IOP Conference Series: Earth and Environmental Science

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IOP Conf. Series: Earth and Environmental Science 1072 (2022) 012005 doi:10.1088/1755-1315/1072/1/012005

The Impact of Eco-retrofitting on Coastal Resilience Enhancement – A Physical Modelling Study

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Abstract. Recent climate change studies highlight that the sea-level rise and increase in intensity and frequency of extreme climatic events and storm surges will result in catastrophic wave overtopping events from coastal defences. Retrofitting of the existing seawalls provides great potentials for enhancement of the climatic resilience in coastal region through overtopping attenuation. With increasing attention towards sustainable and low emission solutions for improving the resilience of critical infrastructures to natural hazards, providing coastal protection service is no longer the only concern of scientists, but the environmental impacts of such interventions also started to be considered. This paper presents a laboratory-scale investigation of 'eco-retrofitting' approaches including vertipools and reef breakwater for their impact on mitigating overtopping from seawall. The laboratory tests were conducted on a vertical seawall with 1(V):20(H) smooth foreshore. Each test was consisted of approximately 1000 pseudo-random waves based on JONSWAP spectrum. Both impulsive and non-impulsive wave conditions were tested. The plain vertical seawall was taken as the reference case, that exhibited an overall good agreement with empirical predictions, when compared to EurOtop. The analysis of data highlights the significance of the tested eco-interventions in mitigating wave overtopping volume, with approximately 70% reduction of mean the overtopping rate.

1. Introduction

The changing climate will increase the frequency and intensity of extreme climatic conditions in coastal regions, resulting in severe floods and erosion [1-6]. In low-lying coastal areas, which are often very densely populated, coastal flooding will be exacerbated by the long-term effects of sea-level-rise and intensified storm surges. Conventional hard-engineered infrastructures are aging, and their freeboard level is continuously reduced due to the rise in sea level, which can result in their failure to provide acceptable level of protection and wave overtopping mitigation in the near future [7-9]. Replacing the existing defence infrastructures with new hard-engineered structures is costly and contribute to more carbon emission both directly and indirectly. Hence, hard-engineered defence structures are not considered a sustainable solution. With increasing attention towards sustainable and low emission solutions for improving the resilience of critical infrastructures to natural hazards, mitigating storm surge flooding is no longer the only concern of scientists and engineers. The environmental impacts of coastal retrofits also started to be considered while designing and implementing a retrofitting solution. Consequently, the use of innovative and sustainable solutions such as ecologically friendly coastal retrofits have been spotlighted in recent studies [3, 10]. Recently, particular emphasis has been given to the value of eco-system in coastal engineering, with the aim of enhancing the ecology of the coastal and nearshore region [12]. However, no clear evidence proves that environmentally friendly solutions provide equal or more substantial contributions compared to the traditional coastal protection structures. This paper presents a two-dimensional laboratory-based physical modelling study to investigate the impacts of eco-retrofitting solutions including vertipools and reef breakwater on wave overtopping characteristics at a vertical seawall. Measurements of overtopping discharge correspond to the plain vertical seawall were used as the reference case (base case configuration) and validated against the empirical predictions of EurOtop manual [11]. The reef breakwater was placed on the foreshore beach, while the vertipools were installed along the seawall. The wave impulsiveness parameter is defined according to Eq. 1-2:

$$\frac{h^2}{H_{m0}L_{m-1,0}} > 0.23 \text{ for non-impulsive conditions} \quad (1)$$

$$\frac{h^2}{H_{m0}L_{m-1,0}} \leq 0.23 \text{ for as impulsive conditions} \quad (2)$$

The overtopping discharge for the non-impulsive conditions is given by Eq. 3:

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

where $s_{m-1,0}$ is the wave steepness = $2\pi H_{m0}/(gT^2_{m-1,0})$, H_{m0} is the significant wave height from spectral analysis, $T_{m-1,0}$ is the spectral wave period. R_c is the crest freeboard, h is the water depth at the toe of the structure, g is the acceleration from gravity, q is the mean overtopping discharge per meter structure width and $L_{m-1,0}$ is the deep water wavelength. The overtopping discharge for impulsive wave conditions is described by Eq.4:

$$\frac{q}{\sqrt{gHm0^3}} = 0.011\left(\frac{H_{m0}}{h\, s_{m-1,0}}\right)^{0.5} exp\left(-2.2\frac{R_c}{H_{m0}}\right); \quad 0.1 < R_c/H_{m0} < 1.35 \text{ (Impulsive condition)} \quad (4)$$

$$\frac{q}{\sqrt{gHm0^3}} = 0.0014\left(\frac{H_{m0}}{h\, s_{m-1,0}}\right)^{0.5}\left(\frac{R_c}{H_{m0}}\right)^{-3}; \quad Rc/Hm0 \geq 1.35 \text{ (Impulsive condition)} \quad (5)$$

