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Physical and Numerical Modelling of Wave Transformation through a Coastal Canopy

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Abstract

Coastal canopies formed by aquatic vegetation (e.g. seagrass, mangroves) or corals can be found along many coastlines worldwide and often have a significant effect on the local wave dynamics. Over the past several decades, many studies have greatly increased our understanding on the physical interaction between coastal canopies and waves in the coastal ocean. However, whereas most studies have investigated (bulk) wave dissipation by coastal canopies through empirical formulations, relatively little attention has been paid to the specific instantaneous wave dynamics inside the canopy and how this mechanistically controls wave transformation over canopies. In this study, we extended a state-of-the-art numerical wave model with a canopy flow model to develop a more accurate formulation of the canopy drag force that controls rates of wave dissipation. To validate the model, experiments were carried in a large wave flume with a rigid, high-density model canopy. Model-data comparison using the in-canopy flow velocity and the wave height distribution over the canopy shows that the model is able to capture the essential physics. The results suggest that the canopy flow model increases the accuracy of the estimation of wave dissipation due to canopy drag. Wave attenuation by coastal canopies may be overestimated by wave models without a canopy flow model due to the lack of physics describing canopy flow attenuation.

Introduction

Coastal canopies formed by aquatic vegetation (e.g. seagrass, kelp or mangroves) or corals can be found along many coastlines worldwide. Over the past several decades, much progress has been made in understanding how waves propagating towards the coast are affected by coastal canopies, with a particular focus on wave attenuation. Research that has been conducted to date ranges from idealised laboratory experiments to several field and numerical modelling studies. In general, coastal canopies are found to substantially enhance the rates at which wave energy is dissipated in the coastal zone, thereby reducing the wave impact on coastlines and increasing resilience against coastal hazards.

In recent years, several numerical wave models have been developed that take into account the presence of coastal canopies. These models can be categorized as either sea-swell wave phase-averaging [e.g., 10] or phase-resolving models [e.g., 2, 6]. For the latter (e.g. Boussinesq-type or nonhydrostatic models), the effect of aquatic vegetation is typically taken into account through the addition of a drag force term in the momentum equations [e.g., 6]. The drag force is computed as a function of the wave-induced orbital velocity, the canopy characteristics (e.g. stem diameter, canopy density and height) and a drag coefficient.

Often the (undisturbed) free-stream velocity is used to compute the canopy drag force, which can lead to significant overprediction of wave attenuation. The canopy drag force may be overestimated as the in-canopy orbital velocity can be significantly attenuated relative to the free-stream velocity, particularly in dense canopies [e.g., 3]. In these cases, it is more appropriate to use the in-canopy velocity to compute the canopy drag force [2]. Lowe et al. [3, 4] developed an analytical model where the in-canopy velocity is computed as function of the wave-induced pressure gradient and the canopy characteristics. Later, this model was extended by integrating it with a flow model for porous media making it applicable for both typical canopy flow (e.g. seagrass or kelp vegetation) and porous media flow (e.g. flow through complex coral canopies or even gravel barriers and breakwaters).

In this study, we extended the vegetation module of XBeach [8, 11] by implementing the canopy flow model (following [3, 4]), and coupling it to the nonhydrostatic (phase-resolving) mode of XBeach. The model computes the instantaneous depth-averaged wave velocity inside the canopy, which is used to compute the canopy drag force. The drag force is then used to compute the canopy-induced wave dissipation. The model was validated against experiments carried out in a large wave flume with a high-density rigid canopy.

Methods

Experimental Setup

Experiments were carried out in a 25 x 1.2 x 1.2 m wave flume at The University of Western Australia. Regular waves were generated by a piston-type wave maker positioned at one end of the flume. In order to minimize wave reflection, the flume was equipped with a 1:10 beach, which acted as a passive wave energy absorber (Figure 1).

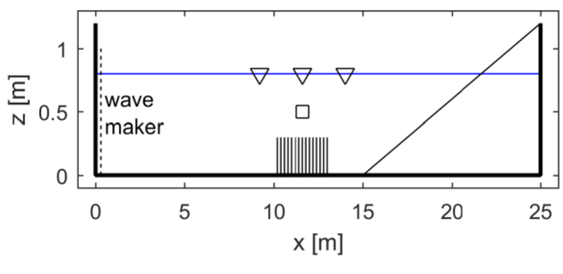

Figure 1. Schematic view of the experimental setup (not to scale), including the locations of the velocimeter (square) and wave gauges (triangles).

A rigid canopy was constructed by inserting wooden dowels (of diameter 6.4 mm and height, h_c, of 30 cm) into a perforated PVC board. The canopy extended for 2.8 m in the direction of wave propagation (between x = 10.2 and 13 m) and extended across the width of the flume. The density was 3200 elements per m^2, resulting in a solid fraction of approximately 10%. The water depth was kept constant throughout the experiments (h = 0.80 m, canopy submergence ratio h_c/h = 0.38).

