EFFECT OF REEF STRUCTURES ON WAVE BREAKING AND OVERTURNING PARAMETERS

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BACKGROUND

Wave breaking occurs when the horizontal particle velocity at the crest exceeds the wave's phase speed, causing the crest to steepen and overturn, forming a jet that impacts the free surface below. The overturn shape governs turbulence generation, bubble formation, sediment transport, and the loads applied to coastal infrastructure. Breaker types such as spilling, plunging, surging, and collapsing, have been traditionally classified using the Iribarren number: a function of the planar beach slope and wave steepness. However, this classification system is based on a planar beach without bathymetric features such as sand bars or reefs. It also only provides a qualitative description of wave breaking and does not capture the geometry of wave overturning. Wave overturning parameters have been investigated mainly on planar slopes through observational and numerical studies (Blenkinsopp and Chaplin 2008, Grilli et al. 1997, Mostert and Deike 2020, Pick and Feddersen 2025), with O'Dea et al. (2021) being an exception by examining barred bathymetry in the field.

Reef structures influence wave breaking and overturning by modification of the natural bathymetry. They can serve multiple functions, including shoreline protection via wave dissipation (van Gent et al. 2023), ecological enhancement (Pickering, Whitmarsh, and Jensen 1998)), and recreational wave riding (Mortensen et al. 2015). The effect of reef structures on wave overturn shape remains largely unexplored. Both laboratory experiments (van Gent et al. 2023) and computational fluid dynamics (CFD) simulations (Norris et al. 2025) have been applied to the design of reefs for wave dissipation. However, application of CFD towards optimizing recreational wave riding is limited. For recreational wave riding, different aspects are important for different skill levels. Recreational wave riding requires consideration of wave breaking and overturning parameters that vary with skill level, such as the break point position x_b, the breaker depth index $\gamma_b = H_b/h_b$, the wave steepening time Δt, overturn area A_O, jet area A_J, overturn aspect ratio W_O/L_O, and overturn angle θ_O. How reef structures influence these parameters remains unknown.

METHODS

To address this gap, we use the open-source CFD software OpenFOAM to simulate two-dimensional (2-D) wave breaking. The multiphase VoF RANS model interFoam is used with a stabilized k-ω SST model to prevent turbulence overproduction in near potential flow.

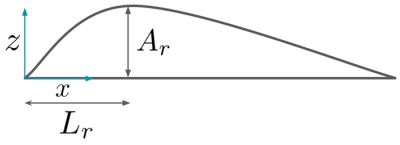


Figure 1: A schematic of the reef profile, defined by its amplitude A_r and length L_r.

The reef structure is represented as a functional perturbation to the slope

$$z(x) = A_r \frac{x'}{L_r} e^{\left(1-\frac{x'}{L_r}\right)}, \; x' > 0 \; (1)$$

where A_r is the reef amplitude, L_r is the cross-shore reef length, and $x' = x - X_r$, where X_r is the position of the toe of the reef. A larger A_r corresponds to a more elevated reef crest relative to the background slope, a larger L_r indicates a longer cross-shore extent (Figure 1). A larger X_r places the reef farther onshore. Simulations are performed across a range of reef geometries (A_r, L_r, X_r), random wave parameters (significant wave height H_s, peak period f_p), and tide levels (MLW, MSL, MHW).

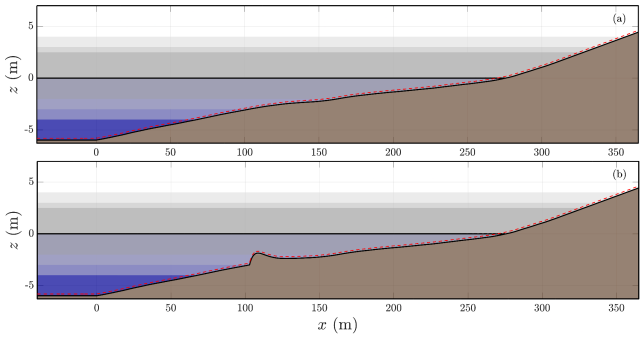


Figure 2: Model domain and initial conditions for (a) a gentle sloped natural bathymetry and (b) the same bathymetry with a reef structure (A_r = 1 m, L_r = 5 m, X_r = 103 m). The still water (z = 0 m), is denoted by the horizontal black line. Brown represents the bathymetry, blue represents the water, and the region above the two represents air. Mesh refinement regions are also shown: an outer coarse region (light gray), an intermediate region of higher resolution (medium gray), an inner region of finest resolution resolving wave breaking (dark gray), and a boundary layer refinement along the bed (red dashed curve).

