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# Effects of Seagrass Vegetation on Wave Runup Reduction – A Laboratory Study

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**Abstract.** Increased intensity of extreme climatic events and natural hazards, combined with sea level rise due to global warming, has increased the vulnerability of nearshore and coastal regions to extreme flooding and erosion. The existing hard-engineered infrastructures for flood protection are mainly built from concrete with very high carbon emissions throughout their life cycle. In recent years, the application of nature-based solutions to tackle adverse climatic events has received attention. Nearshore vegetations such as salt marshes and mangroves have proven to attenuate incoming wave energy, thereby reducing wave runup and overtopping at coastal defences. The effectiveness of seagrass vegetation on wave runup attenuation remains less studied. The aim of this physical modelling study was to investigate the performance of prototype seagrass vegetations on wave runup reductions, for a wide range of wave conditions. Results of this study showed that the seagrass vegetation was effective in reducing wave runup on a 'bare' beach. It was found that the location of the vegetation patch within the surfzone and inner-surf zone can play a key role in wave energy dampening. The vegetation type, and packing density also play a significant role in determining the effectiveness of seagrass in wave energy mitigation.

## 1. Introduction

Coastal regions have become progressively more vulnerable to natural hazards throughout the years due to changing climate consequences such as sea-level rise and increase in intensity and frequency of extreme climatic events from storm surges [1-4]. Recent studies by United Nations [1], has also shown that ocean warming is directly and indirectly correlated to more occurrence of extreme weather events, resulting in more intense tropical cyclones and storm surges worldwide. This intensified storm surges together with global sea level rise will result in reduced crest freeboard of existing coastal defence infrastructures and make them more vulnerable to catastrophic flooding with extreme wave overtopping and wave runup events [5-8]. Conventional engineering approaches resulted in armouring of coastlines with hard engineered structures including seawalls and breakwaters in order to provide protection from flooding and erosion, which are becoming increasingly unsustainable due to their costly maintenance and loss of environmental biodiversity [9-14].

Concrete as a material choice has been widely favoured for building coastal defences due to its ease of casting into heterogeneous three-dimensional shapes and surface topographies [15]. However, for every 1000 kg of Portland cement, between 900 to 1100 kg of $CO_2$ is emitted [16]. Furthermore, the high surface alkalinity (pH 12-13) and leaching metals can impair settlement of marine organisms and contribute to pollution mixing in the nearshore zone [15,17]. Coastal vegetations are sustainable and can adapt to the natural ecosystem of the coastal region without intrusive behaviour [10]. Coastal protection properties of vegetations such as mangroves [18] and saltmarshes [19] have been relatively explored. Seagrass as a coastal protection measure has not been assessed comprehensively, and as such, there is a clear knowledge gap regarding how seagrass vegetation can offer better shoreline protection [20].

Bulk drag coefficient is widely considered as a common parameter to evaluate the wave attenuation of suspended canopies. Kobayashi [21] used the relationship between the effective drag coefficient ($C_D$) and Reynolds number ($R$) to represent the wave attenuation of submerged artificial kelp given by:

$$C_D=\left(\frac{2200}{R}\right)^{2.4}+0.08 \tag{1}$$

However, the kelp motion and viscous effects were ignored. This approach was then further developed for flexible vegetation [22] and random waves [23]. Henderson [24] modelled kelp blades as a continuous cantilever beam using Euler-Bernoulli techniques and ignoring the blade inertia and inertia forces. The model was further developed by Zhu et al. [25] by incorporating the inertia forces for chromatic and random waves using the assumption of a small deflection which linearized the blade curvature.

In a study by Augustin et al. [26] it was shown that at near emergent cases ($10\geq h/l_s\geq 2$) the drag coefficient had a higher correlation with the Keulegan-Carpenter number than with the Reynolds number, which was also reported by Mendez and Losada [27]. This suggests a weaker relation between the drag coefficient and the wave period as the ratio between the stem height and water depth decreases A study from Anderson and Smith [28] on flexible idealized salt marsh vegetation identified that dissipation varied at different frequencies with increased dissipation at frequencies above the spectral peak. This relationship was also identified in a study by Mullarney and Pilditch [29], where field experiments to examine the movement of individual kelp steams were conducted. The study showed that the kelp vegetation moved differently in response to different forcing frequencies. The long blades toward the top of the kelp showed to have larger oscillation at infragravity frequencies as opposed to the swell frequencies. It was suggested that drag from kelp blades prevented movement at the higher sections of the kelp at swell frequencies.

Laboratory experiments from Zhu et al. [30] showed that the ration of dissipated wave energy to incident wave energy of cultivated *Saccharina latissimi* kelp increases with blade size, plant density and longline number, while decreasing with the increase of water depth. The study also showed that the wave energy dissipation ratio was not sensitive to wave height and first increases then decreases with wavelength. For shallow water waves, the wave decay coefficient ($k_D$) was defined as:

$$k_D=\frac{\alpha_\varepsilon C_{DB} bNl}{3\pi h^2} \tag{2}$$

where $\alpha_\varepsilon$is the factor of the sheltering effect between blades, with $\alpha_\varepsilon$=1 indicating no sheltering, $C_{DB}$ is the bulk drag coefficient, $b$ is the kelp blade width, $N$ is the canopy density defines as blades per unit area, $l$ is the kelp blade length, and $h$ is the water depth.

