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Modeling Water Waves with Smoothed Particle Hydrodynamics

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LONG-TERM GOALS

Smoothed Particle Hydrodynamics (SPH) is a meshless numerical method that is being developed for the study of nearshore waves and other Navy needs. The Lagrangian nature of SPH allows the modeling of wave breaking, surf zones, ship waves, and wave-structure interaction, where the free surface becomes convoluted or splash occurs.

OBJECTIVES

To improve the ability of the meshfree Lagrangian numerical method Smoothed Particle Hydrodynamics (SPH) to be a useful hydrodynamics model for breaking waves and the nearshore zone, particularly for case where spray and splash are important. To utilize the massively parallel graphics processing units on computers to develop the GPU-accelerated model GPUSPH to solve a number of problems relevant to the U.S. Navy. The science objective is to be able to accurately model the complex flows associated with breaking water waves, including instantaneous motions as well as (time-averaged) wave-induced flows, such as undertow, longshore currents, and rip currents.

APPROACH

The approach is based on improving various aspects of the SPH code, including the development of a multi-graphics processing unit (GPU) version of the code (GPUSPH); applying the code to more validation tests; and to examine in some detail new aspects of the model by applying it to different situations relevant to Navy needs.

WORK COMPLETED

- Open source version of GPUSPH released on the web: January 17, 2011
- GPUSPH model was extended to find fluid parameters at fixed (Eulerian) test points
- Further validation of nearshore modeling, including waves, a rip current system and related surf zone circulation using the test points

- Free-surface particle detection implemented to simplify determination of the free surface location

RESULTS

Open source release--the GPUSPH model was released as open source in January after a month long interaction with some of the code developers (Alexis Hérault, Eugenio Rustico) in Baltimore, Maryland. The code, in C++, with test problems, is available at www.ce.jhu.edu/dalrymple/GPUSPH.

Test particles--The Lagrangian nature of SPH acts as an advantage to model problems with large deformations. On the other hand, as the SPH particles (or nodes) are moving with each time step, it is difficult to record the fluid parameters in fixed positions as might be recorded in a field or laboratory experiment. In order to look at time-averaged horizontal velocity profiles and time-averaged water elevations, velocities and elevations are required to be measured at fixed spatial positions.

To solve this problem, the GPUSPH was extended to find fluid parameters at fixed spatial positions (as well on the moving particles). A set of testpoints, which have fixed positions in the computational domain, were introduced. Velocity and pressure at these testpoints are computed as a function of time with the SPH interpolation formula, using the properties of moving particles that are currently located in the neighborhood of the testpoint.

In order to validate the extended model, experimental results of a rip current system (Drønen et al., 2002) have been compared to the numerical results of extended GPUSPH model. The laboratory experiments were done in a 4 m wide and 30 m long wave tank. An idealized sand bar was located on one side of the tank that triggers local breaking, leading to the rip current creation. Figure (1) shows the numerical results. Rip currents, which are strong currents flowing in the oposite direction of water waves, are evident on the right side of wave tank.

