WAVE IMPACT ON BREAKWATER ARMOR BLOCKS USING IBM-DEM CFD COUPLING

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INTRODUCTION

The stability of armor units against wave action is a critical issue for coastal and harbor breakwaters. Most of the time, the breakwater stability is determined based on semi-empirical design formulae, as well as with experimental campaigns on scale models in wave basins.

The present work aims to approach breakwater stability through a numerical deterministic approach using a DEM-CFD (Discrete Element Method - Computational Fluid Dynamics) method which simulates the individual motion of armor units inside a fluid solver. The fluid is solved using EDF Eulerian-Eulerian CFD code neptune_cfd, and the contacts between blocks are solved using the DEM code Grains3D (Wachs et al., 2012). The solids are modeled inside neptune_cfd using an IBM (Immersed Boundary Method) technique with discrete forcing.

Two numerical studies are performed to compare the accuracy of the coupling to experimental studies with relevant configuration for coastal engineering. Both studies consist in generating waves in a numerical wave flume and evaluating their impact on armor units, either fixed or free to move. The first set of experiments aims to evaluate the forces exerted by impacting waves on an idealized breakwater and was conducted in EDF R&D laboratory in France. The structure is made of a slope with an array of individual spheres (representing armor blocks) placed on it at two elevations above the slope, some of them being instrumented with 6-axis force sensors. The second test studies the impact of a solitary wave on a row of isolated Tetrapods laid on a horizontal berm based on Mitsui et al. (2023) experiment made in the Fudo Tetra Corporation facilities in Japan.

NUMERICAL MODELING

The CFD code neptune_cfd is a multi-phase solver which follows a Eulerian-Eulerian approach with a single pressure. The interface between air and water is dealt with the LIM (Large Interface Model) model which acts on a three-cell stencil around the interface location and includes interfacial transfer of momentum. The waves are generated using boundary conditions and a momentum generative zone. Using experimental wave height and time span as reference, nonlinear wave signals from the stream-function method are generated (see Fig. 1). The free surface elevation and the velocities are imposed at the inlet of the flume and a momentum generative zone is added next to the inlet, with a decreasing forcing as the waves approach the domain of interest. The method is presented in Benoit et al. (2023).

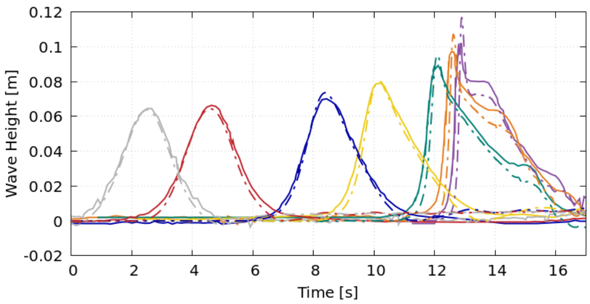

Figure 1 - Wave height at different gauges for a solitary wave, neptune_cfd simulation (–––) vs Mitsui et al. (2023) experiment (—). The wave gauges are represented using different colors.

In order to model the solids inside the fluid, the *Time and Space Dependent Porosity Method* is used, as presented by Benguigui et al. (2018, 2019). A porosity value ranging between 0 and 1 is associated to every cell, 1 being a fully fluid cell and 0 a fully solid cell. Objects are then built in a Lagragian framework using a cut-cell method: the interface between fluid and solid is reconstructed in the cells with porosity between 0 and 1. When an object is mobile, the forces are determined by calculating the pressure and viscous forces at the surface of the object. The velocities and displacements are then deduced through a strong coupling using a Newmark algorithm.

The solid-solid interaction is modeled using the DEM code Grains3D, introduced by Wachs et al. (2012). It is a granular solver with a Lagrangian particle tracking method. The forces are determined using tangential and normal spring models, dissipative forces, and a sliding Coulomb force. The simulation parameters are selected to respect numerical guidelines such as the minimal number of time steps during an impact and physical behaviors such as the coefficient of restitution (the ratio between the relative velocities before and after impact).

The evaluation of contacts between objects is made using the GJK distance algorithm which uses support functions to determine the distance between the closest points of two particles, originally developed by Gilbert et al. (1988). If in contact, the interpenetration length is calculated using the same algorithm with shrinked particles. This method only allows to use some specific convex objects. In order to model complex shapes such as Tetrapods, multiples convex shapes must be glued together as in Rakotonirina et al. (2019). A Tetrapod can be modeled using four truncated cones for the legs and one sphere for the center. The coupling is realized by giving the fluid forces from neptune_cfd to Grains3D, calculating the DEM forces and finally integrating the equations of object motion with a 2nd order Verlet leapfrog scheme.

