PIANC De Paepe-Willems Award Winner 2021

NUMERICAL MODELLING & NEW PREDICTION FORMULAE FOR WAVE AND WAVE-CURRENT ATTENUATION BY VEGETATION AS A NATURAL SHORE PROTECTION

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Keywords: Wave attenuation, submerged vegetation, wave-current conditions, numerical modelling

Mots-clés: Atténuation des vagues, végétation submergée, conditions de courant des vagues, modélisation numérique

1 INTRODUCTION

Biotic components of coastal ecosystems are increasingly incorporated in coastal defence against erosion and floods. In contrast, conventional protective structures such as sea dykes, seawalls, revetments, groins and detached breakwaters are increasingly perceived as coastal armouring which may significantly affect cultural and other types of ecosystem services. Despite this pervasive perception, the application of these 'hard' solutions and their maintenance are expected to rather increase. In fact, they are also still perceived as the most efficient coastal protection against extreme events, particularly in urban areas and in many other cases where softer alternative solutions for managing coastal erosion and floods are unfeasible. Therefore, besides the diverse solutions to ecologically enhance these 'hard' structures, the introduction of vegetation as an integral constituent of coastal defence schemes has also long reached maturity for wider practical applications, and best practice recommendations are beginning to emerge [Feagin, 2008 ; Gedan et al., 2011]. In the latter case, a reliable prediction of wave damping by vegetation might be crucial for the safety of the hinterland. This is particularly the case where vegetation (e.g. seagrass, saltmarsh) is introduced in the foreshore to reduce the height/mass of conventional structures by damping the waves before reaching the latter. There are indeed diverse models and simplified formulae suitable for practical applications to predict with a relatively good engineering accuracy the damping efficacy of vegetation under either pure waves or pure current conditions. Most of these formulae are based on the assumption of stiff plants and/or the effect of plant flexibility is considered by introducing a reduction factor to account for flow resistance. Though combined waves and currents are ubiquitous in coastal areas, particularly in tidal coasts, it is rather surprising that only very few studies have been dedicated to the effect of currents on wave damping by vegetation, some even with contradictory results [Li and Yan, 2007 ; Paul et al., 2012 ; Hu et al., 2014 ; Losada et al., 2016]. Adding the effect of plant flexibility, the wave attenuation becomes even more complicated due to the complex wave-current-vegetation interactions (Figure 1).

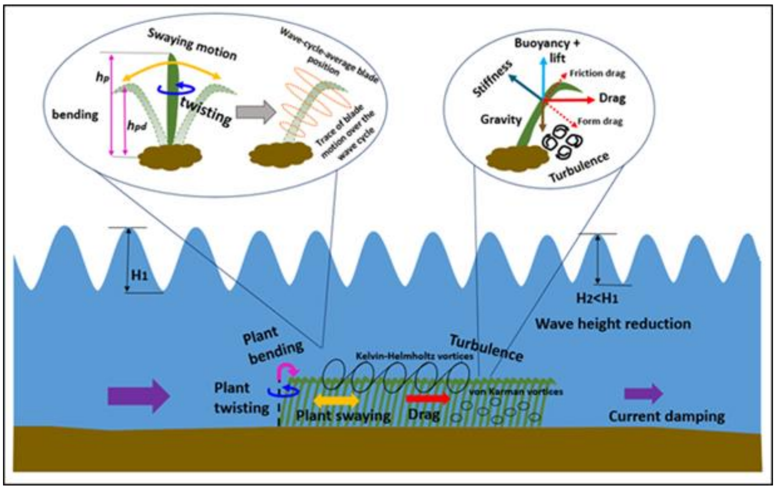

Figure 1: Processes involved in the interactions of flexible vegetation, waves and current. The plant meadow reduces wave height and mean flow velocity by absorbing energy from the flow through drag and turbulent dissipation. Flexible vegetation reconfigures under the influence of water flow depending on the vegetation attributes (h_p and h_{pd} show the plant height and deflected plant height, respectively)

These generally strong and highly complex *'triplet interactions'* might be the reason why no physically-based prediction formulae for engineering applications are yet available to predict wave attenuation by flexible vegetation under wave-current conditions.

With this background, the overarching goal of this study is therefore to improve the understanding of the physical processes and the relative importance of the hydraulic and vegetation parameters which affect wave attenuation by submerged flexible vegetation under wave-current conditions and, based on this improved understanding, to develop new prediction formulae which account for the most relevant influencing parameters. More specifically, it aims at:

(i) selecting the most appropriate CFD model to be used in this study and at improving/validating it to simulate wave attenuation by stiff vegetation under pure waves and wave-current conditions,
(ii) extending this CFD model for wave attenuation by flexible vegetation,
(iii) using this CFD model for a systematic parameter study to determine the relative importance of the hydraulic and vegetation parameters, and
(iv) developing new formulae for the prediction of wave attenuation by stiff and flexible vegetation under pure waves and wave-current conditions based on the analysis of the data and the insight into the underlying processes gained from the parameter study.

2 CFD MODEL FOR STIFF VEGETATION

A numerical wave flume using the CFD model in OpenFOAM® is set up, calibrated and validated for the study of wave attenuation by stiff vegetation under pure waves and wave-current conditions. The four main steps of this modelling process are depicted in Figure 2.

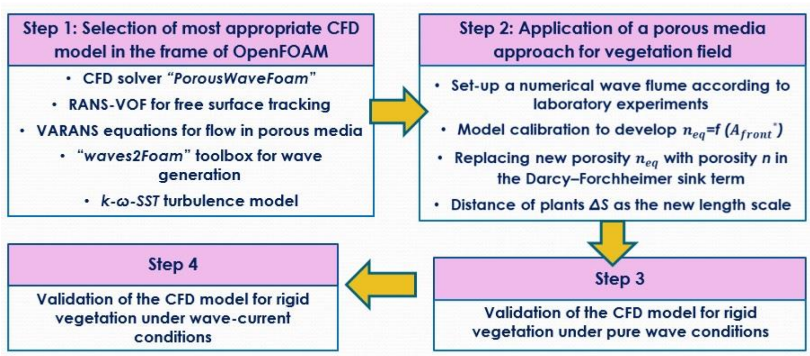

Figure 2: Processes involved in the development of the CFD model for wave attenuation based on a porous media approach for stiff vegetation

Step 1: Selection of the most appropriate CFD model for waves through vegetation

For the modelling of wave propagation through vegetation, the CFD solver *'PorousWaveFoam'* in the frame of OpenFOAM® [Jensen et al., 2014] is selected. This model solves the Volume-Averaged Reynolds-Averaged Navier–Stokes (VARANS) equations for the simulation of flow in porous media without representing the exact geometry of the pores forming the porous media using the Volume Of Fluid (VOF) method for free surface tracking. A description of the governing equations used for the selected CFD solver '*PorousWaveFoam*', including RANS-VOF for free surface tracking, VARANS for the flow in porous media, the *'waves2Foam'* toolbox for wave generation and the RANS type of the *k-ω-SST* model for turbulence can be seen in Hadadpour et al. (2019, 2021) and Hadadpour (2020).

Step 2: Application of a porous media approach for a vegetation field

For applying a porous media approach for a vegetation field, the 'hydraulic' properties of the vegetation meadow, including porosity *n* and characteristic length scale *D*, are required in the Darcy-Forchheimer sink term of the VARANS equations. Vegetation fields are naturally characterized by high porosities (often more than 0.97) and low solid fractions. Hence, a more practical parameterisation is carried out and an '*equivalent porosity* n_{eq}' is proposed to replace porosity *n* in the VARANS equations while the distance between the plants *ΔS* is defined as a new length scale for the new approach.

For this purpose, since the mesh quality affects the accuracy of the numerical simulation results, firstly a sensitivity analysis is performed to determine the "optimum" mesh size leading to a mesh independent solution, i.e. one for which accuracy is not altered when mesh refinement is increased [Hadadpour, 2020].

To obtain the proper porosity of vegetation n_{eq}, the CFD model is set up and calibrated according to laboratory tests of wave attenuation by submerged stiff vegetation from four different studies [Bouma et al., 2005 ; Paul et al., 2012 ; Ozeren et al., 2014 ; Hu et al., 2014]. The new equivalent porosity n_{eq} is developed as a function of dimensionless frontal area per bed area $A_{front}^* = N\, d\, h_p$, where *N* is plant density, *d* is plant width perpendicular to flow direction and h_p is plant height. It is a physically well-defined and measurable parameter of the vegetation field (see more details in Hadadpour et al. (2019) and Hadadpour (2020)):

$$n_{eq} = 1 - 0.22\left(A_{front}{}^{*}\right)^{0.51} \tag{1}$$

Step 3: Model validation under pure wave conditions

The validation is based on the wave damping factor γ (m^{-1}) of the hyperbolic decay law derived by Dalrymple et al. (1984) using linear wave theory for wave attenuation by stiff vegetation:

$$K_v = \frac{H_x}{H_i} = \frac{1}{1 + \gamma x} \tag{2}$$

H_x and H_i are the wave height at propagation distance in the vegetation meadow and the incident wave height at *x*=0, respectively. K_v is the damping coefficient and γ (m^{-1}) is a parameter depending on the vegetation and wave characteristics.

For the validation, two set of laboratory experiments [Bouma et al., 2010 ; Hu et al., 2014] have been used. A comparative analysis of damping factor γ obtained from the CFD model and from the laboratory tests using four statistical indicators (i.e. *Bias*, Root Mean Square Error *RMSE*, correlation coefficient *R* and *Willmott Index*) indicates a very good agreement between numerical and experimental results (Figure 3).

