

Development and Validation of a Wave-Action Model for Simulating Wave Attenuation due to Vegetation

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ABSTRACT

This paper presents a wave-action model to simulate random wave deformation and transformation through a vegetation zone. The energy loss due to vegetation resistance is modeled by the vegetation drag model for random wave conditions. Based on a directional wave action balance equation, the wave energy dissipation effect due to vegetation is implemented into an integrated coastal process model, CCHE2D-Coast. The newly developed capability in the model for simulation of wave transformations through a vegetation field is validated by computing wave heights in two laboratory experiments which were conducted in wave flumes with planted artificial vegetations. The effects of wave breaking and vegetation resistance are investigated in the case with artificial vegetation planted on a beach of a 1:30 slope. Numerical results of wave heights show that this wave-action model is capable of simulating very well energy dissipations due to vegetation resistance and wave breaking.

INTRODUCTION

Vegetation zones in coasts and estuaries are important for protecting coastal wetland, maintaining ecosystem in coastal waters, and preserving coastal environments. It is well-known that vegetations in coastal regions act as a buffer to reduce wave attacks during storm and hurricane seasons, as waves are deformed and energy of waves is attenuated through the vegetation zones. Modeling wave deformation/transformation through vegetation zones can quantify wave attenuation effects under variations of vegetation properties, and therefore enable to improve our understanding of the physical processes, and to eventually provide an assessment tool for management, control, and design of coastal vegetation zone and wetland.

Wave attenuation effect has been studied for several decades. In addition to physical modeling and field observation, two types of mathematical approaches for modeling vegetation effect under wave attack can be identified, i.e., phase-resolving wave model and phase-averaged wave model. The former is to directly simulate dynamic wave shape deformations through vegetation field by solving the time-dependent fluid flow governing equations (e.g. Li and Yan 2007). The later is to directly computed wave spectral variations in space and time by using a time-averaged wave energy equation (e.g. Dalrymple et al. 1984, Kobayashi et al. 1993). Obviously, the phase-resolving model can give detailed wave phase information as waves propagate through vegetation zones. However, it needs extensive computing efforts to solve the dynamic fluid flow problems.

Wave spectral model, which is to solve a wave energy balance equation based on the energy conservation law, can directly output wave energy spectra and statistical wave parameters such as significant wave heights, mean directions etc. It is much more efficient and effective to solve multi-directional random wave propagation problems than a phase-resolving model. Most

wave spectral models for modeling vegetation effect deal with the responses to unidirectional and monochromatic waves under simplified conditions of geometries and vegetation properties. Therefore, analytical solutions of wave heights due to vegetation resistance can be found in an extremely simplified parametric model (e.g., Mendez and Losada 2004). For the application of these models to assessment of practical problems, there is a need to develop a wave model to simulating wave attenuation due to random waves under realistic wave conditions.

This paper presents a wave-action model to simulate directional random wave deformation/transformation through vegetation zones. The energy loss due to vegetation resistance is modeled by a vegetation drag model proposed by Dalrymple et al. (1984) and modified by Mendez and Losada (2004) for random wave conditions. Based on directional wave action balance equation, the wave-action dissipation effect is implemented into an integrated coastal process model, CCHE2D-Coast, in which a wave module is capable of computing various random wave processes such as refraction, diffraction, breaking, wave-current interaction, bottom friction, etc. The newly developed capability in CCHE2D-Coast for simulation of wave attenuation effect due to vegetation resistance is validated by computing wave fields in two laboratory experiments in wave flumes with planted artificial vegetations. The first validation case is to simulate wave deformations in a flat bed wave flume with uniformly-distributed artificial vegetations. The second case is to compute wave heights in a laboratory beach with a slope of 1:30 in which artificial vegetations were planted within the wave breaking zone. The laboratory experiments have provided a set of runs with the vegetation covered and no vegetation planted. Therefore, the vegetation model and the wave breaking model can be validated separately. Numerical results of wave heights show that this wave-action model is capable of simulating energy dissipations due to vegetation resistance and wave breaking.

