Single-Layer Boundary Handling for SPH with Volume-Corrected Mass

Ostap Hrytsyshyn [1], Valeriy Trushevskyy[1]

[1] *Ivan Franko National University of Lviv, Lviv, Ukraine*

Abstract

We present a concise formulation for two-way fluid–rigid coupling in Smoothed Particle Hydrodynamics (SPH) based on a single boundary layer enhanced by a simple volume-corrected mass. Traditional multi-layer sampling ensures complete kernel support near walls but at a significant computational cost. We show that a single layer— augmented by a corrected boundary mass—preserves stability and accuracy in common scenarios, including thin or complex rigid geometries. A compact implementation integrates with standard WCSPH/PCISPH/position- based solvers without custom boundary forces. In a representative setup, the approach reduces fluid–boundary interaction counts by more than twenty percent while maintaining robust two-way coupling. We also outline how the method translates directly to critical infrastructure analysis (dams, levees, gates, and dense urban blocks), enabling faster what-if studies for flood mitigation.

Keywords

Smoothed Particle Hydrodynamics, fluid–rigid coupling, boundary handling, single-layer sampling, volume correction, critical infrastructure, flood mitigation

1. Introduction

Smoothed Particle Hydrodynamics (SPH) represents fluids with particles carrying mass, momentum, and thermodynamic state. Its mesh-free nature makes it attractive for free-surface flows, breaking waves, and complex geometries. When we add solid objects into the fluid, we get more interesting effects, but also new problems near the walls. Fluid particles close to the wall lose some neighbors, so their density and pressure become wrong. This can cause the fluid to stick to the wall or leak through it, and to fix this we often need many boundary particles.

Multi-layer boundary particles reliably fill kernel support but can dominate memory and neighbor-search cost. This paper focuses on a practical alternative: single-layer sampling with volume-corrected boundary mass. The idea is to keep just one layer of boundary particles and compensate for the lack of neighbors by inflating the contribution of each boundary particle according to the local support volume it represents.

2. Background

Given particles j around location x, SPH approximates a field A by

$$A(x) \approx \sum_j A_j \frac{m_j}{\rho_j} W(x - x_j, h), \quad (1)$$

with smoothing kernel W and radius h. Density follows as

$$\rho_i = \sum_j m_j W(x_i - x_j, h). \quad (2)$$

[1]Corresponding authors

ostap.hrytsyshyn@lnu.edu.ua (O. Hrytsyshyn); valeriy.trushevsky@lnu.edu.ua (V. Trushevskyy)

0000-0000-0000-0000 (O. Hrytsyshyn); 0000-0001-8672-7152 (V. Trushevskyy)

Close to solid boundaries, particle deficiency—a lack of neighbors within the kernel—biases (2) and the resulting pressure forces.

3. Method: Single-Layer Sampling with Volume-Corrected Mass

We place one layer of boundary particles on the surface and endow each boundary particle b with an effective volume V_b that compensates for the missing neighbors in its kernel support. The boundary contributes to summations through the *corrected* mass

$$\widehat{m}_b = \rho_0 V_b, \tag{3}$$

where ρ_0 is the reference fluid density. In practice, V_b can be estimated from local surface sampling (e.g. spacing Äx) or from a quick pre-sweep integrating kernel weight in the half-space outside the solid. The correction restores consistent density/pressure near walls without adding extra boundary layers.

3.1. Two-Way Fluid–Rigid Coupling

Let i denote a fluid particle and b a boundary particle. A standard pressure force term reads

$$f_{i \leftarrow b} = -\widehat{m}_b \left(\frac{p_i}{\rho_i^2} + \frac{p_b}{\rho_b^2}\right) \nabla W(x_i - x_b, h), \tag{4}$$

with the equal and opposite reaction applied to the rigid body. Here p_b and ρ_b are boundary-side pressure and density (usually tied to ρ_0 and a stiff equation of state), and $\widehat{m}_b$ comes from (3). Viscous and contact terms follow standard forms. Because the correction lives entirely in $\widehat{m}_b$, integration into existing WCSPH/PCISPH codes needs no special position corrections or ad-hoc wall forces.

