

Extending the Frontiers of Coastal Engineering: Real-World Applications of DualSPHysics to breakwaters and quays

Andrea Marzeddu, Corrado Altomare
Laboratori d'Enginyeria Marítima
Universitat Politècnica de Catalunya - BarcelonaTech
Barcelona, Spain
andrea.marzeddu@upc.edu, corrado.altomare@upc.edu

I. INTRODUCTION

As global climate challenges intensify, coastal infrastructure faces increasing risks from severe storms and rising sea levels. Traditional engineering approaches, often reliant on grid-based methods, frequently struggle to accurately capture the highly dynamic and nonlinear interactions between waves and coastal structures. Smoothed Particle Hydrodynamics (SPH), a meshless Lagrangian method, offers a groundbreaking alternative. Implemented in DualSPHysics ([2]), SPH demonstrates exceptional capabilities in simulating free-surface flows, large deformations, and complex wave-structure interactions ([1]).

This work highlights innovative applications of DualSPHysics in coastal engineering, focusing on harbour infrastructures, such as breakwaters and berthing structures, to illustrate the model's potential in optimizing and enhancing coastal resilience. By integrating SPH simulations with experimental validations, we showcase state-of-the-art advancements in the design and assessment of harbour structures, emphasizing the transformative potential of this meshless approach for modernizing coastal defence strategies. The applications presented have directly contributed to data used or intended for retrofitting structures and assessing coastal safety along the Catalan and Belgian coastlines.

II. THE DUALSPHYSICS MODEL

The simulations are carried out using the open-source DualSPHysics solver, which employs a Weakly Compressible SPH approach. DualSPHysics is designed to operate on both CPUs and Graphics Processing Units (GPUs). By leveraging GPU computing, it achieves high computational efficiency while maintaining accuracy. Each case study combines SPH simulations with experimental validations, offering robust insights into design and performance. DualSPHysics offers a range of tools and features that make it highly suitable for engineering applications, particularly when fluid phases play a significant role in the simulated physics. The code also integrates with various external libraries, enabling the modelling of other physical systems through the generalized coupling strategy detailed

in [3]. Besides, the model incorporates advanced boundary conditions [4]. Model details and implementation are omitted here for the sake of brevity. The reader must refer to [2] for further details.

III. CASES OF STUDY AND MODEL RESULTS

A. Port of Blanes

In January 2020, an extraordinary storm (Gloria) occurred in the Mediterranean Sea, affecting a large part of the Catalan coastline. Among the affected infrastructures, the 3rd alignment of the breakwater of the Port of Blanes suffered significant damage. This study is part of the assessment for the reinforcement and repair of the breakwater of the Port of Blanes. Specifically, the presented modelling reflects the results of the wave-breakwater interaction analysis and its effect on the transition zone. The results obtained have been taken into account, together with the propagation of the waves, for the reinforcement of the section considered.

A 3D DualSPHysics model was used to analyse wave interactions with the breakwater, focusing on a vertical wall connected to a sloped section. An orthophoto of the port is depicted in the bottom-right image in Fig. 1, while on the bottom-left, the contour plot of significant propagated wave height by SWAN model is reported. These values have been used as input for DualSPHysics. The 400 m x 300 m domain was aligned with a wave propagation direction of 128° from North, using regular waves equivalent to a 75-year return period. Waves were generated with a multi-element piston system and active absorption to minimize reflections. Simulations with 1.8 million fluid particles used a resolution of 0.8 m, taking 4.2 hours on a GeForce RTX 2080 GPU. Initial tests verified accurate wave propagation, ensuring reliable results for structural impact analysis. Two configurations were modelled: (a) the first included the vertical breakwater in its actual design; (b) the second replaced the vertical breakwater with fluid and passive wave absorption to isolate its effects.

The wave height and velocity field have been measured at different locations defined in a 320m x 220m grid, with

measurement points every 10m. The in Fig. 1 corresponds to a snapshot of DualSPHysics simulation. The points indicate the wave height sensors in the model, whose colour indicates the free surface elevation relative to the initial mean level. The free surface colour field indicates the horizontal surface velocity of the fluid in X. The first measurement point has the coordinates $x=0$ m and $y=25$ m. From the velocity field obtained in the simulation, the vorticity field in the XY plane has been calculated for the same depth values. Fig. 2 shows two time instants of the horizontal velocity on the free surface and in the Y direction, obtained with a vertical breakwater (a) and without a vertical breakwater (b). It can be observed how the vertical breakwater generates an amplification effect on the fluid velocity field in the transition zone of the dam on the slope, comparing the results obtained with the simulation carried out without the presence of the vertical dam. The negative values of Y (colours tending to blue) indicate peaks of velocities that run up the slope, observed in both cases, but intensified with the vertical dam configuration present.

