

STABILITY OF TETRAPOD MOUND BREAKWATERS AGAINST SOLITARY WAVES USING THE SPH METHOD

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I. INTRODUCTION

The use of artificial armour blocks in mound breakwater construction aims to improve the overall stability of the system by maximising interlocking effects between units. These structures offer significant advantages over traditional rock blocks of comparable weight and size. Tetrapods [1] are typical armour units that have been widely used to effectively dissipate wave energy, as illustrated in Fig. 1. These units are often tested to investigate their hydrodynamic behaviour under extreme wave conditions, which is critical in coastal engineering design. In fact, achieving an optimal balance between the gaps and openings in the breakwater layout is essential, as they play a key role in wave dissipation. Additionally, the complex interaction between service performance and survival performance presents challenges that are difficult to thoroughly examine using traditional methods like experiments or data-driven models.



Figure 1. Tetrapods in the Port of Molfetta (Italy). Source: *Acquatecno Srl*.

High-fidelity numerical modelling, hence, can step in to complement research assessments. This study aims to predict the stability of armour units by numerical simulation. To accomplish this challenging task, numerical modelling may need to combine: i) Computational Fluid Dynamics (CFD) for wave propagation and wave–structure interaction; and ii) rigid body dynamics for collision detection. Specifically, this study evaluates the effectiveness of a Smoothed Particle Hydrodynamics (SPH)-based fluid solver in modelling the

behaviour of a fully deployed breakwater under extreme wave conditions. It leverages experimental data to validate the DualSPHysics software, thanks to the coupling with Project Chrono that allows to simulate collision detections. This coupled code has been already successfully applied to study wave–Tetrapod interaction in [2]. However, in [2] the Tetrapod–Tetrapod interaction was not analysed and there is no proper validation in the literature for SPH-DEM code implementations.

This work presents, for the first time, a validation of the DualSPHysics-Chrono code using a novel experimental campaign to simulate the response of concrete Tetrapod units when subjected to a modelled tsunami bore flow replicated using a solitary wave, for both the wave-Tetrapod interaction and Tetrapod-Tetrapod interactions (*novelty*).

II. NUMERICAL MODELLING

The Smoothed Particle Hydrodynamics (SPH) method is proposed for wave propagation and wave-structure interaction, while the solid-solid dynamics is modelled using the Discrete Element Method (DEM).

A. Smoothed Particle Hydrodynamics

DualSPHysics is a CFD implementation of the SPH method. This CFD is a highly parallelised open-source code, freely available and a reference in the field of coastal and ocean engineering. DualSPHysics offers a distinct advantage in simulating free surface flows and capturing the complex non-linear behaviour of wave-structure interactions and fluid-driven objects. Operating within a Lagrangian framework, SPH characterises fluid motion by discrete entities called particles, allowing continuum properties to be represented by smoothed quantities. Based on such a technique, the DualSPHysics framework [3] is used to simulate the hydrodynamic response of Tetrapod units against solitary waves.

B. Discrete Element Method

The DEM-based solver implemented in the open-source multiphysics engine Chrono provides an accurate tool to simulate the rigid body dynamics. In fact, the solid-solid interaction, which determines the stability of breakwaters, appears to be as important as the fluid-structure interaction due to the very complex shapes of the Tetrapods and the material properties of the block surface. Chrono implements a DEM that introduces Complementarity (DEM-C) conditions to enforce the non-penetration of the elements that are in contact, solving a Differential Variational Inequality (DVI) formulation to deal with this type of problem. Using this formulation, Chrono represents the surface properties of the blocks, being able to solve friction contacts characterised by the material properties of the colliding bodies.

C. Coupling SPH-DEM

A two-way SPH-DEM coupling [4] is implemented to solve complex fluid-solid-solid interactions. DualSPHysics controls the simulation flow with calls to Chrono through the communication interface called DSPHChronoLib. This interface is an open-source code that handles the data exchange between the SPH and DEM solvers. Fig. 2 shows a schematic of the coupling procedure, representing the two-way communication events that occur during a single integration time step.

