EFFECTIVENESS OF ECO-RETROFITS IN REDUCING WAVE OVERTOPPING ON SEAWALLS

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INTRODUCTION

Terms such as 'nature-based', 'living shoreline', 'green infrastructure' and 'ecological engineering' are increasingly being used to reflect biomimicry-based engineering measures in coastal defences. Innovative interventions for nature-based sea defences have included the retrofitting of man-made water filled depressions or 'vertipools' to existing seawalls (Hall et al., 2019; Naylor et al., 2017) and the addition of artificial drill-cored rock pools to intertidal breakwaters (Evans et al., 2016). Through their capacity to retain water, such measures serve to enhance biodiversity in the built environment (Browne and Chapman, 2014). Evans et al. (2016) for example, experimentally demonstrated that the introduction of artificial rock pools to an intertidal granite breakwater enhanced the levels of species richness compared to those observed on plain surfaces of the breakwater.

Notwithstanding these biological benefits, the impetus for incorporating ecologically friendly measures to existing sea defences remains low (Salauddin et al., 2020). This situation could potentially change should it be shown that the addition of 'green' measures to sea defences could enhance wave attenuation and reduce wave overtopping as well as wave pressures on the coastal defence structures. This paper describes small-scale physical modelling investigations of seawalls and explores reductions in wave overtopping that could be realised by retrofitting sea defences with 'green' features (such as 'vertipools'). Surface protrusions of varying scale and density are used in the physical modelling to mimic 'green' features and the results from measurements of overtopping are benchmarked to reference conditions determined from tests on a plain seawall.

For the estimation of mean wave overtopping characteristics at sea defences, considerable field, and laboratory studies have previously been performed (Allsop et al., 2005; Franco et al., 1994; Salauddin et. al., 2017; Van der Meer and Bruce, 2014). Recently, the revised wave overtopping manual, i.e. EurOtop (2018) has been published, incorporating formulae to predict mean overtopping rates at sea defences. Laboratory results of this study are compared with predictions from these empirical relations. Mean wave overtopping rates at vertical seawalls with sloping foreshores are estimated for non-impulsive conditions using Equation 1 and, for impulsive conditions, using Equations 2-3.

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

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.011 \left(\frac{H_{m0}}{h_t s_{m-1,0}} \right)^{0.5} exp \left(-2.2 \frac{R_c}{H_{m0}} \right) \qquad (2)$$

$$0 < \frac{R_c}{H_{m0}} < 1.35$$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0014 \left(\frac{H_{m0}}{h_t s_{m-1,0}} \right)^{0.5} \text{ for } \frac{R_c}{H_{m0}} \geq 1.35 \qquad (3)$$

where, R_c denotes the crest freeboard of the structure, g is the gravitational acceleration, q is the average overtopping discharge per meter width of the structure, and $s_{m-1,0}$ defines the incident wave steepness (= $\frac{H_{m0}}{L_{m-1,0}}$).

Results from recently undertaken physical model investigations on plain vertical seawalls by Dong et al., (2018 and 2020); Salauddin and Pearson (2018 and 2019a), and numerical investigations by Abolfathi et al. (2018), were in good agreement with the empirical predictions of overtopping for both impulsive and non-impulsive conditions. Within this study, the measured overtopping characteristics for both benchmark and artificially roughened conditions are compared with the empirical prediction formulae of EurOtop (2018).

KEYWORDS

eco-retrofits, overtopping, vertical seawall, climate resilience, ecological engineering

LABORATORY SET UP

The laboratory study was undertaken in a two-dimensional wave channel at the University of Warwick, UK. The wave flume was equipped with an active absorption paddle-type wave-maker. An impermeable sloping foreshore with a uniform slope of 1 in 20 was constructed in front of a vertical seawall. The seawall was subsequently modified by including 10 different test combinations of horizontally orientated surface protrusions of varying scale and surface density, replicating 'green' measures suitable for retrofitting to existing seawalls. Wave overtopping was measured for each test case.

Three different lengths of protrusions (0.01 m, 0.03 m and 0.05 m) were tested across three surface densities (2500 protrusions/ m², 5000 protrusions/ m², and 9800 protrusions/ m²). The surface protrusions at the seawall were made of flexible straws circular in section (1 mm in diameter) and sealed on a PVC board along the seaward surface of the structure. The laboratory set up and test arrangements are shown in Figure 1 and Figure 2.
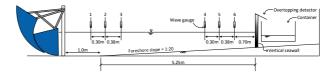

Figure 1 - Layout of the cross-sectional test set-up (plain vertical seawall)

All tests are comprised approximately 1000 JONSWAP pseudo-random wave sequences. Both impulsive and

non-impulsive wave conditions were considered in experiments with two constant deep-water wave steepness values of 1.5% and 6%. The incident wave conditions at deep water and in front of the structure toe were determined by placing six wave probes (one set of three, see Figure 1) along the length of the flume adopting the methodology of Mansard and Funke (1980). Experiments were also carried out to measure the inshore wave conditions without the structure in place (i.e. seawall) to mitigate the uncertainties in wave measurements that may arise from the reflection generated from the structure (see Salauddin and Pearson, 2019b). Table 1 summarises the physical modelling test conditions.