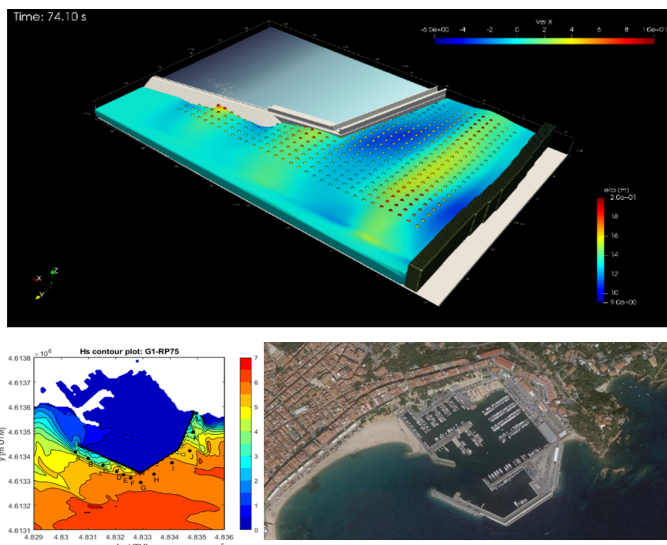


Fig. 1. Image of the simulation with DualSPHysics at an instant in time

The results show that the presence of the vertical breakwater caused wave diffraction, increasing wave heights at the toe of the sloping breakwater by 7%. Flow velocities and average velocities measured 3.5 meters below the mean free surface were amplified due to the vertical breakwater, focusing wave energy toward the sloped section. The amplified velocities increased erosion risks and could negatively affect the backfill foundation at the crest of the sloped section, highlighting potential maintenance challenges. These results emphasize the need to account for diffraction effects and interactions between structural components, such as vertical and sloped sections of breakwaters, in design processes.

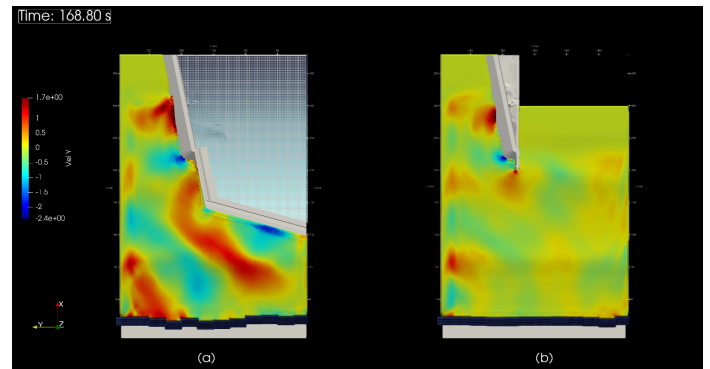


Fig. 2. Image of the simulation with DualSPHysics at a time instant: real case with vertical dam (a) vs equivalent case without vertical breakwater (b). The colors of the free surface indicate the horizontal superficial velocity of the fluid in Y

B. Port of Ostend — Quay 101

A comprehensive study using DualSPHysics was conducted to evaluate wave forces and pressures on Quay 101 of the Port of Ostend. The design provided by the Maritime Access Division of the Flemish Government consists of a platform that includes an underwater slope, a vertical wall, a prestressed beam, a frontal beam, and a slab. The frontal beam is closed, with its bottom level located at approximately +3.13 mTAW (where TAW stays for Belgian reference level). The numerical modelling has been performed, considering quasi-3D modelling of long-crested waves perpendicular to the quay: the actual numerical model domain was narrowed to 1.2 m, including half of the left-side beam and half of the right-side beam. The key geometrical characteristics of the design include a top level at the seaward side of approximately +6.69 mTAW, a bottom level of the slab at the seaward side of approximately +6.42 mTAW, a bottom level of the prestressed beam at the seaward side of approximately +5.27 mTAW, and a bottom level of the frontal beam at approximately +3.13 mTAW. The design incorporates a cofferdam beneath the quay slab and longitudinal prestressed beam was analysed.: the top level of the cofferdam was set at +3.50 mTAW. Two water levels were analysed: +5.27 mTAW and +6.42 mTAW. The model of Quay 101 was executed for a time window of 135 s using a resolution of $dp=0.07$ m, involving 1,685,340 SPH fluid particles at the start of the simulation. Wave were generated using Open Boundary Conditions ([5]). The computation, performed on a GeForce RTX 3080 GPU (8960 CUDA cores), took 59 hours. Snapshots of the DualSPHysics simulations, where the geometrical characteristics of the quay can be appreciated, are reported in Fig. 3.

