SPH on GPU for burst debris flow

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I. PROPOSAL

For a number of important geophysical problems we propose a model development based on a modern particle solver (SPH) for the continuum mechanics equations and to be implemented on the massively parallel hardware recently made available on commodity GPUs through the CUDA interface. For the first time stream processing is available to the model developers, promising 10~100-fold increase in computational power. Even more significant progress has arisen from modelling ideas, particle solvers in continuum mechanics. Where applicable/possible we may perform the comparison with the conventional mesh-based CFD methods (what's Delft3d?) and GPU vs. CPU becnhmarking.

II. WHAT IS SPH

"Smoothed particle hydrodynamics (SPH) is a method for obtaining approximate numerical solutions of the equations of fluid dynamics by replacing the fluid with a set of particles. For the mathematician, the particles are just interpolation points from which properties of the fluid can be calculated. For the physicist, the SPH particles are material particles which can be treated like any other particle system... and may approximate the molecular system underlying more fundamentally than the continuum equations" **?**]

While physists have been validating and improving the main postulates of SPH methods, the application scientists and engineers have welcomed a new mesh-free method in their toolbox. But one community that is really embraced SPH is CG/VFX, because SPH scales up very well from real-time to off-line simulations of fluids. The first realizations of SPH fluid solvers on GPU have appeared in the commercial PhysX and academic groups. The graphics community appears to be one of the locomotives of applying SPH approach to the complex materials and mixtures, through the hybrid methods of SPH+SPH, SPH+DEM, SPH+gridCFD.

- ✓ SPH particles are not the actual grains/molecules. They are material points representing some mass of fluid.
- ✓ SPH is not a molecular simulation or DEM, so there are no inter-particle forces, so the viscosity, turbulence, critical yield stress will have to be accounted for "artificially" from the the corresponding continuum mechanics

✓ SPH is a numerical solver

✓ SPH is a particle dynamics

✓ SPH is a family of methods

  - 2D or 3D
  - various continuum fluid equations to start with
  - the choice of smoothing kernel and the rqadius
  - Boundary conditions treatment.
  - Free surface or bulk
  - Multi-fluids

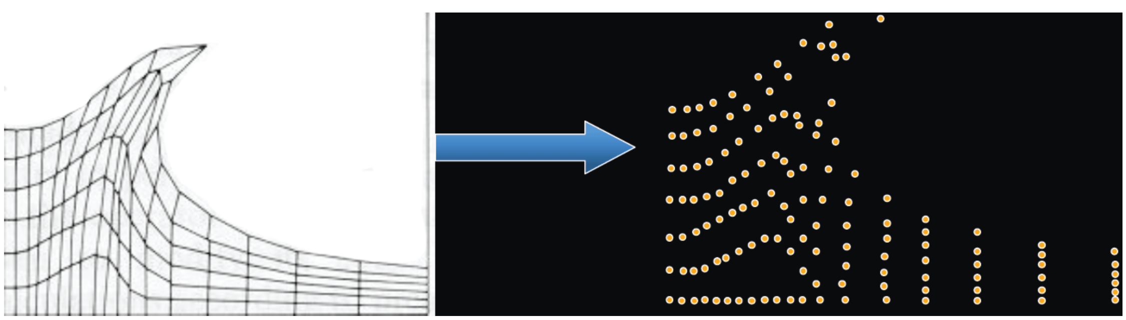
Better than the mesh-based CFD (such as FDM or FEM) at

✓ large deformations

✓ complex and dynamic geometry

✓ advanced materials, nonlinear material behavior, discontinuities and singularities, melting and freezing.

✓ flexible sampling, in contrast to the process of generating finite element meshes whioch may be more difficult and expensive than the remainder of analysis process.



Other attractive features of SPH

✓ Bridges the gap between the continuum and fragmentation in a natural way.

✓ Physically based approximation. Advection is treated exactly. Conservations laws are obeyed. Falls under the broader area of the statistical mechanics of particle systems. Complex physics may be incorporated into the formulation relatively easy.

✓ Accuracy. The motion of a continuum can be represented with very high accuracy by simulating the advection of an increasing large number of such particles. Resolution (h) can be made time and/or location dependent.

- ✓ Naturally allows complex deformable boundaries.
- ✓ A wide range of problems can be modelled: interaction of several fluid phases (different sets of particles, interfaces are trivial); free-surface flows, compressible or incompressible, viscous or inviscid, Newtonian or Non-Newtonian, turbulent or laminar; gravity, shear flow and other external fields; fractures and damaged solids.
- ✓ Computationally effective: only where the matter actually is.
- ✓ Parallel code implementations are available.
- ✓ One of the hottest current topic of research in numerous fields: engineering, environmental, and physical sciences.