BRIEF DESCRIPTION ON WAVE-ACTION MODEL

A wave-action module of an integrated coastal process model (i.e., CCHE2D-Coast) is used to develop a directional spectral wave-action model for simulating wave attenuation effect due to vegetation resistance in waters. In addition to the wave transformation simulation model, this coastal process model contains several other modules for computing currents, sediment transport, and morphological changes in coasts and estuaries. It has been widely used for simulating hydrodynamic and morphodynamic processes under the combined waves and currents driven by astronomical tides, waves, river flows, etc. For the details of CCHE2D-Coast, one may refer to Ding et al. (2006), Ding et al. (2008), and Ding and Wang (2010).

Mathematical Formulations

The spectral wave-action model is governed by a multidirectional wave-action balance equation to compute variations of wave-action density in time, space, wave directions, and frequency. The model formulation is based on the parabolic approximation equation including diffraction terms and energy dissipation terms due to wave breaking, bottom friction, and vegetation resistance. The model can simulate unsteady/steady state spectral transformation of directional random waves. The model takes into account the effect of an ambient horizontal current or wave-current interaction and solves the wave-action balance equation of the wave-action density N as follows:

$$\frac{\partial N}{\partial t} + \nabla \cdot (\mathbf{c}N) + \frac{\partial(c_\theta N)}{\partial \theta} = \frac{\kappa}{2\sigma} \left[\frac{\partial}{\partial y} \left(CC_g \cos^2 \theta \frac{\partial N}{\partial y} \right) - \frac{1}{2} CC_g \cos^2 \theta \frac{\partial^2 N}{\partial y^2} \right] - \varepsilon_b N - Q_v - Q \quad (1)$$

where $N=N(x,y,\sigma,\theta,t)=E(x,y,\sigma,\theta,t)/\sigma$, E is the spectral wave density representing the wave energy per unit water surface area per frequency interval, σ =wave angular frequency (or intrinsic frequency), t = time, x, y = two coordinates in two horizontal directions, $\nabla = (\partial/\partial x, \partial/\partial y)$, the gradient operator in the x - y plane, θ = wave angle relative to the positive x -direction, C, C_g = wave celerity and group velocity, respectively. The first term on the left-hand side of (1) represents the local rate of change of action density in time. The second term represents propagation of wave action density in a horizontal x - y plane (with propagation velocities \mathbf{c}). The third term represents depth-induced and current-induced refraction (with propagation velocity c_θ in θ space). The expressions for these propagation speeds are given by the linear wave theory [e.g., Holthuijsen et al. 1989], i.e.,

$$\mathbf{c} = C_g \mathbf{i}_\theta + \mathbf{u} \quad (2)$$

$$c_\theta = -\frac{1}{k} \frac{\partial \sigma}{\partial h} \frac{\partial h}{\partial n} - \frac{\partial \mathbf{u}}{\partial n} \cdot \mathbf{i}_\theta \quad (3)$$

where \mathbf{u} =depth-averaged velocity vector, k = wave number, $\mathbf{i}_\theta = (\cos\theta, \sin\theta)$, a unit vector following the wave direction, h = water depth, n = wave crest direction. The first term on the right-hand side of (1), introduced by Mase (2001), represents the energy dissipation due to the diffraction effect in the alongshore y -direction, which is implicitly perpendicular to wave direction. κ is an empirical coefficient. Mase (2001) suggested this empirical coefficient has a possible value within a range of 2.0~3.0. To specify an incident wave spectrum in the offshore, the TMA spectrum (Bouws et al. 1985) and the Bretschneider-Mitsuyasu (B-M) spectrum (Mitsuyasu 1970) can be selected in this model. The second term in the right-hand side represents wave energy loss due to wave breaking, where ε_b is a parameter for wave breaking energy dissipation. Similarly, the third term Q_v represents the wave energy loss due to vegetation resistance. The last term Q is source terms of wave energy due to wind forcing, bottom friction loss, nonlinear wave-wave interaction term, etc.

