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Implementation of Flexible Vegetation into CSHORE for Modeling Wave Attenuation

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Bradley D. Johnson

February 2022



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Implementation of Flexible Vegetation into CSHORE for Modeling Wave Attenuation

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Final report

Approved for public release; distribution is unlimited.

Prepared for USACE Flood and Coastal Systems Program
US Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
Vicksburg, MS 39180-6199

Under Funding Account Code 39JK18, AMSCO Code 060000

Abstract

This technical report presents the new numerical modeling capabilities for simulating wave attenuation and mean water level changes through flexible vegetation such as smooth cordgrass in coastal and marine wetlands. These capabilities were implemented into the Cross-SHORE (CSHORE) numerical model. The biomechanical properties of vegetation such as dimensions, flexibility, and bending strength are parameterized in terms of the scaling law. Correspondingly, a new formulation of the vegetation drag coefficient, C_D , is developed using field data from a salt marsh in Terrebonne Bay, LA, by considering spatially varying effective stem and blade heights of species. This report also presents a general procedure for using the model to simulate hydrodynamic variables (i.e., waves, currents, mean water levels) at vegetated coasts, which are used to quantify the effects of wave attenuation and reduction of surge and runup due to vegetation. Preliminary model validation was conducted by simulating a set of laboratory experiments on synthetic vegetation, which mimicked the flexibility of *Spartina alterniflora*. The validation results indicate that the newly developed vegetation capabilities enable CSHORE to predict changes of wave heights and water levels through marshes by considering species-specific biomechanical features. The model is also applicable to assess vegetation effectiveness against waves and surges.

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Preface

This study was conducted for the US Army Corps of Engineers, Flood and Coastal Systems Program, US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), under Funding Account Code 39JK18, AMSCO Code 060000.

The work was performed by the Coastal Processes Branch of the Flood and Storm Protection Division, ERDC-CHL. The general administrative supervision was provided by Ms. Ashley E. Frey, chief, Coastal Processes Branch, and Dr. Cary A. Talbot, chief, Flood and Storm Protection Division. At the time the study was completed, Dr. Julie Dean Rosati was the technical director for Flood and Risk Management; the deputy director of ERDC-CHL was Mr. Jeffrey R. Eckstein; and the director was Dr. Ty V. Wamsley.

At the time of publication of this report, Mr. Keith Flowers was deputy director of CHL, and the director was Dr. Ty V. Wamsley.

Sincere appreciation is expressed to Ms. Margaret B. Owensby and Ms. Sally (Catie) Dillon for their valuable review comments.

The commander of ERDC was COL Teresa A. Schlosser, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Vegetation on coasts and in marine wetlands attenuates wave energy, slows water velocity, reduces wave runup, and stabilizes sediments, thereby providing coastal storm protection (e.g., Leonard and Luther 1995; Nepf 1999; Bridges et al. 2015; Smith et al. 2016). Lower-energy wave attenuation effects of vegetation have been recognized for years based on laboratory and field observations, analytical approaches, and numerical modeling (e.g., Dalrymple et al. 1984; Kobayashi et al. 1993; Baron-Hyppolite et al. 2019). During high-energy events such as tropical storms and cold fronts, high waves and strong currents on high water levels can erode sediments and shorelines and lead to a faster marsh deterioration (e.g., Leonardi et al. 2018; Bondoni et al. 2019). The repeated bending of vegetation due to wave action may lead to broken stems and damaged marshes, dependent on species-specific flexibility (e.g., Rupprecht et al. 2017). However, most existing numerical models for wave attenuation (e.g., SWAN [2020]; XBEACH [2020]) employ simplified empirical vegetation models that were developed for rigid vegetation based on linear wave theory. Therefore, those models are inadequate to simulate hydrodynamic and morphodynamic responses of salt marshes to waves and surges due to varying biomechanical features.

To quantify storm conditions that make vegetation ineffective or permanently damaged, it is imperative to determine how vegetation biogeomechanical features (heights, drag resistance, flexibility, rigidity, bending, and breakage) change with conditions of waves and water levels (surges). The thresholds dependent on wave forcing and those properties of vegetation are key parameters to assess resilience of vegetated coasts against flood risks within dynamic environmental conditions. Therefore, to assess vegetation effects on flood risk reduction and erosion protection, a systematic evaluation methodology or procedure to predict varying capacity of flexible vegetation (e.g., salt marshes) with time and location is needed.

1.2 Objective

The objective of this study is to develop a numerical model and a general simulation procedure to compute wave attenuation and mean water level (MWL) changes through vegetated coasts and marshes by considering

biomechanical features of marshes such as density, sizes, and flexibility. The numerical model for assessment of vegetation effect was developed based on an existing one-dimensional (1-D) coastal profile evolution model. The procedure aims to guide users to using the model for calculation of wave attenuation and drag resistance due to varying flexibility of different species (cordgrasses) on dynamic wave conditions. Thus, the numerical model results can be utilized for evaluating performance of different types of vegetation for flood protection in vegetated coasts and wetlands.

1.3 Approach

For the purpose, the Cross-SHORE Numerical Model (CSHORE) (Johnson et al. 2012), a 1-D cross-shore coastal processes model, was selected as a base model to further develop specific capabilities for simulating wave attenuation, currents, and MWLs (including setup and runup) in vegetated coasts and marine wetlands. Through implementation of those vegetation capabilities into CSHORE, an extension version of this model, named the CSHORE-Vegetation model, has been developed.

For simulation of wave attenuation, the CSHORE-Vegetation model provides two formulations to calculate the energy dissipation due to vegetation. The first formulation is the frequency-independent formulation based on the Rayleigh distribution of random waves proposed by Mendez and Losada (2004). The other is a frequency-dependent energy dissipation formulation developed by Chen and Zhao (2012) based on the measured or a Joint North Sea Wave Project (JONSWAP) spectrum (Hasselmann et al. 1980). The model capabilities for rigid vegetation have been successfully validated by comparing cross-shore profiles of wave heights and MWLs with laboratory experiments (Chen et al. 2017, 2019; Zhu et al. 2019; Ding et al. 2019a,b) and field cases (Chen et al. 2019).

To simulate the hydrodynamic effects of vegetation on waves, a phase-averaged and depth-integrated drag force was added into the momentum equation to model vegetation resistance against propagation of waves and mean currents (Chen et al. 2017, 2019; Zhu et al. 2019). The drag force consists of a Morison-type drag force due to pure wave action and a force against mean currents such as undertow. To simulate the effect of nonlinear wave dynamics on vegetation resistance (Dean and Bender 2006), a novel drag forcing formulation based on nonlinear wave shape models (using the finite-amplitude wave theory to produce skewed and

non-sinusoidal waves) was developed and verified for both submerged and emergent vegetation (Zhu et al. 2019; Zhu and Chen 2019). Meanwhile, Zhu and Chen (2019) have developed a method to use a consistent drag coefficient for calculating wave energy dissipation and drag resistance by using stream-function wave theory.

For modeling aquatic vegetation resistance against waves and currents, the scaling law (Lei and Nepf 2019) is used to estimate the effective vegetation heights in stem and blades by considering vegetation bending and flexibility against wave actions. To provide a general formulation for calculating wave energy dissipation and vegetal drag force due to different types of vegetation, a unified C_D formulation was developed based on field data of vegetation and wave data, obtained at Terrebonne Bay, LA. Validation of the CSHORE-Vegetation model with the unified drag coefficient formulation was conducted by simulating a set of laboratory experiments on flexible/synthetic vegetation (Anderson and Smith 2014), which mimicked the flexibility of *Spartina alterniflora*.

1.4 Scope

This technical report highlights the recent development of simulation capabilities with regards to wave attenuation caused by flexible vegetation in CSHORE-Vegetation. The following sections give (1) a brief description of the mathematical equations of CSHORE-Vegetation, (2) calculations of biomechanical properties of flexible vegetation in terms of the scaling law, (3) determination of the drag coefficient for calculating wave energy loss and drag forcing of flexible vegetation, (4) a procedure for using CSHORE-Vegetation to simulate wave attenuation by considering biomechanical features of plants, (5) development of a unified drag coefficient formulation using field data, (6) model validation using results from the simulation of wave attenuation in a US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), experimental flume, and finally, (7) conclusions based on this work.

2 Mathematical Formulations for Modeling Wave Attenuation due to Vegetation by CSHORE-Vegetation

This chapter presents a brief description of mathematical formulations for implementing vegetation simulation capabilities into the CSHORE model (Johnson et al. 2012). The implementation enables this model, CSHORE-Vegetation, to simulate wave attenuation and changes of mean water elevations due to vegetation resistance against waves and currents.

