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MODELING OF WAVE ATTENUATION BY VEGETATION WITH XBEACH

A.A. VAN ROOIJEN [(1)], J.S.M. VAN THIEL DE VRIES [(2,3)], R.T. MCCALL [(1,4)],
A.R. VAN DONGEREN [(1)], J.A. ROELVINK [(1,5)], A.J.H.M. RENIERS [(1,3)]

[(1)] *Deltares, Dept. of Marine & Coastal Systems, Delft, the Netherlands*
Arnold.vanRooijen@deltares.nl

[(2)] *Royal Boskalis Westminster NV, Papendrecht, the Netherlands*
[(3)] *Delft University of Technology, Delft, the Netherlands*
[(4)] *Plymouth University, Plymouth, United Kingdom*
[(5)] *UNESCO-IHE, Delft, the Netherlands*

ABSTRACT

Over the past decades the effect of vegetation (e.g. kelp, mangroves, sea grass) on nearshore coastal processes has received more and more attention. In recent years several numerical wave models have been extended to include this effect. In the current study, the numerical storm impact model XBeach was extended with formulations found in literature for damping of short waves, infragravity waves, and mean flow. The model was then verified using a number of laboratory test cases. XBeach was well able to reproduce the damping effect of vegetation on waves, even though the amount of calibration done was limited. This work is considered as a first step only, and further model developments regarding vegetation implementation in XBeach are foreseen for the near future. Eventually, XBeach should be able to accurately take into account the effect of relatively complex vegetation species (e.g. mangroves) on the nearshore hydro- and morphodynamics in a computationally efficient way.

Keywords: storm impact model, wave damping, kelp, mangroves, sea grass

1. INTRODUCTION

Over the past decades the effect of vegetation (e.g. kelp, mangroves, sea grass) on nearshore coastal processes has become more and more recognized. On many coasts around the world, vegetation plays a crucial role in the coastal system providing a.o. 1) reduced coastal risk of flooding by dissipating waves, 2) sheltered environments where (fine) sediments can settle, and 3) habitat for numerous species. However, since it is a relatively new field, the effect of vegetation is often not taken into account in coastal safety studies. There is often either a lack of knowledge on the specific vegetation properties, or the modeling tools do not allow for taking vegetation into account.

Over the past years several numerical wave models have been extended to include wave attenuation by vegetation. For example, the widely used wave model SWAN was recently extended with wave dissipation by vegetation (Suzuki et al., 2011). In the current study the process-based model XBeach (Roelvink et al., 2009, www.xbeach.org) was extended with a number of formulations found in literature to take into account the attenuation of short waves by vegetation. In addition, damping of infragravity waves and mean flow was added to the XBeach code.

This paper is organized as follows; section 2 explains the formulations for wave attenuation by vegetation found in literature, section 3 contains a description of the model, the model verification is discussed in section 4, and in section 5 some final considerations are given.

2. WAVE DISSIPATION BY VEGETATION

When waves propagate through a vegetation field, wave energy is dissipated due to the work carried out by the waves on the vegetation. When assuming normally incident waves, and neglecting wave growth, refraction and dissipation due to friction and wave breaking, the wave energy conservation equation can be written as:

$$\frac{\partial E c_g}{\partial x} = -\varepsilon_v \qquad [1]$$

where E is the wave energy density, c_g is the wave group velocity and ε_v is the time-averaged vegetation-induced rate of energy dissipation per unit horizontal area. A widely used method is to compute the time-averaged wave energy loss as the actual work carried out by the waves on the vegetation as function of the wave-induced drag force (e.g. Dalrymple et al., 1984):

$$\varepsilon_v = \overline{\int_{-h}^{-h+\alpha h} F(z)u(z)dz} \qquad [2]$$

where h is the water depth, αh is the vegetation height, F is the horizontal component of the force acting on the vegetation per unit volume, and u is the horizontal velocity. The overbar indicates averaging over time. When neglecting the plant swaying motion and inertial forces, the plant-induced force can be expressed with a Morison-type equation (Morison et al., 1950):