The maximum individual overtopping waves were analysed using EurOtop [11] methodology:

$$V_{max} = a(lnN_{ow})^{1/b} \quad (6)$$

where, V_{max} is the maximum individual overtopping discharge per structure width, N_w is the number of incident waves, N_{ow} is the number of overtopping events. According to the EurOtop [11], N_{ow} is given by:

$$\frac{N_{ow}}{N_w} = exp(-1.21(\frac{R_c}{H_{mo}})^2); \quad \text{non-impulsive conditions} \quad (7)$$

$$\frac{N_{ow}}{N_w} = max\begin{cases} exp(-1.21(\frac{R_c}{H_{mo}})^2) \\ 0.024(\frac{h^2}{H_{m0}L_{m-1,0}}\frac{R_c}{H_{m0}})^{-1} \end{cases}; \quad \text{impulsive conditions} \quad (8)$$

Parameters a and b are the scale and shape factor, respectively, and can be determined using Eq. 9-11:

$$a = \begin{cases} 0.74V_{bar} \\ 0.9V_{bar} \end{cases}, b = \begin{cases} 0.66\ for\ s_{m-1,0} = 0.02 \\ 0.88\ for\ s_{m-1,0} = 0.04 \end{cases} \text{for } h_* > 0.3; \quad \text{non-impulsive conditions} \quad (9)$$

$$V_{bar} = \frac{qT_{m-1,0N_W}}{N_{ow}}; \quad \text{non-impulsive conditions} \quad (10)$$

where $h_* = 1.3\frac{h}{H_{m0}}\frac{2\pi h}{gT^2_{m-1,0}}$,whereas, for impulsive conditions, the shape and scale factors are determined from Eq.11:

$$a = 0.92V_{bar}, b = 0.85\ for\ h_* < 0.3 \quad (11)$$

2. Physical modelling experiments

The experimental study was carried out in the wave flume in the School of Engineering at the University of Warwick, with dimensions 22.0(l) × 0.6(w) × 1.0(h) m with a smooth glass-type foreshore beach slope of 1(V):20(H). A schematic design of the flume is shown in Figure 1. The Flume is equipped with a piston-type wave generator and an active absorption system (AWAS). Experiments were carried out with the vertical seawall fixed at 11.9m from wave paddle, the water depth was varied according to the nominal test condition. The vertical seawall was made of PVC with the height of 0.25m. The thickness of the seawall was designed to be 0.035m to ensure structural stability under impulse wave impacts.

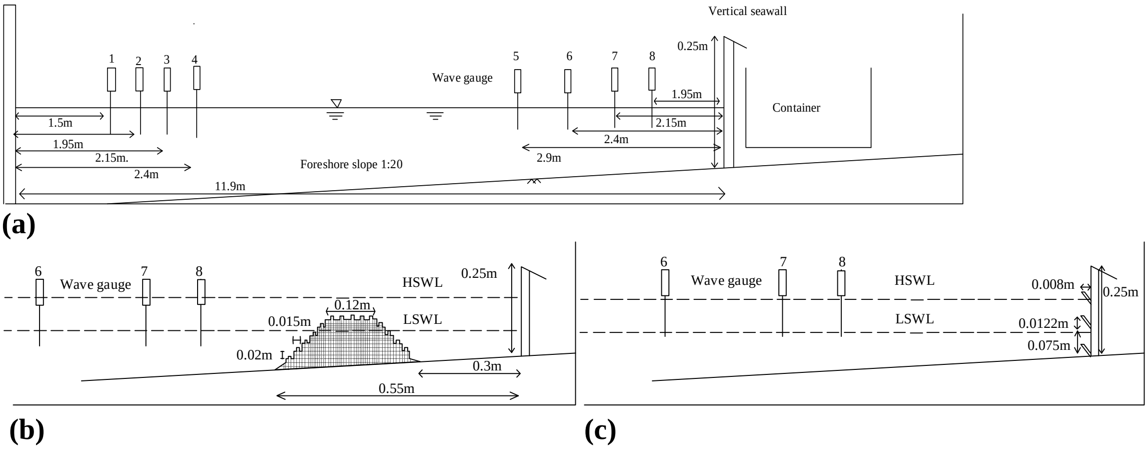

Figure 1(a). Schematic of wave flume experiments; **(b).** reef breakwater; **(c).** vertipools