Table 1: Summary of test conditions

Structural configuration	Test series	h_t [m]	R_d [m]	s_{op} [-]	H_{m0} [m]
Plain vertical seawall	1A	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Vertical seawall with drilled holes	2A	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.01 m in length (98 stems/100 mm²)	3A	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.01 m in length (50 stems/100 mm²)	3B	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.01 m in length (25 stems/100 mm²)	3C	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.03 m in length (98 stems/100 mm²)	4A	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.03 m in length (50 stems/mm²)	4B	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.03 m in length (25 stems/100 mm²)	4C	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.05 m in length (98 stems/100 mm²)	5A	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.05 m in length (50 stems/100 mm²)	5B	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	
Seawall with protrusions of 0.05 m in length (25 stems/100 mm²)	5C	0.09	0.16	0.015	0.05 - 0.15
		0.16	0.09	0.060	

Measurements of wave overtopping volumes in a test sequence followed the approach of Salauddin and Pearson (2020) and used a collection tank and load-cell positioned behind the vertical structure. Additionally, an overtopping detector circuit was positioned on the crest of the seawall to identify the individual overtopping events. The calibrated load-cell, together with the overtopping detector, facilitated measurement of wave-by-wave overtopping volumes by recording mass increments of water in the collection tank with respect to overtopping waves for a test run. A use of a syphon mechanism in the collection tank ensured the uninterrupted sampling of overtopping volumes for the duration of each experiment.

Figure 2 - Test set-up showing overtopping at vertical walls with artificially roughened surfaces

RESULTS AND DISCUSSIONS

The benchmark for the experiments with different protrusions were the experiments performed on a simple plain vertical wall (reference case) for the designed incident wave conditions.

In Figure 3, the resulting average overtopping rates for the benchmark experiments, i.e., with a plain vertical seawall (reference case) are shown for both impulsive and non-impulsive conditions. The measurements are compared with the predicted values using the EurOtop (2018) empirical relations (Equations 1-3). Figure 3 shows that measured data are in good agreement with predictions for impulsive and non-impulsive conditions tested in this study.
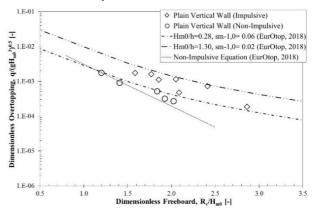

Figure 3 - Mean overtopping rates at plain vertical walls

In Figure 4, the dimensionless mean overtopping rates for all the retrofit cases are plotted against the relative freeboard of the structure for the tested non-impulsive wave conditions. The EurOtop (2018) prediction is also shown. Uncertainty in the prediction of EurOtop (2018) is described by the inclusion of 5% upper and lower limits prediction. Figure 4 shows that in general, the overtopping rates are consistent with those predicted by EurOtop (2018), suggesting that the influence of the surface protrusions on the sea wall is not significant for non-impulsive wave conditions.
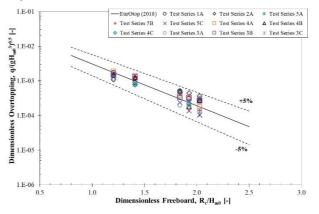

Figure 4 - Mean overtopping rates at vertical walls with artificially roughened surfaces (non-impulsive conditions)

For the impulsive wave conditions that were tested, non-dimensional mean overtopping rates are presented in Figure 5 with respect to the relative freeboard of the structure. The EurOtop (2018) prediction for non-impulsive wave conditions is also included and it is clear that measured overtopping rates follow the trend of the empirical predictions.

Figure 5 shows however, that mean overtopping rates were reduced significantly (by up to a factor of four) for the artificially roughened seawalls, when compared to the EurOtop (2018) empirical predictions. The degree to which overtopping is reduced is clearly related to the geometrical characteristics (length and density) of the roughness configuration - comparing Test Series 4A for

example, to Test Series 4B and 4C for a given wave condition, shows reduced overtopping as the density of surface protrusions on the seawall increases.
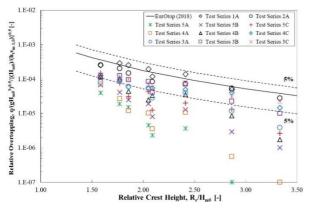

Figure 5 – Mean overtopping rates at vertical walls with artificially roughened surfaces (impulsive conditions)

CONCLUSIONS

This paper presents laboratory-based investigations of the influence of surface roughness on the wave overtopping characteristics at vertical seawalls, subjected to both impulsive and non-impulsive wave conditions. The role of eco-engineered measures on sea defence structures has recently been established. This research highlights a second potential benefit of such interventions in coastal zone management; that of improving the climate resilience of sea defences by reducing the flood risk from wave-induced overtopping, particularly for violent impulsive wave conditions. The research findings from this study will assist coastal engineers, ecologists, and practitioners in incorporating eco-retrofits in the resilient and environmentally sustainable design of sea defence infrastructures to address increasing wave hazards at seawalls.

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