

PERFORMANCE-BASED DESIGN FOR USING EMERGENT VEGETATION TO MITIGATE WAVE OVERTOPPING CONSIDERING CLIMATE CHANGE

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INTRODUCTION

Natural and Nature-Based Features (NNBF) are increasingly growing in popularity as flood risk reduction measures. However, the implementation of these systems is hampered by barriers, including the lack of engineering design methodologies. Existing engineering design methodologies for traditional coastal infrastructure cannot be directly applied to NNBF systems, because NNBF systems contain additional uncertainties. For example, vegetation experiences natural growth and mortality, affecting the engineering parameters associated with its flood protection capabilities.

Performance-based design (PBD) describes a type of engineering design methodology that relies on designing a system to meet a set of performance objectives. The focus on performance, rather than known failure thresholds, makes PBD an appropriate methodology for new technologies (Atkan et al. 2007). Furthermore, PBD allows for the direct incorporation of uncertainties due to vegetation. PBD methodologies already exist in coastal engineering design. For example, Goda (2010) outlined the development of PBD for the design of caisson breakwaters.

To develop an engineering design methodology for emergent vegetation systems, Ostrow (2023) expanded the existing method in Goda (2010), adding extra steps to quantify the engineering characteristics of vegetation. This paper describes the model in Ostrow (2023), improvements made to the model, and the application of the model to climate change.

PERFORMANCE-BASED DESIGN METHODOLOGY

The PBD methodology for emergent vegetation is represented as a flow chart (Figure 1). It is an extension of the flow chart presented in Goda (2010). The goal is to examine a performance variable over the design life of the structure. After establishing the initial conditions, the performance in one year is calculated through selecting an extreme annual storm, considering both growth and during-storm mortality of the vegetation, transforming the waves to the design site, and calculating the performance variable. Allometric and epistemic uncertainties are considered in these steps. The calculations are repeated for each year of the design life, considering delayed mortality of the vegetation in between years. Many Monte Carlo simulations of the design life are carried out to determine the expected performance variable and probability of failure in each year of the design life. The entire process is repeated for many sets of Monte Carlo simulations to determine confidence intervals.

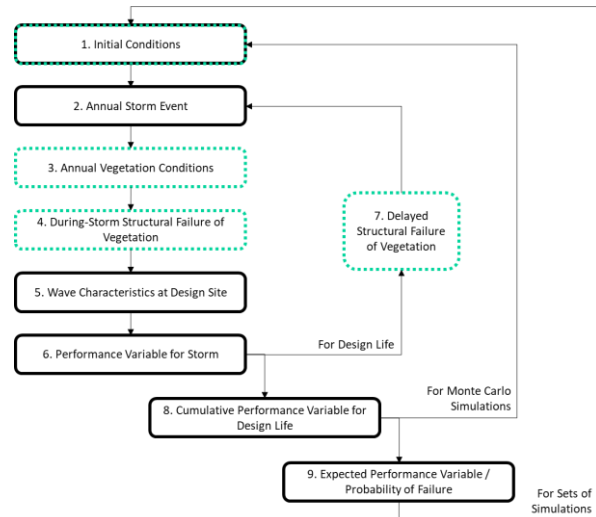


Figure 1 - Performance-based design methodology for emergent vegetation. Black boxes are the same as in Goda (2010) and green dotted boxes are added for vegetation.

APPLICATION OF METHODOLOGY

Ostrow (2023) applied the methodology to an idealized case study of a hypothetical coastal community in Southern Florida on the landward side of a coastal embayment. The case study considered the overtopping onto a coastal road protected by a hybrid system of mangroves and a revetment (Figure 2). The case study considered a 3 km embayment, with the last 30 m having a 1:30 slope. The revetment extended 2 m above the surface. The water depth was 2 m, except for the 1:30 slope. A patch of *Rhizophora* sp. mangroves 20 m in length was placed 10 m away from the revetment.

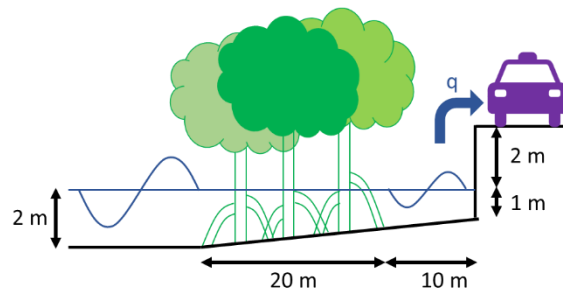


Figure 2 - Schematic of the last 30 m of domain of the idealized case study, including overtopping over a coastal road. Schematic is not to scale.