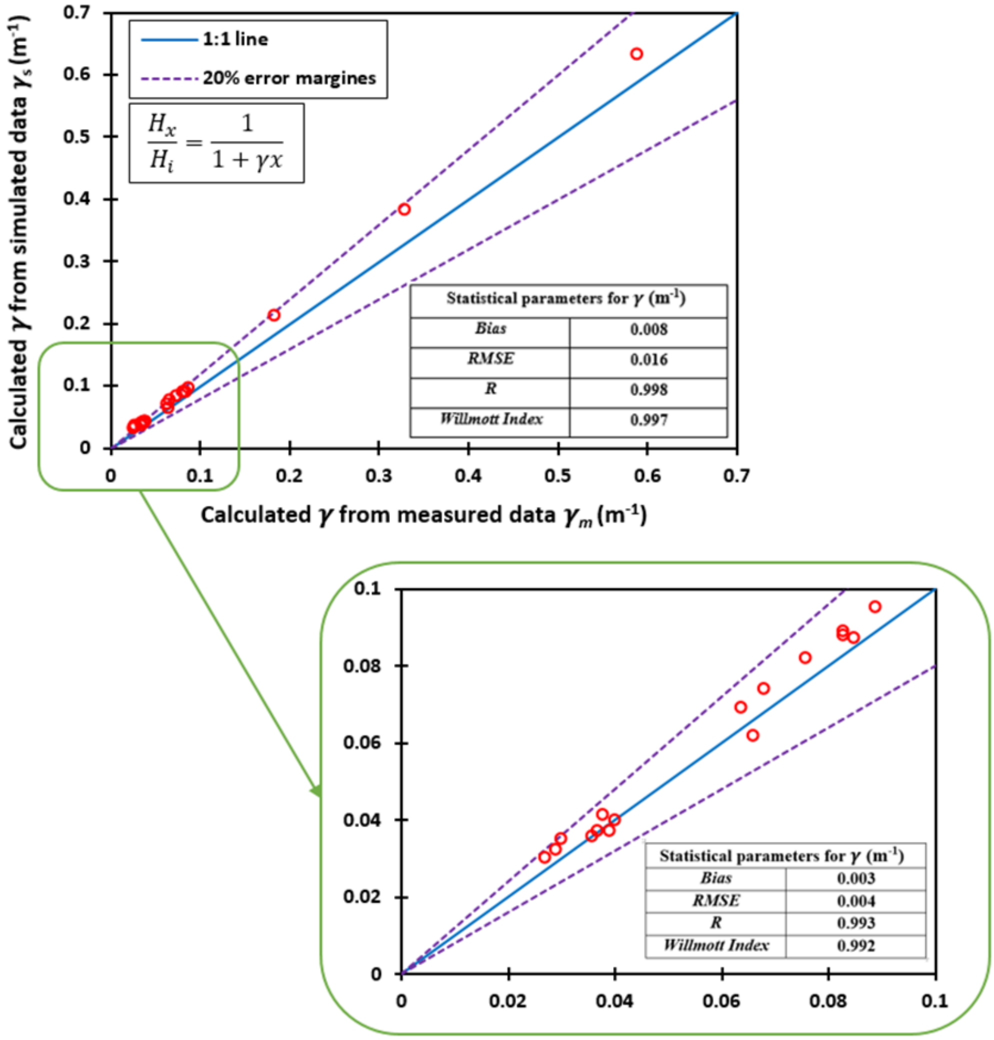

Figure 3: Scatter-plot of the calculated wave damping factor γ (m^{-1}) from the measured data γ_m [Bouma et al., 2010 ; Hu et al., 2014] and simulated data γ_s (present model) using Equation 2 for different wave and vegetation conditions

Step 4: Model validation under wave-current conditions

For model validation under wave-current conditions, the experiments of Hu et al. (2014) are used. The validation is based on the comparative analysis of the wave height reduction per unit distance *ΔH* (m/m) by stiff vegetation measured in the experiments and *ΔH* obtained from the CFD model for regular waves with an underlying current (0.05-0.3 m/s) in the same direction as the waves:

$$\Delta H = \frac{(H_{in} - H_{out})}{B_m} \quad (3)$$

H_{in} and H_{out} are the wave heights at the beginning and end of the vegetation meadow, respectively and B_m is the meadow length. Figure 4 and the embedded tables with the statistical indices show that a relatively good agreement is achieved between computed and measured *ΔH* values and the model performs relatively well for wave attenuation by stiff vegetation under different wave-current conditions.

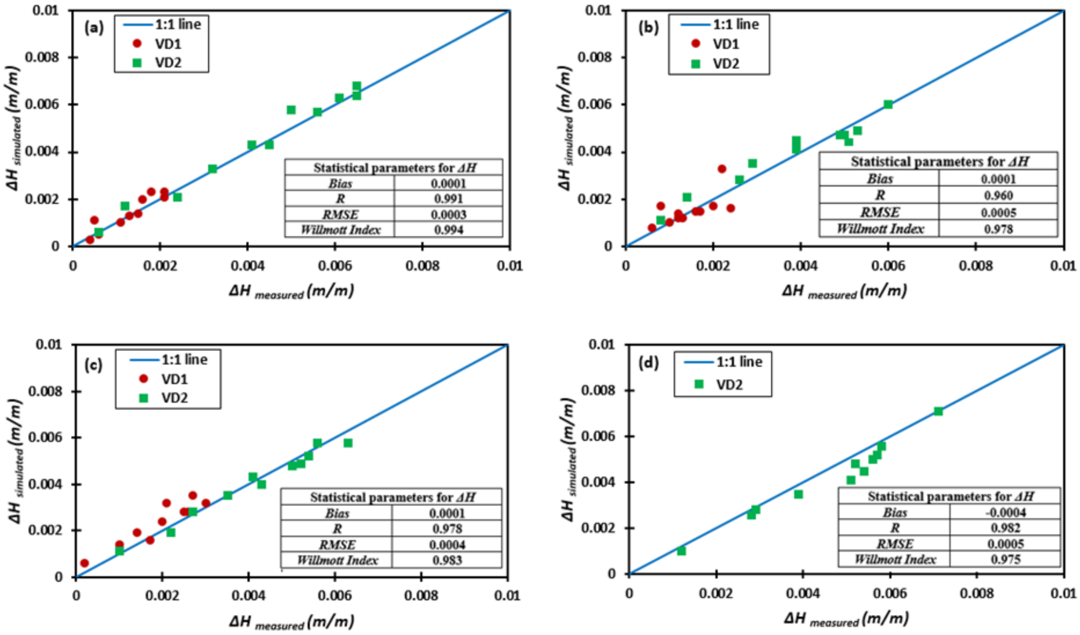

Figure 4: Scatter-plot of measured (Hu et al., 2014) and computed wave height reduction per unit distance inside stiff vegetation ΔH (m/m) for combined waves with: (a) 0.05 m/s, (b) 0.15 m/s, (c) 0.20 m/s and (d) 0.30 m/s current in the same direction. VD1 and VD2 indicate vegetation densities of 62 and 139 stems/m^2, respectively.

3 EXTENSION OF THE CFD MODEL FOR STIFF VEGETATION TO ACCOUNT FOR FLEXIBLE VEGETATION

The validated CFD model for stiff vegetation in the previous section is extended and validated for flexible vegetation by considering the bending of the plant stems and its effect on wave attenuation. The four main steps to achieve this goal are shown in Figure 5.

Step 1: Selection of the most appropriate approach to model the deflection of the plant stems as a compromise between accuracy/sophistication and computational efficiency

In this study, the impact of plant reconfiguration on wave attenuation is characterised in terms of drag force, which depends on the flow velocity and the projected area normal to the flow direction. Hence, the fluid load-deflection relationship can be applied to calculate the deflected height and the actual projected area affecting vegetation-induced flow resistance.

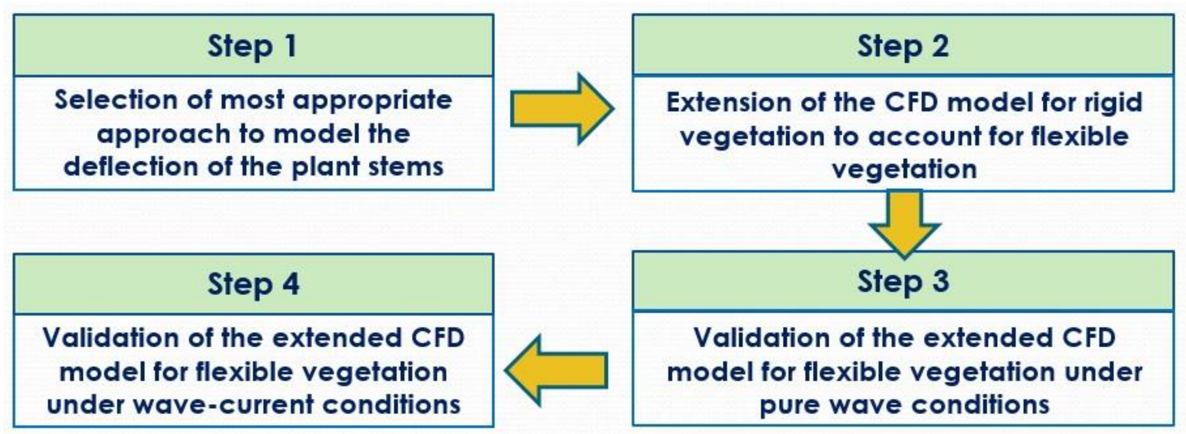

Figure 5: Processes involved in the extension of the CFD model for stiff vegetation to account for flexible vegetation

Therefore, the formulation for large deflections by Li and Xie (2011) is selected as the deflection of vegetation with high flexibility can be predicted accurately by a large deflection analysis based on the Euler-Bernoulli Law for the bending of a slender beam. Moreover, this approach is favoured because the extended CFD model is to be applied (i) for high hydrodynamic loads and large plant deflections, and (ii) for a very extensive parameter study (see Section 4 below); hence it is compromise between model accuracy/sophistication and computational efficiency. For the equations and more details see Hadadpour (2020).

Step 2: Extension of the CFD model for stiff vegetation to account for flexible vegetation

The deflected plant height defined as the actual height that affects the flow due to plant bending is considered as the most important parameter in the energy dissipation associated with the drag force on the vegetation. In this sense, the aforementioned formulation by Li and Xie (2011) is introduced in the extended model to calculate the reduction of the plant height resulting from its large deflection (Figure 6).

