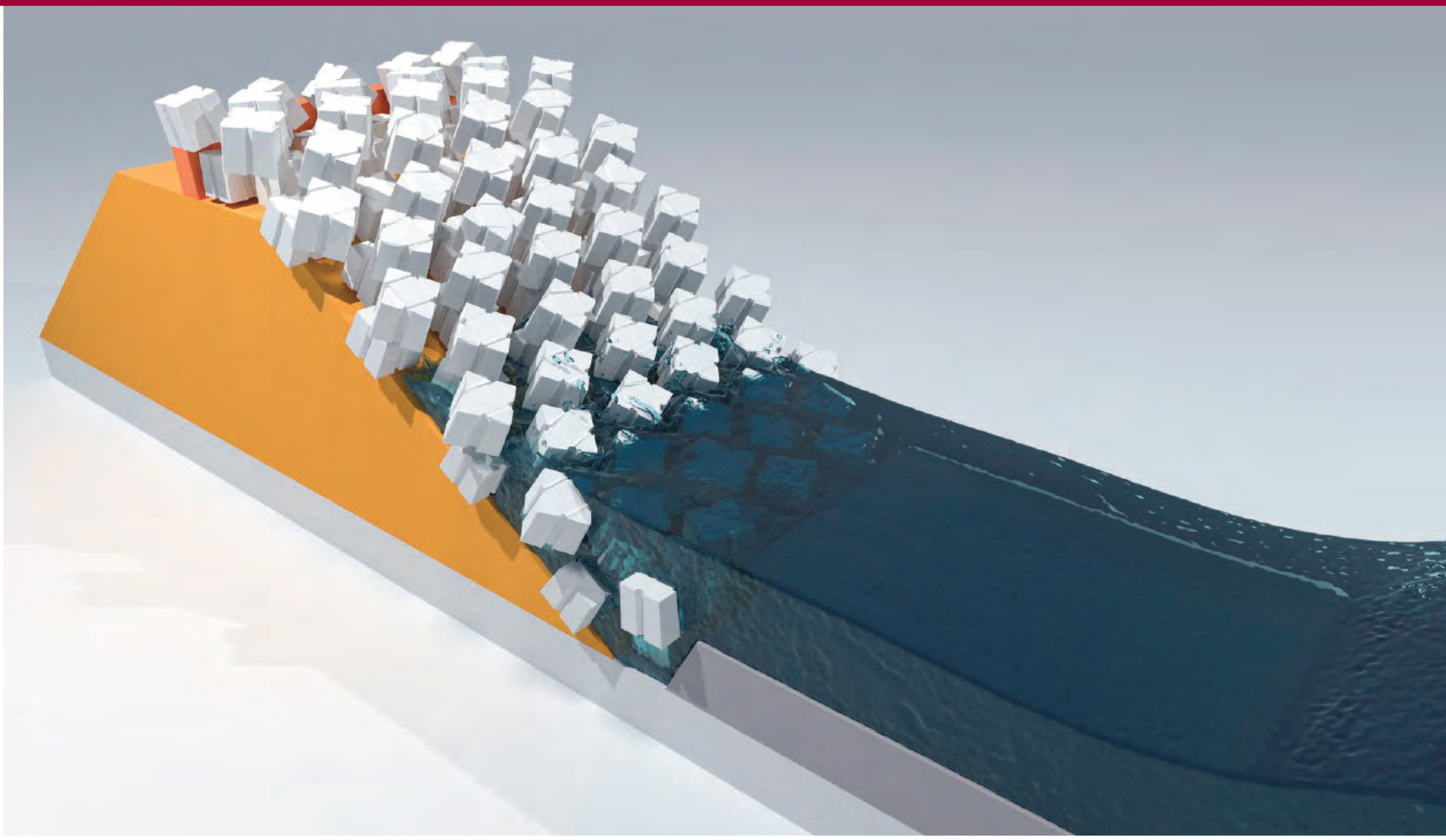
A BRIEF HISTORY OF SPH IN HYDRAULICS

BY JOSEPH J. MONAGHAN



DualSPHsics team

The first description of Smoothed Particle Hydrodynamics (SPH) was published in 1977 by Joe Monaghan and Bob Gingold, and independently by Leon Lucy. The method originated in the desire to simulate the formation of binary star systems. These systems are characterised by flows with complicated geometry and very large variations in density. None of these characteristics could be handled with the finite difference methods that were then available. The basis of SPH was the assignment of the properties of the system to particles with fixed mass. By using interpolation modelled on the kernel method that statisticians used to estimate probability densities, it was possible to estimate derivative of quantities, such as the pressure and temperature that were known at the particles. Gravitational forces could be calculated by summing over the particles, though a straightforward summation was soon replaced by more sophisticated tree-code algorithms. In this way the forces acting on the particles were calculated and the motion of the particles followed. These particles represented elements of fluid and their stream lines and acceleration were estimates of the same quantities for the fluid. The methods were extended to deal with thermodynamic effects in gas dynamics, and to deal with the shock waves that are very common in astrophysical simulations. An attractive feature of SPH was that the resolution could be allowed to vary in space and time, although the correct way to include this in the algorithms was not known for 25 years. Another attractive feature was that the algorithms were simple, but very complicated problems could be simulated easily.

