

THE IMPACT OF DISSIPATION BY VEGETATION ON MEAN WATER LEVEL

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INTRODUCTION

Recently, natural and nature-based features have been considered a preferable alternative to conventional risk reduction engineering projects. For instance, the creation or maintenance of coastal vegetation may provide some measure of coastal protection through wave height reduction. Wave propagation through emergent mangrove forests with dense root mass, in particular, demonstrate energy decay in the field (Kibler et al., 2019) and in carefully controlled laboratory experiments (Kelty et al., 2022).

Efforts to develop a method of predicting wave attenuation in a practical way have been encumbered by complexities of wave-vegetation interaction and the detailed vegetation characteristics. Nevertheless, some measure of capability in predicting drag coefficients has been developed by exploiting a depth- and phase-averaged energy balance along with measured wave height change data.

Coastal storm hazards are typically characterized by large waves and elevated water levels. Wave energy attenuation by vegetation, doubtlessly, reduces the direct threat of waves with lower runup and storm-driven erosion. On the other hand, the impact of highly dissipative vegetation on the elevated water levels, or storm surge, is more complex and uncertain.

The effort outlined herein investigates the component of setup owing to the the forces on vegetation, making use of detailed laboratory measurements. Estimates of bottom friction and vegetation drag coefficients are directly computed with an energy balance using measured velocities and wave height decay. The momentum equation, including the calibrated steady force exerted by the vegetation, is integrated to estimate mean free-surface and compared with laboratory measurements, highlighting the relative importance of the forces on vegetation and wave radiation stress.

EXPERIMENT

A physical model study, undertaken in 2020 and 2021 at Oregon State University, was designed as a prototype-scale investigation of wave energy attenuation by mangrove forests. A description of the study is available in Kelty et al., 2022, detailing the methods where synthetic vegetation was arrayed within a flat section of a long wave flume. Free surface and velocity data were collected throughout the flume and within the 18m vegetated section. The experiment was designed with variations in water depth, wave

characteristics, and vegetation density to effectively span a wide range of naturally occurring conditions. Note that a baseline test condition, without any vegetation, was run for each water level and wave condition to establish wave transformation owing to bottom/wall friction.

MODEL

Conventional efforts to estimate energy loss in waves make use of a depth- and phase-averaged energy balance

$$\frac{\partial E_f}{\partial x} = -\overline{\tau u} - \overline{\int_{z_b}^{\eta} f u dz} \quad (1)$$

where $E_f = (\rho g/8)H^2 c_g$ is the wave energy flux, ρ is the density of water, g is gravitational acceleration, H is the wave height or rms wave height, c_g is the group velocity associated with the peak frequency, x is the horizontal coordinate, positive in the direction of wave travel, $\tau = \rho c_f |u|u$ is the wall/bottom shear stress, u is the depth-averaged velocity, f is the incremental fluid force on the vegetation per unit area. The fluid force on the vegetation is typically (e.g. Dalrymple et al., 1984) expressed

$$f = \rho \frac{C_D}{2} b_v N |u|u = \beta |u|u \quad (2)$$

where C_D is a drag coefficient, b_v is the vegetation diameter, N is the plan-form density of vegetation or number of plants per meter squared, and β is a combination of all factors acting on the velocity terms, used to conglomerate several variable parameters in this effort. Velocity measurements within the vegetated area are available at a single vertical stack near the center of the 18m vegetated section, and initial analysis indicates that the total velocity u is dominated by a wave orbital component that does not vary significantly over the vertical. Estimates of depth-integrated force, F , therefore, are based on velocity from a single instrument located near mid-depth in this effort. Total time-averaged force and dissipation, respectively, are thus simplified

$$\overline{F} = \overline{\int_{z_b}^{\eta} f dz} = \overline{\beta h |u|u} \quad ; \quad \overline{F}u = \overline{\beta h |u|u^2} \quad (3)$$

where h is the instantaneous water depth. Note that the use of time-varying h in (3) for this case of emergent vegetation results a more positive value of F when compared to values obtained from an analysis that uses the mean depth, $\overline{F} = \overline{\beta h} \overline{|u|u}$, due to the correlated velocities and free surface variation for waves propagating in x .

