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Fluid-structure interaction simulation by SPH and reflective boundary conditions

C.A.D. Fraga Filho

Development, Implementation and Application of Computational Tools for Problem Solving in Engineering Research Group - IFES, Brazil

Abstract

The replacement of artificial computational techniques by the physical reflective boundary conditions (RBC) - according to the physical laws in the continuum domain - is a relevant advance in the current scientific community search for a realistic treatment of the interaction between the fluid and the solid boundaries in meshfree particle methods. In most particle simulations of fluid-structure interaction (FSI) problems employing meshfree Lagrangian particle methods, artificial boundary conditions (ghost and dummy particles, dynamic boundary conditions, among others) are used, despite confronting the continuum laws. In this work, the implementation of RBC in the Smoothed Particle Hydrodynamics (SPH) simulation of the benchmark problem of a wave impacting a tall structure - a rigid obstacle fixed inside a reservoir – is presented. The numerical results obtained have been compared to literature results and both are in good agreement. The water wave generated due to the dam break over the dry bed reached the rigid obstacle approximately at the instant of time 0.30 s. The good applicability of RBC coupled with the SPH meshfree particle method encourages the implementation and testing of RBC to solve FSI problems involving fixed rigid boundaries.

Keywords: fluid-structure interaction, FSI, reflective boundary conditions, meshfree particle method, SPH, dynamic boundary conditions.

1 Introduction

Currently, most Lagrangian particle modelling uses artificial computational treatments employ fictitious particles, such as dynamic, ghost and dummy, and/or repulsive intermolecular forces, in the treatment of contours at the continuum domain.

The implementation of reflective boundary conditions (RBC) in the Lagrangian particle modelling is a scientific attempt to avoid the use of artificial computational techniques - ghost, dummy or dynamic particles ([1,2]) - in the boundary treatment at the continuum domain. With the implementation of RBC, the interaction between solid and fluid is done using the physical and real treatment of the contours, respecting the laws of continuum mechanics. The traditional approach of the one-particle model - that is, without considering the interparticle collisions - was used to obtain input data for the collision detection and response algorithm (CDRA). Figure 1 presents the reflection of a particle schematically, avoiding its escaping from the domain.

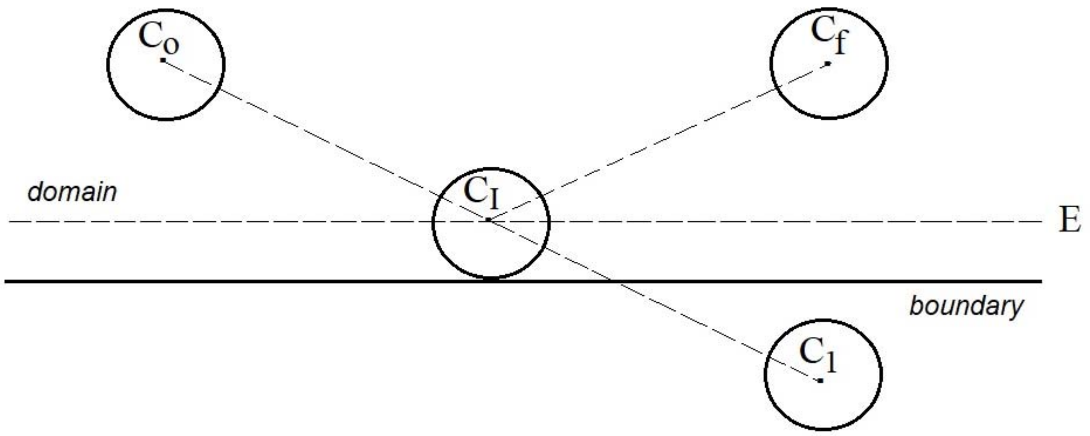

Figure 1. The particle reflection and the boundary. E is the reflection axis. C_o is the initial position of the particle (centre of mass) and C_f is the position after the reflection [3].

