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*

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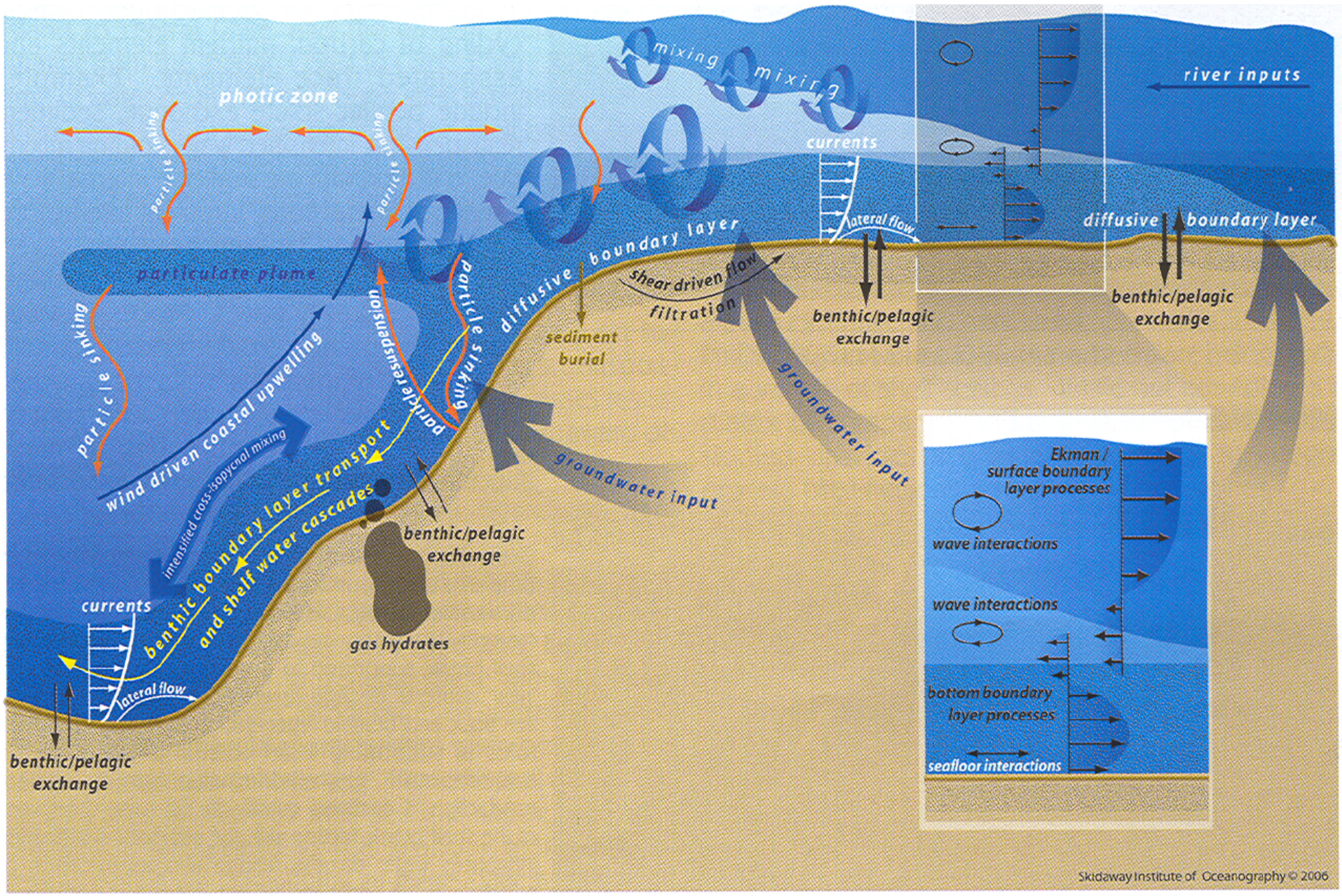
Coastal margin processes