Development of modelling tools for geophisical flows using advances in particle-based method

III. MODELLING CATASTROPHIC GEOPHYSICAL FLOWS

What are the model contituents in simulating the fluid flow throughout the event chain of a {failure, breaking, breach, explosion, landslide} of a {dam, ice, levee, coast, slope} caused by {melting, erosion, shock wave, flooding, earthquake} leading to {fragmentation, collapse, debris flow, massive sediment transport, flooding in populated urban environment, damage to 3D constructs}.

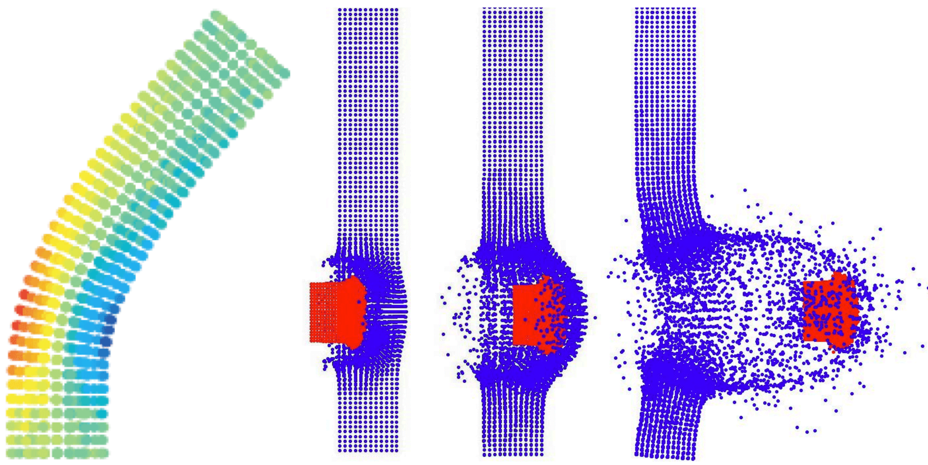
A. Liquid phase: water and dissolved fine debris

One of the main test cases of SPH is the dam break flow, meaning the flow after the release from initial conditions, with the confining dam suddenly dissapear.

The water should be properly "calibrated" to account for the fine debris and sediment it carries along, the main errosive force.

B. Solid phase: 3D constructs, their fracture and fragmentation

The fragments become debris in our two-phase SPH simulation. The same particles cemented into dam. How exactly they used to be we bound? Simply by friction, unyielding to stress below the yiled stress. plastic flow stress. We can control what stress teh dam can sustain.



C. Solid phase: debris and sediment

Let us look at some pictures.

1. Landslides


2. Debris flow deposit


Next, let's look at some drawings.

✓ Debris represents loose unsorted material of low plasticity

✓ It is a mixture of sand, gravel, cobbles, and boulders and can contain organic material (logs, tree stump and tree trunk).

✓ Mud is defined as a soft, remoulded clayey soil whose matrix (sand and finer) is significantly plastic and whose liquidity index during motion is greater than 0.5 (?)

✓ Debris flows are composed of water and debris (solid particles)

✓ The solid particles can be classified in two groups:

✓ fine particles (clay, silt and sand) and

✓ coarse particles (gravel, cobbles, boulders and organic particles too)

✓ Debris flows and mudflows have more or less the same water concentration but they differ in the solid particle size.

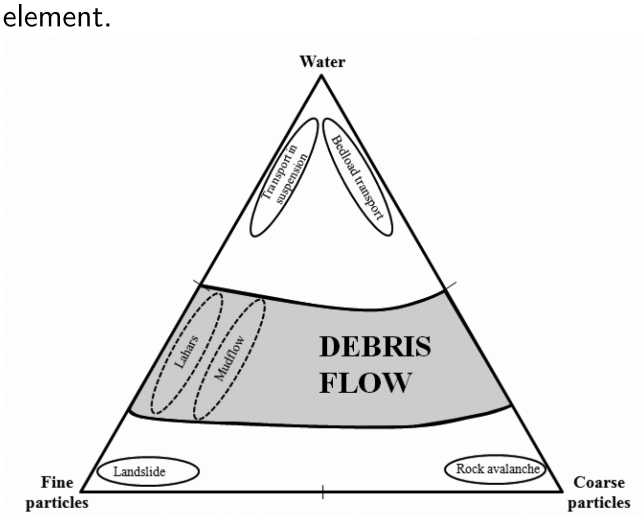
✓ Solid particles of a debris flow are coarser than those of mudflow or lahars. Debris flows and mudflows are mixture of water and fine and coarse particles.

