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Application and Validation of IHFOAM for Modelling Wave Interaction with Rubble-Mound Breakwaters: A Case Study from Bilbao Port (Spain) Supporting Predictive Maintenance Strategies

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ABSTRACT

The Spanish government-funded project, PI-BREAK (Predictive Intelligent System to Optimize BREAKwater Maintenance), aims to address the critical challenge of extending the lifespan of port infrastructure under evolving climate and usage scenarios. Although PI-BREAK focuses on adapting outdated breakwaters, this study highlights advances in the development of a numerical wave tank using OpenFOAM. This work presents a preliminary numerical analysis and validation of the PI-BREAK project, showcasing its potential to improve breakwater design and maintenance strategies through cutting-edge numerical and experimental methodologies which are complementary.

1 INTRODUCTION

PI-BREAK project addresses the challenge of extending the lifespan of port infrastructure under a range of future climatic/exploitation scenarios, introducing predictive intelligent maintenance to reduce risks and enlarge the safe operating space for breakwaters. The project will develop breakwater adaptation pathways with tipping points for the service and ultimate limit states, together with a portfolio of low-carbon footprint interventions to support automated maintenance decisions. PI-BREAK focus on a critical port infrastructure (Punta Lucero breakwater in Bilbao Port) that provides essential services for coastal welfare. From such critical maritime infrastructure, PI-BREAK will demonstrate how predictive maintenance increases port safety and efficiency, contributing to the recovery of economic activities based on breakwater adaptation to future scenarios, with a low carbon footprint.

2 PUNTA LUCERO BREAKWATER

The Punta Lucero breakwater was built on a particularly complex seabed. Within this bathymetric environment, the presence of a rocky cliff at the start of the current Punta Lucero breakwater constrains this study. This rocky formation stands out as a key element in the assessments, being of significant importance and having a considerable impact on the marine dynamics in the immediate vicinity of the existing structure. The Punta Lucero breakwater, constructed between 1971 and 1978 on the left bank of Bilbao Bay, experienced a partial failure during a storm in 1976, prior to completion. Consequently, reinforcement works were undertaken between 1980 and 1985. These involved reshaping the slope and placing a new main armour layer consisting of 150-tonne rectangular parallelepiped concrete blocks along the entire length of the structure. The slope was modified from 1:1.65 to 1:2, enhancing overall stability. Additionally, the crest elevation was uniformly raised to +21 m above Port Datum, and a service gallery was incorporated into the crown structure.

3 SPECIFIC OBJECTIVES AND METHODOLOGY

A comprehensive set of three-dimensional (3D) physical tests was defined to meet the specific objectives of the project: (O1) Assess breakwater performance in terms of the hydraulic stability and wave loads in the interested zone, (O2) Generate data for the calibration and validation of the numerical simulations, (O3) Expanding the knowledge base in terms of predictive maintenance and wave breaking dynamics behavior.

The study involved a comprehensive 3D physical model test of different breakwater maintenance sequences at Punta Lucero, following a methodology that includes the following steps: (M1) Definition of wave and water level conditions, (M2) Definition of different breakwater configurations, (M3) Wave calibration under undisturbed conditions, (M4) Preparation of rock materials and concrete units, (M5) Verification of the friction coefficient between the concrete units and the seabed, (M6) Construction of the bathymetry, incorporating the characteristic rocky cliff of Punta Lucero within the area of interest, (M7) Construction of the structure in the wave basin, (M8) Assessment of breakwater stability under the action of design storm waves and for different scenarios and time horizons and establish the damage curve, (M9) Analysis of the pressure distribution on the rocky cliff of Punta Lucero under design storm wave conditions and for different scenarios and time horizons, (M10) Compilation of data for numerical model input and provision of open-access datasets for the scientific community and the maritime-port sector.