Figures 1 shows the schematic design of eco-retrofitting structures tested within this study. Each test case consisted of approximately 1000 incoming pseudo-random waves based on the JONSWAP (γ= 3.3) spectrum, at a scale of 1:50. The characteristics of incident waves were determined using two packs of wave gauges, placed close to the vertical seawall and wave paddle, respectively. Four wave gauges were used in each set and the distance between them was determined through the wave gauges self-calibrating function provided by Edinburgh Design wave generation system.
Experiments were undertaken to cover a wide range of relative freeboards for both impulsive and non-impulsive conditions. Six water depths were applied to create designed impulsive and non-impulsive wave conditions. Two selected eco-retrofits were tested to investigate their influence in wave overtopping reduction considering their geometrical shapes. The wave conditions employed are shown in Table 1. The significant wave height ranged from 0.04m to 0.105m with 0.01m increment. Four wave periods were tested as Tp= 1.0s, 1.2s, 1.5s and 1.75s, the incident wave steepness ranged from 0.011 to 0.068 that represents typical swell and storm conditions. To minimize the scale effects, the tested significant wave heights were no less than 30mm to ensure the Reynold number is high enough (>30000) and thus, the correct turbulent conditions can be modelled. The effects of wave reflection from the flume boundaries were minimized through the application of active wave absorption system implemented in the wave generation paddle. The accuracy and efficiency of this system was tested during the wave calibration stage prior to undertaking any measurements.

Table 1. Wave conditions tested during the physical modelling study

Water depth [m]	0.07	0.09	0.11	0.13	0.16	0.18
Input wave period [s]	1.0-1.75		1.0-1.75	1.0-1.5	1.0-1.2	
Significant wave height [m]	0.055-0.105		0.065-0.105	0.055-0.065	0.04-0.075	
R_c/H_{mo}	1.52-3.27		1.3-2.15	1.8-2.18	0.93-2.2	

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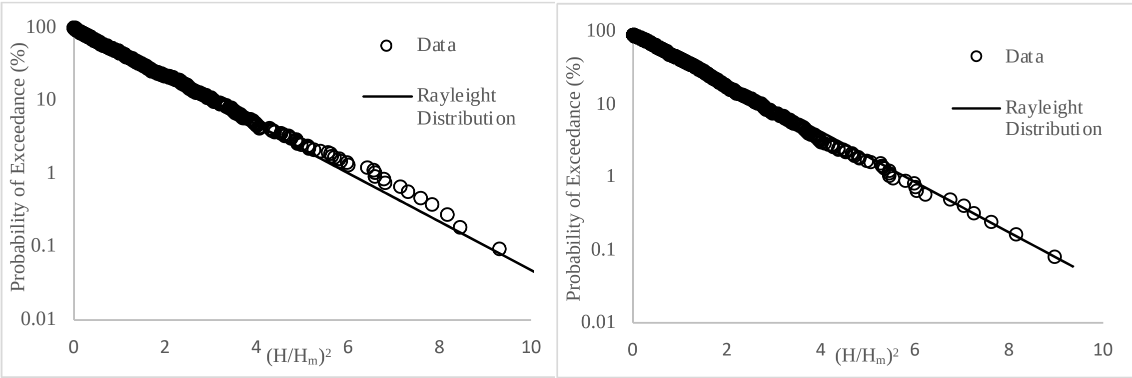
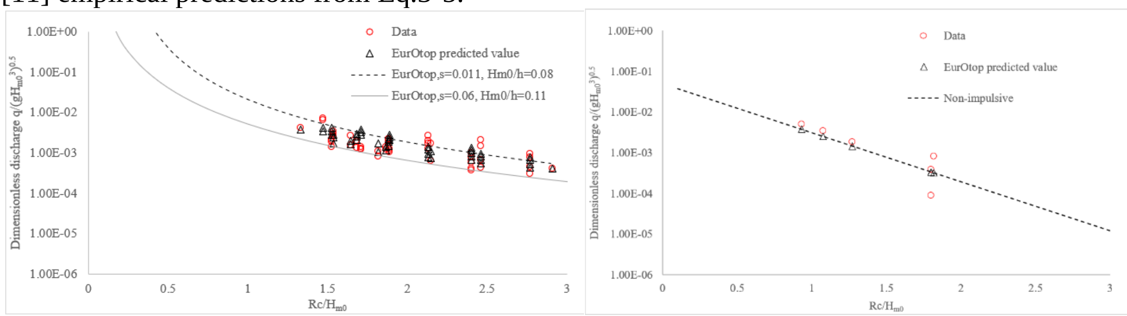