The original CSHORE model simulates phase-averaged wave processes, mean currents, sediment transport, and beach profile morphological changes, under the assumption of the so-called alongshore uniformity which is characterized by alongshore uniform bathymetry (i.e., with regular shore-parallel contours) and currents. For phase-averaged hydrodynamics, CSHORE solves a 1-D cross-shore steady wave energy balance equation and a steady cross-shore momentum equation. As the capability of modeling sediment transport and morphological change is beyond the scope of this study, only the mathematical formulations for conservation of wave energy and momentum are briefly described below.

The 1-D steady wave energy (E) balance equation of CSHORE-Vegetation includes energy damping due to breaking, bottom friction, and newly implemented vegetal energy loss:

$$\frac{\partial}{\partial x} \left[\frac{E}{\sigma} \left(C_g + \frac{Q_x}{h} \right) \right] = - \frac{D_B + D_f + D_v}{\sigma} \quad (1)$$

where x = the cross-shore coordinate, σ = angular frequency, C_g = group velocity, h = total water depth (from bottom to water surface), Q_x = cross-shore volume flux, D_B = energy loss due to wave breaking, D_f = energy loss due to bottom friction, D_v = energy dissipation due to vegetation resistance. CSHORE also includes the roller effect of breaking. The detailed definitions and formulations of D_B and D_f can be found in Johnson et al. (2012).

The CSHORE-Vegetation model provides two options for calculating the energy dissipation due to vegetation. The first is the formulation of Mendez and Losada (2004), in which the irregular waves are based on the

Rayleigh distribution, and the energy attenuation is independent of frequency:

$$D_v = \sigma Q_v = \frac{1}{2\sqrt{\pi}} \rho C_D b_v N_v \left(\frac{kg}{2\sigma} \right)^3 \frac{\sinh^3(kh_v) + 3\sinh(kh_v)}{3k \cosh^3(kh)} H_{rms}^3 \quad (2)$$

where ρ = water density (kg/m³)*, C_D = non-dimensional vegetal drag coefficient for random waves, b_v = the plant area per unit height of each vegetation stand normal to horizontal velocity (m), N_v = number of vegetation stands per unit horizontal area (m⁻²), k = wave number, g = the gravitational acceleration (m/s²), h_v = vegetation height (m), H_{rms} = root-mean-square wave height (m). Another D_v formulation for frequency-distributed wave attenuation has been developed by Chen and Zhao (2012), which uses the measured or a JONSWAP spectrum for irregular waves.

The 1-D momentum equation of CSHORE-Vegetation for calculating the steady mean water surface elevation (MWSE) profile in the cross-shore direction is modified by Zhu et al. (2019) as follows:

$$\rho gh \frac{\partial \eta}{\partial x} = - \frac{\partial}{\partial x} \left[S_{xx} + \rho \frac{Q_x^2}{h} \right] + \tau_{sx} - \tau_{bx} + F_v + F_{v,m} \quad (3)$$

where η is the MWSE above the still water level (SWL), S_{xx} = cross-shore radiation stress (roller effect included), τ_{sx} = surface shear stress due to wind, τ_{bx} = averaged bottom shear stress, $F_{v,m}$ = the drag force of vegetation against the mean current (e.g. undertow, tidal currents), and F_v is the Morison-type drag force on water column by vegetation stems:

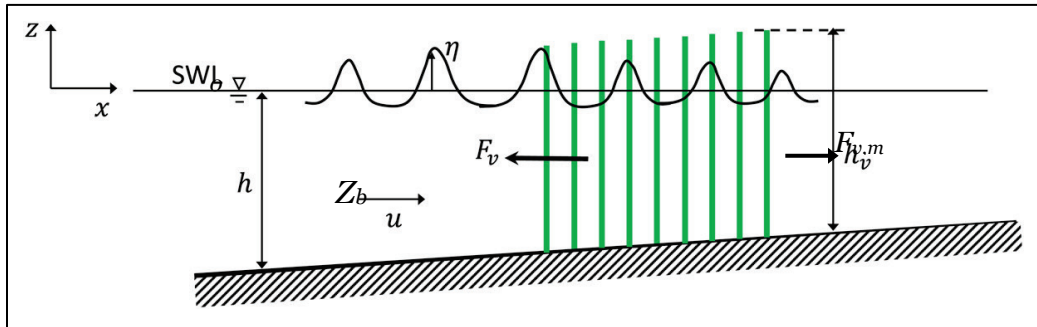
$$F_v = \frac{1}{T} \int_t^{t+T} \int_{Z_b}^{\min(-h+h_v, \eta)} \frac{1}{2} \rho C_D b_v N_v |u| u dz dt \quad (4)$$

where t = time, T = wave period, Z_b = bed elevation relative to the SWL, and $u = u(z,t)$, the horizontal particle velocity of wave. The forces acting on the water column on a sloping beach with vegetation are illustrated in

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Figure 1. Note that the mean (phase- and depth-averaged) velocity is calculated by the total volume flux, consisting of the cross-shore volume flux Q_x , the roller flux, and the flux caused by linear wave propagation (Johnson et al. 2012, Equation 42).

Figure 1. Sketch of wave propagation through vegetation and variables employed in the model



Note that F_v in Equation (4), if integrated from bottom to SWL, becomes zero if using the symmetrical horizontal particle velocities u from linear wave theory; this is not realistic for waves in shallow water and may miscalculate the vegetal drag forcing (Dean and Bender 2006). For CSHORE-vegetation, Zhu and Chen (2019) developed a semi-analytical formulation to calculate the drag force caused by random waves acting on submerged or emergent vegetation using the stream-function wave theory:

$$F_v = \frac{1}{16\sqrt{\pi}} \rho C_D b_v N_v \bar{\omega}^2 H_{rms}^3 \frac{\cosh^2 \bar{k} h_v}{\sinh^2 \bar{k} h_v} f_\alpha \quad (5)$$

where H_{rms} = the root-mean-square wave height, $\bar{\omega}$ = the wave angular frequency corresponding to the mean period, and \bar{k} = the wave number associated with $\bar{\omega}$. f_α is the correction factor that is dependent on vegetation submergence and local wave parameters (wave height, period, and water depth). Zhu and Chen (2019) have provided a comprehensive database of f_α values by calculating the values of this factor in advance for a total of 6,066 waves, which cover a wide range of wave conditions from deep to shallow water.

3 Modeling Resistance of Flexible Vegetation against Waves and Currents

This chapter presents a mathematical model to calculate resistance of flexible vegetation by means of the scaling law, which considers interaction of vegetation biomechanical features and waves. A brief literature review on the existing formulations of drag coefficient of vegetation is provided. A formulation applicable to a wide range of biomechanical parameters is recommended. Then, a general procedure for determining the drag resistance of flexible vegetation in CSHORE-Vegetation is presented.

3.1 Representation of flexible vegetation in CSHORE

Vegetation on coasts and in marshes resists forcing from waves, currents, and wind, and reacts to the influence of these natural forces by bending and swaying. However, if the natural forces acting on vegetation exceed its flexural stress (the limit of recovery capability from bending), vegetation will be partially damaged, or its stem will be broken.

The motion of flexible vegetation leads to smaller relative velocities u_r (which is equal to $u - u_v$) than the orbital velocity u , where u_v is the stem swaying velocity. The smaller relative velocities reduce the vegetation-induced drag force and the associated energy dissipation. To account for the effects of vegetation flexibility and motion on wave attenuation, the concept of effective vegetation height h_e is employed (Lei and Nepf 2019). The essential idea is that rigid vegetation with an effective vegetation height (h_e) dissipates the equivalent amount of wave energy as flexible vegetation with the height of h_v . For vegetation with blades (Figure 2a), wave energy is attenuated by stem and blades, and the total effective vegetation height ($h_{vt,e}$) then consists of the effective stem height ($h_{stem,e}$) and the sum of all the effective individual blade heights ($h_{blade,i,e}$):

$$h_{vt,e} = h_{stem,e} + \sum_i^n h_{blade,i,e} \quad (6)$$

where n is the total number of blades and the subscript i indicates the i -th individual blade. For determining the effective stem height, the following scaling law (Lei and Nepf 2019) is used:

$$h_{stem,e} = 0.94(CaL)_{stem}^{-1/4} h_v \quad (7)$$

where Ca is the wave Cauchy number, L is the length ratio between plant height (h_v) and maximum water particle displacement or wave orbital excursion (A_w), and the subscript “stem” indicates that Ca and L are evaluated for the stem. The definitions of the two variables are given as follows:

$$Ca = \frac{\rho b_v U_w^2 h_v^3}{EI} \quad (8)$$

where U_w is a representative horizontal velocity, defined as the depth-averaged (wave) orbital velocity immediately in the front of the vegetation field, E is the Young’s modulus, and $I (= \frac{\pi b_v^4}{64})$ is the area moment of inertia for a circular cross-section of stem.

$$L = \frac{h_v}{A_w} = \frac{2\pi h_v}{U_w T} \quad (9)$$

where $A_w = \frac{U_w T}{2\pi}$, and T is the wave period. Figure 2(b) plots the curve of the ratio of effective stem height to stem height (h_e/h_v) calculated by Equation (7). The term CaL is a ratio of drag force to vegetation stiffness. A larger CaL value means the vegetation becomes more flexible against the wave, then the effective vegetation height becomes less or shorter. Note that for most flexible vegetation, the effective height should be equal to or shorter than the actual height, as the ratio (h_e/h_v) greater than 1 may not be physical.

