HIGH-FIDELITY NUMERICAL SIMULATION OF OSCILLATING FLOWS AND TURBULENCE STRUCTURES PAST A SINGLE OYSTER INDIVIDUAL

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MOTIVATION

Oysters are an eco-engineering species that build rigid and ultra-rough reef structures in intertidal zones. Oyster reefs effectively attenuate wave energy, offering an intriguing opportunity for integration into nature-based coastal protection systems. In spatially extensive reefs, e.g., formed by the invasive Pacific oyster (*Magallana gigas*; Hitzegrad et al., 2022; Figure 1A)), the wave attenuation is primarily attributed to frictional dissipation induced by the ultra-rough surfaces (Morris et al., 2021).

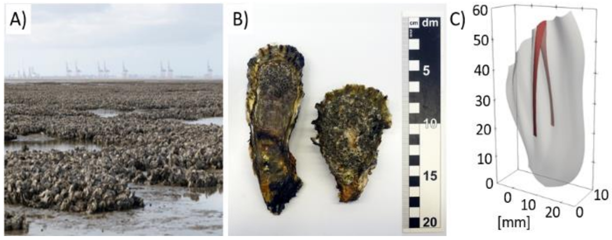

Figure 1 – A) Oyster reef Kaiserbalje near Wilhelmshaven, Germany, B) *M. gigas* individuals (Hitzegrad et al. 2022). C) Idealized oyster shell (red: slice implemented in the NWT).

While the potential to effectively attenuate waves is generally recognized (Borsje et al., 2011), the mechanisms causing the wave energy dissipation over ultra-rough surfaces, particularly bed friction, have not been comprehensively investigated yet. Hitzegrad et al. (2024b) illustrated in an experimental study that the razor-sharp shell margins, in particular, contribute to the turbulence production, increased bed shear stress, and, thus, wave energy dissipation.

The availability of in-depth datasets of experimental studies involving 3D-printed reef structures (e.g., Hitzegrad et al.,2024a) provides calibration and validation of high-fidelity simulations for the first time. These complementary numerical models can now be used to gain a more in-depth understanding of the complex flow kinematics. Therefore, this work aims (1) to simulate the wave-oyster reef interaction on a small scale, i.e., an oyster individual at high fidelity, and (2) to examine the wave-oyster interaction by analyzing the flow field, the turbulence production, and force progression.

NUMERICAL MODEL

A 2D numerical wave tank (NWT) was set up using REEF3D::CFD (Bihs et al., 2016) to solve the two-phase oscillatory flow field around an individual oyster (Figure 2). The NWT utilizes high-order finite differences on rectilinear grids, the level set method for the free surface, and the immersed boundary method for the solid boundary, i.e., the oyster shell. For the turbulence modeling, large-eddy simulation with a Smagorinsky subgrid-scale model was used. A parameterized oyster shell was developed based on roughness parameters by Hitzegrad et al. (2022; Figure 1 B)-C)). A stretched Cartesian grid with a cell size of dx = 1.25 mm around the oyster shell was applied.

To calibrate and validate the model, the vorticity field is compared to a reference case of a vertical plate subjected to oscillating flow (Lin and Huang, 2012). The formed vortices in the present model are in the same order of magnitude as those of the reference case (Figure 3). Uncertainties of 5.9, 12.0, and 8.0% regarding the total horizontal force, F_x, the near-bed velocity overshoot, and the maximum turbulent kinetic energy, *TKE*, are achieved. Based on the validated model, a parametric study was conducted, including 36 hydrodynamic cases reflecting real conditions in the central Wadden Sea (Froude similitude with a length scale of 1:3) varying the water depth d = 0.4 - 0.8 m, the wave period T_m = 1.5 - 3.0 s, and wave height H_m = 0.05 - 0.20 m.

RESULTS

The phase-averaged distributions of the horizontal velocity $\langle u \rangle$ (Figure 4) reveal increased residual velocities

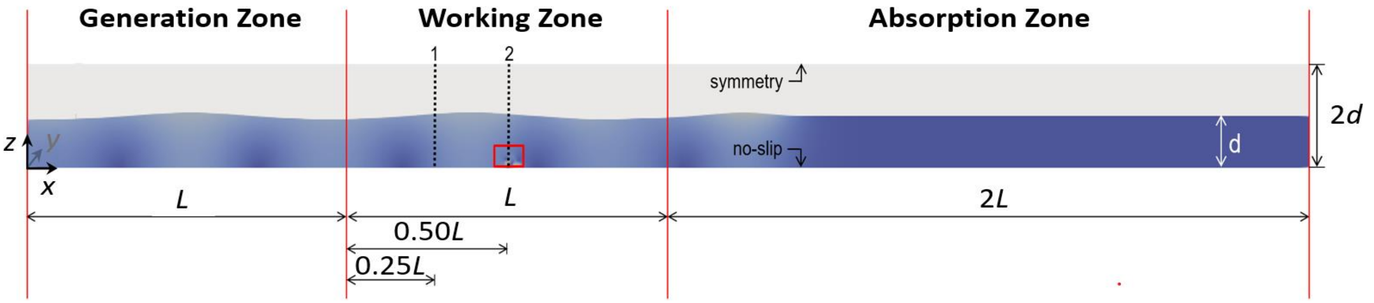

Figure 2 - Visualization of the NWT, including positions of the oyster shell (red box), the wave gauges and line probes (1,2).

