NEW INSIGHTS ON USING SCALED MARSH PLANT SURROGATES FOR WAVE ATTENUATION

Acacia Markov, University of Ottawa, Canada, amark043@uottawa.ca
Margo Muller, Université Bretagne-Sud, France, muller.e2002453@etud.univ-ubs.fr
Scott Baker, National Research Council of Canada, scott.baker@nrc-cnrc.gc.ca
Ioan Nistor, University of Ottawa, Canada, inistor@uottawa.ca
Enda Murphy, National Research Council of Canada, enda.murphy@nrc-cnrc.gc.ca
Jacob Stolle, Institut National de la Recherche Scientifique, Canada, jacob.stolle@inrs.ca
Andrew Cornett, University of Ottawa, Canada, acornet2@uottawa.ca

BACKGROUND

It has been widely demonstrated in literature that coastal marshes provide positive ecosystem services related to coastal protection, including wave attenuation, storm surge reduction, and erosion prevention (Moller et al., 2014; Wang et al., 2021; Paul & Kerpen, 2021). Physical modelling presents a useful tool for investigating the coastal protection function provided by marsh vegetation in a controlled, repeatable environment, to inform design of nature-based coastal protection strategies, or "nature-based solutions" (NBS). To date, physical modelling studies have been used to investigate the influence of plant biophysical parameters (stem width, stem height, stem flexibility) and hydrodynamic conditions on wave attenuation (e.g., Augustin et al., 2009; Anderson & Smith, 2014; Moller et al., 2014; Ozeren et al., 2014; van Veelen et al., 2020). Such studies have predominantly used surrogate vegetation due to the logistical challenges and facility requirements associated with live plant experiments. Furthermore, most studies have been performed at or near full-scale to reduce uncertainties and scale effects associated with downscaling vegetation, particularly where Reynolds number similarity cannot be preserved (Blackmar et al., 2014). To address existing knowledge gaps related to physical modelling of marsh vegetation at small-scale, experiments were conducted in a 63 m long by 1.22 m wide wave flume at the National Research Council of Canada's Ocean, Coastal and River Engineering Research Centre, Ottawa, in collaboration with the University of Ottawa and the Institut National de la Recherche Scientifique, Quebec City.

OBJECTIVES AND NOVELTY

This is one of the first experimental programs to compare different methods of downscaling live vegetation, which will allow researchers to better interpret the results of small-scale testing with surrogate plants under wave action. Primary objectives of this novel study were to:

(1) Quantify the wave attenuation capacity of an artificial *Spartina alterniflora* field under wave action, in realistic constructed marsh scenarios (1:20 sloped shoreline, irregular waves).
(2) Investigate alternative methods for downscaling live vegetation in laboratory settings.
(3) Compare the performance of various surrogate proxies for the semi-flexible *S. alterniflora*, to inform guidelines for selection of vegetation surrogates.

EXPERIMENTAL PROGRAM

Tests were conducted at 1:4 scale following Froude similitude. Irregular waves synthesized from JONSWAP spectra were generated using a piston-type wavemaker. Wave conditions ranged from 0.075 m < H_{m0} < 0.23 m, with peak wave periods between 2.0 s < T_p < 3.25 s, at two water depths, d = 0.60 m and 0.75 m. A rigid 1:20 (v:h) slope was constructed and surfaced with pre-fabricated plywood panels that could be quickly interchanged to support the investigation of various vegetation surrogates in different test series (TS). The vegetated slope section represented a 15 m long (x-shore direction) prototype marsh. Figure 1 provides more details on the experimental set-up. Four TS were conducted to investigate the influence of simulated *S. alterniflora* on wave transformations across the fixed 1:20 slope. Two factors were considered in development of the surrogate TS: (I) downscaling method, and (II) flexibility considerations.