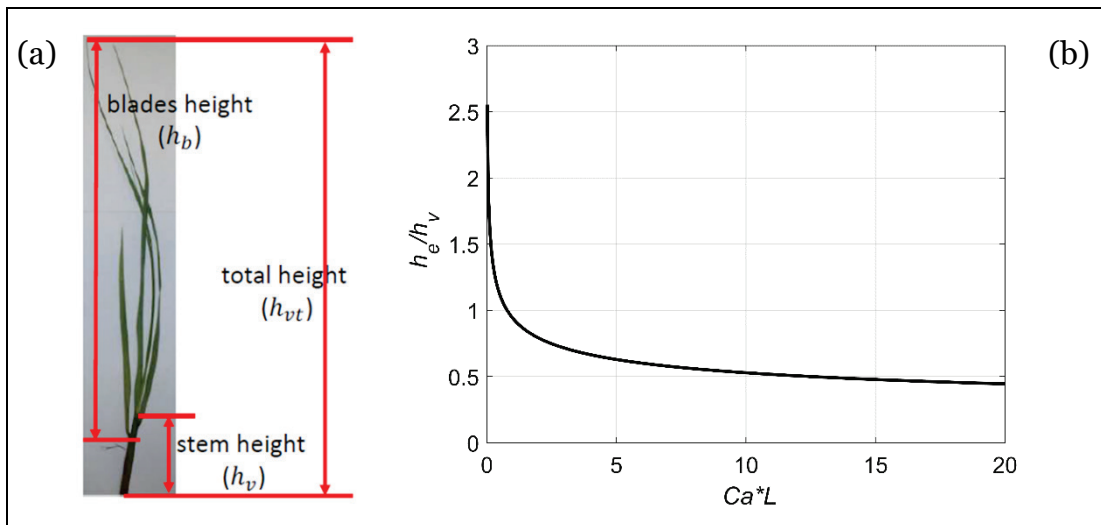
Similarly, the scaling law is applied to calculate the effective height (or length) of the i -th individual blade:

$$h_{blade,i,e} = 0.94(CaL)_{blade,i}^{-1/4} h_{b,i} \quad (10)$$

where the subscript “blade” indicates that the two variables Ca and L are evaluated for the blades, and $h_{b,i}$ is the height (or length) of the i -th blade.

When the CSHORE-Vegetation model calculates the energy dissipation D_v due to flexible vegetation, the vegetation height h_v in Equation (2) will be replaced by the total effective vegetation height $h_{vt,e}$. Similarly, for calculation of the vegetal drag force by Equation (5) in the momentum equation, the total effective vegetation height will be used.

Figure 2. (a) Height variables for vegetation with blades; (b) Ratio of effective stem height to stem height calculated by Equation (7).



3.2 Determining drag coefficient C_D for flexible vegetation

The drag coefficient C_D is an empirical parameter for calculating wave energy loss and drag resistance of vegetation against waves and currents. The C_D values can be calibrated based on a wave attenuation model by using observation data measured in laboratories and field studies. Therefore, C_D represents the *bulk* value over a measured transect or a vegetation patch rather than the drag coefficient of a single cylinder-like vegetation stem. For prediction purposes, there were a number of empirical formulations developed for estimating C_D by building up a regression relationship between C_D and wave parameters from the calibrated values. The applications of those empirical C_D formulations are limited by the type of vegetation (rigid/flexible), the wave properties (regular/irregular), the data range, and the wave models (analytical or process-based models) used for calibrating the bulk values.

Pioneering research by Dalrymple et al. (1984) derived an analytical solution of wave height decay due to arrays of cylinders (a rigid vegetation patch) from the linear wave theory for monochromatic (regular) waves. Kobayashi et al. (1993) developed a wave energy balance equation for submerged rigid vegetation and established a regression relationship between C_D and the Reynolds number (Re) for non-breaking regular waves, where

$$Re = \frac{u_c b_v}{\nu} \quad (11)$$

where u_c is the maximum near-bed orbital velocity in the absence of vegetation and ν is the kinematic viscosity of water. Mendez and Losada (2004) extended the study to wave attenuation due to breaking irregular waves and derived two analytical solutions of wave height profiles in a horizontal vegetated flume: one for non-breaking waves and another for breaking irregular waves. Under random wave conditions, they developed an empirical C_D formulation for rigid vegetation related to the Keulegan–Carpenter number (K_C):

$$K_C = \frac{u_c T_p}{b_v} \quad (12)$$

where u_c is defined as the maximum horizontal velocity at the middle of the vegetation field at the canopy and T_p is the peak wave period.

Based on the analytical solution of Mendez and Losada (2004) for random waves, Jadhav (2012) calibrated the C_D values for *Spartina alterniflora* using field data from Terrebonne Bay, LA, and found a regression relation for C_D with the Reynolds number (Re). Anderson and Smith (2014) conducted a large number of experiments for studying wave attenuation in the ERDC CHL, wave flume in which the vegetation mimicked the flexibility of *Spartina alterniflora*. Using their non-breaking wave data, they developed four C_D formulations related to the Reynolds number or the Keulegan–Carpenter number (K_C) and found the C_D curve related to a modified Re value provided the best fit with their laboratory datasets. All the above-mentioned C_D formulations are limited to rigid vegetation, due to a lack of representation of vegetation flexibility.

Finally, applying the scaling law to *Spartina alterniflora* as described in the previous section, Zhu et al.* have developed a new $C_D \sim Re$ formulation for *Spartina alterniflora* based on the field data from Terrebonne Bay and the calibrated C_D values produced by the CSHORE-Vegetation model. It was also successfully validated by simulating the wave attenuation experiments by Anderson and Smith (2014). More information on the calibration of C_D and validation of this formulation is given in the next sections.

* Zhu, L., Q. Chen, Y. Ding, J. Navid, H. Q. Wang, B. Johnson, and J. D. Rosati. In preparation. "Universal Relation of Drag Coefficient for Quantifying Wave Energy Reduction by Salt Marshes." Submitted to PNAS, Aug. 2020.

Table 1 provides more detailed information on the above-mentioned five C_D formulations. It includes wave data conditions, vegetation properties, the models used for developing the formulations, and limitations for application. All five curves are linked to Re or K_C , and each one uses a specific definition of u_c . As the drag coefficient is in inverse proportion to both K_C or Re , the resistance of a species is decreased as wave height or energy increases. The limitation of each C_D formulation is indicated in the table by the type of vegetation (rigid or flexible) and the application ranges of the parameters (C_D , Re , and K_C).

In Table 1, except for the field data of *Spartina alterniflora* measured in Terrebonne Bay, LA, during Tropical Storm Lee in 2011, all of the other laboratory data sets (Kobayashi et al 1993; Dubi 1995; Anderson and Smith 2014) were measured in wave flumes using artificial vegetation to mimic real vegetation in the field. However, the C_D formulae by Mendez and Losada (2004) (Equation 14), Jadhav (2012) (Equation 15), Jadhav et al. (2013) (Equation 16), and Anderson and Smith (2014) (Equation 17) were developed for rigid vegetation without considering the flexibility of vegetation. Only the C_D formulation Equation (18) by Zhu et al.* was developed by using the scaling law and the process-based model CSHORE-Vegetation. It therefore is able to quantify the effects of vegetation flexibility, rigidity, and bending stress.

Table 1. Empirical formulations of C_D for rigid and flexible vegetation.