WAVE IMPACT ON AN IDEALIZED BREAKWATER

The experiments took place in EDF R&D laboratory in a 45 m long, 0.60 m wide and 0.83 m deep wave flume. The still water depth is 0.60 m. During the experiment, several types of regular waves were generated towards a 2/3 plane slope with fixed spheres mounted on it (see Fig. 2). The spheres have a diameter of 10 cm with their centers placed on two planes parallel to the slope. Four spheres are instrumented in order to measure the time series of forces exerted by the fluid.

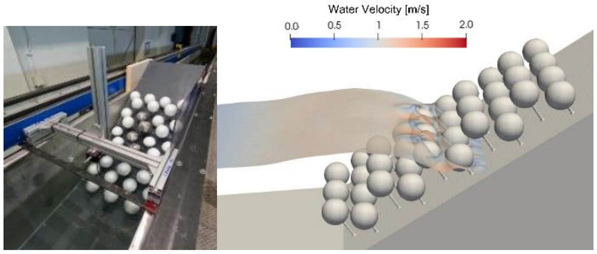

Figure 2 - Picture of the experimental setup (left) and numerical wave impacting the breakwater (right).

WAVE IMPACT ON MOBILE TETRAPODS

Mitsui et al. (2023) set of experiments consists in sending a solitary wave on a row of 15 isolated Tetrapods laid on a horizontal berm (see Fig. 3). The experiment is realized in a 55 m long flume with a 1.2 m width, 1.5 m height and a still water depth of 0.8 m. A 1/30 slope is built in front of the test area and the water depth over the flat berm is 53 mm. The Tetrapods are 77 mm high with a mass of 300 g.

The simulations are made using a smaller domain for wave propagation, but with identical dimensions otherwise. Three solitary waves are evaluated with distinct wave heights: 2.6, 4.5, and 6.4 cm, as measured at the first gauge (see Fig. 1). The comparison of the experimental and numerical studies is based on the displacements made by the line of Tetrapods after wave impact (see snapshot of the wave before impact in Fig. 4).

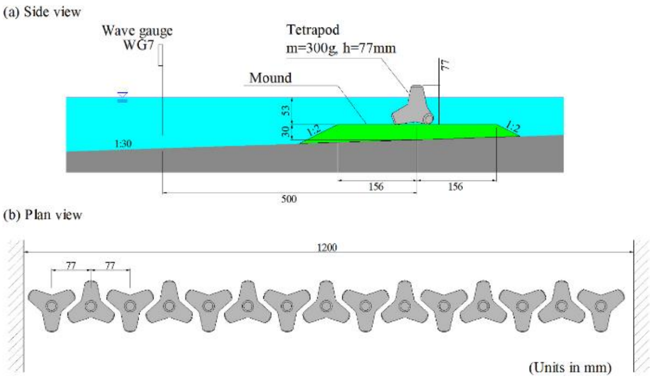

Figure 3 - Schematic of the flume and the set of Tetrapods in the case by Mitsui et al. (2023).

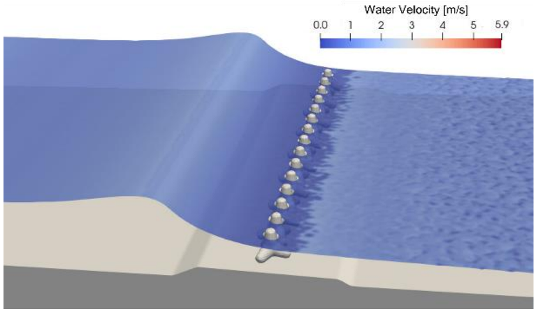

Figure 4 - Snapshot of a numerical solitary wave impacting the row of Tetrapods.

CONCLUSION & PERSPECTIVES

This study shows the capabilities of the DEM-CFD coupling between neptune_cfd and Grains3D for coastal engineering applications. These simulations are a step toward the simulation of breakwater degradation using a deterministic approach, as a complement to the experimental and empirical methods currently used. The following steps will be to get closer to a realistic structure by studying the impact of waves on armor units densely packed as in conventional breakwater armors.

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