Enhancing breaking wave impact predictions on vertical piles: about the influence of dissipation terms in SPH momentum equation

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

Yuzhu Pearl Li
Department of Civil and Environmental Engineering
National University of Singapore
Singapore
pearl.li@nus.edu.sg

I. INTRODUCTION

Predicting the forces exerted by waves on coastal and offshore structures is a cornerstone of marine engineering. The increasing frequency of severe weather events, exacerbated by the changing climate, accentuates the importance of accurately simulating extreme hydrodynamic conditions, particularly those involving wave breaking. While much progress has been made in modelling forces from non-breaking waves, the dynamics of breaking waves present unresolved complexities. This study investigates the potential of energy dissipation mechanisms in Smoothed Particle Hydrodynamics (SPH) to enhance the reliability of simulations for specific scenarios, with a particular focus on interactions with vertical piles. A vertical pile is defined as a supporting element of a pier, an offshore platform, a berthing structure, or an offshore wind turbine. Given the wide range of applications of piles in marine environments, which are exposed to extreme wave conditions, it is essential to understand how SPH can model these phenomena and how different numerical implementations affect the accuracy of the modelling.

II. METHODOLOGY

The simulations are carried out using the open-source DualSPHysics solver [1], which employs a Weakly Compressible SPH approach. DualSPHysics is designed to operate on both CPUs and Graphics Processing Units (GPUs). Usually, in Smoothed Particle Hydrodynamics (SPH), viscosity effects are incorporated into the momentum equation to simulate fluid resistance to deformation and internal friction. Among the commonly used techniques, the artificial viscosity (AV) term [2] is widely employed to mimic the behaviour of real viscosity in fluid dynamics. This term plays a crucial role in smoothing flow discontinuities and mitigating numerical instabilities, particularly in areas with steep velocity gradients or shock waves. The artificial viscosity is typically calibrated based on local gradients of velocity or density, ensuring the desired level of dissipation while minimizing disruptions to the overall flow behaviour. Its primary purpose is to dissipate kinetic energy and stabilize velocity fluctuations, effectively simulating viscous effects.

Beyond artificial viscosity, the laminar + Sub-Particle-Scale (SPS) model is utilized to address turbulent flows in situations where resolving fine-scale turbulence directly is computationally expensive. This hybrid approach combines laminar flow treatment with a sub-grid turbulence model. The laminar model, as proposed by [3], simplifies the bulk flow by solving the Navier-Stokes equations without explicitly modeling turbulence. To account for unresolved turbulent structures, an SPS model is applied, as elaborated by [4]. The SPS model captures the dynamics of turbulent eddies at scales smaller than the SPH particle size using an eddy viscosity framework. Specifically, the Smagorinsky model forms the basis of this formulation, adding a viscosity term to the Navier-Stokes equations to dampen turbulent fluctuations and enhance the accuracy of the simulation.

III. CASE-OF-STUDY AND NUMERICAL LAYOUT

This investigation replicates the experiment conducted by [5], which involved waves travelling along a sloped bed with a 1:10 ratio and breaking at the forefront of a vertical pile positioned at the end of the slope. The pile is circular with a diameter, D,of 0.7m. The numerical setup closely follows the experimental configuration outlined by [5] and is illustrated in Figure 1. The origin of the coordinate system is located at the centre of the pile, precisely at the undisturbed free surface. The x-axis indicates the propagation of waves, while the y-axis denotes the transverse direction. The pile is situated equidistantly between the two sides of the 5-metre-wide flume. The wave period and the incident wave height are set at 4.0s and 1.3m, respectively. The boundary conditions for the simulation are established as follows. The generation of waves is facilitated by open boundary conditions (OBCs), as outlined in the work of [6], and employs a stream function solution that draws upon the contributions of Fenton's research. A wave damping zone is applied at the outlet to reduce wave reflection. The boundary particles, encompassing the pile surface, tank bottom, and tank sides, are governed by the modified Dynamic Boundary Conditions (mDBC) proposed by [7]. It is important to note that the model under consideration is one that considers only the fluid phase and does not take into account the presence of air. In DualSPHysics, three values of initial inter-particle distance, dp, have been analysed, equal to 0.076m, 0.065m and 0.05 m, resulting in an initial number of fluid particles varyinb between 1.2 and 4.5 million particles. Artificial viscosity, laminar viscosity and laminar + SPS have been analysed for each resolution.