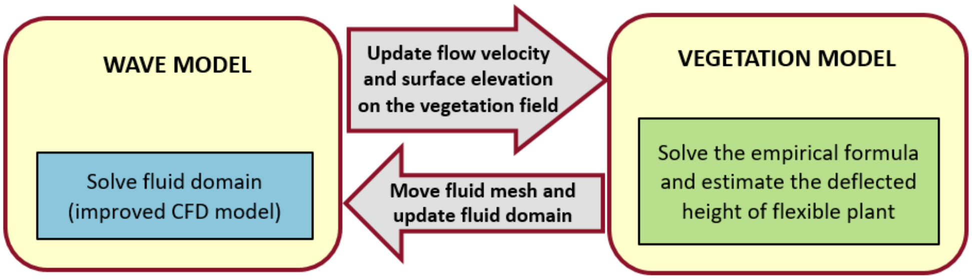

Figure 6: Solving procedure of the extended model system for wave attenuation by introducing flexible vegetation

In the present approach, the wave model, which considers the vegetated region as a porous media continuum using VARANS equations, is first solved. The vegetation deflection is calculated based on the drag force exerted on the plant stem located at the first row of the vegetation field, which experiences maximum velocity values and thus maximum deflection within the vegetation field. The fluid domain is then modified accordingly and fed back to the wave model to calculate new flow velocities and surface elevation. The two models are hence coupled through the vegetation-induced hydrodynamic forces. Moreover, the proposed coupling approach makes it possible to replace any of the coupled models with alternative solvers without having to adapt the remaining solver.

Step 3: Validation of the extended CFD model for flexible vegetation under pure wave conditions

The validation is based on the comparative analysis of the dimensionless parameter $K_D a_0 \lambda$ (m^{2}m^2) measured in the experiments of Luhar et al. (2017) and $K_D a_0 \lambda$ calculated from the CFD model:

$$\frac{a}{a_0} = \frac{1}{1 + K_D a_0 x} \tag{4}$$

where a_0 is the initial wave amplitude at *x*=0 and K_D is a parameter depending on the vegetation frontal area per unit volume, the drag coefficient, the wave number and the water depth (see Equation 7 in Luhar et al. (2017)).

The CFD model is shown to reproduce relatively well the wave height evolution over the vegetation field and the damping coefficient. As seen from Figure 7 and the four statistical indicators in the embedded table, it may be concluded that the wave height attenuation by flexible vegetation can be predicted by the extended model within the range of common engineering accuracy.

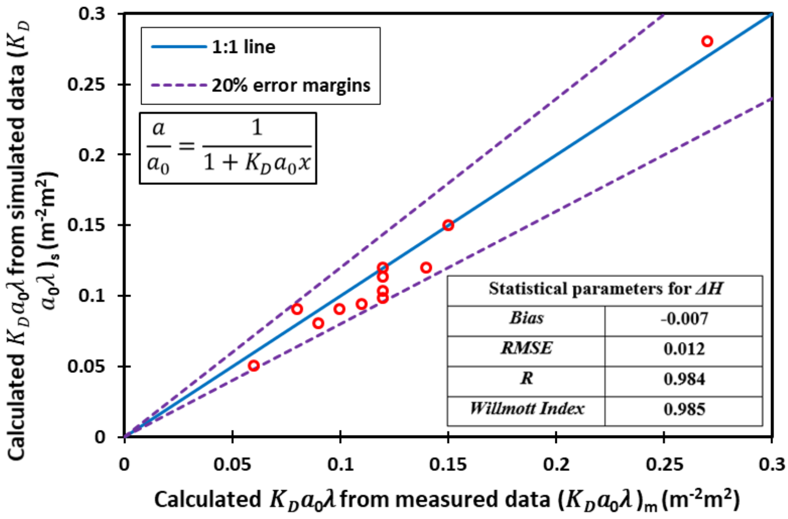

Figure 7: Scatter-plot of calculated $K_D a_0 \lambda$ (m^{-2}m^2) from measured data $(K_D a_0 \lambda)_m$ [Luhar et al., 2017] and simulated data $(K_D a_0 \lambda)_s$ (present model) using Equation 4 for different wave and vegetation conditions

Step 4: Validation of the extended CFD model for flexible vegetation under wave-current conditions

The model is then validated for wave attenuation under wave-current conditions based on linear assumption of wave attenuation (Equation 3) to make the results comparable with the experiments of Paul et al. (2012). According to Figure 8 and the statistical indicators in the embedded table, the model performs relatively well in simulating wave attenuation by flexible vegetation under wave-current conditions. However, the tentative validation is based on a limited number of data with moderate hydrodynamic conditions due to the lack of appropriate experimental data.

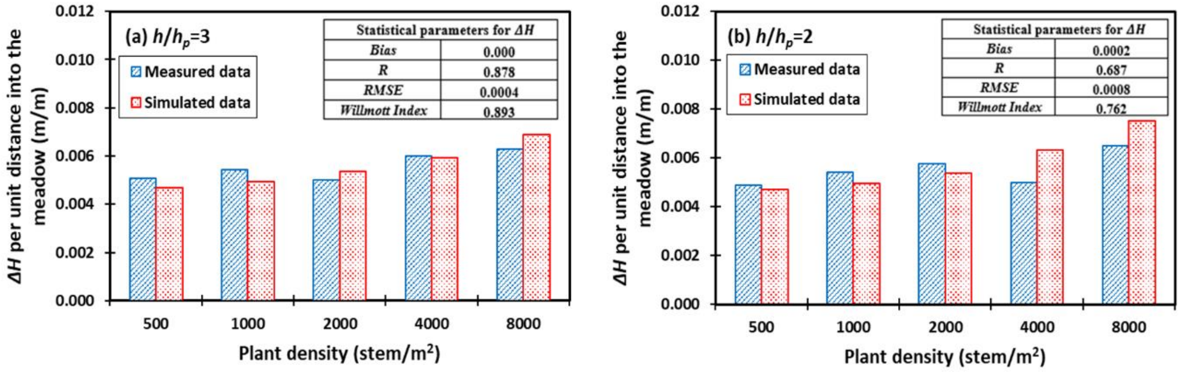

Figure 8: Measured [Paul et al., 2012] vs. simulated (present model) wave height reduction ΔH per unit distance in a flexible mimic meadow in the presence of underlying current for submergence ratio (a) h/h_p=3 (b) h/h_p=2

4 SYSTEMATIC PARAMETER STUDY: SELECTED RESULTS

Overall, previous studies have shown that wave attenuation by vegetation is highly dependent on both hydrodynamic conditions and vegetation properties including individual plant and meadow characteristics. Regarding these diverse dependencies and also the extensive variety of coastal plants, a high variability of wave attenuation by vegetation would be expected; hence more investigation is required to analyse the underlying processes and influencing parameters. Therefore, an extensive parameter study with around 300 numerical tests is performed and the results are analysed in order (i) to better understand the relative importance of the effects of the key parameters and underlying processes influencing wave attenuation by stiff and flexible vegetation under both pure wave and wave-current conditions, and (ii) to develop wave attenuation formulae as a function of the most relevant parameters for both types of vegetation under both types of flow conditions.

To this end, the effect of the following seven parameters on wave attenuation by stiff and flexible vegetation are considered: vegetation density N (stem/m^2), submergence ratio h/h_p, relative meadow length B_m/L_w, vegetation stiffness EI, incident wave height H and wave period T, and following current velocity U_c. In addition, the combined effects of these parameters on wave attenuation is also quantified. The range of variation of these parameters in the numerical tests is meaningfully based on the values considered in the most relevant studies. For more details including different test conditions, see Hadadpour (2020) and Hadadpour et al. (2021). Results of the extensive parameter study reveal that wave attenuation increases with increasing plant density N, plant height h_p, plant stiffness EI and meadow length B_m; however, the effect of plant height h_p dominates. Regarding the effect of wave parameters, wave attenuation increases with increasing incident wave height H_i, increasing wave period for B_m/L_w=1, and decreasing wave period for B_m=3.1 m. Overall, the effect of vegetation characteristics appears to be more influential than that of the wave parameters. The main results are briefly summarised in Table 1 supported by Figures 9-12.

Parameter	Effect on wave attenuation and relative importance
Vegetation characteristics	• *Plant height (h_p)*: Wave attenuation increases with increasing plant height h_p under a constant water depth, i.e. decreasing submergence ratio h/h_p, for both stiff and flexible vegetation (Figures 9, 10 and 11a) • *Plant density (N)*: wave attenuation increases with increasing plant density *N* for both stiff and flexible vegetation (Figures 9 and 11a) • *Plant stiffness (EI)*: Wave attenuation increases with increasing stiffness *EI* for the same wave forcing (Figures 10 and 11a) • *Length of vegetation field (B_m)*: Wave attenuation increases with increasing meadow length B_m under the same wave conditions for both stiff and flexible vegetation (Figure 9)
Wave parameters	• *Incident wave height (H_i)*: Wave attenuation increases with increasing incident wave height H_i for both stiff and flexible vegetation (Figure 10) • *Incident wave period (T)*: For both stiff and flexible vegetation, increasing the wave period *T* results in higher wave attenuation when the analysis is based on a constant relative meadow length B_m/L_w=1 (Figure 5-19 in Hadadpour (2020)). While, conversely, the wave attenuation decreases with increasing the wave period when the wave height reduction is considered over a constant meadow length B_m=3.1 m (Figure 5-20 in Hadadpour (2020))
Combined effects of the diverse parameters	• Plant height h_p and hence, submergence ratio h/h_p, appears to be more influential than plant density *N* on wave attenuation (Figure 11a) • Plant stiffness *EI* and density *N* can compensate each other depending on the submergence ratio h/h_p, i.e. flexible vegetation at higher densities might be able to induce the same wave height reduction as stiff vegetation at low densities (Figure 11a) • The impact of meadow length B_m on wave attenuation increases with increasing plant density *N* and decreasing submergence ratio h/h_p; however, the effect of submergence ratio dominates (Figure 9) • The impact of incident wave height H_i increases with decreasing plant density *N* and increasing submergence ratio h/h_p, i.e. decreasing plant height h_p under a constant water depth *h* (Figure 11b) • The effect of vegetation characteristics is likely more significant than that of the wave parameters (Figure 11b)
Following current	• The impact of a following current on wave attenuation can be seriously affected by submergence ratio h/h_p (Figure 5-23 in Hadadpour (2020)) • For almost all tested cases, a following current causes a decrease of the wave-attenuating capacity of vegetation. This decrease becomes more significant with increasing current velocity U_c (Figures 5-22 and 5-23 in Hadadpour (2020)) • For a very sparse stiff meadow (*N*=139 stem/m^2), a following current can increase the wave height attenuation depending on the incident wave and current velocity (Figure 5-31 in Hadadpour (2020)) • The current presence does affect wave propagation depending on the rate of change of velocity amplitude ($U_r=U_{cw}/U_{pw}$), which defines the change of velocity amplitude in the presence of currents U_{cw} compared to pure waves U_{pw}, which may differ as a function of the wave and vegetation characteristics (Figure 12) • Wave height attenuation decreases with increasing U_r, while it increases with decreasing U_r (Figure 12)

