

CONSTRAINED FLUID-DEBRIS IMPACTS ONTO NON-RIGID STRUCTURES IN EXTREME HYDRODYNAMIC EVENTS USING DUALSPHYSICS+CHRONO

Gioele Ruffini, Paolo De Girolano
Sapienza University of Rome
DICEA
Italy
gioele.ruffini@uniroma1.it

Riccardo Briganti, Alessandro De Iasio
University of Nottingham
Department of Civil Engineering
UK

Nils Goseberg
Technische Universität Braunschweig
Germany

Jacob Stolle
Institut National de la Recherche
Scientifique Eau Terre Environnement
Canada

Iván Martínez-Estévez
Universidade de Vigo
Spain

Bahman Ghiassi
University of Birmingham
School of Engineering
UK

I. INTRODUCTION

Extreme hydrodynamic events, such as tsunamis ([1], [2]), usually have a significant impact on coastal environments both anthropised and natural. These events are very likely to entrain in the resulting flow a large number of solid objects such as cars, containers, vessels etc. Their impact with structures in anthropised areas can substantially increase the loading, potentially causing additional damage as documented after the the 2011 Tōhoku event ([3]). Correctly estimating these loads is often crucial for sustainable and optimised designs of coastal structures and infrastructures ([4], [5]) due to their higher risk of damage due to e.g., containers transport hazard ([3], [6]).

Smoothed Particles Hydrodynamics (SPH) based numerical models are a very good alternative to other Eulerian mesh-based methods to simulate this type of problems since large deformations and transport processes do not need complex techniques to be implemented. Coupling SPH models with DEM, e.g. CHRONO project have demonstrated the capability in accurately simulating debris transport ([7]–[9]). This study, by using a novel set of laboratory experiments, aims at: (I) validating the ability of this numerical strategy to represent complex constraint conditions for the impacting debris, and (II) investigating the complex fluid-debris-structure interaction, including post impact rotation of the debris and subsequent impacts.

II. GOVERNING EQUATIONS

The SPH solved used in the present study is DualSPHysics ([10]) based on the Weakly Compressible Smoothed Particle Hydrodynamics method with the fluid phase governed by the

Navier Stokes equation for which the mass and momentum conservation equations in a Lagrangian framework for a particle a can be written, respectively, as:

$$\frac{d\rho_a}{dt} = \sum_{b=1}^{N_k} m_b \mathbf{v}_{ab} \cdot \nabla_a W_{ab} + \delta_\phi h_p c_0 \sum_{b=1}^{N_k} \Psi_{ab} \cdot \nabla_a W_{ab} \cdot \frac{m_b}{\rho_b} \quad (1)$$

$$\frac{d\mathbf{v}_a}{dt} = - \sum_{b=1}^{N_k} m_b \left(\frac{P_b + P_a}{\rho_b \rho_a} \right) \nabla_a W_{ab} + \langle \Gamma \rangle_a + \mathbf{g} \quad (2)$$

These equations are applied by using a summation extended to all the particles $b = 1, \dots, N_k$ with N_k the number of particles inside a weighting function called smoothing kernel W to which it is also associated a smoothing length h_p . m , ρ , v and P are, respectively, the mass, the density, the velocity vector, and the pressure of a particle. In Eq. 1, the second term on the right-hand side is the Density Diffusion Term (DDT, [11]). Here, δ_ϕ is a free parameter, c_0 is the speed of sound at the reference density taken with a value of at least 10 times the reference velocity of the simulation due to the weakly compressible hypothesis and Ψ_{ab} is an artificial dissipation term that follows [12] formulation. In Eq. 2, Γ_a groups all the dissipative terms for which two formulations are available ([10]), both used herein to analyse their effect on the impact forces accuracy, i.e. the artificial viscosity formulation and the formulation that applies a viscous dissipation term in laminar regime plus a large eddy simulation sub-particle scale model (Laminar+SPS). Finally, $\mathbf{g} = (g_x = 0 \text{ m/s}^2, g_y = 0 \text{ m/s}^2, g_z = -9.81 \text{ m/s}^2)$ is the gravitational acceleration.