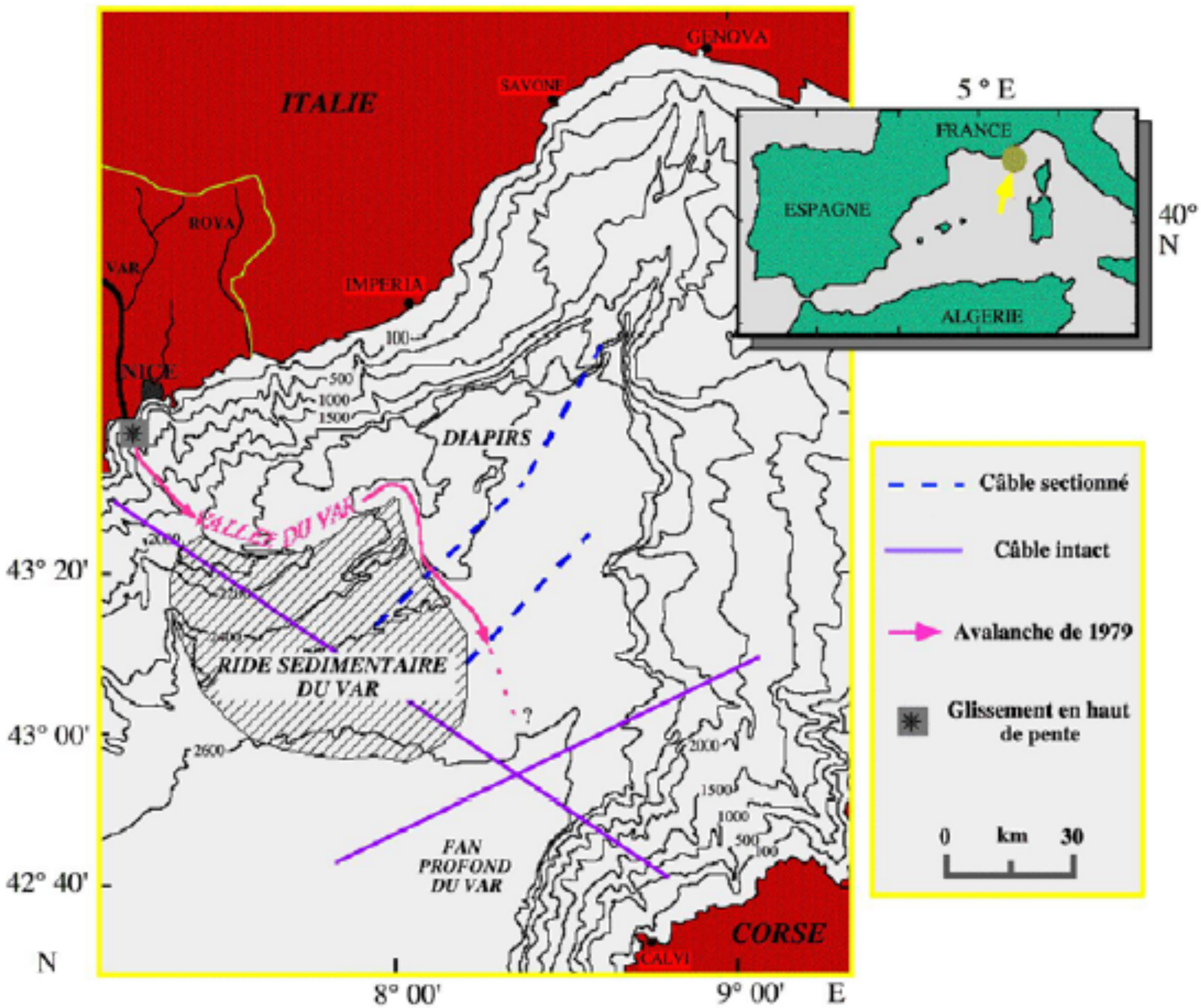


Turbidity current

- *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*

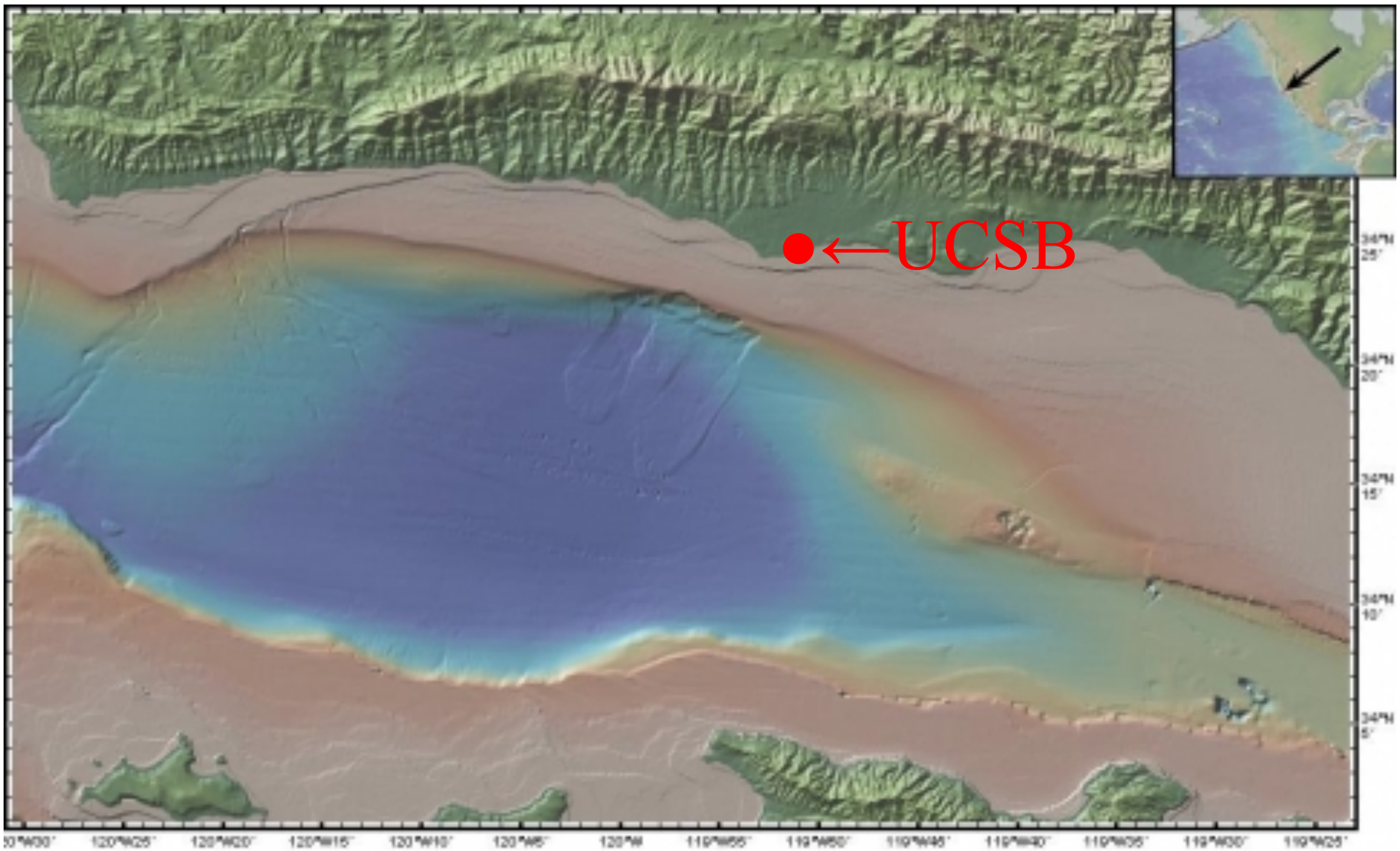
Turbidity current.
http://www.clas.ufl.edu/

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 « particle separation*
- *particle radius « 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*

$\rightarrow$ *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)

$$\nabla \cdot \vec{u}_f = 0$$

$$\frac{\partial \vec{u}_f}{\partial t} + \left(\vec{u}_f \cdot \nabla\right) \vec{u}_f = -\nabla p + \frac{1}{Re} \nabla^2 \vec{u}_f + c\, \vec{e}_g$$

effective density

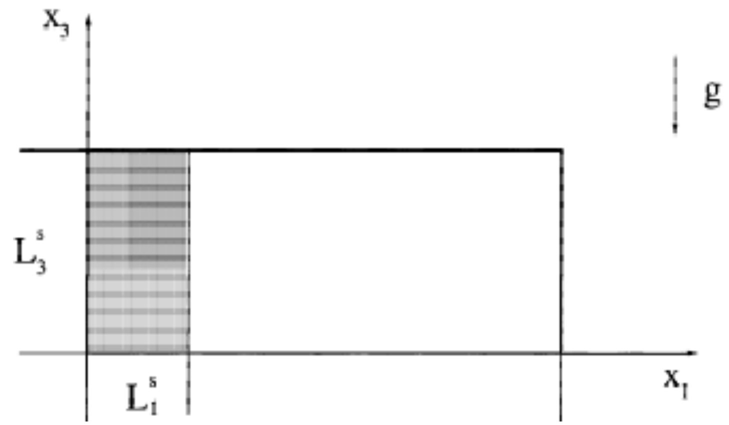
$$\frac{\partial c}{\partial t} + \left[\left(\vec{u}_f + \vec{U}_s\right) \nabla\right] c = \frac{1}{Sc\, Re} \nabla^2 c$$

settling velocity

$$Re = \frac{u_b\, L}{\nu} \quad , \quad Sc = \frac{\nu}{D} \quad , \quad U_s = \frac{u_s}{u_b}$$

