Unraveling the Wave-Attenuating Potential of Oyster Reefs by means of Surrogate Models: A Comprehensive Experimental Analysis

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Keywords: Oyster Reefs; Surrogate Modeling; Hydraulic Roughness; Turbulence Production; Nature-based Coastal Protection

Introduction

Oyster reefs exhibit the potential to attenuate wave energy, presenting an intriguing opportunity for integration into nature-based coastal protection systems. Frictional dissipation caused by the ultra-rough surfaces (Fig. 1A) significantly contributes to the wave attenuation by oyster reefs, particularly in spatially extensive reefs, e.g., formed by the invasive Pacific oyster in the Wadden Sea in Northern Europe (Hitzegrad et al., 2022; Morris et al., 2021). Despite the general knowledge of their wave-attenuating potential (Borsje et al., 2011), the mechanisms causing the wave energy dissipation, in particular bed friction, have not been comprehensively investigated yet. Physical modeling using scaled oyster reef surrogate models with parameterized roughnesses has thus been employed to gain a deeper understanding of the fundamental hydraulic processes. This work attempts a comparison of different approaches to parameterize and manufacture ultra-rough oyster reef surfaces for physical modeling and presents an analysis of their wave-attenuating effects.

Methods

Wave flume experiments at a Froude scale of 1:3 have been conducted employing two distinct surrogate model types: (1) a primitive 2D model (Fig. 1B) and (2) an intricate 3D model (Fig. 1C). To quantify the wave-induced hydraulic roughness attributed to oyster reefs, the models had to feature relevant parameters and a length of twice the highest wavelength (L = 16 m). The 2D model parameterizes the natural roughness by means of primitive shapes (vertical plates and semicircles) with a uniform lateral distribution (Hitzegrad et al., 2024a). The 3D models consist of parameterized individual shells arranged in a 3D pattern based on in-situ measured topographical parameters (Hitzegrad et al., 2022). The 3D models were manufactured using a particle bed 3D printer with selective cement activation (Hitzegrad et al., 2024b).

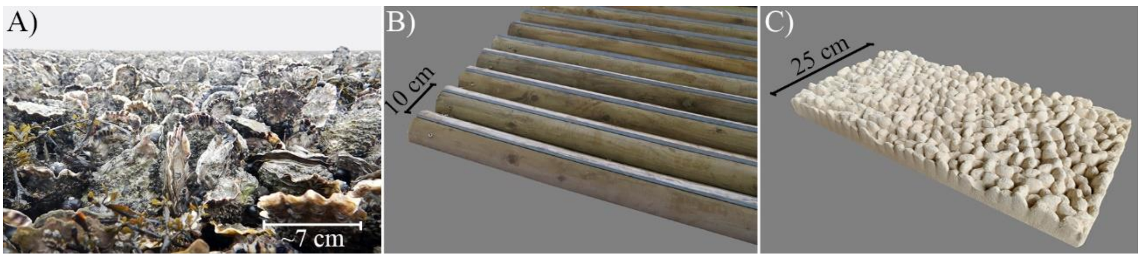

Fig. 1. Photographs of (A) an *M. gigas* reef, (B) the 2D model, and (C) the 3D surrogate model.

The surrogate models were exposed to regular and irregular waves modeling realistic sea state conditions in the German Wadden Sea, with a water depth d = 0.7 m, a wave height H = 0.15 m, and varying wave periods T = 1.0 – 3.0 s.

Results

The results demonstrate distinct wave height reductions for both model types. The 2D model exhibits transmission coefficients of K_T = 0.86 - 0.92, while the 3D model yields K_T = 0.90 - 0.95. The vertical distribution of the phase-averaged turbulent kinetic energy (*TKE*) reveals turbulence production of 1.2 ± 0.2 higher of the 2D model compared to the 3D model (Fig. 2). The higher *TKE* and wave attenuation induced by the 2D model are attributed to a better representation of the sharp edges of the shells. However, the 2D parametrization overlooks the intricacies of flow around the oyster shells (in-canopy flow with the vertical exchange of volume and momentum to/from cavities) and the interaction with the flow above the reef. In contrast, the 3D model offers a more realistic representation of the three-dimensional flow patterns within and above the oyster reef. Ultimately, limitations in replicating the sharp edges with the 3D printer may result in the underestimation of the wave attenuation.

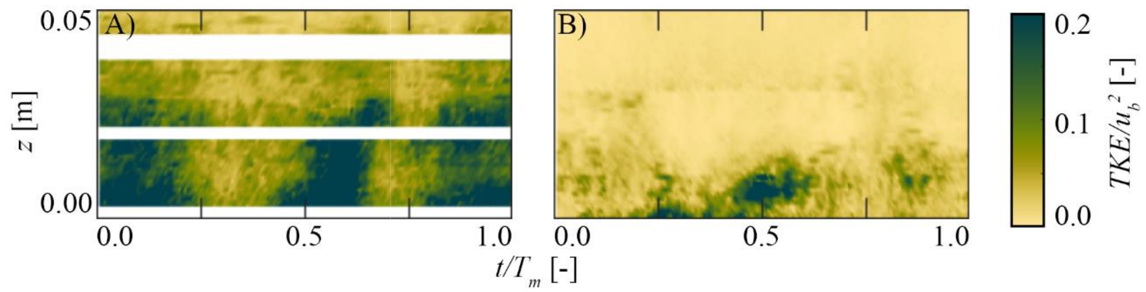

Fig. 2. Vertical and temporal distributions of the phase averaged normalized turbulent kinetic energy *TKE* for an exemplary case for (A) the 2D model and (B) the 3D model.

Conclusions

In light of the recent progress in additive manufacturing, a substantial step forward has been taken in accurately representing ultra-rough oceanic surfaces, i.e., oyster reefs. The results underscore the valuable insights offered by both 2D and 3D models to understand the complex interactions between ultra-rough surfaces and waves, as well as their suitability for incorporation into coastal protection strategies.

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