Fluid-structure interaction of a leading depression N-wave shaped tsunami

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Abstract: In this work, we present a 2DV study of the interaction of a tsunami wave with the Cascais marina breakwater. The numerical modelling is performed with the open-source computational fluid dynamics software OpenFOAM and the olaFlow toolbox. The tsunami wave, which resembles a leading depression N-wave, enters the domain from Southwest with a wave height of about 6 m. We show that the Cascais breakwater is overtopped by the tsunami wave and that vortices are generated on the seaward and leeward sides of the breakwater. We perform an analysis of the pressure distribution on the walls and crest of the breakwater and show that negative pressures arise on the leeward side of the breakwater.

Key words: computational fluid dynamics, fluid-structure interaction, N-wave; tsunami.

1. THE N-WAVE CONCEPT

A tsunami wave can be described as a long wave in shallow water. Such a wave has a wavelength λ which is much larger than the depth h of the water it is propagating in, i.e. $h/\lambda \ll 1$. A common approach is to model tsunamis as solitary waves, both in experimental and numerical studies. Madsen et al. (2008) discussed the solitary wave paradigm in tsunami research and concluded that, in general, tsunamis do not generate solitary-like waves in the ocean or on the continental shelf. In fact, not all tsunami events are alike and reports of shoreline receding support the concept of N-shaped tsunami waves (cf. Figure 1). The N-wave concept was introduced by Tadepalli and Synolakis (1994), who suggested that an N-wave is the most adequate to describe the main tsunami wave. N-waves can be described as having a leading trough, the so-called leading depression N-wave (LDN-wave), or a leading crest, a leading elevation N-wave (LEN-wave). A conceptual N-wave was modelled by Tadepalli and Synolakis (1994, 1996) as

$$\eta(x,t) = \varepsilon\,(\theta - \kappa\,\delta)\,H\,\mathrm{sech}^2\big(\kappa\,(x - c\,t - x_1)\big)\,,$$

where ε is a scale factor necessary to define the wave height as H, $\delta = x_2 - x_1$ is an eccentricity parameter, defined as the distance between $x = x_2$, the location of the inflexion point of the wave profile at $t = 0$, i.e. $\eta(x_2, 0) = 0$, and $x = x_1$, the location at $t = 0$ of the crest of a solitary wave of the same height H and length λ, c is the wave velocity, and $\kappa = 2\pi/\lambda$ is a generalized wavenumber. The wave height H of a N-wave is obtained as $H = a^+ + a^-$, where a^+ is the amplitude of the wave crest and a^- is the amplitude of the wave trough.

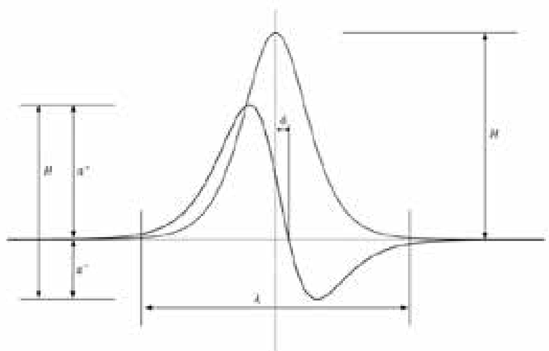

Figure 1. N-wave profile and corresponding solitary wave of the same height H and length λ.

2. COMPUTATIONAL MODELLING

To model nearshore processes in two- and three-dimensional domains and to determine the properties and characteristics of tsunami interaction with coastal structures and surrounding areas, the open access numerical code OpenFOAM (OpenCFD Limited, 2019) and the olaFlow toolbox (Higuera, 2019) are used. OpenFOAM uses the finite volume method to solve computational fluid dynamics problems and includes several approaches to tackle turbulence. The olaFlow solver package (Higuera, 2019) consists of a set of solvers for the simulation of wave dynamics, enabling the generation and absorption of waves at the boundaries and wave interaction with coastal structures. olaFlow solves the Volume Averaged Reynolds-Averaged Navier-Stokes (VARANS) equations for the two incompressible phases, applying the finite volume (FV) discretisation method for numerical integration, and the volume of fluid (VOF) method for phase definition.

3. SIMULATION AND RESULTS

We modelled an earthquake event, located at the Horseshoe Abyssal Plain, triggering a tsunami with SW–NE incident direction (for more details see Lima, 2022). The modelled tsunami wave signal (see Figure 2) was retrieved at a point in the vicinity of the Cascais marina, at a depth $d = 16$ m. At that point, the wave closely resembled the Tadepalli and Synolakis' conceptual LDN-wave, with $a^+ = 4.44$ m, $a^- = 1.68$ m, and an apparent period $T = 12$ min. Assuming $c = \sqrt{g(d + a^+)}$, with the acceleration of gravity $g = 9.81$ m/s^2, the apparent wavelength can be estimated as $\lambda = 10.2$ km. The free surface elevation time series (Figure 2) and the horizontal particle velocity, considered as constant in the water column, computed as

$$u(t) = c\ \eta/h\,,$$

were used as boundary condition for the 2DV (two dimensional vertical) simulation.

