s_{m-1,0}$ around 0.05.

equipped with a piston-type wave generator and an active absorption system (AWAS). Experiments were carried out with the vertical seawall fixed at a distance of 12.21 m from wave paddle and the water depth was varied according to the desired nominal test conditions.

To mitigate the statistical uncertainties in overtopping experiments, each test case consisted of approximately 1000 incoming pseudo-random waves (Pearson et al., 2002) based on the JONSWAP ($\gamma = 3.3$) spectrum, at a scale of 1:50. The characteristics of incident waves were determined using two sets of three wave gauges, placed close to paddle and seawall respectively. The distance between wave gauges was determined based on the Least-square method, as illustrated by Mansard and Funke (1980). Physical experiments were performed under both impulsive and non-impulsive conditions. The significant wave height ranged between 0.043 m and 0.105 m, and wave periods were generated ranging from 0.79s to 2.00s (see Table 1). Wave steepness varied from 0.016 to 0.058, covering both swell and storm sea states.

Overtopping measurements were compared between configurations for the sensitivity of recurve sizes and wave characteristics in the shallow water zone. An overtopping container was suspended by a loadcell right behind the model seawall to catch overtopping volume generated in each test. The load-cell had a measurement range of 100 kg maximum and sensitivity of 5 g. This sensitivity guaranteed the detection of even a small overtopping volume. A syphon was fixed over the container to ensure continuous sampling of overtopping discharges during each test.

To provide a systematic exploration of the influence of recurve dimensions on wave mitigation effects, four different shapes of recurve wall were tested in this study, including Small Recurve (SR), Long Recurve (LR), Long Recurve 2 (LR2) and High Recurve (HR). The dimensions of tested recurve structures are shown in Fig. 3.

Experiments were initiated on the recurve wall with similar height and overhang length, named as the Small Recurve (SR). Its nose angle was very close to 45°, as Van Doorslaer and De Rouck (2011) recommended, based on carefully considering the ease of construction, stability, and performance of recurve wall. HR was built to investigate the influence from the recurve height to effectiveness of recurve wall. In this configuration, the nose angle was close to 30°. To investigate the effects of the overhang length, LR was constructed with a nose angle of approximately 60°. An extra recurve wall was made called Long Recurve 2. The overhang length was even increased to detect the threshold that

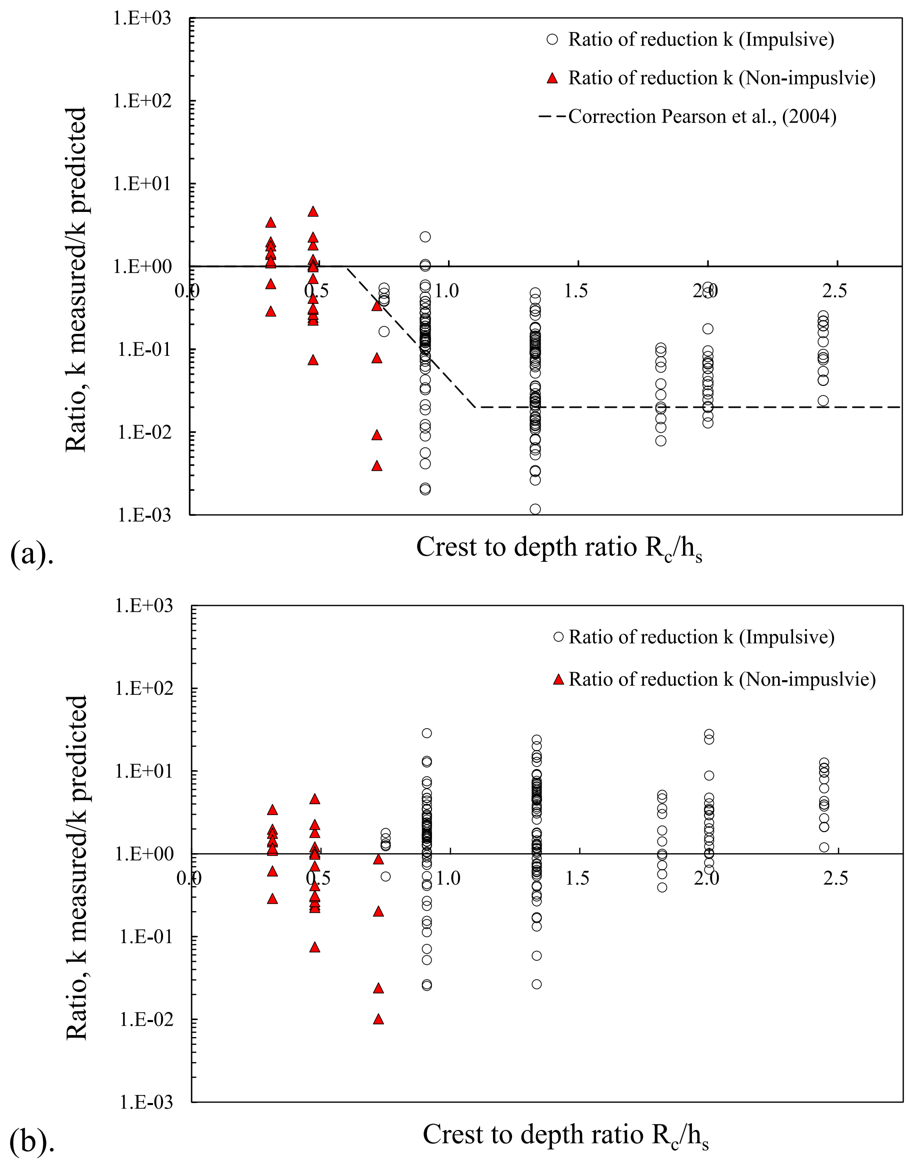

Fig. 6. Ratio of k measured to k predicted plotted against crest to depth ratio – (a) reduction factor k predicted by Kortenhaus et al. (2003) and (b) reduction factor k predicted by Pearson et al. (2004).

