ASSESSMENT OF RANDOM WAVE ENERGY DISSIPATION DUE TO SUBMERGED AQUATIC PLANTS IN SHALLOW WATER USING DEEP WATER WAVE CONDITIONS

Dag Myrhaug[1*], Pierre-Yves Henry[2]

[1]Department of Marine Technology

Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[2]Sintef Ocean, Department of Ship and Ocean Structures

***Corresponding author at: Department of Marine Technology,**

Norwegian University of Science and Technology (NTNU), Otto Nielsens vei 10,

NO-7491 Trondheim, Norway

E-mail address: dag.myrhaug@ntnu.no

Abstract

This article addresses the random wave energy dissipation due to submerged aquatic vegetation plants in shallow water based on deep water wave conditions including estimation of wave damping. The motivation is to provide a simple engineering tool suitable to use when assessing random wave damping due to small patches of plants in shallow water. Examples of application for typical field conditions are provided. The present method versus common practice is discussed. A possible application of the outcome of this study is that it can be used as a parameterization of wave energy dissipation due to vegetation patches of limited size in operational estuarine and coastal circulation models.

Keywords: Random waves; Dissipation; Wave damping; Drag coefficient; Shallow water; Deep water wave conditions; Submerged aquatic plants; Estuaries; Coastal zones.

1. Introduction

At shallow water depths in estuaries and coastal zones, the flow is induced by surface waves and currents. In general, coastlines are vulnerable due to the combined action of waves and currents and the effect of this on sediment transport and consequently on coastal erosion. Submerged vegetation represents a natural protection to estuaries and coastal zones, by modifying the hydrodynamics and sediment transport processes in comparison to locations without vegetation. Paul[1] has recently addressed the role of seagrass for coastal protection, identifying that knowledge gaps exist regarding the support that seagrass can provide for sandy shorelines protection. The damping effect of vegetation on waves in an estuary was clearly documented by Nowacki et al.[2]; they found that the wave-induced seabed shear stress is about 15% less in the presence of vegetation, than the bed shear stress due to the higher waves which would be present with no vegetation.

In general, coastal flow circulation models are commonly used tools in coastal protection work, where the wave damping e.g. due to vegetation has to be represented, i.e. often in terms of a bulk drag coefficient. However, at present there is no consensus on how this wave damping due to vegetation shall be taken into account. Henry et al.[3] gave a comprehensive and critical review of the available drag coefficient formulations under wave conditions as well as a literature review up to that date (see the references therein). More recent works, also addressing wave energy dissipation and containing literature reviews, include those of Liu et al.[4], Tinoco and Cuo[5], Losada et al.[6], Luhar and Nepf[7], Henderson et al.[8], Nowacki et al.[2], Paul[1] and Maza et al.[9]. The present work is supplementary to Myrhaug[10] who provided a simple analytical method on estimating random wave-driven drag forces on near bed vegetation in shallow water based on deep water wind statistics.

This paper is organized as follows. The Introduction is followed by Section 2, giving the general formulation of the wave energy dissipation including the wave-induced drag force formula used here in terms of a slightly revised version of the Sànchez–Gonzàlez et al.[11] drag coefficient for submerged vegetation. Section 3 gives the wave energy dissipation for random waves in shallow water expressed in terms of the deep water wave amplitude spectrum including an estimate of wave damping. Section 4 provides examples of results for a Pierson-Moskowitz wave amplitude spectrum by first demonstrating application of results (Section 4.1), and then comparing the present model predictions with one case from Mendez and Losada[12] (Section 4.2). Section 5 discusses the present approach versus common practice. A summary is given in Section 6. Overall, the present formulation provides an estimation of wave energy dissipation due to a small vegetation patch based on solely offshore wave conditions. Because these parameters are usually easier to derive than the wave parameters at the coast, this approach offers a cost-efficient method which should have the potential to be used as a parameterization in operational estuarine and coastal circulation models.