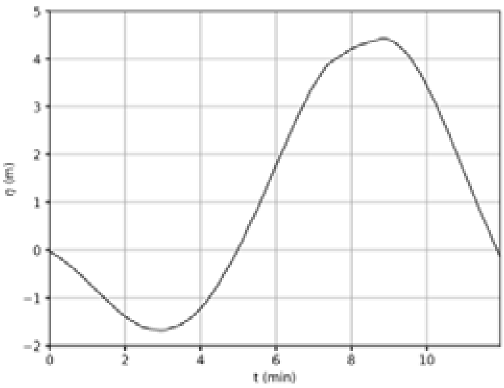

Figure 2. Free surface elevation time series of the leading wave.

The computational domain contemplates an initial 650 m-long slope, followed by the 50 m-wide breakwater berm. The computational domain includes a cross-section through the marina southwest breakwater, the marina basin, and the marina technical pier wall (cf. Figure 4).

For the simulations, we consider a 3D canal, one cell wide ($Ly = 10$ m), with a total length $Lx = 830$ m and height $Lz = 30$ m. The cell resolution varies along the computational domain. In the x-direction, for instance, the cell size varies from $\Delta x = 1$ m to $\Delta x = 5$ m (cf. Table I). The still water depth was $d = 16$ m, the total run time was 715 s, and a time step $\Delta t = 1$ s was used.

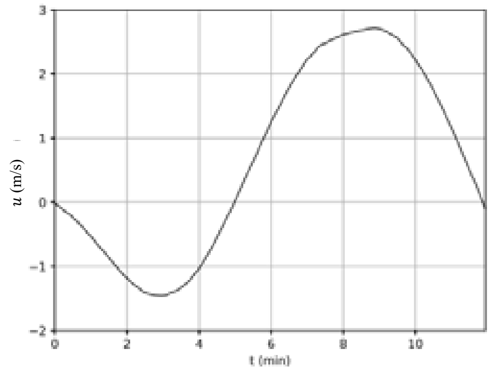

Figure. 3. Horizontal particle velocity time series.

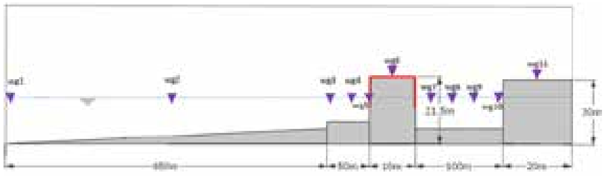

Figure 4. 2DV computational domain for the Cascais marina (not to scale) and wave gauges locations.

Table. I. Computational domain and mesh characteristics.

Zone	Slope	Berm	Breakwater	Basin	Technical pier
Lx (m)	650	50	10	100	20
Ly (m)	10	10	10	10	10
Lz (m)	10	13.5	21.5	11	20
Δx (m)	5	1	1	1	5
Δy (m)	10	10	10	10	10
Δz (m)	0.5	0.5	0.5	0.5	0.5

The buoyancy-modified κ-ω SST turbulence model (Devolder et al, 2017) was used. This is a turbulence model tailored for simulation of wave propagation in VOF models. To mode correctly model the surface waves more correctly, those authors introduced an additional buoyancy term to eliminate the spurious turbulence generation, hence the wave height dissipation of surface waves. They concluded that the inclusion in their model of a density gradient at the air-water interface better simulated the turbulent wave energy dissipation.

Figure. 5 and Figure. 6 illustrate the propagation of the tsunami wave from the beginning of the simulation until after the wave overtop the breakwater at $t = 7.6$ min. At $t = 3.7$ min, the wave receding is perfectly perceptible. After $t = 10$ min, the technical pier wall is flooded. The flow depth reaches 1 m both at the top of the breakwater and at the top of the technical pier (Figure. 7 and Figure. 8).

The streamlines are shown in Figure. 9 and Figure. 10. A vortex is clearly identifiable over the seaward side berm of the breakwater. A second vortex is observed on the leeward side of the breakwater. Higher velocities are registered on the leeward side of the breakwater and between that structure and the technical pier.on the leeward side of the breakwater. Higher velocities are registered on the leeward side of the breakwater and between that structure and the technical pier.