the recurve wall would entirely stop wave overtopping. With these four recurve walls, this study proposes to explore the effects of recurve sizes in wave overtopping reductions and the upper limits in mitigating the effects of the recurve wall.

Experiments were carried out for the effects of recurve dimensions and the incoming wave characteristics to undertake systematic analyses of parameters influencing recurve performance. As per the prediction formulae initially developed by Kortenhaus et al. (2003) and Pearson et al. (2004), reductions in the mean overtopping discharge can be estimated by dimensions of recurve wall and water depth at the toe of the structure. However, significant deviations were observed between measurements and predictions from Kortenhaus et al. (2003) and Pearson et al. (2004).

4. Results and discussions

4.1. Mean overtopping discharges

Mean overtopping discharge is often considered as major indicator in assessing the risk of wave overtopping behind the coastal defences. Figs. 4 and 5 show the mean overtopping discharge on tested recurve walls under both impulsive and non-impulsive waves, respectively. Since the wave steepness is hypothesised to affect the performance of recurve walls, results from large and small wave steepness conditions are plotted separately. Measurements are grouped as $s_{m-1,0}\approx 0.02$ for small wave steepness conditions and $s_{m-1,0}\approx 0.05$ for large wave steepness.

All tested recurve walls were somewhat able to limit overtopping discharge with favourable effects. As shown in Fig. 4, overtopping discharges are reduced by up to a factor of 8 when compared to the predicted values of EurOtop for plain seawalls. Nevertheless, scatter data points in Fig. 4 report that reduction percentages were not consistent for all conditions. It is evident from Fig. 4 that reductions in the mean overtopping discharge increase with the dimensionless freeboard. When $R_c/H_{m0} = 0.85$, reductions were 74%, 71%, 90% and 96% for SR, HR, LR and LR2, respectively. This reduction tends to approach the upper limit when R_c/H_{m0} passes 2.2, around a factor of 500 in all tested configurations. For this freeboard range, the mean overtopping discharges tend to remain unchanged under both large and small wave steepness conditions, which are consistent with the findings of Dong et al. (2020).

The recurve wall with the longest overhang length, named LR, was observed to provide the best overtopping mitigating effects among all tested sizes, with the maximum reduction at 3 orders of magnitude. This was also the case for the experiments with extra structures, i.e., LR2. Two recurve walls with the same overhang length (SR and HR) act almost identically in reducing overtopping discharge (96% reduction on average). The height changes in recurve wall dimensions do not really affect the performance of recurve wall significantly, as evident from Fig. 4.

Research on recurve walls' performance mainly focuses on the impulsive overtopping processes. It was summarised with existing databases that recurve walls do not significantly help reduce non-impulsive overtopping waves (Kortenhaus et al., 2003; Pearson et al., 2004). This phenomenon was also observed under wave conditions with low relative freeboard. However, as freeboard increases, the reduction in non-impulsive mean overtopping appears significant, especially under relatively large wave steepness conditions.

Fig. 5 shows mean overtopping discharge measured on all tested recurve walls under non-impulsive wave conditions. For low wave steepness (Fig. 5a), mean overtopping discharges were reduced at an average factor of 3 on SR for low relative freeboards which then further increased for the large freeboards. The influence of freeboard becomes more predominant under incident waves with large steepness. For example, data correspond to SR under large wave steepness conditions (Fig. 5b) show that the reduction rises from a factor of 8 as the minimum up to two orders of magnitudes as the maximum for the tested conditions. With longer overhang length in LR and LR2, the further reduction in mean overtopping discharge can be reported with dimensionless freeboard, as evident from Fig. 5b. The results of this study therefore suggest that the recurve wall is capable of mitigating wave overtopping rates at seawalls under non-impulsive wave conditions.

In both Fig. 4 (impulsive conditions) and Fig. 5 (non-impulsive conditions), overtopping discharges correspond to HR can be reported somewhat similar with those observed for SR configuration, indicating that the height of recurve wall does not significantly affect the overtopping reduction performance of recurve walls. Overall, larger wave steepness was observed to cause greater reduction in mean overtopping discharges. It can be inferred that the space under recurve wall is not likely to be filled under steep wave conditions. Therefore, waves are less likely to overflow the structure, and more overtopping water is returned by recurve wall. Similar interpretations are also applicable for larger reductions in the mean overtopping discharge with relatively longer overhang length.