Based on the monochromatic linear wave theory and an assumption of impermeable bottom proposed by Dalrymple et al. (1984), Mendez and Losada (2004) established a relationship between the wave energy loss and vegetation parameters under a condition of random wave incidence. The Reyleigh probability density distribution function (Thornton and Guza 1983) is assumed to model random wave actions. As a result, the source term of the wave energy loss due to vegetation, Q_v , is obtained as follows:

$$Q_v = \frac{1}{\sigma 2\sqrt{\pi}} \rho C_D b_v N_v \left(\frac{kg}{2\sigma} \right)^3 \frac{\sinh^3(k\alpha h) + 3 \sinh(k\alpha h)}{3k \cosh^3(kh)} H_{rms}^3 \quad (4)$$

where ρ =water density (kg/m^3), 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}), C_D = drag coefficient for random waves, g =the gravitational acceleration (m/s^2), α = relative vegetation height, H_{rms} = root-mean-square wave height (m). Because the random wave energy can be defined as $E = \frac{1}{8} \rho g H_{rms}^2$, the source term can be written as the local linear form of the wave action density, i.e., $Q_v = \varepsilon_v N$. Then the coefficient ε_v can be given as follows:

$$\varepsilon_v = \frac{4}{g\sqrt{\pi}} C_D b_v N_v \left(\frac{kg}{2\sigma} \right)^3 \frac{\sinh^3(k\alpha h) + 3 \sinh(k\alpha h)}{3k \cosh^3(kh)} H_{rms} \quad (5)$$

According to Takayama et al. (1991), the wave energy dissipation due to wave breaking is calculated by assuming that (1) the probability distribution of breaking wave height can be represented by the Rayleigh distribution (Thornton and Guza 1983); (2) over a computational

cell, the local bathymetry can be approximated as shore-parallel contours. Then, the local rate of wave breaking energy dissipation ε_b in a computational cell can be calculated as the time-averaged energy loss over a time that an individual wave travels through a cell from the seaward side to the inland side, i.e.

$$\varepsilon_b = \varepsilon'_b C / \sqrt{\Delta x \Delta y} \quad (6)$$

where Δx , Δy = the grid size in x - and y -directions, respectively. Based on the Rayleigh probability distribution of wave energy, Takayama et al. (1991) derived the coefficient ε'_b as follows:

$$\varepsilon'_b = 1 - \frac{1 - \left[1 + \frac{\pi}{4} \left(1.6 \frac{H_{bo}}{H_{1/3}} \right)^2 \right] \exp \left[-\frac{\pi}{4} \left(1.6 \frac{H_{bo}}{H_{1/3}} \right)^2 \right]}{1 - \left[1 + \frac{\pi}{4} \left(1.6 \frac{H_{bi}}{H_{1/3}} \right)^2 \right] \exp \left[-\frac{\pi}{4} \left(1.6 \frac{H_{bi}}{H_{1/3}} \right)^2 \right]} \quad (7)$$

where H_{bo} , H_{bi} = breaking wave heights at the offshore side and the onshore side of a computational cell, respectively, $H_{1/3}$ = the local significant wave height. The breaking wave height is calculated based on the breaking wave criterion proposed by Goda (1970), or the one extended by Sakai et al. (1988), i.e.,

$$H_b = \begin{cases} AL_0 \left\{ 1 - \exp(-1.5 \frac{\pi h}{L_0} (1 + 15\beta^{4/3})) \right\} C(\varepsilon_d) & \beta \geq 0 \\ AL_0 \left\{ 1 - \exp(-1.5 \frac{\pi h}{L_0}) \right\} & \beta < 0 \end{cases} \quad (8)$$

where H_b = breaking wave height, L_0 = wave length of the wave at the offshore side of the computational cell, A = empirical coefficient (0.12 – 0.18), β = sea bed slope, $C(\varepsilon_d)$ is a coefficient given by Sakai et al. (1988):

$$C(\varepsilon_d) = \begin{cases} 0.506 & \varepsilon_d \geq 0.0024 \\ 1.13 - 260\varepsilon_d & 0.0024 > \varepsilon_d \geq 0.0005 \\ 1.0 & \varepsilon_d < 0.0005 \end{cases} \quad (9)$$

where $\varepsilon_d = \frac{|\mathbf{u}| L_0 \beta^{1/4}}{g^2 T^3}$, T = the significant wave period for random waves.

