TURBINS: An Immersed Boundary, Navier-Stokes Code for the Simulation of Gravity and Turbidity Currents Interacting with Complex Topographies

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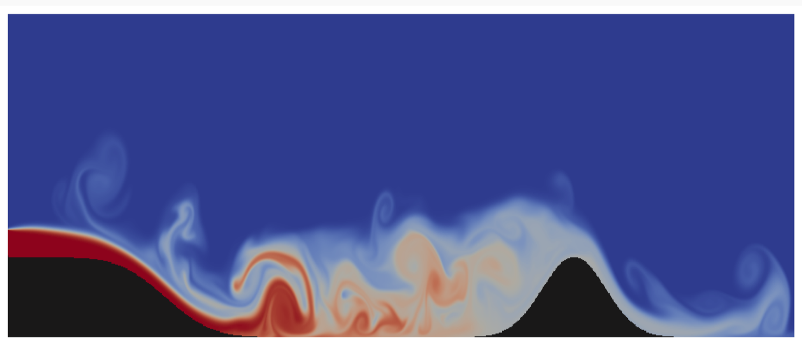
Introduction

TURBINS (**TURB**idity currents via **I**mmersed boundary **N**avier-**S**tokes simulations) is a highly parallel three-dimensional DNS based code developed to simulate gravity and turbidity currents propagating over complex topographies.



Left: Particle concentration contour for a turbidity current flowing into a mini-basin and interacting with a hump. Transient deposit profiles, interaction of the current with the hump, vortical structrues and etc can be studied via TURBINS.

TURBINS provides detailed information on the sediment transport from river deltas into the deep ocean via turbidity currents for complex seafloor topographies.

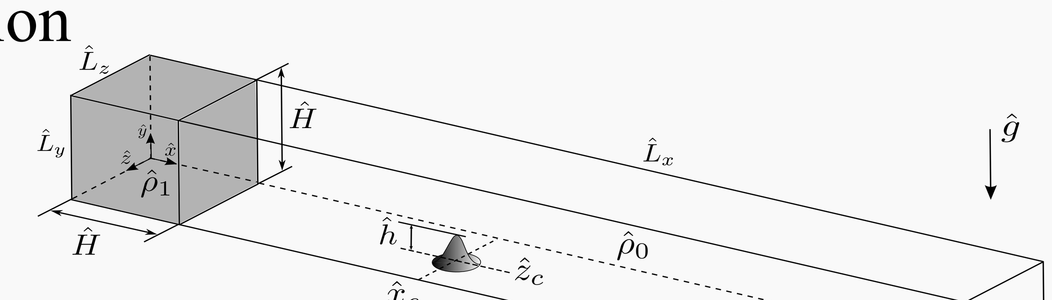
Modeling approach

- Divergence free velocity field $\nabla \cdot \mathbf{u} = 0$
- Incompressible Navier-Stokes equations (Boussinesq). $\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \frac{1}{Re} \nabla^2 \mathbf{u} - \nabla p + c\mathbf{e}^g$
- Transport equation for describing particle motion $\frac{\partial c}{\partial t} + (\mathbf{u} + u_s \mathbf{e}^g) \cdot \nabla c = \frac{1}{ScRe} \nabla^2 c$
- Constant settling velocity

$$Re = \frac{\hat{u}_b \hat{H}}{\hat{\nu}}$$

Characteristic velocity: buoyancy velocity $\hat{u}_b = \sqrt{\frac{\hat{H}\hat{g}(\hat{\rho}_1 - \hat{\rho}_0)}{\hat{\rho}_0}}$