4.2. Overtopping reductions

Explorations were conducted over the years for deriving empirical prediction tools in accurate estimation of overtopping reductions by recurve retrofits. Kortenhaus et al. (2003) recommended empirical formulae based on overhang length B_r, recurve height h_r, and freeboard R_c. The reduction was described as the ratio of discharges on recurve wall over the discharges on vertical seawall. Fig. 6 compares the predicted values of reduction in mean overtopping discharge with measurements of this study. Predictions in Fig. 6a were obtained using empirical formulae (Eqns. (4)–(7)) provided by Kortenhaus et al. (2003). Identically, as concluded by Kortenhaus et al. (2003), predictions align very well with measurements roughly with low crest to depth ratio. When the crest to depth ratio is over 0.5, over-prediction appears and becomes significant as crest to depth ratio increases.

To mitigate the over-prediction, Pearson et al. (2004) applied a correction factor on Kortenhaus et al. (2003) equations. This correction factor falls into three regimes, corresponding to low, medium, and high crest to depth ratio (Fig. 6a). Fig. 6b shows comparisons between measured reductions and corrected predictions. Scatters are still perceptible between tests, which are observed up to two orders of magnitude when $0.9<R_c/h_s<1.5$. Nevertheless, it can be also observed that almost identical estimations are reported for cases with the same crest to depth ratio. It is hypothesised that there are wave characteristics (e.g., steepness) play roles in determining the effectiveness of recurve walls.

Table 2
Characteristics of incident wave conditions tested within this study.

h_s [m]	Test No.	H_{m0} [m]	$T_{m-1,0}$ [s]	R_c/H_{m0}	$S_{m-1,0}$	h_*	Impulsiveness
0.09	1	0.071	0.9345	1.701	0.055	0.084	Impulsive
	2	0.071	0.9641	1.681	0.051	0.078	
	3	0.068	1.025	1.754	0.040	0.072	
	4	0.071	1.103	1.697	0.034	0.060	
	5	0.066	1.142	1.831	0.028	0.061	
	6	0.071	1.216	1.697	0.025	0.050	
	7	0.067	1.278	1.790	0.022	0.047	
	8	0.066	1.478	1.818	0.015	0.036	
0.11	1	0.078	0.97	1.283	0.055	0.106	
	2	0.084	1.007	1.195	0.054	0.091	
	3	0.082	1.039	1.222	0.049	0.088	
	4	0.083	1.115	1.200	0.041	0.075	
	5	0.082	1.186	1.216	0.033	0.067	
	6	0.078	1.229	1.274	0.029	0.065	
	7	0.082	1.282	1.224	0.028	0.058	
	8	0.077	1.484	1.294	0.019	0.046	

4.3. Improvements on existing prediction guidance

As observed in Fig. 6, overtopping predictions of recurve wall using existing empirical tool deviate from measurements of this study with noticeable scatter. Despite the different tested wave conditions, it is evident from Fig. 6 that the current empirical formulae provide identical predictions for the structure with similar configurations, indicating the potential influence of wave conditions on predictions. To improve predictions by accounting the influence of wave conditions, we proposed new empirical formulae adopting the empirical formulae of Kortenhaus et al. (2003) but with taking the characteristics of incident waves into considerations.

Furthermore, it can be also inferred that larger reductions of overtopping discharges were observed for experiments with relatively higher wave steepness (see Figs. 4 and 5). Similarly, for smooth dike with storm wall and bullnose, a larger wave overtopping reduction was found that for larger wave steepness (Van Doorslaer et al., 2015; EurOtop, 2018; Formentin and Zanuttigh, 2019). Pearson et al. (2004) highlighted that non-impulsive wave overtopping rates for recurve parapets are more sensitive to incident wave conditions. Nevertheless, the influence of impulsive waves on overtopping performance of recurve parapets remains vague. Albeit physically, it is more difficult for steep waves to fill the space between vertical parts and recurve wall. Thus, steep waves are more likely to be trapped under recurve wall and will not overflow the crest of the structure. Two set of experiments were carried out to further investigate the influence of wave steepness to overtopping response, where the tested wave steepness was in the range from 0.02 to 0.06. The characteristics of tested incident wave conditions are presented in Table 2.

The sensitivity of predicted wave overtopping rates to incident wave steepness for the tested Small Recurve configuration is shown in Fig. 7. The ratio of measured and predicted reduction of overtopping is plotted against the incident wave steepness at the toe of the structure (Fig. 7) for a relative freeboard of 1.24 and 1.73. The resulting data points demonstrate that wave steepness had very limited influence on measured overtopping rates for the conditions tested with a relative freeboard of 1.73. Nevertheless, under relatively low freeboard, it can be reported that the deviation between measured and predicted values decreases with the increase of wave steepness, i.e., from a factor of 10 to