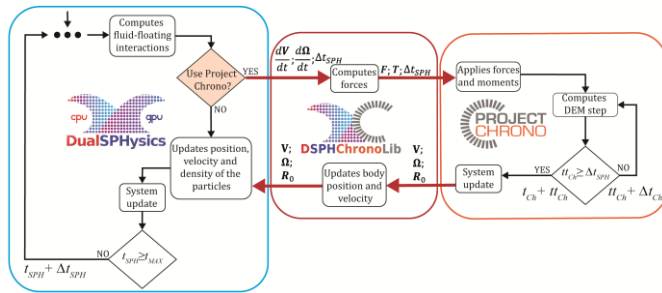


Figure 2. Flowchart of the DualSPHysics-Chrono coupling [4].

III. EXPERIMENTAL CAMPAIGN

A series of physical tests were carried out at the facilities of Fudo Tetra Corporation (Japan) to analyse the behaviour of Tetrapod units against a solitary wave. The experimental campaign was designed to validate the proposed SPH-DEM coupled code by comparing the displacement of units in numerical simulations with physical experiments. The experiments were conducted in a wave flume with the following dimensions: a length of 50 m, a width of 1.0 m, and a height of 1.30 m. The solitary waves were generated with a piston-type wave generator. The unit blocks were moulded with mortar, scaling down the Tetrapod model to a suitable 1:50 scale, resulting in a block size of 7.70 cm in height, a volume of 128 cm³ and a mass of 294 g, with a density of 2.30 g/cm³. The friction coefficient between two Tetrapods in wet conditions was experimentally measured to be 0.65. The seabed consisted of a fixed mortar bed, and the friction coefficient between the bed and the blocks was also determined. The Tetrapods were placed 34.5 m away from the wave paddle on a 1:30 slope. Two layers of Tetrapods were

arranged, as shown in Fig. 3, with a total of 68 units. The first layer consisted of 3 rows with 14 units, while the second layer comprised 13 units in 2 rows.

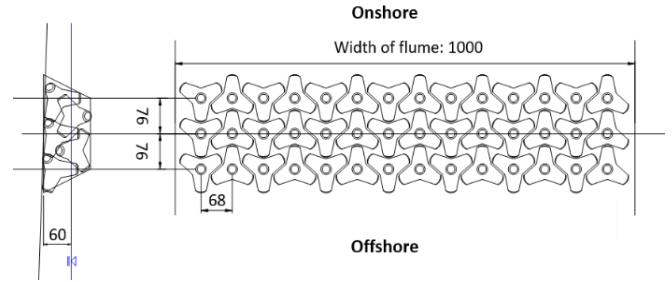


Figure 3. Layout of the two-layer breakwater (unit in mm).

The water depth offshore was set to 0.61 m, whereas at the breakwater location was 0.06 m, such that the first layer was almost completely submerged (side view in Fig. 3). Several solitary waves were simulated, with wave heights (H) ranging from 3 to 11 cm at a uniform water depth on the offshore side. The collected experimental data includes information on i) incident waves without structure; ii) wave elevations at different locations; and iii) in-time unit displacement captured through video imaging techniques. To ensure repeatability, the units were stacked in a consistent manner, with the exact initial positions of the blocks used to initialize DualSPHysics (with particles) and Chrono (with geometries). Notably, the experiments were conducted three times under identical conditions.

IV. RESULTS

It should be noted that the proposed tool allows to easily introduce the data measured from the experiments to mimic for the material properties of the rigid bodies (*usability*). Fig. 4 shows a side view of the initial configuration in the experiment (left) and the initial setup for DualSPHysics (right). Then, the results presented here comprise a two-layer breakwater where the interaction between Tetrapod units is also numerically solved. Note that the armour units are coloured per rows in the same way than in the experiments to visually identify them.

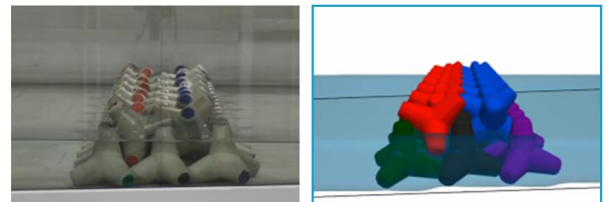


Figure 4. Initial setup in experiments (left) and in DualSPHysics (right).

Three different wave conditions have been simulated, $H=7.0, 9.0,$ and 11 cm; the individual displacement of each tetrapod has been used to validate the numerical model against experimental data. A visual comparison is provided in Fig. 5 that represents the final tetrapod configuration after each solitary wave has arrived and impacted the armour units in the experiments (left) and the numerical model (right), respectively. This comparison gives an overview of the

displacement of Tetrapods by rows, where it can be seen that the model is able to reproduce the nature of these seemingly chaotic phenomena quite well.