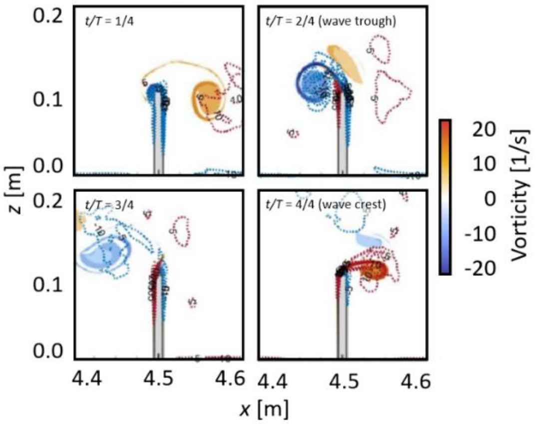

Figure 3 - Comparison of the vorticity field of the reference study (Lin and Huang, 2012; filled color patches) and this model (dotted isolines) at four *t/T* = 1/4; 2/4; 3/4; and 4/4. Red: clockwise rotation; blue: anticlockwise rotation.

and a phase shift near the shell margin. The temporal distribution of the *TKE* reveals intrawave variations. The most significant levels of *TKE* develop at the shell margin, and the same t/T_m as the velocity overshoots.

The vorticity fields reveal an interplay of the vortices on lee and weather side of the oyster shell caused by the flow separation at the shell margin with implications for the force acting on the oyster. The maximum horizontal wave force amplitude dF_x = 0.05 – 0.25 N/cm (Figure 5) shows dependencies on the Keulegan-Carpenter number, *KC*, and the wave steepness, *H/L*.

CONCLUSIONS AND OUTLOOK

This work investigates the wave-oyster reef interaction utilizing validated state-of-the-art numerical models, thus providing previously unavailable, detailed insights into the flow fields, the turbulence structures, and the wave-induced forces acting upon an individual oyster under a wide range of realistic hydraulic boundary conditions.

The outcomes of this work are a stepping stone towards the development of a novel roughness parametrization to predict the wave energy dissipation and the forces acting on oyster individuals. In combination with additional validation by laboratory studies, the now available detailed understanding of the flow kinematics around and the forces acting on an individual oyster enable upscaling to larger oyster reef sections consisting of multiple oysters, e.g., clusters, patches, and the central reef, or the transition from different structural classes.

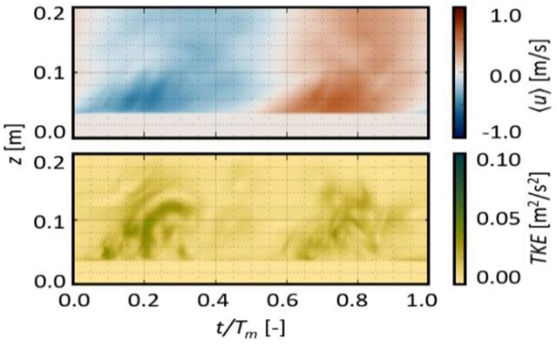

Figure 4 - Exemplarily distributions of $\langle u \rangle$ and *TKE* over *z* at the shell margin and a dimensionless wave cycle *t/T*.

These insights advance the understanding of the ecohydraulic processes, specifically in the context of their application as a nature-based solution in coastal protection.

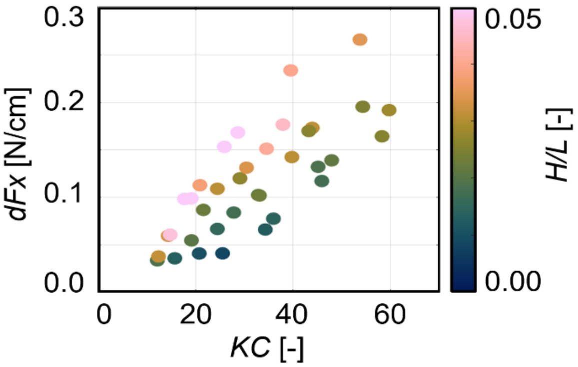

Figure 5 - Phase-averaged maximum horizontal wave force amplitude dF_x as a function of the *KC* number and the wave steepness *H/L*.

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