2. General formulation

The drag force is the main component of the fluid forces acting on plants and is expressed in terms of a Morison-type equation when the sway motion of the vegetation as well as inertial forces are neglected (Mendez and Losada[13]). Furthermore, by neglecting the vertical force component, the fluid force is given by the horizontal component, and the horizontal time-varying force per unit volume exposed to regular waves is given as (Mendez and Losada[13])

$$F(t) = \frac{1}{2}\rho C_D bN\, u(t)\,|u(t)| \tag{1}$$

Here $u(t)$ is the undisturbed horizontal regular wave-induced velocity in the area with plants, t is the time, ρ is the water density, b is the plant width, i.e. corresponding to the plant area per unit height of each plant normal to $u(t)$, N is the number of plants per unit horizontal area, and C_D is a bulk (i.e. depth-averaged) drag coefficient. Strictly, the correct calculation of $F(t)$ demands that the relative velocity between fluid and plant is used rather than $u(t)$; however, Eq. (1) is also used for flexible plants by using other C_D expressions than for rigid plants.

The wave energy dissipation due to plants is obtained as the time-average over one wave period T of the work done by the drag force:

$$E_D = \frac{1}{T}\int_0^T F(t)\,u(t)\,dt \tag{2}$$

Then, for $u(t) = U\sin\omega t$ where U is the amplitude of the horizontal velocity during the regular wave cycle with the angular wave frequency $\omega = 2\pi/T$, the result of combining Eqs. (1) and (2) gives

$$E_D = \frac{2}{3\pi}\rho C_D\, bN U^3 \tag{3}$$

Although based on some strong assumptions, Eq. (1) is often used as an estimation of the forces on vegetation thanks to its simple formulation (e.g. van Rooijen et al.[14]; Vuik et al.[15]). The drag force depends on the mechanisms of plant-flow interaction covering a wide range of flow regimes and its estimation is difficult; to this date no consistent theory or formulae exist including these mechanisms. In the present work the C_D formula proposed by Sànchez-Gonzàlez et al.[11] is adopted, which can be approximated by

$$C_D = cKC^d,\ \ (c,d) = (15.2,\ -1) \tag{4}$$

Here, *c* and *d* are coefficients originally given as $(c,d)=(22.9,-1.09)$ and valid in the range 15 < *KC* < 425. However, as shown in Fig.1, Eq. (4) is a good representation of the original formula and estimated by a least root-mean-square fit to the original formula. The original formula was obtained as a best fit to flume test results of regular and irregular waves over submerged artificial flexible seagrass, and $KC = UT/b$ is the Keulegan-Carpenter number. For linear waves in shallow water, *U* is independent of the vertical coordinate *z* and given by $U = \omega a / kh$, where *a* is the linear wave amplitude, *h* is the water depth, and *k* is the wave number determined from the shallow water dispersion relationship as $k = \omega / \sqrt{gh}$. By using these relationships and substituting Eq. (4) (i.e. using *c* = 15.2, *d* = -1) in Eq. (3), the wave energy dissipation in regular waves in shallow water becomes

$$e_D \equiv \frac{E_D}{\frac{1}{3\pi^2}\rho c b^2 N} = \frac{g}{h}\omega a^2 \tag{5}$$

3. Wave energy dissipation for random waves in shallow water

The wave energy dissipation for an individual wave component with amplitude a_n and angular wave frequency ω_n at a shallow water depth *h* is given for regular waves in Eq. (5) as

$$e_{Dn} = \frac{g}{h}\omega_n a_n^2 \tag{6}$$

Now $a_n^2 = 2S(\omega_n, h)\Delta\omega$ where $S(\omega,h) = (h/2g)\omega^2 S(\omega)$ is the wave amplitude spectrum in shallow water (Massel[16], Section 7.3), $S(\omega)$ is the deep water wave amplitude spectrum, and $\Delta\omega$ is a constant separation between frequencies. It should be noted that no energy is lost in this transformation from deep to shallow water. Thus, substituting a_n^2 in Eq. (6), it follows for an infinite number of wave frequencies that the wave energy dissipation is