I. Downscaling method

A percent volume fraction scaling approach was applied to select multiple stem width and stem density combinations representative of a prototype-scale *S.*
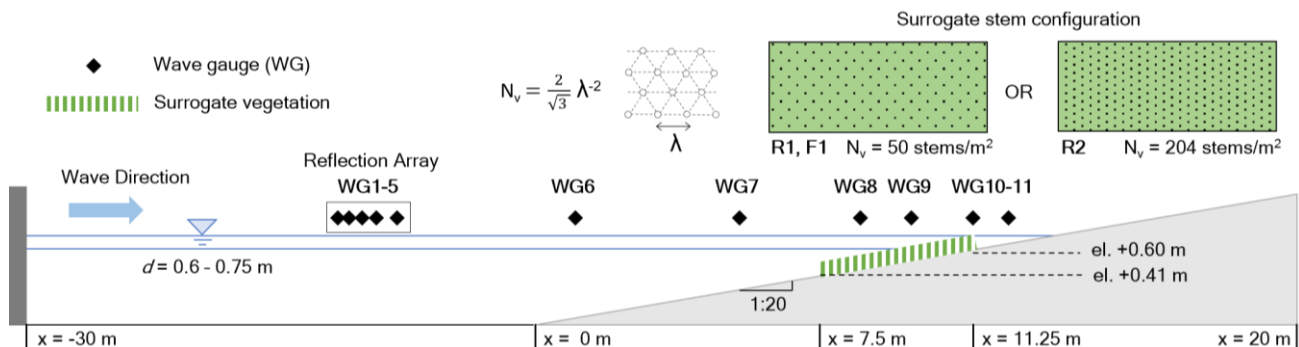

Figure 1 - Experimental set-up and instrument locations.

alterniflora field with 51 stems/m², 4.5 mm plant stem diameters, and 62 cm stem lengths, while maintaining stem Reynolds numbers reasonably consistent with prototype conditions. The following scale factor (α) was applied, from Baker et al. (2022):

$$\alpha = \frac{\pi}{4} b_v^2 * l * N_v \tag{1}$$

where b_v is stem diameter (m), l is stem length (m) and N_v is the stem density (stems/m²).

Considering reasonable prototype:model stem Reynolds similarity, stem diameters of 9.5 mm (TS-R1) and 4.75 mm (TS-R2) were selected, yielding (through Eq. 1) surrogate densities of 50 stems/m² and 204 stems/m², respectively. This dual selection allowed investigation of the downscaling method's sensitivity to stem diameter and element spacing. Both R1 and R2 consisted of rigid wooden dowels, to isolate such effects without the influence of flexibility.

II. Flexibility considerations
Similar to the flexible surrogate selection methods employed by Lima et al. (2006), Augustin et al. (2009), Manca et al. (2012) and Koftis et al. (2013), model-scale flexible elements were selected to match the bending response of live *S. alterniflora* under prototype-scale irregular wave action. Only flexible elements that could remain upright under their self-weight were deemed viable, to minimize buoyancy influences. The bending response of two flexible materials (silicone tubing and latex rubber tubing) to wave forcing was initially investigated, with the same element dimensions as TS-R1. Latex rubber tubing performed more closely to the stem bending of live *S. alterniflora* and was thus selected as the flexible surrogate element for the present study (TS-F1). Key surrogate vegetation parameters for the four TS are provided in Table 1.

Table 1 - Summary of experimental TS, including surrogate element parameters and configurations for simulated vegetation tests.

TS	*l* (cm)	*b_v* (mm)	*N_v* (stems/m²)	*λ* (cm)	Material
0	-	-	-	-	Bare slope (no vegetation)
R1	15.5	9.5	50	15	Wooden dowel (rigid)
R2	15.5	4.8	204	7.5	Wooden dowel (rigid)
F1	15.5	9.5	50	15	Latex rubber tubing (flexible)

RESULTS AND DISCUSSION

Results from surrogate vegetation tests were compared with the unvegetated slope case (TS-0) to estimate vegetation-induced wave attenuation. Wave height attenuation, μ, was quantified for every wave gauge located within or following the surrogate field, considering wave height measurements in the time domain (zero-downcrossing analysis), and using Eq. 2.

$$\mu = \frac{(H_s/H_{s,0})_{TS0} - (H_s/H_{s,0})_{TSveg}}{(H_s/H_{s,0})_{TS0}} \tag{2}$$

