Levee Breaching with GPU-SPHysics Code

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***Abstract*—A GPU-based Smoothed Particle Hydrodynamics model is used to model the water flooding associated with various types of levee failures. The failures include instantaneous flood wall section failure, a slowly toppling wall, and a dropping wall. The intent of the paper is to illustrate the complex non-hydrostatic flows associated with the levee failures, and their resulting impact on the nearby structures.**

I. Introduction

The failure of levees around the City of New Orleans during Hurricane Katrina turned a bad hurricane into a major urban catastrophe. Although levees would have been overtopped in the eastern portion of the city due to the high storm surge during the storm (leading to local flooding), the major storm damage was due to the levee failures along the Industrial Canal, which bisects the city into eastern and western portions, and the 17th Street and the London Avenue Canals.

The floodwall failures were due to geotechnical failure of the wall foundations, resulting in a horizontal sliding and the overturning of the wall at the 17th Street Canal or simply an overturning as at the Industrial Canal [1]. In many locations, the force of the water was strong enough to move structures from foundations–such as would occur during a tsunami. In the analyses post-storm, the time at which flooding occurred or the extent of flooding by a single breach was important. This flooding of course is dependent on the nature and timing of the breach and the nature of the land over which the flooding occurred.

II. Modeling

A. Flood Modeling

The numerical modeling of floods in rivers has been underway for a long time. However, most of these models are based on solving the shallow water equations or the St. Venant equations, with the underlying assumptions that the flow is hydrostatic, or nearly so. Examples of such models are HEC-RAS [2]. However, there have been very few models that include non-hydrostatic flows and deal with dam breaks and levee breaches. Hesselink et al. [3] examined the historical flooding of a Dutch polder using a two-dimensional hydrostatic flow model. Ying et al. [4] use similar equations for dam and levee breaches along with riverine modeling. Jaffe and Sanders [5] examine the use of engineered breaches as a way to reduce riverine flooding, by diverting water in a breach-like manner into a designed storage area.

Fig. 1. Flow-related damage immediately landward of the 17th Street Canal breach site. In addition to the structural damage, trees were uprooted.

Satter et al. [6] examined via a 1:50 scale hydraulic model of the 17th Street Canal breach in New Orleans various closure schemes for breaches. For example rather than dumping sand bags in the breach site, where the velocities are the highest, they recommended a variety of other options that involved wider ”coffer dams” based on the existing structures in the area.

This paper uses the Smoothed Particle Hydrodynamics methology to examine the dramatic flow near a breach site, where the flow is non-hydrostatic and is dependent on the nature of the breach. The breaches will be due to the failure of a section of the floodwall. Several different breaching mechanisms are examined: instantaneous section failure, basically a 3-D dam break problem; a falling wall section, where the speed of falling is controlled, and a downward moving vertical wall section.

III. GPU-SPHysics

GPU-SPHysics is a Smoothed Particle Hydrodynamics model, programmed in CUDA and running on Nvidia graphics cards (GPUs). It was developed by Herault and presented at the Third SPHERIC meeting in Lausanne [7]. The formulation follows the open-source code SPHysics ([8], http://wiki.manchester.ac.uk/sphysics, which in turn follows the methodology of Monaghan [9]. Examples of some GPU-SPHysics capabilities in the fields of free surface flows and volcanology are shown at http://www.ce.jhu.edu/dalrymple/GPU.

GPU-SPHysics provides the SPH user with a variety of kernel choices (quadratic, cubic, Wendland), kernel gradient correction [10], [11], XSPH [12], and Shepard or MLS filtering, *e.g.*, [13].

A. Model Features

The three-dimensional GPU-SPHysics model (discussed by Herault *et al.* [14] in this workshop) uses an object oriented approach. The model is governed by the ParticleSystem object, which carries out the various tasks associated with SPH, including the neighbor list search, the evaluations of the particle forces in the equation of motion, and then the time-stepping.

A particular problem is developed via the Problem class. As Herault *et al.* [14] point out, "The Problem class provides all the simulation parameters (domain size, smoothing length, kernel type, initial density, coefficients for the equation of state) and options (periodic boundary, variable time step, kernel correction to apply,). In addition it must fill an array with the initial particle positions, velocity and density. This is done by implementing the virtual functions defined in the Problem class." For each of the levee breaching problems, a child of the Problem class object, was created to handle the specific geometry of the wall failure. These objects are Breach, WallFail, and DamBreakGate, which represent the following kinds of failures: an instantaneous loss of a section of the floodwall, a slowly fallling wall that pivots about the bases, and a vertically dropping wall.