A one-dimensional model was developed in Python to determine the expected overtopping and probability of failure of the hybrid system. A critical overtopping of 10^{-6} $m^3/s/m$ was considered. Extreme annual winds were generated probabilistically from a Gumbel distribution, and significant wave height and peak period were generated assuming fetch-limited waves. The hydrodynamic conditions were assumed stationary, and the waves were shore normal.

To track mangrove growth, a random growth rate for diameter at breast height, D , was selected for each year from a uniform distribution. Allometric relations empirically derived from data were used to relate D with important physical properties of the mangroves. For example, the projected area of the roots, A_R , as a function of D was derived from Yoshikai et al. (2021) (Figure 3).

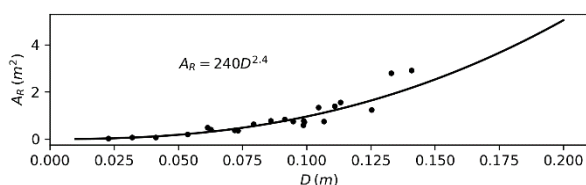


Figure 3 - Projected area of the roots as a function of diameter at breast height; data from Yoshikai et al. (2021).

The waves were transformed through the mangroves using the Mendez and Losada (2004) formulation. Shoaling and breaking were considered. The Franco and Franco (1999) relation was used for overtopping over the revetment. The model was run for 50 years, with 100 sets of 10,000 Monte Carlo simulations.

The performance metrics were calculated for configurations without and with the mangroves, assuming no mangrove mortality (Figure 4). Without mangroves, the performance metrics were constant throughout the 50 years considered. With mangroves, the performance metrics were improved. The performance metrics were not constant over the design life and reflected the changes in vegetation parameters.

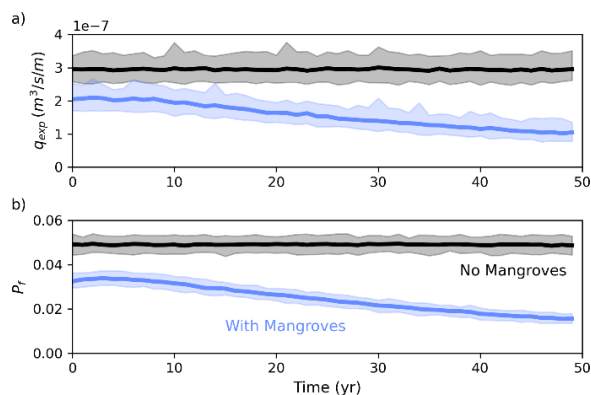


Figure 4 - a) Expected overtopping and b) probability of failure in each year of the design life with 95% confidence intervals without mangroves (black) and with mangroves (blue).

An examination of sensitivities in the model revealed that the model was most sensitive to the calculation and uncertainty of hydrodynamic parameters.

Improvements to the model presented in Ostrow (2023) were made. This includes updated allometric relations, overtopping formulations based on experimental results (Libby et al. 2023), and characterizations of mangrove mortality. The model was also expanded to include the effects of climate change, considering changes to the wind and wave climate and vegetation.

CONFERENCE PRESENTATION

At the conference, we will present the details of the methodology in Ostrow (2023), with emphasis placed on the uncertainties involved in the calculation. We will also present improvements to the model, and apply the model to the design of NNBF systems under climate change.

REFERENCES

Atkan, Ellingwood, Kehoe (2007): Performance-Based Engineering of Constructed Systems, *Journal of Structural Engineering*, AMERICAN SOCIETY OF CIVIL ENGINEERS, vol. 133, pp. 311-323.

Franco, Franco (1999): Overtopping Formulas for Caisson Breakwaters with Nonbreaking 3D Waves, *Journal of Waterway, Port, Coastal, and Ocean Engineering*, AMERICAN SOCIETY OF CIVIL ENGINEERS, vol. 125, pp. 98-108.

Goda (2010): *Random Seas and Design of Maritime Structures*, WORLD SCIENTIFIC.

Libby, Ostrow, Cox, Tomiczek, Lomonaco (2023): Large-scale physical model to quantify overtopping performance of hybrid green-gray infrastructure, *Proceedings of ASCE INSPIRE*, Arlington, VA, Nov. 16-18.

Mendez, Losada (2004): An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. *Coastal Engineering*, ELSEVIER, vol. 51, pp. 103-118.

Ostrow (2023): *Performance-Based Design Methodology for Using Emergent Vegetation to Mitigate Wave Overtopping*, MS Thesis, OREGON STATE UNIVERSITY.

Yoshikai, Nakamura, Suwa, Rollon, Nadaoka (2021): Measurement and Modeling of Above-Ground Root Systems as Attributes of Flow and Wave Attenuation Function of Mangroves, in Rastogi, Phulwaria, Gupta (eds.), *Mangroves: Ecology, Biodiversity and Management*, SPRINGER.