MODELLING WAVE PROPAGATION AND OVERTOPPING WITH THE SWASH MODEL IN THE PORT OF PRAIA DA VITÓRIA

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Abstract

The primary objective of this research was to enhance the accuracy of overtopping predictions using the SWASH (Simulating WAves till SHore) model (Zijlema, *et al.* 2011), for inclusion in the Early Warning System (EWS), HIDRALERTA (Pinheiro *et al.,* 2023), currently operational in Praia da Vitória. The capabilities of the SWASH model were examined by simulating past storm events and typical wave conditions across the two-dimensional model of the entire port and bay areas with complex coastal structures and bathymetry. The outcomes of the simulations were compared to predictions from the NN_OVERTOPPING2 (NN2) (Coeveld *et al.*, 2005,) neural network and observed images from extreme events. This study was conducted using SWASH numerical model version 11.01A.

Introduction

The HIDRALERTA system currently couples the DREAMS model with the NN_OVERTOPPING2 neural network to estimate overtopping at port structures. While DREAMS simulates monochromatic wave propagation into sheltered areas, it cannot fully capture real sea states. NN_OVERTOPPING2, predicts mean overtopping discharges from laboratory and utilises hydraulic and structural parameters from the EurOtop manual. This study tests the SWASH model to better reproduce wave propagation and overtopping at the scale of Praia da Vitória's port and bay, aiming to build a database that will support the training of an Artificial Neural Network (ANN) capable of predicting local wave conditions and overtopping volumes more accurately.

Methodology

In this study, breakwater friction and roughness were represented using a Manning's coefficient. To determine its value for the south breakwater's outer slope, Tests 112 and 113 from the physical model (Lemos *et al.*, 2025) were replicated at prototype scale in a quasi-2D SWASH flume. A sensitivity analysis evaluated the effects of mesh resolution, mesh quality, and seeding on computational time, cumulative overtopping predictions, and wave parameter accuracy. Water levels at gauges positioned in front of breakwater were used to evaluate SWASH simulations against the physical model, applying Root Square Percentage Error ($RSPE^{WP}$) for wave parameters and Root Square Percentage Error ($RSPE^{V}$) for cumulative overtopping volume.

Past storms and typical waves at Praia da Vitória were simulated with the 2D SWASH model Ten scenarios were selected from HIDRALERTA simulations data (1989–2024): four most frequent (MF) and six storms (ST). Detailed bathymetry (Figure 1(b)) of the harbour and bay was compiled, and an unstructured triangular mesh (Pinheiro *et al.,* 2008) was used as the computational grid, with bottom roughness applied via Manning's coefficient. Time integration scheme used was implicit Crank-Nicolson, and a single layer model with non-hydrostatic BOX vertical integration scheme was used. At the incident wave boundary, a one-hour time series with JONSWAP spectra (γ = 3.3) was generated and replicated to span three hours. On outgoing boundaries, a Sommerfeld radiation condition was applied to allow the waves exit. Nine observation points in front of the structures recorded water levels, and nine others on the crests monitored overtopping, with results compared to NN2 predictions (Figure 1(a)).

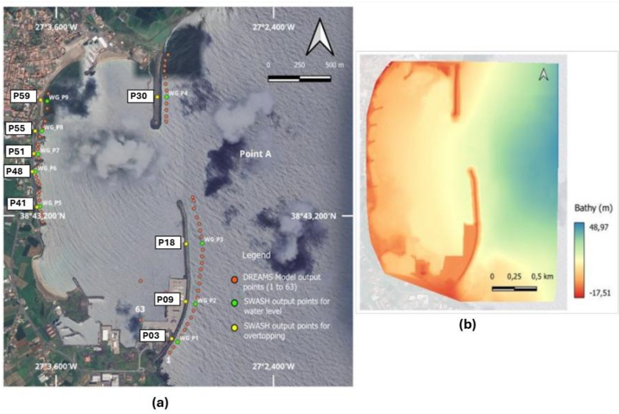

Figure 1- Observation points for wave overtopping at crest of the structures (a) and Final Topo-bathymetry of Praia da Vitória harbour and bay area (b).