$$F = \frac{1}{2}\rho C_D b_v N u|u| \qquad [3]$$

where ρ is the water density, C_D is a drag coefficient, b_v is the vegetation stem diameter, and N is the vegetation density. By applying linear wave theory to compute the horizontal component of the velocity, Dalrymple et al. (1984) found an expression for the time-averaged energy dissipation for regular waves propagation through a vegetation field on a uniform bed. This expression was extended by Mendez and Losada (2004) to include random waves, and waves propagating over a sloping bed, given by:

$$\langle \varepsilon_v \rangle = \frac{1}{2\sqrt{\pi}}\rho \widetilde{C}_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3 k\alpha h + 3\sinh k\alpha h}{3k\cosh^3 kh} H_{rms}{}^3 \qquad [4]$$

where k is the wave number, g is the gravitational acceleration, σ is the wave frequency, h is the water depth, C_D is the (bulk) drag coefficient and H_{rms} is the root mean square wave height.

3. MODEL DESCRIPTION

In this study the XBeach model (Roelvink et al., 2009) was used. XBeach is a depth-averaged two-dimensional (2DH) process-based numerical modeling software that was originally developed to simulate dune erosion (e.g. Van Thiel de Vries, 2009) and overwash (e.g. McCall et al 2010). For incident waves, XBeach solves the time dependent short wave action balance on the scale of wave groups, while infragravity wave motions and mean flow are fully resolved using the nonlinear shallow water equations.

For this study, the model formulations were extended to take into account the effect of vegetation. Although, the model formulations were implemented in 2DH, the current study focused on the wave propagation in cross-shore direction. Therefore, all model formulations are written in their 1D equivalent.

3.1 Damping of short waves

To take into account the damping effect of vegetation on the incident waves, the expression derived by Mendez and Losada (2004) was added to the short wave action balance:

$$\frac{\partial A}{\partial t} + \frac{\partial c_g A}{\partial x} = -\frac{D_{break} + D_{veg}}{\sigma} \qquad [5]$$

where $A = E_w/\sigma$, E_w is the wave energy, D_{break} is the wave dissipation due to breaking and D_{veg} is the wave energy dissipation due to the presence of vegetation, which can be computed using Eq. [4], and where the root mean square wave height is given by:

$$H_{rms} = \sqrt{\frac{8E_W}{\rho g}} \qquad [6]$$

Following Suzuki et al (2011) the expression was slightly adjusted to take into account vertical layering of the vegetation:

$$D_{veg} = \sum_{i=1}^{n_v} D_{veg,i} \qquad [7]$$

where D_{veg} is the total short wave energy dissipation due to vegetation, n_v is the number of vertical vegetation segments and $D_{veg,i}$ is the short wave energy dissipation due to vegetation layer i:

$$D_{veg,i} = \frac{1}{2\sqrt{\pi}} \rho \widetilde{C}_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\left(\sinh^3 k\alpha_i h - \sinh^3 k\alpha_{i-1} h\right) + 3\left(\sinh k\alpha_i h - \sinh k\alpha_{i-1} h\right)}{3k \cosh^3 kh} H_{rms}{}^3 \quad [8]$$

By using this expression not only vertically uniform vegetation (e.g. sea grass) but also vegetation with a (strong) variation in characteristics over the vertical axis can be modeled (e.g. mangroves).

