Sedimentation and Deposition Simulation with LibMesh

Jose J. Camata
Andre Rossa
Adriano Cortes
Alvaro L. G. A. Coutinho

High Performance Computing Center (NACAD)
Federal University of Rio de Janeiro (UFRJ)

Rio de Janeiro, Brazil

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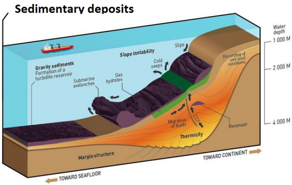
Outline

Motivation

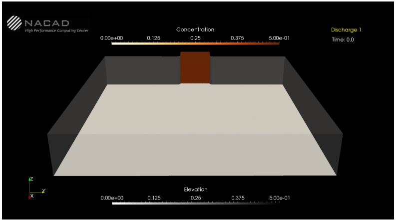
- Understand geological processes leading to the formation of oil fields is challenging;
- A large amount of Brazilian oil reservoirs were formed by sediments deposited by turbidity currents;
- Geological studies in this area are still based on experiments or nature observation;
- Modelling reservoir structures may help decision making on well placement in O&G industry;
- Highly coupled and non-linear problem: incompressible flow, polydisperse mixture transport, interaction with bottom morphology; erosion (not considered here)
- Multiphysics and Multiscale process;

What are Turbidity Currents?

- A turbidity current is a rapid, downhill flow of water caused by increased density due, for example, to high amounts of sediment.
- Turbidity currents can change the physical shape of the sea floor by eroding large areas creating underwater geological formations with oil and gas reservoirs
- Reynolds numbers in nature $\mathcal{O}(10^9)$ viz. Meiburg and Kneller, 2010



from: Magazine Total S.A., Understanding deepwater reservoirs



Succesive discharges over evolving bottom at Re=5000 (EdgdCFD solver) Courtesy of PETROBRAS

Related works

- Lock exchange configurations (2 phases/monodisperse, no bed interaction)
  - DNS/Pseudo-spectral: 2D Hartel et al, 3D Cantero et al, 2006
  - DNS/LES spectral element methods: 2D/3D Ozgokmen et al, 2005/2006
  - LES/pseudo-spectral methods: 2D Hall and Meiburg, 2005
  - LES/FEM: 3D Elias et al, 2008, RBVMS/FEM, Guerra et al, 2013
  - LES/FV: 3D, Ooi, 2006
  - AMR/C: 2D, O'Callaghan et al, 2010; 2D Hiester et al, 2011; 3D Rossa & Coutinho, 2013 (libMesh)
- Polydisperse turbidity currents propagating over complex topography, Nasr-Azadani et al, 2012, Guerra et al, 2013
- Coupled flow and bed morphodynamic interactions due to sediment transport phenomena: Curvilinear immersed boundary method, Khosronejad, et al, 2011; SUPS+LSIC ALE-FEM, Camata, Elias & Coutinho, 2013
- No AMR/C simulations with bed interactions so far

Flow and Sediment Transport Governing Equations with Bed Morphology

ALE Incompressible Navier Stokes Equation

$$\frac{\partial \mathbf{u}}{\partial t} + \tilde{\mathbf{u}} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re}\nabla^2 \mathbf{u} + \mathbf{e}^g \sum_{i=1}^{NP} c_i \qquad \text{in} \qquad \Omega \times [0, t_f] \tag{1}$$

$$\nabla \cdot \mathbf{u} = \mathbf{0} \qquad \text{in} \qquad \Omega \times [0, t_f] \tag{2}$$

$$\tilde{\mathbf{u}} = \mathbf{u} - \mathbf{u}_{mesh} \tag{3}$$

Polydisperse mixture equation for sediment transport

$$\frac{\partial c_i}{\partial t} + (\tilde{\mathbf{u}} + u_s^i \mathbf{e}^g) \cdot \nabla c_i = \frac{1}{ReSc_i}\nabla^2 c_i \qquad \text{in} \qquad \Omega \times [0, t_f] \tag{4}$$

Particle Deposition and Bed Movement

Bed load flux

$$q_{BL} = -\frac{C_r}{\sigma} \int \left(\sum_{i=1}^{n} u_s^i \mathbf{e}^g c_i \right) d\Gamma \tag{5}$$

where C_r is reference concentration and σ is is the packaging fraction of the settled sediment