Table 1: Effects of individual and combined parameters on the wave-attenuating capacity of vegetation based on the results of the parameter study, including their relative importance

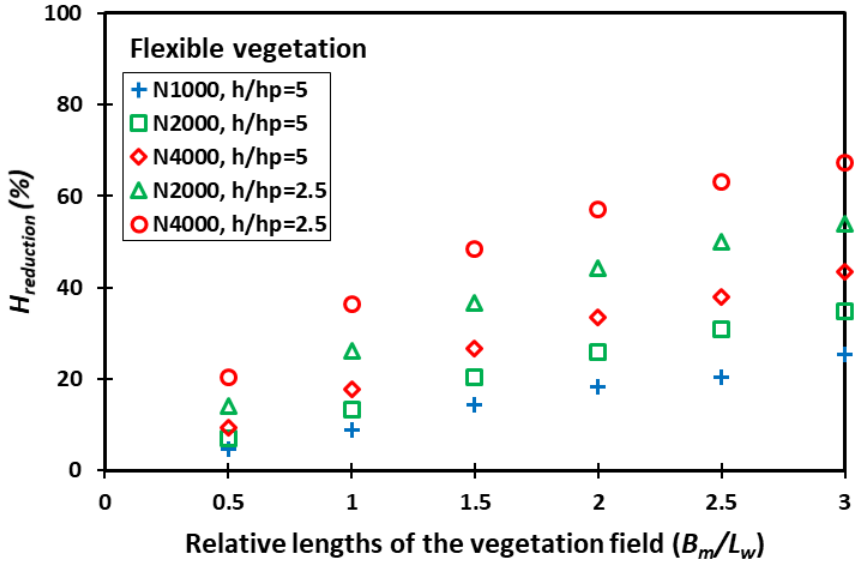

Figure 9: Effect of relative meadow length B_m/L_w on $H_{reduction}$ for flexible ($EI = 2.4 \times 10^{-6}$ N.m²) vegetation field with different plant densities N and submergence ratios h/h_p and a constant wavelength L_w=3.1 m for B_m/L_w=0.5 to 3. $H_{reduction}$ shows the wave height reduction at the end of vegetation field $H_{reduction}(\%) = \left(\frac{H_{front}-H_{behind}}{H_{front}}\right) \times 100$

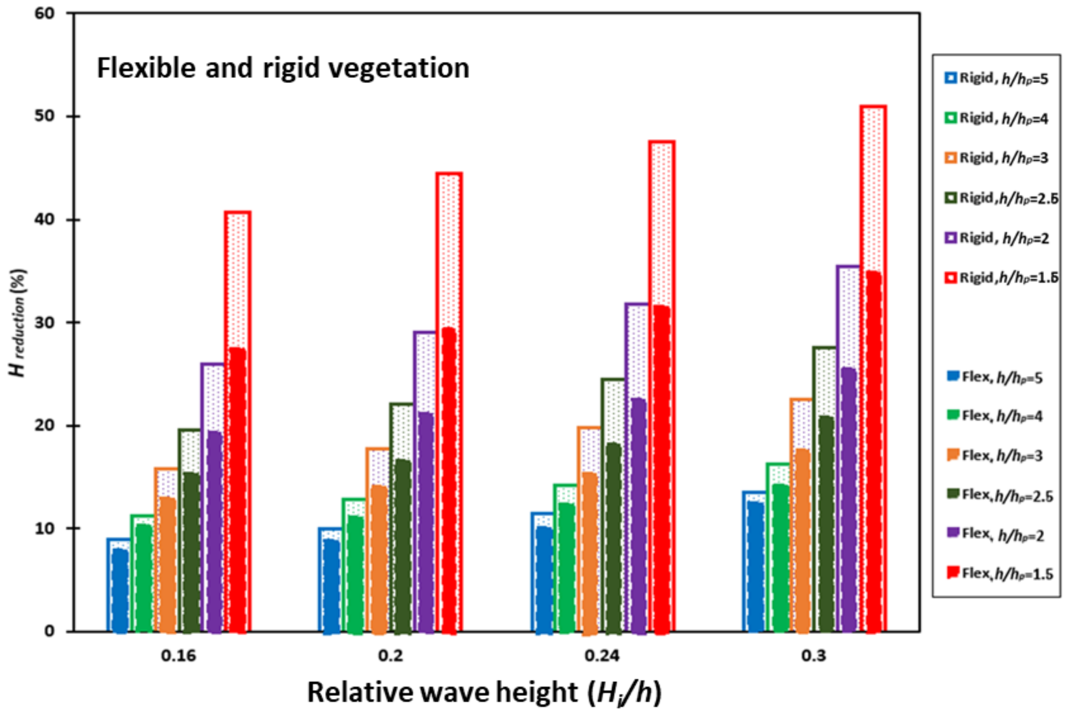

Figure 10: Effect of relative incident wave height H_i/h on $H_{reduction}$ for stiff (empty bars) and flexible ($EI = 2.4 \times 10^{-6}$ N.m²/ filled bars) vegetation field with length B_m=3.1 m, plant density N=1000 stems/m² and different submergence ratios h/h_p for H_i/h=0.16 to 0.3. $H_{reduction}$ shows the wave height reduction at the end of vegetation field $H_{reduction}(\%) = \left(\frac{H_{front}-H_{behind}}{H_{front}}\right) \times 100$

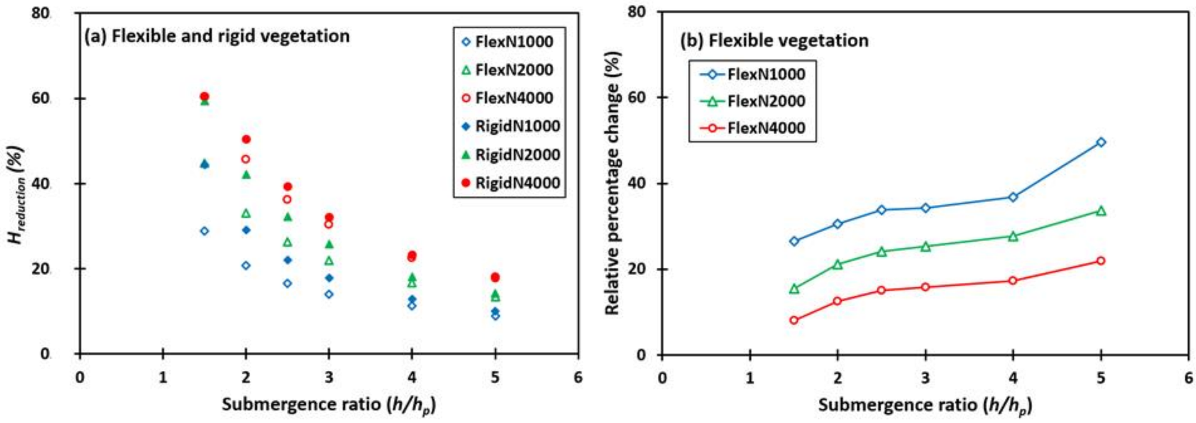

Figure 11: Combined effects of the diverse parameters including (a) effect of submergence ratio h/h$_p$ on the relationship between $H_{reduction}$ and plant density N for stiff and flexible ($EI = 2.4 \times 10^{-6}$ N.m^2) vegetation field, (b) effect of submergence ratio h/h$_p$ on the increasing effect of relative incident wave height Hi/h on $H_{reduction}$ for flexible vegetation field with length B$_m$=3.1 m with different plant density N. Wave attenuation $H_{reduction}$ shows the wave height reduction at the end of vegetation field $H_{reduction}(\%) = \left(\frac{H_{front}-H_{behind}}{H_{front}}\right) \times 100$. Relative percentage change shows the relative increase between wave height reduction $H_{reduction}$ for Hi/h=0.16 and Hi/h=0.3, i.e. $Relative\ percentage\ change\ (\%) = \left|\frac{(H_{reduction})_{Hi/h=0.3}-(H_{reduction})_{Hi/h=0.16}}{(H_{reduction})_{Hi/h=0.16}}\right| \times 100$