Study	Wave Conditions	Vegetation	Model for Rigid or Flexible Vegetation	C_D Formulation
Kobayashi et al. (1993)	Monochromatic Waves: $h=0.45-0.52$ m $H_o=0.036-0.194$ m $T=0.71-2.0$ s	Artificial kelp $h_v=25$ cm $b_v=5.2$ cm $t=0.03$ mm $N_v=1100$ and $1490/m^2$	Analytical solution for <i>non-breaking regular</i> waves over a flat bed (<i>rigid</i>)	$C_D = \left(\frac{2200}{Re}\right)^{2.4} + 0.08$ (13) $2,200 < Re < 18,000$, $0.08 < C_D < 1.08$ u_c for Re : Maximum near-bed orbital velocity of H_o
Mendez and Losada (2004)	Wave flume (Dubi 1995): $h=0.40-1.00$ m $H_{rms}=0.045-0.17$ m $T_p=1.26-4.42$ s	Artificial kelp $h_v=20$ cm $b_v=2.5$ cm $N_v=1200/m^2$	Analytical solution for <i>non-breaking irregular</i> waves over a flat bed (<i>rigid</i>)	$C_D = Q^{-0.3} e^{-0.0138Q}$ (14) $Q = \frac{K_C}{\alpha^{0.76}}$, $\alpha = h_v/h$, $7 \leq Q \leq 172$

* Zhu, L., Q. Chen, Y. Ding, J. Navid, H. Q. Wang, B. Johnson, and J. D. Rosati. In preparation. "Universal Relation of Drag Coefficient for Quantifying Wave Energy Reduction by Salt Marshes." Submitted to PNAS, Aug. 2020.

Study	Wave Conditions	Vegetation	Model for Rigid or Flexible Vegetation	C_D Formulation
				u_c for K_C : Maximum orbital velocity at the middle of the vegetation field at canopy
Jadhav (2012)	Waves measured in Terrebonne Bay, LA $h = 0.20\text{-}1.10$ m $H_{m0} = 0.20\text{-}0.40$ m Mean period $\bar{T} = 3\text{-}9$ s	<i>Spartina alterniflora</i> $h_v = 20$ cm $b_v = 8.5$ mm $N_v = 420/\text{m}^2$	Analytical solution for <i>breaking</i> irregular waves over a flat bed (Mendez and Losada 2004) (<i>rigid</i>)	$C_D = 0.36 + \frac{2600}{Re}$ (15) $600 \leq Re \leq 3,200$, $1.1 < C_D < 4.7$ u_c for Re : the same definition as Kobayashi et al. (1993)
Jadhav et al. (2013)	Same as above	Same as above	Same as above (<i>rigid</i>)	$C_D = 70K_C^{-0.86}$ (16) $25 < K_C < 135$, $1.0 < C_D < 4.4$ u_c for K_C : the same definition as Kobayashi et al. (1993)
Anderson and Smith (2014)	Waves Flume: $h = 0.31\text{-}0.53$ m $H_{m0} = 0.05\text{-}0.19$ m $T_p = 1.25\text{-}2.25$ s	Polyolefin tube $h_v = 41.5$ cm $b_v = 6.4$ mm $N_v = 200, 400/\text{m}^2$	Same as above (<i>rigid</i>)	$C_D = 0.11 + \left(\frac{2067.7}{Re/\alpha^{1.5}}\right)^{0.64}$ (17) $500 < Re < 2,500$, $1.0 < C_D < 2.4$ u_c for Re : Maximum horizontal velocity immediately in the front of the vegetation field at the top of the stems
Zhu et al.*	Waves measured in Terrebonne Bay, LA (Jadhav 2012).	<i>Spartina alterniflora</i> Blade: $E = 500$ KPa Stem: $E = 80$ MPa	CSHORE-Vegetation (<i>rigid / flexible</i>) using the scaling law	$C_D = 0.62 + \left(\frac{1492}{Re}\right)^{1.15}$ (18) $300 < Re < 6,000$, $0.8 < C_D < 7.0$ u_c for Re : the same definition as Kobayashi et al. (1993)

3.3 Procedure for simulating wave attenuation due to flexible vegetation

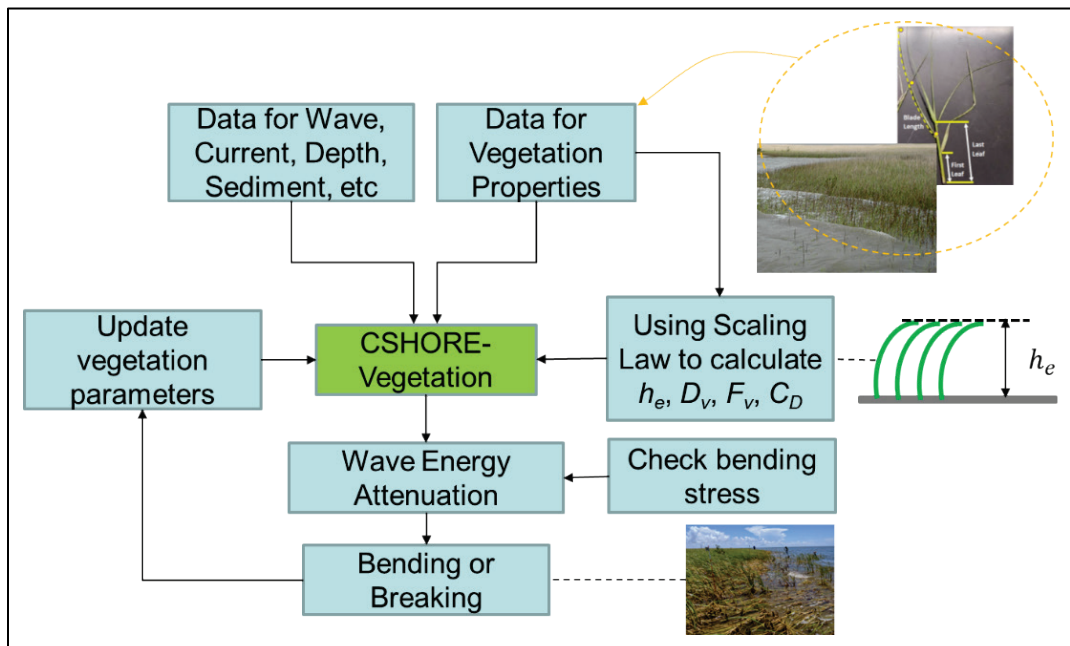
A general procedure for using the CSHORE-Vegetation model for simulating waves and water levels through a flexible vegetation zone (patch) includes the following major steps:

* Zhu, L., Q. Chen, Y. Ding, J. Navid, H. Q. Wang, B. Johnson, and J. D. Rosati. In preparation. "Universal Relation of Drag Coefficient for Quantifying Wave Energy Reduction by Salt Marshes." Submitted to PNAS, Aug. 2020.

1. For configuration of a CSHORE-Vegetation simulation model, data collection is essential to represent vegetation biomechanical properties for stems and blades (e.g., type of species, population density, height, diameter, thickness, Young's modulus, flexural stresses), morphology (bed elevations, sediments), hydrodynamic forcing (waves, currents, tide levels), and winds. The stem flexural strength is an input parameter defined by the user to check the vegetation's state of bending or breakage (i.e., being ineffective).
2. For quantifying flexibility or rigidity, the scaling law is applied to calculate spatially varying or uniform effective heights of stem and blades (Equations 6–10) based on the vegetation biomechanical properties and local wave characteristics.
3. The total effective vegetation height ($h_{vt,e}$) from Equation (6) is then used to compute the wave energy reduction D_v and the drag resistance F_v (Equation 5) caused by the deformable vegetation. The empirical formulation (Equation 18 in Table 1) is recommended for estimating the bulk C_D value for each vegetaton patch. For a given incident wave condition, flexible vegetation may lead to a significant reduction of wave damping capability compared to rigid vegetation, and CSHORE-Vegetation quantifies such a reduction.
4. Near the marsh edge where the wave height is typically large, if the bending stress exerted by waves on the vegetation exceeds the stem flexural strength, the vegetation breaks, and the affected stems are removed from CSHORE automatically.

A flowchart for the procedure proposed above to apply CSHORE-Vegetation is illustrated in Figure 3. It indicates that simulations may be iterative or time dependent if evaluation of vegetation's response to varying wave conditions, such as bending and breakage, is included. Then, the model will be able to produce time-varying results of wave attenuation and MWLs that can be used for assessing seasonal and storm-related changes of flexible vegetation.