This wave-action model can also take into account the wave-current interaction. Under the circumstance of co-existence of wave and current, wave frequency is changed with water depth and velocities. According to small-amplitude wave theory, the resulting wave number can be calculated by the dispersion equation with the Doppler frequency shift. For the description on the wave-current interaction, one may refer to Ding and Wang (2010). The source term Q in (1) includes the wave energy dissipation due to bottom friction and the wave energy input induced by winds. The energy loss by bottom friction is calculated by a drag law model (Collins 1972). In this study, the energy input by wind forcing is not considered in the laboratory experiments.

Numerical Approaches

In CCHE2D-Coast, by means of finite difference schemes, the wave action balance equation (1) is numerically discretized in a geophysical domain which taking into account non-uniform grid size and a general quadrilateral mesh shape. In addition, the wave spectra are discretized into a number of frequency bins, based on the equal energy dividend, by which each frequency bin represents an individual wave. The bins for wave directions are also discretized to cover a half-plane wave direction (θ) domain from $+\pi/2$ to $-\pi/2$. A first-order upwinding finite difference scheme is applied to discretize the second, third, and fourth terms which represent the

propagation of wave action in the horizontal plane and wave refraction due to varying water depth. The central difference scheme is applied to discretize the first term in the right-hand side for the diffraction term. A semi-implicit treatment is applied to the source terms for vegetation resistance, wave breaking, and bottom friction in order to increase the stability of the numerical model. Finally, the discretized wave action balance equation is solved by means of the parabolic approximation, in which the waves are assumed to have a principal propagation direction from offshore toward onshore. An iterative solver, the Gaussian-Seidel algorithm, is used to solve the linear algebraic equations of the wave action balance equation in every y - θ plane arranged from offshore to onshore. The computed wave actions in all the frequency bins add up to the total wave energy, which can be used to calculate statistical wave parameters such as wave heights, mean wave directions, and peak/mean periods.

Moreover, this integrated coastal process model (CCHE2D-Coast) has been built in a well-established numerical software package called CCHE2D (CCHE2D 2011), which is a general numerical tool to analyze 2-D shallow water flows, sediment transport, and water quality, with natural flow boundary conditions. Similar to the CCHE2D hydrodynamic model, the wave and hydrodynamic models in CCHE2D-Coast were discretized in a non-orthogonal grid system so that the models have more flexibility to simulate physical variables in complex coastal zones with irregular coastlines. This coastal process model has been validated by simulating waves, wave-induced currents, and morphological changes in coastal applications in various laboratory and field scales (e.g., Ding et al. 2006, Ding et al. 2008, and Ding and Wang 2010).

Boundary Conditions

Boundary conditions for simulating wave deformation over a computational domain covering ocean, coast and estuary are comprised of offshore wave spectra determined by incident wave parameters (i.e., wave heights, peak or significant periods, and mean directions). The present wave spectral model supports two kinds of offshore (deepwater) wave spectrum inputs, i.e., the TMA spectrum (Bouws et al. 1985) and the Bretschneider-Mitsuyasu (B-M) spectrum (Mitsuyasu 1970). The multi-directional spreading function is given by a directional function proposed by Mitsuyasu (1970). The boundary condition at the onshore side is the non-reflective condition, namely, the waves reaching the shoreline are absorbed completely.