(a) **(b)**

Figure 2. Comparison between measured and predicted distribution of incident wave height (a) h_s=0.07, T_p=1.5, and (b) h_s=0.09, T_p=1.5

3. Overtopping measurements

Previous studies suggested that the incident wave heights in relatively deep water follow the Rayleigh distribution whereas in nearshore regions, wave heights deviate from the Rayleigh distribution [13-15]. For the wave conditions examined here, the comparison between predicted Rayleigh distribution and the observed distribution of incident wave heights is shown in Figure 2. The measured data correlate reasonably well with the Rayleigh distribution although a small deviation can be observed, which can be associated with wave breaking near the paddle. This was also the case in previous studies (e.g., [16-18]). Measurements of the plain vertical seawall case from laboratory test were compared to the EurOtop [11] empirical predictions from Eq.3-5.



(a) (b)

Figure 3. Comparison between measured and predicted mean overtopping discharge on plain vertical seawall (base case)- (a) under impulsive conditions, and (b) under non-impulsive conditions

For the tested wave conditions, both the results of overtopping discharge and maximum individual overtopping volume showed good agreement with the empirical predictions (Figure 3 & 4). Overtopping measurements of vertical seawall were taken as the reference case for the comparison with eco-retrofits cases. Figure 5 shows significant overtopping reduction for the eco-retrofits, varied with dimensionless freeboard.

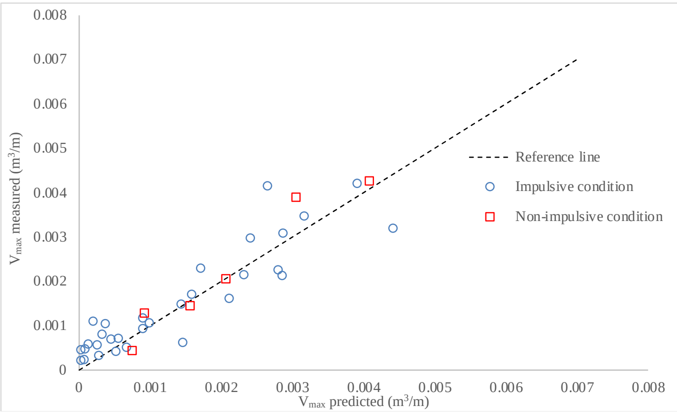


Figure 4. Comparison between measured and predicted maximum individual overtopping volume on plain vertical seawall (base case)

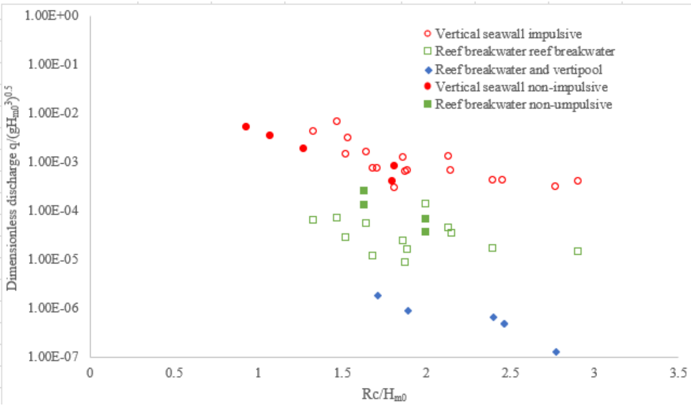


Figure 5. Mean overtopping discharge on vertical seawalls with selected eco-retrofits

Figure 6 presents the comparison of overtopping proportion for vertical seawall and reef breakwater under both impulsive and non-impulsive conditions. The good correlation between the measured value for vertical seawall cases and the empirical predicted value of EurOtop [11] further validates the accuracy of the reference cases. The significant scatter between the vertical seawall cases and the reef breakwater cases confirms the efficiency of reef breakwater in reducing overtopping proportion. Figure 6 indicates the reduction due to reef breakwater becomes more significant as the relative freeboard grows. For the case of reef breakwater, the overtopping proportion decreased by 70% for relative freeboard value of 1.86.