To handle solid-solid impacts, DualSPHysics is coupled

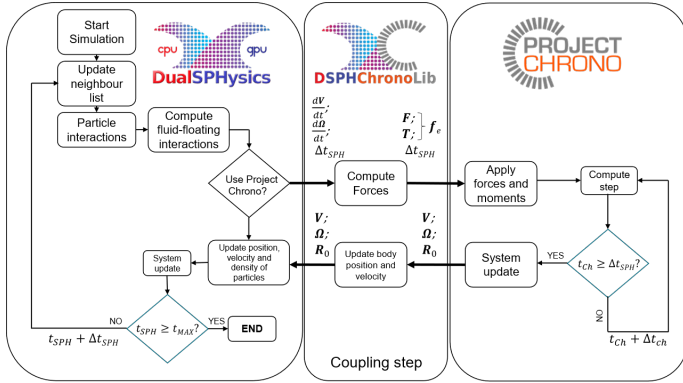


Fig. 1. Coupling flowchart for DualSPHysics with CHRONO.

([13]) with CHRONO using its DEM-P formulation. This formulation solves deformable contacts by using the penalty method ([14]), which calculates collisions between solids considering an overlapping distance. When an overlapping between two solid is detected then the tangential and normal forces are calculated applying the hertzian contact theory. The flow chart in Fig. 1 explains the coupling process between the two models ([13]).

III. METHODOLOGY

The novel set of laboratory experiments (Fig. 2) that are herein used for the numerical validation consist of dam-break generated flows mobilising a single debris (reproducing the dimensions of a 1:40 scale 20 ft container), positioned slightly above the flume bottom (+0.01 m) and tethered by four strings (one at each corner) to obtain a pendulum-like constrained motion, impacting a vertical structure on initial dry conditions. Different container materials, i.e., aluminium, HMWPE and pine wood, were tested. The structure consists of a 6.3 kg hollow acrylic cuboid equipped with a 6-axis Force-Torque Transducer (FTT, ≈ 1 kg) inside its base. Everything was connected to the flume bottom using a series of metal rods and plates resulting in a total weight of 11.9 kg for the entire structure. Here, the same experimental setup as described in [4], with impoundment depths of $h_0 = 0.2$ m and 0.4 m, was used.

DualSPHysics coupled with CHRONO ([15]) was used to simulate the experimental setup. DualSPHysics solved the hydrodynamics of the problem while CHRONO was used to solve solid-solid and solid-constraint interactions in its DEM-P formulation. The four constraint lines were represented as non-stretchable mooring lines with no internal dissipation using MoorDynPlus (based on Moordyn, [16]). The FTT was simulated using CHRONO with a spring-damper constraint on the dam-break propagation direction. The remaining 5 degrees of freedom (dof) of the structure were instead locked as first attempt. The debris was defined as a rigid, floating object with 6 dof. The forces extracted are the structural response calculated for the spring-damper constraint consistently to what was directly measured by the FTT.

Additionally, the offline coupling technique MESH-IN ([8])

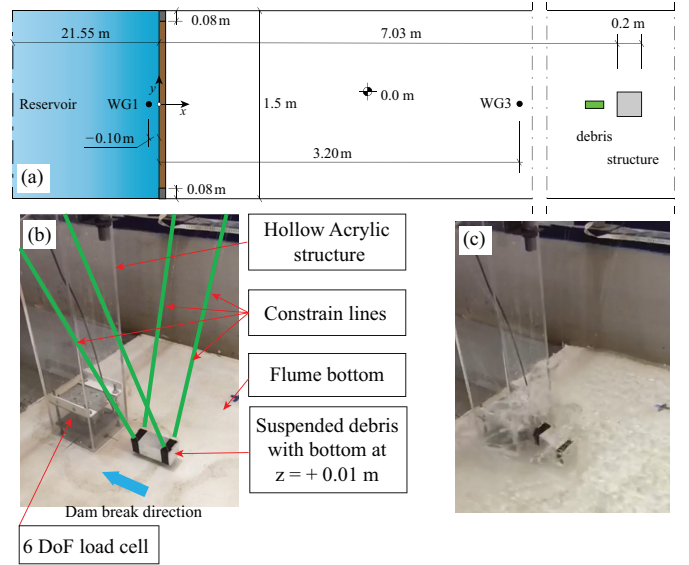


Fig. 2. Experimental setup for the constraint debris impact; (a) planimetric view of the facility and numerical domain, (b) close-up of the structure and constraint debris, (c) snapshot of sample laboratory experiments at the moment of impact between debris and structure.

was applied to improve resolution and decrease computational time close to the impact area. A minimum initial inter-particle distance $dp = 0.005$ m was used only close to the impact zone reducing the computational time from 23 h (with the entire domain with $dp = 0.01$ m) simulating the entire setup to only 4.7 h with MESH-IN.

