DEVELOPMENT OF AN OPTIMIZED BOUSSINESQ-TYPE MODEL FOR OPERATIONAL ASSESSMENT OF WAVE-DRIVEN FLOODING

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INTRODUCTION

The prediction and accurate estimation of wave-driven run-up hold paramount significance in coastal management, emergency preparedness, and environmental risk assessment. Coastal areas around the world are particularly vulnerable to the devastating effects of wave-driven flooding, especially during extreme weather events and sea-level rise due to climate change. Understanding and forecasting the potential reach and impact of these waves on the shoreline is essential for mitigating the associated risks.

Supported by the significant increase in computing power, numerical models have emerged as reliable and cost-effective tools for assessing nearshore wave dynamics. As wave run-up represents the final stage in the transformation of ocean waves as they approach the shoreline, accurate estimation of flood extent requires numerical models to account for intricate phase-dependent wave-by-wave transformations. These processes can pose significant challenges to both the quality and computational complexity of the numerical solution. Moreover, the high grid resolution required to account for the details in the coastline and the nearshore terrain, including infrastructure, leads to increased numerical cost and potentially limits the applicability of such models.

In this study, we present the strategic development of a new Boussinesq-type computer model with the objective of building a fast and reliable tool for wave-driven run-up and flood hazard assessment.

METHODOLOGY

The numerical model is built around a streamlined second-order conservative staggered scheme combining shock-capturing capabilities necessary for wave breaking and runup with low sensitivity to numerical diffusion. The latter is a very important feature that allows the computation of general wave transformation processes over long distances at a low grid resolution (e.g., $\Delta x > 5m$). The fine details in the terrain near the shore are then resolved by strategically placing higher-resolution nested grids in locations of interest (e.g., $\Delta x < 3m$).

In order to account for wave-breaking effects in the depth-integrated model, an eddy viscosity approach based on the solution of turbulent kinetic energy is implemented. This robust wave-breaking formulation improves the accuracy and stability of the computed results and provides better grid convergence compared to standard methods that rely on the deactivation of dispersion.

The wave generation implemented in the model can deal with spatially variable spectral wave input, which is necessary to account for the high variability of the wave energy and its composition along the offshore boundary.

Finally, the new model has been efficiently implemented using both CPU- and GPU-based parallelizations. This further enhances its overall performance and provides greater hardware flexibility for users.

RESULTS

This research effort introduces a new Boussinesq-type model designed for fast computation of complex wave transformations that lead to hazardous wave run-up and flooding. Thanks to the optimized numerical structure and efficient parallelization, the new model is able to render accurate results while significantly reducing the computation time. This paves the way for real-time simulations of large coastal areas on standard hardware, (Mihami, 2023). The low sensitivity of the numerical solution to grid diffusion coupled with the nested grid implementation leads to high-resolution runup calculations while reducing the computational cost to a fraction of what is usually required for a comparable solution with a single grid (Mihami et al., 2022).

Performance assessment of both the CPU and GPU parallelizations highlights the cost-effectiveness of GPU computing for nearshore wave modeling, especially when dealing with large numerical domains with high grid counts.

Finally, the new model has been rigorously validated using a variety of standard benchmark tests. The overall agreement between the computed results and laboratory data demonstrates the capability of the model to accurately compute important nearshore wave transformations. The model results have also been compared to large-scale field data, showcasing its performance and robustness and, thus, its applicability in an operational framework.

CONCLUSION

The accuracy and speed of this new Boussinesq-type model encourage its use in an operational coastal flooding forecasting system. With the achieved computational performance, we are now able to produce high-resolution run-up predictions in real-time.

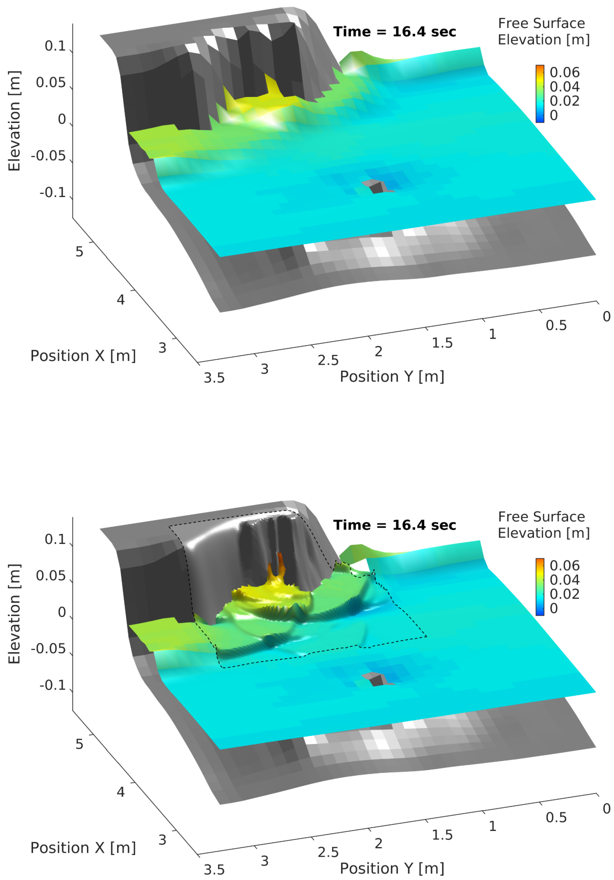

Figure 1 – Wave run-up computation at Monai Valley (Matsuyama and Tanaka, 2001). The top plot shows the computed results with a uniform coarse grid (Δx=10cm). The bottom plot shows the results obtained with the nested grid method, where the grid is locally refined to capture the details in the run-up (Δx=1.25cm). The black dashed lines outline the boundaries of the high-resolution nested domain.

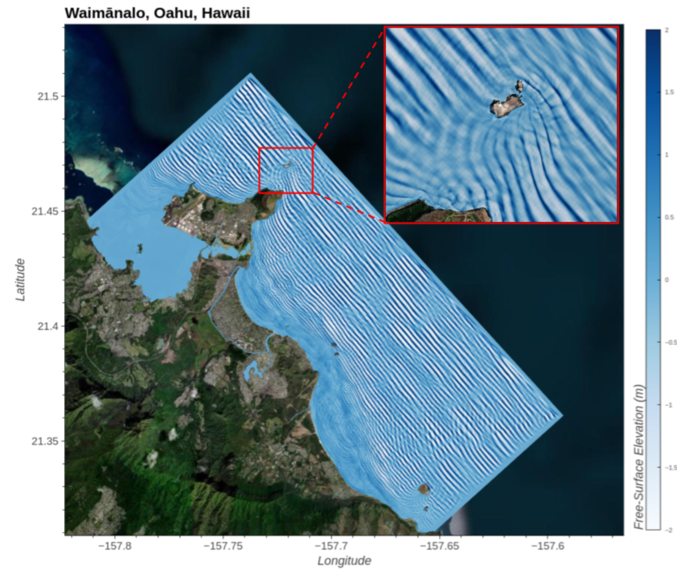

Figure 2 – Free surface elevation computed with the new model for a large segment of the coast: 25 km (alongshore) x 15 km (cross-shore). The zoomed-in area shows the intricate phase-dependent wave transformations around an island.

REFERENCES

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