The wave attenuation of the kelp model was then quantified using the wave transmission ratio (HTR) and wave energy dissipation ration (ETR). The wave transmission ratio is defined as the ratio of the wave height at the ending edge of the canopy to the incident wave height given by:

$$HTR=\frac{H(L_v)}{H(0)}=\frac{1}{1+k_D H_0 L_v} \tag{3}$$

where $k_D$ is the wave decay coefficient, $H_0$is the incident wave height, $L_v$ is the canopy length and $H(x)$ is the transmitted wave height at distance $x$ in relation to the incident wave height $H_0$ at $x=0$.

The wave energy dissipation ratio is defined as the ratio of the dissipated wave energy to the incident wave energy given by:

$$EDR=\frac{H(0)^2-H(L_v)^2}{H(0)^2}=1-HTR^2=\frac{1}{(1+k_D H_0 L_v)^2} \tag{4}$$

where $L_v$ is the canopy length and $H(x)$ is the transmitted wave height at distance $x$ in relation to the incident wave height $H_0$ at $x = 0$.
This study examines the effectiveness of seagrass vegetation for wave runup reduction, using a prototype physical seagrass model representing a vegetated foreshore slope. The performance of the vegetation model in reducing wave runup is evaluated under different water levels and incoming wave conditions to provide a deeper understanding of the effectiveness of seagrass as a coastal protection approach and therefore derive potential design metrics for implementation of seagrass as coastal resilience enhancement schemes.

## 2. Experimental setup and methods

*2.1 Experimental setup*
Physical modelling tests of wave runup measurements for plain and vegetated foreshore were conducted in a two-dimensional laboratory wave flume at the University of Warwick, UK. The flume is 22.0m long, 0.6m wide and 1.0m high with a 1:20 uniform smooth impermeable beach slope. The facility is equipped with a piston-type wave generator with an active wave absorption system (AWAS). For each test case monochromatic waves were generated at a 1:50 scale. An imaging system was setup to record the wave runup height ($R_{u2\%}$), which was identified by placing the measuring tape on the still water line at the foreshore slope (see Figure 1). The seagrass vegetation model (Figure 2) was made of polyester sheets that were cut to form 18cm long and 3cm wide strips which were then taped onto the slope to form a 1m width vegetation patch. Wave runup measurements were taken for still water level (SWL) 0.5m (emerged), 0.6m (partially submerged), and 0.7m (fully submerged) from wave period of 1.0 to 4.0 seconds. A summary of wave conditions and test configurations investigated in this study is shown in Table 1. Incident wave conditions (i.e., wave heights and periods) were tested on a 'bare' beach and then measured wave heights were compared with Rayleigh predictions, as following the typical physical modelling approach in a two-dimensional wave flume (see [31-33]).

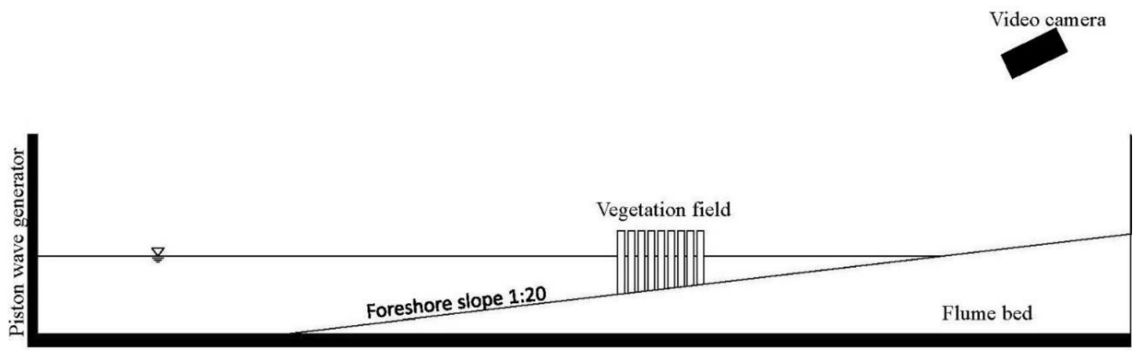


**Figure 1.** Schematic of wave flume setup

**Figure 2.** Seagrass vegetation model

**Table 1.** Wave conditions tested for the physical modelling tests

| $T_p$ (s) | $H_s$ (m) | Steepness |
|---|---|---|
| 1.0 | 0.12 | 0.096 |
| 2.0 | 0.12 | 0.048 |
| 3.0 | 0.12 | 0.032 |
| 4.0 | 0.12 | 0.024 |

*2.2 Wave runup height*

The wave runup height ($R_{u2\%}$) is the wave runup, measured vertically from the still water line, which exceeds by 2% of the other incident waves. Due to very thin layers of water capable of being blown a long way up a slope, it is suggested that the wave run-up level is determined when the water tongue becomes less than 2cm thick [35-37].