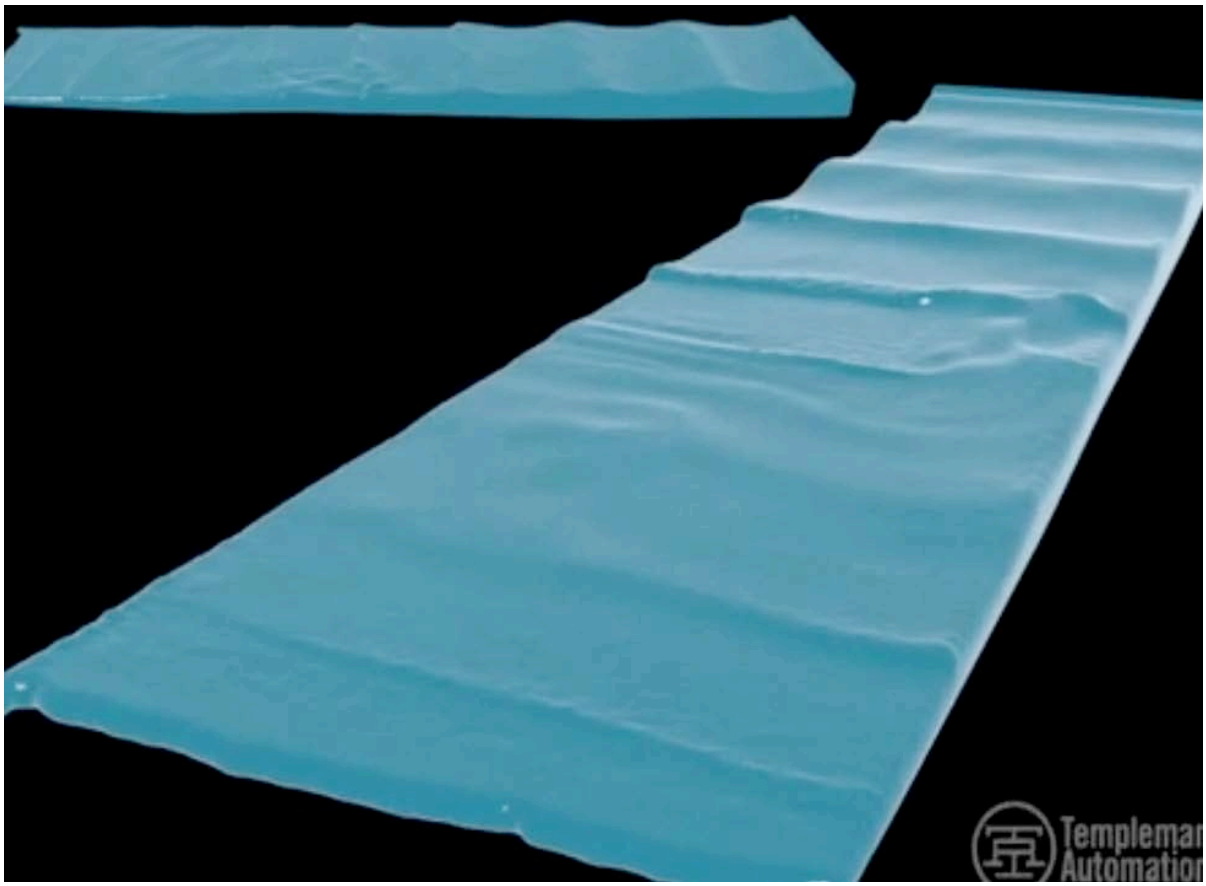

Figure 1. Numerical results of rip current simulation based on the laboratory experiments of Drønen et al. 2001. The wavemaker is located at the upper right, and an idealized sand bar on the left side. In this frame, wave breaking, harmonic generation over the bar, wave refraction, diffraction, shoaling, and wave-current interaction are all visible. Visualization provided by Templeman Automation.

The numerical model is capable of modelling wave-current interaction, harmonic generation (a shallow water nonlinear process), wave breaking, wave diffraction, refraction and nearshore circulations. The rip current system, which consists of (1) an offshore-directed rip current in the channel on the right of Figure 1, (2) a circulation cell over the sand bar, and (3) an onshore oppositely-rotating circulation cell in the bar trough is sucessfully modeled.

Figure 2 shows the mean vorticity, mean horizontal velocity profile and related wave-induced circulation. Here, wavemaker is located outside of the figure to the right and beach is located in the left hand side. In the bottom frame of Figure 2, the mean water elevation is also shown in different parts of the tank. A large portion of the elevation is the set-up on the beach and in the bar trough, incuded by the breaking on the bar. Gradients of the mean water level provide the hydrostatic head to drive the rip current (in the rip channel) and the associated circulation cells.