2-D simulations are set up in a field-scale model domain with an offshore region of flat bathymetry with length L_0 = 40 m and water depth h_0 = 6 m, constant in all simulations (Figure 2). Waves propagate from the offshore flat region into a natural sloped bathymetry, representative of a San Diego, CA, USA beach. The beach bathymetry was obtained from in-situ surveys of beach profiles during the spring months, when the strongest wave energy typically occurs. Random waves are generated at the offshore boundary with f_p and H_s characteristic of this time of year.

The model domain is initialized with a base mesh resolution of $\Delta x = \Delta z = 0.32$ m. Three levels of refinement are applied to better capture wave breaking, with the smallest cell size $\Delta x = \Delta z = 0.04$ m in the wave breaking region and along the boundary layer (Figure 2).

RESULTS

We investigate how reef parameters modify wave overturn characteristics, including x_b, γ_b, Δt, A_O, A_J, W_O/L_O, and θ_O.

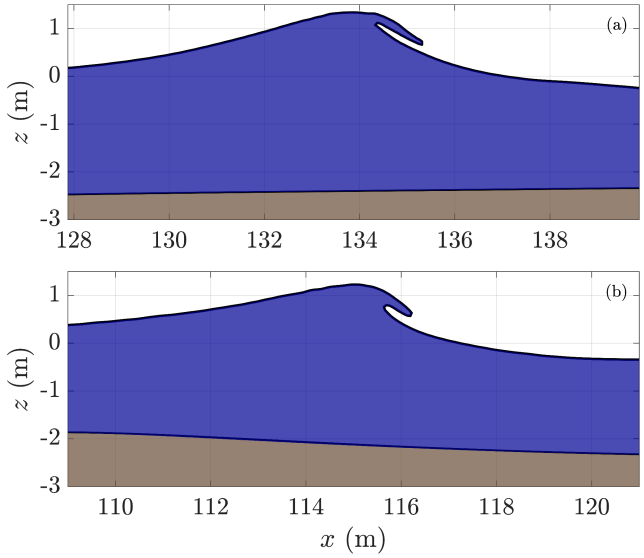


Figure 3: Wave breaking just before the moment of jet impact at mid-tide for (a) the natural beach profile and (b) a reef case (A_r = 1 m, L_r = 5 m, and X_r = 103 m) with identical wave forcing. Blue shading denotes the water and brown shading the bathymetry.

Lower tides and smaller reef crest submergences (h_c) cause wave breaking to occur earlier. We also see that the front face of the wave steepens up faster when the tide is lower. The rate of wave steepening is a key parameter linking shoaling to wave overturning (Pick and Feddersen, 2025) and is important for determining the type of wave suitable for different recreational surfing skill levels. Faster-steepening waves produce more intense plunging breakers with larger overturn and jet areas, as illustrated qualitatively in Figure 3. In contrast, higher tides generally produce waves with smaller overturn and jet areas. Variations in reef amplitude A_r, length L_r, and position X_r also strongly influence the initiation and shape of wave overturning. Reefs positioned far offshore, where the crest submergence h_c is much greater than the instantaneous wave height, have little influence on wave breaking. In contrast, reefs with crest submergence near the breaker depth of the corresponding case without a reef $h_c \approx h_b$ produce significant modifications in wave shape. Reefs located farther offshore produce waves with a larger γ_b. Our results reveal clear differences between wave breaking on natural versus engineered profiles. Understanding these changes is important for predicting wave energy dissipation and informing the design of multi-benefit coastal resilience structures that can reduce beach erosion, foster marine habitat growth, and enhance surfing conditions.

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