For the different problems, several different objects are employed to generate the correct geometry. These objects are either rectangles (Rects), polygons, or cubes. These objects are specified by their dimensions: a point is established for one corner of the object, and then the object is defined by two or three vectors originating at the point. These objects, once defined, permits calls to fill either the object boundaries with particles, or, in the case of a cube, the interior of the cube can be filled with particles.

The particles are of several types. Boundary particles boundary-fixed particles, which interact with the fluid particles via a Lennard-Jones force currently. Moving boundary particles are particles that move in a fixed fashion–say, for a falling wall, all particles move as they are fixed to the wall. For wavemaker problems, these are the paddle particles. Finally, there are the fluid particles, which must obey the equations of motion and conservation of mass.

To develop a problem, an experimental box is defined, which conveniently defines the domain as it has a bottom and four sides. This box can be defined several ways depending on the nature of the problem. A rectangular bounding box with a horizontal bottom is readily defined with the Cube object, and the boundaries are filled with boundary particles. Alternatively, for the case of a sloping beach, the box can be defined several ways, using rectangles. The sloping bottom is an inclined rectangle. The side walls can either be rectangle or polygons, and the end walls are rectangles. All rectangles and polygons then have their surfaces filled with boundary particles.

The intact levee floodwall is simulated by a vertical wall (Rect object) spanning the width of the experimental box. Between this wall and the end wall (located at x=0, on the left), fluid particles fill a cube of similar size, representing the fluid within the levee. Depending on the nature of the problem, the flood wall components are boundary particles or moving boundary particles. For the case of Breach, a section of the floodwall disappears instantaneously. This results in a three-dimensional dam break of finite width. For the case of WallFail, a section of floodwall rotates about its base, tilting from vertical to horizontal in the x direction as a function of time. Finally for the case of DamBreakGate, a vertical floodwall section drops at fixed speed vertically–representing an "erosion" of the floodwall with time.

In some of the examples, structures are placed in the flood plain to be struck and inundated by the flood wave. These structures can be constructed by Rects for the case of walls, or by Cubes, in the cases of buildings. These structures are easily added to the code: only three lines of code are used for each structure: the first locates the cube, the second assigns the appropriate mass to particles that comprise the cube, and finally the third line of code places boundary particles on the faces of the cube.

IV. Results

A. Overtopping

As water begins to rise in the levee/floodwall system, wind waves, whipped up by hurricane force winds, impact the floodwalls and reflect. As the wave height and water levels increase, the waves begin to overtop the walls. In this case, we model the system with a wavemaker at $x = 0$ to simulate the wind waves (presently with a single frequency) and a vertical wall is located prior to the other end of the tank. The space between the wall and the end of the tank serves to capture the overtopping water.

In Figure 2, a wave generated by the paddle at the left side of the figure impacts the flood wall and flows over the top. In Figure 3, the second wave, again generated by the wave paddle, but influenced by the reflection of the first wave from the floodwall and the wave paddle, also overtops the flood wall, adding volume to the catchment area. Subsequent waves overtop less as the water depth in the "levee" system has been decreased by the overtopping volume losses. Finally no more overtopping occurs.

This example illustrates the potential of using GPU-SPHysics to determine overtopping volumes for different size waves and water levels. Realistic flood wall cross-sections or levee cross-sections can be readily created using Rect objects or Cubes.

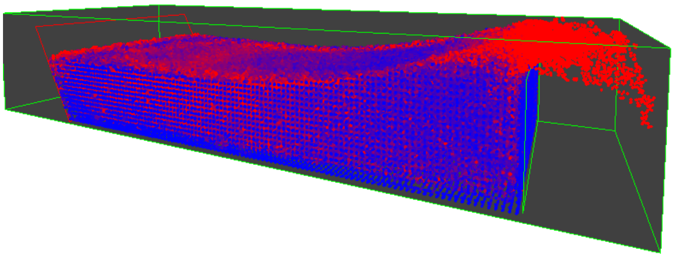

Fig. 2. Flood wall, at incipient overtopping by a large wave. The fluid is color coded to represent velocity, with the highest velocities occurring in the overtopping jet.