Figure 3. Flow chart for determining capacity of living vegetation using CSHORE-Vegetation.



4 Calibration of C_D Using Field Data from Tropical Storm Lee

The recommended empirical formulation of C_D (Equation 18) in Table 1 was developed by means of a regression analysis of the C_D values, which were calibrated by using the CSHORE-Vegetation model and field data (for vegetation and waves). The field data were collected by Jadhav and Chen (2012) on 3–4 September 2011 during Tropical Storm Lee (Brown 2011) at Terrebonne Bay on the Louisiana coast (Figure 4). Terrebonne Bay is a shallow estuary where salt marshes line the upper portion of the bay (Figure 4a), including vegetation such as smooth cordgrass (*Spartina alterniflora*, as shown in Figure 4b) and salt meadow cordgrass (*Spartina patens*).

This set of field data includes marsh physical properties and wave gage data. Five wave gages (W0 through W4) were deployed along a north-south transect nearly perpendicular to the marsh edge (Figure 4a). Gage W0 was located in the open water on the up-wave side of the marsh approximately 47 m away from the marsh edge to measure incoming wave energy (Figure 4c). The still water depth relative to the MWL at the location of the gage is approximately 1.4 m. Table 2 summarizes the observed vegetation properties such as density, stem height, total plant height, diameter, modulus, second moment of inertia of the stem, and flexural rigidity (EI), in the two sections from W1 to W2 and W2 to W3. Vegetation properties are similar in the two sections while the population between W1 and W2 is slightly denser than that in section W2-W3, and the mean stem height (W1-W2) is approximately 2 cm shorter than the one in W2-W3.

Figure 4. Study site at Terrebonne Bay, LA: (a) Close-up aerial view of the study site showing wave gage configuration (the background Google Earth satellite image is dated to 11/14/2012). The line W1-W3 (28 m, drawn to scale) shows transect alignment. (b) A *Spartina alterniflora* plant collected from the site for measurements. (c) Profile view of the experimental set up. (from Jadhav 2012)

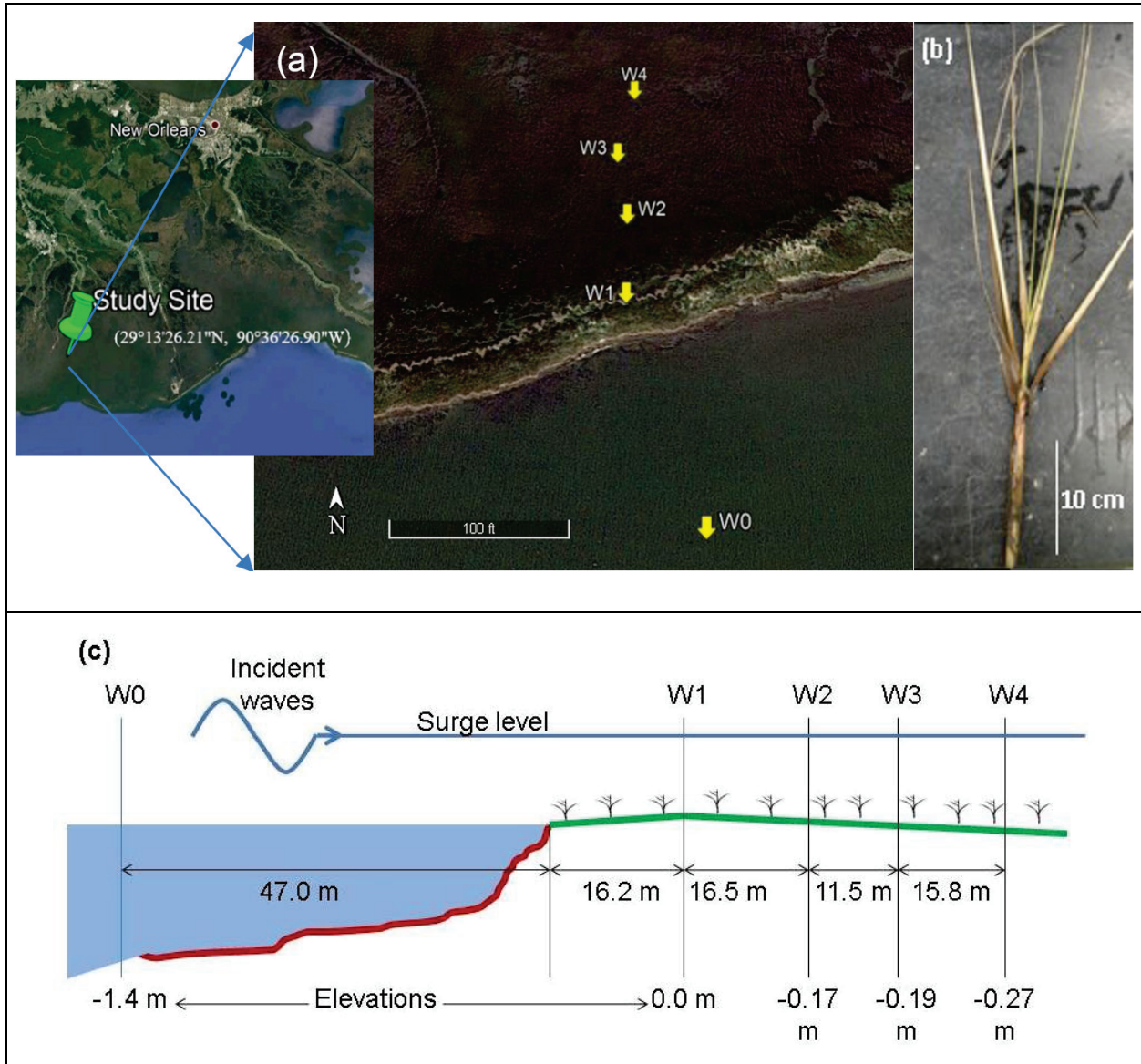


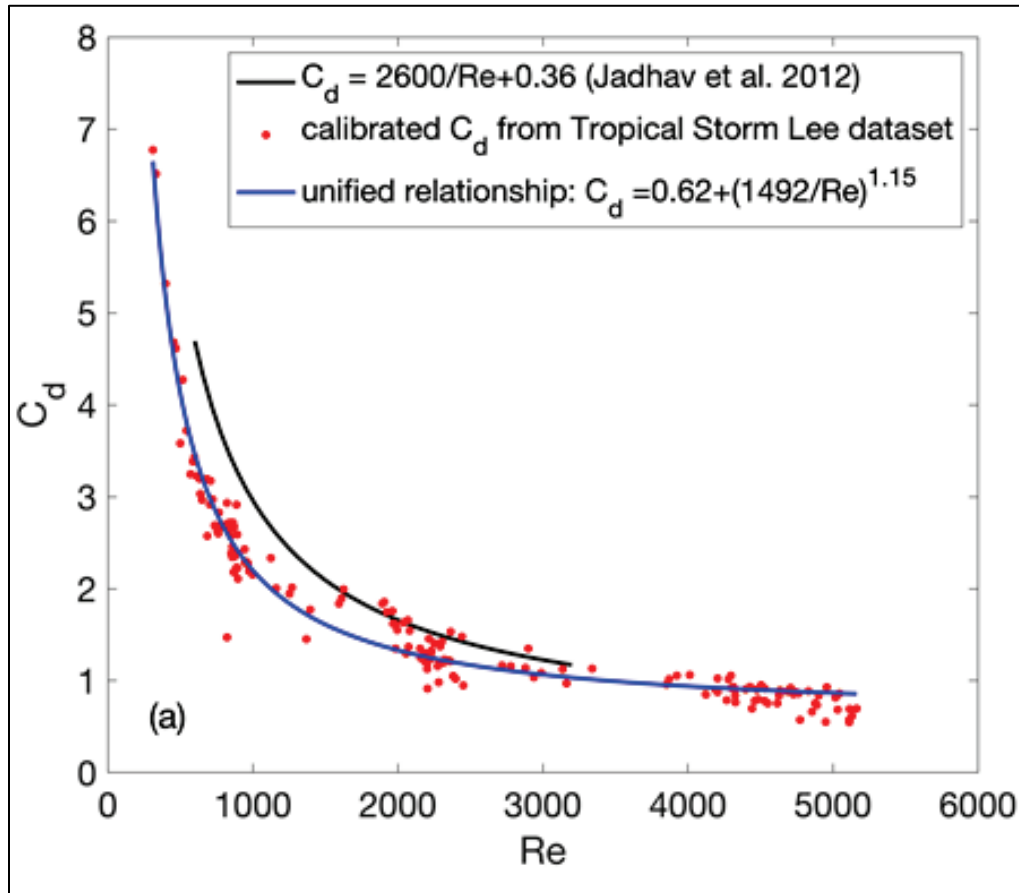
Table 2. Vegetation properties (units, mean, and standard deviation) (Jadhav 2012).