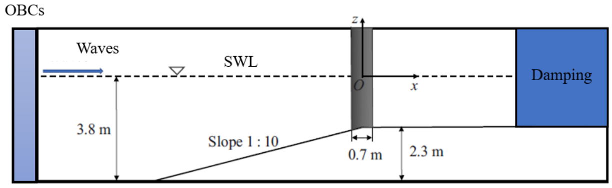

Fig. 1. Layout of the present setup in DualSPHysics model

IV. Results and Discussion

Initial results indicate that SPH simulations effectively capture force peaks generated by breaking waves when dissipation parameters are adequately calibrated. Artificial viscosity helps stabilize the numerical simulations but introduces a time shift in peak force predictions, which depends on the particle resolution. This time shift is noticeable in 2. In the simulation that employed artificial viscosity, the wave front attained the vertical column at an earlier point in time than in the other two cases and with higher velocities.

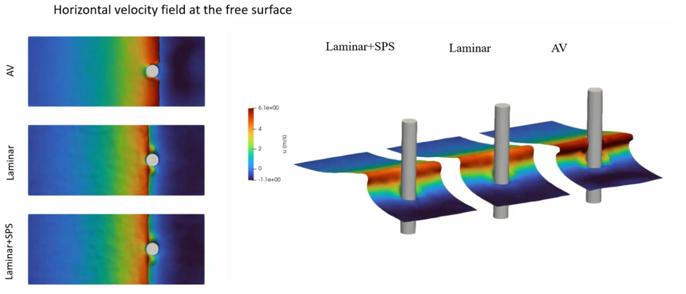

Fig. 2. Comparison of wave front and free surface flow velocities

Figure 3 compares the vorticity field and horizontal velocity field at a depth of $z = -D/2$ for three dissipation schemes: Laminar+SPS, Laminar, and Artificial Viscosity (AV). In the vorticity field, the Laminar+SPS approach presents sharp and well-defined counter-rotating patterns around the circular structure, effectively preserving turbulent structures. The Laminar scheme captures similar patterns but with smoother gradients, indicating reduced turbulence preservation. In contrast, the AV scheme diffuses the vorticity significantly, dampening small-scale structures and producing a more simplified representation.

For the horizontal velocity field, Laminar+SPS shows clear velocity gradients and consistent flow near the structure, maintaining higher velocity magnitudes. The Laminar scheme provides slightly less pronounced gradients with visible diffusion in the flow. In comparison, the AV scheme produces a heavily smoothed velocity field with minimal variations and reduced sharpness, reflecting the strong damping effect of artificial viscosity. Overall, Laminar+SPS offers the most detailed and accurate representation, while AV significantly simplifies the flow, potentially limiting its effectiveness for capturing complex turbulence.

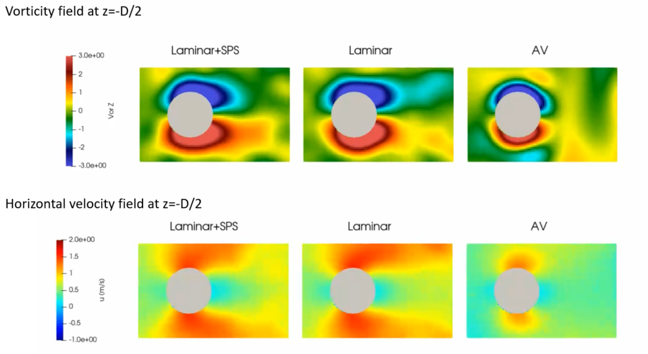

Fig. 3. Comparison of vorticity field and horizontal velocity field at a depth of $z = -D/2$

Finally, forces exerted on the cylinder are compared, see example in Figure 4 for one of the simulated model resolutions. The plot shows the force F exerted on a vertical pile as a function of normalized time t/T, comparing the three dissipation schemes against experimental data. The filtered experimental data, processed with Empirical Mode Decomposition (EMD), serves as the reference. Numerical results are filtered using low-pass filters (cutoff frequency: 20 Hz) and empirical mode decomposition (EMD) to isolate the net breaking wave forces. Laminar and Laminar+SPS models closely replicate the experimental peak force and post-peak trends, whereas AV shows and early impact. The unfiltered experimental data shows oscillations due to structural vibrations, absent in the filtered data. Overall, Laminar+SPS demonstrates the most accurate results, highlighting the critical role of dissipation mechanisms in modeling wave-induced forces.

Comparisons with mesh-based turbulence models - not shown here -, such as the LF18 k–ω and Wilcox ([8]) stress–ω models (see [9] demonstrate SPH's capability to capture complex wave-structure interactions.