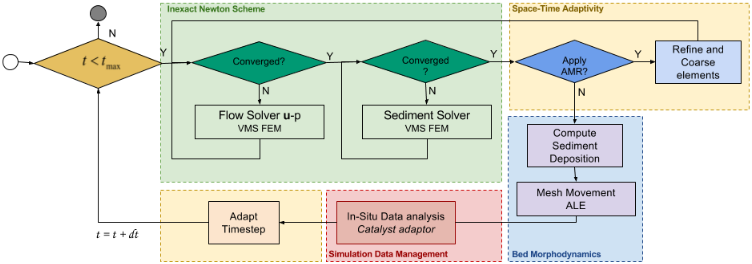
Bottom velocity (Exner-Polya equation)

$$\dot{h} = -\nabla \cdot q_{BL} \tag{6}$$

Deposited particle layer thickness

$$D(x,t) = \frac{C_r}{\sigma} \int_0^t \left(\sum_{i=1}^{n} u_s^i \mathbf{e}^g c_i \right) d\tau \tag{7}$$

libMesh Kernel



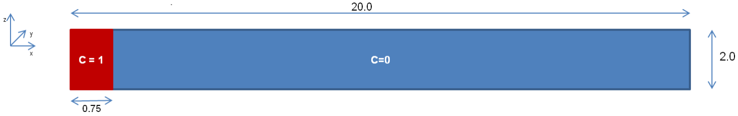
libMesh sedimentation implementation

- VMS: Guerra et al, Numerical simulation of particle-laden flows by the residual-based variational multiscale method, IJNMF, 2013
- ALE: Kanchi & Masud, A 3D adaptive mesh moving scheme, IJNMF, 2007
- Adaptive Feedback Time Step Control: Valli et al, IJNMF 2005 (PID), Ahmed & John, CMAME, 2015, PC11

In Situ Data Analysis at MS48

Monodisperse current

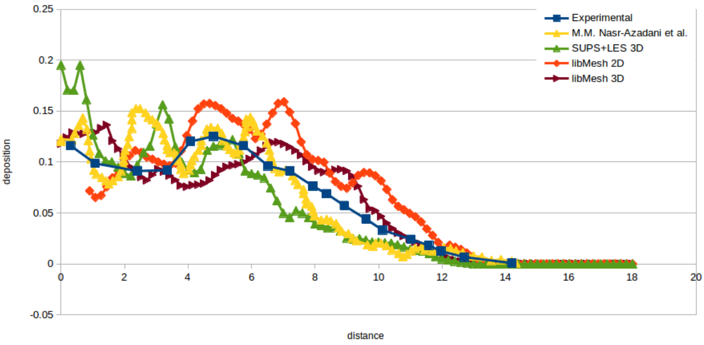
- Computational setup:
  - Domain size: $L_x \times L_z = 20.0 \times 2.0$
  - Initial uniform grid in all directions, with grid spacing of 0.1.
  - Three initial uniform refinements, solution with max_refine_level=3
  - Kelley's error estimator for $\mathbf{u}$ and c
  - The lock, in which the fluid initially is at rest, has a dimensionless height of $H = 2$ and length of $L_s = 0.75$
  - Reynolds number $Re = 5000$



- Boundary Conditions:
  - For the velocity field, no-slip condition at the top, bottom, right and left walls. Slip condition at front and back walls.
  - For concentration field,
    - No-flux boundary condition at the top wall: $cu_s - \frac{1}{ScRe}\frac{\partial c}{\partial n} = 0$ at $\mathbf{x} = \Gamma_F$
    - At the bottom wall, sediments should leave the computational domain freely with flow rate $u_s c$ and $\frac{\partial c}{\partial n} = 0$ at $\mathbf{x} = \Gamma_C$
    - Sediment deposited is used to update BC at the bottom

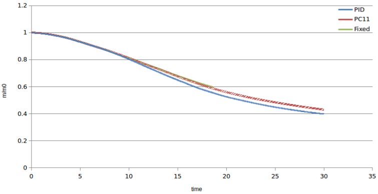
Monodisperse current

- Sediment deposit profile: experiments of de Rooij and Dalziel (2001) with simulations of Nasr-Azadani et al, 2011 (FD-2D), Camata et al, 2013 (SUPS+LES 3D) & VMS AMR/C (libMesh)