$$e_D = \frac{1}{2}\int_0^{\infty} \omega^3 S(\omega)\, d\omega = m_3 \tag{7}$$

where m_3 is the third spectral moment of $S(\omega)$, and the spectral moments for deep water waves are defined as $m_n = \int_0^{\infty} \omega^n S(\omega) d\omega;\ n = 0,1,2,----$. Then, it follows from Eqs. (5) and (7) that

$$E_D = \frac{1}{3\pi^2} \rho c\, b^2\, N\, m_3 \tag{8}$$

which is known for given wave conditions in deep water.

The damping of random waves in shallow water due to a patch containing N stands per unit area with a height Δh can be estimated by the change in wave energy flux caused by energy dissipation as

$$\frac{d}{dx}(E_h c_{gh}) = -E_D \cdot \Delta h \tag{9}$$

where x is the horizontal coordinate, $E_h = \frac{1}{8}\rho g\, {H_{sh}}^2$ is the wave energy in shallow water, H_{sh} is the significant wave height in shallow water, and $c_{gh} = \sqrt{gh}$ is the group velocity in shallow water (see Appendix 1). Substitution in Eq. (9) and integrating over the patch length L (i.e. from x = 0 to x = L) yields the significant wave height H_{shL} at x = L when the significant wave height H_{sh0} at x = 0 is known:

$$H_{shL} = \left({H_{sh0}}^2 - \frac{8c\, b^2\, N\Delta h}{3\pi^2 g\sqrt{gh}}\, m_3 L \right)^{1/2} \tag{10}$$

It should be noted that the results are valid if the Ursell number in shallow water, U_{Rhs}, is smaller than 0.5, i.e. (see Eq. (18) in Appendix 1)

$$U_{Rhs} = 0.062\frac{H_s\, T_p^{2.5}}{h^{2.25}} \le 0.5 \tag{11}$$

where H_s is the significant wave height in deep water, and T_p is the spectral peak period. Thus, the results for given values of H_s and T_p are valid for the water depth h consistent with Eq. (11), and for the deep water wave steepness $s_p < 0.04$ (see Eq. (23) in Appendix 1).

It should also be noted that Eq. (4) is valid for $KC = UT / b$ in the range 15 to 425. As shown in Appendix 1, the Keulegan-Carpenter number can also be defined for random waves in shallow water, KC_{sh}, i.e. (see Eq. (22) in Appendix 1)

$$KC_{sh} = \frac{U_{sh} T_p}{b} \ ; \ \ 15 < KC_{sh} < 425 \tag{12}$$

where U_{sh} is the wave-induced velocity given in Eq. (21).

The present model is a so-called point model, i.e. depending on the local wave parameters regardless of the history of the waves as they propagate from deep to shallow water. Further aspects of this model will be discussed in Section 5.

4. Examples of results for a PM spectrum

The Pierson-Moskowitz (PM) wave amplitude spectrum with the mean wind speed at the 10 m elevation above the sea surface, U_{10}, as the parameter is applied as the deep water wave amplitude spectrum. One should notice that the PM spectrum is valid for fully developed wind waves, but as a compromise between simplicity and accuracy it is adopted here to demonstrate how a standard wave amplitude spectrum can be used analytically. Some further comments are provided in Section 5. According to Tucker and Pitt[17] the PM spectrum is $S(\omega) = A\omega^{-5} exp(-B\omega^{-4})$ where the spectral moments for $n < 4$ are $m_n = 0.25AB^{n/4-1}\Gamma(1-n/4)$, Γ is the gamma function, $A = \alpha g^2, \alpha = 0.0081$, $B = 1.25\omega_p^4$, $\omega_p = 2\pi/T_p$ is the spectral peak frequency corresponding to the spectral peak period T_p. Then it follows that $m_3 =$