Eight different wave conditions with a range of wave heights and periods were tested (Table 1). A Sontek 3D Acoustic Doppler Velocimeter (ADV) was positioned in the middle of the canopy and obtained vertical profiles of wave-induced velocity at 25 Hz (Figure 1). The duration of each velocity record was at least 50 wave periods in all cases. To allow measurement inside the canopy, a limited number of stems were removed. Three wave gauges (RBR-WG50) were employed to measure the instantaneous water surface elevation: one was positioned halfway along the canopy, with one on either side of the canopy (Figure 1).

Exp.	H [cm]	T [s]	$u_{\infty,rms}$ [cms^{-1}]
R1	4.7	3	6.9
R2	11.5	3	15.5
R3	20.4	3	26.5
R4	6.2	5	6.6
R5	14.6	5	16.6
R6	20.4	5	24.4
R7	15.4	7	13.6
R8	19.6	7	18.4

Table 1. Experimental wave conditions: wave height upstream of the canopy (H), wave period (T) and above-canopy RMS orbital velocity ($u_{\infty,rms}$).

Model Description

XBeach [7, 8] is an open-source storm impact model that can be run in sea-swell wave phase-averaged (stationary or surfbeat) or phase-resolving (nonhydrostatic) mode. Recently, a vegetation module was implemented for both modes allowing quantification of the effect of coastal canopies on waves and flow [11]. Here, the nonhydrostatic mode is used [9], which is similar to a depth-averaged version of the SWASH model [12].

The (1D) governing equations are based on the (depth-averaged) nonlinear shallow water equations, extended with a nonhydrostatic pressure term (see [11] for details). Here, we use the in-canopy velocity rather than the free-stream wave velocity to compute the drag force. The canopy-induced drag force ($F_{v,nh}$) in equation (3) of [11] is then given by:

$$F_{v,nh} = \rho \frac{h_c |u_c| u_c}{L_D} \tag{1}$$

where ρ is the water density, h_c is the canopy height, and u_c is the instantaneous depth-averaged velocity within the canopy. The drag length scale (L_D) is given by:

$$L_D = \frac{2h_c(1-\lambda_p)}{C_D \lambda_f} \tag{2}$$

Here, C_D is the drag coefficient, λ_p the solid fraction of the canopy and λ_f the frontal area per unit bed area. To compute the depth-averaged in-canopy wave velocity (u_c) the canopy model by [3, 4] was implemented in XBeach:

$$\frac{\partial u_c}{\partial t} = \left(1 + \frac{C_M \lambda_p}{1-\lambda_p}\right)^{-1} \cdot \left(g\frac{\partial \eta}{\partial x} + \frac{|u_c| u_c}{L_D} + \frac{\partial u_\infty}{\partial t}\right) \tag{4}$$

where C_M is the inertia force coefficient, g is the gravitational constant, η is the instantaneous water surface elevation and u_∞ is the free-stream velocity. Whereas [11] used the free-stream velocity to compute the drag force, here we use the (instantaneous) in-canopy flow velocity (u_c) which is expected to provide a more accurate prediction of canopy drag.

Results

The resulting wave-induced root-mean-square (rms) velocity profiles show a clear effect of the canopy, with significant velocity attenuation inside the canopy (Figure 2A). The velocity magnitudes are directly related to the imposed wave height, while an increase in wave period leads to slightly lower orbital velocities (see also Table 1). For most of the tested wave conditions the largest velocity occurred at the top of the canopy and can likely be attributed to the formation of a local shear layer [e.g., 5]. However, velocity measurements with higher vertical resolution around the top of the canopy would be required to study this in detail.