MODEL VALIDATIONS

Nonbreaking random waves through a vegetation zone

Mendez and Losada (2004) presented an analytical solution for a non-breaking water through a vegetation zone in a straight flume in which the still water depth is uniform. The root-mean-square wave height evolution is equal to

$$H_{rms} = \frac{H_{rms,o}}{1 + \bar{\beta}x} \quad (10)$$

where $H_{rms,o}$ is the offshore incident root-mean-square wave height,

$$\bar{\beta} = \frac{1}{3\sqrt{\pi}} C_D b_v N_v H_{rms,o} k \frac{\sinh^3 k\alpha h + 3 \sinh k\alpha h}{(\sinh 2kh + 2kh) \sinh kh} \quad (11)$$

Mendez and Losada (2004) have calibrated the bulk drag coefficient C_D by comparing analytical solutions with the experimental data obtained by Dubi (1995).

The experiments were carried out in a 33-m-long, 1-m-wide and 1.6-m-high flat-bed wave flume. The width of the channel was partitioned to give a width of 0.5 m. The vegetation

field, located at the center of the flume, had a total width of $b = 9.3$ m. The artificial kelp models were *L. hyperborean* with a plant area per unit height of $b_v = 0.025$ m and a height of $d_v = 0.2$ m. The number of uniformly distributed plants per unit horizontal area was $N_v = 1200$ units/m². At the end of the wave flume, a wave absorber was installed to reduce reflection.

Dubi (1995) has carried out a total of 154 runs with varying water depth $h = 0.4$ – 1.0 m, wave peak periods, $T_p = 1.26$ – 4.42 s, and root-mean-square wave heights, $H_{rms} = 0.045$ – 0.17 m. The input for irregular waves was the Joint North Sea Wave Project (JONSWAP) spectrum with shape parameter $\gamma = 3.3$. There were eight wave gauges installed in the wave flume for measuring free surface oscillations, including one was set up at the front face of the vegetation field. Among the experimental runs, a total of six experimental cases as shown in Table 1 were selected for validations of the wave action model. The values of the bulk drag coefficient C_D were adopted from the model calibration results of Mendez and Losada (2004). The vegetation zone with a domain size of 9.0m long and 0.5m wide was discretized into a grid of 181×11 with a uniform grid spacing of 0.05m. A total of 200 frequency bins cover a wide range of frequency from 0.001Hz to 10 Hz. In order to be comparable with the analytical solution given by Mendez and Losada (2004), in the numerical simulations by the wave-action model, the effects of wave diffraction, breaking, bottom friction, and unsteadiness were neglected.

Table 1. Experimental parameters in validation cases

Case No.	$H_{rms,o}$ (m)	T_p (s)	h (m)	C_D
1	0.084	3.79	0.4	0.21
2	0.150	2.53	0.5	0.08
3	0.114	1.58	0.6	0.28
4	0.131	2.21	0.6	0.18
5	0.161	1.89	0.7	0.18
6	0.187	2.53	1.0	0.09

By using the present wave-action model, the computed root-mean-square wave heights (H_{rms}) for the six cases are compared with their analytical solutions given by (10) and the experimental data observed by Dubi (1995). Figure 1 plots all the longitudinal profiles of the wave heights obtained from the three approaches. Since the computed wave parameters are uniformly distributed in the transverse direction of the computational wave flume, the longitudinal profiles are located at the center of the flume. The intercomparisons showing in the figures imply that the numerical wave heights are in excellent agreement with the analytical solutions. Despite the some discrepancies in Case 1, the numerical results are also in good agreement with the experimental gauge data.

Breaking random wave through a uniform vegetation zone

The laboratory data of Lovas (2000) are used to validate the numerical model for the transformation of random waves including dissipation by vegetation and breaking. The experimental setup was carried out in a 40-m-long and 5-m-wide wave flume at SINTEF (Norway). The width of the channel was partitioned to give a width of 0.6 m. To model a real beach, sand was put on top of the concrete (slope 1:30). Above the mean water level shoreline, the slope was increased (1:10) towards the dune foot. The front of the sand dune was shaped with a slope of 1:1.5 and a height of 30 cm.