3.2 Damping of infragravity waves and mean flow

XBeach uses the depth-averaged Generalized Lagrangian Mean (GLM) formulations (Andrews & McIntyre, 1978; Walstra et al., 2000) to solve the mean flow and the infragravity water level motions and velocities. Since here the instantaneous velocities are directly resolved, the effect of vegetation can be directly included using the drag force (Eq. [3]):

$$\begin{aligned} &\frac{\partial \eta}{\partial t} + \frac{\partial u^L h}{\partial x} = 0 \\ &\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} = -g \frac{\partial \eta}{\partial x} - \frac{\tau_b}{\rho h} + \frac{F_x}{\rho h} + \frac{F_{veg}}{\rho h} \end{aligned} \quad [9]$$

where η is the water surface elevation, u^L the depth-averaged velocity, h is the water depth, τ_b is the bed shear stress, and F_x is the wave force resulting from a radiation stress gradient which is computed using the short wave action balance (Eq. [5]). The vegetation-induced drag force is calculated as the sum of the vegetation-induced drag force per vegetation layer:

$$\begin{aligned} &F_{veg}(t) = \sum_{i=1}^{n_v} F_{veg,i}(t) \\ &F_{veg,i}(t) = \int_{\alpha_{i-1}h}^{\alpha_i h} \frac{1}{2} \rho \widetilde{C}_{D,i} b_{v,i} N_i u^L(t) \left|u^L(t)\right| dz \end{aligned} \quad [10]$$

4. MODEL VERIFICATION

To test the ability of the model in taking into account the wave damping effect of vegetation, a number of lab datasets are available. In most experiments, however, a horizontal bed was used in the flume, thereby excluding the effect of wave dissipation by wave breaking. For XBeach, being a nearshore storm-impact model, it is more interesting to test the model formulations on a case with a sloping bed. One of the few datasets in which wave dissipation by vegetation was measured on a sloping bed is described by Løvås and Tørum (2001) and Løvås (2000). Their data has been used to validate several models (e.g. Mendez and Losada, 2004; Suzuki et al., 2011; Ma et al., 2013). However, in their experiments only two different wave heights and two different wave periods were used, leading to four different hydrodynamic test cases. Another, less known, lab experiment was carried out in the same wave flume by Kansy (1999, data was later re-analyzed by Løvås and Tørum, 2000). Kansy carried out experiments very similar to Løvås and Tørum (2001), but used 20 different wave conditions (4 wave heights x 5 wave periods) over a sloping bed with and without kelp model plants. This resulted in a dataset with a relatively broad range of wave conditions, which are suitable for testing the model.

4.1 Kansy (1999) experiments

The measurements were carried out in a 40 m long wave flume at SINTEF, Trondheim (Norway) in a 1:10 scale, and the main objective was to study the effect of kelp vegetation on waves propagating towards a sloping beach. Therefore a 1:30 slope was added starting at about 12 m from the wave paddle board. A series of wave simulations were carried out with and without a patch of kelp model plants. The kelp model plants were taken from a previous lab experiment (Dubi, 1995) and applied over a total length of 7.27 m. The plant height was about 9 cm, and the plants were uniformly distributed over the (fully submerged) vegetation patch with a density of 1200 plants/m^2. The relative vegetation height (α) ranged between about 0.25 – 0.65. An overview of the flume setup is shown in Figure 1.