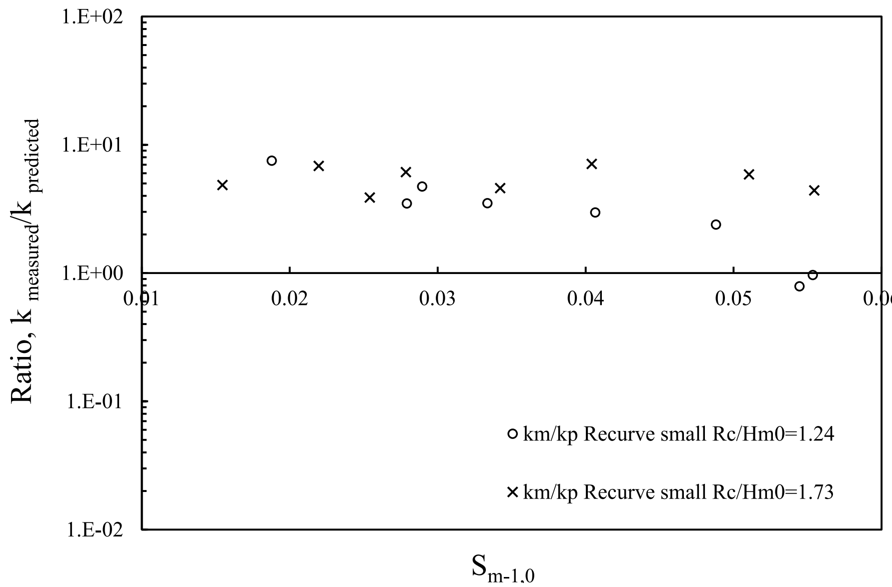

Fig. 7. Ratio of k measured to k predicted (Pearson et al., 2004) plotted against incident wave steepness (Small Recurve Configuration).

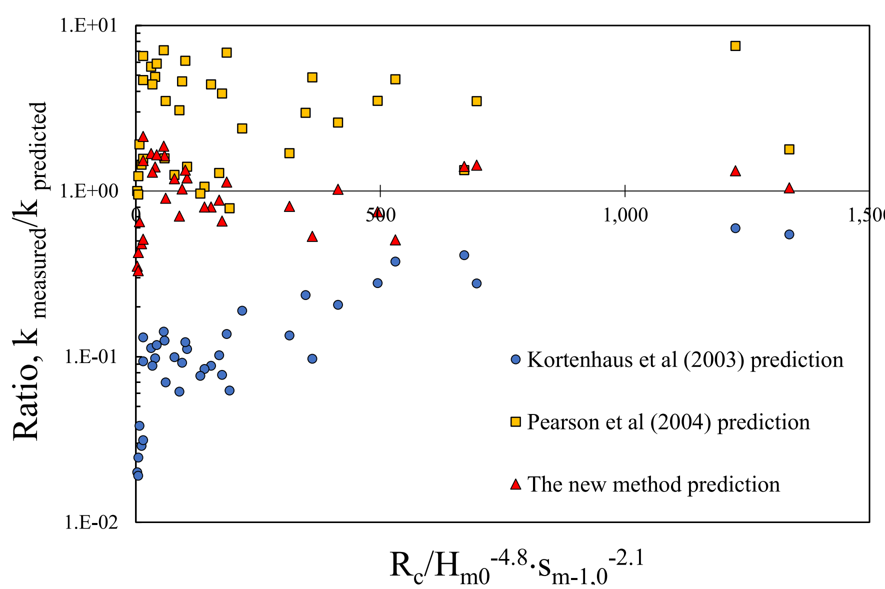

Fig. 8. Ratio of k measured to k predicted plotted against relative freeboard and incident wave steepness for Small Recurve Configurations. Circles, Squares, and Triangles are predictions from Kortenhaus et al. (2003), Pearson et al. (2004), and This study, respectively.

1 when wave steepness rises from 0.019 to 0.056. The results of this study showed that while Pearson et al. (2004) empirical formulae provide better estimations under relatively large wave steepness with low freeboard, predictions for high freeboard cases remain approximately one eighth as large as measurements (indicating little sensitivity on wave steepness).

In addition to incident wave steepness, it is evident from the results of this study (Figs. 4 and 5) that as the overtopping reduction k factor has a strong correlation with the relative freeboard R_c/H_{m0} of the structure. It can be inferred that as either the higher freeboard or the larger wave steepness will bring additional challenges for incoming waves' overflowing, and overtopping discharge will decrease as a result. To investigate and quantify the combined influence of both parameters, i.e., R_c/H_{m0} and $s_{m-1,0}$ on overtopping reduction, the measured k is fitted as a function of two dependent variable of R_c/H_{m0} and $s_{m-1,0}$, see Fig. 8. Here, the empirical predictions of existing formulae, i.e. Kortenhaus et al. (2003) and Pearson et al. (2004), are also plotted. It is apparent from Fig. 8 that resulting data points corresponding to low freeboard or wave steepness ($R_c/H_{m0}^{-4.8}s_{m-1,0}^{-2.1}$>1000) show overall a good agreement with existing formulae. It can be also noticed that Pearson et al. (2004) equation mostly under estimate the k factor with considerable scatter, while Kortenhaus et al. (2003) results gradually become too conservative. Notably, Fig. 8 also illustrates that predicted k from Kortenhaus et al. (2003) gradually agrees with measurements as $R_c/H_{m0}^{-4.8}s_{m-1,0}^{-2.1}$ increases. To improve the existing prediction guidance, we hereby propose a new formula by establishing a relationship between k as a function of $R_c/H_{m0}{}^{-4.8}s_{m-1,0}^{-2.1}$ (see Equation (9)).

$$\alpha = 0.056 + 0.00035\left(\frac{R_c}{H_{m0}}\right)^{-4.8} s_{m-1,0}^{-2.1} \tag{9}$$

where α is the new correction factor applied to Kortenhaus et al. (2003) predictions.