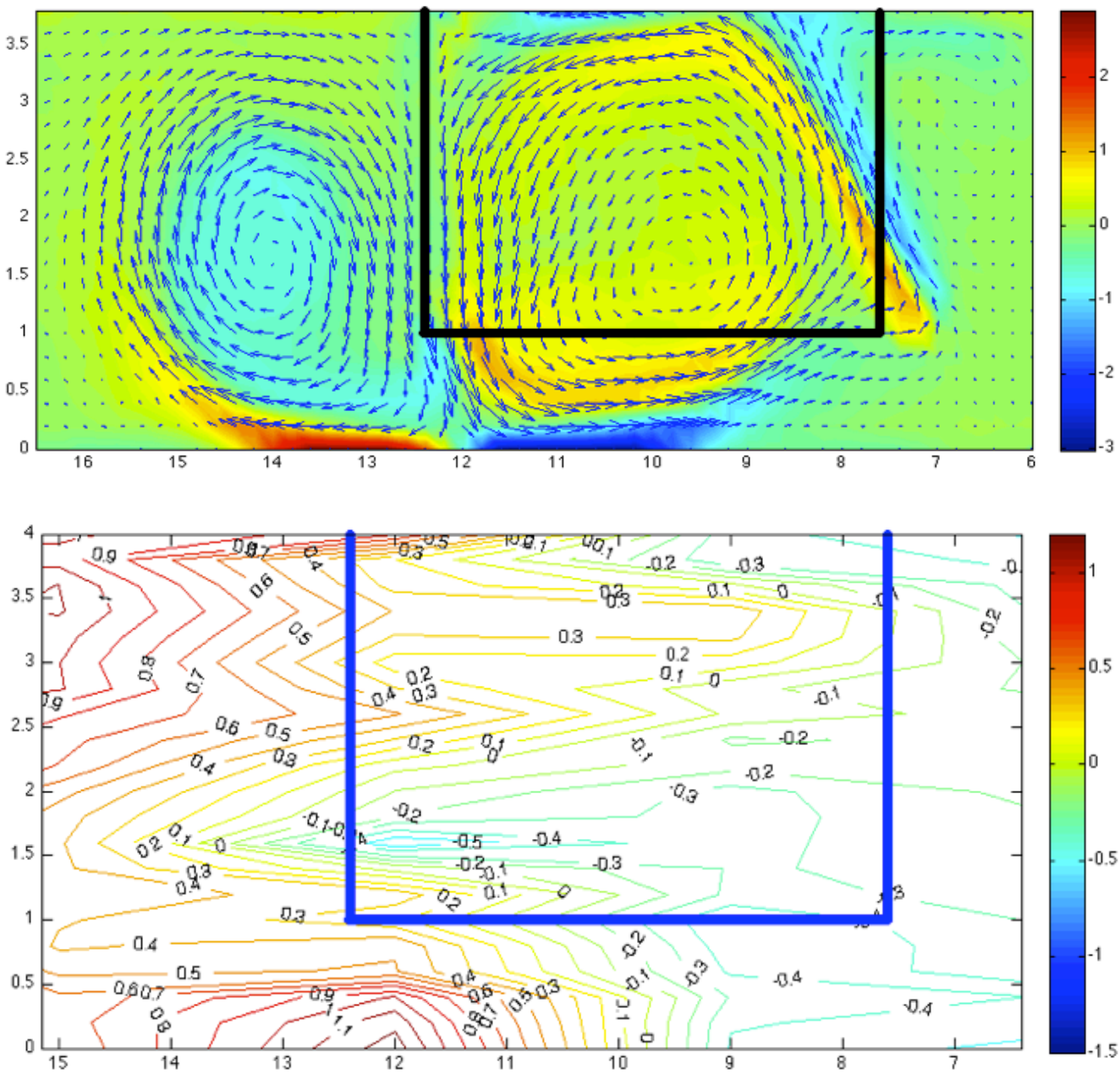

Figure 2. Top: Mean vorticity associated with the wave-induced currents and mean horizontal velocity. Bottom: Mean water level elevations, including the wave set-up.