Plant parameters	Unit	Between W1 and W2	Between W2 and W3
Population density (N_v)	[m ⁻²]	424	420
Stem height (h_v)	[m]	0.21±0.04	0.23±0.06
Total plant height (h_{vt})	[m]	0.62±0.05	0.63±0.11
Stem diameter (B_v)	[mm]	8.0±1.1	7.5±1.3
Young's modulus (E)	[MPa]	80±27	79±32
Second moment of inertia of stem (I)	[m ⁴]	2.01×10 ⁻¹⁰	1.55×10 ⁻¹⁰
Flexural rigidity (EI)	[N-m ²]	0.017±0.009	0.013±0.007

Zhu et al.* applied the CSHORE-vegetation model to calibrate the C_D in three sections, W0-W1, W1-W2, and W2-W3, for which the scaling law was used to estimate the effective stem height (ESH) and the effective blade heights (EBH) of the plants (*Spartina alterniflora*). The obtained regression relation (the refitted $C_D \sim Re$ curve, Eq. 18), plotted in Figure 5, provides a higher accuracy ($R^2=0.96$) and a wider range of Re for applications than the formulation by Jadhav (2012) (i.e., Equation 15). Note that Jadhav (2012) developed Equation (15) using only the measured stem height without applying the scaling law.

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Figure 5. C_D vs. Re for CSHORE-Vegetation for *Spartina alterniflora*. The re-fitted curve was obtained by including ESH and EBH.* The curve developed by Jadhav (2012) was using stem height only.



* Zhu, L., Q. Chen, Y. Ding, J. Navid, H. Q. Wang, B. Johnson, and J. D. Rosati. In preparation. "Universal Relation of Drag Coefficient for Quantifying Wave Energy Reduction by Salt Marshes." Submitted to PNAS, Aug. 2020.

5 Model Validation for Simulation of Wave Attenuation in Laboratory

The CSHORE-Vegetation model with the proposed C_D formulation (Equation 18) was validated by simulating the wave attenuation due to flexible, idealized vegetation measured in a wave flume by Anderson and Smith (2014). The experimental vegetation patch in the flume was built using polyolefin tubes, which can model the flexibility of *Spartina alterniflora*. This flume measured 63.4 m long, 1.5 m wide, and 1.5 m deep. The 9.8 m long vegetation field started approximately 26.9 m from the wave paddle. There were eight gages inside the vegetation patch (i.e., Gages 6 to 13 shown on Figure 1 of Anderson and Smith [2014]). They provide a comprehensive dataset of laboratory experiments that cover experimental conditions of emergent ($\frac{h_v}{h} = 1.36$), near-emergent ($\frac{h_v}{h} = 0.91$), and submerged vegetation ($\frac{h_v}{h} = 0.78$). Table 3 presents the basic properties of the vegetation in the experiments. The flexural rigidity (EI) is close to the mean value observed in section W2-W3 of the salt marsh in Terrebonne Bay (Table 2). The irregular incident waves in the flume were generated by using the TMA* spectrum. The waves in all the tests were non-breaking as the ratio of significant wave height to depth ranges from 0.10 to 0.42.

Even though no vegetation blades were modeled in the experiments, the flume layout and the collected wave gage data are useful for validating the CSHORE-Vegetation capacity for simulating wave attenuation due to flexible vegetation. Meanwhile, control tests without vegetation were also performed, which provides experimental data for calibrating other empirical parameters (e.g., bottom friction coefficient f_b) in the model, which are not associated with vegetation.

* named after three field data sets – Texel, MARSEN, and ARSLOE – used for the validation of the spectrum (Bouws et al. 1985)

Table 3. Vegetation properties in laboratory experiments by Anderson and Smith (2014).

Plant parameters	Unit	Value
Population density (N_v)	[m ⁻²]	200,400
Stem height (h_v)	[m]	0.415
Total plant height (h_{vt})	[m]	0.415
Stem diameter (B_v)	[mm]	6.4
Young's modulus (E)	[MPa]	172.4
Second moment of inertia of stem (I)	[m ⁴]	8.23×10^{-11}
Flexural rigidity (EI)	[N-m ²]	0.0142

For model simulations, a 1-D computational grid was built up by aligning it with the wave flume from the edge of the vegetation patch and covering all the vegetation. Grid resolution was set to 0.02 m. The empirical wave breaker index was 0.78. The newly developed C_D curve (Equation 18) was used to estimate the drag coefficient of the flexible vegetation. The energy dissipation function (Equation 2) by Mendez and Losada (2004) was employed to calculate wave energy dissipation. The scaling law (Equation 7) was applied to calculate the effective stem heights. In addition to the vegetation property data in Table 3, the other parameters for the CSHORE-Vegetation model are listed in Table 4. Each simulation by CSHORE-Vegetation took only approximately 2 s to find steady solutions for waves and currents (i.e., mean velocity and water level profiles) on a standard laptop computer using a single Intel i7-8650U CPU@1.90GHz.

Table 4. Model parameters.

Model Parameter	Unit	Value
Grid size	[m]	0.02
Bottom friction factor (f_b)	[1]	0.160
Drag coefficient of vegetation (C_D)	[1]	Formulation $C_D(Re)$ by Zhu et al.*
Energy dissipation (D_v)	[J/m ² /s]	Equation (2) by Mendez and Losada (2004)

All 30 experimental cases were simulated by CSHORE-Vegetation. For six selected tests with a near-emergent condition ($\frac{h_v}{h} = 0.91$), Figure 6 shows

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the comparisons of H_{rms} between the simulated results and the experimental data. Three pairs of cases represent three types of incident waves: small ($H_{rms0} \sim 3.4$ cm), intermediate (~ 7.7 cm), and large (14.4 cm). The three cases on the left panel are for the coarser vegetation ($N_v = 200$), and those on the right for the denser ($N_v = 400$). Using the $C_D(Re)$ formulation Equation (18) and the scaling law, the CSHORE-Vegetation model reproduces accurately the spatial distributions of wave heights through the species patch in response to varying vegetation flexibility and wave conditions. It also shows that the effective stem height (i.e., h_e/h_v) is decreased as the incident wave energy increases. It means that based on the scaling law, large waves can scale up the relative flexibility and then weaken the vegetation's ability to reduce the wave energy.

Figure 6. (a)–(f): Comparisons of profiles of wave heights (H_{rms}) through the vegetation patch ($x = 0.0 \sim 9.8$ m).

