Direct Numerical Simulation of Particle Erosion

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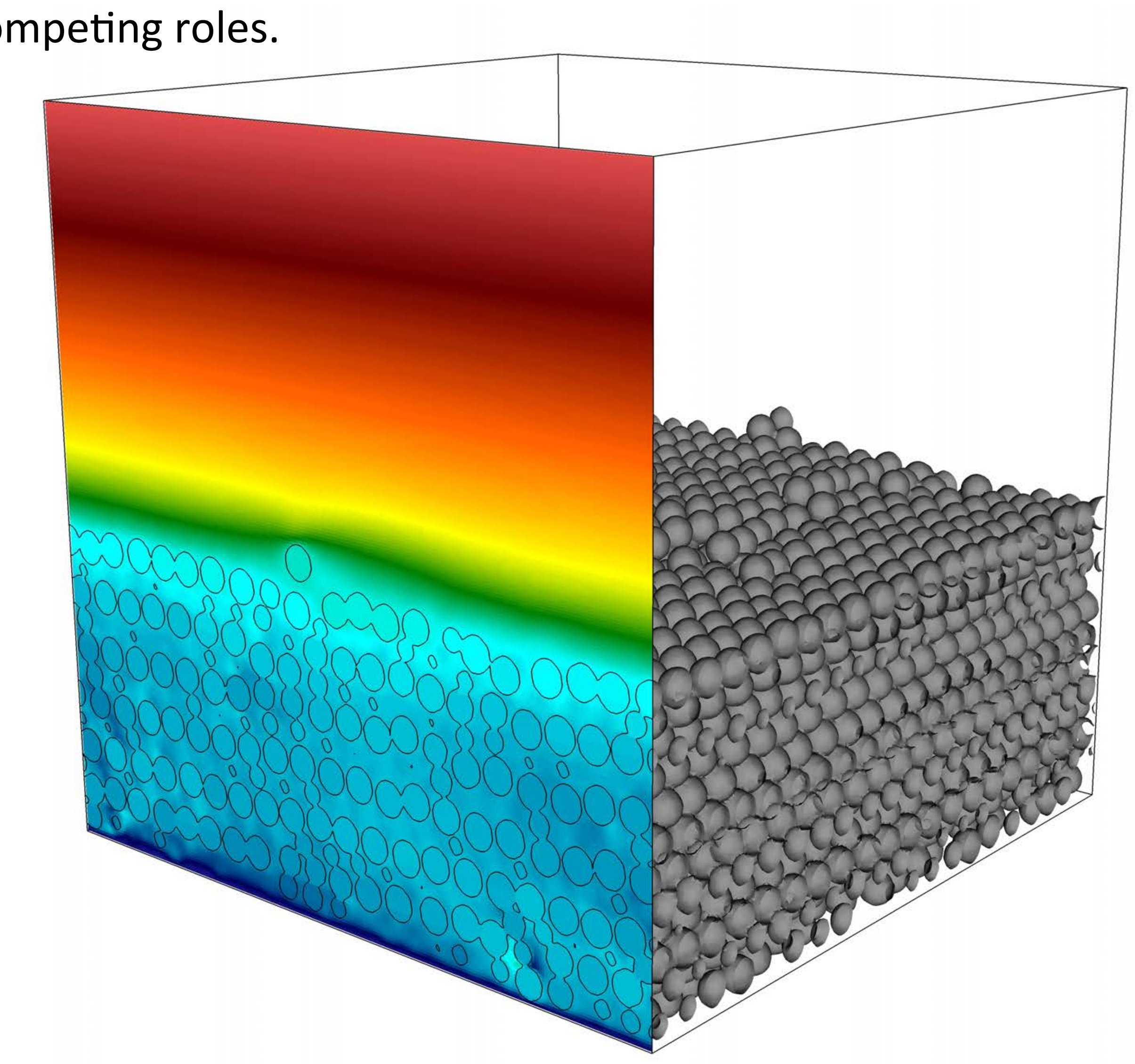
Research Objectives

Turbidity currents, or underwater avalanches, represent an important class of geophysical phenomena. Transporting up to hundreds of cubic kilometers of sediment, they are the main mechanism by which deep ocean sediment deposits form, making them a major research interest for oil exploration.

Computational fluid dynamics (CFD) codes such as the code TURBINS developed in our research group[1] allow us to understand the behavior of these turbidity currents and the deposits they form. However, in order for these codes to be accurate, we need to understand the interactions between the current and the sediment bed, where erosion and deposition play competing roles.