*2.3 Damping ratio*

The effectiveness of the seagrass vegetation model is evaluated using the damping ratio ($\xi$) given by:

$$Damping\ ratio(\zeta) = \frac{R_v}{R_0} \tag{5}$$

where $R_v$ is the recorded wave runup height ($R_{u2\%}$) when the vegetation model is installed and $R_0$ is the recorded wave runup height ($R_{u2\%}$) of the bare flume.

## 3.Results and discussion

The relationship of the damping ratio and wave frequency for emerged (SWL=0.5m), partially submerged (SWL=0.6m), and fully submerged (SWL=0.7m) test conditions are illustrated in Figure 3. The seagrass model showed to have the highest wave runup reduction when it is partially submerged (SWL=0.6m) and the least wave runup reduction when fully submerged (SWL=0.7m) across all test cases, with the highest wave runup reduction was observed at SWL=0.6m and $T_p$=2.0s with 32% reduction in wave runup and the least wave runup recorded at SWL=0.7m and $T_p$=3.0s where the wave runup was increased by 29% instead. For both $T_p$=1.0s and 2.0s, wave runup heights were reduced at all three tested water levels. However, for $T_p$=3.0s wave runup was reduced only at SWL=0.6m with no reduction at SWL=0.5m and an increase in wave runup at SWL=0.7m instead. For $T_p$=4.0s, wave runup reduction was only observed for SWL=0.7m and overall negligible reduction was reported for SWL=0.5 and 0.6m (Figure 3).

Overall, the model showed to have higher wave reduction when the incoming waves have lower periods and less reduction at higher incoming wave periods. However, the variance of the wave runup reduction at $T_p$=3.0s shows that the relationship between wave runup reduction and incoming wave periods does not have an inverse correlation, instead might have different integrals of incoming wave periods in which the relationship varies between a positive or inverse correlation. This integral of incoming wave periods shows to vary for different SWL conditions, with the emerged and fully submerged seagrass model showing to have no wave runup reduction or even increasing wave runup while the partially submerged seagrass model being unaffected and still reduces the incoming wave runup. Further research will be needed to identify the integrals for different incoming wave periods and SWL which will provide crucial data for the use of seagrass as coastal defence structures.

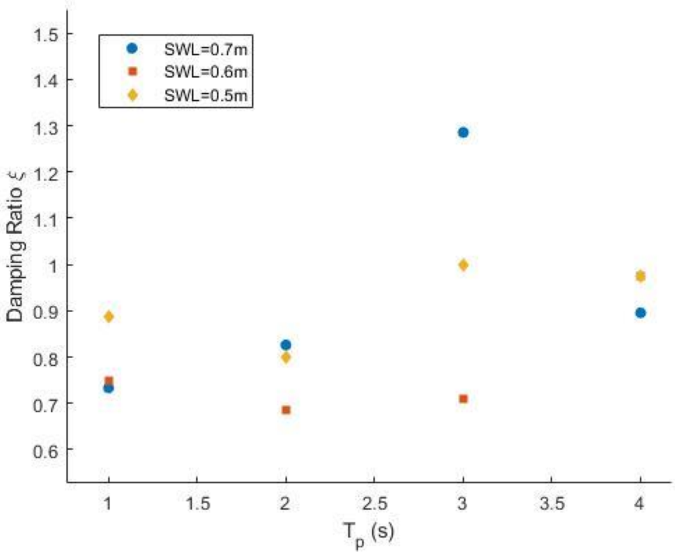


**Figure 3.** Damping ratio to frequency graph for the tested configurations

## 4.Conclusion

A physical modelling study of wave attenuation over prototype seagrass vegetation model were undertaken to investigate the effectiveness of seagrass in wave runup reduction. The experiments were undertaken covering a wide range of wave conditions and water levels (i.e. submerged, semi-submerged). For the wave conditions tested in this study, the vegetation model showed to have the best performance when partially submerged, i.e., at SWL=0.6m, with the highest wave runup reduction observed for the wave period of 2s. The incident wave periods showed to have complicated effects on the wave runup reduction performance for the vegetation model, which can be associated with the changes in wave breaker type that can significantly influence the wave energy decay in the surfzone and inner-surfzone and consequently influence the wave runup in the swash zone.

The analysis of the experimental data presented in this paper follows the results of Zhu et al. [11], in which water level and incoming wave periods showed also significant impact on the extent of the wave runup for the case of vegetated foreshore with seagrass. The variations in the performance of seagrass for the same incoming wave period and at different water levels, show that different water levels might have different integrals of wave periods where wave runup is either increased or decreased. This is vital information which needs to be understood for further implementation of seagrass as a coastal protection approach (see [10]). Nevertheless, further laboratory studies are clearly needed to robustly quantify the effects of seagrass vegetations on the wave energy dampening and runup reductions. The influence of vegetation characteristics such as surface roughness, elasticity, packing density, and stem height to water depth ration, as well as hydrodynamic parameters will need to be quantified to provide comprehensive predictive relationships to model the performance of seagrass vegetations as a coastal resilience enhancement solution.

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