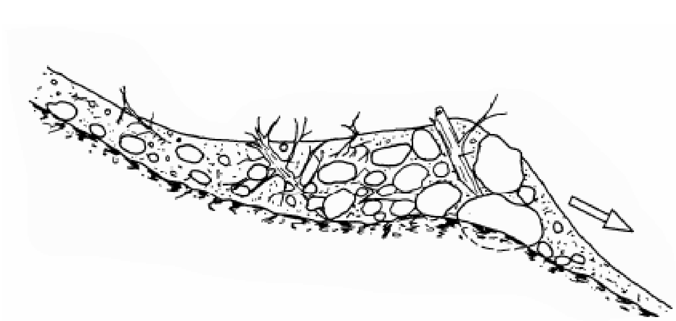
✓ Mudflows can be defined as a fine-grained debris flow

✓ If it derives from volcanic sources, it is called lahar.

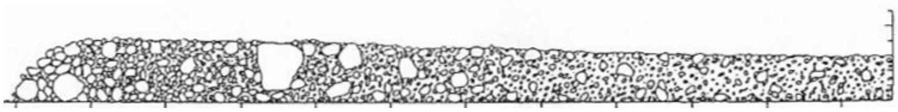
✓ Boulder diameters go up to a few meters. Generally boulders look suspended in the mass.

Compositions can be represented in an equilateral triangle. Each corner represents an element (water, fine particles, coarse particles), and each side a binary system. Ternary compositions (like debris flow) are represented by points within the triangle, the relative proportions of the elements being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element.





This diagram shows that the proportion of solid particle, in a debris flow, is bigger than 50 %. The difference between lahars, mudflow and debris flow is well represented: Solid particles of a debris flow are coarser than the one of mudflow or lahars. Finally, composition of debris flow can be compared to others natural hazards composition (as landslide, bedload transport. . .).



IV. SPH MODELLING OF DEBRIS FLOW

A. Particle size

Particle size. Although SPH allows dynamically variable particle size just allowing adaptive sampling, it is not too straighforward to sort such particles into spatial domains for parallel processing. Besides, there will always be the lower limit for the particle size. In a macroscale geophysical fluid modelling, we neither want to simulate water molecules, nor the tiny sand grains. We begin by choosing just one particle size for both liquid and solid phases. These particle will therefore carry different mass.

How may types of particles. Two types of particles: liquid and possible large solid debris. Liquid particle will represent the whole range from the clear water to the mud flow. This is achieved by varying the concentration of dissolved sand.

Sub-particle solids. Each liquid particle's mass and viscosity will reflect the fine sediment concentration. The sediment concentration is naturally advected with the host particle. However some inter-particle transport should be supersimposed on the particle system: settling, diffusion, and deposition. Erosion will be the source of for the fine sediment concentration increase. Erodible points will be the bed boundary particles and solid particles (solid particle clusters).

Supra-particle clusters, breaking. Each solid erodable particle can be initially a prt of a larger local cluster to represent big solid constructs. The clusters are to be broken above critical shear stress.

Supra-particle clusters, coalescence. Cohesion or solidification can be studied by allowing the liquid particles to coalesce into larger clusters when the sand concentration is within some cohesion interval (wetting when adding water to the pure sand? making clay by adding sand to water? Which fluids cannot be described by just increasing the viscosity and have to be modelled by clusterization?)

B. Sub-particle suspended sediment and muddy fine debris flow

C. Intro

We can identify several substances in the aforementioned catastrophic geophysical flows: water,solid dam (concrete, etc.), large debris, small debris and sediment which is entrained and eventually adds to the movable bed, the bedload (bedload), suspended sediment (sand, fine debris), and fixed bed boundary (what's the proper name). In our physical model we will consider three phases: water, debris, and "sand" (sub-particle sediment fraction). They are described by two SPH particle sets, liquid and solid, corresponding to water+sand, and debris+sand. The pressure on the free surface and fixed bed paricles will close the boundary conditions.

Sand is attributed to each particle, either liquid or solid, as a scalar concentration to be governed by an advection-diffusion transport equation and transported between particles in donor-acceptor scheme. The sand movement will be different in the fluid and in the movable bed. In the latter sand is considered as fluid flow through porous media with the corresponding transport relation which is still sampled at the location of large particles. Sand should be able to find its way all the way to the soil (fixed bed). When sand reach the fixed bed particles, it will be deposited as mud elevating the fixed bed particles accordingly. Conversly, the fixed bed can be allowed to be slowly eroded by moving bed depending on the local stress, giving back some sand.

Free-surface fluid simulation in the SPH is well established (ref. to Monaghan). In fact, fluid flow following a dam release is a common test case for SPH fluid model developments, see Spheric examples.

Some results on SPH that are or may be relevant to debris flow are available (2D SPH, 3D SPH with dissolved sediment, CG sand not exactly).

