

# SPH MODELING FOR PLASTIC TRANSPORT IN THE NEARSHORE ZONE: A LABORATORY-SCALE VALIDATION STUDY

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## I. INTRODUCTION

Waste dispersion in the environment has severe social, economic, health, and environmental impacts [1]. The marine coast is particularly affected by chemical waste, microplastics, packaging, and fishing equipment. Understanding the dynamic links between sources and accumulation points is crucial for studying marine waste dispersion [2]. Numerical modeling is essential for understanding the transport and distribution mechanisms of marine debris. In the literature, most research on computational methods focuses on oceanic and dispersion models suitable for offshore investigations [3], while few studies address waste transport and dispersion in coastal areas [4], even less so with the SPH method. This study is the first step towards filling the gap and focuses on developing a numerical model based on SPH to simulate the transport, beaching, and dispersion of plastic waste in coastal areas.

## II. MATERIALS AND METHODS

For this study, we use GPUSPH, the first SPH implementation to run entirely on GPUs [5], to reproduce numerically the analogue experiments discussed in [6], originally conducted in the Hydraulics Laboratory of the University of Messina (Sicily, Italy; Fig. 1), with the aim to identify the most appropriate SPH formulation and simulation parameters to model plastic transport.

Both 2D and 3D configurations were tested, with particle spacing varying from 64 to 128 particles per meter (ppm) in 3D, and from 64 to 512 ppm in 2D, to account for the difference in computational resources (around  $10^5$  total particles with around 30 neighbors per particle in 2D, versus  $10^7$  total particles with around 80 neighbors per particle in 3D at a resolution of 256 ppm).

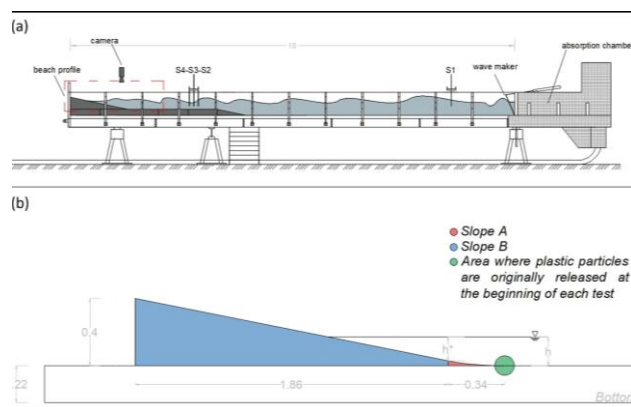


Figure 1. (a) General overview of the wave flume used in the Hydraulics Laboratory of Messina. (b) Closer view of the profile of the studied beach. Dimensions are in meters [6].

In 3D configurations, the bathymetry of the flume was imported from a Digital Elevation Model (DEM) and treated geometrically [7], reducing the total number of particles and simplifying the initial geometry setup.

Simulations were all done using a weakly-compressible SPH formulation, with the Wendland quintic smoothing kernel. The at-rest density is taken to be the physical one ( $\rho = 1000 \text{ kg/m}^3$ ), and the sound-speed for the equation of state is computed to maintain density variation within 1% of the at-rest value, as typically done in WCSPH, by taking a value an order of magnitude higher than the maximum fluid velocity, taking into account also the hydrostatic fall velocity. The Molteni & Colagrossi [8] density diffusion model was used, as in our tests it gave similar results to the Antuono et al. diffusion [9], with a lower computational load.

For the laminar viscous contribution, both a Newtonian and an inviscid (no laminar viscosity) rheology were considered, with the constant Smagorinsky SPS model for turbulent dissipation [10].

To avoid the common WCSPPH issue of energy dissipation over multiple wavelengths, the CCSPPH correction [11] was adopted.

We tested three boundary models in 2D: dynamic, dummy and Lennard-Jones. In 3D, these were only used for the paddle, while the bathymetry was represented as a single geometrical entity (DEM) exerting a Lennard-Jones repulsive force normal to the local tangent plane [7].

For all boundary models except the geometric DEM, we have observed some infiltration of fluid particles into the boundary. Although these particles do not usually affect the simulation, they can lead to numerical instabilities, particularly at higher resolutions. To avoid the issue, we have introduced the “boundary shield” mechanism discussed by [12], so that particles that get too close to the boundary will have their normal velocity replaced by the normal velocity of the boundary itself.

### III. RESULTS AND DISCUSSION

Preliminary tests have shown 3D and 2D simulations to give comparable results, so the results presented here will focus on the 2D simulations, which could be carried out at higher resolutions.

Validation of the formulations is done by comparing the wave parameters, including the incident wave height ( $H_{si}$ ), reflected wave height ( $H_{sr}$ ) and reflection coefficient ( $k_r$ ), as well as the time-averaged and velocity profile the velocity over time measured at specific points.

The wave parameters obtained from the simulations are consistent with the parameters measured in laboratory (Tab. 1), although a slightly higher reflection is observed in some configurations.