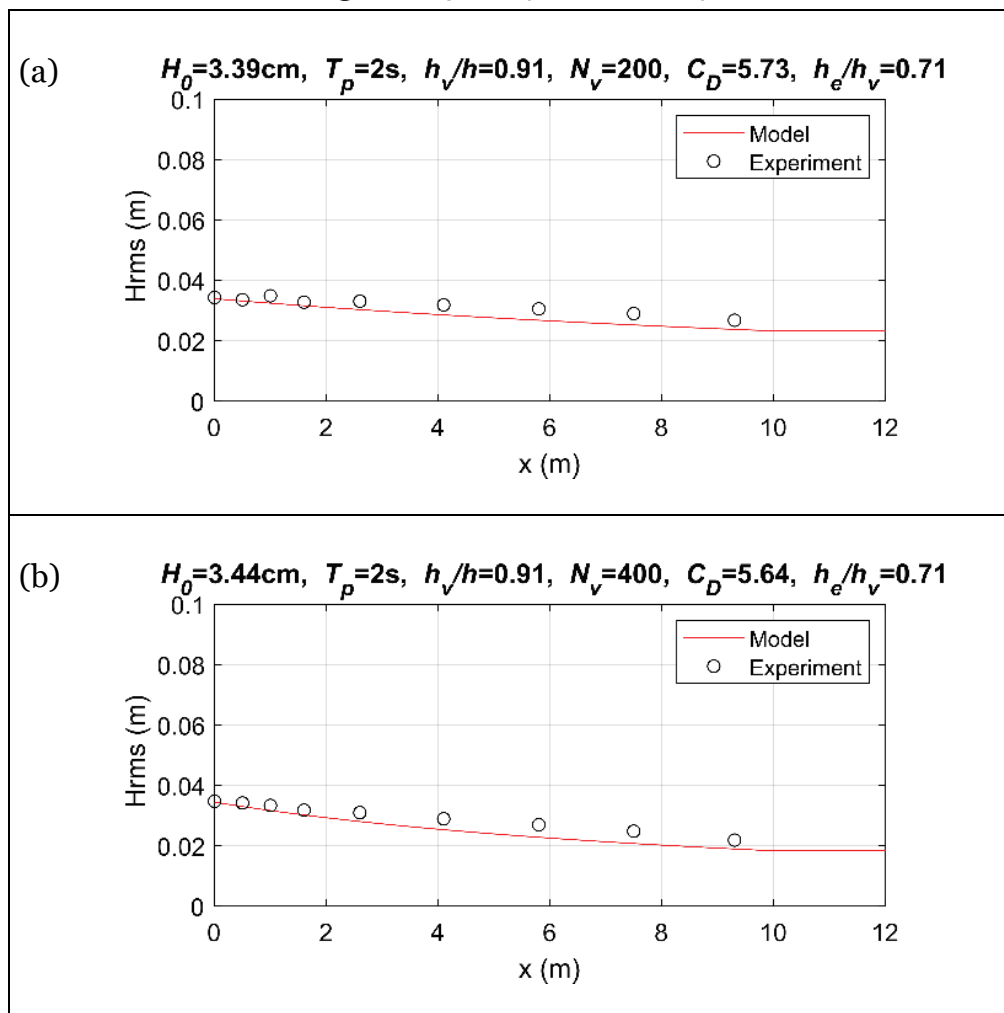


Figure 6. Continued.

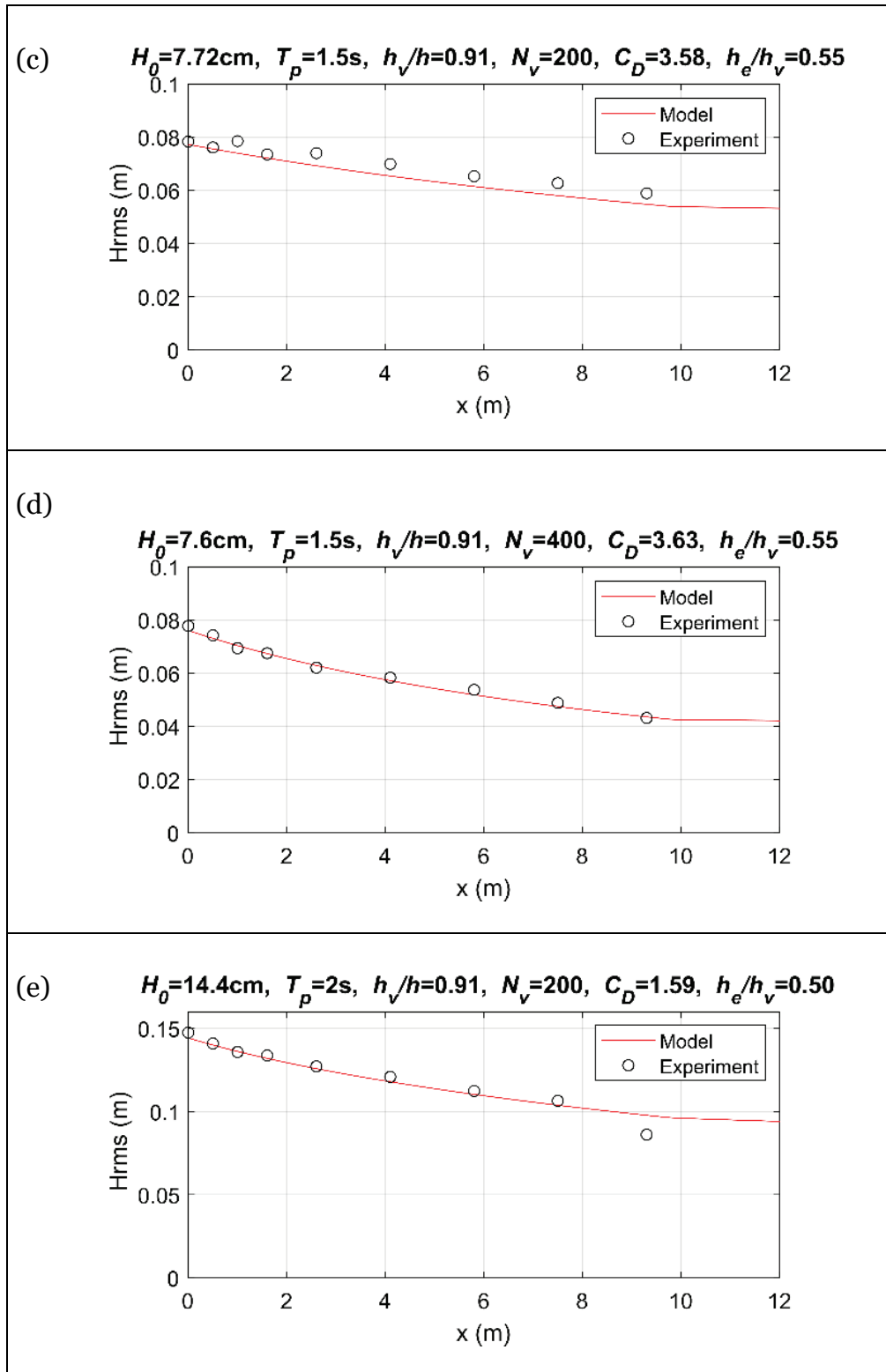
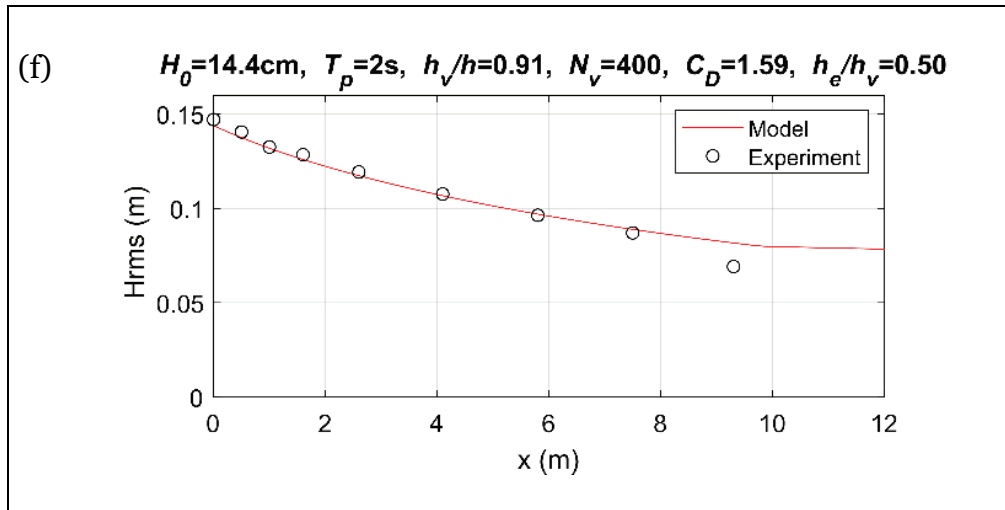
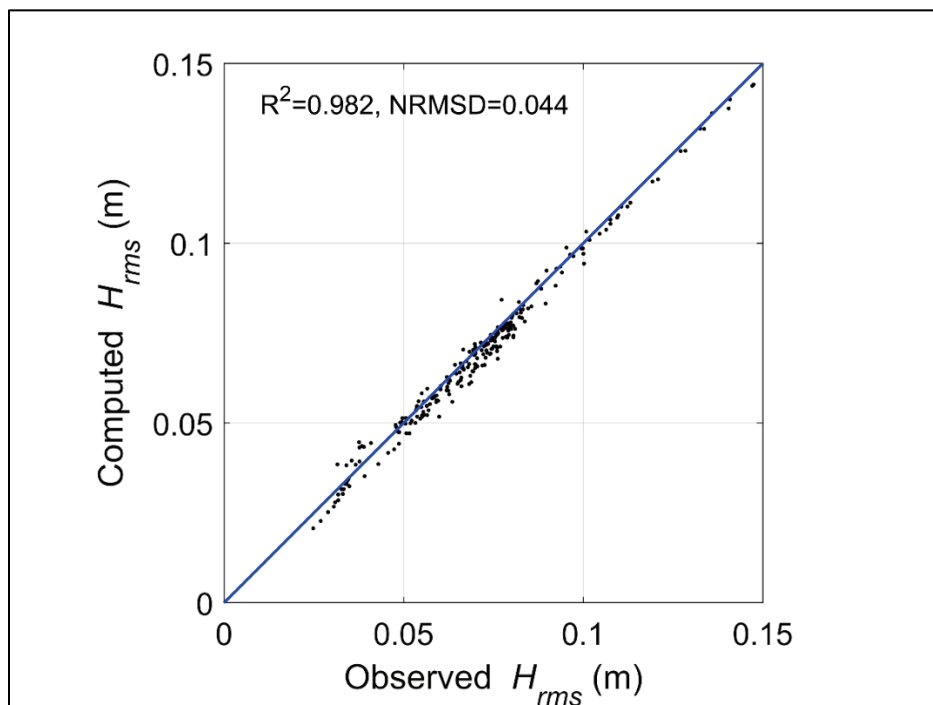


Figure 6. Continued.



