CONNECTING THE CANOPIES: SUBMERGED AND EMERGENT AQUATIC VEGETATION

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BACKGROUND AND MOTIVATION

Coastal green infrastructure has increasingly been touted as a sustainable alternative to traditional gray infrastructure such as bulkheads and seawalls. In particular, aquatic vegetation (e.g., salt marshes, seagrasses) has been cited for its capacity to buffer storms and protect coastlines. One of the key remaining challenges with utilizing these (eco)systems is engineers' ability to gauge their efficacy in a variety of environmental conditions. In order for green infrastructure to be a viable option for coastal communities, engineers need the tools to rigorously evaluate the expected performance of a proposed project, whether it be a marsh restoration or hybrid levee system. For the evaluation of nearshore coastal green infrastructure, engineers turn to hydrodynamic models.

Aquatic vegetation is often described in the context of canopy literature, which is a well-studied field in environmental fluid mechanics. Many studies describe the influence of ecosystems on hydrodynamic quantities of interest, such as current velocities or wave heights. However, it is often challenging to use the same methodologies to model distinct ecosystems; for example, while some salt marshes will be emergent (extend above the water height), many seagrasses will live submerged in the shallows. These types of canopies influence the hydrodynamics differently, and an ecosystem's exact submergence will also depend on the environmental conditions, including tide- and surge-driven water levels. In regions with large tidal variability, plant canopies may even vary between submerged and emergent conditions within a tidal cycle. Similarly, in regions with large extents of salt marsh, storm events may cause variable submergence among different areas of the marsh. Therefore, reconciling model approaches that can appropriately reflect both submerged and emergent ecosystems within a single hydrodynamic model is a key area of interest for coastal engineers. Accurately modeling the submergence effects of these ecosystem canopies across space and time normally requires a 3D model, which becomes computationally prohibitive for large-scale assessments.

XBeach non-hydrostatic is a widely used coastal wave model that solves the depth-averaged nonlinear shallow water equations (e.g., de Ridder et al., 2021). Recent developments include the implementation of a canopy subgrid model that solves a simplified momentum balance in order to more accurately capture the dynamics associated with velocity differentials induced by a vegetated canopy (van Rooijen et al., 2022). By solving for an in-canopy velocity, the subgrid model is able to capture and account for the vertical attenuation of velocity, thus allowing for the depth-averaged XBeach to resolve the vertical gradient in velocity associated with a canopy flow. A better approximation of the in-canopy velocity allows for a more robust drag force and corresponding wave attenuation estimate, while also reducing the reliance on calibration typically required for these quantities. This capability comes at a far more manageable computational cost than would be required by a multi-layered nonlinear shallow water model. However, due to simplifying assumptions, the subgrid model is not readily applicable to vegetation where the canopy height starts to approach the height of the water column (i.e., emergent vegetation). Therefore, in this study, we define and implement a physical threshold in the XBeach vegetation module that allows for the subgrid canopy model to be used in conjunction with the standard approach for vegetation, thereby better simulating submerged canopy flows while also allowing for time- and space-variable submergence of various ecosystems across different timescales (e.g., tidal, storm surge).

METHODS

To define an appropriate physical threshold at which to switch the canopy parameterization and implementation in XBeach non-hydrostatic, we used a combination of results from previous vegetated flows literature and laboratory data, in addition to utilizing two hydrodynamic models, XBeach and SWASH (Simulating WAves till Shore; Zijlema et al., 2011). SWASH can resolve a large range of coastal dynamics, in part due to its extension beyond the depth-averaged equations of XBeach. An idealized 2DV numerical wave flume was set up in SWASH, with a minimum of ten vertical layers to capture velocity variations. Varying the environmental conditions such as water depth and wave properties ($kh < 1.5$), as well as canopy characteristics (e.g., densities from 0-3000 stems per square meter), across dozens of lab-scale model simulations allowed an exploration of the resulting velocity profiles and associated attenuation of both the velocities and overall wave heights.

ANALYSIS

In terms of the sensitivity of the subgrid model to its low submergence criterion, we do indeed find that velocities (free-stream vs. in-canopy) can start to diverge as the vegetation height approaches the water depth. As a result, it is necessary to be able to switch the parameterization before the assumptions of the subgrid model become invalid. For insight, we first looked into rigid canopy laboratory experiments, including the wave-only cases of Hu et al. (2014) which demonstrated nonlinear wave-generated mean currents in intermediate depths, similar to results in Pujol et al. (2013). These experiments served as a basis for parameter exploration in SWASH, with the following figure showing an example model output demonstrating the attenuation shifts in vertical profiles of velocity that occur with changes to vegetation characteristics, namely canopy height and density.