TABLE I. COMPARISON BETWEEN PARAMETERS OBTAINED FROM SIMULATIONS AND THOSE MEASURED IN LABORATORY EXPERIMENTS

Boundary models	Resolution	Wave parameters		
		$H_{si}$	$H_{sr}$	$k_r$
Lab	—	0.077	0.014	0.175
Dummy boundaries	256 ppm	0.08	0.02	0.255
Dynamic boundaries		0.079	0.008	0.101
Lennard - Jones boundaries		0.074	0.009	0.118
Dummy boundaries	512 ppm	0.081	0.024	0.294
Dynamic boundaries		0.079	0.009	0.118
Lennard - Jones boundaries		0.076	0.07	0.098

In the laboratory experiment, plastic samples with sizes in the order of millimeters are released at the bottom of the first slope, and their motion is tracked to study how plastic is transported by the larger turbulent structures in the undertow of the breaking wave.

Due to the plastic sample size and the distance from the bottom where the Stokes drift below the undertow is maximal, modeling this aspect of the experiment in SPH via Direct Numerical Simulation would have required extremely high resolutions (no less than 4000 particles per meter), which would lead to prohibitive computational loads even in 2D simulations.

At the resolutions we have employed, we can clearly see an improvement of the fitting between the time-averaged velocity profile in our simulations with the one measured in the laboratory, plotted in Fig. 2 in the case of inviscid rheology (no laminar viscosity contribution, at resolutions of 256 and 512 ppm). The plots show that at lower resolutions the transport current peak is located further from the bottom compared to the lab experiments, and with a less prominent profile, but as the resolution grows the profile gets closer to the experimental profile both in depth and in extent.

Interestingly, the dummy boundary model in this case seems to produce worse results compared to less rigorous (and less computationally expensive) dynamic and Lennard-Jones models. This is consistent with the fact that the dummy boundary model is able to better represent the free-slip boundary conditions at the bottom, although in this particular case the numerical contribution introduced at the boundary in the other models seems to fit the physical behavior better. It is likely that with the use of an appropriate boundary layer model the dummy boundaries would achieve similar or better results, although the performance of the other models is worth taking into account.

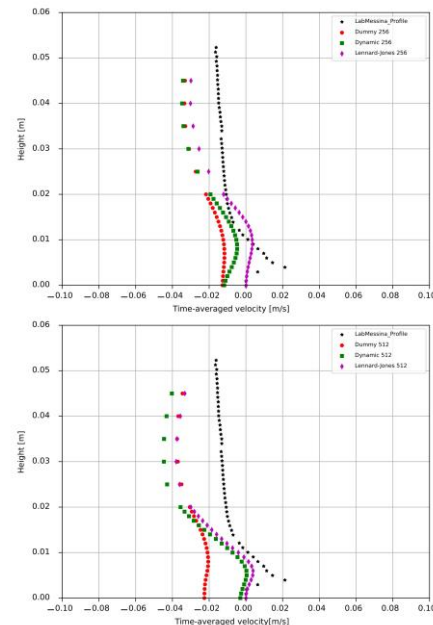


Figure 2. Time-averaged vertical velocity profile for severe boundary models, at 256 (left) and 512 (right) particles per meter, compared with the profile obtained in the Hydraulics Laboratory in Messina (black profile).

Comparing the velocity profile over time at a specific test-point (Fig. 3), we can also see the good fit between the

simulated and physical experiment, again with higher resolutions producing more accurate results, as expected.

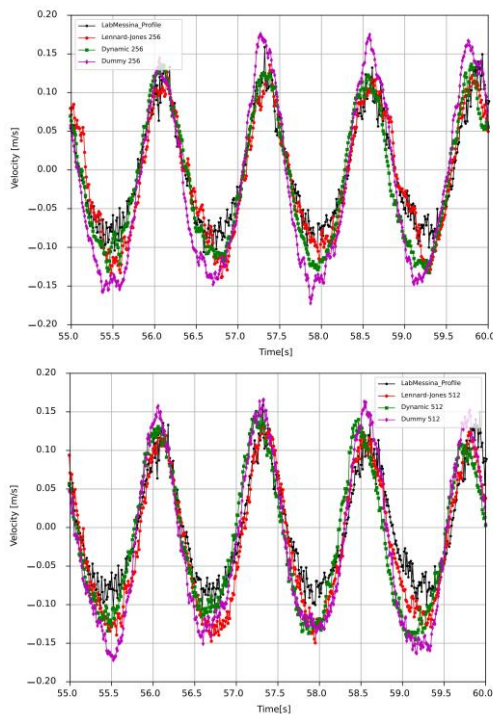


Figure 3. Velocity over time at a specific test-point, compared with the profile obtained in the laboratory of Hydraulics in Messina (black profile).

With the validation of the macroscopic behavior presented in this contribution, it is also possible to expand the scope of the simulations to focus on the small-scale behavior of macroscopic plastic bodies, with displacement subject to wave motion, to determine e.g. beaching, unbeaching and sinking/floating conditions and behavior. Some preliminary simulations have been run on the same flume geometry and wave motion setup of the model calibration.