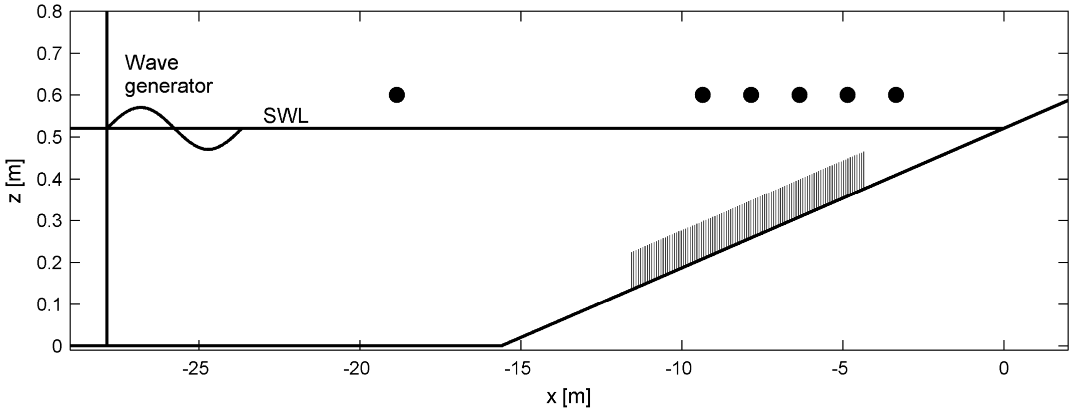

Figure 1. Overview of the wave flume setup as used by Kansy (1999), including the location of the kelp vegetation field and the wave gauges (black dots).

In total Kansy (1999) conducted 20 irregular wave experiments in which he varied the wave height (4x) and peak period (5x), and studied the wave energy dissipation by wave breaking and kelp vegetation, and the effect of the vegetation on the wave run-up. Each individual experiment took 8 minutes, and the water surface elevation was measured by six wave gauges with a 20 Hz sampling frequency. One wave gauge was located at the deeper horizontal part of the profile, and one wave gauge was located onshore of the vegetation field. The remaining 4 wave gauges were located in the vegetation field with a uniform spacing of 1.5 m, see Figure 1.

4.2 Model setup

For the current study 8 cases with a range of wave heights (6.2 – 19.3 cm) and peak periods (2.56 – 5.12 s) were selected to verify the model, see Table 1. For all cases a 1D XBeach model was setup on laboratory scale (1/10, see Figure 1), and ran for 600 s with an offshore water depth of 0.52 m. The offshore wave conditions were applied using a JONSWAP spectrum (γ_{jsp}=3.3), and use was made of first-order wave steering (i.e. no incoming bound long waves, only short wave energy). Since the flume at SINTEF did not have active wave reflection compensation at the wave board, this was also turned off in the model.

Table 1. Overview of Kansy (1999)-experiments used in this study.

CASE	H_{M0} [CM]	T_P [S]
1	6.9	2.56
2	13.6	2.56
3	16.5	2.56
4	19.3	2.56
5	6.2	5.12
6	12.9	5.12
7	15.9	5.12
8	18.9	5.12

The kelp vegetation was represented by rigid cylinders of 9 cm high and a density of 1200 units/m^2. The plant area per unit height (b_v) of the vegetation was 2.5 cm. For the bulk coefficient Mendez and Losada (2004) derived a formulation based on the experiments carried out by Dubi (1995), which used the identical artificial kelp models as Kansy (1999). They expressed the bulk drag coefficient as function of the Keulegan-Carpenter number (K= $u_c T_p / b_v$, in which u_c is a characteristic velocity acting on the plant). In this study, however, we assume that a constant bulk drag coefficient can be applied to all cases, thereby neglecting the effect of the wave induced velocity and the plant swaying motion. Based on a number of simulations with C_D-values ranging between 0 and 1, a bulk drag coefficient of 0.4 was found the give best results, and was therefore used.

Finally, the wave breaking model described by Daly et al. (2011) was used with α-parameter of 1.5. All other model parameters were kept default.

4.3 Results

The modeled (short) wave height evolution is compared with the measurements as described in Kansy (1999). The results for case 1 to 4 (peak period of 2.56 s) are plotted in Figure 2. When looking at the cases without vegetation, it can be seen that the model is able to reproduce the shoaling and dissipation due to breaking rather well, except for the case with the lowest waves. The measurements show that the waves of about 7 cm shoal up to about 10 cm, while the model only reaches a maximum wave height of about 8 cm. Further inspection of the results show that the local water depth at x = -5 m is about 17 cm, which results in an H/h-ratio of about 0.59 for the measurements. This suggests that a higher γ_{break}-parameter for the wave breaker model may be applicable here (default = 0.55). For the other cases, however, this will result in an overestimation of the wave height in the breaker zone, and is therefore not applied here.