After the detection of the particle's collision against the real boundaries (planes that define the reservoir walls or sides of the rigid obstacle), its velocity and position of the centre of mass must be corrected using coefficients of restitution of kinetic energy and friction. Previous author’s studies carried out from 2019 to 2021 shows the validation of RBC in two-dimensional (2D) and three-dimensional (3D) domains ([3,4,5]).

The objective of this work is to show the applicability of realistic and physical reflective boundary conditions in the Lagrangian particle simulation of fluid-structure-interaction (FSI) problems, being an advance to the artificial boundary treatments still widely used in particle simulations in physical and engineering problems. In this sense, the improvement of the simplest 3D fluid-structure interaction (FSI) study validated in 2019 – dam-break flow over a dry bed presented in [5] – was done with the implementation of a rigid structure inside the reservoir.

2 Methods

The benchmark problem simulated in this work ([6-8]) is presented in Fig. 2. The dammed water was treated as an incompressible, uniform, and isothermal Newtonian fluid. The reservoir was 160 cm long, 61 cm wide and 75 cm high. The initial volume of water dammed was 40 cm long x 61cm wide x 30 cm high. The rigid obstacle inside the tank was 12 cm x 12 cm x 75 cm and placed 50 cm downstream from the gate (located at x = 40 cm) and 24 cm from the nearest sidewall of the tank.