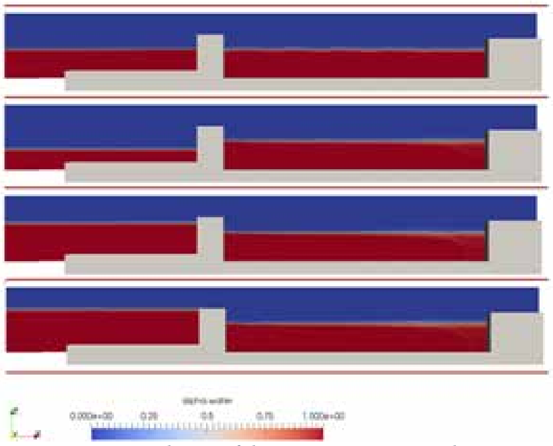

Figure. 5. Time evolution of the tsunami wave over the marina of Cascais. Top to bottom: $t = 5$ *s,* 3.7 *min,* 6.7 *min and* 7.2 *min.*

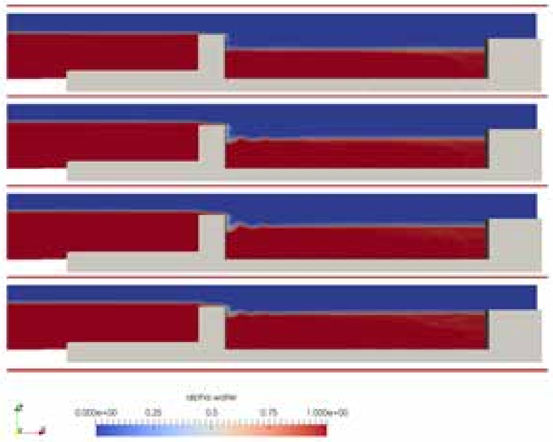

Figure. 6. Time evolution of the tsunami wave over the marina of Cascais. Top to bottom: $t = 7.6$ *min,* 8.0 *min,* 8.7 *min and* 9.4 *min.*

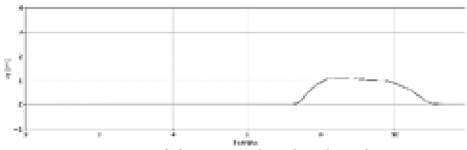

Figure. 7. Time series of the water level at breakwater crest (gauge wg6).

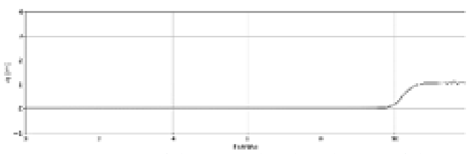

Figure. 8. Time series of the water level at the top of the technical pier (gauge wg11).

Numerical pressure gauges were placed along the breakwater walls and crest (see Figure 4). Analysis of the instantaneous pressure distribution along these surfaces showed that the pressures on the crest decrease from the seaward to the leeward side, becoming negative, i.e. below atmospheric pressure, at the inner end of the crest and at the upper end of the leeward wall of the breakwater (cf. Figure 11, Figure. 12, Figure. 13).

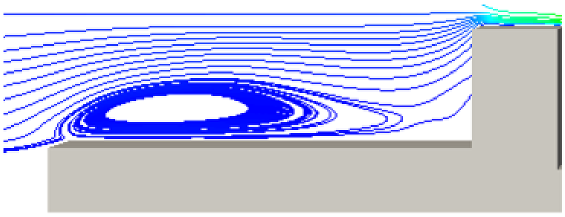

Figure. 9. Streamlines on the seaward side of the breakwater for $t = 8.7$ *min.*

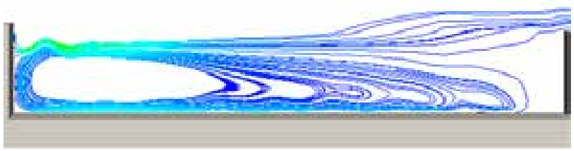

Figure. 10. Streamlines within the marina basin, for $t = 8.7$ *min.*

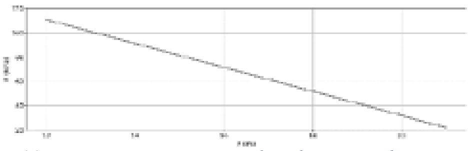

Figure 11. Instantaneous pressure distribution on the seaward side of the breakwater for $t = 8.2$ *min.*

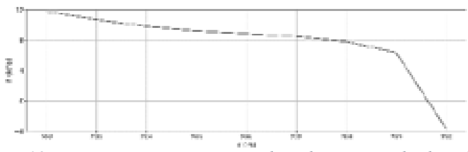

Figure. 12. Instantaneous pressure distribution on the breakwater crest for $t = 8.2$ *min.*

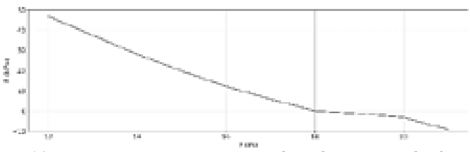

Figure. 13 – Instantaneous pressure distribution on the leeward side of the breakwater for $t = 8.2$ *min.*

The vortices and recirculation effects observed on both sides of the breakwater point to the possible occurrence of scouring, sand suspension and erosion, and consequent deballasting of the structure. This, together with the negative pressure recorded on the leeward side of the breakwater, may lead to the collapse of the structure.