For the cases with vegetation, it can be noticed that, while for the case with the lowest wave height the dissipation by vegetation is underestimated, for the other cases the wave evolution is well captured. This may partly be due to the underestimated wave height in general for this case. Another possible explanation is the constant bulk drag coefficient assumption which may not be applicable here. Overall the model seems to be able to reproduce the effect of the kelp vegetation satisfactorily.

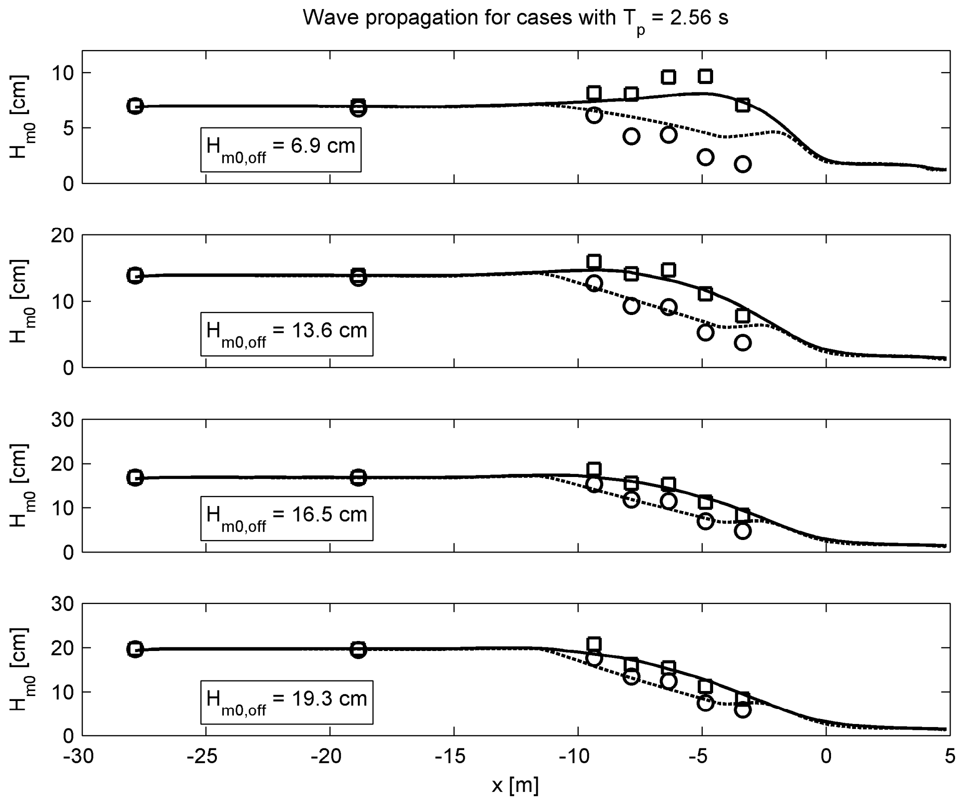

Figure 2. Measured and computed wave height evolution for cases 1-4 (T_p = 2.56 s), with (measured: circles, model: solid line) and without (measured: squares, model: dashed line) vegetation.

Figure 3 shows the same plots but now for the cases with a peak period of 5.12 s (case 5-8). Again, the wave evolution for the lowest wave height case (case 5, H_{m0} = 6.2 cm) is underpredicted by the model. The waves shoal less, and start breaking sooner in the model. For the other cases the wave propagation in cross-shore direction is captured better although the wave height is somewhat overestimated at the two most shoreward wave gauges. The wave evolution in case of vegetation seems well captured by the model for all four cases.