4 PHYSICAL EXPERIMENTS

The 3D physical model tests were carried out at the Wave Directional Basin (TOD as acronym), located at the Ocean and Coastal Laboratory (IH Lab) at the University of Cantabria, Santander, Spain. This state-of-the-art facility is specifically designed for advanced physical modeling and testing of coastal and maritime structures. The basin is 28 m long, 8.6 m wide, and 1.2 m deep, equipped with a multi-board electric-drive piston wave maker. The wave ma-

chine is made of 10 independent paddles and is equipped with a sophisticated control system for the generation of long- and short-crested directional waves, with full 3D active wave absorption.
A total of six different geometric configurations were analyzed in the 3D physical model test campaign (1:45 scale). During the stability tests, the detailed bathymetry and the topo-bathymetry were constructed, representing the Punta Lucero rocky cliff in which the different breakwater configurations had to be placed. Eight irregular sea states, two regular sea states, and a solitary-type sea state were tested. Irregular wave conditions are used to obtain the spectral and statistical characteristics of the responses of the different configurations. Regular and solitary wave conditions make it possible to better understand wave structure interactions and inter-comparisons with numerical modeling.

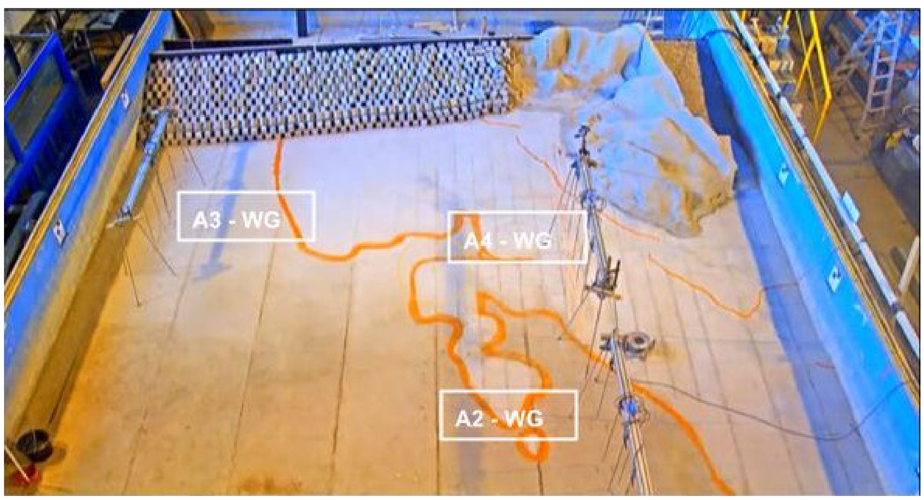

Figure 1: A photograph taken of the current configuration layout for the stability test phase

During the test campaign, water surface elevation data was recorded at various locations using a series of capacitance wave gauges, based on IHCantabria technology. An array of five wave gauges (Array A1) was installed at the generation depth (22.54 m Port Datum) with the objective of monitoring the wave energy generated by the paddle system. Additionally, a second array (Array 2) was deployed closer to the structure, at 15 m Port Datum, to characterise the incident wave conditions. The purpose of this array was to quantify the incoming wave energy. In addition, two further control arrays were installed: Array 3 and Array 4. Of these, Arrays 2 and 4 were selected for comparison with the numerical simulation results, as they provide key information on the incident wave conditions and wave transformation in the vicinity of the structure.

5 NUMERICAL SIMULATION

The numerical simulation builds upon the IHFOAM suite of tools (Higuera (2013), Romano (2020), Di Paolo (2021)), which is integrated into the open-source OpenFOAM platform (ESI (2021)). The geometry of the numerical wave tank (NWT) is based on the experimental wave basin described in the previous section. The NWT is 15 m long, 20 m wide, and 2 m high (Figure 2), and is characterized by a cell resolution of 0.05 m along the x direction, 0.05 m along the y direction, and 0.025 m along the z direction, with an extra refinement around the bathymetry, the breakwater and the rocky cliff to reduce the cell sizes by an order of 4. The computational domain is discretized into a structured grid and contains 22.3 M cells.

The initial water level (IWL) is set to 0.63 m (+5.81m Port datum in prototype scale). Wave generation and active absorption (shallow water active absorption boundary) are set at the inlet, and absorption (shallow water active absorption boundary) has been set at the outlet of the domain. Walls are defined as slip boundaries, the bottom as a non-slip boundary and the top as an open boundary. A regular sea state was simulated, with H=0.17 m and T=1.9 s, at a depth of -15.0m Port Datum in prototype scale. The k-ω-SST model from Larsen-Fuhrman (2018) has been used for turbulence modeling as it provides a stable solution for the overproduction of turbulence levels beneath waves. MULES algorithm to solve the VoF equation and the PIMPLE algorithm to solve the velocity-pressure coupling. Figure 2 shows the numerical free surface gauges (black lines), and Figure 3 depicts the numerical pressure gauges on the rocky cliff (purple points).