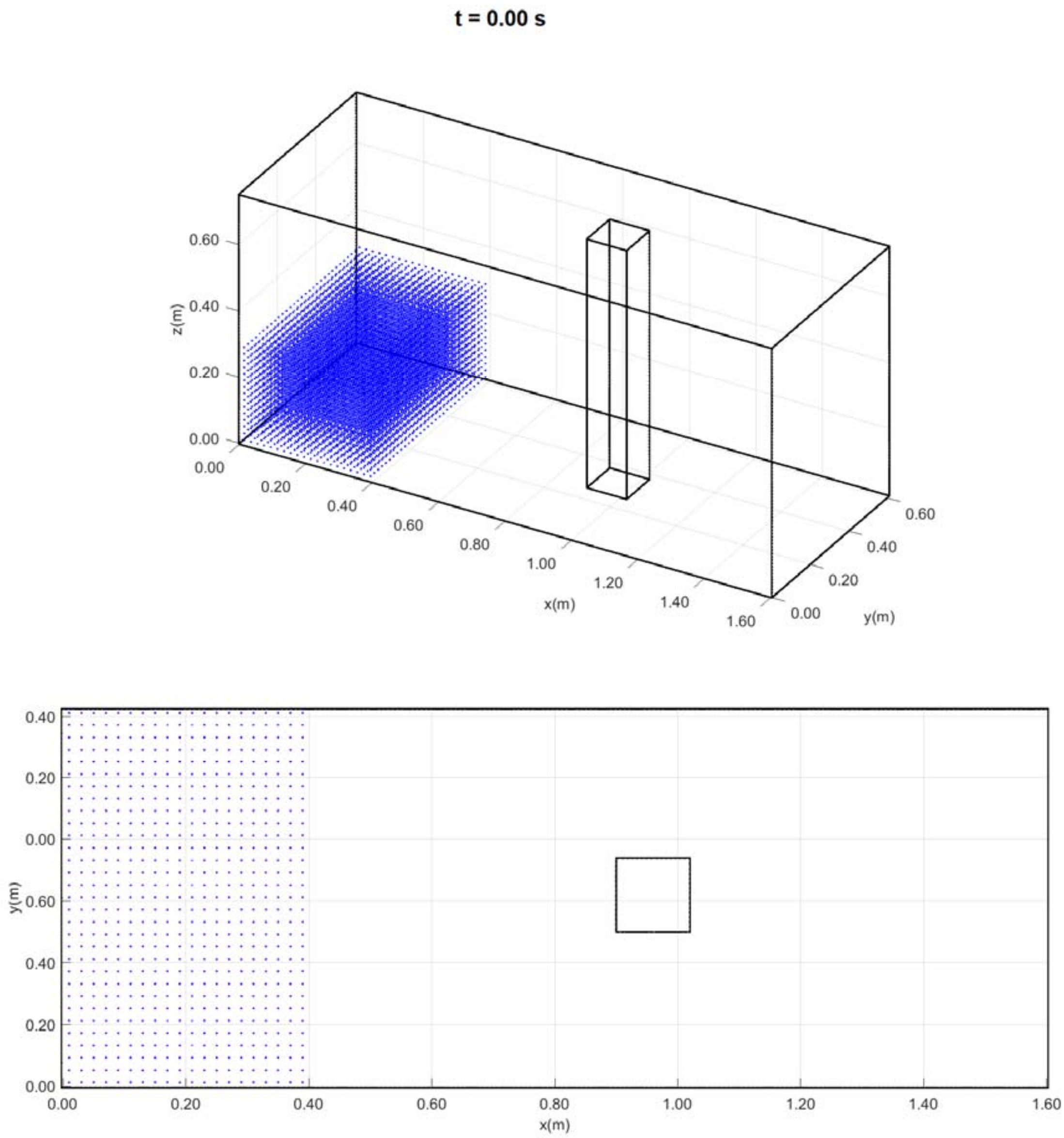

Figure 2. The computational domain simulated and initial particle setup (represented by points in blue).

The equations of conservation of mass and momentum (Equations (1) and (2)) were solved using the SPH formulation [9].

$$\frac{d\rho_a}{dt} = \sum_{b=1}^{n} m_b (\mathbf{v}_a - \mathbf{v}_b).\nabla W\left(\mathbf{X}_a - \mathbf{X}_b, h\right) \tag{1}$$

$$\begin{aligned}\frac{d\mathbf{v}_a}{dt} &= \sum_{b=1}^{n} m_b \left[\frac{P_a}{{\rho_a}^2} + \frac{P_b}{{\rho_b}^2} + \pi_{ab}\right] \nabla W\left(\mathbf{X}_a - \mathbf{X}_b, h\right) + \\ &+ \sum_{b=1}^{n} \frac{m_b}{\rho_b}\left[2\lambda_a \frac{(\mathbf{X}_a - \mathbf{X}_b)}{\left|(\mathbf{X}_a - \mathbf{X}_b)\right|^2}.\nabla W\left(\mathbf{X}_a - \mathbf{X}_b, h\right)\right](\mathbf{v}_a - \mathbf{v}_b) + \mathbf{g}\end{aligned} \tag{2}$$

where ρ is the density of the fluid; t is the time; m is the mass; d/dt is the Lagrangian (or material) derivative; $\mathbf{v}$ is the fluid velocity; ∇ is the vector differential mathematical operator; P is the absolute pressure acting on the fluid; π_{ab} is the artificial viscosity; λ is the kinematic viscosity; $\mathbf{g}$ is gravity; n is the number of neighbouring particles inside the domain of influence; a and b are subscripts that refer to the reference and neighbour particle, respectively; W is the smoothing function; $\mathbf{X}$ is the position of the particle and h is the smoothing length.

In the discretisation of the fluid, 9,300 Lagrangian particles were used. The density and kinetic viscosity of the water were 1.00 x 10^3 kg/m^3 and 1.00 x 10^{-6} m^2/s. The smoothing length varied with time. The particles defining the free surface at the initial time instant were marked, and their pressures set to zero (Newman boundary conditions). The dynamic pressure was obtained using Tait's state equation, in which B was equal to 0.85 x 10^5 Pa, the density of the fluid at rest was 1.0 x 10^3 kg/m^3, the sound velocity in the fluid was 24.26 m/s, and γ was 7. The temporal integration was done using Euler's method. The initial time step was 2.07 x 10^{-4} s and varied with time. The Courant number was 0.20. The density renormalization was applied every 30-time steps and the correction of the pressure gradient was done at each numerical iteration. Laminar shear stress modelling and artificial viscosity (α_π= 0.10) were used [10]. XSPH correction method was applied (ε = 0.50). Cubic spline kernel was applied in the simulation [5]. In RBC, the coefficients of restitution of kinetic energy (CR) and friction (CF) were 1.00 and 0.00, respectively.