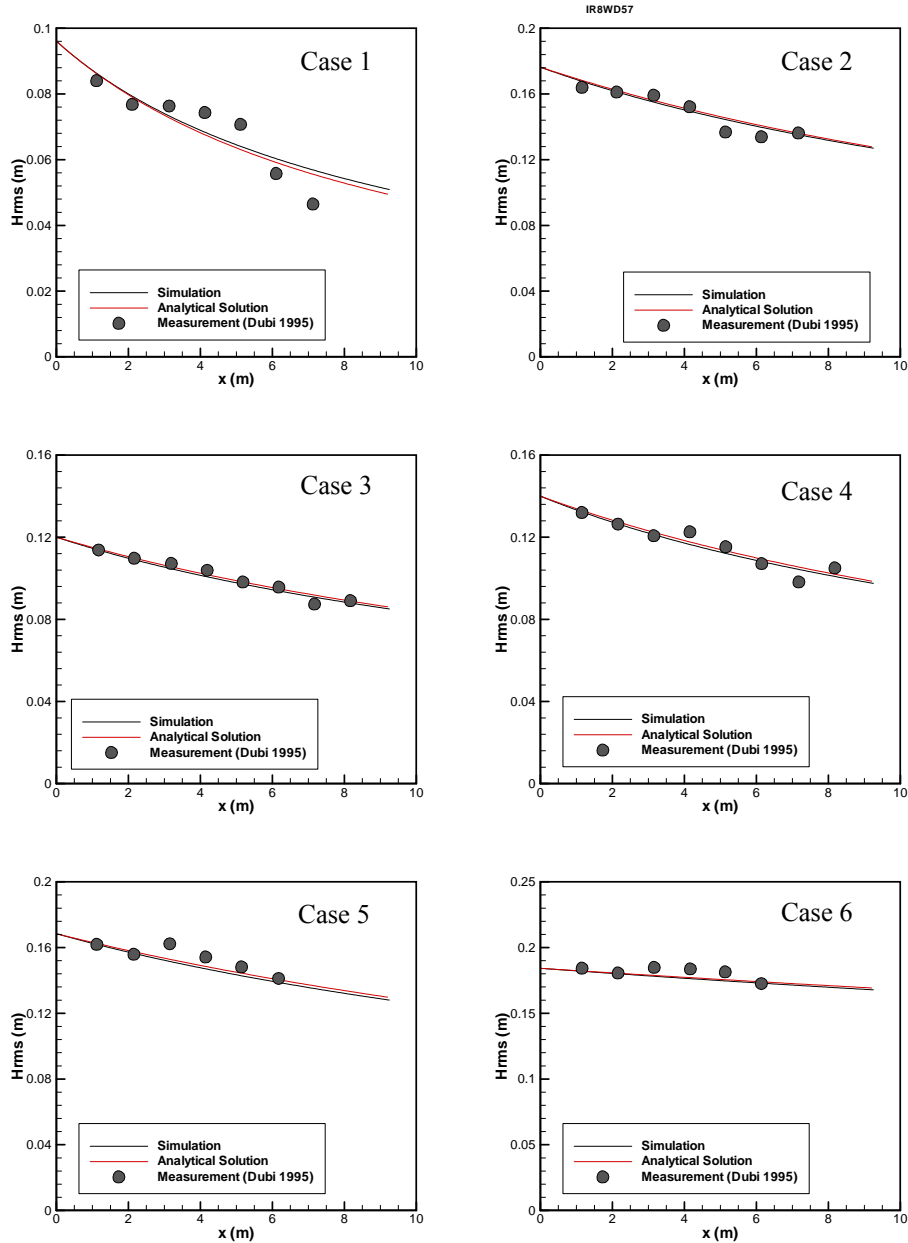


Figure 1 Numerical, experimental, and analytical results of H_{rms} profiles

Five thousand *L. hyperborea* model plants were prepared on a sandy 1:30 slope (see Figure 2 (a)). The sand used in the experiment had a median size of 0.22 mm and its density was 2650 kg/m^3 . The vegetation field, located at the center of the flume, had a total width of $b = 7.27 \text{ m}$ (Lovas and Torum, 2001, Fig. 2). The maximum number of uniformly distributed plants per unit horizontal area was $N = 1200 \text{ units/m}^2$. For the validation of the root-mean-square wave height evolution, 13 runs were analyzed, with varying water depth $h = 0.69\text{--}0.77 \text{ m}$, wave peak periods $T_p = 2.5$ and 3.5 s , significant wave heights $H_{mo} = 0.12\text{--}0.22 \text{ m}$ and varying N (0, 600 and 1200 units/m^2). The input for irregular waves was the Joint North Sea Wave Project (JONSWAP) spectrum with shape parameter $\gamma = 7.0$. For each run, free surface oscillations were