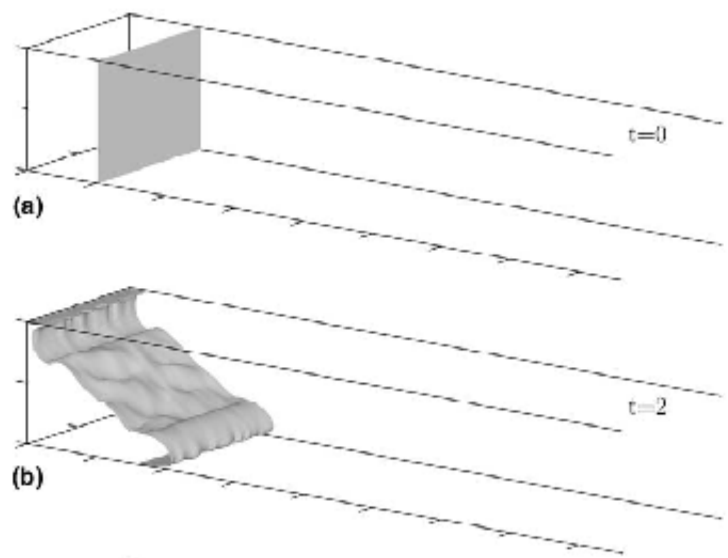
Model problem

Lock exchange configuration



Dense front propagates along bottom wall

Light front propagates along top wall



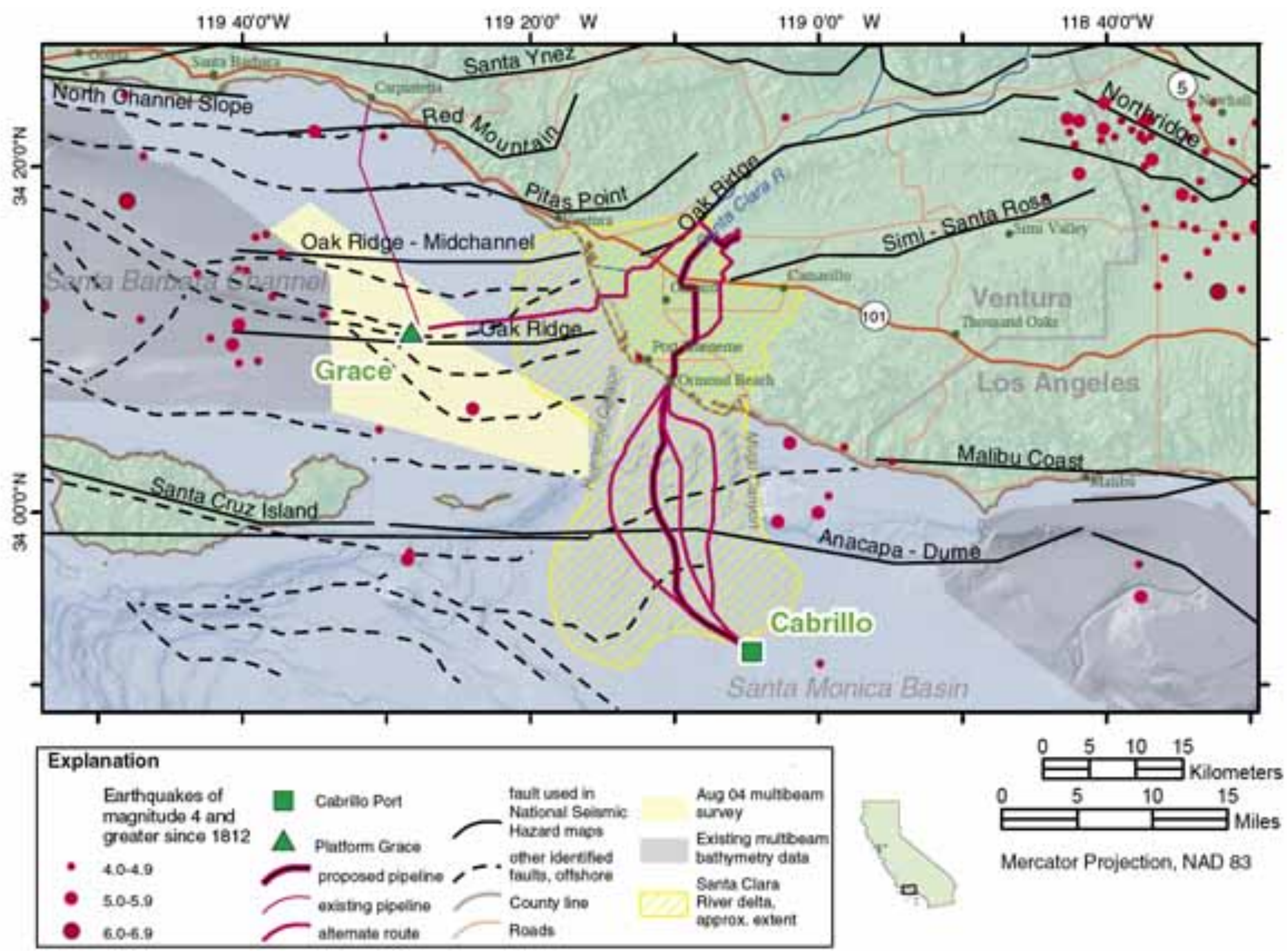
3D turbidity current – Temporal evolution

DNS simulation (Fourier, spectral element, $7x10^7$ grid points)

Necker, Härtel, Kleiser and Meiburg (2002a,b)

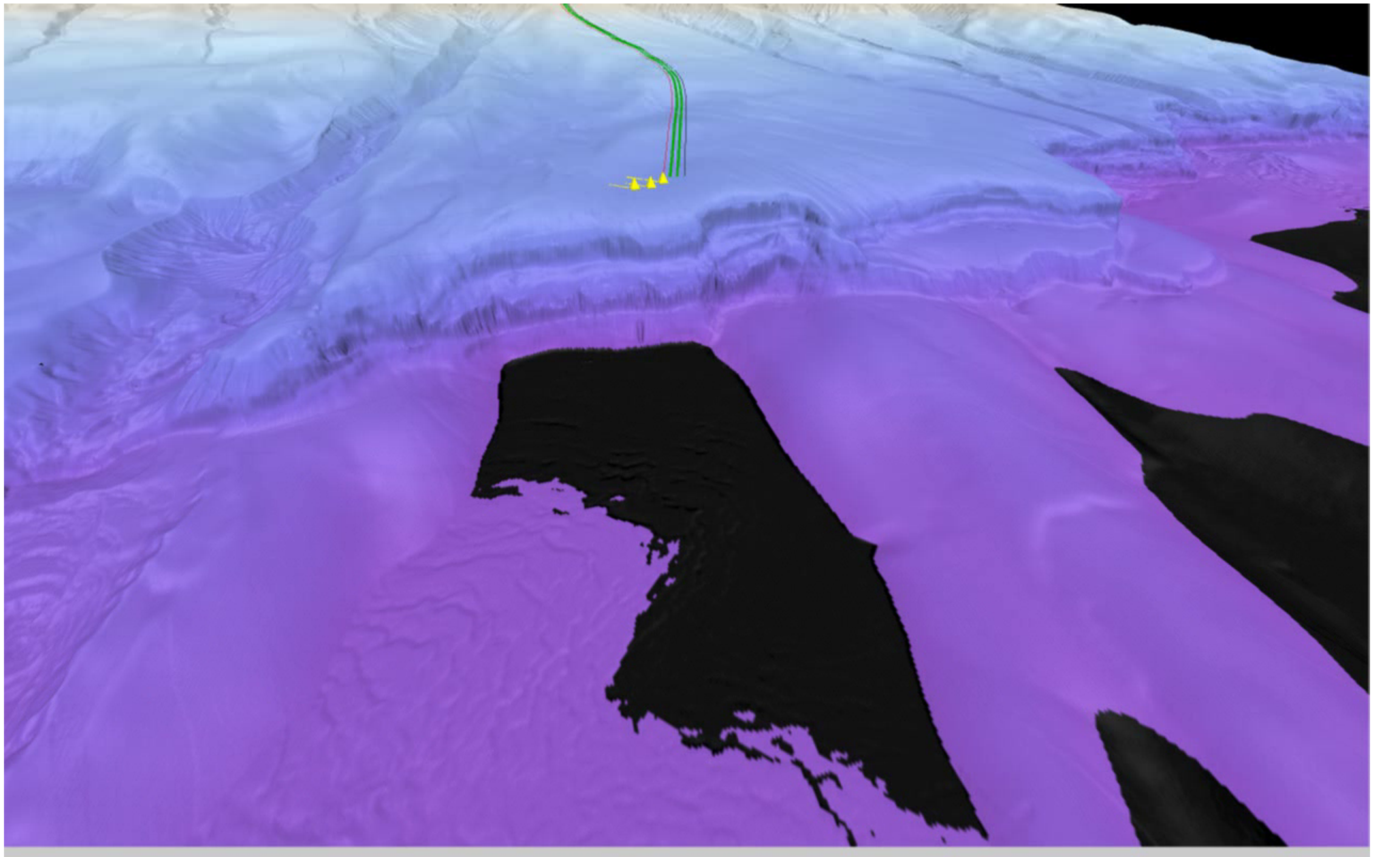
- *turbidity current develops lobe-and-cleft instability of the front*
- *current is fully turbulent*
- *erosion, resuspension not accounted for*