3 Results

Simulation results (the evolution of the centres of mass of the Lagrangian particles in some instants of time) are graphically presented in Figs. 3 and 4. The first collision of particles against the tall structure occurred at the time instant of 0.300 s is in concordance with literature data [6-8].

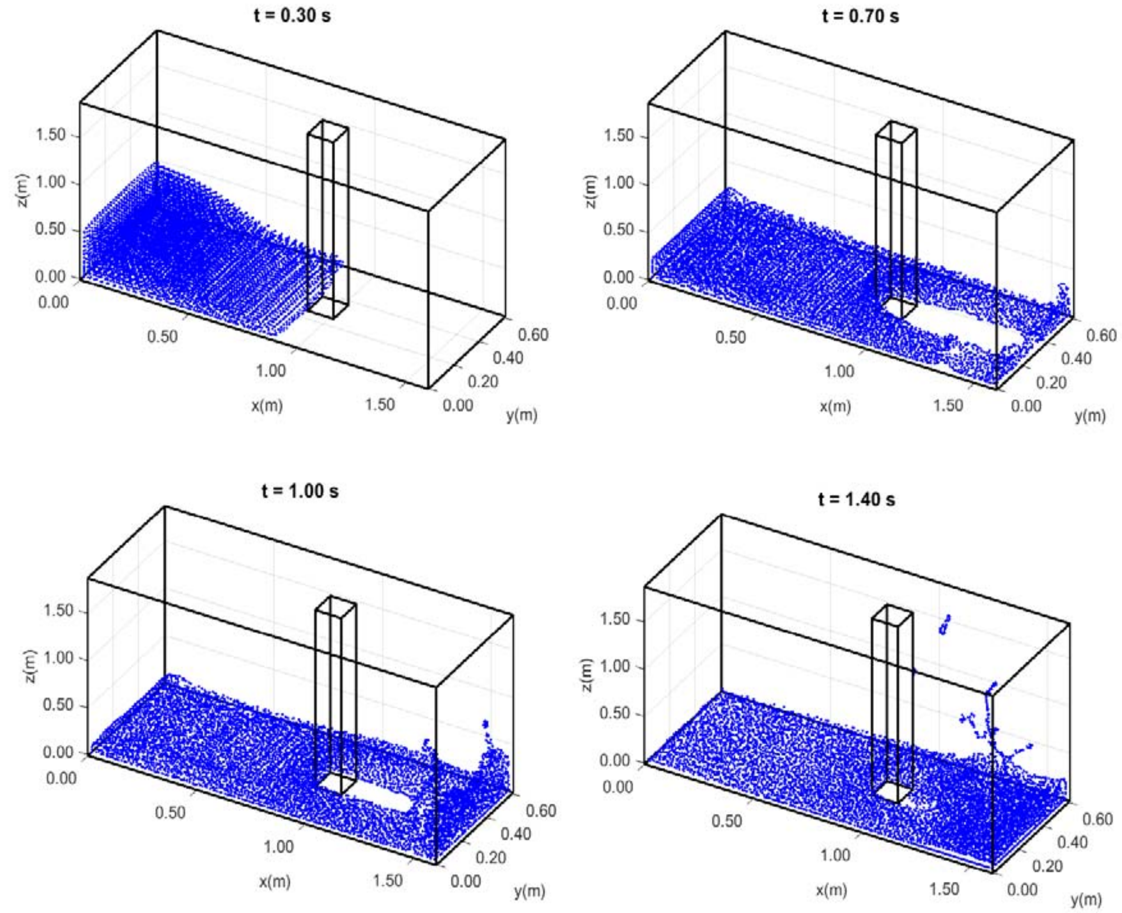

Figure 3. 3D SPH simulation results. Evolution of the particles in some instants of time.