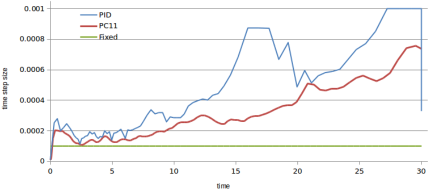


Monodisperse particle-driven current with settling velocity 0.02

Monodisperse current



Temporal evolution of suspended particle mass normalized by initial mass



Time step evolution

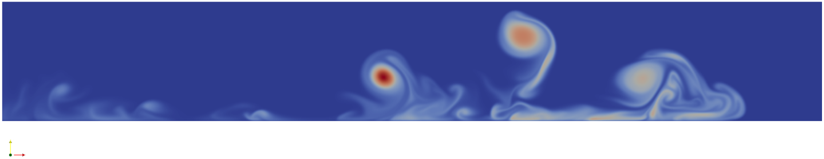
	Fixed	PID	PC11
Average Stepsize	0.0001	0.00036	0.00024
#Time steps	300,000	84,050	122,825
#Elements	72,543	70,727	62,102
CPU Time	1.0	0.17	0.23

Space-time adaptivity costs

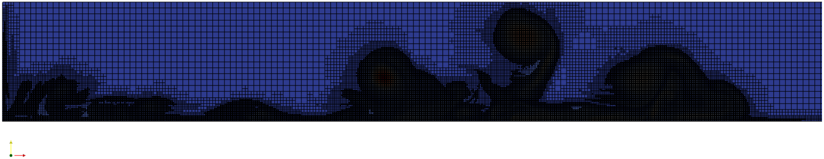
PID rejected steps 1270

PC11 rejected steps 212

libMesh 2D Solution and Mesh at $t = 30$



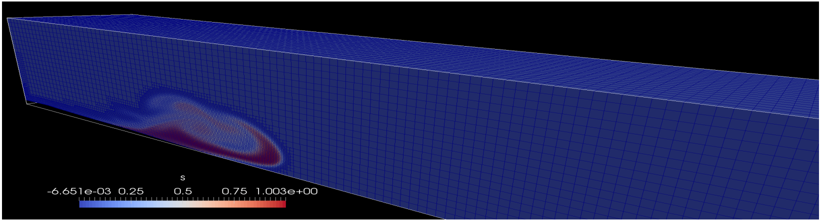
Concentration profile



Adapted Mesh

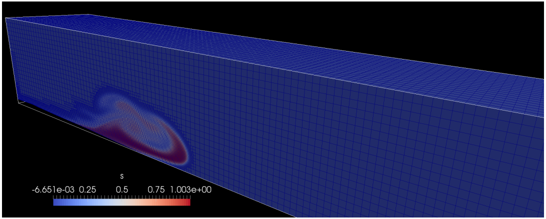
Bed Morphodynamics Test Case

- Computational setup:
  - Domain size: $L_x \times L_y \times L_z = 20.0 \times 2.0 \times 2.0$
  - Initial uniform grid in all directions, with grid spacing of 0.1.
  - One initial uniform refinement, solution evolves with max_refine_level=3
  - Kelley's error estimator for $\mathbf{u}$ and c
  - The lock, in which the fluid initially is at rest, has height & width $H, W = 2$ and length $L_s = 0.75$
  - Reynolds number $Re = 5000$, Setting velocity Us $= 0.02$, Bed movement enabled

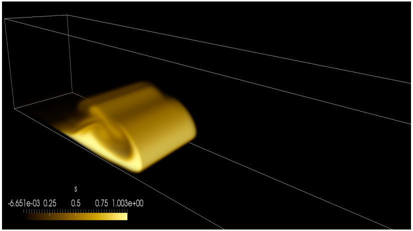


Bed Morphodynamics Test Case

Mesh and concentration snapshots at $t = 8.75$ - bounding box represents original domain



Adapted mesh



Concentration profile

Concluding Remarks and Future Directions

- We have discussed libMesh extensions for simulating sedimentation problems found in turbidity currents
- Good agreement was obtained for deposit profiles in a monodisperse particle-driven current with available experimental and computational data
- Space and time-adaptivity interesting for such problems
- Results suggest that libMesh is a versatile numerical tool for investigating the interations between turbidity currents and seafloor topography, helping fundamental sedimentological studies for oil reservoirs characterization.
- Need to add erosion and compaction for high fidelity simulations
- Time step controllers (PID, PC11) will be available soon for libMesh users

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