Force results of laminar+SPS scheme with three different model resolutions are shown in Figure 5. The plot illustrates the force F exerted on a vertical pile for different particle resolutions, compared to experimental data. The particle resolution has a significant impact on the rise time and magnitude of the peak force, with finer resolutions providing more accurate predictions. The simulations with dp=0.05m and dp=0.065m closely match the filtered experimental data, particularly in capturing the peak force and post-peak trends. In contrast, the dp=0.076m resolution produces a slightly higher and broader peak, reflecting reduced accuracy relative to finer resolutions. This highlights the importance of resolution in SPH simulations for achieving

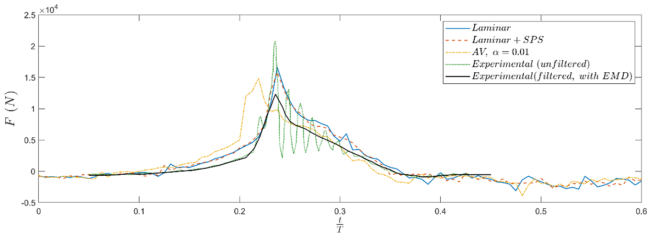

Fig. 4. Comparison of horizontal force signal on the cylinder for different schemes

results that closely replicate experimental observations.

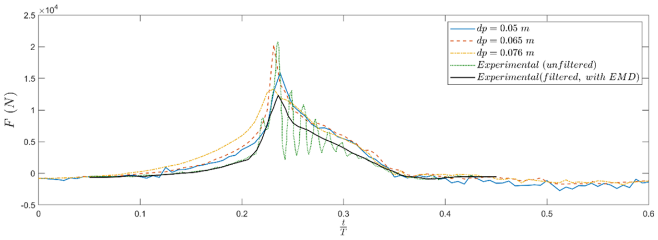

Fig. 5. Comparison of horizontal force signal on the cylinder for different model resolutions

V. CONCLUSIONS

The present study underscores the critical role of advanced dissipation terms in improving the predictive accuracy of Smoothed Particle Hydrodynamics (SPH) models for wave-structure interactions, particularly for breaking wave impacts on vertical piles. The inclusion of dissipation mechanisms in the SPH momentum equation influences the timing, evolution, and magnitude of forces, with distinct effects observed for different schemes. While artificial viscosity affects wave crest formation and impact timing, the laminar-turbulent SPS model provides a more detailed representation of turbulence, aligning closely with experimental data after filtering.

The results also demonstrate the sensitivity of SPH models to resolution, especially concerning peak force magnitude and rise time, emphasizing the need for careful calibration. Before the impact, negligible differences are observed between the Laminar and Laminar+SPS schemes, but the overall wave shape and impact characteristics depend on the dissipation coefficient.

Using DualSPHysics, an open-source solver, and experimental data, this research highlights the potential of SPH in addressing the complexities of breaking waves, which traditional methods often struggle to resolve. By enhancing the simulation of wave impacts, this work contributes to the development of safer and more resilient coastal infrastructure.

Future research will focus on exploring different boundary implementations (i.e. no-slip conditions) in combination with new shifting algorithms and adaptive schemes aiming to enhance the accuracy of the boundary layer modelling. These efforts will extend the applicability of SPH to diverse hydrodynamic challenges, reinforcing its role as a robust tool for designing infrastructure capable of withstanding extreme environmental conditions.

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).

REFERENCES

[1] J. Domínguez, G. Fourtakas et al. “DualSPHysics: From fluid dynamics to multiphysics problems,” Computational Particle Mechanics, 2021, 03.
[2] J.J. Monaghan, R.A.Gingold. “Shock Simulation by the Particle Method,” Journal of Computational Physics, 1983, 52(2), 347–389.
[3] E.Y.M. Lo, S. Shao. “Simulation of near-shore solitary wave mechanics by an incompressible SPH method,” Appl. Ocean Res.,2002, 24 (5), 275–286.
[4] R.A. Dalrymple, B.D. Rogers. “Numerical modeling of water waves with the SPH method,” Coast Eng., 2006, 53 (2–3), 141–147
[5] Irschik, K., Sparboom, U., Oumeraci, H. “Breaking wave loads on a slender pile in shallow water,” 29th Int. Conf. Coast. Eng., 2004.
[6] A. Tafuni, J.M. Domínguez, R. Vacondio, A.J.C. Crespo. “A versatile algorithm for the treatment of open boundary conditions in Smoothed particle hydrodynamics GPU models,” Comput. Methods Appl. Mech., 2018, Eng. 342, 604–624
[7] A. English, J.M. Domínguez et al. “Modified dynamic boundary conditions (mDBC) for general-purpose smoothed particle hydrodynamics (SPH): application to tank sloshing, dam break and fish pass problems,” Computational Particle Mechanics, 2022, 9 (5), 911–925.
[8] D.C. Wilcox. “Turbulence Modeling for CFD,” 3rd edn. DCW Industries, 2006.
[9] Y. Li, D.R. Fuhrman. “On the turbulence modelling of waves breaking on a vertical pile,” Journal of Fluid Mechanics, 2022.