$0.25\alpha g^2 1.25^{-0.5}\omega_p^{-1}\Gamma(0.25)$, which combined with $T_p = 0.785U_{10}$ and $\Gamma(0.25) = 3.6256$ gives $m_3 = 0.101\,T_p = 0.0793U_{10}$ (m^2/s^3). Substitution of this in Eq. (10) with $c = 15.2$ yields

$$H_{shL} = \left(H_{sh0}{}^2 - 0.0135\frac{b^2\,N\Delta h}{\sqrt{h}}\,T_p L \right)^{1/2} \tag{13}$$

It also follows that $H_s = 4\sqrt{m_0} = 0.04T_p^2 = 0.0246U_{10}^2$, and thus, $T_p / \sqrt{H_s} = 5$ for all combinations of H_s and T_p in a PM spectrum.

4.1 Example 1

This example is included to demonstrate the application of the results for some typical field conditions with spectral peak period $T_p = 11.8\,\text{s}$ and significant wave height in deep water $H_s = 5.6\,\text{m}$ (i.e. $U_{10} = 15\,\text{m/s}$) as an example. Then it follows that:

Spectral wave steepness from Eq. (23), $s_p = 0.026 < 0.04$

Water depth from Eq. (19), $h \geq 13.2\text{m}$. Thus, $h = 15\,\text{m}$ as an example, which gives:

Shallow water Ursell number from Eq. (11) (or Eq. (18)), $U_{Rhs} = 0.38 < 0.5$

Wave energy dissipation, $E_D \cdot \Delta h$, from Eq. (8) (with c = 15.2) for $\rho = 1027\,\text{kg/m}^3$, b = 0.1 m , $\Delta h = 1\text{m}$ and $N = 1$ (i.e. per plant), $E_D \cdot \Delta h = 6.3W$

Significant wave height in shallow water from Eq. (20), $H_{sh} = 4.9\,\text{m}$

Shallow water wave-induced velocity from Eq. (21), $U_{sh} = 2.0\text{m/s}$

Shallow water Keulegan-Carpenter number from Eq. (22) with b = 0.1 m, $KC_{sh} = 236$, i.e. in the validity range of the formula.

Next, consider a patch with N = 100 plants/m^2, L = 100 m and $H_{sh0} = 4.9\,\mathrm{m}$. Then, substitution in Eq. (13) gives

$$H_{shL} = \left(4.9^2 - 0.0135 \frac{0.1^2 \times 100 \times 1}{\sqrt{15}} 11.8 \times 100 \right)^{1/2} = 4.5\,\mathrm{m} \qquad (14)$$

i.e. the significant wave height is reduced by 8.2 %.

4.2 Example 2

This example provides a comparison between the present predictions and a case from Mendez and Losada[12], who presented a model using potential flow and an eigenfunction expansion considering regular and irregular incidental waves on a vegetation field taking into account vegetation motion. The model results show very good agreement with existing experimental data for regular and irregular waves. Here the results presented in Fig. 5(c) in Mendez and Losada[12] are used to compare with. In terms of the present notation their results correspond to the following shallow water random wave conditions: $k_p h = 1.05$, h = 10 m, $H_{sh0} = 2.8\,\mathrm{m}$, N = 15 stands/m^2, b = 0.1 m, $\Delta h = 0.7\,\mathrm{m}$, L = 100 m. Thus, this corresponds to $T_p = 2\pi / (k_p h \sqrt{gh}) = 6.0\,s$. Substitution in Eq. (13) gives

$$H_{shL} = \left(2.8^2 - 0.0135 \frac{0.1^2 \times 15 \times 0.7}{\sqrt{10}} 6.0 \times 100 \right)^{1/2} = 2.3\,\mathrm{m} \qquad (15)$$

i.e. corresponding to a significant wave height reduction of 18 %, while the reduction given in Mendez and Losada[12], Fig. 5(c) is 19 %, i.e. a priori the agreement appears to be excellent. However, a closer inspection of the results using the conditions in Appendix 1 yields: $H_s = 4.1\,\mathrm{m}$ (Eq. (20)), $s_p = 0.073$ (Eq.