GPU-SPH is capable of three dimentional analysis of flow which leads to a better understanding of flow structure. Three dimentional velocity profiles in different positions located in rip channel, over the bar and near the beach, are illustrated in figure (3).

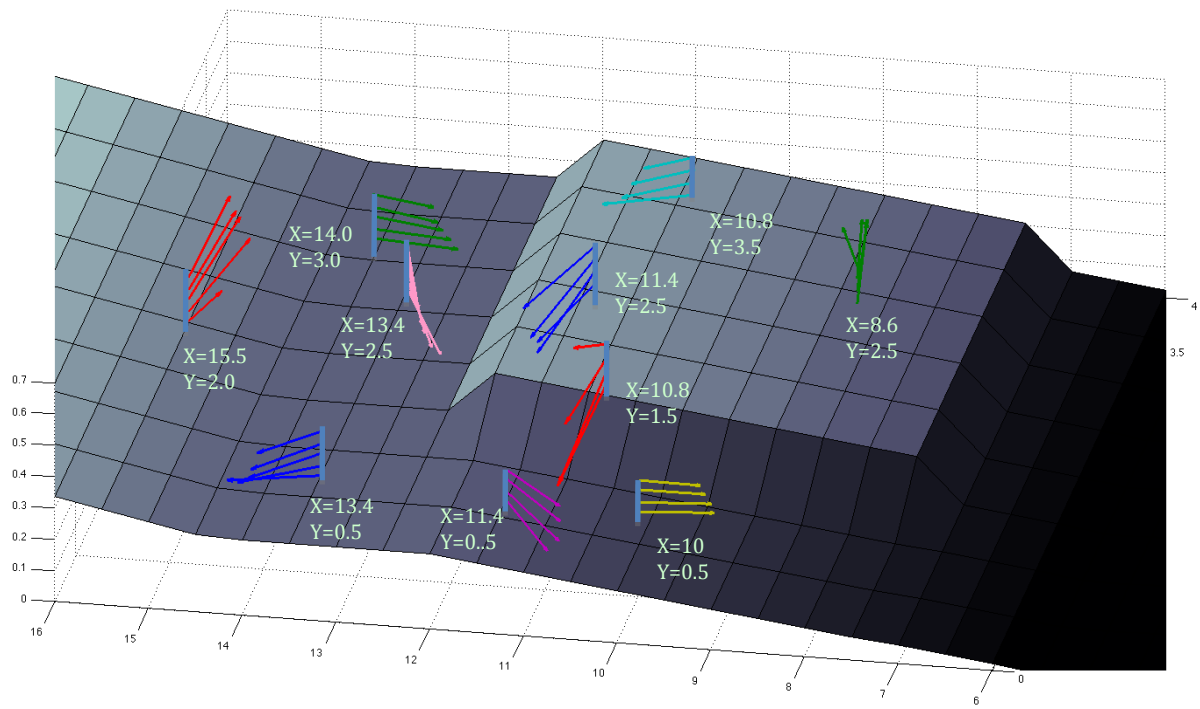

Figure 3. Three dimensional velocity profiles at fixed locations over the Drønen et al. bathymetry

Free-surface particle detection--To study free surface flows and analyze their complex deformations, we need to know which particles are located on the free surface. Free surface detection algorithm that is used here is similar to Marrone et al. (2010) approach and consists of two steps: first, the local normal vector for each particle is computed using gradient of kernel function. In the second step, geometric properties of free surface particles are used for their accurate detection. For each particle a cone is defined with particle's normal vector as its axis and a cone angle that has been set to be equal to $\frac{\pi}{6}$. Then a control check is applied to find whether or not at least one neighboring particle exist in this cone region. If no neighboring particle is found within the cone region, then that particle belongs to the set of surface particles. This control condition is given as:

$$\left[\forall j, \frac{\vec{n}.\vec{r}_{ji}}{r} \prec \cos(cone_angle) \Rightarrow i \in Free_surface_particles\right]$$

where i is the particle of interest, j is its neighboring particle, $\vec{n}$ is local normal vector for particle i and $\vec{r}_{ij}$ is the distance from particle i to particle j. Figure (4) shows a sketch of fluid domain and free surface detection using cone region. Since we are using the gradient of kernel function that has been computed previously in another part of the model, this algorithm doesn't impose a significant increase in computational cost.