4. Results

In a representative scene with 20,000 fluid particles, a multi-layer boundary discretization (about 14,000 boundary particles) was compared to a single-layer setup (about 3,000 boundary particles). Over a short run, the single layer reduced fluid–boundary interaction counts by roughly **20–25%** while preserving stable pressure and preventing visible penetration. Normalized per boundary particle, the single layer was substantially more efficient, indicating that dense multi-layer sampling often overshoots what is needed for accurate forces. Thin plates and shells remained stable thanks to the volume correction in (3).

5. Application: Critical Infrastructure Protection

Accurate, fast fluid–structure interaction is central to protecting critical infrastructure subject to floods or surge events. The single-layer approach is well suited for:

- **Dams and levees:** simulate overtopping, controlled releases, and breach scenarios with complex wall geometry;
- **Urban blocks and barriers:** model flow through streets, gates, and temporary defenses with thin panels;
- **Lifeline corridors:** assess loads on bridges, substations, and pump stations where thin members dominate.

Because only one boundary layer is required, pre-processing is minimal and neighbor searches are lighter, enabling larger domains, finer fluid resolution, or more what-if scenarios under fixed compute budgets.

6. Conclusion

We presented a compact and efficient method for handling fluid–rigid interaction in SPH using a single boundary layer with volume-corrected mass. This correction restores missing kernel support near walls and allows stable two-way coupling even for thin or complex geometries. The main idea is simple but powerful: by adjusting the effective mass of each boundary particle, we keep pressure and density consistent without adding extra layers or heavy preprocessing.

Compared to traditional multi-layer sampling, the proposed approach cuts the number of interactions by more than twenty percent, which means less memory use and faster computation. At the same time, pressure distribution and fluid stability stay nearly the same, proving that accurate coupling can be achieved with much lighter boundaries. Because the change is local and solver-independent, it can be integrated easily into existing SPH solvers like WCSPH, PCISPH, or IISPH without special wall forces or custom constraints.

This approach is especially useful for large-scale or real-time simulations, where performance and simplicity matter as much as accuracy. It is well suited for interactive visualization, training systems, and emergency prediction models where results must be available quickly. In addition, the same concept is relevant for protecting critical infrastructure such as dams, levees, flood barriers, or bridges. By reducing the cost of high-fidelity fluid simulations, engineers can explore more what-if scenarios, evaluate different designs, and prepare better for risk events.

Future work may focus on automatic volume estimation for irregular geometry, coupling with deformable solids, and GPU optimization for even larger domains. We also plan to test the approach in realistic flood simulations and infrastructure models to confirm its efficiency and predictive capability. Overall, the single-layer method with volume correction offers a good balance between accuracy, simplicity, and performance, making it a practical choice for both research and applied engineering.

References

[1] R. A. Gingold and J. J. Monaghan, Smoothed particle hydrodynamics: theory and application to non-spherical stars, *Mon. Not. R. Astron. Soc.* 181(3) (1977) 375–389.

[2] M. Becker and M. Teschner, Weakly compressible SPH for free surface flows, in: *Proc. SCA*, 2007, pp. 209–217.

[3] B. Solenthaler and R. Pajarola, Predictive-corrective incompressible SPH, *ACM Trans. Graph.* 28(3) (2009) 1–6.

[4] M. Ihmsen, N. Akinci, M. Gissler, and M. Teschner, Boundary handling and adaptive time-stepping for PCISPH, in: *VRIPHYS*, 2010, pp. 79–88.

[5] K. Bodin, C. Lacoursière, and M. Servin, Constraint fluids, *IEEE Trans. Vis. Comput. Graph.* 18 (2012) 516–526.

[6] J. Monaghan and J. Kajtar, SPH particle boundary forces for arbitrary boundaries, *Comput. Phys. Commun.* 180(10) (2009) 1811–1820.