- Lock-exchange configuration



Numerical Method

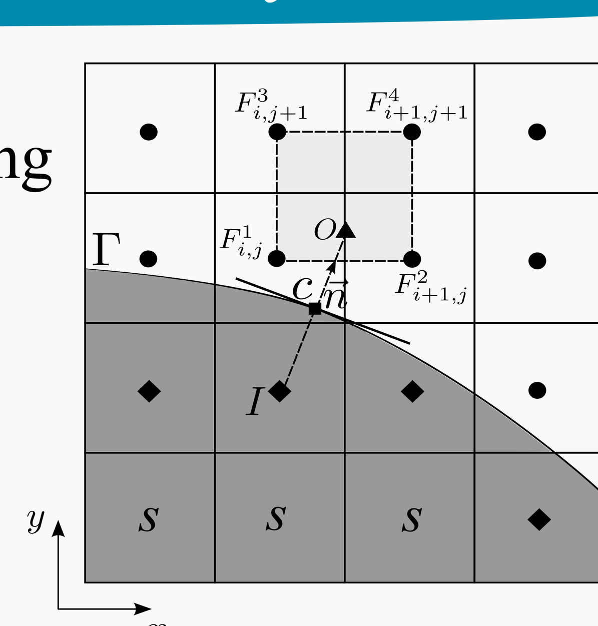
Viscous terms: fully implicit second order finite difference method.
Convective terms: explicit third order Essentially Non-Oscillatory (ENO) scheme.
Projection method: impose incompressibility condition.
Time integration: third order TVD Runge-Kutta method.

Boundary treatment: Immersed boundary method

Immersed boundary method is used to impose the correct boundary conditions along solid boundaries.

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} = \mathbf{RHS} + \mathbf{f}^{n+1}$$

Direct forcing approach is employed to compute **f** to ensure no extra restriction on time step.



Bilinear (trilinear in 3D) interpolation is used to obtain the value of any fluid quantity (q) at the mirrored node O via the neighboring fluid nodes F's

$$q_O = \Sigma_{l=1}^{N} w_l q^l$$

Immersed node I is updated depending on the boundary condition imposed on the solid surface

Dirichlet B.C., $q_C = 0$ $\qquad q_I = -q_O$

Neumann B.C., $\nabla q \cdot \mathbf{n}|_C = 0$ $\qquad q_I = +q_O$

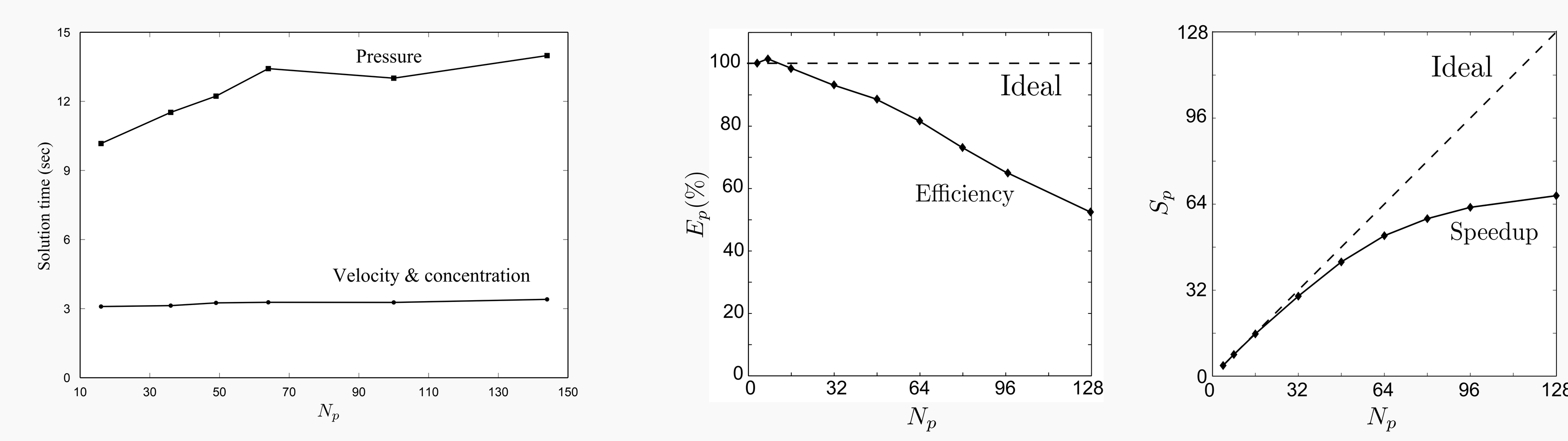
Parallelism

Domain decompostion approach is adopted to parallelize TURBINS. PETSc is used to distribute data among processors, update ghost nodes, and solve the linear systems via parallel Krylov solver (e.g. GMRES). HYPRE is incorporated to solve pressure Poisson equation via Algebraic MultiGrid preconditioner: *BoomerAMG*.

