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Application of the SPH method in turbulent free-surface flow for pressure calculation on structures and simulation of debris accumulation during flood events

Master thesis submitted in fulfilment of the requirements for the degree of Master in Engineering Physics by Luca Santoro

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Abstract

Flood events represent a recurring natural hazard requiring accurate prediction of hydrodynamic forces on structures and debris accumulation patterns. This master thesis evaluates the capability of the Smoothed Particle Hydrodynamics (SPH) method, specifically through the SPlisHSPlasH software implementation, to simulate three-dimensional turbulent free-surface flows with dynamic rigid bodies.

The methodology employs a systematic validation approach through progressively complex configurations. First, turbulent flow behaviour is isolated and analysed in a two-dimensional pipe configuration with Reynolds number $Re = 1.7 \times 10^7$, where the numerical velocity profile correctly fits the analytical solution derived from Generalized Hydraulic Equations. Subsequently, free-surface flow characteristics are examined through a horizontal channel with parabolic obstacle, correctly capturing hydraulic jump phenomena and head loss distributions despite local pressure instabilities inherent to the SPH formulation.

The final validation integrates both phenomena in a laboratory-scale bridge configuration with seven floating wood logs. The simulation successfully reproduces obstacle formation at the bridge entrance, with distinct behaviours observed between pressurized and free-surface flow conditions. Quantitative analysis reveals accurate head loss predictions and flow distribution patterns, though with the requirement that particle size remains below one-fifth of the rigid body characteristic dimension to ensure numerical stability.

While certain limitations exist, particularly concerning local pressure calculations and the necessity for manual tuning of physical parameters, this study demonstrates that SPlisHSPlasH can effectively simulate complex hydraulic phenomena relevant to flood engineering applications. The continuous development of the software and capability to handle coupled fluid-structure interactions yield it as a valuable tool for hydraulic engineering analyses, encouraging more systematic adoption in the field.

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CHAPTER 1

Introduction and motivation

1.1 Introduction and motivation

Flood events have been a recurring natural hazard throughout human history, occurring when water accumulates beyond the capacity of natural or urban drainage systems. Since the early 20th century, engineers have recognized the critical need to design buildings and infrastructure capable of withstanding flood-induced forces. Traditional engineering approaches rely on simplified calculations and numerous approximations to estimate the pressure loads that structures must endure [1]. While these methods generally provide reasonable order-of-magnitude estimates, they are time-consuming and resource-intensive. Moreover, the prediction of the motion of rolling wooden debris, for instance, has been studied for more than two decades [2].

This master thesis proposes an alternative approach: directly simulating flood flows using computational fluid dynamics to evaluate their impact on building boundaries. This approach requires selecting an appropriate numerical method to solve the fluid dynamic equations. Several Eulerian models have already been used to simulate free surface flows, including methods such as the finite volume method [3] and the finite element method [4], which have already proven their performance.

However, this study chooses the Lagrangian Smoothed Particle Hydrodynamics (SPH) method [5], which raises important questions about computational efficiency and accuracy that this master thesis will address. The SPH method, originally developed in 1977 for astrophysical simulations, has since found widespread application in fluid mechanics, particularly for hydraulic problems. Successful applications in dam break scenarios and water splash simulations [6] as well as free surface flow over a sharp-crested weir [7] have demonstrated the capability of the method to handle free-surface flows accurately. Moreover, turbulence with SPH has already been studied [8] and accurately validated. Finally, the fluid-solid interactions with SPH had been studied, for intsance, a decade ago in the context of rigid bodies inside visco-elastic fluid [9].

However, all theses studies did not provide simulations considering these phenomenom altogether. Hence, this thesis investigates whether SPH can effectively simulate turbulent free-surface flows, particularly those occurring during river and canal flooding and clogging.

1.2 Objectives of this master thesis

The primary objective is to evaluate the capability of the SPH method to simulate 3D turbulent free-surface flows with dynamic rigid bodies acting as obstacles. While experimental studies of such flows exist, they are limited by scale constraints. This numerical approach could potentially overcome these limitations.

1.3 Methodology

One will use the SPlisHSPlasH software [10], which offers competitive performance in terms of computation time and provides various modeling options (pressure solvers, kernels, boundary handling methods). Although this software is focused on graphical visualization through its integrated OpenGL preview system, one will assess its capacity to produce physically accurate results.

This master thesis will first describe the mathematical and physical framework in which the equations dictate the laws of physics in chapter 3. Chapter 4 will then review and fully explain the fundamentals of the SPH method. The fifth chapter will explain the SPlisHSPlasH algorithm logic and detail each method employed in the subsequent simulations.

Chapter 6 discusses the data treatment procedures used to exploit outputs. The performances of the software will then be tested in two specific configurations in chapter 7, with each configuration focused on a unique physical aspect that contributes to the final goal of the master thesis.

After all components have been assessed, the final simulations will be performed in chapter 8, incorporating all the confidence gained throughout the previous discussions.

Bibliography

[1] R. B. Haehnel and S. F. Daly, "Maximum impact force of woody debris on floodplain structures," *Journal of Hydraulic Engineering*, vol. 130, no. 2, pp. 112–120, 2004.

[2] D. Bocchiola, M. C. Rulli, and R. Rosso, "Flume experiments on wood entrainment in rivers," *Advances in Water Resources*, vol. 29, no. 8, pp. 1182–1195, 2006.

[3] E. Bresciani, P. Davy, and J.-R. de Dreuzy, "A finite volume approach with local adaptation scheme for the simulation of free surface flow in porous media," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 36, no. 13, pp. 1574–1591, 2012.

[4] M. J. Kazemzadeh-Parsi, "Numerical flow simulation in gated hydraulic structures using smoothed fixed grid finite element method," *Applied Mathematics and Computation*, vol. 246, pp. 447–459, 2014.

[5] R. A. Gingold and J. J. Monaghan, "Smoothed particle hydrodynamics: theory and application to non-spherical stars," *Monthly Notices of the Royal Astronomical Society*, vol. 181, no. 3, pp. 375–389, 1977.

[6] L. Goffin, "Development of a didactic sph model," Master's thesis, University of Liège, June 2013. Master's Thesis.

[7] M. Lodomez, S. Erpicum, B. Dewals, M. Pirotton, and P. Archambeau, "Comparison between experimental and sph models over a sharp-crested weir," in *5th IAHR International Junior Researcher and Engineer Workshop on Hydraulic Structures*, 2014.

[8] S. Adami, X. Hu, and N. Adams, "Simulating three-dimensional turbulence with sph," tech. rep., Citeseer, 2012. Technical Report.

[9] M. R. Hashemi, R. Fatehi, and M. T. Manzari, "Sph simulation of interacting solid bodies suspended in a shear flow of an oldroyd-b fluid," *Journal of Non-Newtonian Fluid Mechanics*, vol. 166, no. 21-22, pp. 1239–1252, 2011.

[10] J. Bender *et al.*, "SPlisHSPlasH Library," 2024. MIT License.