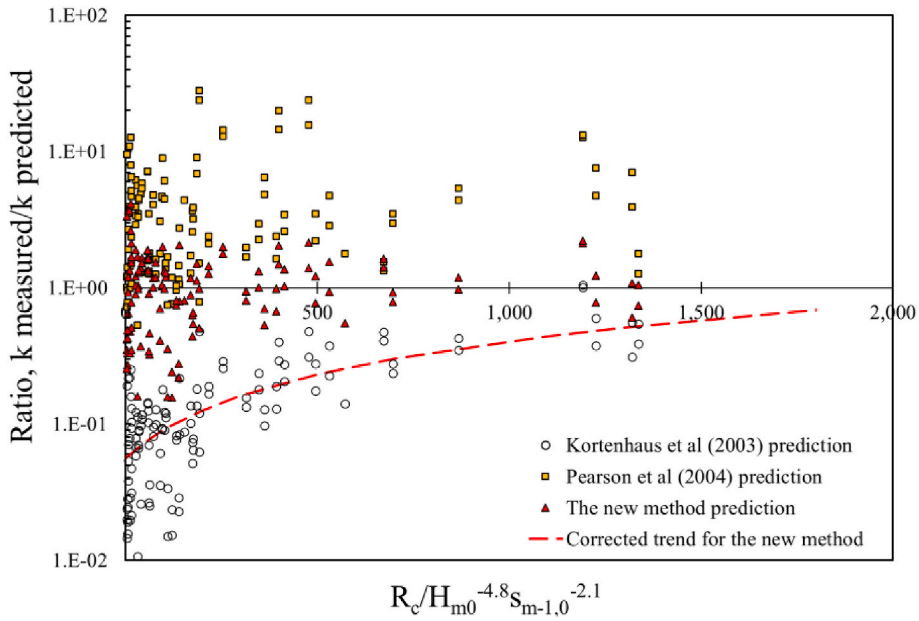

Fig. 9. Ratio of *k* measured to *k* predicted plotted against relative freeboard and incident wave steepness for Small and High Recurve Configurations. Circle Square and Triangle predictions from Kortenhaus et al. (2003), Pearson et al. (2004) and This Study, respectively.

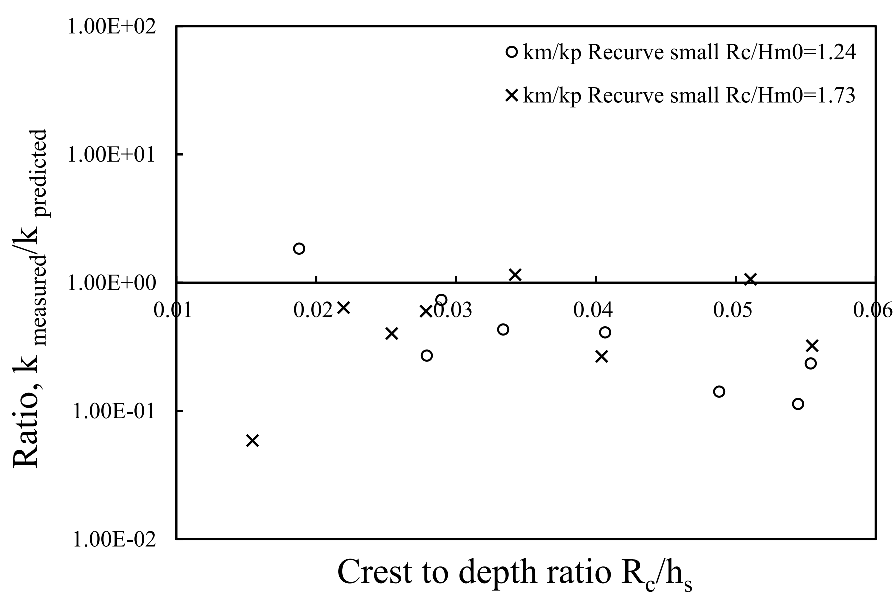

Fig. 10. Ratio of *k* measured to *k* predicted plotted against incident wave steepness (Long Recurve Configuration).

4.4. Validation of the proposed new formulae

The improved correction factor (Equation (9)) as obtained based on results of SR configuration was then applied in measurements from all other tested recurve walls. Fig. 9 compares the predictions from Kortenhaus et al. (2003) and Pearson et al. (2004) formulae with measured overtopping discharges on HR and SR configurations. The new correction factor as proposed in this study is also plotted in Fig. 9. It can be inferred that Pearson et al. (2004) predictions mostly locate above the x-axis, suggesting underestimation of overtopping discharge rates. Nevertheless, predictions from Kortenhaus et al. (2003) somewhat cluster around the trend proposed by this study, again with quite some scatter.

With the application of new correction factor, it is certainly evident that the predicted values of the mean overtopping discharges on recurve walls are overall identical to the measured values, particularly for low freeboard or wave steepness (large $R_c/H_{m0}^{-4.8}s_{m-1,0}^{-2.1}$ values). It is therefore the proposed method helps to improve the accuracy of overtopping predictions on small recurve configurations, where large overtopping events are in highly likelihood to happen.