(23)), $U_{Rhs} = 0.126$ (Eq. (18)), $KC_{sh} = 84$ (Eqs. (21) and (22)). Moreover, $T_p / \sqrt{H_s} = 6/\sqrt{4.1} = 3$, i.e. smaller than 5 for a PM spectrum. Thus, although $U_{Rhs} < 0.5$ and $15 < KC_{sh} < 425$, the deep water wave conditions correspond to a steeper sea state than strictly required, i.e. 0.073 > 0.04. However, despite this inconsistency the results are physically sound and reasonable, and should therefore support and justify the method. Detailed field and/or experimental datasets on random wave dissipation over submerged vegetation are still scarce and the comparison of this approach against new datasets (out of the scope of this technical note) would be required to confirm the results presented here.

5. Discussion

This section provides further aspects of the present point model as well as some comments on this approach versus a procedure which commonly is used. For calculating the random wave energy dissipation and the resulting wave damping due to submerged aquatic plants in shallow water, common practice would be to start with available data on joint statistics of H_s and T_p (or other characteristic wave periods); preferably within directional sectors at a nearby location offshore (in deep water). The next step would be to apply an appropriate wave simulation model including effects of dissipation such as bottom friction and wave breaking, to obtain the joint statistics of H_s and T_p at the shallow water site; then finally to use this as input for calculating the wave energy dissipation and wave damping. In general this practice would also include shallow water regions exposed to sea states with combined wind waves and swell waves from different directions. Here an alternative is presented providing a simple analytical method which can be used to make assessment of the random wave energy dissipation and wave damping du to vegetation from given values of H_s and T_p, exemplified by including results using the PM deep water wave amplitude spectrum representing wind waves. The transition from deep water to the shallow water site is assumed to be smooth, neglecting wave energy dissipation effects over changing bed conditions with varying shallow water depths. The feature of a point model also implies that the dependence on the spatial coordinates is discarded; it only depends on the local water depth and the local wave conditions via the transformed deep water wave spectrum for long-crested waves in terms of the sea state parameters H_s and T_p. Consequently, several aspects affecting the assessment of the wave energy dissipation due to vegetation are neglected, i.e.: that the wave field is inhomogeneous; from where the waves are coming and the location of the assessment point; return flows from dissipation effects which in turn will affect the local wave spectrum, the C_D coefficient, and the velocity field $u(t)$. However, the point model enables analytical estimates of the wave energy dissipation and wave damping due to plants from vegetated patch of a limited size, which are appropriate for making quick estimates. Then, these estimates can be used to compare with more complete computationally demanding methods. Under field conditions such an easily accessible and simple tool might also be useful as there is usually limited time and access to computational resources. Although the presented results are based on a specific drag coefficient formula and the PM deep water wave amplitude spectrum, the method can also be applied for other drag coefficient formulations, other deep water wave amplitude spectra including directional spreading effects, or joint distributions of sea state wave parameters. However, in such cases numerical calculations are probably required. It is important, however, to assess the accuracy of this approach versus common practice, which is only possible to quantify by comparing with such methods over a wide parameter range, also including a sensitivity analysis of the results regarding the assumptions considered, but this is beyond the scope of this article.

6. Summary

A simple analytical method for estimating random wave energy dissipation and wave damping due to submerged aquatic vegetation in shallow water using deep water wave conditions is provided. The wave energy dissipation is based on a drag force formula for submerged artificial flexible seagrass adopting a slightly revised version of the Sànches-Gonzàles et al.[11] drag coefficient in terms of the Keulegan-Carpenter number. This formulation of wave energy dissipation is applied for random waves by transformation of deep water waves to shallow water. The wave energy dissipation and wave damping due to plants in shallow water are then obtained expressed in terms of the third spectral moment of the deep water wave amplitude spectrum. Results are exemplified for sea states described by the PM deep water wave amplitude spectrum representing wind waves. An example gives favorable results compared with one case from Mendez and Losada[12] based on their model results. The present method versus common practice is also discussed. Although simple, the present approach should represent a useful tool for the assessment of random wave energy dissipation and wave damping due to small submerged vegetation patches in shallow waters of estuaries and coastal regions. The present formulation may also have the potential to serve as a useful parameterization of wave energy dissipation due to vegetation patches of limited size, which can be used in operational estuarine and coastal circulation models.

