Article, Published Version

Rogersm, Benedict D.; Mokos, Athanasios; Fourtakas, Georgios; Crespo, Alejandro J. C.; Domínguez, J. M.; Altomare, Corrado; Canelas, R.

Developing SPH simulations for coastal applications accelerated on GPUS using dualphysics

Hydrolink

DEVELOPING SPH SIMULATIONS FOR COASTAL APPLICATIONS ACCELERATED ON GPUS USING DUALSPHYSICS

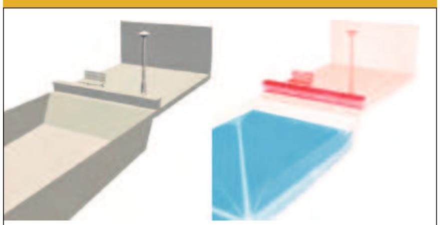
BY BENEDICT D. ROGERS, ATHANASIOS MOKOS, GEORGIOS FOURTAKAS , ALEJANDRO J.C. CRESPO, J.M. DOMÍNGUEZ, CORRADO ALTOMARE, AND R. CANELAS

Coastal defences in the next 20-100 years will be subject to increased stress as sea level rise becomes significant and climate change modifies the magnitude and frequency of storms to an uncertain degree. At the same time, coastal populations are expected to grow and the exploitation of marine resources will increase requiring development of existing and new coastal infrastructure. Furthermore, there is a risk of disasters involving multiple factors; such as severe storms or tsunamis affecting defences designed with outdated guidelines and already subject to sea-level rise. Coastal structures need to be adapted to these new scenarios of coastal vulnerability.

Analysing structures effectively requires new tools building on the highly empirical approaches presently used with conservative safety factors. Sophisticated tools are now at a formative stage and here we are actively developing the novel, flexible numerical technique Smoothed Particle Hydrodynamics (SPH). As a meshless and Lagrangian technique SPH is ideally suited to fluid and solid mechanics with highly nonlinear deformation and is opening new avenues of research in several areas, notably fluid-structure interaction, multi-phase flows and importantly, engineering application.

Traditionally an expensive computational technique, in the past few years significant advances have been made in the acceleration of SPH simulations. This has largely been due to the emergence of graphics processing units (GPUs) whose streaming multi-processor technology has enabled the acceleration of SPH for desktop applications without the need for massive high-performance computing (Crespo et al., 2011). Several GPU-based codes for SPH have now been developed. At the Universities of Vigo, Manchester, Parma, Lisbon and Flanders Hydraulics we have been developing SPH codes accelerated by GPUs for applications including wave impact, fluid-structure interaction and multi-phase flows in industrial processes. This has led to the development of the open-source DualSPHysics code (www.dual.sphysics.org).

Figure 1 – Pre-processing: CAD to SPH geometry (Barreiro et al., 2013)



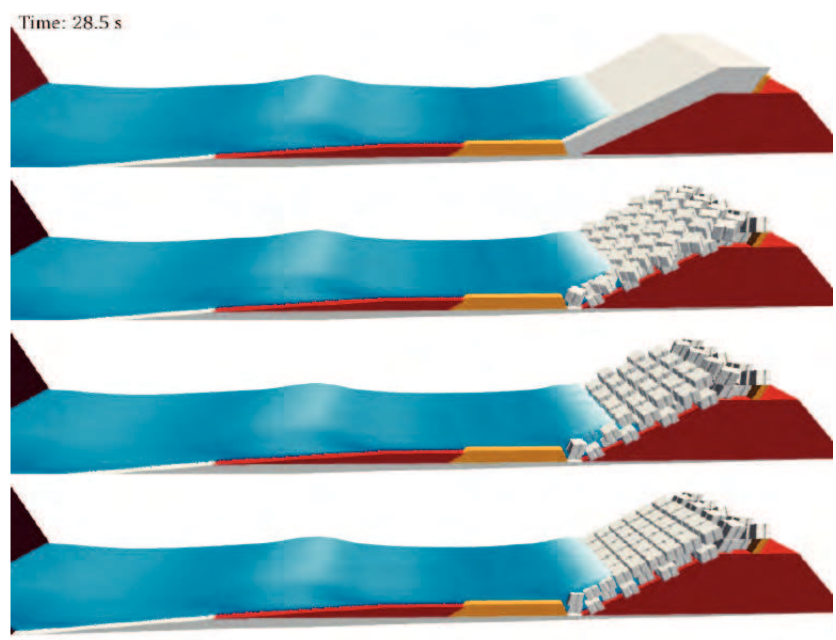
(a) CAD file (b) Initial particle arrangement