Scaling performance

Weak scaling: size of the sub-domain on each processor is constant.

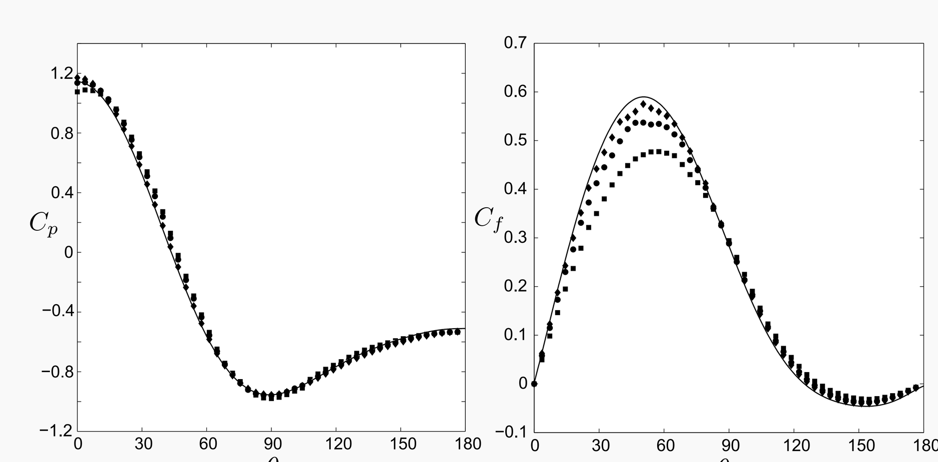
Strong scaling: total size of the domain is constant.



Results

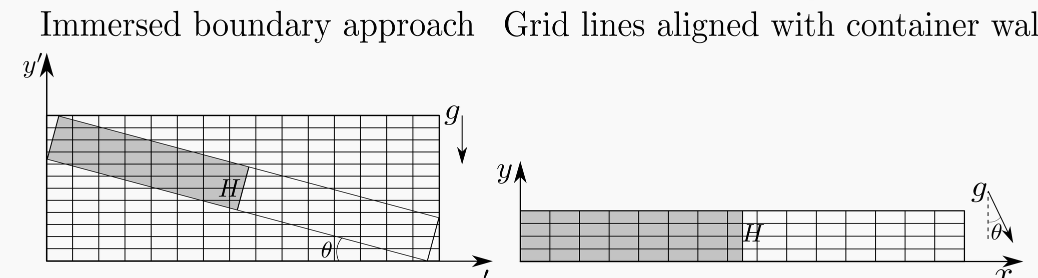
Validation

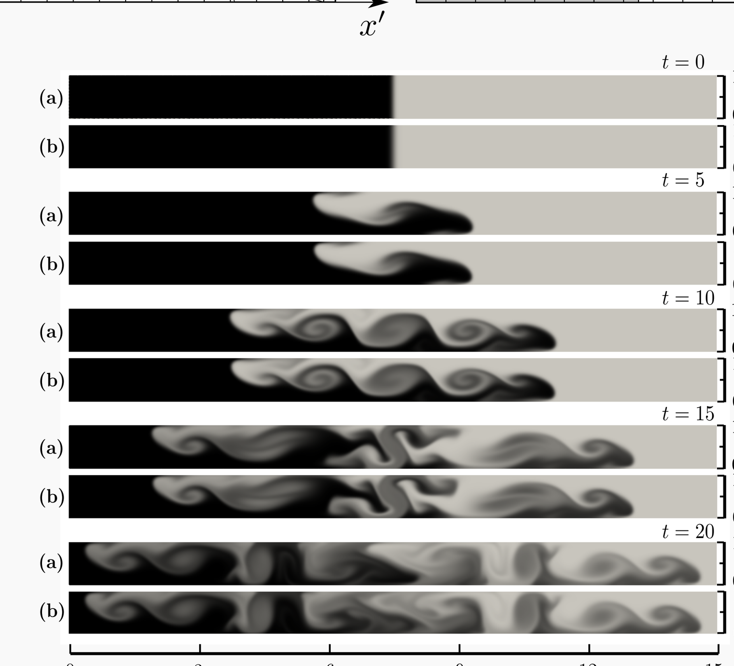
1) Uniform flow over a cylinder
Surface pressure and wall shear stress are calculated very accurately (important for erosion)



