

Numerical modeling of rubble mound breakwaters to support predictive maintenance actions: an example of the Spanish coasts

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The primary purpose of a breakwater is to ensure the safety of docking operations, providing secure navigation and operational stability within designated areas. In response to the challenges presented by climate change and rising sea levels, coastal engineers and scientists are actively conducting research to assess the implications of the increased demand for artificial armor units and to develop appropriate solutions. This will likely contribute to driving a growing trend in the refurbishment of current coastal defense structures, due to changes in the intensity and frequency of events within a specified return period, coupled with a decreased acceptance for events that are disproportionately severe. Consequently, in the coming years, it would be advantageous to have updated design guidelines capable of incorporating the latest engineering methodologies, such as *digital twins*, which can in principle provide, a comprehensive understanding of the maximum dynamic loads a structure may face during its duty cycle.

THE PROJECT FRAMEWORK

The Spanish government-funded project, PI-BREAK, addresses the challenge of extending the lifespan of port infrastructure in *changed* climate and usage scenarios. It focuses on adapting outdated breakwaters for continued functionality and ultimate performance. PI-BREAK aims to connect the national breakwaters (Figure 1) to a multiplatform monitoring system and thus becoming part of hybrid modeling tool chain, including advanced hydraulic facilities and numerical codes, driven by artificial intelligence. It aggregates data and simulations across short to long-term scales, enabling the development of *adaptation* for critical breakwater infrastructures through an integrated analysis framework. The intelligent system for predictive maintenance should reduce operational and survival risks, enhancing infrastructure reliability, port efficiency, environmental sustainability, and the well-being of coastal communities dependent on port systems. The success of the project hinges on the integration of both physical and numerical modeling of breakwaters. These tools are essential for designing and evaluating the performance of both current and potential future configurations, which may evolve over time.

BREAKWATERS' PERFORMANCE ASSESSMENT

The assessment of hydraulic stability and determining the necessary rubble mound structures are established practices in coastal engineering (e.g., CEM 2011). Formulas in existing literature heavily rely on empirical

methods. As clearly stated by Stagnitti (2023) “Despite of the advances of numerical CFD [Computational Fluid Dynamics] models, physical modeling still remains the most reliable methodology to study the complex interactions between water flows and rubble-mound structures”, the literature still recognizes that breakwater physics is to be out of reach for numerical models. The authors acknowledge that ground-truth must be gathered from physical modeling yet, which continues to be fundamental for meeting structural requirements and underpins current standards, but, nonetheless, numerical modeling techniques have consistently evolved to enhance breakwater performance predictions. Recent advancements in numerical modeling have produced high-fidelity solutions capable of addressing hydrodynamic challenges for breakwaters, regarding both wave overtopping and breakwater stability.



Figure 1 - Breakwater of Punta Lucero (Bilbao, Spain) - reproduced with permission from AZTI.

STRATEGY FOR NUMERICAL MODELING

Alongside mesh-based methods for CFD (Guler 2018), meshfree particle methods (MPMs) stand out for several advantages in simulating free-surface flows and their interaction with fixed or moving structures. They usually develop within Lagrangian frameworks, in which the computational nodes move according to conservation laws making it easier to track interfaces and compute deformations. For the research we present, the SPH-based DualSPHysics solver (Domínguez 2022) is used, which has revealed very efficacious since its first

applications (Altomare 2014, Zhang 2018). However, for an accurate simulation of the armour blocks subjected to wave loads, the code provides access to a Discrete Element Method (DEM)-based solver (Tasora 2016) using the generalized coupling strategy presented in Martínez-Estévez (2023). Recent applications have also seen the use of DualSPHysics to study the scattering process of solitary wave impacts with Tetrapods (Mitsui 2023) or to estimate impact load induced by tsunami waves on elevated coastal structures (Reis 2022). Figure 2 exemplifies the capabilities of the SPH and DEM approaches combined in the same framework to simulate a breakwater that comprises 77 Tetrapod units. Note that the blocks move in response to the loads induced by the waves and the resulting relative effects these forces produce among them.

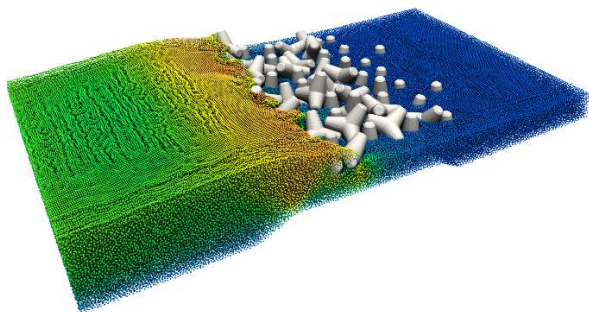


Figure 2 - Demonstrative simulation of 77 Tetrapods using an SPH and DEM coupling.

OPERATIVE METHODOLOGY

The primary objective of this work is to utilize experimental data gathered from two wave facilities where the entire breakwater is constructed and tested, namely a large-scale wave flume and a wave basin, both equipped with long-crested wave generation systems. This data is employed to validate the numerical model under a range of operational conditions, including future scenarios. Once the tool achieves the desired level of fidelity through a multi-tier application process, the model is assessed to determine its performance. This includes:

1. Conducting runup/overlapping testing using block layouts with diverse geometric configurations to replicate the effects of changes in block configurations.
2. For stability testing, we introduce innovative approaches including assessing breakwater damage through compressed events (such as solitary or focused waves); evaluating block properties in alignment with the designated performance level for of wear and degradation on the block material.

MAIN CONTRIBUTION TO THE STATE OF THE ART

As a significant outcome of the PI-BREAK project, our comprehensive numerical investigation will provide unprecedented insights into the behavior of an 'as-built' breakwater. This advanced simulation allows for a detailed assessment of its stability and potential vulnerabilities, a level of detail only achievable through high-fidelity numerical modeling techniques. Moreover, drawing from the latest advancements in coastal engineering, our research aims to refine current

methodologies and contribute to the development of more effective breakwater designs, ensuring enhanced coastal resilience in the face of the foreseeable changes in the frequency and intensity of extreme events.

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