The cofferdam was introduced to effectively dissipate wave energy, thereby reducing the force and pressure on the quay slab. The modelling results showed that forces on the slab were significantly reduced, with a maximum of approximately 20 ton/m, representing a threefold reduction compared to previous solutions. Maximum pressures were observed at the rear of the beam near the cofferdam, although they were generally lower

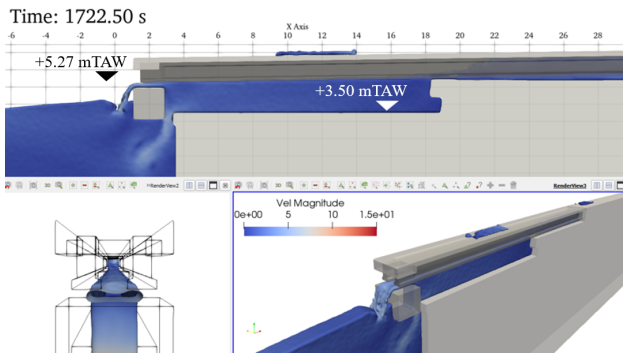


Fig. 3. Snapshots of DualSPHysics simulation of the quay 101

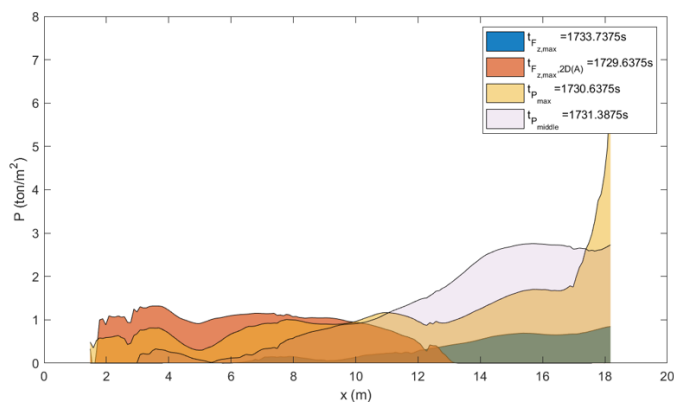


Fig. 4. Pressure distribution along the quay slab for +5.27 mTAW

than those recorded in prior layouts without a cofferdam. An example of the pressure distribution on the slab is shown in Fig. 4, where $t_{F_{max}}$ corresponds to the time instant of the maximum total force exerted on the slab (shaded in blue in Fig. 4), $t_{P_{max}}$ corresponds to the time instant of the largest pressure, and $t_{P_{middle}}$ represents the time step of maximum pressure at the midpoint of the span of the prestressed beam/slab. The results from previous 2D simulations, are also shown ($t_{F_{max,2D(A)}}$), however they do not capture the three-dimensional effects due to the geometry of the beam cross-section.

Thus, the key results from the 3D modelling, which incorporates a cofferdam modifying the original layout of Quay 101, demonstrate a notable decrease in forces and pressures by +5.27 mTAW. The cofferdam effectively shields the slab from direct wave impacts and further dissipates wave energy, thereby reducing peak loads on the longitudinal prestressed beam. However, analysis at a higher water level (+6.42 mTAW), not shown here, shows a significant rise in forces and pressures, particularly affecting the slab.

IV. CONCLUSIONS

This study demonstrates the significant potential of DualSPHysics, a meshless Lagrangian approach, in the assessment and optimization of coastal infrastructure under challenging environmental conditions. The case studies presented illustrate

how this tool can enhance the design and evaluation of harbour structures, improving resilience against severe weather events and rising sea levels. To the Authors' knowledge, these cases are among the first ones where an SPH-based model is applied to aid the design and adaptation of coastal structures under complex wave-structure interaction.

The Port of Blanes study revealed how wave interactions with breakwaters can cause diffraction effects, amplifying wave heights and flow velocities, which could increase erosion risks and affect structural stability. The results emphasized the importance of considering these interactions during the design process to mitigate potential risks.

For the Port of Ostend, the incorporation of a cofferdam in the quay design showed a substantial reduction in wave forces and pressures on the quay slab, enhancing the structural performance. The cofferdam effectively dissipated wave energy, reducing peak loads on the longitudinal prestressed beam, particularly at the lower water level of +5.27 mTAW. However, higher water levels resulted in increased forces and pressures, indicating that further investigation is necessary to optimize the design for varying conditions.

These findings underscore the transformative potential of SPH in coastal engineering, offering a more accurate and efficient method for simulating complex wave-structure interactions. Results demonstrate the model's competitiveness over standard tools, achieving high accuracy in simulating 3D wave dynamics with computational efficiency. These findings emphasize SPH's role as a cutting-edge alternative for tackling complex coastal engineering challenges, offering unparalleled insights into wave-structure interactions and design resilience. All detailed results for both cases of study will be shown at the conference.

ACKNOWLEDGMENTS

Dr. Corrado Altomare acknowledges funding from the Spanish government and the European Social Fund (ESF) under the program 'Ramón y Cajal 2020' (RYC 2020-030197-I/AEI/10.13039/501100011033). The authors would like to thank Flanders Hydraulics to ensure free access to data and reports on the Port of Oostende Quay 101.

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