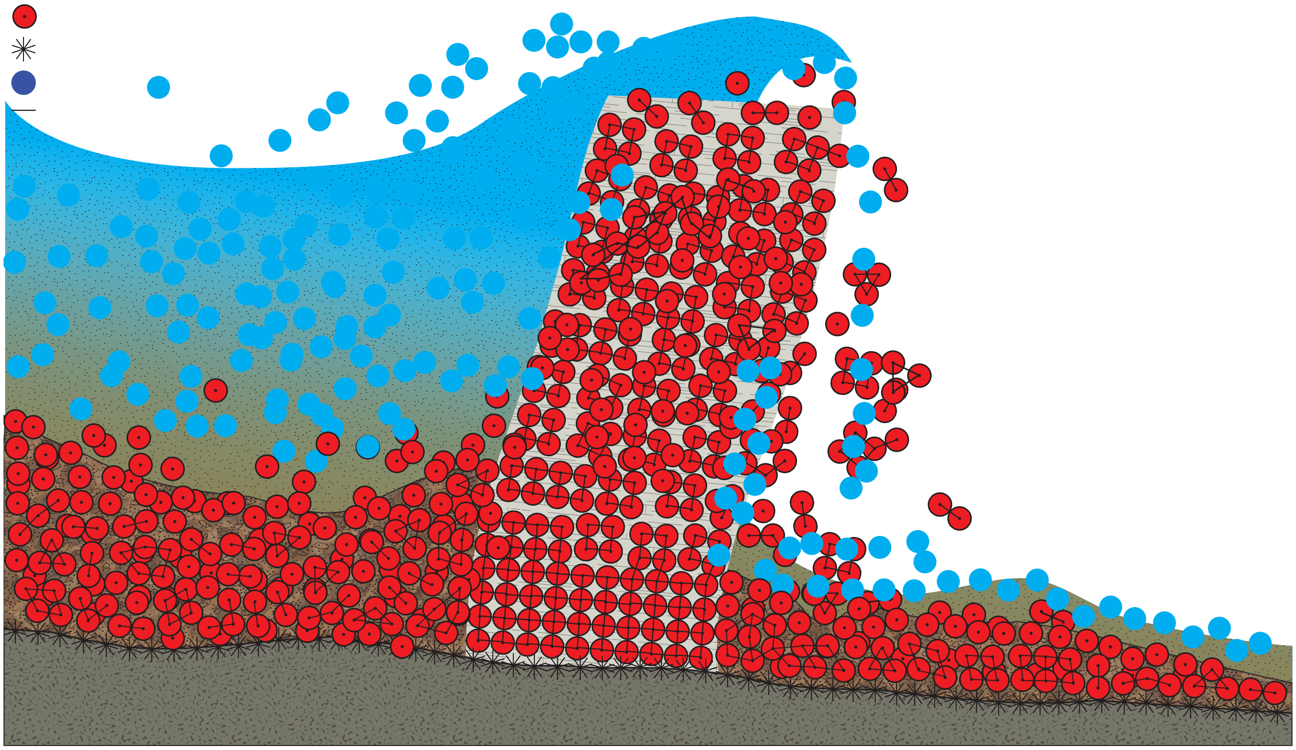
If we introduce the idea of solid clustering (particles rigidly interconnected and moved as whole in translation/rotation) into debris flow we can simulate large fragments. Moreover we can consider the whole dam before breakage as one big solid cluster, to be broken into fragments when local stress exceeds a yiled stress of the material.

Why not DEM? SPH is a discretization of continuum dynamics and contituent equations. It requires a continuum model first, for example the stress tensor and material values. Otheriwise one would have to resort to a real particle methods such as DEM. The ultimate reductionist particle method in classical statistical physics would be molecular dynamics, where the atoms interact via stiff repulsive and slightly attractive Lennard-Jones potential. The DEM particles will provide the microscopic (or mesoscopic) expression for the stress tensor and other continuum thermodynamic notions. However, with the excpetion of MD when the particles represent actual atoms, DEM particles usually represents much larger masses, which may prove controversial.

SPH-DEM hybrids have been reported when some inter-particle interactions have to be introduced into what otherwise would be multiphase SPH in order to stabilize some structures or imitate the surface tension.

In our model the solid-liquid system could be described in a hybrid SPH-DEM method, where the solid fragments are described by as ensemble of DEM particles held together by spring-like potentials. Such potentials would be much stiffer compared to the depression/compression interactions in the surrounding SPH and would require a smaller time step to integrate, calling for a multi-time-step SPH-DEM algorithm.

As we will be working with masses of substance, be it litres of water or kilograms of debris, we can use their contituitive relations and material properties and describe them in a pure multi-phase SPH. The solid clustering methods mentioned earlier provide the missing link to simulate dynamic debris of different sizes and shapes in SPH framework.



V. GPU

But an example of stream hardware, just as CUDA is an example of stream processing API to GPU

VI. POSSIBLE APPLICATIONS

evaluation of the hazard and risks associated with catastrophic geophysical fluid flows in the context of the world's rapidly deglaciating mountain environments and technological failures (e.g., man-made dam bursts/levee breaches).