Overtopping discharges on the tested LR cases, nonetheless, show deviations from results explained above. As evident from Fig. 9, the ratio of *k* measured to *k* predicted plotted against relative freeboard and incident wave steepness for Small and High Recurve Configurations. Circle, Square and Triangle predictions from Kortenhaus et al. (2003), Pearson et al. (2004) and This Study, respectively. Fig. 9, the resulting discharges on the SR and HR configurations are under estimated by Pearson et al. (2004). Regarding the results of experiments on LR, Pearson et al. (2004) methodology on the contrary, provides reasonably good predictions of overtopping discharge when $R_c/H_{m0} = 1.73$ (see

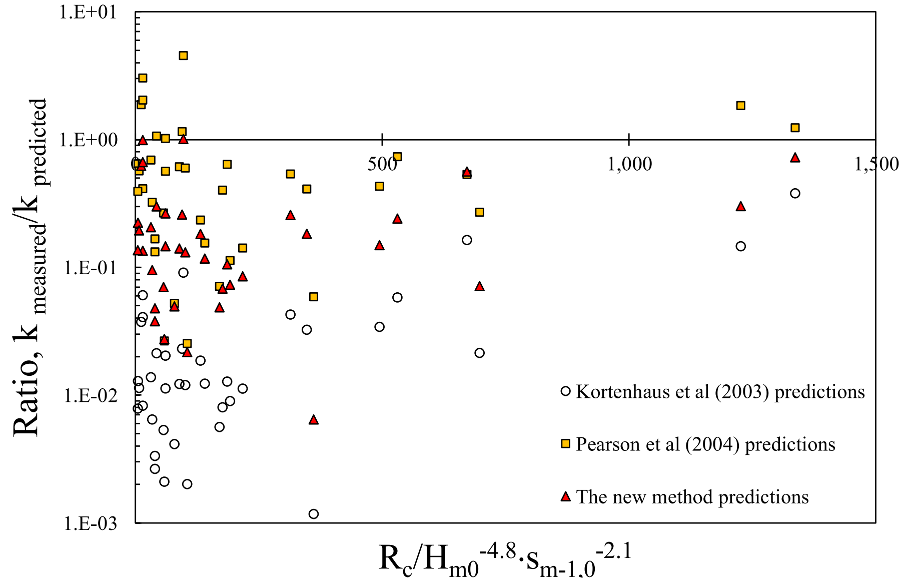

Fig. 11. Ratio of k measured to k predicted plotted against relative freeboard and incident wave steepness for Long Recurve Configurations. Circles, Squares, and Triangles are predictions from Kortenhaus et al. (2003), Pearson et al. (2004), and This study, respectively.

Fig. 10). Nevertheless, when $R_c/H_{m0} = 1.24$, overtopping rates on recurve wall are overestimated under steep incident waves, as seen in Fig. 10. This highlights the fact that the proposed new correction factor when applied to the LR configurations, while the results improve overall, the method still somewhat overestimates the overtopping rates for low relative freeboard cases.

Fig. 11 compares predicted results from this study with predictions from Pearson et al. (2004) and Kortenhaus et al. (2003). Results from Pearson et al. (2004) agree with measurements satisfactorily while Kortenhaus et al. (2003) over predicts overtopping discharges. The proposed method although optimises results based on the outcomes form Kortenhaus et al. (2003), it still somewhat gives too conservative predictions which may results in higher requirements or difficulties in design processes. Fig. 11 also suggests that prediction on LR from Pearson et al. (2004) method shows a limit response to wave steepness. It is possibly explained that prediction tools given by Kortenhaus et al. (2003) and Pearson et al. (2004) are produced with datasets from the recurve wall with relatively long overhang parts. Thus, predictions of recurve wall performance have higher dependency upon the overhang length, and effects of wave steepness to short overhang length are less considered. The new method as developed in this work emphasises that the overrating in contribution of short overhang length against smooth incident waves. The improved new equation provides safer and somewhat conservative predictions for recurve wall with short overhang parts.

Overall, for Long Recurve wall, the results of this study showed an overall good agreement with the predictive empirical formulae of Pearson et al. (2004), however, the formulae (Equation (10)) for Small Recurve and High Recurve configurations could be improved as following by incorporating the new correction factor as proposed in this study:

$$k = \begin{cases} \alpha & R_c/H_s \le R_0^* \\ \alpha\left[1 - \frac{1}{m}\left(\frac{R_c}{H_s} - R_0^*\right)\right] & R_0^* < R_c\big/H_s \le R_0^* + m^* \\ \alpha\left[k_{23} - 0.01\left(\frac{R_c}{H_s} - R_0^* - m^*\right)\right] & R_c\big/H_s \ge R_0^* + m^* \end{cases} \quad (10)$$

$$\alpha = 0.056 + 0.00035\left(\frac{R_c}{H_{m0}}\right)^{-4.8} s_{m-1,0}^{-2.1}$$

where k is the reduction coefficient, $k = q_{recurve}/q_{vertical}$, P_c and h_r is the distance from the bottom of recurve to SWL and the height of recurve respectively, B_r is the overhang length of recurve and k_{23} is the lowest k-factor, which was set to. $k_{23} = 0.20$, R^* and m^* are the key parameter of the recurve structure, $R^* \equiv 0.25h_r/B_r + 0.05P_c/R_c$, $m1.1\sqrt{h_r/B_r} + 0.2P_c/R_c$ and $m^* \equiv m\cdot(1\text{-}k_{23})$.

4.5. Predictive performance analysis

Statistical error measures are calculated to evaluate the goodness of fit between the new proposed predictive method and the measurements from the physical modelling study. The robustness of the proposed method is also compared with the empirical formula suggested by Pearson et al. (2004). The magnitude of deviations between predictions and measurements are determined by root-mean-square error (RMSE), for all the tested configurations (Eq. (11)).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(log\ y_i - log\hat{y}_i)^2}{n}} \quad (11)$$

where y_i is the individual measurement in the analysed dataset, and $\hat{y}_i$ denotes the predicted values. n is the total number of samples in the analysed dataset.