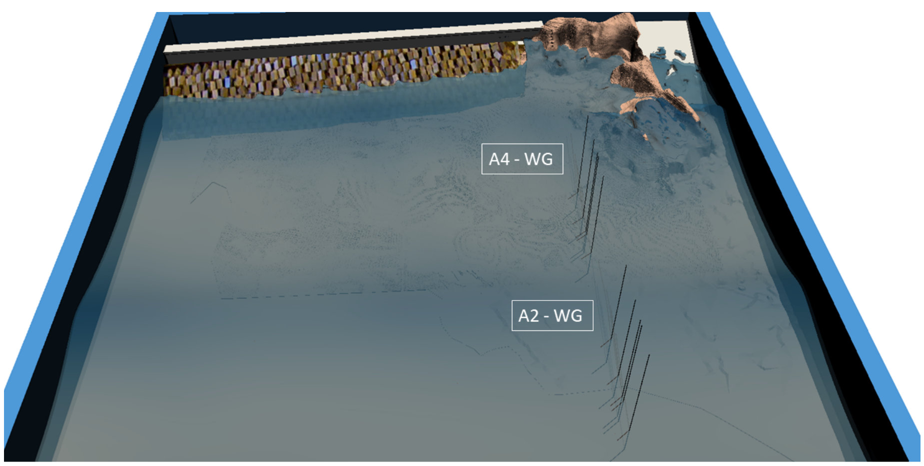

Figure 2: NWT and numerical free surface gauges (black lines)

During the numerical campaign, water surface elevation data and pressure were recorded at the same location as the experimental gauges to quantify the precision of the NWT.

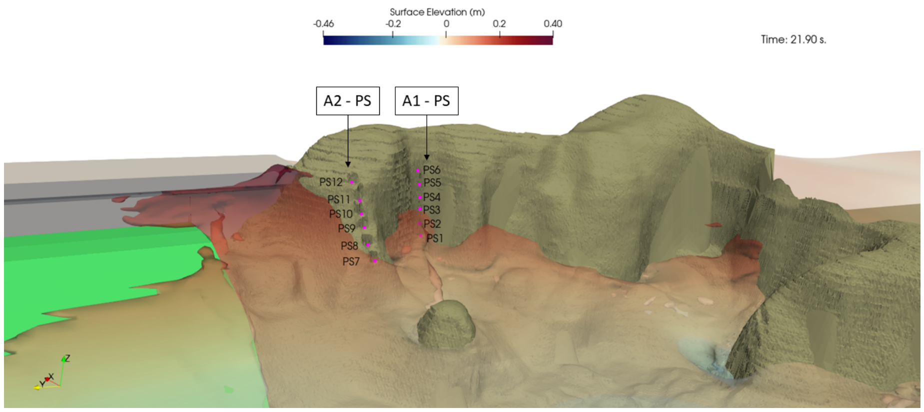

Figure 3: Numerical pressure gauges on the rocky cliff (purple points).

6 RESULTS

To test the capability of the NWT to reproduce simulations within the PI-BREAK project, an experimental benchmark case of the campaign carried out at the 3D wave basin (TOD) has been numerically reproduced. Figure 4 presents the comparison between the experimental (black line) and numerical (blue line) time series of the elevation of the free surface measured in the 10 wave gauges (Arrays A2-WG and A4-WG from the experimental configuration). The uppermost panel refers to WG1 (that is, the closest to the generation area), while the lowest one refers to WG10 (that is, the farthest from the generation area), respectively. The Root Mean Square Error (RMSE) is a standard statistical measure that is used to quantify the difference between predicted and observed values. It represents the square root of the average squared error, providing an overall measure of the accuracy of the model. The Normalized RMSE (NRMSE) scales the RMSE relative to the mean of the observed data, allowing comparison between different datasets or models. The calculation of these parameters (Table 1) shows that, in general, very good agreement has been achieved between the experimental and numerical results as low NRMSE values (e.g., below 10%) are considered indicative of high accuracy in numerical modeling applications.