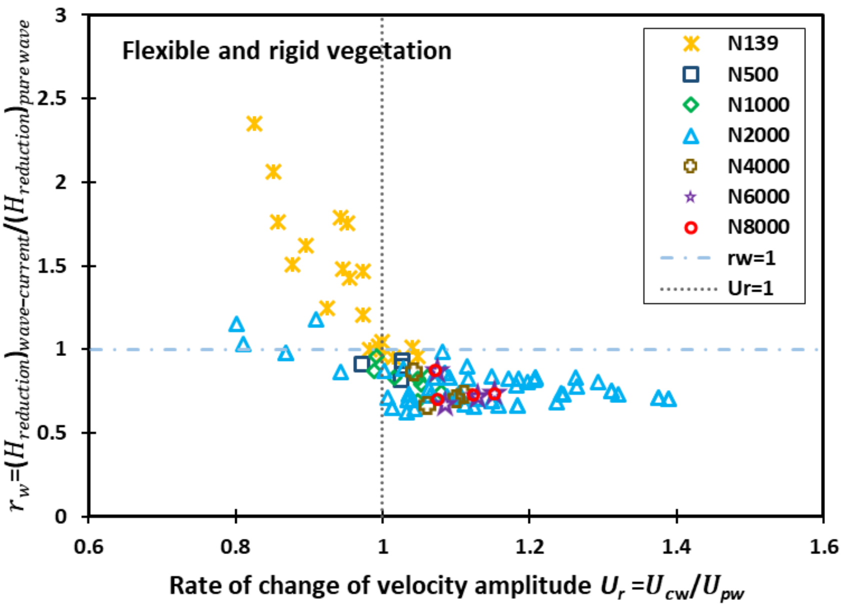

Figure 12: Relative wave height decay $r_w = \frac{(H_{reduction})_{wave-current}}{(H_{reduction})_{pure\ wave}}$ vs rate of velocity amplitude changes in current presence $U_r = \frac{U_{cw}}{U_{pw}}$, which defines the change of velocity amplitude in the presence of currents U_{cw} compared to pure wave conditions U_{pw}, for both stiff and flexible ($EI = 2.4 \times 10^{-6}$ N.m^2) vegetation field with different plant densities N and submergence ratios h/h$_p$ under various combinations of waves and currents

Hu et al. (2014) concluded that a following current may increase or decrease wave attenuation by vegetation depending on velocity ratio $\alpha = \frac{U_c}{U_w}$; U_c and U_w are the current velocity and the horizontal orbital velocity, respectively. They also attributed the inconsistency of previous studies to different ranges of this ratio in their investigations (e.g. α=1.5–3.5 in Li and Yan (2007) and α <0.5 in Paul et al. (2012)). In the present study, for almost all tested cases with a wide range of velocity ratio $\alpha = 0.3 - 8.0$, the presence of a following current causes a decrease of the wave-attenuating capacity of vegetation, which is in agreement with the previous findings in Paul et al. (2012) and Losada et al. (2016). However, the results might not be directly comparable to those by Hu et al. (2014) because the latter increased the generated incident wave height in the wave-current tests for different current velocities which may enhance wave attenuation. Moreover, wave and current velocities were linearly superposed without accounting for their nonlinear interaction. Furthermore, only the frontal area per canopy volume was considered for comparing their tests with others, but without considering plant density, which may strongly affect the flow patterns around the meadow as well as the flow penetration within the vegetation meadow.

In this study, therefore, a very sparse rigid meadow with plant density *N*=139 stems/m^2 is also tested to make it comparable to that of the VD2 tests in Hu et al. (2014), which shows that a following current can indeed increase wave attenuation over a sparse vegetation field. This is likely due to the non-linearity effect caused by wave deformation in non-linear wave-current interaction as well as the attenuation effect of vegetation.

In this respect, Figure 13 compares the horizontal velocity component U_x and the flow patterns for reference case (i.e. without vegetation) as well as a submerged vegetation meadow with plant densities *N*=100 and 1,000 stems/m^2 under combined wave-current conditions. The horizontal velocity U_x according the Stokes second order theory [Svendsen and Jonsson, 1976] is given as below:

$$U_x = U_c + \frac{H}{2}\frac{gk}{\omega_{w-c}}\frac{\cosh k(z+h)}{\cosh kh}\cos(kx - \omega_w t) + \frac{3}{16}\frac{H^2\omega_{w-c}k\cosh 2k(z+h)}{\sinh^4 kh}\cos 2(kx - \omega_w t) \qquad (5)$$

where U_c is the uniform current velocity, *H* is the wave height, *g* is acceleration due to gravity and h is the water depth. *z* and *t* represent the vertical coordinate and time, respectively. The quantity *x* is the distance along longitudinal direction. ω_{w-c} represents the frequency of the wave-current, $\omega_{w-c} = \omega_w - k.U_c$, ω_w and *k* are the wave angular frequency and the wave number.

As shown in Figure 13, the flow pattern can be significantly influenced by the presence of submerged vegetation, especially for a relatively dense vegetation meadow with *N*=1,000 stem/m^2 due to their capacity to induce larger current blocking, thus causing current to diverge vertically over the meadow instead of passing through it. For strong currents with velocity U_c=0.2 m/s, the difference of flow velocity above and below the vegetation meadow is extremely high.

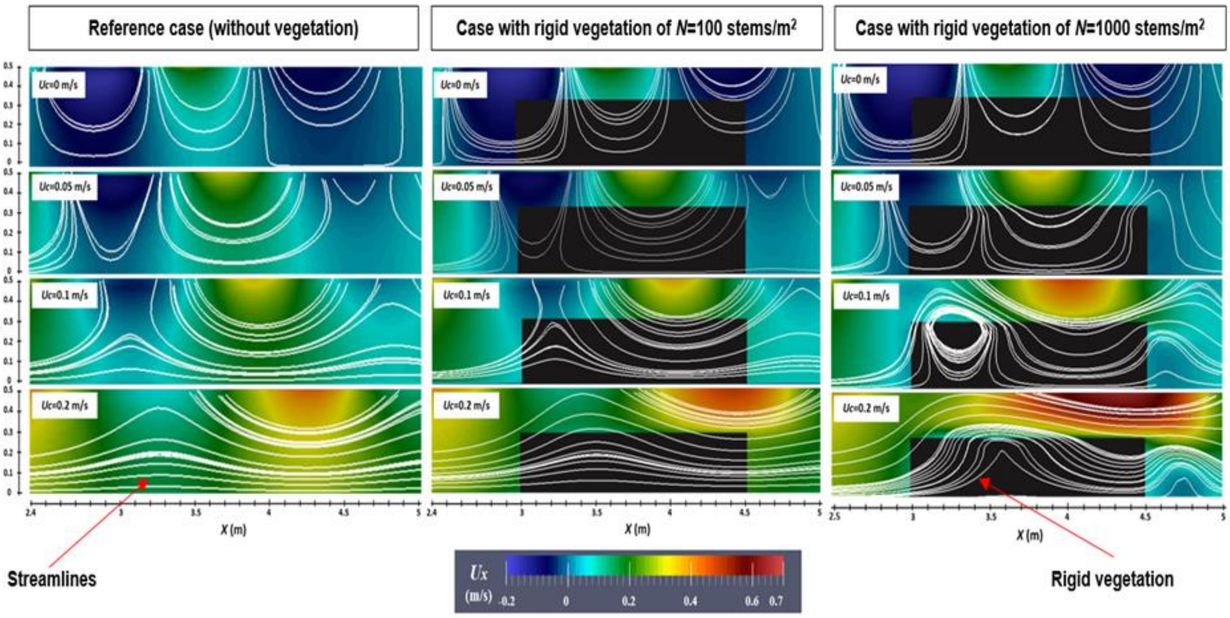

Figure 13: Effect of plant density N and current velocity U_c on the flow pattern in/near a rigid vegetation meadow for reference case (i.e. without vegetation) as well as a submerged mimic meadow with different plant densities N=100 and 1,000 stems/m^2 for wave-current conditions with wave H_i=0.08 m, T=1 s in 0.5 m water depth following the currents with different velocities U_c =0, 0.05, 0.1 and 0.2 m/s. The black area indicates the vegetation meadow B_m=1.5 m and h_p=0.3 m, and the white lines represent streamlines

In this sense, a shear layer can be generated at the water-vegetation interface due to the flow velocity difference above and below the vegetation meadow, where Kelvin-Helmholtz (KH) instability may develop [Ghisalberti and Nepf, 2002]. This instability may form coherent vortices within the mixing layer (in dense vegetation meadow with *N*=1000 stem/m^2), which dominate the vertical momentum transfer across the water-vegetation interface.

5 DEVELOPMENT OF A WAVE ATTENUATION FORMULAE FOR FLEXIBLE VEGETATION

Based on the data and insight obtained from the results of the parameter study in Section 4, a set of prediction formulae for wave attenuation by both stiff and flexible submerged vegetation under both pure wave (Phase 1) and wave-current conditions (Phase 2) is developed for the first time.

Phase 1: Wave attenuation formulae for flexible vegetation under pure wave conditions

The development is performed in four main steps summarised in Figure 14.

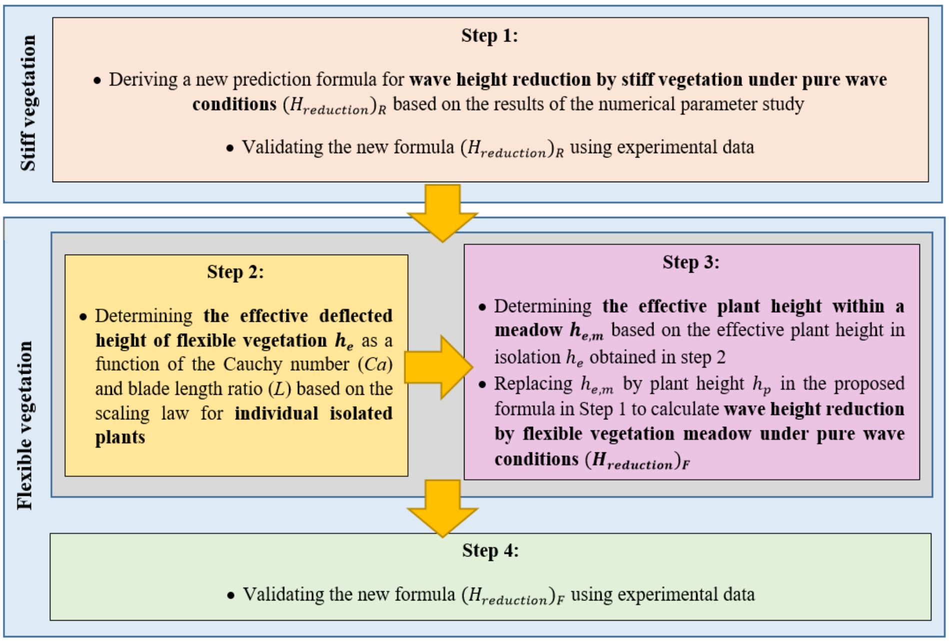

Figure 14: Steps of the procedure to derive a new prediction formula for wave attenuation by flexible vegetation under pure wave conditions

Formula for wave attenuation by stiff vegetation under pure wave conditions $(H_{reduction})_R$: The formula is derived based on multiple regression analysis as a function of five dimensionless parameters $(A_{front}{}^*, {}^{h_p}/_{h}, {}^{B_m}/_{L_w}, {}^{H_i}/_{h}, {}^{h}/_{L_w})$ determined from the parameter study. The relative importance of these independent variables are compared in the scatterplot matrix (Figure 15).