Pearson et al. (2004) correction method improved the estimation of the reduction factor k for overtopping discharge on recurve wall, based on R_c/h_s. In this study, analysis of the physical modelling results highlighted the significance of wave steepness on the reduction of overtopping discharge from recurve walls. Hence, this study proposed an improved empirical-based predictive method, by introducing a new correction factor, determined by R_c/H_{m0} and $s_{m-1,0}$ instead for individual

Table 3
Comparison of the RMSE for the existing and the proposed prediction methodologies for the mean overtopping discharge reduction from the plain vertical seawall with recurve retrofitting.

	Kortenhaus et al. (2003) Eqn. 7	Pearson et al. (2004) Eqn. 8	This study Eqn. 10
RMSE	1.06	0.64	0.44

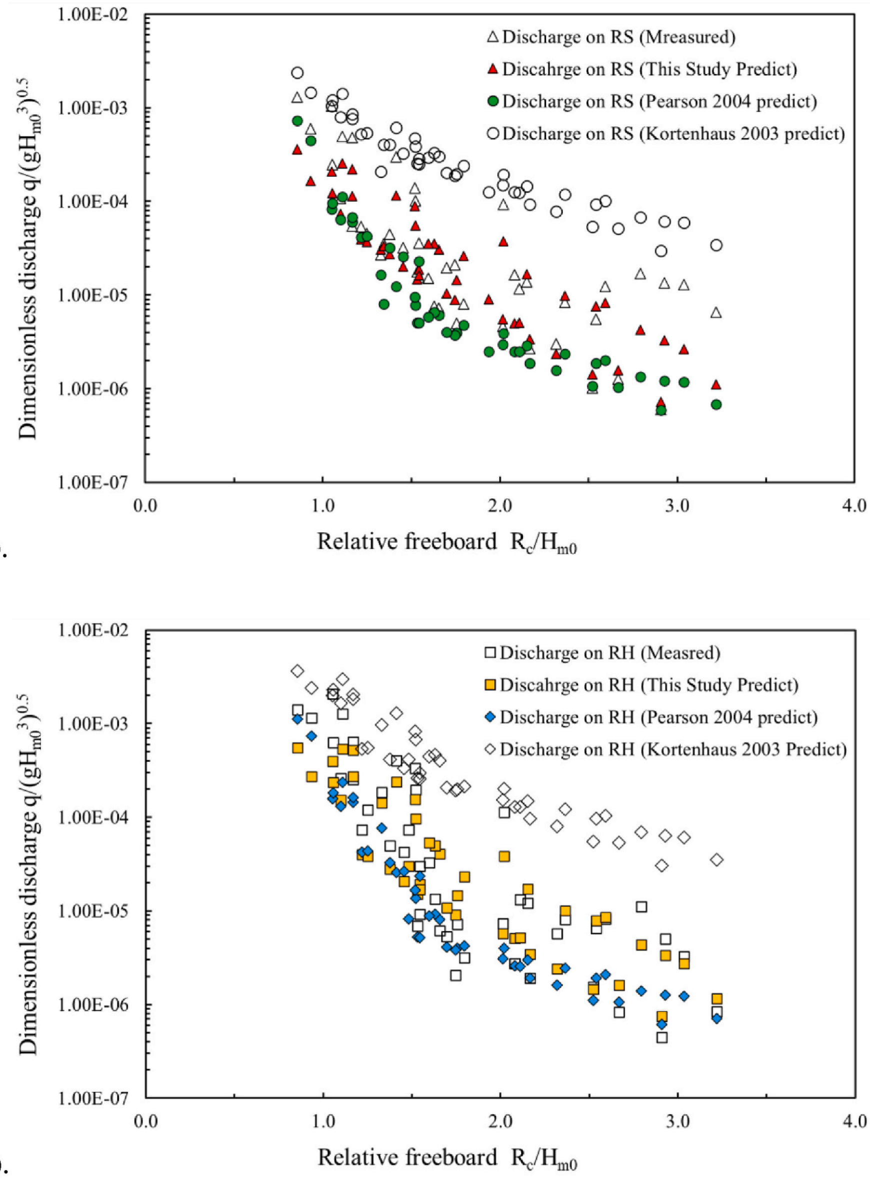

Fig. 12. Comparisons between measured and predicted overtopping discharges on recurve configurations: (a) RS (Recurve Small) (b) RH (Recurve High).

case. The RMSE is determined for the predictions from Pearson et al. (2004) and the new proposed method.

Predicted reduction factors k from Kortenhaus et al. (2003), Pearson et al. (2004) and the new method are compared with measurements in Fig. 9. Ratio of $k_{measured}/k_{predicted}$ is presented on y-axis. When more data points are clustered near the x-axis, the ratio approaches 1, indicating a closer alignment between the measured and predicted values of k. This implies a higher degree of similarity between the observed and predicted outcomes. The ration of $k_{measured}/k_{predicted}$ are calculated for RMSE between data and predictions from both methods. Table 3 presents the RMSE value from the predictive tool suggested by Kortenhaus et al. (2003), Pearson et al. (2004) and the current study. It is shown that the new method suggested in this study (Eq. (10)) significantly enhance the predictions, with the RMSE reducing from 0.64 to 0.44 when compared to Pearson et al. (2004) method. The RMSE values shown in Table 3 are determined based on the predictions from all the wave conditions for both HR and SR recurves. The results obtained for the LR cases are not included as Pearson et al. (2004) method provided better predictions. It can be inferred that wave overtopping processes is mainly dominated by crest freeboard and wave height due to long overhang length in the LR configuration, whose influences have been well considered in Pearson et al. (2004) method. Effects of wave steepness investigated in this study makes little influences.