Examples of pipelines under threat from gravity currents



U.S. Geological Survey Open-File Report 2004-1286

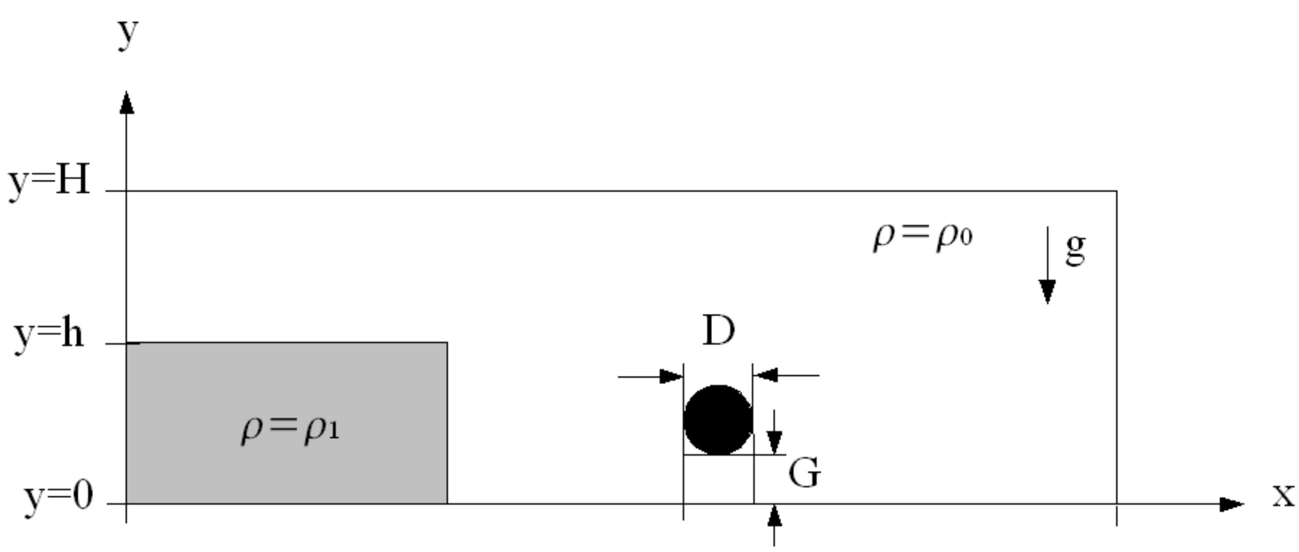
Placement of pipelines on the ocean floor



- *avoid submarine canyons*

Flow configuration for numerical simulation

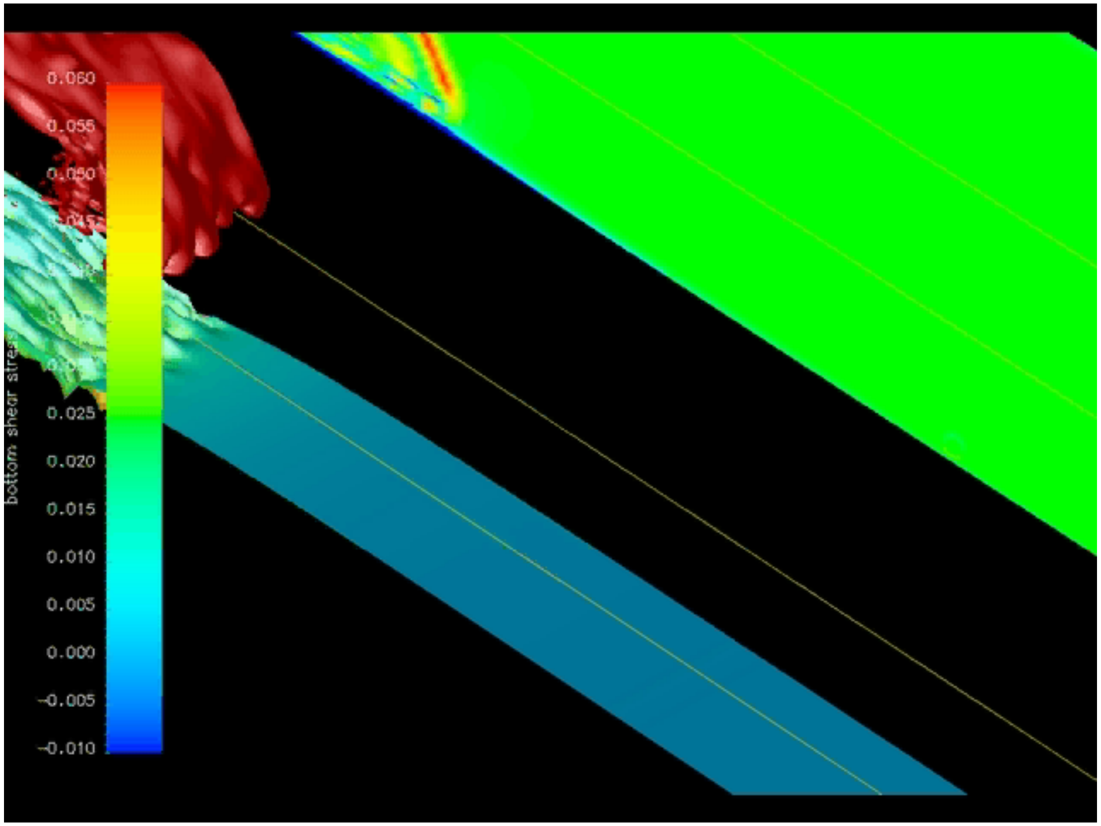
Lock release flow, compositional current only:



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*

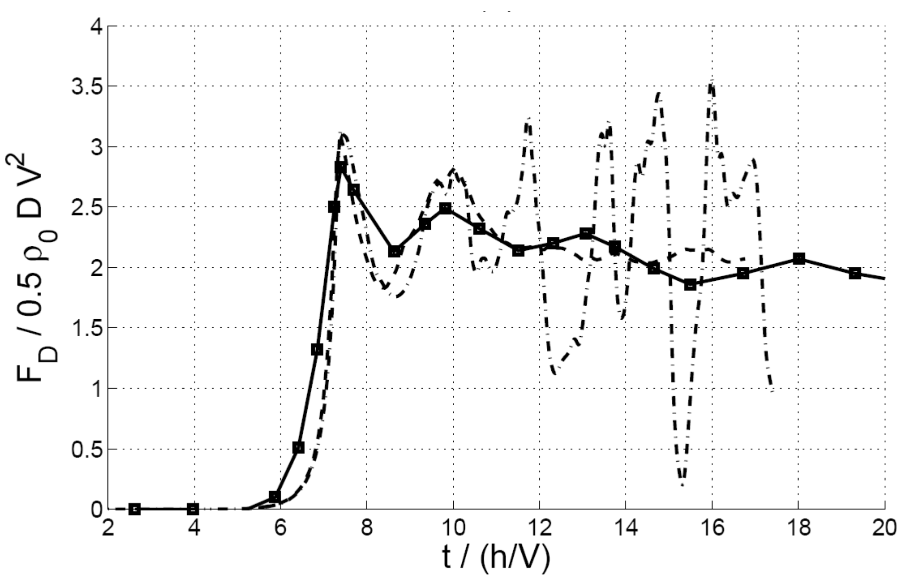
Temporal evolution of the flow

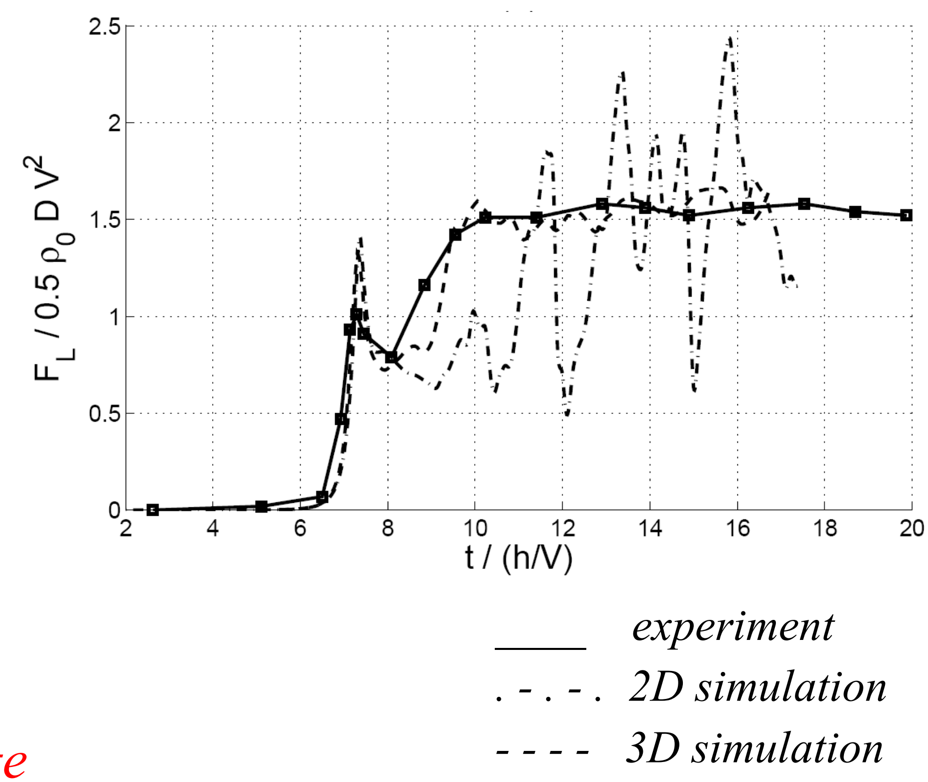


- *what magnitude forces and moments are exerted on the obstacle?*
- *steady vs. unsteady?*
- *erosion and deposition near the obstacle?*

Results: Drag and lift force

Comparison with experiments by Ermanyuk and Gavrilov (2005):

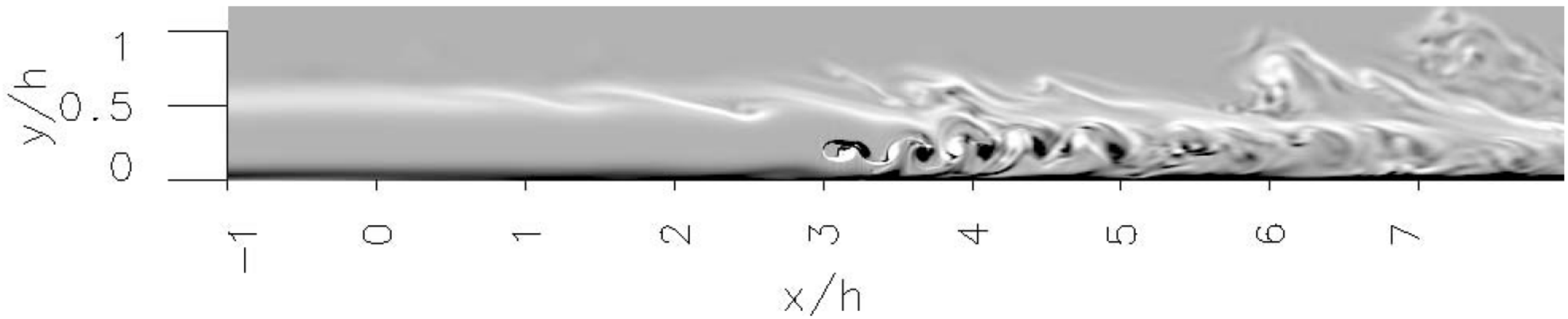


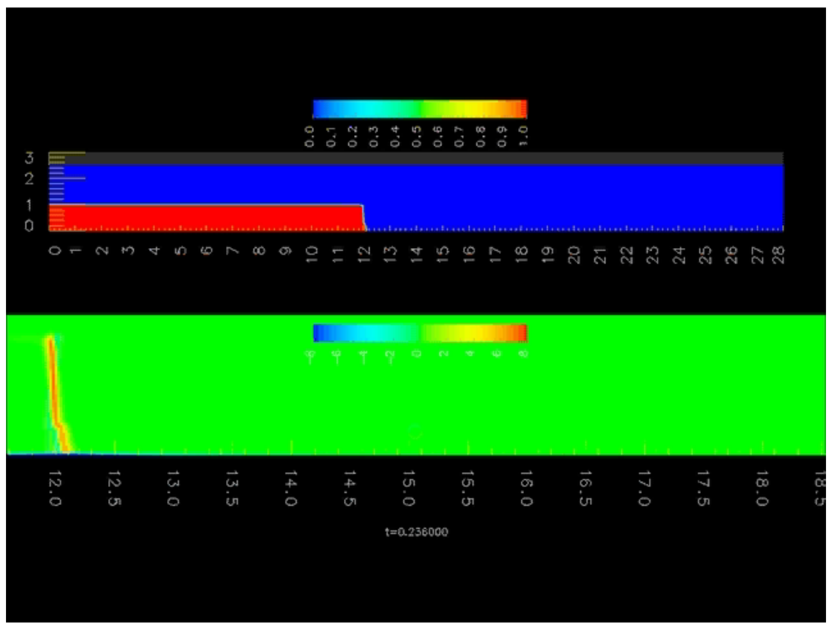


- *impact, transient and quasisteady stage*
- *2D simulation captures impact, overpredicts quasisteady fluctuations*
- *3D simulation captures impact and quasisteady stages well*
- *difference between 2D and 3D similar to uniform flow past cylinder*