Results

Manning's Friction Coefficient for Outer Slope of South Breakwater- Physical Model Test

In Tests 112 and 113, SWASH free surface elevations were compared with physical model results for the first five runs, with Manning's coefficient fixed at 0.04 s/m$^{1/3}$. The lowest average RSPE^{WP} was 5% in Test 112 (Hs = 6.8 m, Tp = 15.8 s) and 12.4% in Test 113 (Hs = 9 m, Tp = 17 s). The Figure 2 shows energy spectra comparisons at S1–S3. In both tests, RSPE^{V} decreased with increasing Manning's coefficient, reaching a minimum (0.13 s/m$^{1/3}$ in Test 112, 0.11 s/m$^{1/3}$ in Test 113) before rising again.

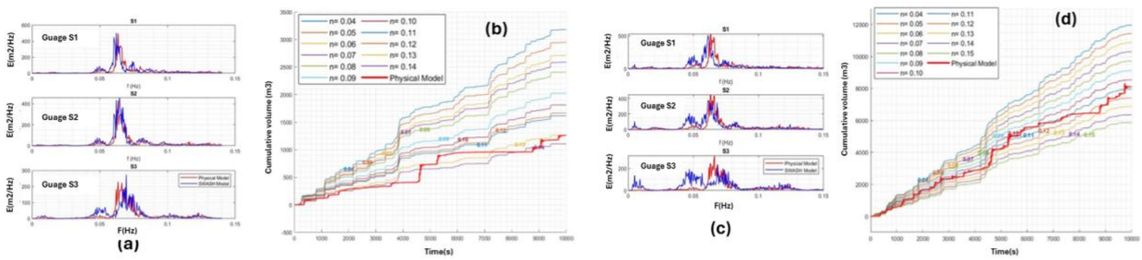

Figure 2- (a) comparison of spectrums for Test 112 (Hs=6.8m, Tp=15.8s), (b) sensitivity runs for Manning for Test 112, (c) comparison of spectrums for Test 113 (Hs=9m, Tp=17s), and (d) sensitivity runs for Manning for Test 113.

Sensitivity Analysis - Mesh Resolution, Mesh Quality and Seeding

Four mesh resolutions were tested by varying points per wavelength at constant period. CPU time rose with node count, peaking at 58.46 h, then declined, with the minimum at bandwidth 53. After 10,000 s, overtopping deviated most at 58.8% mesh quality, while 90.8% (1263.9 m³) best matched the physical model. Higher qualities caused increasing divergence, indicating reduced accuracy beyond the optimum (Figure 3).

Three different randomly selected seed numbers, 21436587, 87654321, and 12345678, were used for this sensitivity analysis. The seed number 12345678 was the default number in the SWASH model. In both test cases, RSPE^{V} decreases across all seeding scenarios as the simulation time window increases (Figure 4). However, in Test 113, significant RSPE^{V} values persist even after 10,000 seconds, whereas in Test 112 the differences become negligible beyond this duration. Among all seeding options, the default seeding consistently produced the lowest error as the simulation time increased.

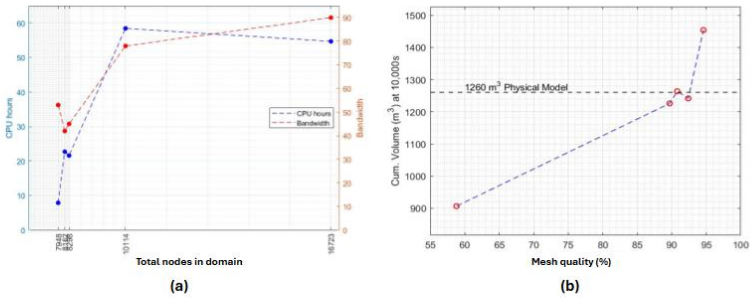

Figure 3- Impact of total node count on CPU time and bandwidth across different meshes (a) and Cumulative volume versus mesh quality for Test 112.

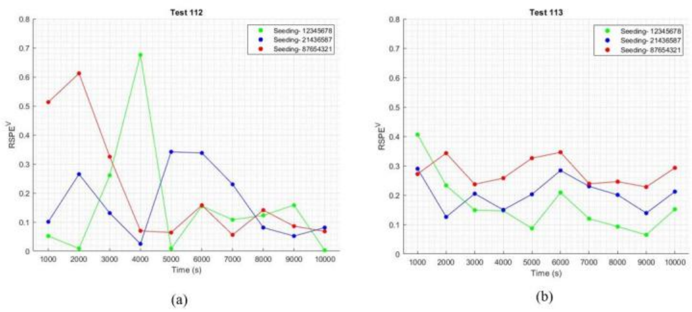

Figure 4- Variation of $RSPE^V$ (0 to 1 scale) for different seedings for Test 112 (a) and Test 113(b)