Appendix 1

For harmonic waves in finite water depth the Ursell number is defined as (Dean and Dalrymple[18]) $U_R = ka/(kh)^3$. In general, U_R gives the ratio between the nonlinearity of the waves in terms of the wave steepness *ka*, and the dispersive properties of the waves in terms of *kh*. Linear waves are valid for $U_R \leq 0.5$ and the deep water wave steepness $s = H_\infty / ((g/2\pi)T^2) \leq 0.04$ (Hedges[19]), where the index ∞ refers to deep water.

Furthermore, for linear harmonic waves propagating over a gently sloping flat bottom approaching a straight coastline at normal incidence, the wave amplitude is found by using that the energy flux is constant (Dean and Dalrymple[18]), i.e. $a^2 c_g = \text{constant}$, where $c_g = (c/2)(1+2kh/\sinh 2kh)$ is the group velocity, and $c = \omega / k$ is the phase velocity. Using deep water as a reference ($a = a_\infty$ and $c_\infty = \omega / k_\infty$), the wave amplitude a in shallow water $(kh << 1)$ (using $\omega^2 = gk_\infty$ in deep water, $\omega = k\sqrt{gh}$ in shallow water, and that $\omega = \text{constant}$) is

$$\frac{a}{a_\infty} = \frac{1}{(2kh)^{1/2}} \tag{16}$$

Substitution of $k = 2\pi / (T\sqrt{gh})$, $a_\infty = H_\infty / 2$ where H_∞ is the deep water height, gives the Ursell number in shallow water as

$$U_{Rh} = 0.062 \frac{H_\infty T^{2.5}}{h^{2.25}} \tag{17}$$

By replacing H_∞ with H_s and T with T_p , the Ursell number for a sea state is defined as

$$U_{Rhs} = 0.062 \frac{H_s T_p^{2.5}}{h^{2.25}} \tag{18}$$

Thus, Eq. (18) is the Ursell number in shallow water depth h in terms of the deep water sea state parameters H_s and T_p, which is valid for $U_{Rhs} \leq 0.5$, and consequently the results are valid for

$$h \geq (0.124 H_s T_p^{5/2})^{4/9} \tag{19}$$

Similarly, by replacing a with $a_h = H_{sh} / 2$, a_∞ with $H_s / 2$ and T with T_p, Eq. (16) gives the significant wave height H_{sh} in shallow water as

$$H_{sh} = \frac{H_s}{2} \left(\frac{T_p}{\pi} \sqrt{\frac{g}{h}} \right)^{1/2} \tag{20}$$

The Keulegan-Carpenter number in shallow water representing random waves can also be defined. For shallow water linear waves the horizontal wave-induced velocity amplitude is (Dean and

Dalrymple[18]) $U = a(g/h)^{1/2}$. Thus, by replacing a with $a_h = H_{sh}/2$, the corresponding wave-induced velocity becomes

$$U_{sh} = \frac{H_{sh}}{2}\left(\frac{g}{h}\right)^{1/2} \tag{21}$$

Similarly, $KC = UT/b$ is re-arranged to KC_{sh} for random waves in shallow water, i.e.

$$KC_{sh} = \frac{U_{sh}T_p}{b} \tag{22}$$

which is taken to be valid for $15 < KC_{sh} < 425$.

Moreover, the wave steepness in deep water expressed in terms of the sea state parameters is

$$s_p = \frac{H_s}{\frac{g}{2\pi}T_p^2} \tag{23}$$

which should satisfy that $s_p < 0.04$.

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Figure caption

Fig. 1 C_D versus KC for two (c, d) sets.