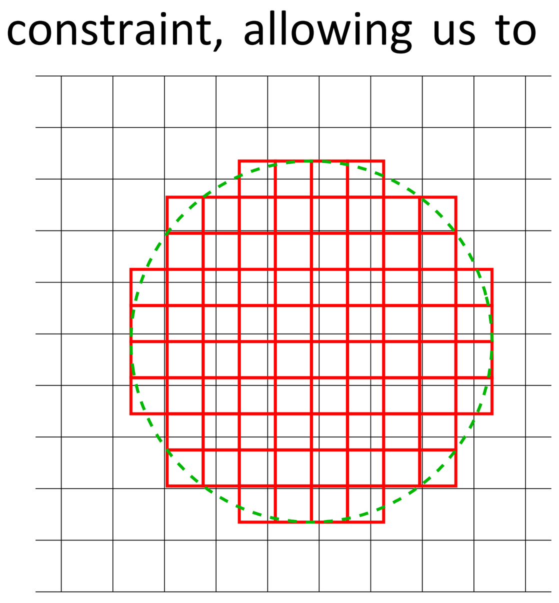


Our objective is to build a CFD code to simulate particle-fluid interactions, which will allow us to observe the micro-scale erosion of a sediment bed. We would like to gain a better understanding of bed-load transport by discovering physical mechanisms, rather than using empirical correlations.

Research Methods

In order to simulate the interactions of thousands of particles within a fluidized bed, we utilize the following methods:

- The distributed Lagrange multiplier (DLM) method of Sourabh Apte et al.[2] treats the entire domain as a fluid, enforcing rigid body motion within the particle domain as an additional constraint, allowing us to efficiently solve for the solid-fluid coupling.
  - Treat the particle (green) as a group of material volume elements (red cells).
  - Interpolate quantities (e.g. density, velocity) from the Cartesian fluid mesh (black) to the material volume mesh (red) using a Dirac delta function.



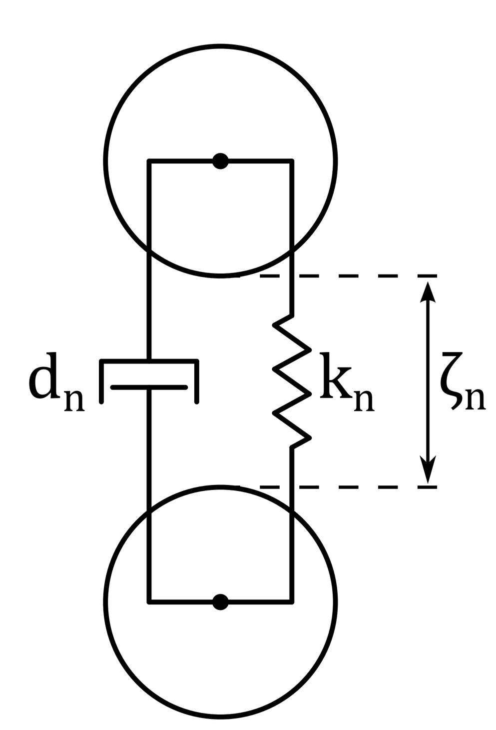
- The Adaptive Collision Time Model (ACTM) of Tobias Kempe et al.[3] uses Hertzian contact theory, but lengthens the duration of particle contact to several (e.g. 10) fluid timesteps. This method allows for accurate collision modeling for large timesteps.
  - Normal force is modeled as a spring-damper system

$$F_n = k_n |\zeta_n|^{\frac{3}{2}} + d_n \frac{\mathrm{d}\zeta_n}{\mathrm{d}t}$$

where k_n and d_n are tuned in order to produce the correct exit velocity of the particles for a given restitution coefficient e.

  - Tangential force is modeled using the Coulomb friction law.

$$F_t = \mu_f F_n$$



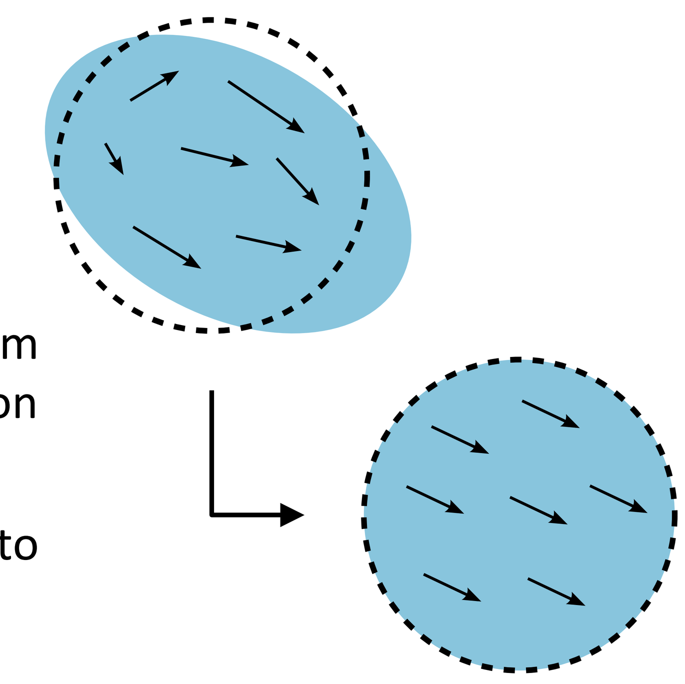
Implementation

1. Project particle density onto fluid domain using the local grid volume fraction.
2. Solve the Navier-Stokes equations over entire domain