The DualSPHysics project

DualSPHysics started from the weakly compressible SPH formulation implemented in the computer code SPHysics. Using CUDA (Compute Unified Device Architecture), a parallel architecture language for Graphics Processing Units (GPUs) provided by Nvidia (an American worldwide technology company manufacturing GPUs), DualSPHysics has been developed to be open source and freely available putting the power of mini-supercomputers in the hands of engineers in industry (Crespo et al., 2015). The code is now being used by industry for a range of applications from coastal protection schemes to energy converters.

The DualSPHysics code comes with dedicated pre-processing software which can use a whole range of different input files for the geometries including CAD, STL, PLY files, etc., making setting up simulations straightforward. Figure 1 below shows a CAD file for a coastal walkway being converted into particles.

Figure 2 - Using DualSPHysics to investigate the runup for different armour units for a rubble-mound breakwater (Altomare et al., 2014)

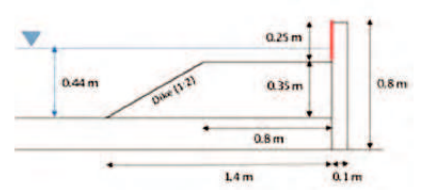


Application to Coastal Defences

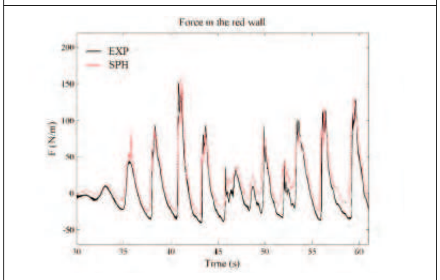
The DualSPHysics model has already been applied to coastal defence applications involving wave interaction with complex geometries such as rubble mound breakwaters. We used DualSPHysics to investigate the effect of waves with different armour units in different arrangements as shown in Figure 2. DualSPHysics was able to reproduce the wave run up over a range of Iribarren numbers, Ir, in close agreement with the well documented experimental data ($Ir = (L_0/H)^{1/2} \tan \alpha$, where L_0, H and tan α are offshore wavelength, wave amplitude and dyke slope, respectively). However, in comparison with experiments, the DualSPHysics code with its powerful pre-processing allowed us to run many simulations very quickly changing the geometry without needing the expensive laboratory resources of physical experiments.

DualSPHysics has also demonstrated that it can be used to assess accurately the forces exerted by sea waves on coastal defences. For example, we have applied DualSPHysics to wave–structure interaction computing forces exerted by large waves on the urban furniture of a realistic promenade. That study presented a very preliminary analysis of the accuracy of the model when simulating hydraulics loadings. Moreover, DualSPHysics has been further validated against experimental data from physical model tests in Altomare et al. (2015) with a close agreement between numerical solutions and the experimental results both for water surface elevation and wave forces exerted on a vertical and parapet storm return walls (Figure 3).

Figure 3 – Estimation of sea wave impact on coastal structures (Altomare et al., 2015)



(a) Numerical model setup



(b) Comparison between numerical and experimental wave

Fluid-Structure Interaction

Many problems in the coastal zone involve a combination of the incoming wave and fluid motion interacting with structures that are often moving. Canelas et al. (2014) have coupled the SPH method with the discrete element method (DEM) to provide a robust and versatile description of fluid-structure interaction. This model has been applied to the arrival of an extreme wave arriving at a port where the containers are modelled using the DEM while the SPH model predicts the fluid motion as shown in Figure 4.

Multi-Phase Flows with SPH

Many SPH codes, such as DualSPHysics, have been released mainly for single-phase simulations. However, there is a great need within the engineering industry to simulate multi-phase problems where conventional grid-based solvers struggle. Developing multi-phase SPH to run on GPUs with CUDA raises other issues that need to be considered, for example, the efficiency of the code for different phases which may have very different physical properties and hence numerical properties (Mokos et al., 2015).