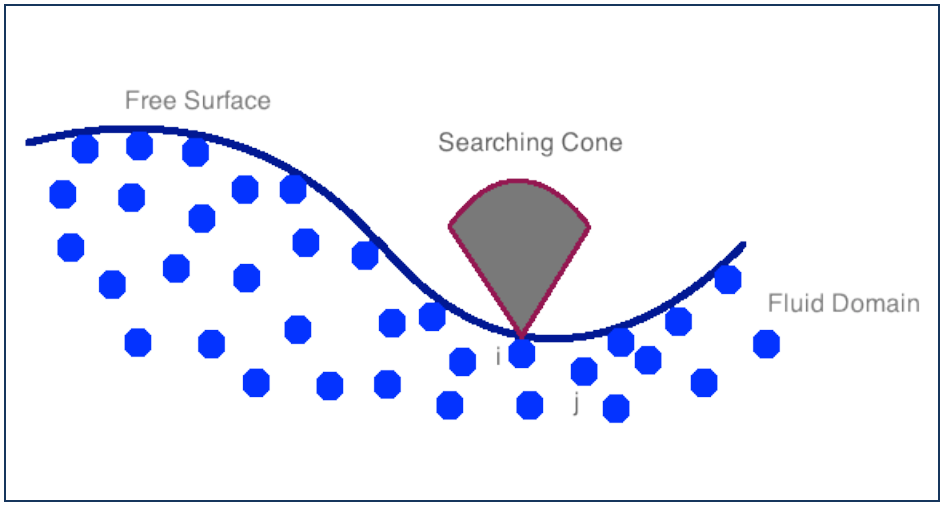

Figure 4. Schematic plan of fluid domain and free surface

The free surface detection algorithm as applied to different cases is shown in figure 5 and 6. Free surface particles are shown in red and other particles are shown in light blue. Note that the model resolution is deliberately low, so that the free surface particles are readily viewed. The first case shows a plunging wave. As it can be seen in the picture, free surface detection algorithm is capable of capturing the cavity that occurs with a plunging wave. The second case shows a dam break problem and the interaction of the waves with a structure. The last case shows an open channel problem with periodic boundary condition.