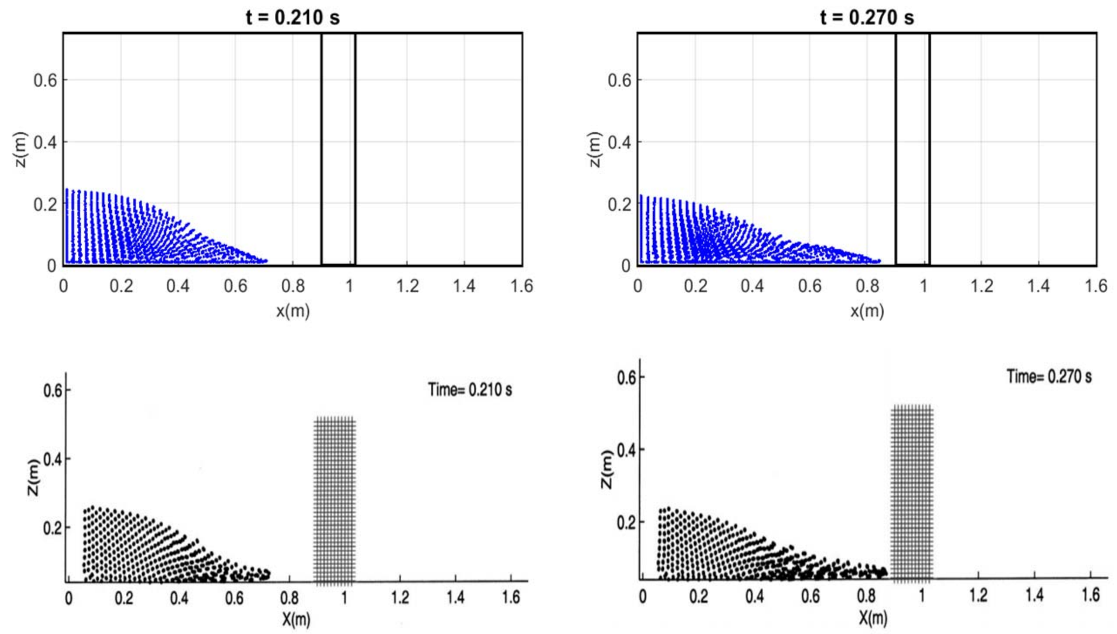

Figure 4. Lateral xz cross-section showing the evolution of the particles in the simulation at the first line. It has shown good agreement with the literature results (validated from experiments) [6], at the second line. With permission from ASCE.

4 Conclusions and Contributions

In the simulation performed with the author's code, 9,300 fluid particles were used and the realistic boundaries (of the reservoir and rigid obstacle) were defined by geometric planes. In [6], 15,000 water particles moved in the fluid flow, and 19,000 others were used in the definition of layers of fixed boundary particles (for the tank and rigid obstacle). In [7], 300,000 fluid particles were employed and dynamic boundary conditions were used in the treatment of the contours.

The considerable computational cost of the serial CPU simulation in this work - processing time in the range of 8 hours - could be minimised using GPU. [11] presented a GPU implementation of a particle collision detection method with much better performance than CPU.

The replacement of artificial computational techniques by physical and real reflective boundary conditions (according to the physical laws in the continuum domain) is a relevant advance in the current search of the scientific community for a realistic treatment of the interaction between the fluid and the solid contours.

Good agreement between the numerical results was obtained and the literature data encourage further RBC implementation (coupled with the Lagrangian particle method) and testing for the solution of FSI problems in 2D and 3D domains. In the next stages of this research, numerical parametrization tests must be done, aiming at the optimization of the simulation, evaluating the number of particles and the parameters of the simulations utilised.

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