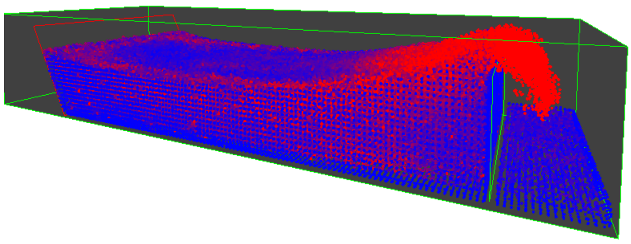

Fig. 3. A second wave overtopping the floodwall. The different trajectory of the overtopping jet a result of the influence of reflected waves in the levee system.

B. Instantaneous Floodwall Section Failure

The problem Breach handles the 3D dam break problem. A section of flood wall falls instantaneously creating a flooding event that flows radially into the flood plain from the breach site. Figure 4 shows a Breach example. The modeled breach can be considered as reflected about the far wall. In this case, the use of cube objects to represent structures is shown, with three "houses" added to the dry upland. As the water flows from the levee, there is a jet that flows in the x direction, impacting the first structure and being deflected into the air. As the flow continues, it creates a run-up jet against the second structure that is ultimately deflected into the air, and then finally the flowing water impacts the experimental sidewall, which can be considered a plane of symmetry for periodic breaches. Flow occurs between the structures at later stages of flooding.

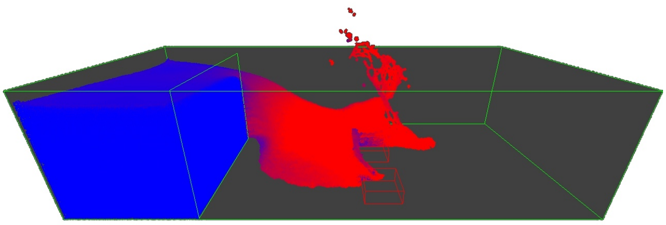

Fig. 4. Three dimensional dam break, with the flood flow striking three structures. At the depicted instant, the first structure closest to the jet center line, is completely overwashed and the jet is deflected into the air. Flow is occurring between that structure and the next. Run-up on the second structure is occurring.

C. Falling Floodwall Section

In this problem, WallFail, a section of the levee floodwall fails at a given speed, by tipping over into the flood plain. The width of the section, and the speed of failure affects the nature of the resulting flooding. Figures 5 and 6 show two stages of flood wall failure. At first, the flow out of the levee system occurs laterally from the gap opened near the water surface by the rotating wall. Not until the top of the wall has rotated below the instantaneous water level in the breaching section does water overtop the failing flood wall. In Figure 5, there is a splash shown, which occurred as the flood wall failure first occurred and some water hit the failing wall and splashed over. This problem is difficult to model at low resolutions (with large SPH particle size) as the particles can not squeeze through the opening gap in the flood wall, until that gap exceeds the particle size (as fixed by the smoothing length). Clearly water should be leaking as soon as the gap opens, not when it is wide enough for the particle to fit through.

The lateral flow from the failing flood wall lands directly at the base of the floodwall, flowing along the wall, which potentially could lead to scour at the base of the wall, undermining the lateral stability of neighboring sections.

In Figure 6, the flow out of the levee system is beginning to overtop the failing wall section as well as flowing out the gap.

D. Dropping Floodwall

The problem DamBreakGate models a floodwall section that drops vertically with time, which might represent an eroding section of a wall or a weir gate. The problem consists of including two fixed floodwall sections to comprise most of the levee and then a movable floodwall section (here located in the center of the domain that drops with a fixed velocity as the problem proceeds). Of course this velocity could be variable with time, and problem could be made more sophisticated by using three sections: the dropping section teamed up with two horizontal sliding sections so that the flow area of the flood wall failure increased both in width and depth with time.

Figure 8 shows flow over the weir section using a model of only 163,000 particles.

V. Conclusion

GPU-SPHysics, with its object oriented programming and use of the GPU for computation is readily used to do complex flow situations, such as floodwall failures in a reasonable amount of time, due to the massively parallel graphics card computation power. The existing code can be easily modified to treat a variety of problems, based on its abilities to including moving boundaries and to treat non-hydrostatic flows.