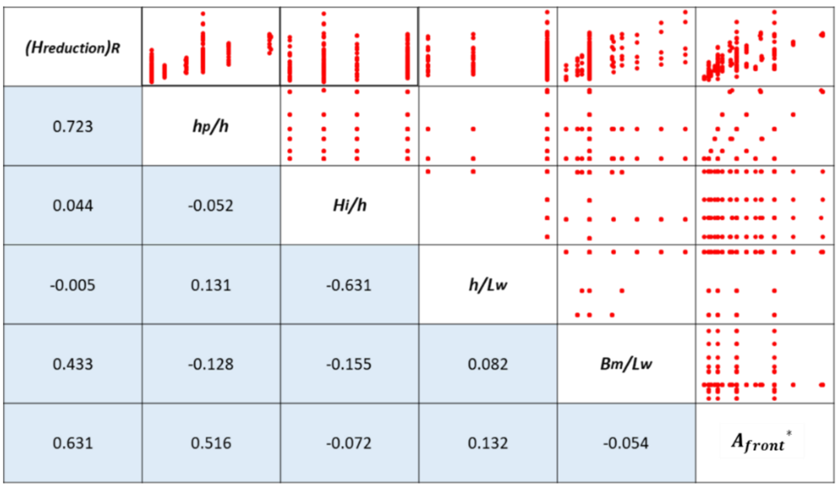

Figure 15: Scatterplot matrix (upper diagonal elements) and correlation matrix (lower diagonal elements) which show the relationships between wave attenuation by rigid vegetation under pure wave conditions and the effective parameters identified in the parameter study

The findings of the regression analysis, namely that the correlation of $(H_{reduction})_R$ is strongest with $\frac{h_p}{h}$ while it is negative and positive for the four other parameters $({}^{H_i}/_{h}, {}^{h}/_{L_w}, {}^{B_m}/_{L_w}, A_{front}{}^{*})$, are confirmed by the scatter matrix:

$$(H_{reduction})_R = 11.5\left(A_{front}{}^{*}\right) + 37.5\left(\frac{H_i}{h}\right) + 61\left(\frac{h_p}{h}\right)\left(\frac{B_m}{L_w}\right) - 70.3\left(\frac{h}{L_w}\right) \tag{6}$$

This formula is validated against laboratory experiments, showing that it performs relatively well in predicting wave attenuation by stiff vegetation (Figure 16).

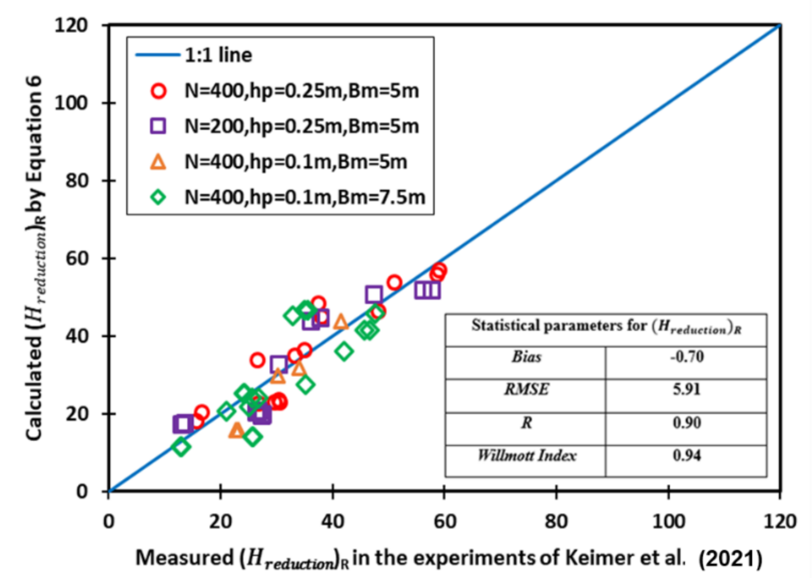

Figure 16: Comparison of the measured [Keimer et al., 2021] and calculated (Equation 6) wave height reduction by stiff vegetation $H_{reduction}$ under pure wave conditions, the blue line shows 1:1 line

Effective deflected height of a flexible plant in isolation h_e: h_e is calculated as a function of the Cauchy number Ca and blade length ratio L based on the scaling law for individual isolated plants using the formulation presented by Lei and Nepf (2019a):

$$\frac{h_e}{h_p} = (0.94 \pm 0.06)(Ca.L)^{-0.25\pm0.02}, \qquad 1 < (Ca.L) < 10000 \tag{7}$$

Effective height of a flexible plant within a meadow $h_{e,m}$: $h_{e,m}$ is calculated based on h_e and the difference between the effective plant height in isolation and in a meadow $h_{r,m}$, which is obtained as a function of plant density N and plant height h_p, as follows:

$$h_{e,m} = h_e + h_{r,m} = 0.94(Ca.L)^{-0.25} \times h_p + 0.64(A_{front}{}^{*})^{0.22}\left(\frac{h_p}{h}\right)^{0.94} \times h_p \tag{8}$$

The new formula for wave attenuation by flexible vegetation under pure wave conditions $(H_{reduction})_F$ is obtained by replacing plant height h_p in Equation 6 by effective height $h_{e,m}$ calculated from Equation 8.

$$(H_{reduction})_F = 11.5\left(N \times d \times h_{e,m}\right) + 37.5\left(\frac{H_i}{h}\right) + 61\left(\frac{h_{e,m}}{h}\right)\left(\frac{B_m}{L_w}\right) - 70.3\left(\frac{h}{L_w}\right) \tag{9}$$

Validation of a new wave attenuation formula for flexible vegetation $(H_{reduction})_F$: two set of small-scale and large-scale experiments are used for validation. As shown in Figure 17, the formula performs well in predicting small-scale experiments, while the data shows more scatter for large-scale experiments. This might be attributed to the fact that the CFD model, from which the numerical data used for the multiple regression analysis to develop the new formula are obtained, was calibrated and validated mainly using data from small-scale experiments.

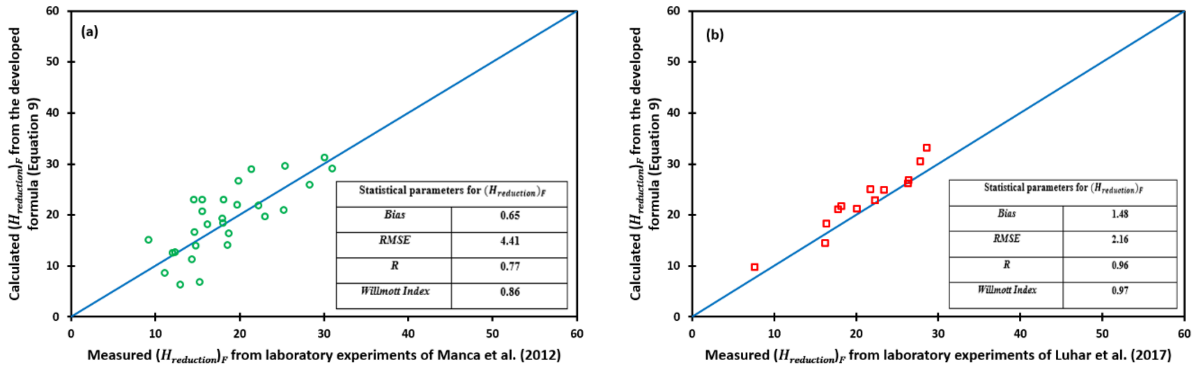

Figure 17: Comparison of the calculated (using Equation 9) and measured from (a) large-scale experiments by Manca et al. (2012), (b) small-scale experiments by Luhar et al. (2017) wave attenuation by flexible vegetation under pure wave conditions $(H_{reduction})_F$

Phase 2: Wave attenuation formulae for flexible vegetation under wave-current conditions

The development is performed in four main steps as summarised in Figure 18.

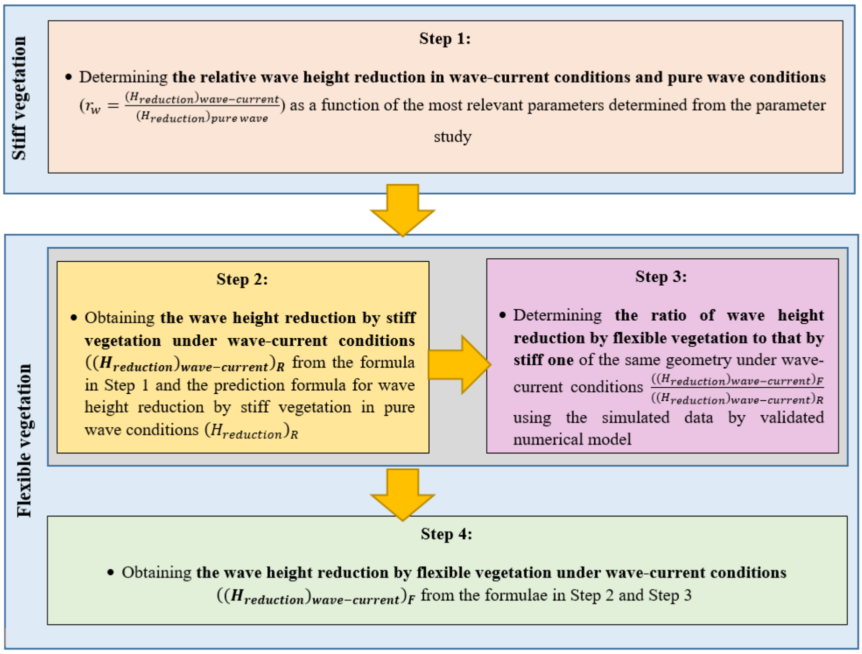

Figure 18: Steps of the procedure to derive a new prediction formula for wave attenuation by flexible vegetation under wave-current conditions