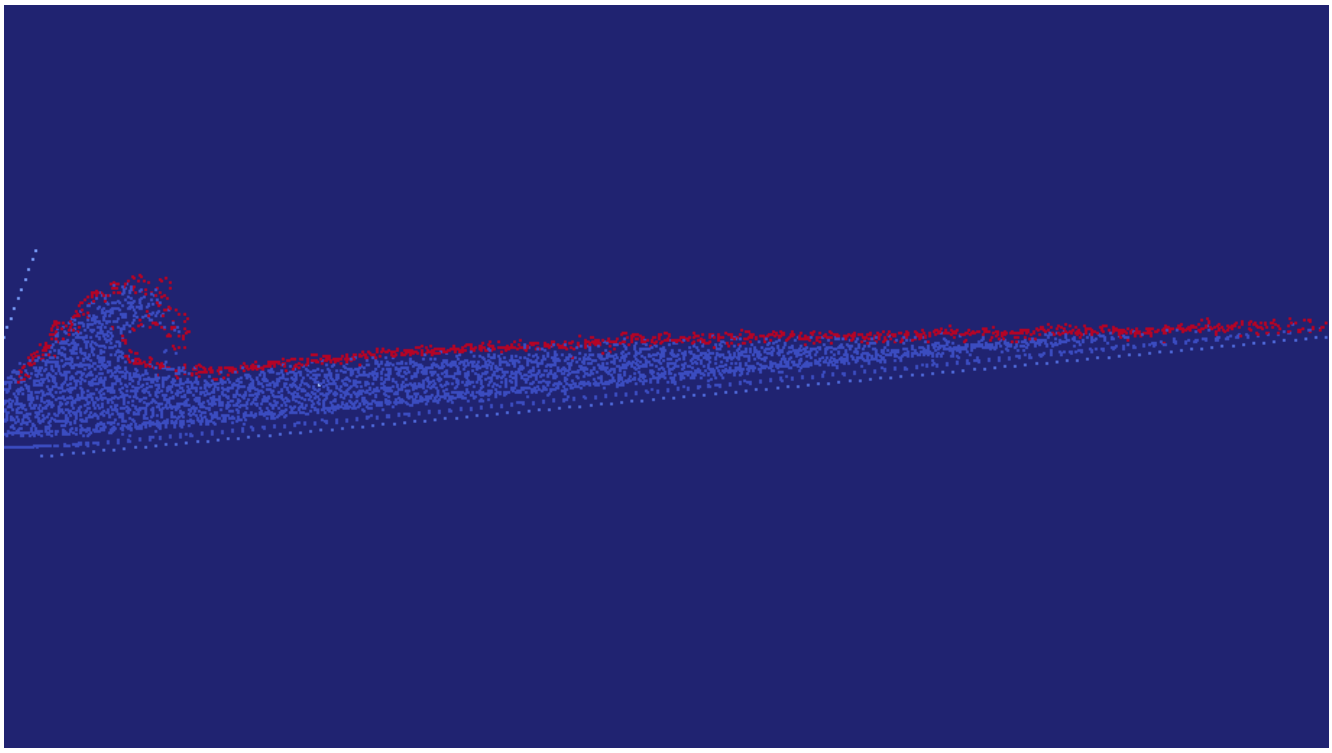

Figure 5. Free surface detection for plunging wave. The irregularity of the free surface particles is due to the low number of particles used to clearly show the free surface particles, and the 3D nature of the irregular free surface as viewed from the side.