A cursory analysis making use of the baseline cases and $f = 0$ in (1) and measured representative u concluded that $c_f = 0.05$ is sufficiently accurate to reflect wave height decay in the absence of vegetation, and was used for the remainder of this initial analysis.

Direct estimates of β (or, alternatively, C_D) can be readily attained through integration of the energy balance in (1) across the vegetated patch, making use of measured wave heights on the boundaries. Strictly speaking, the dissipation terms due to wall/bottom stress and vegetation in (1) are a function of location, x , although velocity data are only available at a single x location. Given the variation in wave height is $\sim 20\%$, the assumption was made that the dissipation terms were spatially invariant in this analysis. The first panel of Fig 1 shows along-flume variation of wave height for a monochromatic case with high vegetation density and offshore $H = 1.25m, T = 4.2s$, where the vegetated region from $36 < x < 54$ is shaded. Data converted from pressure data (blue) and from surface piercing capacitance gauges (red) are provided and demonstrate some degree of difference, although the dissipation trends are similar. The computed variation of wave height over the vegetated length, as governed by (1) with the calibrated β , making use of the capacitance gauge data as the offshore boundary, is also provided.

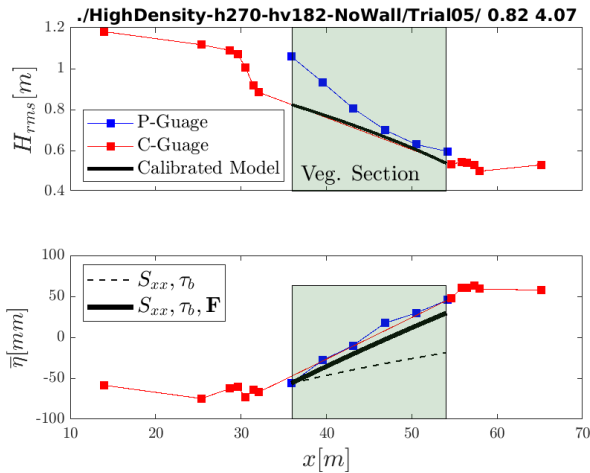


Figure 1: Variation in wave height and mean water level for Trial 5, high density vegetation, and still-water depth of 1.85 m in vegetated section.

The time-averaged momentum equation, consistent with (1), is given as

$$\rho g h \frac{\partial \bar{\eta}}{\partial x} = -\frac{\partial S_{xx}}{\partial x} - \bar{\tau} - \bar{F} \quad (4)$$

where $S_{xx} = (\rho g / 8) H^2 (2n - 1/2)$ is the linear represen-

tation of the wave radiation stress, n is the ratio of group speed to phase speed, and $\bar{\eta}$ is the mean free surface departure from the still water level. While methods to predict C_D have considerable scatter, the momentum balance used herein benefits from the use of a calibrated value, tailored to match the measured energy balance identically.

Conventional phase-averaged wave/circulation model coupling neglects the last term in (4), although a significant vegetation force, \bar{F} , can develop due to either the presence of non-zero current or nonlinear wave shape. Panel 2 of Figure 1 shows the average free-surface position data for both the pressure and capacitance gauges. Predictions of $\bar{\eta}$ over the vegetated length are also provided, where measured data at the seaward edge of the vegetated length are utilized as the boundary condition. The conventional balance, including radiation stress and bottom shear but neglecting the vegetation force is depicted as a dashed black line, while the full balance, making use of calibrated dissipation and measured velocity is shown as a solid black trace. The impact of including \bar{F} is a dramatic increase in the predicted free-surface slope and an overall increase in the setup by a factor of two. This substantial effect originates in a large measured seaward-directed return current with $\bar{u} = .18m/s$, although other cases have less impact. Note that while steady currents derive from the mass-conservation of the closed tank, the vertical variation of wave Reynolds stresses deriving from vegetation characteristics that vary as distance from the bed can also result in steady currents. The proposed effort will make use of the suite of measurements for varied wave conditions and the outlined model in the development of a rational method to include the impact of highly dissipative elements when predicting mean water levels.

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