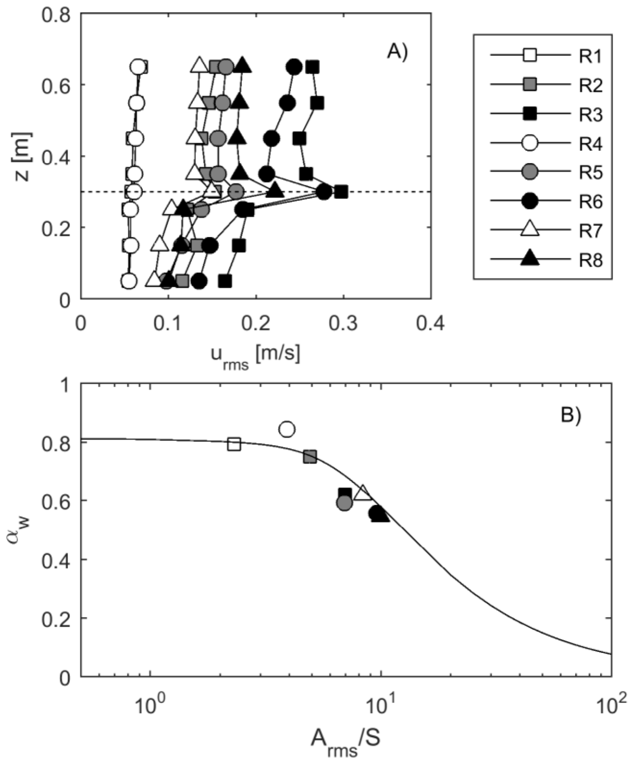

Figure 2. Measured (root-mean-square) velocity profiles above and inside the canopy for all eight wave conditions (Panel A), and measured (symbols) and theoretical (solid line, based on [3]) canopy attenuation parameter (α_w) as function of the wave orbital excursion A_{rms} over canopy spacing S (Panel B).

In each experiment, the depth-averaged velocity within the canopy (denoted by $u_{c,rms}$) and depth-averaged velocity above the canopy ($u_{\infty,rms}$) were calculated. Following [3], the canopy attenuation parameter for oscillatory flow (α_w) was computed:

$$\alpha_w = \frac{u_{c,\mathrm{rms}}}{u_{\infty,rms}} \tag{5}$$

The resulting value of α_w in each experiment is compared to the theoretical model of [3], where this ratio is a function of the wave orbital excursion length ($A_{rms} = u_{rms} \cdot T/2\pi$) divided by the canopy spacing (S = 1.1 cm here). The measurements show good agreement with the theory, with flow attenuation ranging between 20 and 50% (Figure 2B). Larger attenuation is found with larger wave excursion length A_{rms}, i.e. longer wave periods and larger (free-stream) orbital velocities.

Model simulations were subsequently carried out for each experiment using the extended version of XBeach as described above. The model settings were defined to match the experimental setup (Figure 1). At the offshore model boundary stationary (regular) wave conditions were applied, as specified in Table 1, and a uniform grid resolution of 10 cm was used. The drag coefficient C_D was set to 1.

First, the canopy attenuation parameter (α_w) was computed and compared with the measurements (Figure 3). The model shows good agreement with the measurements, with oscillatory flow attenuation for most wave conditions. The model underestimates the in-canopy velocity for the two cases with largest wave periods (R7 and R8, T = 7 s). Reflection from the shoreline was determined by applying the method described by [1], and it was found that for wave conditions R1-R6, wave reflection was negligible (reflection coefficient $K_R < 0.1$); however, the reflected wave energy for case R7 and R8 was more substantial ($K_R > 0.35$). Note that the canopy flow model assumes (fully) propagating, linear waves [2] and XBeach takes into account wave absorption, which may explain the differences between model and measurements. Finally, the canopy flow attenuation for wave condition R4 is overestimated, which is consistent with the findings from comparing the measurements with the theoretical model for this particular case (Figure 2). Nonetheless, the model is generally able to provide a reasonable prediction of the in-canopy flow velocity that is required to compute the canopy drag force.

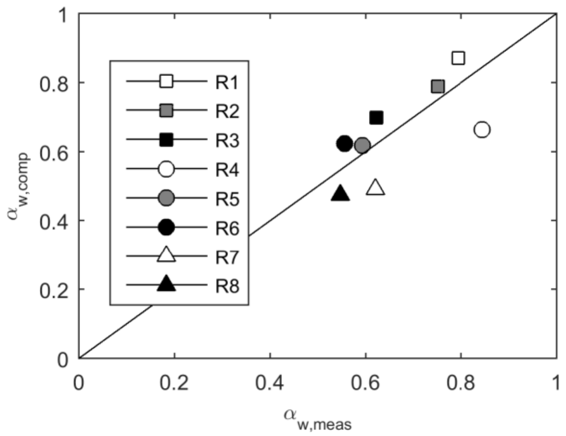

Figure 3. Measured vs. computed (XBeach) canopy attenuation parameter for oscillatory flow (α_w).

Second, the effect of using the canopy flow model on wave transformation is considered. Whereas many numerical models utilize the free-stream velocity, here we use the in-canopy velocity to compute the canopy drag force. The high-density canopy in the current experiments causes significant drag and therefore results in significant canopy flow attenuation, which in turn results in a lower drag force. It is therefore expected that wave attenuation is less than that predicted by the original model [9].

To verify our hypothesis, the water surface elevation was measured at three locations (before, mid-way and after the canopy) for three of the experiments (R1-R3) with a 25 Hz sampling rate. A subset of the water level time series of 100 wave periods is used to compute the local wave heights and compare with the modelled wave height distribution along the canopy.