IV. RESULTS AND DISCUSSION

The described approach allowed to compare the structural response between simulations and experiments. The experimental natural oscillation frequency is used to estimate an initial value for the stiffness coefficient of the spring constraint by using the following equation valid for a spring mass system:

$$\omega = \sqrt{\frac{k}{m}} \quad (3)$$

where $\omega = 2\pi f$, is the angular frequency of the spring with f the oscillation frequency of the system, k the spring stiffness and m the mass of the structure. $f = 70 \pm 2.2$ Hz was estimated in the laboratory for dry conditions. For the damper a damping of $c = 150$ Ns/m was used following [17], which numerically analysed the same structure.

The initial validation of the impact forces is conducted for the HMWPE container and $h_0 = 0.40$ m, after analysing the effect of different mass contributions. Fig. 3 shows the effect of different natural oscillation frequencies of the structure starting from $f = 72.2$ Hz, which corresponds to the upper boundary of the measured values in the laboratory. It should be noted that slightly different natural frequencies were measured even with small changes in water depth in the laboratory. Due to this, an in-depth analysis was carried out by varying the

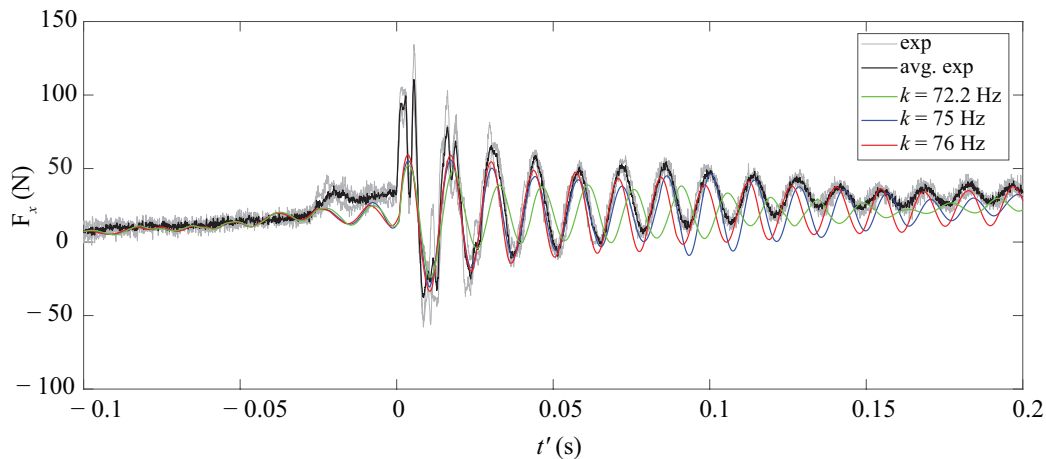


Fig. 3. Validation results for different k values analysed.

natural frequency of the structure in the simulations. Fig. 3 shows that the best correspondence between simulation and laboratory measurements for the oscillation period is reached for $f = 76$ Hz. Note that, only the first peak is found to be underestimated by the numerical model compared to the laboratory measurements. This is estimated to be caused by a different fluid-structure interaction before the container impact, see e.g. $-0.05 \text{ s} < t' < 0 \text{ s}$, likely caused by the lack of additional dof on the structure. This possible cause was found by simulating a case without flow. A prescribed initial velocity was used for the debris so that the impact velocity would match the case with flow. In this additional case the simulated forces, shifted for the hydrostatic one, resulted in a better agreement with the laboratory measurements.

V. CONCLUSIONS

The present study shows that DualSPHysics+CHRONO are accurate in reproducing debris-structure impact forces and structural response. However, it is planned to further improve the results by analysing the effect of the laminar+SPS formulation in force estimation, adding dof to the structure and compare the results for the remaining two types of debris materials. These, more in-depth, results will be presented at the conference.

ACKNOWLEDGMENT

R.G thanks Sapienza University of Rome for supporting part of this research with the fundings of "Progetti per Avvio alla Ricerca - Tipo 2, anno 2024 - CUP B83C24006280001".