Where H_s is the significant wave height (average height of the highest one-third of all waves) as measured by the canopy-proximate WGs (WG8-10), and $H_{s,0}$ is the incident significant wave height, defined as the average significant wave height at five gauges (WG1-5) located up-wave from the 1:20 slope. *TSveg* refers to any of the TS with surrogate vegetation. All wave heights were normalized by offshore wave height to account for slight variations in incident wave conditions between TS. Sample results from the analysis of wave height attenuation are plotted in Figure 2.
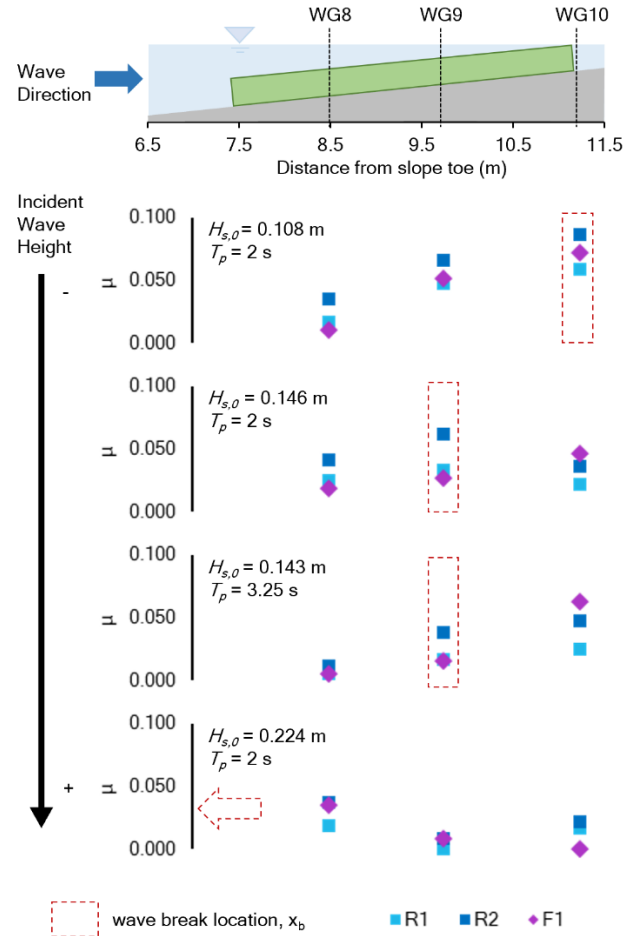

Figure 2 - Attenuation of wave shoaling by surrogate vegetation for sample wave conditions at an incident water depth of *d* =0.75 m.

Preliminary results indicate that downscaling of vegetation using the percent volume fraction approach (α, Eq. 1) is sensitive to the selection of stem diameter, as demonstrated through comparison of the wave attenuation observed in TS-R1 and TS-R2. The more slender 4.5 mm diameter, higher density vegetation field (TS-R2) consistently yielded a greater reduction in wave height compared to the more sparse 9.5 mm surrogate elements (TS-R1), despite identical solid volume fractions. Further study is necessary to determine the cause for this discrepancy, with potential contributors being differences in projected frontal area, stem Reynolds conditions, and stem spacing.

Flexible surrogate elements (TS-F1) produced similar levels of wave attenuation as the geometrically equivalent rigid elements (TS-R1) under the tested hydrodynamic conditions, despite measurable stem deformation being observed. However, substantial stem bending was not sustained over a large portion of the wave cycle, and thus canopy height reduction was not significant for most of the conditions tested herein. This, combined with the dominance of wave shoaling and overall minimal impact of surrogate vegetation at larger wave heights, could potentially contribute to the similarity in attenuation observed between TS-R1 and TS-F1.