Whole Harbour Simulation

Whole harbour and bay simulations were run on the INCD cluster with a target duration of 3 hours (10,800 s). Some runs ended early due to the 4-day cluster limit or model instability. SWASH Mean overtopping discharges were computed from instantaneous discharge outputs and compared with NN_OVERTOPPING2 (NN2). Figure 5 presents overtopping results for storm events ST3 (Hs=6.04m, Tp=12.33s, tide=+1.5m(ZH), theta=77.8^0, date= 27/2/2005, time = 3hrs) and ST5 (Hs=4.79m, Tp=10.07s, tide=+0.53m(ZH), theta=95.4^0, date= 15/1/2016, time = 13hrs).

In the full harbour simulation, SWASH reproduced instantaneous overtopping at observation points, with mean discharges generally matching the order of magnitude of NN2 predictions. Some discrepancies occurred at specific locations. As Manning's coefficient was calibrated only for the south breakwater, further calibration is needed for the north breakwater and groyne series.

Conclusions

Overtopping discharge decreased with higher Manning's coefficients in both preliminary tests (quasi-2D numerical flume). However, calibration was performed only at tide level +3.0 m (ZH); future studies should test additional tide levels for greater accuracy. Sensitivity analysis showed mesh resolution and quality strongly affects overtopping, with gains diminishing beyond an optimum and sharp decreases at lower quality. No significant difference was found between 89.7%–92.4% quality. These results align with Suzuki *et al.* (2014), confirming grid resolution effects on overtopping and extending their applicability to unstructured grids. This study shows the seeding effect diminished with longer simulation durations, emphasizing the need for adequate simulation length.

The SWASH model demonstrated its ability to simulate wave propagation across the entire harbour and bay area, from the foreshore to shallow waters, as well as modelling overtopping processes over complex coastal structures and bathymetric domains. Unstructured meshes allowed the simulation of a large domain within a reasonable time frame by taking advantage of the non-uniform mesh resolution based on the water depths and corresponding wavelengths, and a powerful mesh renumbering algorithm to minimise the mesh's bandwidth.

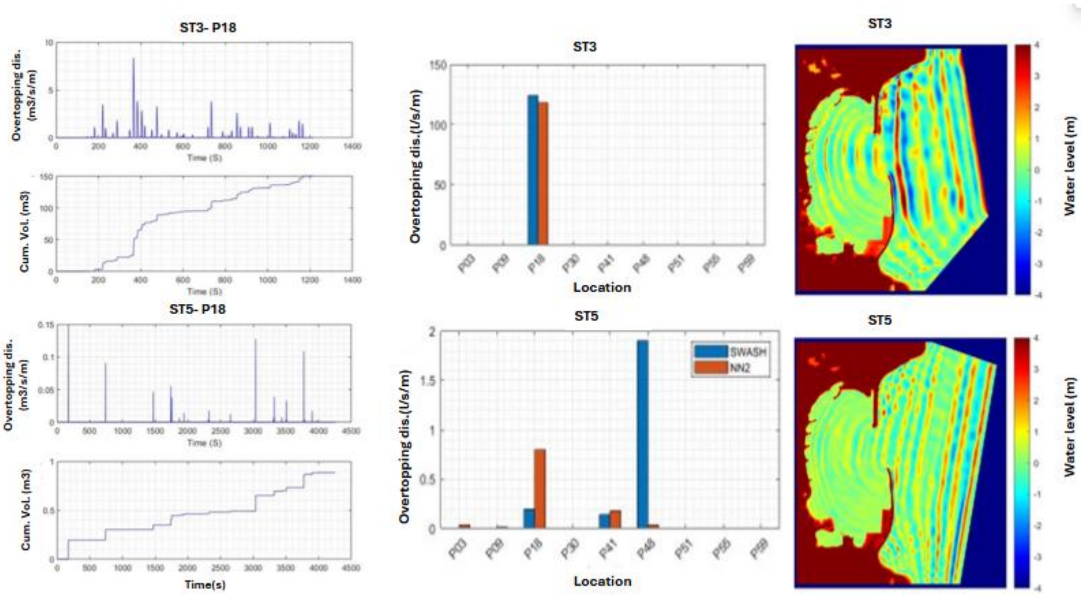

Figure 5 – Instantaneous overtopping rate (left), comparison of SWASH predictions with NN2 (middle), and Snapshot of simulation domain (Water levels) at 1000s (right)

Acknowledgement

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