Results: Drag and lift force (cont’d)

Origin of force fluctuations:



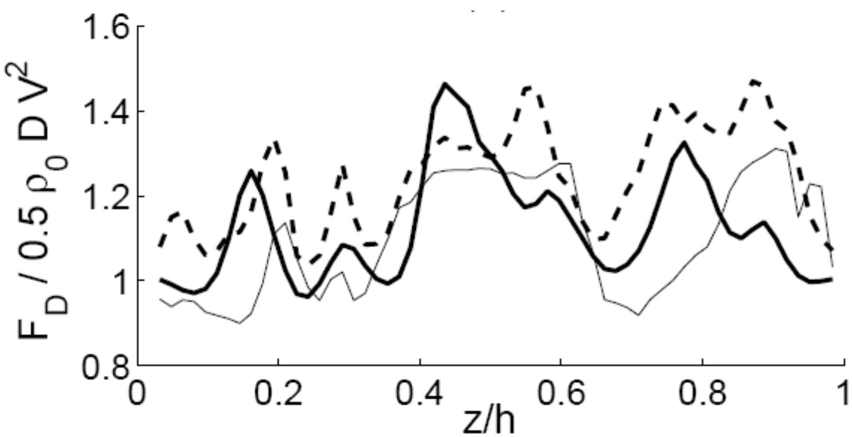


- *Karman vortex shedding from the cylinder*

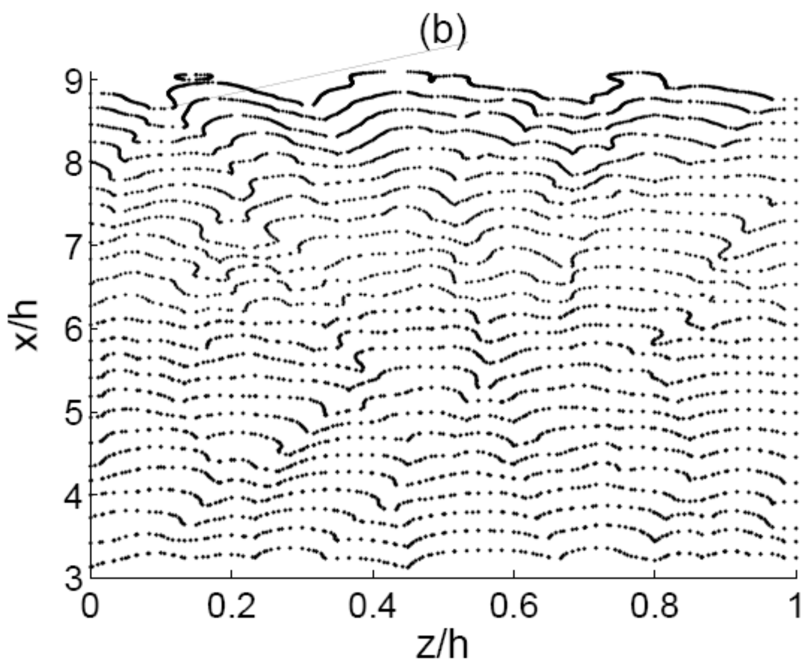
Results: Spanwise drag variation

Impact stage:

local drag coeff. value along span



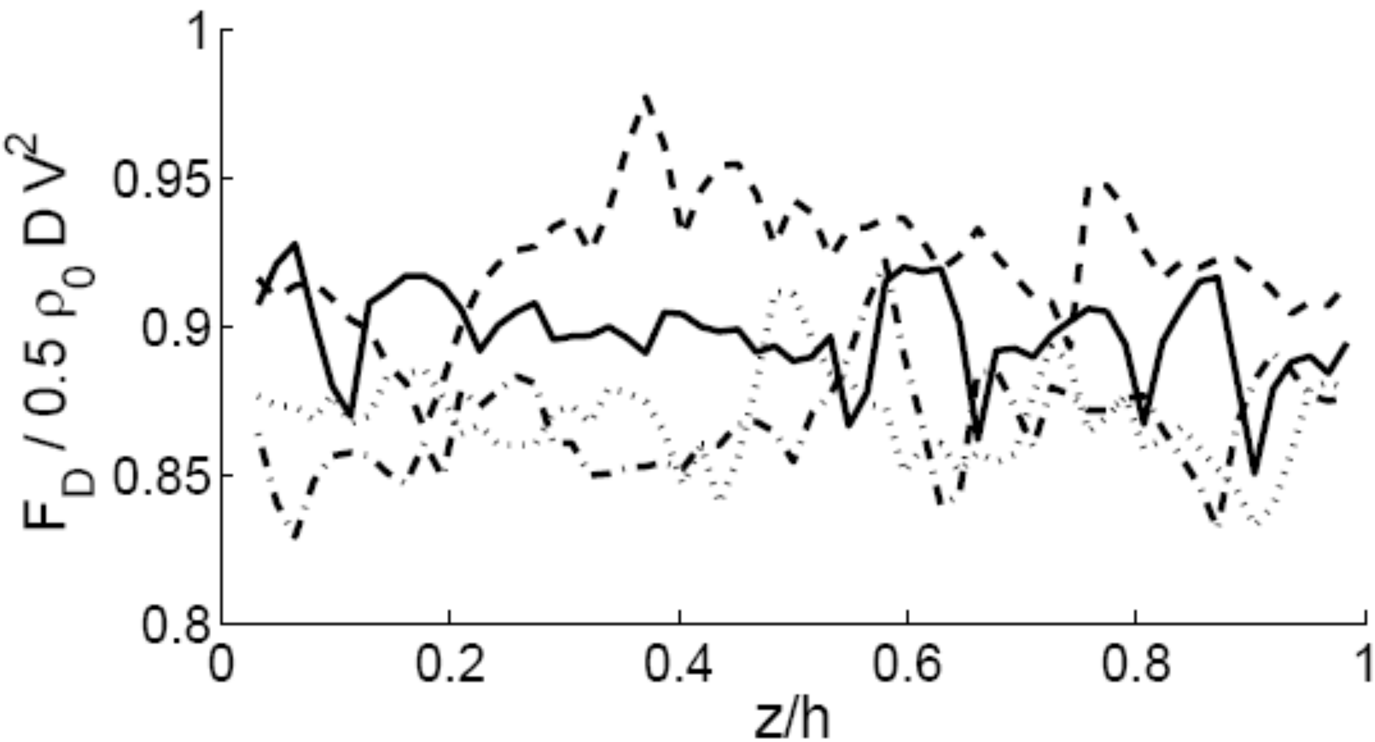
front location vs. time



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

Results: Spanwise drag variation (cont'd)

Quasisteady stage:

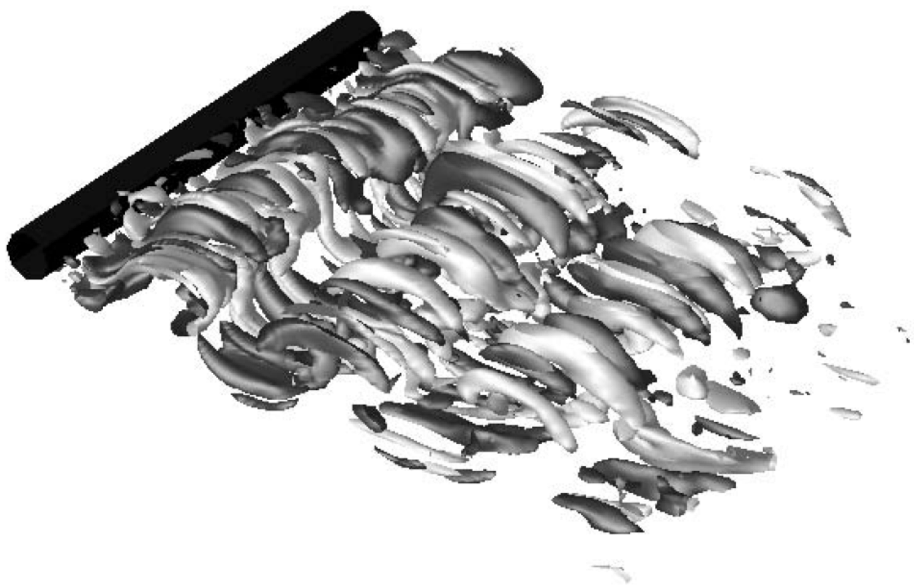


- *spanwise drag variation scales with cylinder diameter*

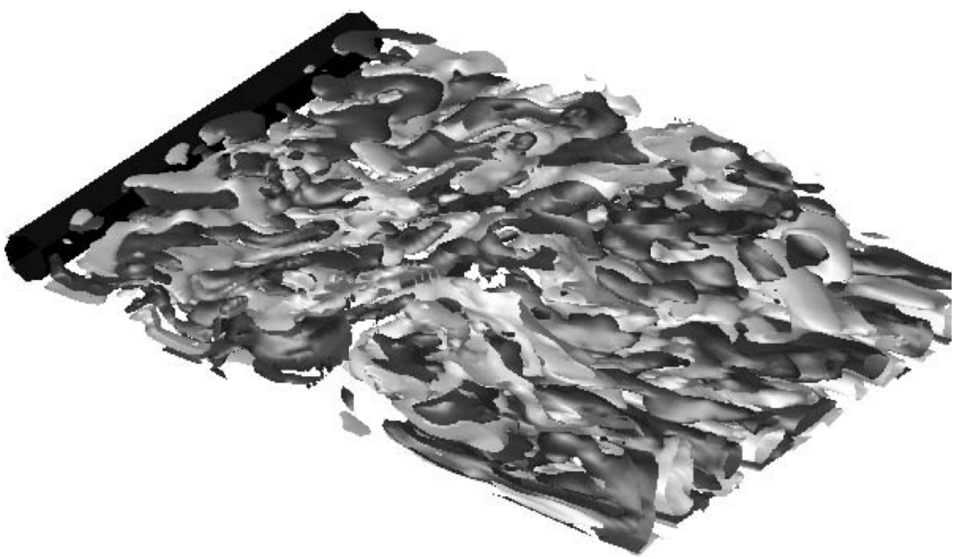
Results: Influence of gap size

Streamwise vorticity structure:

gap width ~ cylinder diameter



gap width « cylinder diameter

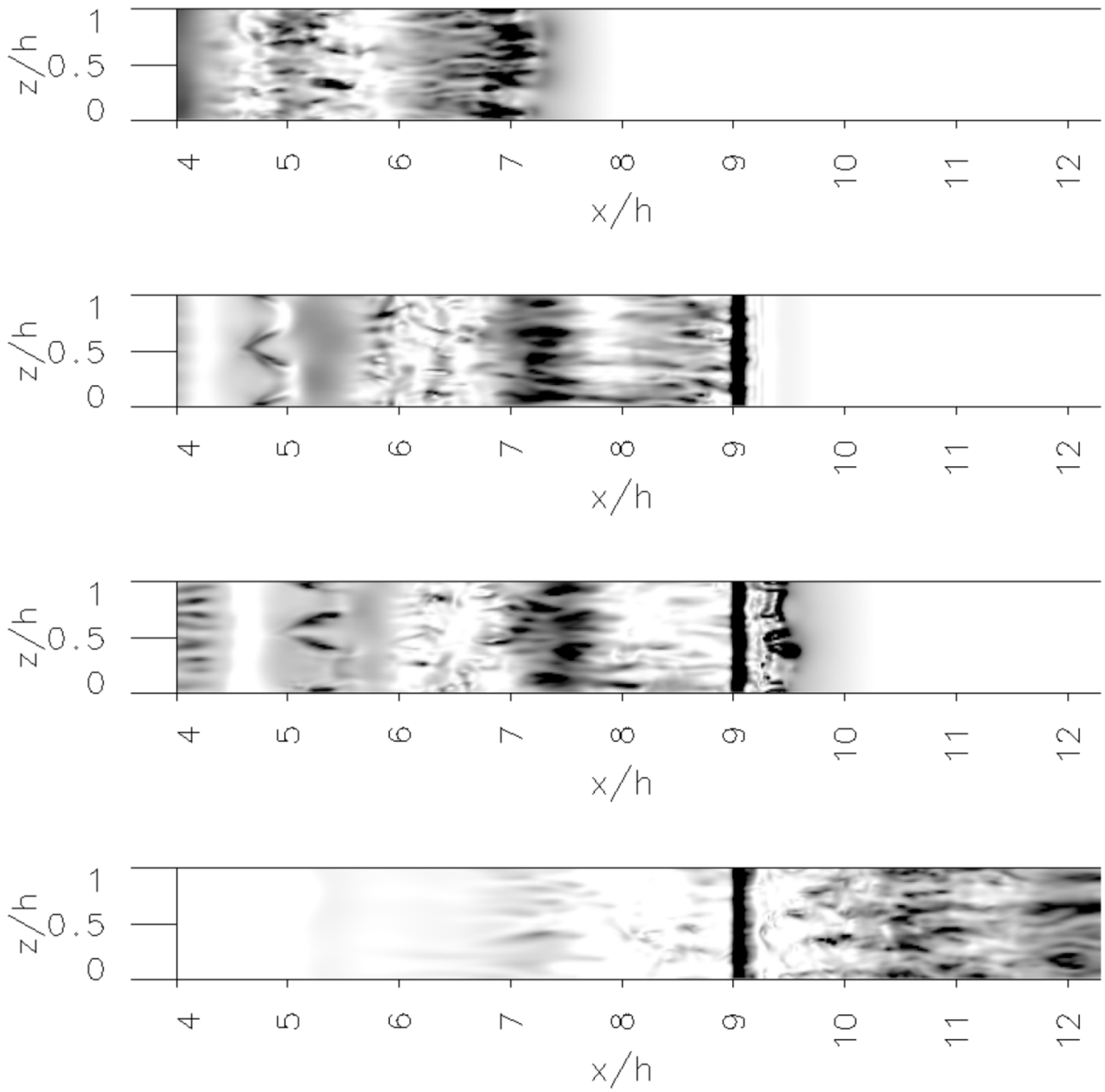


- *small gap size distorts vortex structure in the near wake*

Results: Wall shear stress

Friction velocity:

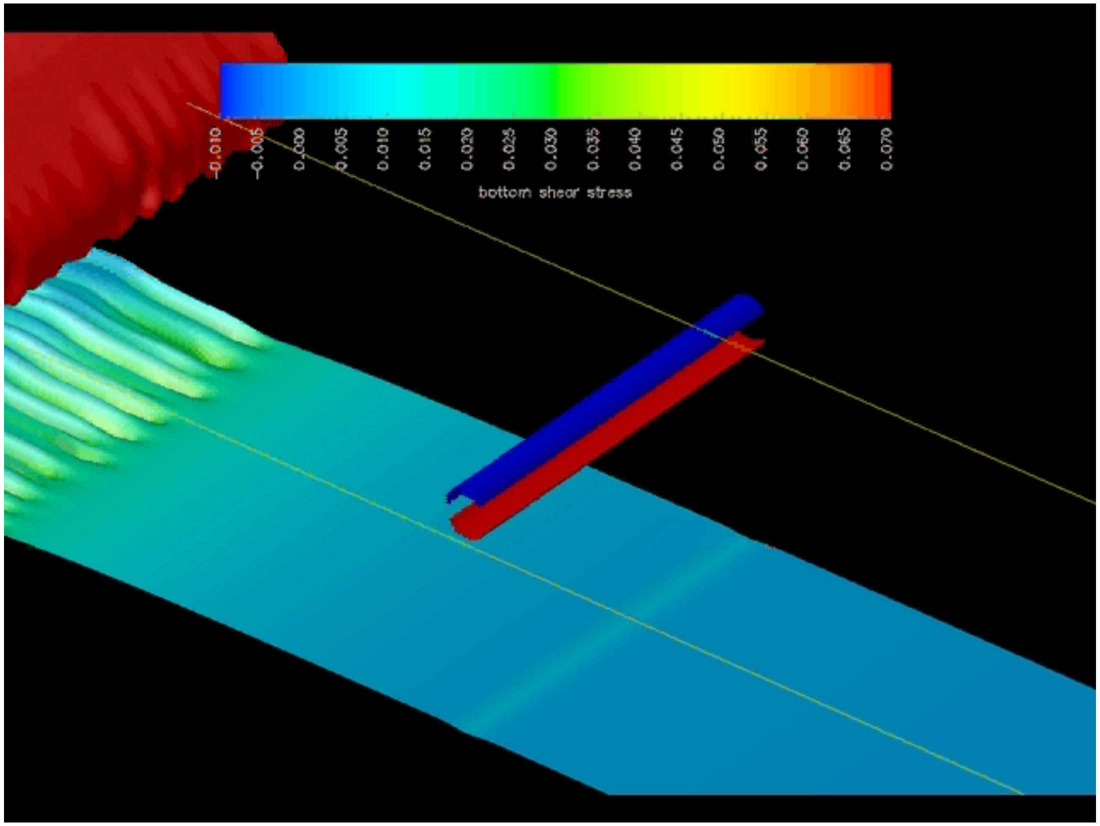
$$\frac{u_\tau}{V} = \sqrt{\frac{|\tau_w|}{\rho_0 V^2}}$$



- *longitudinal structures, maximum under the cylinder*

Results: Wall shear stress (cont'd)

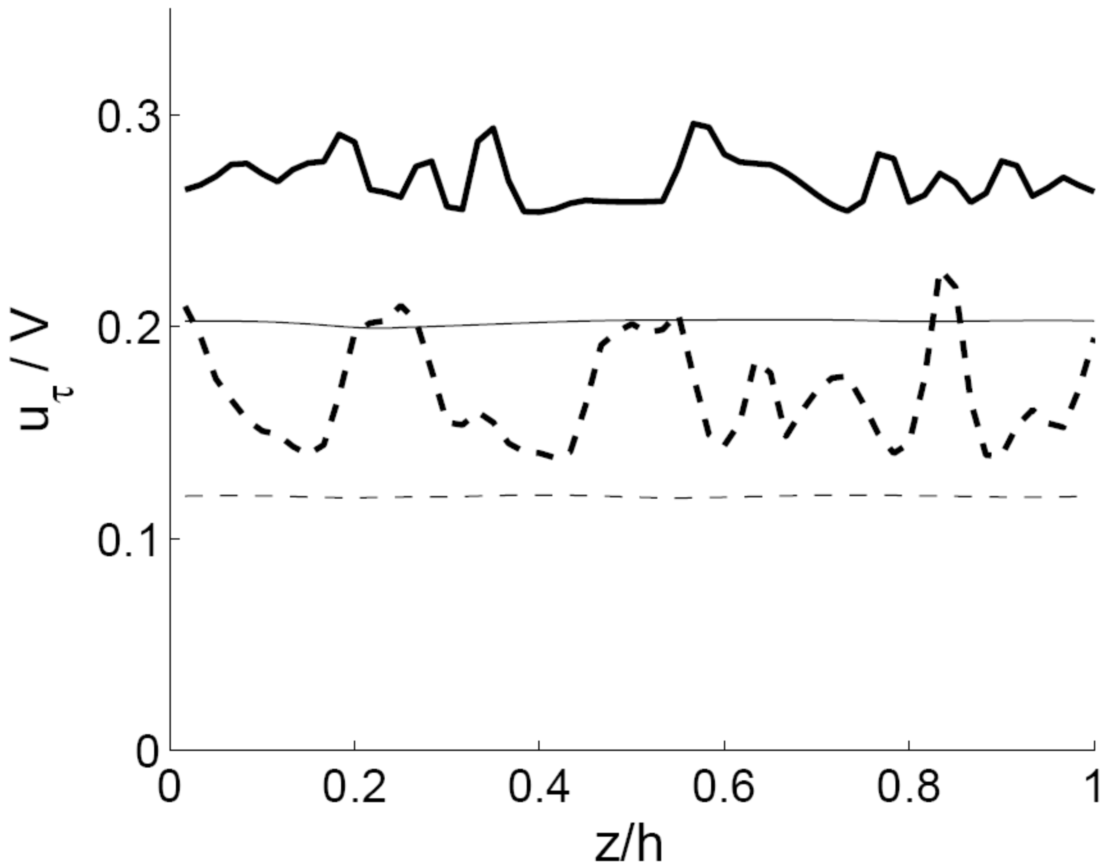
Friction velocity:



- *longitudinal structures, maximum under the cylinder*

Results: Influence of gap size

Friction velocity below the cylinder:



thick lines : impact

thin lines : quasisteady

————— *: small gap*

- - - - - - - - *:large gap*

- *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 ≥ cylinder diameter, the structure is similar to uniform flow past cylinder*
- *for gap sizes « 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 → potential for localized scour*

Acknowledgments

- *IGERT fellowship for Esteban Gonzalez-Juez*