Figure 5 presents the total horizontal force in both pressure gauge arrays. The blue line represents experimental data, while the purple line represents numerical data. The red circle represents the maximum measured force, while the green circle is the maximum simulated force. For Array A1-PS (upper panel), experimental data provides a F_{max}=90.96 N/ml at t=18 s, and numerical data a maximum measured force, F_{max}=111.02 N/ml at t=18 s. For Array A2-PS (lower panel), experimental data provides a F_{max}=44.93 N/ml at t=18 s, and numerical data a maximum measured force, F_{max}=10.95 N/ml at t=18 s.

Wave Gauges	*RMSE* H(m)	*RMSE* T(s)	*NRMSE* H(%)	*NRMSE* T(%)
A2-WG01	0.010	0.032	5.72	1.67
A2-WG02	0.014	0.044	7.92	2.30
A2-WG03	0.015	0.042	8.46	2.19
A2-WG04	0.012	0.039	7.36	2.04
A2-WG05	0.004	0.025	2.47	1.32
A4-WG06	0.013	0.028	8.03	1.47
A4-WG07	0.003	0.025	1.89	1.34
A4-WG08	0.007	0.019	4.28	1.02
A4-WG09	0.012	0.030	7.68	1.58
A4-WG10	0.011	0.030	8.18	1.61

Table 1: *RMSE* and *NRMSE* values for wave height (H) and period (T), from the free surface sensors, experimental and numerical.

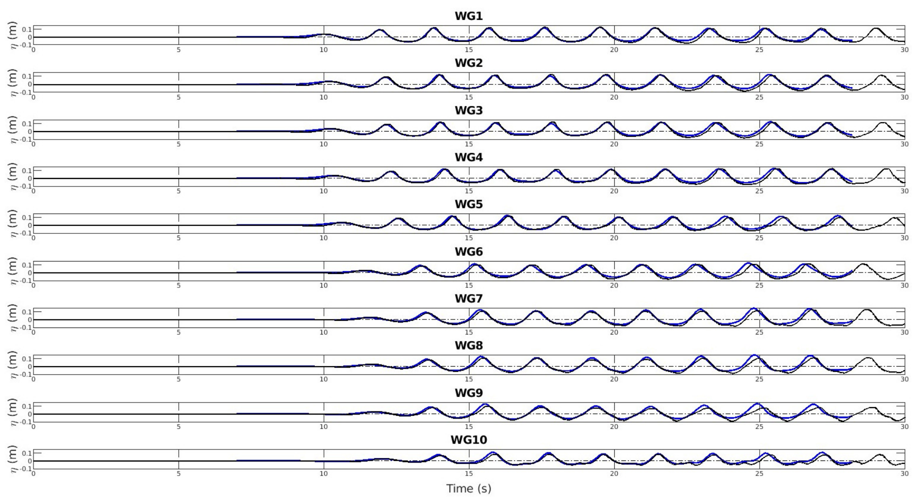

Figure 4: Comparison between experimental (black line) and numerical (blue line) free surface elevation time series measured at 10 wave gauges.

Both results are in phase, but differ in magnitude, caused by the complexity of the simulation: non-linear waves interacting and impacting with very complex geometries. Finally, Figure 6 reproduces the pressure profile of the pressure gauge arrays of both pressure gauges at the moment of maximum forces (t=18 s). The left panel presents the comparison between the experimental data (red line) and the numerical data (blue line) for Array A1-PS, while the right panel presents the comparison for Array A2-PS. Again, results show good agreement but some gauges differ in magnitude, due to the very complex scenario where non-linear waves impact on the rocky cliff. Reproducing accurately the free-surface evolution of broken waves is still an open challenge for OpenFOAM.