Formula for the relative wave attenuation by stiff vegetation in wave-current conditions and pure wave conditions $(r_w)_R = \frac{((H_{reduction})_{wave-current})_R}{(H_{reduction})_R}$: $(r_w)_R$ is obtained as a function of the most relevant parameters from the parameter study:

$$(r_w)_R = 0.024\left(A_{front}{}^*\right) + 0.083\left(\frac{h_p}{h}\right) - 8.47\left(\frac{h_p}{h}\right)\left(\frac{U_c}{U_w}\right)\left(\frac{H_i}{L_w}\right) + \frac{0.011}{A_{front}{}^*} + 0.81 \tag{10}$$

Formula for the wave attenuation by stiff vegetation under wave-current conditions $((H_{reduction})_{wave-current})_R$: it is calculated based on $(r_w)_R$ from Equation 10 and wave attenuation by stiff vegetation under pure wave conditions $(H_{reduction})_R$ according to Equation 6:

$$((H_{reduction})_{wave-current})_R = (r_w)_R \times (H_{reduction})_R \tag{11}$$

Formula for the ratio of wave attenuation by flexible vegetation $((H_{reduction})_{wave-current})_F$ to that induced by stiff vegetation $((H_{reduction})_{wave-current})_R$ under wave-current conditions: it is obtained as a function of dimensionless parameters $({}^{h_e}/_{h_p}, {}^{\Delta S}/_{d})$ based on the proposed porous media approach in the sense that the effect of flexible vegetation on energy dissipation is a reduction of the drag force due to plant reconfiguration, which results in a reduced frontal area of the vegetation:

$$\frac{((H_{reduction})_{wave-current})_F}{((H_{reduction})_{wave-current})_R} = 1.57\left(\frac{h_e}{h_p}\right)^{0.15}\left(\frac{\Delta S}{d}\right)^{-0.16} \tag{12}$$

The effective plant height h_e, defined as the height of a stiff plant that generates the same energy dissipation as the flexible plant of height h_p, is obtained from the equation proposed by Lei and Nepf (2019b) for combined wave-current conditions.

Formula for the wave attenuation by flexible vegetation under wave-current conditions $((H_{reduction})_{wave-current})_F$: it is calculated based on $\frac{((H_{reduction})_{wave-current})_F}{((H_{reduction})_{wave-current})_R}$ from Equation 12 and $((H_{reduction})_{wave-current})_R$ according to Equation 11:

$$((H_{reduction})_{wave-current})_F = \frac{((H_{reduction})_{wave-current})_F}{((H_{reduction})_{wave-current})_R} \times ((H_{reduction})_{wave-current})_R \tag{13}$$

To the best of the author's knowledge, there is no appropriate experimental data, which fulfil the requirements of the proposed model and formula to validate the new prediction formula. Hence, Figure 19 indicates the comparison of the calculated (Equation 13) with simulated (CFD model) wave attenuation by flexible vegetation under wave-current conditions for all tested cases in the parameter study. As shown in Figure 19 and the embedded table, it may be concluded that the wave attenuation by flexible vegetation under wave-current conditions can be predicted reasonably well (within ±15 %) by the proposed new formula (Equation 13).

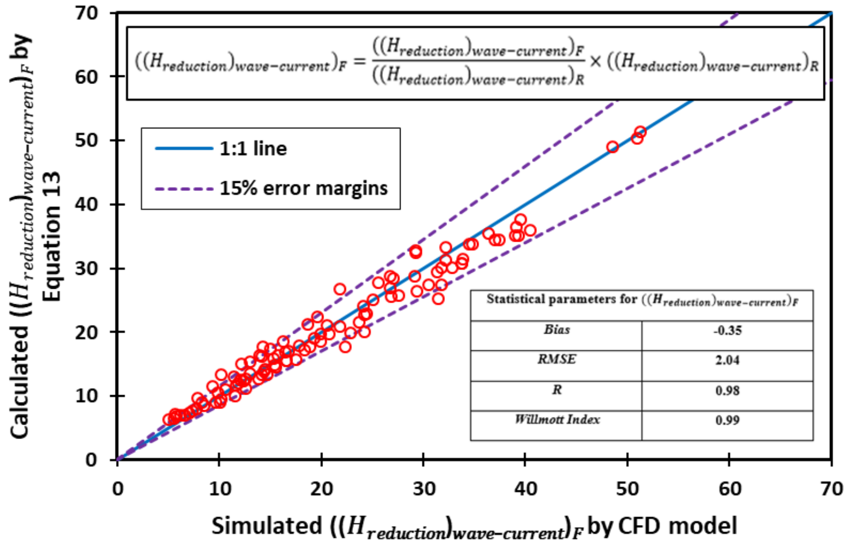

Figure 19: Scatter plot of calculated (Equation 13) and simulated (CFD model) wave attenuation over a flexible vegetation meadow under wave-current conditions for all tested cases in the parameter study (see Table 5-7 in Hadadpour (2020)). The solid line shows the perfect 1:1 line and dashed lines show the 15 % error margins.

6 POTENTIAL CONTRIBUTION OF THE PROPOSED APPROACHES TO ADVANCE THE SCIENTIFIC KNOWLEDGE AND TOOLS

Despite the gradual growth of available approaches on the development of nature-based solutions for coastal protection which are appropriate to adapt to climate changes, further modelling and engineering assessments of the efficiency of natural protection are still needed to better understand the potential of vegetation in shore protection. In this sense, field observations can provide valuable data under realistic conditions; however, they are difficult to perform; yet, they also have some limitations such as controlling hydrodynamic conditions and vegetation characteristics or replicating the tests. Besides, several laboratory studies have been carried out to study wave-vegetation interaction under controlled conditions. This particularly underlines the potential applications of the proposed modelling approach. The latter can indeed provide useful results with less costs and efforts than laboratory testing, and contribute to advance the scientific knowledge and tools which are required for a safer and more effective implementation of the 'Working with Nature philosophy' of PIANC.

In this scope, some benefits of the present model approach deserve to be highlighted: (i) despite the complicated vegetation structure and despite some simplifying assumptions, the use of A_{front}* in the relationship for the equivalent porosity represents an important step in the proposed porous media approach for vegetation, (ii) the model is easy to use and relatively fast, because the vegetation field is presented as a porous block in this model and there is no need to generate a complicated mesh to model the plants, (iii) the model calibration is based on only one parameter (i.e. equivalent porosity n_{eq}) which is determined as a function of A_{front}*, an easily measurable and commonly used vegetation parameter in the field, (iv) the model can easily be calibrated for further experimental studies and an improved relationship for the equivalent porosity could be proposed to reproduce many conditions which are not possible to test due to the limitation of the laboratory facilities, and also to save both money and time, (v) the proposed coupling approach for the extended model for flexible vegetation enables the users to replace any solver of the model system with an alternative solver without having to adapt the other solver; however, more complicated models may possibly need much more computational power and are, particularly in the case of monolithic fully coupled fluid-vegetation models, more difficult and much less flexible/adaptive in practical applications.

The results of the comprehensive parameter study add two important new insights to the existing knowledge. First, it is necessary to consider the mutual interaction of the individual effects of the parameters on wave attenuation; ignoring these effects may result in incorrect and even contradictory conclusions. Second, for investigating the effect of different parameters on wave attenuation, the assumed conditions and applied approaches need to be taken into account. In fact, previous studies have shown that contradicting conclusions may arise from differences in the approaches used for testing and/or analysing the results (see examples in Section 4).

7 CONCLUDING REMARKS AND IMPLICATIONS FOR PRACTICAL APPLICATIONS

Overall, the study has successfully attempted (i) to develop and systematically validate a CFD model system for wave attenuation by both stiff and flexible vegetation under pure wave and wave-current conditions, (ii) to systematically identify the most relevant hydraulic and vegetation parameters affecting wave attenuation based on an extensive parameter study by applying the developed/validated model system, and (iii) to develop a new set of formulae for the prediction of wave attenuation by both stiff and flexible vegetation under pure wave and wave-current conditions.

The limitations of the proposed model system and of the results are systematically identified and recommendations to overcome them are made accordingly [Hadadpour, 2020]: (i) as the formula and the CFD model for flexible submerged vegetation under wave-current conditions are not yet validated due to the lack of appropriate data, well-designed laboratory experiments would be required for a final validation, (ii) as the relationship of equivalent porosity $n_e = f(A_{front}*)$ is crucial for the proposed porous media approach and as it is simply obtained by calibration using limited laboratory data, further data and studies would be needed. (iii) as density and buoyancy are kept constant in vertical direction, the effect of a non-uniform vertical biomass distribution on wave attenuation still needs to be investigated, (iv) as fluid and vegetation in the proposed model are not fully coupled, it is still unclear how and to which extent *'monami'* could affect the accuracy of the results.

Based on the findings, the following aspects are recommended for practical implications:

- The proposed numerical approach is recommended as an appropriate tool to extend the range of conditions tested in the laboratory and assess the wave-attenuating capacity of vegetation for coastal protection purposes.
- Considering the effect of plant flexibility is crucial to avoid overestimation of wave energy dissipation in coastal protection projects, which may result in substantial damages.
- In most natural environments, particularly in tidal coasts, it is crucial to consider the effect of underlying currents on wave-attenuating capacity of vegetation and its potential as a natural solution for shore protection.
- A sufficient length of vegetation field is needed for each condition to maximise the effect of vegetation on wave height dissipation and hence the knowledge of this optimal meadow length is crucial for improving natural coastal defence planning.
- The proposed new prediction formulae for wave attenuation by stiff and flexible vegetation under both wave and wave-current conditions, which accounts for the most relevant parameters of vegetation and wave conditions, might represent an important step towards more reliable and well-validated formulae to help coastal communities to better assess coastal protection by different vegetation meadows.
- This is also particularly the case as these approaches can easily be adapted to also address the attenuation of ship-induced waves by both stiff and flexible vegetation which is commonly employed to mitigate bank erosion in waterways.