Figure 4 – SPH-DEM simulation for fluid-structure interaction of a container ship (Canelas et al. 2014)

(a) Incoming wave (b) Containers in motion

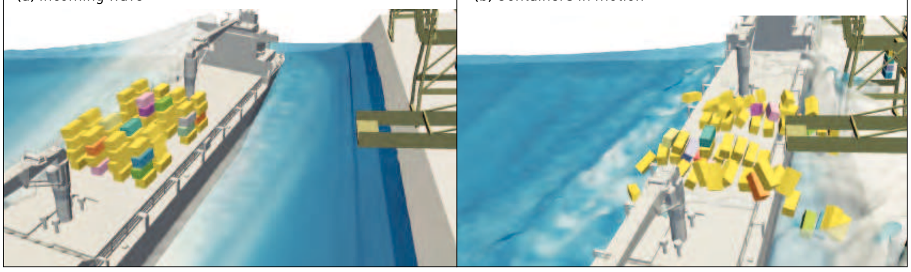


Figure 5 – 3.5 million particle air-water multi-phase simulation for a dam break impacting an obstacle (Mokos et al., 2013)

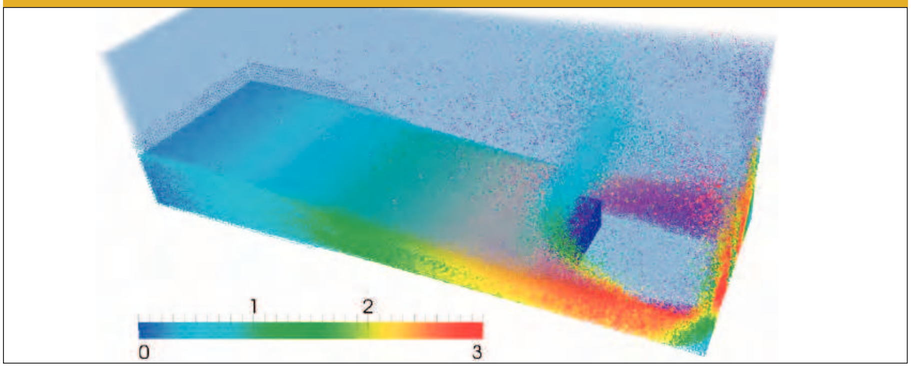


Figure 6 – 3-D erodible dam break: (Fourtakas et al., 2014)

(a) Position of the bed (b) Velocity field of the water

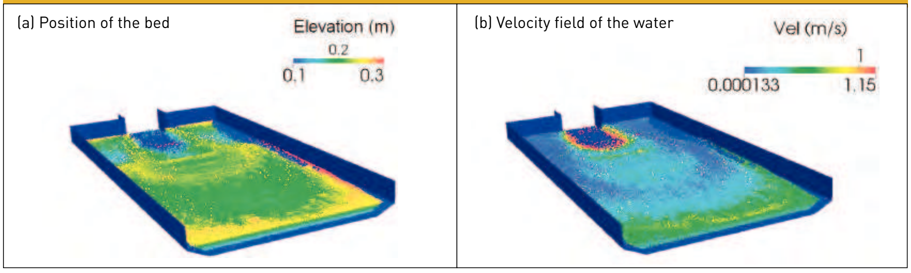
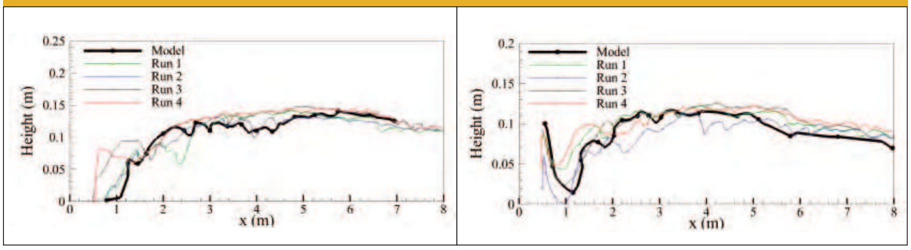
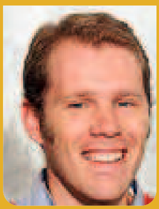


Figure 7 – Bed profiles at locations y1 and y2 of the experiment (Soares-Frazão et al. 2012) and comparison with the numerical results (Fourtakas et al. 2014)