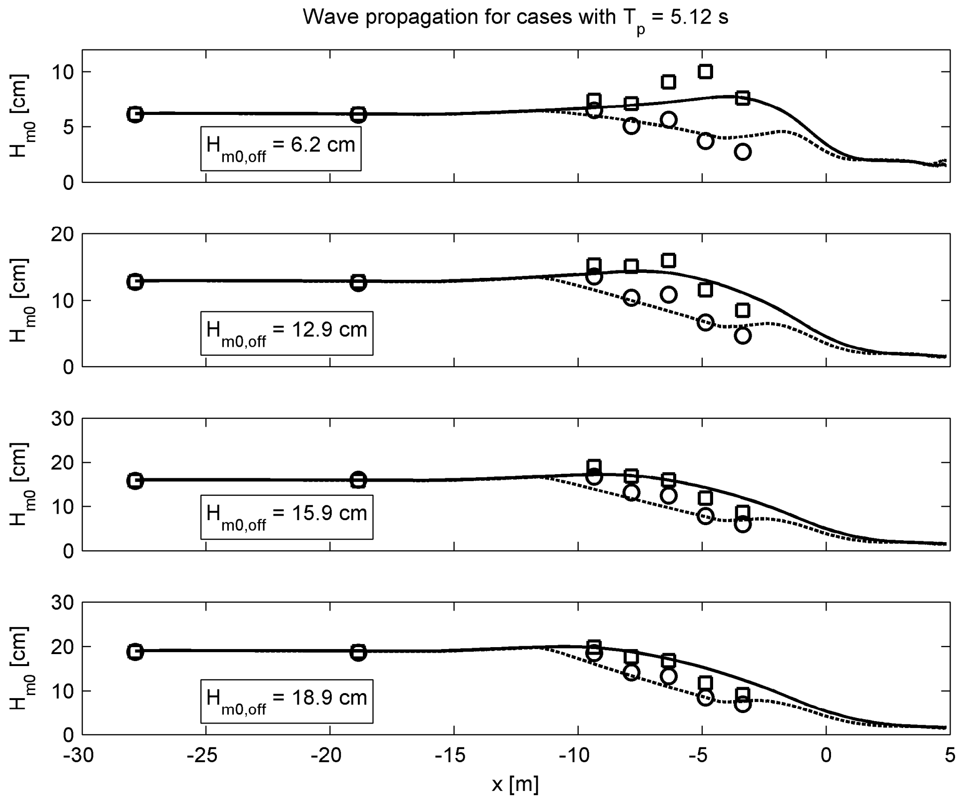

Figure 3. Measured and computed wave height evolution for cases 5-8 (T_p = 5.12 s), with (measured: circles, model: solid line) and without (measured: squares, model: dashed line) vegetation.

5. FINAL CONSIDERATIONS

In this study the numerical storm impact model XBeach was extended with formulations by Mendez & Losada (2004) to take into account wave attenuation by vegetation. In addition, the effect of vegetation on infragravity waves and mean flow was incorporated using a Morison-type equation. The model was tested using lab experiments with submerged model kelp vegetation carried out by Kansy (1999). In total 8 test cases with varying wave conditions were modeled and the measured and computed wave heights were compared. Even though calibration was very limited, the model reproduced the wave height evolution over the cross-shore profile reasonably well. The wave attenuation by the vegetation was well reproduced after a constant value for the bulk drag coefficient was selected on a number of calibration runs.

The current work is considered a first step into further incorporating vegetation effects in the XBeach model. Here, use was made of vertically uniform vegetation elements, although the code extension allows for vertically non-uniform vegetation species (e.g. mangroves). Furthermore, formulations for damping of infragravity waves and mean flow were incorporated, but could not be tested yet. This will be part of future work, as well as the effect of emerged vegetation and nonlinear wave effects.

One of the main uncertainties in the current approach is the determination of the bulk drag coefficient. For simplicity, use was made of a value which was kept constant throughout all simulations. In future work variation of the bulk drag coefficient will be investigated in more detail.

As mentioned, this work is considered as a first step only, and more model developments regarding vegetation in XBeach are foreseen for the near future. The objective is to have XBeach accurately take the effect of relatively complex vegetation species into account (e.g. mangroves) in a computationally efficient way.

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