measured at 10 wave gauges, the first defining the offshore wave conditions and the other nine over the sloping beach.

A total of 3 experimental cases are used to validate the wave-action model, of which the model input parameters are listed in Table 2. The vegetation zone with a domain size of 20.0m long and 0.6m wide was discretized into a grid of 201×7 with a uniform grid spacing of 0.1m. A total of 200 frequency bins cover a wide range of frequency from 0.001Hz to 10 Hz. In the numerical simulations by the wave-action model, the effects of wave diffraction, bottom friction, and unsteadiness were neglected.

The bulk drag coefficient C_D given in Table 2 was determined by the formulation proposed by Mendez and Losada (2004), i.e.,

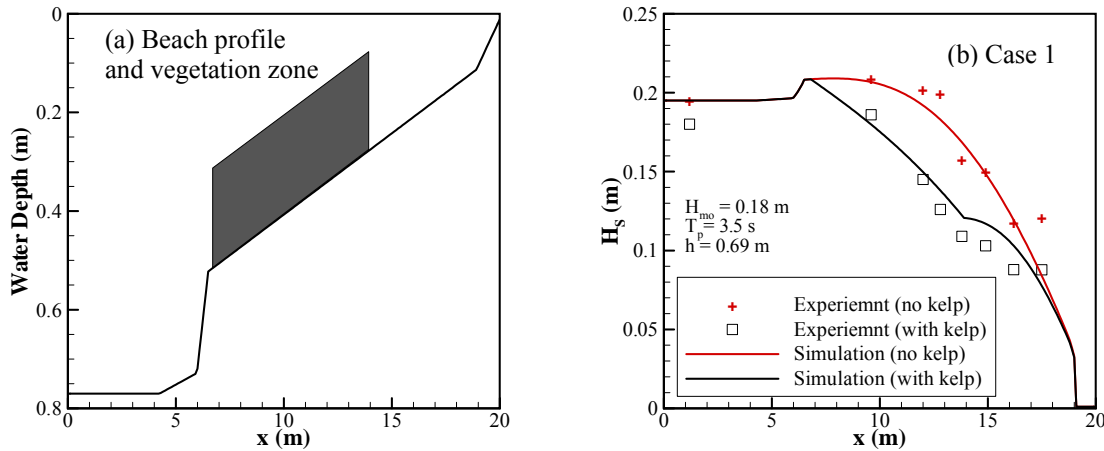
$$C_D = \frac{\exp(-0.0138Q)}{Q^{0.3}}, \quad 7 \leq Q \leq 172 \quad (12)$$

where $Q = K/\alpha^{0.76}$, $K = Keulegan-Carpenter number$, $K = u_c T_p / b_v$, $u_c =$ maximum horizontal velocity at the middle of the vegetation.

