Gravity Current Flow past a Circular Cylinder: 
Forces, Wall Shear Stresses and Implications for Scour

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• Motivation
• Governing equations / computational approach
• Results
  - drag and lift forces
  - wall shear stress
• Summary and outlook
Coastal margin processes
Turbidity current

• Underwater sediment flow down the continental slope
• Can transport many km$^3$ of sediment
• Can flow O(1,000)km or more
• Often triggered by storms or earthquakes
• Repeated turbidity currents in the same region can lead to the formation of hydrocarbon reservoirs

Turbidity current.
http://www.clas.ufl.edu/
Turbidity current (cont’d)

Var Fan, off Nice coast, caused in 1979 by airport construction accident
Turbidity current (cont’d)

Off the coast of Santa Barbara/Goleta
Theoretical framework: Dilute flows

Volume fraction of particles of $O(10^{-2} - 10^{-3})$:

- particle radius $\ll$ particle separation
- particle radius $\ll$ characteristic length scale of flow
- coupling of fluid and particle motion primarily through momentum exchange, not through volumetric effects
- effects of particles on fluid continuity equation negligible
Moderately dilute flows: Two-way coupling

Mass fraction of heavy particles of $O(10\%)$, small particle inertia (e.g., sediment transport):

- particle loading modifies effective fluid density
- particles do not interact directly with each other

Current dynamics can be described by:

- incompressible continuity equation
- variable density Navier-Stokes equation (Boussinesq)
- conservation equation for the particle concentration field

→ don’t resolve small scale flow field around each particle, but only the large fluid velocity scales
Moderately dilute flows: Two-way coupling (cont’d)

\[ \nabla \cdot \vec{u}_f = 0 \]

\[ \frac{\partial \vec{u}_f}{\partial t} + (\vec{u}_f \cdot \nabla) \vec{u}_f = -\nabla p + \frac{1}{Re} \nabla^2 \vec{u}_f + c \bar{e}_g \]

\[ \frac{\partial c}{\partial t} + \left[ (\vec{u}_f + \vec{U}_s) \nabla \right] c = \frac{1}{Sc Re} \nabla^2 c \]

settling velocity

effective density

\[ Re = \frac{u_b L}{\nu} \quad , \quad Sc = \frac{\nu}{D} \quad , \quad U_s = \frac{u_s}{u_b} \]
Model problem

Lock exchange configuration

Dense front propagates along bottom wall

Light front propagates along top wall
3D turbidity current – Temporal evolution

DNS simulation (Fourier, spectral element, $7 \times 10^7$ grid points)

- turbidity current develops lobe-and-cleft instability of the front
- current is fully turbulent
- erosion, resuspension not accounted for

Necker, Härtel, Kleiser and Meiburg (2002a,b)
Examples of pipelines under threat from gravity currents

Placement of pipelines on the ocean floor

• avoid submarine canyons
Flow configuration for numerical simulation

Lock release flow, compositional current only:
Numerical technique

• DNL/LES finite volume code (Pierce & Moin 2001)
• central differencing, Crank-Nicolson time stepping
• Poisson equation for pressure solved by multigrid technique
• FORTRAN code parallelized with MPI
• simulations on up to 64 CPUs
Temporal evolution of the flow

- what magnitude forces and moments are exerted on the obstacle?
- steady vs. unsteady?
- erosion and deposition near the obstacle?
Results: Drag and lift force

Comparison with experiments by Ermanyuk and Gavrilov (2005):

- impact, transient and quasisteady stage
- 2D simulation captures impact, overpredicts quasisteady fluctuations
- 3D simulation captures impact and quasisteady stages well
- difference between 2D and 3D similar to uniform flow past cylinder
Results: Drag and lift force (cont’d)

Origin of force fluctuations:

• Karman vortex shedding from the cylinder
Results: Spanwise drag variation

Impact stage:

- spanwise drag variation dominated by lobe-and-cleft structure

local drag coeff. value along span

front location vs. time
Results: Spanwise drag variation (cont’d)

Quasisteady stage:

• spanwise drag variation scales with cylinder diameter
Results: Influence of gap size

Streamwise vorticity structure:

- Small gap size distorts vortex structure in the near wake
Results: Wall shear stress

Friction velocity:

\[ \frac{u_T}{V} = \sqrt{\frac{|\tau_w|}{\rho_0 V^2}} \]

- longitudinal structures, maximum under the cylinder
Results: Wall shear stress (cont’d)

Friction velocity:

- longitudinal structures, maximum under the cylinder
Results: Influence of gap size

Friction velocity below the cylinder:

- Large spanwise variations during impact
- Small gap size results in larger friction velocity
- Spanwise variations can result in local scouring
Summary

- high resolution 2D and 3D simulations of gravity currents interacting with submarine pipelines
- 2D simulations capture impact, but overpredict force fluctuations during quasisteady stage, 3D simulations capture both stages
- for gap sizes $\geq$ cylinder diameter, the structure is similar to uniform flow past cylinder
- for gap sizes $\ll$ cylinder diameter, the flow structure is distorted
- during impact stage, spanwise drag variation determined by lobe-and-cleft structure
- during late stages, spanwise variations scale with cyl. diameter
- wall shear stress has longitudinal structures, max. under cylinder
- strong spanwise wall shear stress fluctuations during impact $\rightarrow$ potential for localized scour
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