The application of SPH to liquid problems began in 1993. I had an interest in Archaeology and attended a seminar on the demise of the Minoans. The speaker pointed out that there was considerable evidence that the Minoan civilisation on Crete had been badly disrupted at the time of the eruption of a massive volcano on Thera (Santorini), and some investigators thought the volcanic eruption had produced tsunamis that destroyed the coastal towns of Crete. I was intrigued by this and asked an archaeologist, Peter Bicknell (an old friend, who worked with us on this problem), if the archaeologists would be interested in a fluid dynamicist calculating whether tsunamis would have been produced, and then what damage they might cause. He said they would be, and he referred to the fluid dynamics simulations as "the hard evidence" that was all too rare in Archaeology. At this time I had never simulated any problem in liquid dynamics but I was convinced that waves breaking on the Cretan coast could be simulated using SPH. It seemed to me too difficult to treat a liquid as incompressible and I decided to explore the possibility that slightly compressible fluids could give a good approximation to liquids like water. Incidentally, water is slightly compressible, but with a speed of sound of around 1500 m/s and this was too high for the simulation of a fluid on a macroscopic scale of 10 or 20 km. I therefore gave the fluid an artificial equation of state that was large enough to guarantee, in most cases, that the fluctuations in the density were small. For me small was ~ 1%, and this could be achieved by ensuring the speed of sound was a factor 10 greater than the impact speeds in the fluid dynamics problems we might consider. Apart from that, I used the same algorithm that I used for gas dynamics, with the exception that the astrophysicists calculated the density by a summation over the SPH particles while I found that, for liquids, it was better to integrate the continuity equation. The resulting algorithm was applied to a dam breaking over a triangular obstacle, a bore, and the generation of waves surging up a beach (Monaghan 1994). The resolution was poor but the main features of the flow were correct to within 10%. To end this story we set up a laboratory and studied waves produced by moving bodies and we received a grant for a team to core likely areas on the coast of Crete for evidence of marine inundation. The work was exciting but the results were meagre. Following this we began extending SPH to a wider class of problems including waves breaking on beaches, and waves produced by rigid bodies sliding down ramps (Monaghan and Kos 1999, 2000). This was taken up and applied successfully by Colagrossi and Landrini (2003) and later by Landrini et al. (2007)). Good examples of the application of SPH to problems involving liquids is the work on oil spill over and under booms (Violeau et al. 2007) and sloshing (Souto-Inglesias et al. 2006). It was also immediately clear that SPH could be easily used to simulate problems involving two or more fluids (Monaghan et. al. 1999) as in the simulation of flow into a stratified fluid. During the same period we got interested in the fracture mechanics of materials largely because we wanted to consider geological fractures like those produced by magma beneath volcanoes (Gray and Monaghan 2004). Now we are simulating fracture produced by boat hulls hitting water. Fracture was the focus of the work of Willy Benz who used SPH very successfully to model the impact of asteroids (Benz and Asphaug 1994). When we started we had no knowledge of fracture mechanics, but I was also sure that few (if any) people could simulate the fractures seen in practice. I can still remember being in the Monash library and looking at the several shelves of books on fracture and convincing myself that most of them were either wrong or described methods that could not be used for complicated fracture problems. I still think I was right.