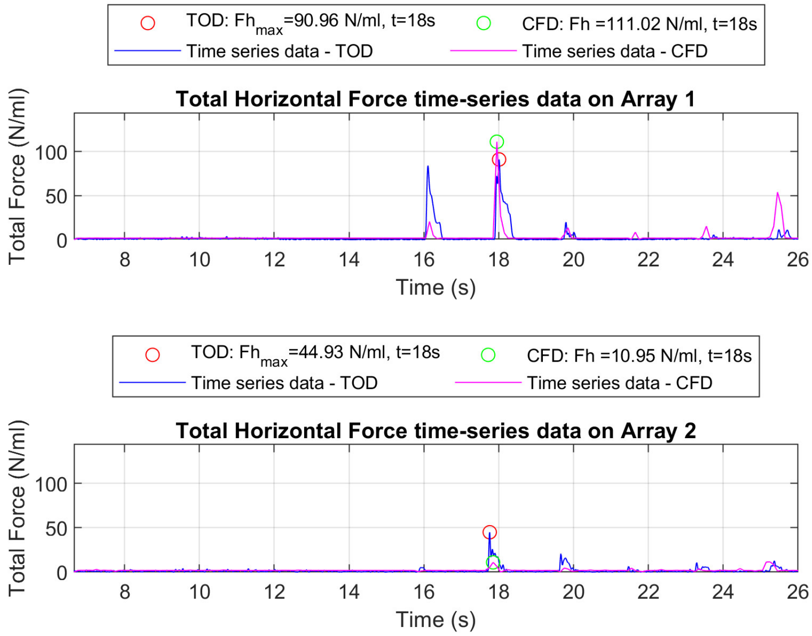

Figure 5: Total Force evolution for Array A1-PS (upper panel) and Array A2-PS (bottom panel) of pressure gauges. Blue line represents experimental data, purple line represents numerical data. Red circle represents the maximum measured force, green circle is the maximum simulated force.

7 CONCLUSIONS

This work outlines the results of the 3D physical and numerical model studied carried out by the Environmental Hydraulics Institute of the University of Cantabria (IHCantabria) for the project "PI-BREAK". The 3D physical model tests aimed to assess breakwater performance in terms of hydraulic stability and wave loads for several maintenance sequences, with the aim of finding a characteristic damage curve which allows predicting the size of the units necessary to support the loads produced by the incident waves. The 3D numerical model aimed to prove that CFD simulations are a valuable and complementary tool for experimental campaigns, because of their ability to simulate different scenarios at the same time. Finally, a new set of public data (https://pi-break.upc.edu/) has been produced within the framework of the project, in order to provide more information in terms of predictive maintenance and wave breaking dynamics behavior for calibrating and validating numerical models.

ACKNOWLEDGEMENTS

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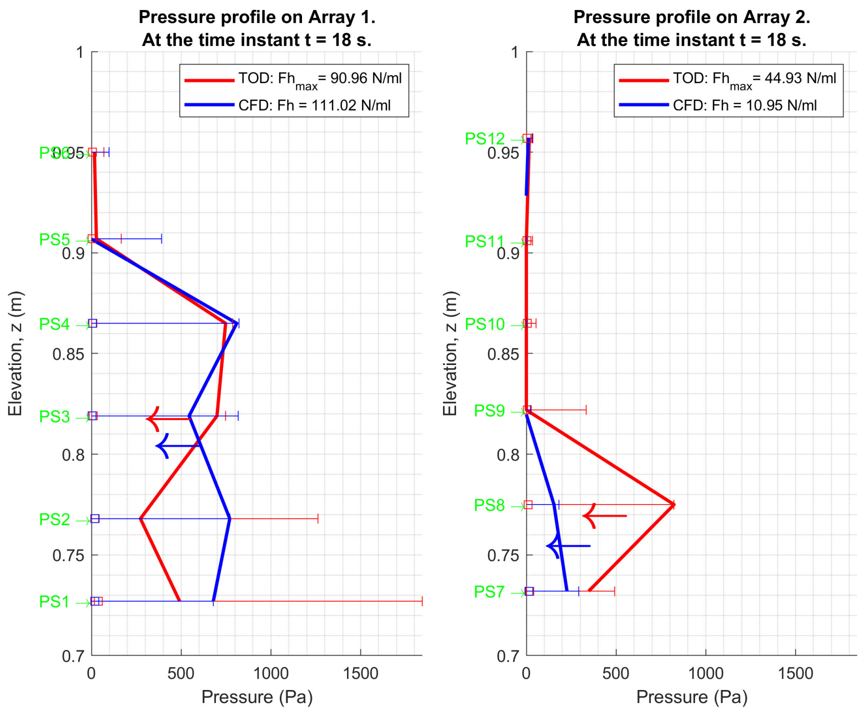

Figure 6: Pressure profile at the instant of maximum force (t=18s). Left panel, Array A1-PS and right panel, Array A2-PS. Red line represents experimental data, blue line represents numerical data.

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