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = \nabla p + \mu\nabla^2\mathbf{u} + \rho\mathbf{g}$$

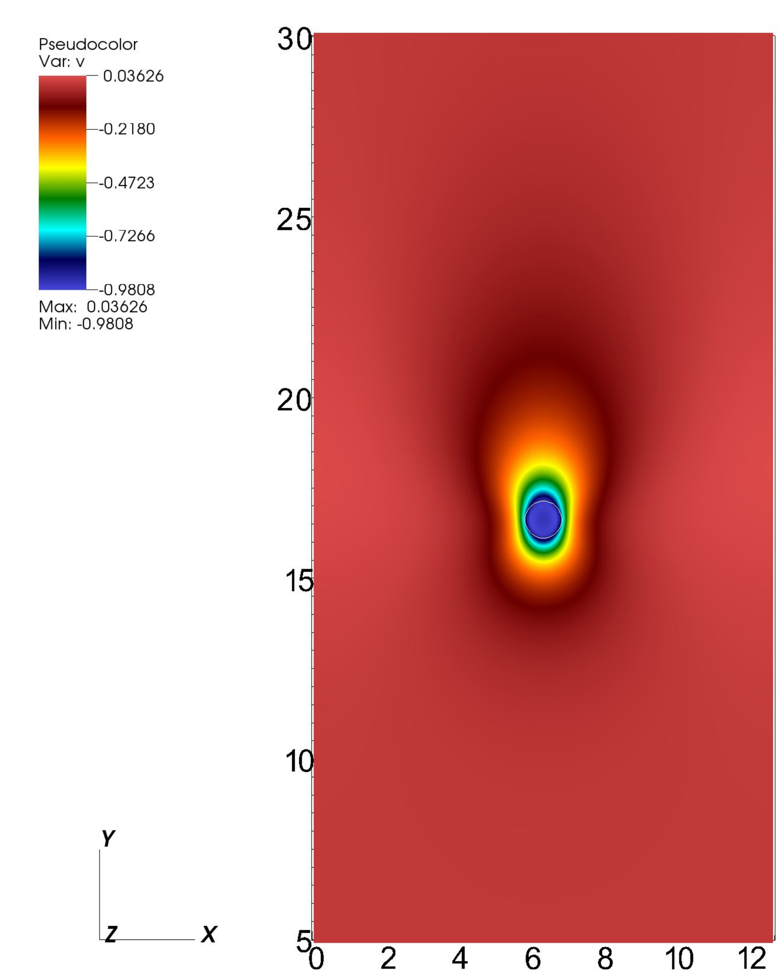
$$\nabla\cdot\mathbf{u} = 0$$

3. Predict the locations of the particles and interpolate fluid velocities onto material volumes.
4. Find particle velocity from material volumes and collision forces.
5. Update fluid velocity field to enforce rigid body motion.

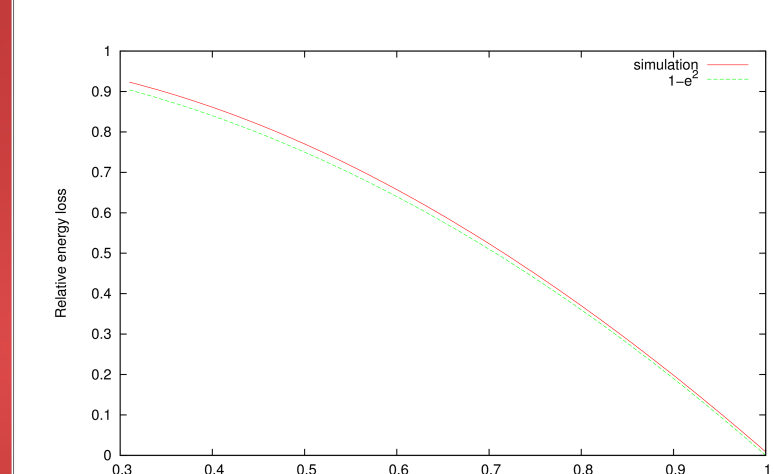


Results

We have validated the collision model for a number of dry collision test cases. We are currently testing the particle-fluid coupling.



Settling of a sphere with particle/fluid density ratio 1.05 and Reynolds number Re = 10. Fluid velocity is non-dimensionalized against the particle Stokes settling velocity.



Energy loss comparison between simulation and theory for the dry collision between two particles, varying the coefficient of restitution e.

Conclusions

The code we are building will allow us to simulate thousands of particles submerged in a fluid. We will then be able to study high-particle-concentration phenomena such as erosion of a sediment bed. Our ultimate goal is to develop predictive tools for academic and industrial researchers to minimize the number of deep ocean wells that need to be drilled.

Acknowledgements

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2. 3. S. Apte et al., 2009, *J. Comput. Phys.* vol. 228, 2712-2738.

3. T. Kempe et al., 2014, *Int. J. Multiphas. Flow* vol. 58, 214-235.