8 ACKNOWLEDGMENTS

I would like to gratefully acknowledge the continuous support and help of my doctoral advisor Professor Hocine Oumeraci. The financial support of this PhD study by the Deutscher Akademischer Austauschdienst (DAAD) is gratefully acknowledged. I also thank Dr. Mitul Luhar, Dr. Zhan Hu, Dr. Tomohiro Suzuki and Dr.-Ing. David Schürenkamp for providing the data for the model validation.

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SUMMARY

Recently, coastal protection has developed to one of the most crucial issues, resulting in a significant number of studies on the role of vegetation in shore protection. From the review of these studies, there is a general agreement that many complex physical processes are involved in the interaction of waves and currents with vegetation. Hence, there is still a need for further research of wave and/or current-vegetation interactions to improve the understanding of eco-hydraulic processes. This study[1] therefore aims to improve the understanding of the highly complex wave-current-vegetation interaction, including a more precise and systematic identification of the most influential parameters on the wave attenuation.

For this purpose, a new porous media-based approach for the modelling of wave attenuation by stiff vegetation is applied using the Computational Fluid Dynamic (CFD) model, which is extended for flexible vegetation by considering the dynamic response of flexible vegetation subject to water waves/currents. The CFD model is systematically validated against laboratory tests for wave attenuation by both stiff and flexible vegetation. In addition, the wave damping effect of vegetation is investigated also for combined wave-current, which has been considered only in very few studies due to the high complexity of wave-current-vegetation interactions. A systematic parameter study using the extended model is performed for various vegetation and hydrodynamic conditions in order to better understand the relative contribution of the parameters and physical processes to wave attenuation by vegetation and thus, to provide a substantially larger dataset for the development of a new set of prediction formula for wave attenuation by vegetation under pure wave and wave-current conditions.

The results show that the proposed porous media modelling approach and the obtained new formulae perform relatively well for predicting wave attenuation by both stiff and flexible vegetation. Moreover, an improved insight not only into the effects of vegetation and hydraulic parameters but also into the mutual interaction of the individual parameters on wave attenuation is provided, highlighting the necessity to also consider the effects of these parameters in combination.

RESUME

Récemment, la protection des côtes est devenue l'une des questions les plus cruciales, ce qui a donné lieu à un nombre important d'études sur le rôle de la végétation dans la protection des côtes. D'après l'examen de ces études, il est généralement admis que de nombreux processus physiques complexes sont impliqués dans l'interaction des vagues et des courants avec la végétation. Par conséquent, il est encore nécessaire de poursuivre les recherches sur les interactions entre les vagues et/ou les courants et la végétation afin d'améliorer la compréhension des processus éco-hydrauliques. Cette étude vise donc à améliorer la compréhension de l'interaction très complexe entre les vagues, les courants et la végétation, y compris une identification plus précise et systématique des paramètres les plus influents sur l'atténuation des vagues.

Dans ce but, une nouvelle approche basée sur les milieux poreux pour la modélisation de l'atténuation des vagues par la végétation rigide est appliquée en utilisant le modèle CFD (Computational Fluid Dynamic), qui est étendu à la végétation flexible en considérant la réponse dynamique de la végétation flexible soumise aux

[1] The presented study is conducted within the author's doctoral studies at the Leichtweiß-Institute from October 2015 to April 2020. This article summarizes the main findings of the author's doctoral dissertation (Hadadpour, 2020). The main outcomes of this dissertation are prepared for publication in journal papers (Hadadpour et al., 2019,2021; Hadadpour and Oumeraci, 2022).

vagues/courants. Le modèle CFD est systématiquement validé par rapport aux tests de laboratoire pour l'atténuation des vagues par la végétation rigide et flexible. En outre, l'effet d'amortissement des vagues par la végétation est également étudié pour les vagues et les courants combinés, ce qui n'a été pris en compte que dans très peu d'études en raison de la grande complexité des interactions vagues-courants-végétation. Une étude systématique des paramètres utilisant le modèle étendu est réalisée pour diverses conditions de végétation et hydrodynamiques afin de mieux comprendre la contribution relative des paramètres et des processus physiques à l'atténuation des vagues par la végétation et ainsi, fournir un ensemble de données beaucoup plus important pour le développement d'un nouvel ensemble de formules de prédiction pour l'atténuation des vagues par la végétation dans des conditions de vagues pures et de vagues-courant.

Les résultats montrent que l'approche de modélisation des milieux poreux proposée et les nouvelles formules obtenues fonctionnent relativement bien pour prédire l'atténuation des vagues par la végétation rigide et flexible. De plus, une meilleure compréhension non seulement des effets de la végétation et des paramètres hydrauliques mais aussi de l'interaction mutuelle des paramètres individuels sur l'atténuation des vagues est fournie, soulignant la nécessité de considérer également les effets de ces paramètres en combinaison.

ZUSAMMENFASSUNG

In letzter Zeit hat sich der Küstenschutz zu einem der wichtigsten Themen entwickelt, was zu einer beträchtlichen Anzahl von Studien über die Rolle der Vegetation beim Küstenschutz geführt hat. Aus der Auswertung dieser Studien geht allgemein hervor, dass viele komplexe physikalische Prozesse an der Interaktion von Wellen und Strömungen mit der Vegetation beteiligt sind. Daher besteht noch immer Bedarf an weiteren Untersuchungen der Wechselwirkungen zwischen Wellen und/oder Strömungen und Vegetation, um das Verständnis der ökohydraulischen Prozesse zu verbessern. Diese Studie zielt daher darauf ab, das Verständnis der hochkomplexen Wechselwirkung zwischen Welle, Strömung und Vegetation zu verbessern, einschließlich einer genaueren und systematischen Identifizierung der einflussreichsten Parameter auf die Wellendämpfung.

Zu diesem Zweck wird ein neuer, auf porösen Medien basierender Ansatz für die Modellierung der Wellendämpfung durch steife Vegetation unter Verwendung des Computational Fluid Dynamic (CFD)-Modells angewandt, das für flexible Vegetation erweitert wird, indem die dynamische Reaktion flexibler Vegetation auf Wasserwellen/ Strömungen berücksichtigt wird. Das CFD-Modell wird systematisch anhand von Labortests zur Wellendämpfung durch starre und flexible Vegetation validiert. Darüber hinaus wird die wellendämpfende Wirkung der Vegetation auch für die Kombination von Welle und Strömung untersucht, die aufgrund der hohen Komplexität der Wechselwirkungen zwischen Welle, Strömung und Vegetation bisher nur in sehr wenigen Studien berücksichtigt wurde. Eine systematische Parameterstudie unter Verwendung des erweiterten Modells wird für verschiedene Vegetations- und hydrodynamische Bedingungen durchgeführt, um den relativen Beitrag der Parameter und physikalischen Prozesse zur Wellendämpfung durch die Vegetation besser zu verstehen und somit einen wesentlich größeren Datensatz für die Entwicklung einer neuen Reihe von Vorhersageformeln für die Wellendämpfung durch die Vegetation unter reinen Wellen- und Wellenstrombedingungen bereitzustellen.

Die Ergebnisse zeigen, dass der vorgeschlagene Ansatz zur Modellierung poröser Medien und die erhaltenen neuen Formeln relativ gut für die Vorhersage der Wellendämpfung sowohl durch steife als auch durch flexible Vegetation geeignet sind. Darüber hinaus wird ein besserer Einblick nicht nur in die Auswirkungen der Vegetation und der hydraulischen Parameter, sondern auch in die gegenseitige Wechselwirkung der einzelnen Parameter auf die Wellendämpfung gewährt, was die Notwendigkeit unterstreicht, auch die Auswirkungen dieser Parameter in Kombination zu berücksichtigen.

RESUMEN

Recientemente, la protección de las costas se ha convertido en uno de los temas más cruciales, lo que ha dado lugar a un número importante de estudios sobre el papel de la vegetación en la protección de las costas. De la revisión de estos estudios se desprende que hay un acuerdo general en que en la interacción de las olas y las corrientes con la vegetación intervienen muchos procesos físicos complejos. Por lo tanto, sigue siendo necesario seguir investigando las interacciones entre las olas y/o las corrientes y la vegetación para mejorar la comprensión de los procesos ecohidráulicos. Por lo tanto, este estudio pretende mejorar la comprensión de la

complejísima interacción oleaje-corriente-vegetación, incluyendo una identificación más precisa y sistemática de los parámetros más influyentes en la atenuación del oleaje.

Para ello, se aplica un nuevo enfoque basado en medios porosos para la modelización de la atenuación del oleaje por parte de la vegetación rígida utilizando el modelo de Dinámica de Fluidos Computacional (CFD), que se amplía para la vegetación flexible considerando la respuesta dinámica de la vegetación flexible sometida a las olas/corrientes de agua. El modelo CFD se valida sistemáticamente frente a las pruebas de laboratorio para la atenuación de las olas por parte de la vegetación rígida y flexible. Además, el efecto de amortiguación del oleaje por parte de la vegetación se investiga también para la combinación oleaje-corriente, que sólo se ha considerado en muy pocos estudios debido a la gran complejidad de las interacciones oleaje-corriente-vegetación. Se realiza un estudio sistemático de parámetros utilizando el modelo ampliado para diversas condiciones de vegetación e hidrodinámicas con el fin de comprender mejor la contribución relativa de los parámetros y los procesos físicos a la atenuación del oleaje por la vegetación y, por tanto, proporcionar un conjunto de datos sustancialmente mayor para el desarrollo de un nuevo conjunto de fórmulas de predicción de la atenuación del oleaje por la vegetación en condiciones de oleaje puro y de corriente de oleaje.

Los resultados muestran que el enfoque de modelización de medios porosos propuesto y las nuevas fórmulas obtenidas funcionan relativamente bien para predecir la atenuación del oleaje por la vegetación, tanto rígida como flexible. Además, se proporciona una visión mejorada no sólo de los efectos de la vegetación y los parámetros hidráulicos, sino también de la interacción mutua de los parámetros individuales en la atenuación de las olas, destacando la necesidad de considerar también los efectos de estos parámetros en combinación.