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Discovering Boundary Equations for Wave Breaking using Machine Learning

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Abstract

Many supervised machine learning methods have revolutionised the empirical modelling of complex systems. These empirical models, however, are usually "black boxes" and provide only limited physical explanations about the underlying systems. Instead, so-called “knowledge discovery” methods can be used to explore the governing equations that describe observed phenomena. This paper focuses on how we can use such methods to explore underlying physics and also model a commonly observed yet not fully understood phenomenon - the breaking of ocean waves (with overview of the study in Figure 1).

In our work, we use symbolic regression to explore the equation that describes wave-breaking evolution from a dataset of in silico waves generated using expensive numerical methods. Our work discovers a new boundary equation that provides a reduced-order description of how the surface elevation (i.e., the water-air interface) evolves forward in time, including the instances when the wave breaks - a problem that has defied traditional approaches. Compared to the existing empirical models, the unique equation-based nature of our model allows further mathematical interpretation, which provides an opportunity to explore the fundamentals of breaking waves. Further expert-AI collaborative research reveals the physical meaning of each term of the discovered equation, which suggests a new characteristic of breaking waves in deep water - a decoupling between the water-air interface and the fluid velocities. This novel reduced-order model also hints at computationally efficient ways to simulate breaking waves for engineering applications.

Keywords: Wave Breaking, Symbolic Regression, Boundary Equations, Math Interpretable Modelling, Reduced-order models

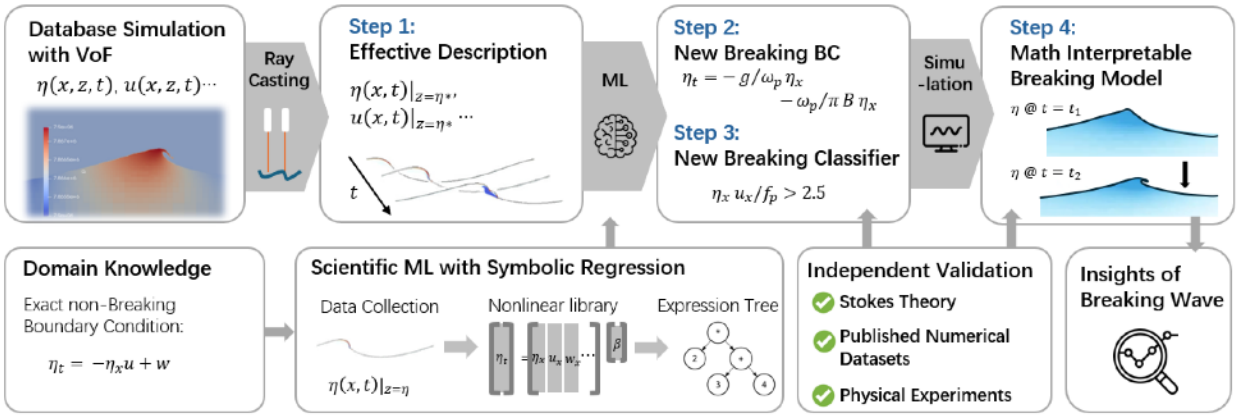

Figure 1: Overview of our study. We start with large amounts of high-fidelity numerical simulated data. We then describe the air-water interface with a ray-casting approach. We use the domain knowledge from non-breaking waves to inform the construction of the nonlinear library, where in this study we focused on the evolution of the air-water interface, so only the kinematics boundary condition is considered. We then use symbolic regression and classification to discover a novel equation that models the evolution of the air-water interface during wave breaking, and also an expression that classifies the spatio-temporal location of the breaking region. We combine the breaking Boundary Condition (BC) and the classifier into an operational wave-breaking model, where we further analyse the performance on unseen experimental, independent datasets and compare them to existing theory. Finally, we reveal the physical insights from the validated breaking wave model in a human-AI collaborative approach.