Benedict Rogers **is a Reader at the School of Mechanical, Aerospace and Civil Engineering (MACE) in the University of Manchester. With his doctoral studies in numerical simulation of free-surface flow for shallow water, he has more than 13 years of experience of SPH research having published over 30 journal papers on SPH investigating fundamental formulations, hardware acceleration and engineering applications such as wave breaking, wave impact and multi-phase flows.**

Athanasios Mokos **is a post-doctoral research assistant at the School of Mechanical, Aerospace and Civil Engineering (MACE) in the University of Manchester. He obtained his PhD in 2014 developing a two-phase air-water SPH model to run on GPUs and is now working on applying this to bubbly flows.**

Georgios Fourtakas **is a post-doctoral research assistant at the School of Mechanical, Aerospace and Civil Engineering (MACE) in the University of Manchester. He obtained his PhD in 2014 developing a two-phase water-sediment SPH model to run on GPUs and is now working on incompressible SPH.**

Ricardo B. Canelas **is a post-doctoral researcher at CERIS, IST, Univ. of Lisbon. Main research focuses on high-performance computational fluid dynamics applied to fluvial and coastal geomorphic processes, particularly on the link from phenomenological to regional scales.**

Alejandro J. C. Crespo **is "Ramon y Cajal" Research Fellow at Universidade de Vigo. His research activity is mainly focused on computational fluid dynamics and its application to coastal engineering. He works on the development of a novel meshless particle method (Smoothed Particle Hydrodynamics - SPH) to study free-surface problems with real-life applications.**

J.M. Domínguez **is a research fellow at Universidade de Vigo. His research activity is mainly focused on HPC (High Performance Computing) applied to Computational Fluid Dynamics, in particular to improve a Smoothed Particle Hydrodynamics model in order to develop a SPH code capable of performing simulations of real-life applications at a reasonable time.**

Corrado Altomare **is a post-doctoral researcher from Ghent University actually working as engineer/researcher at Flanders Hydraulics Research, in Antwerp (Belgium). PhD in Engineering and Chemistry for the Protection of the Ecosystems. He worked also in the Maritime Engineering Laboratory of the Technical University of Catalonia, in Barcelona, Spain.**

At present we have been developing multi-phase DualSPHysics for two separate types of multi-phase flows described briefly here: (i) liquid-gas mixtures, and (ii) liquid-sediment mixtures.

(i) Liquid-gas mixtures
Figure 5 shows a snapshot from a multi-phase dry-bed dam break simulation for the SPHERIC benchmark number 2 test case. The two-phase simulation uses nearly 4 million particles which includes both the water and air phases and particles to represent the boundary. The multi-phase simulation produces close agreement for the impact pressures measured on the block and captures the mixing of the two phases post impact. This case showed that multi-phase GPU simulations requiring millions of SPH particles can now be performed in a matter of hours rather than months using conventional codes.

(ii) Liquid-sediment mixtures
Many applications in the marine and coastal environment involve a mixture of liquid and sediment. DualSPHysics has been modified for this application by modelling the water as a Newtonian liquid within the standard weakly compressible SPH, while the sediment phase is represented by a non-Newtonian Bingham-type constitutive model (Fourtakas et al., 2014). Surface yield criteria are used to initiate movement of the sediment particles, while a sediment skeleton lithostatic pressure under the yield surface predicts the state of unyielded particles. Additional equations are used to represent the sediment shear layer at the surface and sediment suspension models and seepage forces.

The multi-phase model has been compared with experimental and 2-D reference numerical models for scour following a dry-bed dam break. Figure 6 shows snapshots from a simulation for the position and velocity of the bed sediment for a 3-D erodible bed dam break simulation. The water is released behind the constriction and erodes the sediment. Profiles of the sediment along the tank were measured in the experiment by Soares-Frazão et al. (2012) providing useful 3-D validation data.