Table 4
Comparison of the RMSE for the existing and the proposed prediction methodologies for the mean overtopping discharge from the plain vertical seawall with recurve retrofitting.

	Kortenhaus et al. (2003) Eqn. 7	Pearson et al. (2004) Eqn. 8	This study Eqn. 10
RMSE	5.67×10^{-4}	3.49×10^{-4}	3.42×10^{-4}

Fig. 12 compares the measured overtopping discharge with the prediction results based on Kortenhaus et al. (2003), Pearson et al. (2004), and the new method proposed in this study. The results show that the formulae given by Kortenhaus et al. (2003) generally overestimate the overtopping discharges for both RS and RH configurations, while Pearson et al. (2004)'s formulae underestimate the measured overtopping values. The new predictive formulae proposed in this study show an improved agreement with the measurements for both recurve configurations. Table 4 compares the RMSE value from the predictive tool suggested by Kortenhaus et al. (2003), Pearson et al. (2004), and the current study, highlighting the relative improvement in the method proposed here.

Overall compared with the prediction from Pearson et al. (2004) and Kortenhaus et al. (2003), the new proposed method is expected to yield higher accuracy. The smaller RMSE obtained from predictions of the new method highlights the enhanced capability of our proposed approach for predicting the reduction factor k on recurve wall, providing more reliable overtopping prediction results.

5. Conclusions

This study described a comprehensive investigation into the overtopping discharge along a vertical seawall with a recurve subjected to a wide range of geometrical configurations and incident wave conditions. Physical modelling experiments were conducted to measure the overtopping discharges from plain vertical seawall and with recurve retrofitting on the crest. The overtopping discharges were measured for both swell and storm wave conditions. The effectiveness of recurve retrofitting cases was analysed by comparing the overtopping discharges from plain wall (reference case) with the recurve cases. The data presented in this paper shed new lights on the effects and contributions of geometrical design of recurve retrofitting on the wave overtopping mitigation.

The analysis highlighted the significance of recurve retrofitting on mitigating wave overtopping discharges from vertical seawall. It is found that recurves are effective in reducing wave overtopping discharges across all the tested wave conditions. The minimum discharge reduction observed in this study is a factor of 8 when compared with the reference case on the HR configuration. As the relative freeboard (R_c/H_{m0}) increases from 0.96 to 3.2, overtopping discharge reduction rises significantly, and a reduction of three orders of magnitude were measured as the maximum.

The geometrical shapes of recurve wall i.e., overhang length and hight, strongly influence its mitigating performance. Specifically, a longer overhang length results in a smaller discharge measured over the crest of seawall. Increasing the overhang length from the SR to LR configuration leads to a substantial increase in the reduction of overtopping discharge, ranging from a factor of 25–100 on average. The overhang length plays a significant role in enhancing the effectiveness of recurve in mitigating wave overtopping discharge, while the contributions from recurve height was found to be limited.

This study conducted a significant range of hydrodynamic tests to comprehensively cover data from swell to storm conditions and quantify the influence of wave steepness on the mitigating performance of recurve wall. With $R_c/H_{m0}<1.5$, overtopping discharges were found to be reduced with increasing wave steepness. When $R_c/H_{m0}>1.5$, the wave steepness parameter has minimal influence on overtopping discharges. Previous studies did not include the wave steepness in overtopping predictive formulae, resulting in significant scatter of up to 3 orders of magnitude in the predictions obtained from the equation proposed by Pearson et al. (2004).

This study, for the first time, considered the combined effects of wave steepness and freeboard for vertical structure with a recurve wall. A new empirical-based correction factor is proposed for Kortenhaus et al. (2003)'s equation. With the introduction of this new correction factor, deviations in overtopping discharges on the SR configuration are reduced from a maximum of 15 times lager to 5 times larger. This improvement represents a substantial enhancement in our current predictive capability for overtopping reduction from recurve walls. The statistical analyses show an RMSE of 0.44 for the predictions from the new formula which is noticeably smaller than the RMSE of predictions from Pearson et al. (2004)'s equation (RMSE = 0.64) and Kortenhaus et al. (2003) equation (RMSE = 1.06). The new equation proposed in this study, provides enhanced predictive robustness for overtopping discharges from recurve walls with overhang length/hight <1.5. For relatively longer overhang recurve wall configurations, Pearson et al. (2004) empirical relation can provide reasonable predictions. The proposed improved assessment approach for overtopping estimations at recurved seawalls overall provides a framework for evaluating overtopping estimations at such critical coastal infrastructures considering a wide range of geometrical configurations of recurve parapets.

CRediT authorship contribution statement

S. Dong: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **M. Salauddin:** Conceptualization, Writing – original draft, Writing – review & editing, Methodology. **S. Abolfathi:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Methodology. **J.M. Pearson:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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