REFERENCES

- [1] Mori N., Takahashi T., Yasuda T., Yanagisawa H., 2011, "Survey of 2011 Tohoku earthquake tsunami inundation and run-up," *Geophysical research letters*, vol. 38(7).
- [2] Sassa S., Takagawa T., 2019, "Liquefied gravity flow-induced tsunami: First evidence and comparison from the 2018 Indonesia Sulawesi earthquake and tsunami disasters," *Landslides*, vol. 16, pp. 195-200.
- [3] Naito C., Cercone C., Riggs H., Cox D., 2014, "Procedure for site assessment of the potential for tsunami debris impact," *Journal of Waterway, Port, Coastal, Ocean Engineering*, vol. 140(2), pp. 223-232.
- [4] Stolle J., Goseberg N., Nistor I., Petriu E., 2019, "Debris impact forces on flexible structures in extreme hydrodynamic conditions," *Journal of Fluids and Structures*, vol. 84, pp. 391-407.
- [5] De Iasio A., Ghiassi B., Briganti R., Milani G., 2023, "High strain rate effects in masonry structures under waterborne debris impacts," *Engineering Structures*, vol. 297, pp. 116911.
- [6] Koh M.J., Park H. and Kim A.S., 2024, "Tsunami-driven debris hazard assessment at a coastal community: Focusing on shipping container debris hazards at Honolulu Harbor, Hawaii," *Coastal Engineering*, pp. 104408.
- [7] Ruffini G., Briganti R., De Girolamo P., Stolle J., Ghiassi B., Castellino M., 2021, "Numerical modelling of flow-debris interaction during extreme hydrodynamic events with DualSPHysics-CHRONO," *Applied Sciences*, vol. 11(8), pp. 3618.
- [8] Ruffini G., Domínguez J.M., Briganti R., Altomare C., Stolle J., Crespo A.J.C., Ghiassi B., Capasso S., De Girolamo P., 2023, "MESH-IN: a MESHed INlet offline coupling method for 3D extreme hydrodynamic events in DualSPHysics," *Ocean Engineering*, vol. 268, pp. 113400.
- [9] Bonus J., Spröer F., Winter A., Arduino P., Krautwald C., Motley M., Goseberg N., 2024, "Tsunami debris motion and loads in a scaled port setting: Comparative analysis of three state-of-the-art numerical methods against experiments," *Journal of Fluids and Structures*, vol. 197, pp. 104672.
- [10] Domínguez J.M., Fourtakas G., Altomare C., Canelas R.B., Tafuni A., García-Feal O., Martínez-Estévez I., Mokos A., Vacondio R., Crespo A.J., et al., 2022, "DualSPHysics: From fluid dynamics to multiphysics problems," *Computational Particle Mechanics*, vol. 9(5), pp. 867-895.
- [11] Molteni D., Colagrossi A., 2009, "A simple procedure to improve the pressure evaluation in hydrodynamic context using the SPH," *Computer Physics Communications*, vol. 180, pp. 861-872.
- [12] Fourtakas G., Domínguez J.M., Vacondio R., Rogers B.D., 2019, "Local uniform stencil (LUST) boundary condition for arbitrary 3-D boundaries in parallel Smoothed Particle Hydrodynamics (SPH) models," *Computers & Fluids*, vol. 190, pp. 346-361.
- [13] Martínez-Estévez I., Domínguez J. M., Tagliaferro B., Canelas R. B., García-Feal O., Crespo A. J. C., Gómez-Gesteira M., 2023, "Coupling of an SPH-based solver with a multiphysics library," *Computer Physics Communications*, vol. 283, pp. 108581.
- [14] Fleischmann J., Serban R., Negrut D., Jayakumar P., 2016, "On the importance of displacement history in soft-body contact models," *Journal of Computational and Nonlinear Dynamics*, vol. 11, pp. 044502.
- [15] Anitescu M., Tasear A., 2010, "An iterative approach for cone complementarity problems for nonsmooth dynamics," *Computational Optimization and Applications*, vol. 47(2), pp. 207-235.
- [16] Hall, M., 2018, "MoorDyn user's guide," [Online] www.matt-hall.ca/moordyn.
- [17] Xiong Y., Liang Q., Zheng J., Stolle J., Nistor I., Wang G., 2022, "A fully coupled hydrodynamic-DEM model for simulating debris dynamics and impact forces," *Ocean Engineering*, vol. 255, pp. 111468.