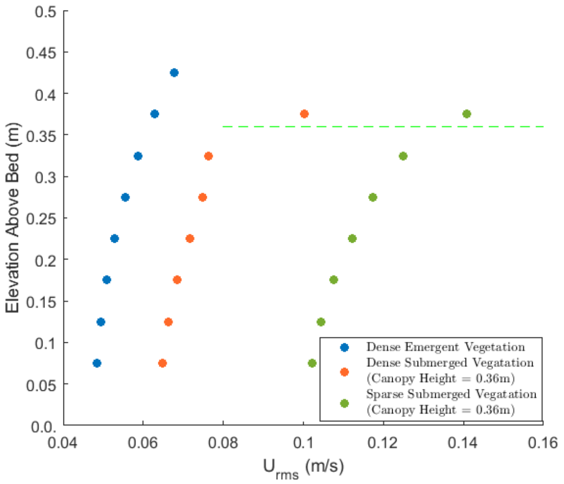

Figure 1 - Aquatic Vegetation Orbital Velocity Profiles with Varying Density and Submergence simulated with SWASH based on the laboratory experiments by Hu et al., (2014).

Extending the cases of Hu et al. (2014) into shallower water by raising the incoming wave peak period leads to more distinct canopy-flow regimes, as displayed in Figure 2. As vegetation height increases, the depth-averaged velocity starts to converge to the in-canopy velocity. In this case of dense vegetation, the in-canopy velocity increases from 88% of the depth-averaged velocity for a submergence ratio (height of vegetation / water depth) of 0.4 to 93% of the depth-averaged velocity for a submergence ratio of 0.72.

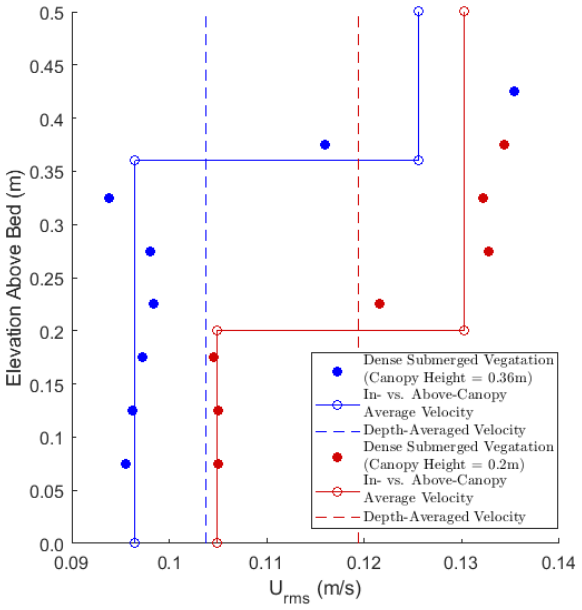

Figure 2 - Aquatic Vegetation Orbital Velocity Profiles with Vegetation Height of 0.36m (blue) and 0.2m (red) with SWASH, extended based on the laboratory experiments by Hu et al. (2014)

Preliminary results indicate that a threshold based on the canopy drag length scale and the submergence ratio can provide insight regarding when a canopy transitions from being described by a two-layer attenuated flow (one that can be captured by the subgrid model) into a mixed velocity profile that can be approximated by the standard depth-averaged flow used in XBeach.

CONCLUSIONS

This work helps to bridge the gap between the improved behavior of a subgrid canopy approach and the inherent complications arising from incorporating aquatic vegetation that can exist in a nonuniform and time-variable submergent state. These developments allow for a better characterization of various types of aquatic vegetation and associated canopy hydrodynamics, while also helping to preserve the relatively low computational cost associated with XBeach. The current model implementation and results will be validated using wave flume experiments.

REFERENCES

de Ridder, et al., (2021): “Efficient two-layer non-hydrostatic wave model with accurate dispersive behaviour.” Coastal Engineering 164: 103808.

Hu, et al., (2014): “Laboratory study on wave dissipation by vegetation in combined current-wave flow.” Coastal Engineering 88: 131-143.

Pujol, et al., (2013): “Flow structure in canopy models dominated by progressive waves.” Journal of Hydrology 486: 281-292.

van Rooijen, et al., (2022): “Modelling wave attenuation through submerged vegetation canopies using a subgrid canopy flow model.” Coastal Engineering 176: 104153

Zijlema, et al., (2011): “SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters.” Coastal Engineering 58.10: 992-1012.