Table 2. Breaking random waves

Case No.	$H_{rms,o}$ (m)	T_p (s)	h (m)	C_D
1	0.18	3.5	0.69	0.079
2	0.22	2.5	0.77	0.115
3	0.125	3.5	0.77	0.136

Numerical simulations of wave fields by CCHE2D-Coast were carried out under two types of conditions: (1) without vegetation in the flume, and (2) with vegetation. To do so, the wave breaking model can be validated independently, and the energy dissipation effect due to vegetation resistance can be identified in the case that waves are breaking in a vegetation zone. Figure 2 gives longitudinal profiles of significant wave heights computed under the two conditions. Through incomparisons of significant wave heights from experiments (Lovas 2000) and simulations, it is found that both the wave breaking model and the vegetation model work very well so that the integrated wave model reproduced the wave deformations in the flume under the condition of only wave breaking and the combined breaking and vegetation resistance.



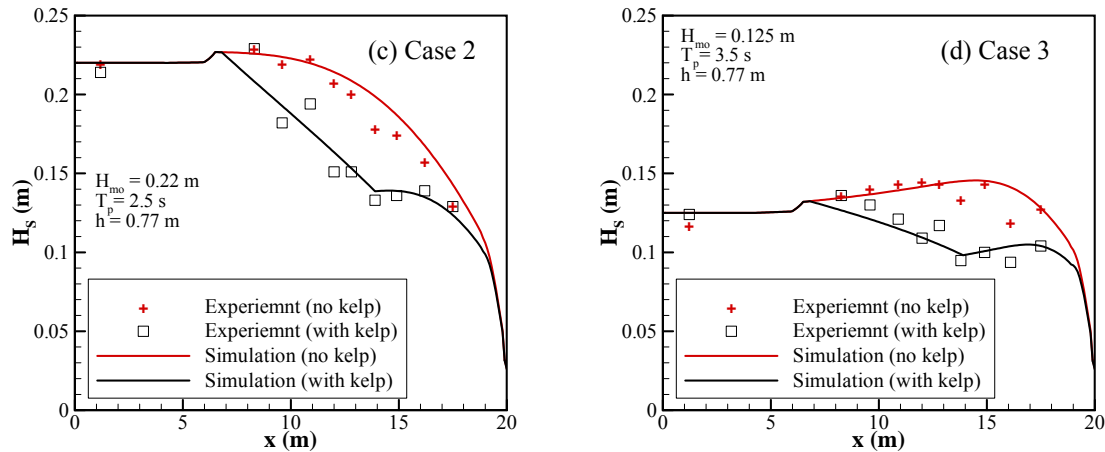


Figure 2 Computed and observed significant wave heights

CONCLUSIONS

This paper presents a wave-action model to simulate random wave deformation/transformation through vegetation zones. The energy loss due to vegetation resistance is modeled by a vegetation drag model proposed by Dalrymple et al. (1984) and modified by Mendez and Losada (2004) for random wave conditions. Based on directional wave action balance equation, the wave-action dissipation effect was implemented into an integrated coastal process model, CCHE2D-Coast, in which a wave module is capable of computing various random wave processes such as refraction, diffraction, breaking, wave-current interaction, bottom friction, etc.

The newly developed capability in CCHE2D-Coast for simulation of wave attenuation effect due to vegetation resistance is validated by computing wave fields in two laboratory experiments in wave flumes with planted artificial vegetations. The first validation case is to simulate wave deformations in a flat bed wave flume with uniformly-distributed artificial vegetations. The computed wave heights were compared with their experimental data and analytical solutions. It is shown that the vegetation attenuation effects on various incident wave conditions were well reproduced by the wave model. The second case is to compute wave heights in a laboratory beach with a slope of 1:30 in which artificial vegetations were planted within the wave breaking zone. The laboratory experiments have provided a set of runs with the vegetation covered and no vegetation planted. Therefore, the vegetation model and the wave breaking model can be validated separately. Numerical results of wave heights show that this wave-action model is capable of simulating energy dissipations due to vegetation resistance and wave breaking.

For future research topics, this model will be validated by simulating practical field application problems on wave attenuation due to vegetation coverage in coastal wetlands.

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