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Coastal Wave Dynamics: Transformation, Breaking, and Dissipation

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Introduction

The intricate dynamics of coastal wave propagation are fundamental to understanding nearshore processes, encompassing phenomena such as wave shoaling, breaking, and the generation of undertow currents. These processes are significantly influenced by non-linear wave-wave interactions and turbulent dissipation, which dictate the energy transfer from incoming waves to the coastal environment, thereby impacting sediment transport and altering coastal morphology. Advanced numerical modeling, often validated by experimental data, is crucial for accurately predicting wave behavior in shallow water conditions [1].

The behavior of wave breaking itself is a focal point of extensive research, with detailed analyses of the turbulent flow structures and energy dissipation mechanisms characterizing different breaker types, such as plunging and spilling breakers. Techniques like particle image velocimetry (PIV) and advanced computational fluid dynamics (CFD) are employed to quantify air-water mixing and its effect on wave energy reduction, a critical aspect for accurate coastal flooding and erosion predictions [2].

Within the surf zone, the interplay between waves and currents profoundly modifies wave spectra and energy dissipation rates. Opposing currents can lead to wave steepening and enhanced breaking, while following currents can induce wave damping. This intricate relationship is essential for comprehending the nearshore energy balance and sediment dynamics [3].

Beyond surface gravity waves, the generation and evolution of infragravity waves (IGWs) are significantly influenced by interactions with complex nearshore bathymetry. Alongshore depth variations and the presence of structures can trigger resonant excitation of IGWs, which in turn drive nearshore currents and contribute to beach erosion. Advanced spectral analysis techniques are vital for their study [4].

In recent years, machine learning models, particularly neural networks, have emerged as powerful tools for predicting coastal wave characteristics. Trained on extensive wave data, these models can effectively capture non-linear dynamics, offering computationally efficient alternatives to traditional numerical models for real-time forecasting and coastal management [5].

The seabed's morphology, characterized by features such as bars and troughs, exerts a notable influence on wave transformation and breaking processes. High-resolution bathymetry data combined with wave modeling reveals how these underwater features can cause localized wave amplification and breaking, thereby impacting sediment transport and shoreline evolution. This understanding is vital for coastal protection strategies [6].

The dynamics of rip current generation and their interaction with incident waves are critical areas of study for understanding sediment transport and beach safety. Coupled wave-current models are employed to explore how wave groups and nearshore bathymetry contribute to the formation and strength of these hazardous features [7].

Forecasting the impact of climate change, particularly sea level rise, on coastal wave dynamics and their interaction with coastal structures is paramount. Integrating wave propagation models with sea level rise projections allows for an assessment of how changing water depths affect wave shoaling, breaking, and run-up, informing the design of resilient coastal infrastructure and adaptation planning [8].

High-fidelity simulations, such as Large Eddy Simulation (LES), provide detailed insights into the three-dimensional turbulent structures generated during wave breaking. These simulations offer unprecedented resolution of vortex dynamics, air entrainment, and energy dissipation rates at the breaking crest, enhancing fundamental understanding of wave energy loss mechanisms in the surf zone [9].

Permeable coastal structures, like submerged breakwaters, play a significant role in modifying wave propagation and energy dissipation. Physical model experiments and numerical simulations are used to quantify how the porous nature of these structures alters wave reflection, transmission, and breaking characteristics, providing valuable data for effective coastal defense design [10].

Description

The complex fluid dynamics governing coastal wave propagation, specifically wave shoaling, breaking, and the generation of undertow currents, are explored through an examination of non-linear wave-wave interactions and turbulent dissipation processes. These mechanisms are critical for understanding energy transfer to the nearshore environment and their subsequent impact on sediment transport and coastal morphology. Advanced numerical modeling, validated by experimental data, is employed to achieve accurate predictions of wave behavior in shallow water [1].

Research into the dynamics of wave breaking provides a detailed analysis of turbulent flow structures and energy dissipation mechanisms associated with plunging and spilling breakers. The application of particle image velocimetry (PIV) and advanced computational fluid dynamics (CFD) allows for the quantification of air-water mixing and its effect on wave energy reduction, which is indispensable for precise coastal flooding and erosion predictions [2].

Within the surf zone, the interaction of waves and currents significantly modifies wave spectra and energy dissipation. The study demonstrates that opposing currents can steepen waves and intensify breaking, while following currents can lead to wave damping, contributing to a better understanding of the nearshore energy balance and sediment dynamics [3].

The generation and evolution of infragravity waves (IGWs) over complex nearshore bathymetry are investigated, revealing how variations in depth and the presence of structures can induce resonant excitation of IGWs. These waves are known to play a substantial role in driving nearshore currents and influencing beach erosion processes, with advanced spectral analysis techniques being key to their study [4].

The application of machine learning models, specifically neural networks, for predicting wave height and period evolution in coastal regions is a significant development. By training on extensive wave data, these models exhibit a remarkable capacity to capture non-linear wave transformation dynamics, offering an efficient alternative to traditional numerical models for operational forecasting and coastal management [5].

The influence of seabed morphology, including features like bars and troughs, on wave transformation and breaking processes is a critical aspect of coastal studies. Using high-resolution bathymetry data and wave modeling, it is shown how these features can lead to localized wave amplification and breaking, directly impacting sediment transport patterns and shoreline responses, which is invaluable for coastal protection and engineering [6].

The fluid dynamics of rip current generation and their interaction with incident waves are investigated using coupled wave-current models. This research aims to elucidate how wave groups and complex nearshore bathymetry contribute to the formation and strength of rip channels, a crucial factor for understanding sediment transport and ensuring beach safety [7].

The impact of sea level rise on coastal wave dynamics and their interaction with coastal structures is assessed by integrating wave propagation models with sea level rise projections. This approach evaluates how alterations in water depth affect wave shoaling, breaking, and run-up, providing essential information for the design of resilient coastal infrastructure and the planning of adaptation strategies [8].

Three-dimensional turbulent structures and energy dissipation during wave breaking are explored through the use of Large Eddy Simulation (LES). These high-fidelity simulations provide detailed insights into vortex dynamics, air entrainment, and energy dissipation rates at the breaking crest, thereby advancing the fundamental understanding of wave energy loss mechanisms in the surf zone [9].

The modification of wave propagation and energy dissipation over permeable coastal structures, such as submerged breakwaters, is examined through physical model experiments and numerical simulations. The study quantifies how wave reflection, transmission, and breaking are altered by the porous nature of these structures, offering crucial insights for the effective design of coastal defense systems [10].

Conclusion

This compilation of research explores various facets of coastal wave dynamics, focusing on wave transformation, breaking, and energy dissipation in nearshore environments. Studies examine the influence of non-linear interactions, turbulent processes, and the role of bathymetry and currents in shaping wave behavior. Advanced numerical modeling techniques, including high-order spectral methods and Large Eddy Simulations, are employed alongside experimental data and machine learning approaches to enhance predictive capabilities. Key areas of investigation include the dynamics of wave breaking, the generation of infragravity and rip currents, and the impact of climate change factors like sea level rise. The research collectively aims to improve understanding for effective coastal management, engineering, and hazard prediction.

Acknowledgement

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Conflict of Interest

None.

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