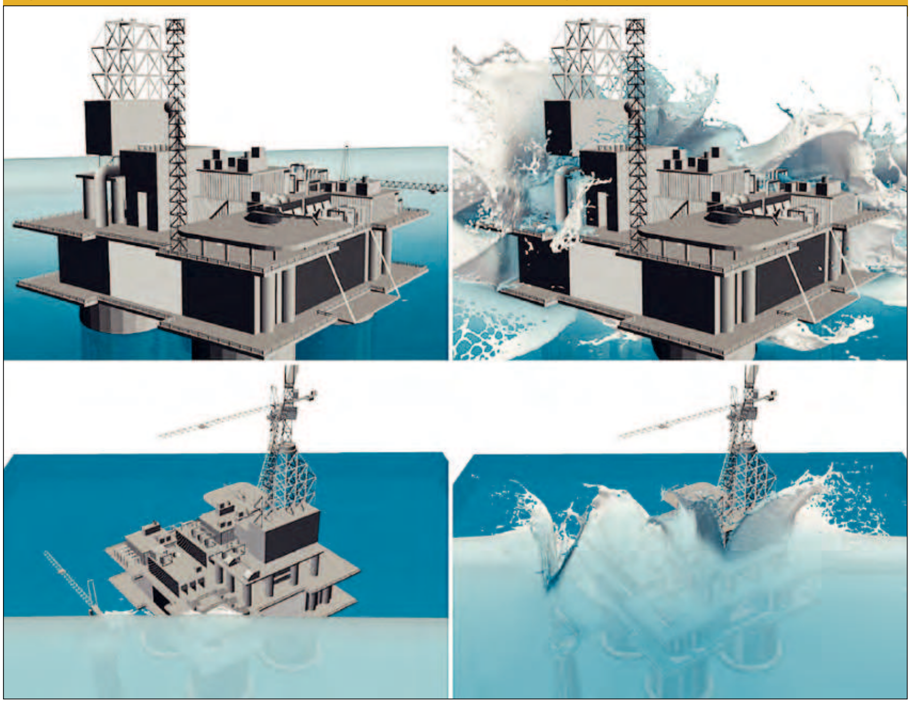
Figure 7 shows comparisons of the bed profile along two sections; the SPH simulation is shown in red and the repeated runs from the experiment in black. The agreement between the SPH and experiment is generally close and is promising for future application and development.

The need for Multi-GPU simulations

The memory of a single GPU card is finite. Hence, large simulations that require in excess of 100 million particles require multiple GPUs. We expanded the DualSPHysics code to a multi-GPU implementation. With many clusters now being constructed from a range of different hardware types, the multi-GPU DualSPHysics was modified to be suitable to heterogeneous clusters leading to the world's first 1-billion particle simulation for free-surface flow as shown in Figure 8.

With SPH simulations accelerated using GPUs, the intention now is to expand the future development of DualSPHysics for a greater range of physical processes and applications incorporating the latest developments in multi-phase, boundary conditions and numerical accuracy. The newest developments are being prepared for general release as open-source codes which will be available to be downloaded from the DualSPHysics website in 2015.

Figure 8– 1-billion particle simulation for free-surface flow (Domínguez et al., 2013)



References

Altomare C, Crespo AJC, Domínguez JM, Gómez-Gesteira M, Suzuki T, Verwaest T. 2015. Applicability of Smoothed Particle Hydrodynamics for estimation of sea wave impact on coastal structures. Coastal Engineering, 96: 1-12. doi:10.1016/j.coastaleng.2014.11.001.
Canelas R, Ferreira RML, Domínguez JM, Crespo AJC. 2014. Modelling of Wave Impacts on Harbour Structures and Objects with SPH and DEM. Proceedings of the 9th SPHERIC Workshop. Editor D. Violeau, A. Hérault, A. Joly, pp 313-320. 3-5 June.
Crespo, A.J.C., Dominguez, J.M., Rogers, B.D., Gómez-Gesteira, M., Longshaw, S.M., Canelas, R., Vacondio, R., Barreiro, A., Garcia-Feal, O. (2015) "DualSPHysics: Open-source parallel CFD solver based on Smoothed Particle Hydrodynamics (SPH)". Computer Physics Communications. Vol. 187. pp 204-216. February. DOI: 10.1016/j.cpc.2014.10.004
Fourtakas, G., Rogers, B.D., Laurence, D.L. (2014) "3-D SPH Modelling of Sediment Scouring Induced by Rapid Flows", Proc. 9th International SPHERIC Workshop. Editor D. Violeau, A. Hérault, A. Joly, pp 9-16. 3-5 June.
Soares-Frazão, S., et al., Dam-break flows over mobile beds: experiments and benchmark tests for numerical models. Journal of Hydraulic Research, 2012. 50(4): p. 364-375.
Mokos, A., Rogers, B.D., Stansby, P.K., Domínguez, J.M., 2015, Multi-phase SPH modelling of violent hydrodynamics on GPUs, Computer Physics Communications, 196, 304-316.