The results show a clear effect of the canopy with decreasing wave height over the canopy, except for R1 where the effect of the canopy is limited (Figure 4). All three cases have identical wave periods (T = 3 s), so here the rate of wave energy dissipation is solely dependent on the imposed wave height, where the highest waves experience largest dissipation (R3). The modelled wave height distribution agrees well with the observations, in particular for R2 and R3. For R1, the wave height dissipation is limited, consistent with the limited effect of the canopy on the in-canopy flow velocity (see Figures 2 and 3).

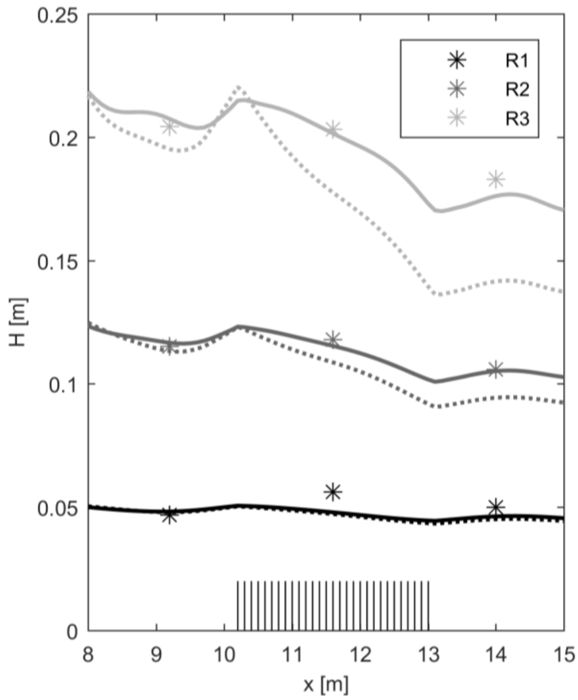

Figure 4. Measured (symbols) and computed (line) wave height distribution over the canopy with (solid line) and without (dotted line) using the canopy flow model. The location of the canopy is indicated with the black vertical lines between x = 10.2 and 13 m.

To verify whether better results are obtained when including the canopy-flow model, the model is re-run with identical model settings (e.g. C_D = 1) but without the canopy flow model (i.e. using the free-stream velocity to compute the canopy drag force). As expected, wave dissipation increases as the drag forces are larger (Figure 4). Although the effect in case R1 is limited, the other two conditions show a clear underprediction of the wave heights halfway and shoreward of the canopy. This suggests that neglecting the canopy flow may result in a substantial underestimation of the nearshore wave height and overestimation of the coastal protection services that can be provided by coastal canopies such as seagrass meadows or mangrove forests.

Discussion

The results from this study suggest that it is important to use the in-canopy flow velocity rather than the free-stream velocity when computing the canopy drag force. In many studies, the lack of an accurate representation of the canopy flow velocity is accounted for by using a calibrated (constant) drag coefficient (C_D) or an empirical formulation. However, based on these results it is suggested that using a canopy flow model to estimate the canopy flow velocity provides a more sophisticated method and reduces model calibration. Note that this study only considered a limited number of wave conditions and no variation in canopy characteristics. More measurements over a range of wave conditions and canopy characteristics (i.e. density and relative canopy height h_c/h) are now needed to confirm this hypothesis, and to further validate the modelling methodology.

Conclusions

In this study we extended the vegetation module of the open-source XBeach model with a canopy flow model to provide a more accurate description of the canopy drag force. To validate the model, we carried out experiments with different wave conditions and a rigid high-density (model) canopy in a large wave flume.

The measurements show a clear effect of the canopy with lower velocity magnitudes in the canopy compared to those above the canopy, consistent with previous findings. The in-canopy flow attenuation, which is observed to be up to 45%, is a function of wave height and period (or, more precisely, the orbital excursion length). The computed in-canopy flow velocity shows generally good agreement with the measurements. The computed in-canopy velocity is used to compute the canopy drag force in the model, which eventually accounts for the rate of wave dissipation. A model-data comparison of wave height evolution for three cases shows that a better agreement is found when using the in-canopy flow velocity in the drag model, compared to the free-stream velocity.

The results of this study suggest that without taking into account canopy flow attenuation, wave heights may be underestimated shoreward of the canopy, in particular for high-density canopies. Although this is often accounted for by adjusting the drag coefficient, it is suggested that the current methodology provides a more sophisticated approach and reduces the need for model calibration. As this work was based on a limited number of wave conditions and only one canopy configuration, more observations for a range of wave conditions and canopy configurations are now needed to further support this hypothesis.

Acknowledgments

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