Progress has been made in a number of areas (for a review see Monaghan 2012). The first of these is in modelling surface tension and multi-phase problems (Adami et al. 2010), the most important of which is the combination of air and water as in a breaking wave (Grenier et al. 2009, Monaghan and Raffiee 2013). The mass of the air is negligible but its pressure isn't and that makes air important. The second is the study of the accuracy of SPH algorithms near boundaries (see for example Macia et al. 2011) which shows that improvements can be made using an appropriate mapping of the velocity field of the fluid onto ghost particles in the boundary. The third is improvements in the modelling of boundaries (for example Adami et al. 2012 and Leroy et al. 2014). Adami et al. (2012) use ghost particles with a pressure and velocity interpolated from the fluid particles. The density of these particles is then calculated from the pressure using the equation of state. Leroy et al. (2014) use analytical methods. The fourth improvement is the extension of SPH algorithms to three dimensions. It is ironic that the application of SPH to astrophysics always used algorithms for three dimensions whereas all the early SPH applications to fluids were for 2D. It is one of the pleasures of using SPH that the code for three dimensions is as easy to write as one for two dimensions. However, in the case of nearly incompressible flow, the time steps are small, and the computations in 3D were too time consuming. The situation has now changed with progress being driven by new hardware. Looking back 10 years, we can see that the astrophysicists were using between 105 to 109 SPH particles for their simulations. These simulations required parallel processing units, and there is publicly available software for astrophysical gas dynamics (Gadget) pioneered by Volker Springel. In the last 2 years there have been increasing applications of GPUs (Graphics Processing Units) to SPH problems relevant to Engineering problems (Hérault et al. 2010), and public software (SPHysics) due to Ben Rogers and Tony Dalrymple and their colleagues is now available. This hardware allows ~ 106 SPH particles to be used in hydraulic computations. Finally, it is worth remembering, that SPH is widely used for special effects in movies where its ability to model violent impact with water is appreciated.

Joe Monaghan **is Emeritus Professor of Applied Mathematics in the School of Mathematical Sciences, at Monash University, Australia. He is the author of numerous papers concerned with the development of SPH and its application to astrophysical problems, the motion of liquids and gases, elasticity and fracture, and the dynamics of dusty liquids and gases.**

REFERENCES

S. Adami, X.Y. Hu, N. A. Adams, A generalized wall boundary condition for SPH, J. Computat. Phys. 231, 7057-7075, (2012).
S. Adami, X.Y. Hu, N. A. Adams, A new surface tension formulation for multi-phase SPH. J. Computat. Phys., 229, 5011-5021, (2012).
W. Benz and E.Asphaug, Impact simulation with fracture: 1. Methods and tests, Icarus, 107, 98-116, (1994).
J.P. Gray and J. J. Monaghan, Numerical modelling of stress fields and fracture around magma chambers, J. Volcanology and Geothermal Research, 135, 259-283, (2004).
N. Grenier, M. Antuono, A. Colagrossi, and D, le Touz e, An Hamiltonian interface SPH formulation for multi-fluid and free surface flows, J. Comptat. Phys. 228, 8380-8393, (2009).
R.A. Gingold and J. J. Monaghan, Smoothed particle hydrodynamics: theory and applications to non spherical stars, Mon. Not. Roy. Astr. Soc. 181, 375-389, (1977).
A. Hérault, G. Bilotta, and R. A. Dalrymple, SPH on GPU with CUDA, J. of Hydraulic Res., 48(s1), 74-79, (2010).
M. Landrini, A. Colagrossi, M. Greco, M. P. Tulin, Gridless simulationof splashing processes and near-shore bore propagation, J. Fluid Mech., 591,183-213, (2007).
A. Leroy, D. Violeau, M. Ferrand, and C. Kassiotis , Unified semi-analytical wall boundary conditions for 2D incompressible SPH, J. Computat. Phys. 261, 106-129, (2014).
L.B. Lucy, A numerical approach to the testing of the fission hypothesis, The Astron. J. 82(12), 1013-1024, (1977).
F. Macia, M. Antuono, L.M.Gonzalez, A. Colagrossi, Theoretical analysis of the no-slip boundary condition enforcement in SPH methods, Prog. Theor. Phys., 124(6), 1091-1121. (2011).
J. J. Monaghan, Simulating free surface flows with SPH, J. Computat. Phys., 110, 399-405, (1994).
J. J. Monaghan, SPH and its diverse applications, Ann. Rev. Fluid Mech., 44, 323-346, (2012).
J. J. Monaghan and A. Kos. Solitary waves on a Cretan beach, J. Waterways Ports, Coastal and Ocean engineering, 125, 145-154, (1999).
J.J. Monaghan, R.F. Cas, A. Kos, M. Hallworth, Gravity currents descending a ramp in a stratified tank. J. Fluid Mech. 379, 39-69, (1999).
J. J. Monaghan and A. Kos, Scott Russell's wave generator, Phys. of Fluids, 12(3), 622-630, (2000).
J.J. Monaghan and Ashkan Raffiee, A simple SPH algorithm for multi-fluid flow with high density ratio, Int. J. for Num. Methods in Fluids, 71(5), 537-561, (2013).
A. Souto-Inglesias, L. Delorme, L. Perez-Rojas, and S. Abril-Perez. Smoothed particle hydrodynamics simulation of a tuned liquid damper (TLD) with angular motion, Ocean Eng. 33(11-12), 1462-1484, (2006).
D. Violeau, C. Buvat, K. Abed-Merain, and E. de Nanteuil, Numerical modeling of book and oil spill, Coastal Eng., 54, 895-913, (2007).