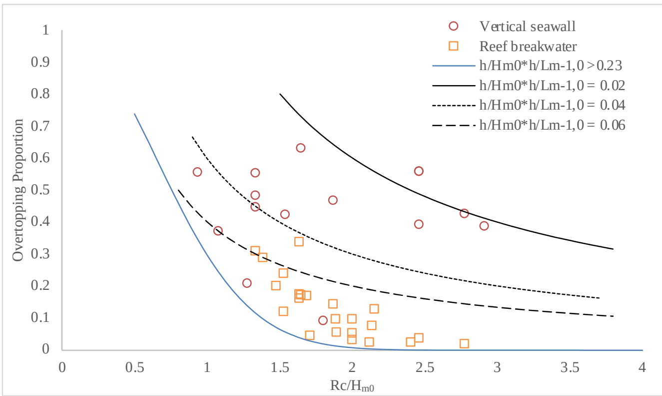


Figure 6. Proportion of overtopping waves at a plain vertical wall compared to reef breakwater under both impulsive and non-impulsive conditions

The eco-retrofits tested in this study have all been previously examined for their ability on ecological enhancement. However, for each of these ecologically enhanced retrofits, there is limited evidence and data on their capability to mitigate incident wave height, as well as reducing mean wave overtopping discharge. Although the ecological retrofitting solutions have great potential in offsetting carbon and providing sustainable protection against storm surges, there have been no significant data in understanding the performance of eco-retrofits beyond the ecological aspects. It is also undetermined that whether the benefits of eco-engineering from these eco-retrofits will be compensated when they are used as coastal resilience enhancement schemes. Furthermore, there are no guidelines on the optimum design (e.g. dimension, type, etc.) of eco-retrofits to maximize their functionality in enhancing climate resilience and endurance during extreme wave pressure force. It is difficult to assess and compare the performance of eco-retrofits with conventional hard engineered structures under a comparable environmental condition [10]. Transferring the full benefits of eco-retrofit from an ecological enhancement to coastal protection solution requires comprehensive investigations, data, predictive models, and design guidelines.
The results for the base case of vertical seawall were used as the reference case and compared with the empirical prediction method from EurOtop [11], no significant difference was observed whereas small deviation can be noticed under waves with small steepness. Similar observation was found from Dong et al. [17] and Besley et al. [19]. The analysis of physical modelling data proved the addition of eco-retrofit effectively contribute to the reduction of maximum wave-by-wave overtopping. The application of eco-retrofits not only affects the mean overtopping discharge, but also the overtopping proportion. The measurement of proportion of overtopping waves for the vertical seawall shows that the obtained proportion of overtopping (P_{ov}) correlates well with the predicted value. Also, it can be observed that approximately 50% reduction was achieved for reef breakwater. Despite the results of this study, it is expected that the application of eco-retrofits for wave overtopping mitigation still demanding further investigation. As most coastal infrastructures are crucial, it is important to demonstrate that whether the long-term structural stability and maintenance of coastal infrastructures will be compromised after adding eco-retrofits.

4. Conclusion

This paper presents a physical modelling study to investigate the performance of eco-retrofits on wave overtopping reduction. The parametric analysis confirms that relative freeboard and overtopping rate are the key parameters determining resilience of eco-retrofits. Mean overtopping discharges for the plain vertical seawall case were validated against empirical predictions. No significant differences were observed between measurements and empirical predictions. Comparison of mean overtopping discharges between plain vertical seawall and eco-retrofits highlights the effectiveness of the selected eco-retrofits in overtopping attenuation within the wave conditions tested. Despite the encouraging results of this study pertaining to benefits of eco-retrofits, it is foreseeable that the adoption of eco-retrofit for both biodiversity enhancement and wave overtopping mitigation may continue face challenges associated with long-term maintenance and sustainability due to artificially modified coastal defences. Additionally, engineering design guidance of eco-enhanced seawall is still limited. Further validation of measurements with field data would be desirable in deriving a robust model that can be used for design in prototype scenarios.

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