Plastic waste will in general have irregular shapes, which can be imported in GPUSPH in the form of an STL mesh. Preliminary experiments with a plastic bottle (Fig. 4) have shown that the mesh quality and resolution are critical factors in ensuring the stability of the simulation.

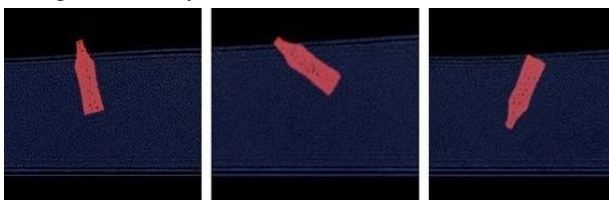


Figure 4. External mesh with a bottle shape that has been imported into the GPUSPH simulation.

#### IV. CONCLUSION

This work presents preliminary work on modelling with SPH the behaviors of waste materials under wave motion in the

coastal area, in order to study the conditions for buoyancy, beaching, and washing out of plastic waste. Our results show good results in modeling macroscopic behavior, but highlight the need for a boundary layer model or very high resolutions (possibly in conjunction with an Adaptive Particle Resolution model such as [13]) to better represent the Stokes drift below the undertow, which plays a significant role in the waste transport.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] J. Dąbrowska, M. Sobota, M. Świąder, P. Borowski, A. Moryl, R. Stodolak, E. Kucharczak, Z. Zięba and J. K. Kazak "Marine Waste—Sources, Fate, Risks, Challenges and Research Needs," *Int. J. Environ. Res. Public Health*, 2021. <https://doi.org/10.3390/ijerph18020433>
- [2] P. G. Ryan, C. J. Moore, van J. A. Franeker, C. Moloney, "Monitoring the abundance of plastic debris in the marine environment," *Philos. Trans. R. Soc.*, 2009. 10.1098/rstb.2008.0207
- [3] L.C.-M. Lebreton, S.D. Greer, J.C. Borrero, "Numerical modelling of floating debris in the world's oceans," *Mar. Pollut. Bull.*, vol. 64, Issue 3, pp. 653-661, 2012. <https://doi.org/10.1016/j.marpollbul.2011.10.027>
- [4] J. Jiang, L. He, S. Zheng, J. Liu, L. Gong, "A review of microplastic transport in coastal zones," *Mar. Environ. Res.*, vol. 196, 2024. <https://doi.org/10.1016/j.marenvres.2024.106397>
- [5] A. Hérault, G. Bilotta, and R. A. Dalrymple, "SPH on GPU with CUDA," *JHR*, 2010. 10.1080/00221686.2010.9641247
- [6] G. Passalacqua, C. Iuppa, and C. Faraci, "A Simplified Experimental Method to Estimate the Transport of Non-Buoyant Plastic Particles Due to Waves by 2D Image Processing," *J. Mar. Sci. Eng.*, 2023. <https://doi.org/10.3390/jmse11081599>
- [7] G. Bilotta, A. Hérault, A. Cappello, G. Ganci, C. Del Negro, "GPUSPH: a Smoothed Particle Hydrodynamics model for the thermal and rheological evolution of lava flows," *Geol. Soc.*, vol.426, pp. 387-408, London, Jan 2016.
- [8] D. Molteni, A. Colagrossi, "A simple procedure to improve the pressure evaluation in hydrodynamic context using the SPH," *Comput. Phys. Comm.* vol. 180, pp. 861-872, 2009. <http://dx.doi.org/10.1016/j.cpc.2008.12.004>.
- [9] M. Antuono, A. Colagrossi, S. Marrone, "Numerical diffusive terms in weakly compressible SPH schemes," *Comput. Phys. Comm.*, vol. 183, Issue 12, pp. 2570-2580, 2012. <http://dx.doi.org/10.1016/j.cpc.2012.07.006>
- [10] R. A. Dalrymple, B.D Rogers, "Numerical modeling of water waves with the SPH method," *Coastal Engineering*, 2006. <https://doi.org/10.1016/j.coastaleng.2005.10.004>
- [11] V. Zago, L.J. Schulze, G., Bilotta, N. Almashan, R.A. Dalrymple, "Overcoming excessive numerical dissipation in SPH modeling of water waves," *Coast. Eng.*, 2021. <https://doi.org/10.1016/j.coastaleng.2021.104018>
- [12] H.-G. Lyu, P.-N. Sun, X.-T. Huang, M.-B. Liu, H.-Y. Zha, A.-M. Zhang, "Numerical investigation of vehicle wading based on an entirely particle-based three-dimensional SPH model," *Comput. Fluids*, 2024.
- [13] Z. Zhao, G. Bilotta, Q. Yuan, Z. Gong, H. Liu, "Multi-GPU multi-resolution SPH framework towards massive hydrodynamics simulations and its applications in high-speed water entry," *J. Comput. Phys.*, vol. 490, 2023 <https://doi.org/10.1016/j.jcp.2023.112339>.