The nature of the flooding from a failing floodwall depends on the nature of the breaching. If the wall falls instantaneously, there is a very strong flow directly in front of the breach site. Maximum hydrodynamic impacts occur. For a slowly falling wall, the flow exits through the growing gap in the wall laterally, which reduces the hydrodynamic impact on

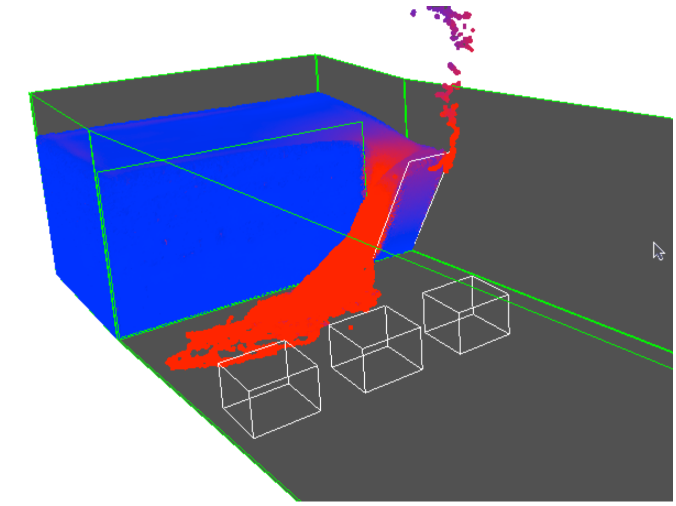

Fig. 5. Failing floodwall section, early stages. Note that the flow is alongside the levee and that there is an initial spray off the top of the falling wall.

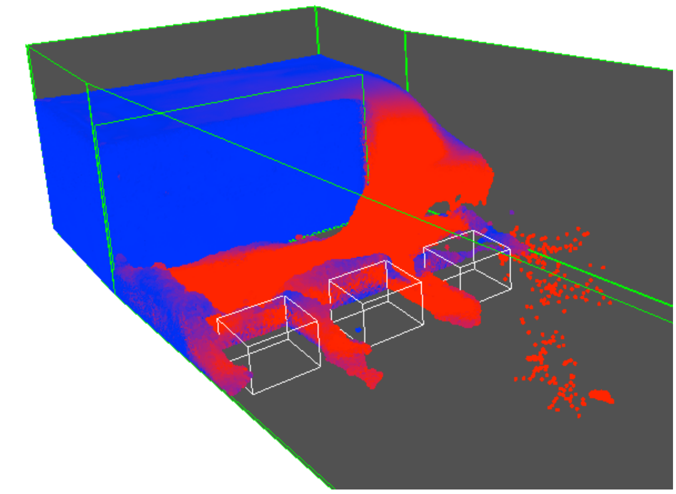

Fig. 6. Failing floodwall section. Flooding occurring between the homes. Note the run-up on the front of the homes.

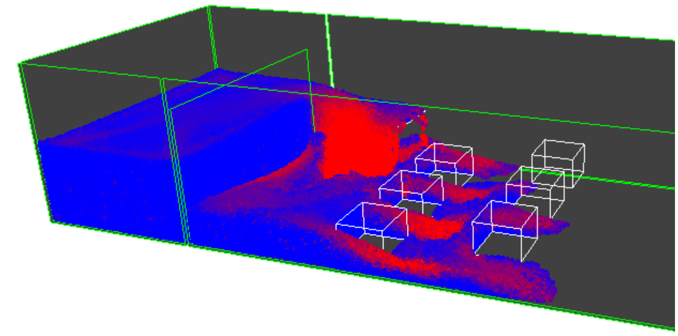

Fig. 7. Failing floodwall section, with six structures, which are located in a staggered pattern so that the flow can not go directly through the structures.

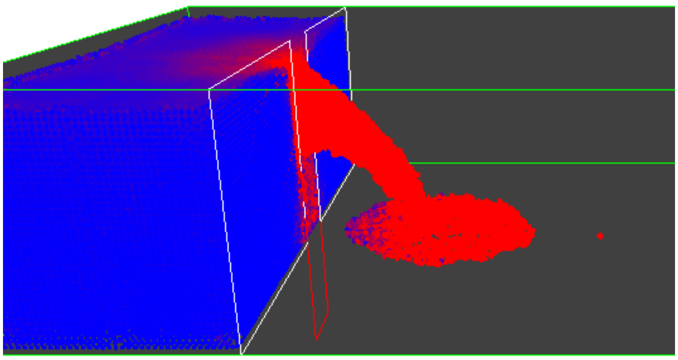

Fig. 8. Dropping floodwall section, showing the weir behavior of the flow from the levee.

nearby structures, but could lead to erosion at the base of the floodwall.

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