For all 27 validation cases with a total of 240 data points, Figure 7 presents a quantile-quantile plot for the simulated root-mean-square wave heights and observed values that were measured at all eight gages inside the vegetation patch (i.e., Gages 6 to 13). A small normalized root-mean-square deviation (NRMSD = 0.044) and a close-to-unity R^2 value (0.982) were obtained.

Figure 7. Observed vs. computed H_{rms} at all the gages and for all the 27 experiments. (R^2 = Coefficient of Determination, NRMSD = Normalized Root-Mean-Square Deviation from the mean observed H_{rms}).



6 Conclusions and Recommendations

6.1 Conclusions

This technical report presents the development of a semi-empirical and data-driven numerical model (CSHORE-Vegetation) for predicting wave energy dissipation and flood level changes through marshes or vegetated coasts. The new capabilities for simulating flexible vegetation were implemented by formulating the relationship between vegetation resistance with its biomechanical properties such as density, dimension, flexibility/rigidity of stem and blades, bending, etc. In terms of the scaling law (Lei and Nepf 2019), species-specific responses to wave attenuation and resistance are characterized by the effective stem/blade heights and wave conditions. By using the field data of waves and properties of salt marsh in Terrebonne Bay, LA, a new formulation of the vegetation drag coefficient (C_D) (Equation 18) (Zhu et al. 2020) was developed through regression analysis of the calibrated C_D values at the site. Preliminary validation of the new C_D regression formulation was achieved by simulating a set of laboratory experiments on flexible vegetation (Anderson and Smith 2014), which mimicked the flexibility of *Spartina alterniflora*. It shows the effectiveness of the new C_D formulation for simulating wave energy dissipation and flow resistance in response to species-specific biomechanical features. This capability for flexible vegetation will enable the CSHORE-Vegetation model to quantify flood protection benefits of different types of vegetation and eventually to predict variation of vegetation resilience in locations and times.

6.2 Recommendations

As the capability for simulating vegetation has been implemented into the CSHORE model, when running the model for wave simulations, users still can refer to the user manual (e.g., Johnson et al. 2012). However, for setting up the CSHORE-Vegetation model, users must select a vegetation model, of which the indices and the model control variables are briefly described in the Appendix. Although a Python-based user interface for pre- and post-processing of the model is still under development, users are recommended to directly contact the authors for technical support of using CSHORE-Vegetation.

As for future development of the research and its applications, work must continue on the two aspects: one is for technical transfer, and another for applicability to large-scale engineering problems. Technical transfer is a key to succeed in applications of the research results (models, data, and knowledge), partially because the developed techniques (numerical models) are parametric semi-empirical models and relatively new. Thus, it is imperative to accomplish the development of the Python-based user interface and to provide users with a user-friendly graphic interface. Documentations for technical report, user manual, training materials (tutorials, webinars, website/wiki, etc.) also have to be completed. Second, to provide solutions covering large-scale wetlands, there is a need to develop multidimensional vegetation simulation models to compute spatially varying wave fields across a large-scale wetland. There is also a need to advance the research on development of data-driven empirical models/formulations based on continuous field observation data on changes of biomechanical properties of marshes, morphological changes of wetlands, and hydrodynamic forcing. Furthermore, it is also critical to demonstrate the model and the developed procedure to study the effects of episodic events (cold storms, hurricanes) on marshes and vegetated coasts for understanding fragile and damage of vegetation.

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Appendix: Control Variables of CSHORE-Vegetation for Selecting Model Capabilities

This appendix provides additional information on the new model capabilities, which can be selected by giving specific values of the CSHORE-Vegetation control variables (e.g., IVEG) when configuring the CSHORE-Vegetation input file. Table 5 gives descriptions of the optional values of the control variables for specifying the calculation approach, input conditions, and vegetation features.

Table 5. Control variables and optional values for selecting the model vegetation capabilities.

Variable Name	Optional Value	Descriptions
IVEG=	0	No vegetation
	1	For vegetation whose density, width, height, and root depth are specified as input. The height and root depth vary with the bottom elevation change.
	2	For vegetation whose constant density, width, and height are specified as input.
	3	For vegetation whose density, width, height, and root depth are specified as input. User can select energy dissipation model (D_v) and the drag resistance (F_v) for the phase-averaged depth-integrated momentum equation. This is the <i>default option</i> to use the newly implemented features of vegetation described in this technical report.
IDISS=	1	D_v is calculated by Equation (2) (Mendez and Losada 2004).
	2	D_v is calculated using the formulation developed by Chen and Zhao (2012) with the JONSWAP spectrum.
	3	D_v is calculated using the formulation developed by Chen and Zhao (2012) with a user-input spectrum.
IFV=	1	The original approach to calculate F_v (Chen et al. 2017).
	2	F_v calculated by Equation (5) for both submerged and emergent vegetation (Zhu and Chen 2019) (the <i>default option</i>).
	3	F_v calculated by a hybrid model for both submerged and emergent vegetation (Zhu et al. 2018).

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
mils	0.0254	millimeters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms and Abbreviations

1-D	One-dimensional
CHL	Coastal and Hydraulics Laboratory
EBH	Effective blade heights
ERDC	US Army Engineer Research and Development Center
ESH	Effective stem height
JONSWAP	Joint North Sea Wave Project
K_c	Keulegan–Carpenter number
MWL	Mean water level
MWSE	Mean water surface elevation
Re	Reynolds number
SWL	Still water level

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1. REPORT DATE February 2022		2. REPORT TYPE Final Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Implementation of Flexible Vegetation into CSHORE for Modeling Wave Attenuation				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Yan Ding, Q. Jim Chen, Ling Zhu, Julie Dean Rosati, and Bradley D. Johnson				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Coastal and Hydraulics Laboratory US Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199		Department of Civil and Environmental Engineering and Department of Marine and Environmental Sciences Northeastern University 471 Snell Engineering Center 360 Huntington Ave. Boston, MA 02115		8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CHL TR-22-2	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) USACE Flood and Coastal Systems Program US Army Engineer Research and Development Center Coastal and Hydraulics Laboratory Vicksburg, MS 39180-6199				10. SPONSOR/MONITOR'S ACRONYM(S) USACE FCSP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Funding Account Code 39JK18, AMSCO Code 060000					
14. ABSTRACT This technical report presents the new numerical modeling capabilities for simulating wave attenuation and mean water level changes through flexible vegetation such as smooth cordgrass in coastal and marine wetlands. These capabilities were implemented into the Cross-SHORE (CSHORE) numerical model. The biomechanical properties of vegetation such as dimensions, flexibility, and bending strength are parameterized in terms of the scaling law. Correspondingly, a new formulation of the vegetation drag coefficient, CD, is developed using field data from a salt marsh in Terrebonne Bay, LA, by considering spatially varying effective stem and blade heights of species. This report also presents a general procedure for using the model to simulate hydrodynamic variables (i.e., waves, currents, mean water levels) at vegetated coasts, which are used to quantify the effects of wave attenuation and reduction of surge and runup due to vegetation. Preliminary model validation was conducted by simulating a set of laboratory experiments on synthetic vegetation, which mimicked the flexibility of <i>Spartina alterniflora</i> . The validation results indicate that the newly developed vegetation capabilities enable CSHORE to predict changes of wave heights and water levels through marshes by considering species-specific biomechanical features. The model is also applicable to assess vegetation effectiveness against waves and surges.					
15. SUBJECT TERMS Coastal plants—Effect of water levels on, Hydrodynamics, Salt marshes, Mathematical models, Water levels, Water waves—Attenuation, Wetlands					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Yan Ding
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 601-634-5374
Unclassified	Unclassified	Unclassified	SAR	39	