The numerical simulations results presented herein have not been validated with any laboratory experiments nor with a real tsunami event. However, OpenFOAM has been previously used for this type of study (Morichon et al., 2021) and validated by Jiang et al. (2016), who performed small-scale laboratory experiments of tsunami-like solitary waves impacting a rectangular seawall.

In a preliminary stage, an attempt was made to perform 3D simulations, but these proved not to be supportable due to the limited cluster resources available, the large amount of time required for the simulations, the large size occupied by the output simulation results and the limited post-processing capabilities.

For this reason, it was chosen to perform the 2DV simulations. However, this will ignore some 3D effects, such as currents generated along the breakwaters, and the 3D patterns of the vortices that may lead to asymmetric erosion along the breakwater walls. In addition, inundation of the marina basin will also occur due to overtopping of the southeast breakwater. Finally, the effect on the northeast marina entrance is also overlooked. However, we believe that this 2DV analysis, although limited, can prove quite useful on a breakwater stability analysis of the breakwaters in the event of a tsunami impact.

4. CONCLUSIONS

A 2DV study of the interaction of a tsunami wave with the defence structures of the Cascais marina was presented. It was found that the initial tsunami wave shows a profile very close to the conceptual N-wave model of Tadepalli and Synolakis, thus the N-wave profile is used in this study for the tsunami wave numerical modelling.

The numerical modelling performed with OpenFOAM and the olaFlow toolbox showed that the Cascais breakwater is subject to overtopping by the tsunami wave and consequent inundation of the marina basin. We also show that vortices are generated on the seaward and leeward sides of the breakwater.

Analysis of the pressure distribution on the walls and crest of the breakwater shows that the leeward side of the breakwater is subjected to negative pressures. Together with the recirculation effect generated by the vortices, this may contribute to scouring, sand suspension and erosion at those location, which may lead to the collapse of the breakwater.

As future work, a full 3D simulation will be carried out to analyse how the vortices develop along the breakwater walls, to describe the currents generated within the marina, and to quantify the forces applied on the structures and their risk of collapse.

The numerical simulation of the wave-shore interaction must be limited in terms of area, due to the constraints in the computational resources available.

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REFERENCES

Devolder, B., Rauwoens, P., and Troch, P. (2017). Application of a buoyancy-modified κ – ω SST turbulence model to simulate wave run-up around a monopile subjected to regular waves using OpenFOAM®. *Coastal Engineering*, 125, 81–94.

Higuera P. (2019). olaflow. https://olaflow.github.io/, https://doi.org/10.5281/zenodo.1297012. Accessed: 2022-05-08.

Jiang, C., Liu, X., Yao, Y., Deng, B., and Chen, J. (2017). Numerical investigation of tsunami-like solitary wave interaction with a seawall. *Journal of Earthquake and Tsunami*, 11(01), 1740006.

Lima, V.V. (2022). *A Combined Model for Tsunami Wave Propagation, Dispersion, Breaking and Fluid-Structure Interaction*. Doctoral dissertation. Faculty of Sciences of the University of Lisbon, Portugal.

Madsen, P.A., Fuhrman, D.R., and Schäffer, H.A. (2008). On the solitary wave paradigm for tsunamis. *Journal of Geophysical Research: Oceans*, 113(C12).

Morichon, D., Roeber, V., Martin-Medina, M., Bellafont, F., and Abadie, S. (2021). Tsunami impact on a detached breakwater: Insights from two numerical models. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 147(2), 05021001.

OpenCFD Limited (2019). OpenFOAM® - The Open Source CFD Toolbox. https://www.openfoam.com/. Accessed: 2022-05-08.

Tadepalli, S., and Synolakis, C.E. (1994). The run-up of N-waves on sloping beaches. *Proceedings of the Royal Society: Mathematical and Physical Sciences,* A445, 99–112.

Tadepalli, S., and Synolakis, C.E. (1996). Model for the leading waves of tsunamis. *Physical Review Letters*, 77, 2141–2144.