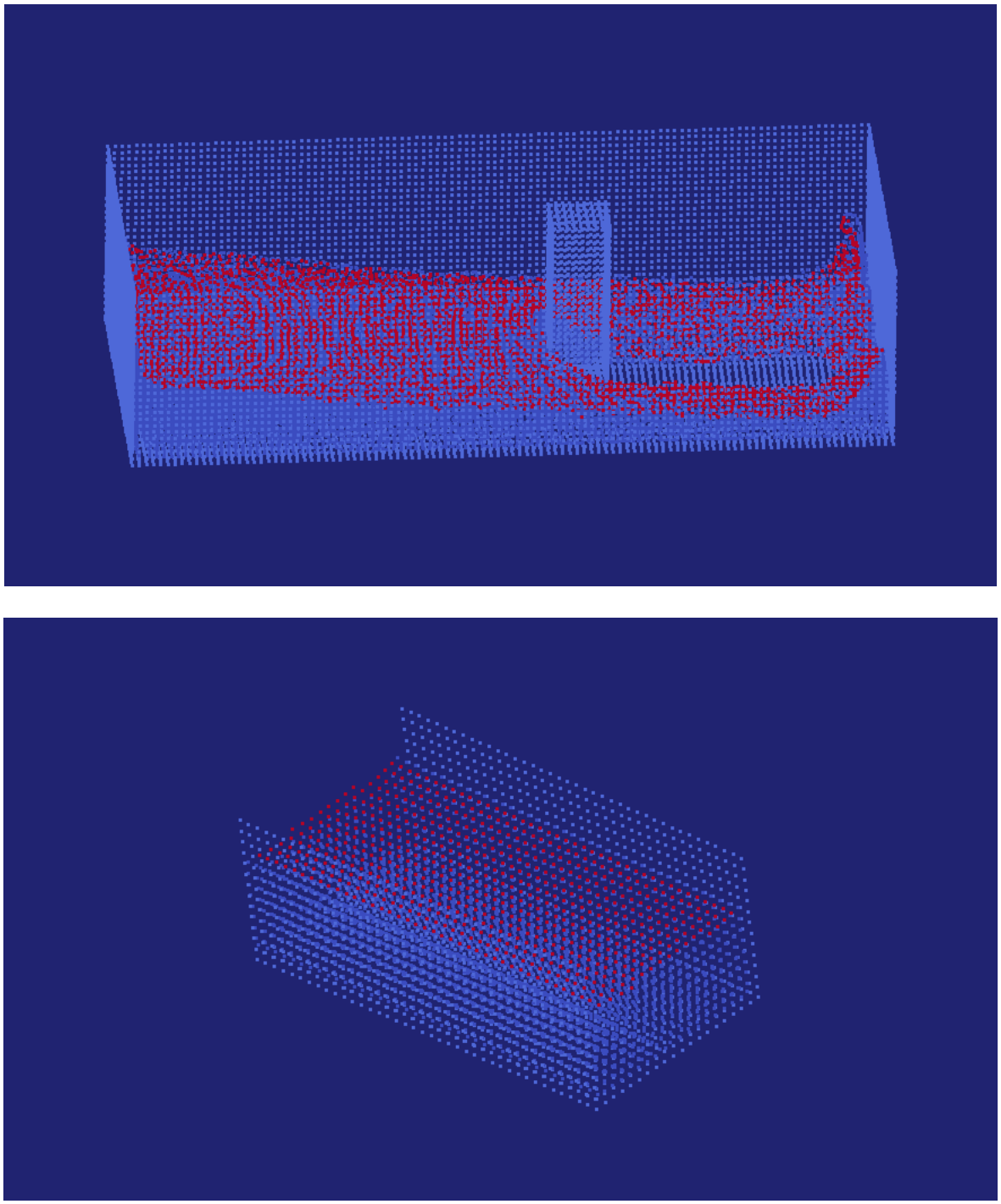

Figure 6. Free surface detection for (a) dam break problem with an obstacle, and (b) open channel flow problem

International Collaborations: We currently have a strong international collaboration in the developer group for GPUSPH with the Istituto Nazionale di Geofisica e Vulcanologia (sezione di Catania), the Università di Catania, Conservatoire National des Arts et Métiers, Paris, for the development of GPU-SPHysics. Dr. Hérault (CNAM and INGV), Dr. Bilotta (UC), and Mr. Eugenio Rustico (UC) are

members of this collaboration. A new collaborative organization is being set up in October 2011 that will include the original GPUSPH developers and EDF R&D (the research and development division of Electricité de France) for the joint development of GPUSPH. EDF has an existing SPH code, SPARTACUS, but is interested in co-developing the GPU accelerated GPUSPH code. It is anticipated that other European institutes will join the effort.

Ongoing efforts—There are three major initiatives underway. The first involves adding the ability to model floating bodies with GPUSPH. This involves determining the forces on an object and then allowing the object to respond to the forces appropriately. The second is lead by Eugenio Rustico, which is the development of multi-GPU configurations of the GPUSPH. This is critical as the GPUSPH code on a single GPU card is only capable of handling 5 million particles in a simulation. JHU is currently completing the construction of a 100 GPU computing cluster, which will permit extensive testing of high resolution GPUSPH simulations. Finally multi-fluid versions of GPUSPH are underway.

IMPACT/APPLICATIONS

Smoothed Particle Hydrodynamics is proving to be a competent modeling scheme for free surface flows in two and three dimensions. As the GPU hardware improves, it is expected that the resolution of SPH will increase tremendously bringing the modeling into realistically sized domains.

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