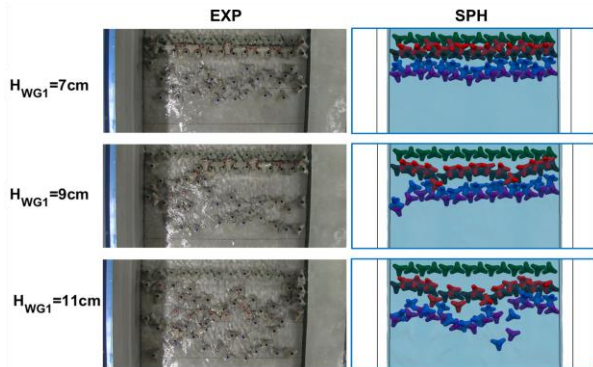


Figure 5. Visual comparison between experiments (left) and the numerical model (right) for the three selected wave conditions.

In addition to the previous comparison, the total displacement per row for each solitary wave is presented in Fig. 6. Note that the colour of each x -axis title is defined according to the representation in Fig. 5, to identify each row of blocks. Overall, this result shows that the numerical model is able to accurately reproduce the displacement for every row (*quality of results*). However, the results for the fifth row (top land) for the three waves and the fourth for $H = 9.0$ and 11 cm (second and third panels, respectively) should be discussed further. Looking at the top land row, it is clear that the displacement of the Tetrapods in the numerical model is lower than expected, with an error of about 50% for all waves. On the other hand, for the top sea row, the second panel reveals that the displacements in SPH are higher than the results of EXP2 and EXP3, but in agreement with EXP1. Finally, the displacement observed in the third panel of the numerical method is less than the three experimental repetitions with an error of 15%.

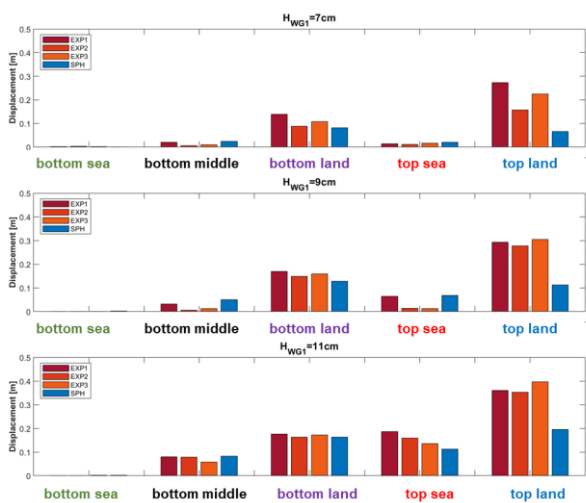


Figure 6. Comparison of the displacements of Tetrapods per row between the three repetitions in experiments (EXP) with results from the numerical simulations (SPH) for the three selected wave conditions.

In general, the provided results here are promising, in spite of some aspects that need to be analysed in order to further reduce the discrepancies between the presented and the physical models. We would like to emphasise the importance of accurately reproducing the wave shape, especially when wave breaking occurs, as in these cases. Therefore, the stimulation of the wave loads should be better analysed, as the air phase is not modelled here and could play an important role in solving the wave–structure interaction.

V. CONCLUSIONS

This DualSPPhysics-Chrono coupled code stands out as a highly competitive engineering tool for the SPH community, particularly due to its ability to model coastal processes, such as the behaviour of a fully deployed breakwater under extreme wave conditions (*applicability*). Likewise, its versatility extends to any application requiring the capability to handle highly non-linear effects with multi-body frictional contacts that traditional mesh-based approaches or alternative methods may struggle to address (*competitiveness*).

The preliminary validations conducted in this work show the good fit of the model, considering the displacement of the blocks under solitary waves. Results prove that the model can predict the overall displacement of each row of Tetrapods. However, many aspects need further investigation in order to improve the quality of the model. Some discrepancies can be attributed to uncertainties on the friction coefficient variability, which is difficult to physically measure and estimate. Other relevant variables to be investigated are represented by: water flowing between blocks at different numerical resolutions, the importance of the initial block positioning, wave shape, wave breaking, and wave loads.

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