2) Gravity current in a sloping channel

Immersed boundary approach   Grid lines aligned with container walls

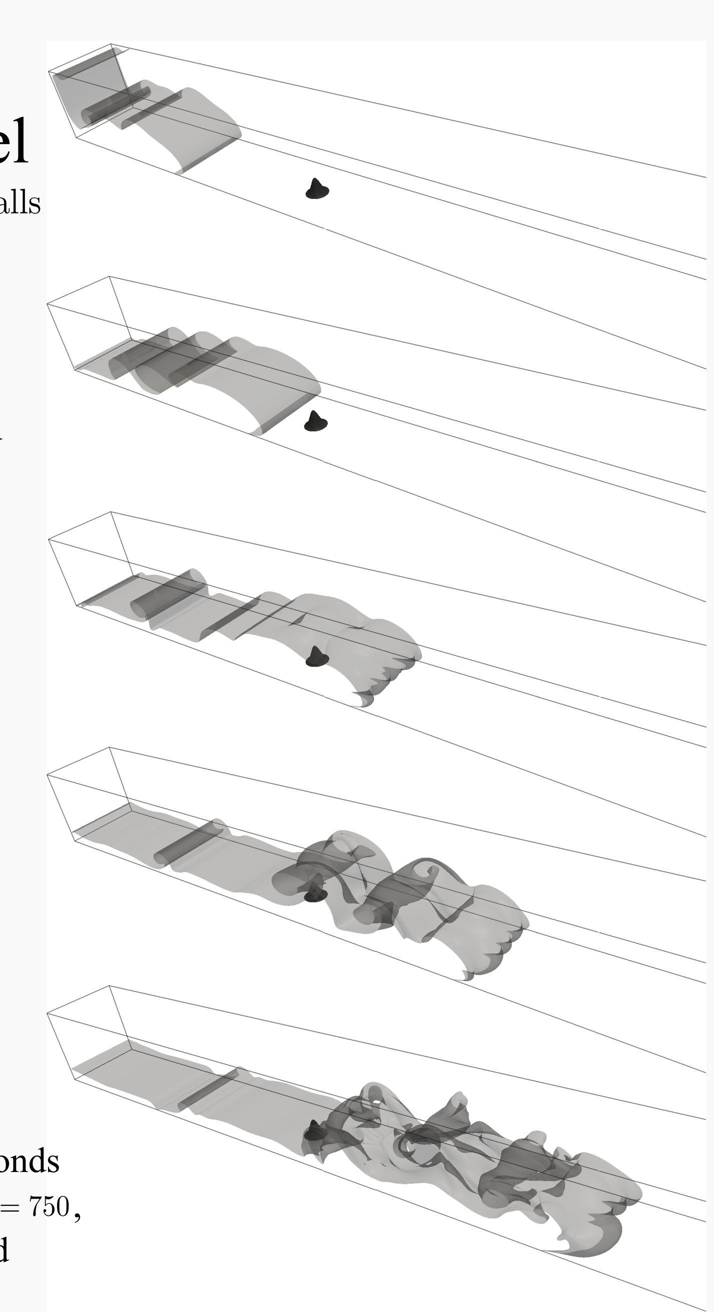




Comparison of the gravity current concentration fields (white corresponds to $c = 0$ and black to $c = 1$) in a sloping channel with $\theta = 15^o$ and $Re_H = 750$, obtained via two different numerical approaches. a): present immersed boundary approach, b): coordinates aligned with container walls.

Flow Over a Bump

Time evolution of the gravity current produced by a lock-exchange configuration interacting with a Gaussain bump. Strong three-dimensional effect on the flow behavior, e.g. development of lobe-and-cleft instabilities can be studied via depth-resolved simulations.



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