For the tests run at a water depth of d = 0.75 m, wave attenuation due to the presence of the surrogate vegetation was minimal, if not negligible, until the second in-canopy wave gauge (WG9), located 2.25 m from the edge of the vegetated section. Contrastingly, for the d = 0.6 m tests, wave attenuation was measurable at WG8, just 1 m from the edge of the surrogate vegetation. Furthermore, as offshore incident waves exceeded H_{m0} > 0.188 m, wave heights measured across the vegetated slope remained relatively unchanged from the bare slope results (TS-0), for all tested surrogates and for both water depths. These findings suggest that wave attenuation by vegetation decreases with increasing submergence, in agreement with Augustin et al. (2009) and Maza et al. (2015), among others, and thus provide design insight for the optimal placement of vegetation on an inclined structure or shore relative to the still water level (i.e., stem submergence considerations), as well as to the hydrodynamic limitations of vegetated dyke structures.

CONCLUSIONS
This novel study presents critical knowledge and guidance on small-scale physical modelling of marsh vegetation on shorelines and structures with moderate slopes, and ultimately the design of coastal marsh-based NBS. Several methods of downscaling surrogate vegetation were investigated based on a percent volume fraction scaling approach. Experimental outcomes indicate that wave height attenuation is sensitive to the selection of surrogate stem diameter, and thus further studies are needed to investigate the validity of this scaling method over a broad range of conditions. Overall, the results demonstrated that wave attenuation was relatively insensitive to stem rigidity, which suggests that arrays of rigid cylinders may provide suitable surrogates for *S. alterniflora* meadows in downscaled physical models. The results also indicate that on a moderate beach slope wave attenuation by vegetation decreases with increased submergence, and that the effect of *S. alterniflora* fields on wave attenuation decreases for wave heights exceeding 0.188 m (0.75 m prototype-scale), for the stem densities and field length considered. These findings would benefit from comparisons to live *S. alterniflora* within a similar experimental program, which is a planned next step.

REFERENCES
Anderson, & Smith (2014): Wave attenuation by flexible, idealized salt marsh vegetation. Coastal Engineering, vol. 83, pp. 82-92.

Augustin, Irish & Lynett (2009): Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation. Coastal Engineering, vol. 56, pp. 332-340.

Baker, Murphy, Cornett & Knox (2022): Experimental Study of Wave Attenuation Across an Artificial Salt Marsh. Frontiers in Built Environment, vol. 8.

Blackmar, Cox, & Wu (2014): Laboratory Observations and Numerical Simulations of Wave Height Attenuation in Heterogeneous Vegetation. Journal of Waterway, Port, Coastal, and Ocean Engineering, pp. 56-65.

Koftis, Prinos & Stratigaki (2013): Wave damping over artificial Posidinia oceanica meadow: A large-scale experimental study. Coastal Engineering, vol. 73, pp. 71-83.

Lima, Neves & Rosauro (2006): Damping of gravity waves by fields of flexible vegetation. Coastal Engineering, pp. 491-503.

Manca, Caceres, Alsina, Stratigaki, Townend & Amos (2012): Wave energy and wave-induced flow reduction by full-scale model Posidinia oceanica seagrass. Continental Shelf Research, pp. 100-116.

Maza, Lara, Losada, Ondiviela, Trinogga & Bouma (2015): Large-scale 3-D experiments of wave and current interaction with real vegetation. Part 2: Experimental analysis. Coastal Engineering, pp. 73-86.

Moller, Kudella, Rupprecht, Spencer, Paul, van Wesenbeeck, . . . Schimmels (2014): Wave attenuation over coastal salt marshes under storm surge conditions. Nature Geoscience, vol. 7, pp. 727-731

Ozeren, Wren & Wu (2014): Experimental Investigation of Wave Attenuation through Model and Live Vegetation. Journal of Waterway, Port, Coastal, and Ocean Engineering, vol. 140.

Paul & Kerpen (2021): Erosion protection by winter state of salt marsh vegetation. Journal of Ecohydraulics.

van Veelen, Fairchild, Reeve & Karunarathna (2020): Experimental study on vegetation flexibility as control parameter for wave damping nd velocity structure. Coastal Engineering, vol. 157.

Wang, Yin, Luan, Wang & Liu (2022): Hydrodynamic Characteristics of Idealized Flexible Vegetation under Regular Waves: Experimental Investigations and Analysis. Journal of Coastal Research, pp. 673-680.