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A turbulence-resolving Eulerian two-phase model for coastal sediment transport applications

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Motivation

- The coastal zone is a very important **human habitat** of high ecological diversity and critical economic importance. Over 38% of the world's population lives within 100 km of the coast or estuaries (1995, from *World Resource Institute*).

- **Accelerated sea-level-rise**, due to the global climate change during the past century, makes coastal zone more vulnerable to natural hazards such as storm surges.

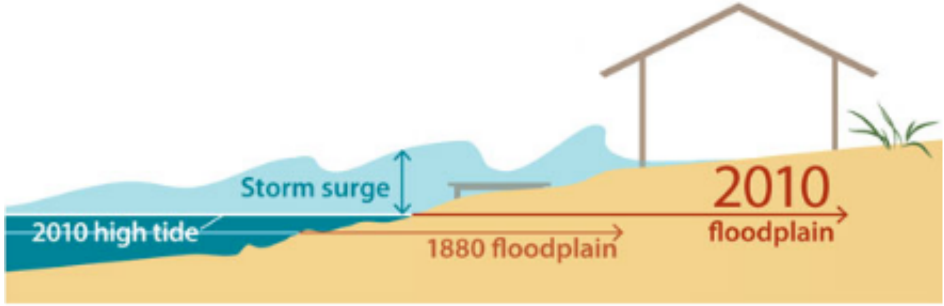
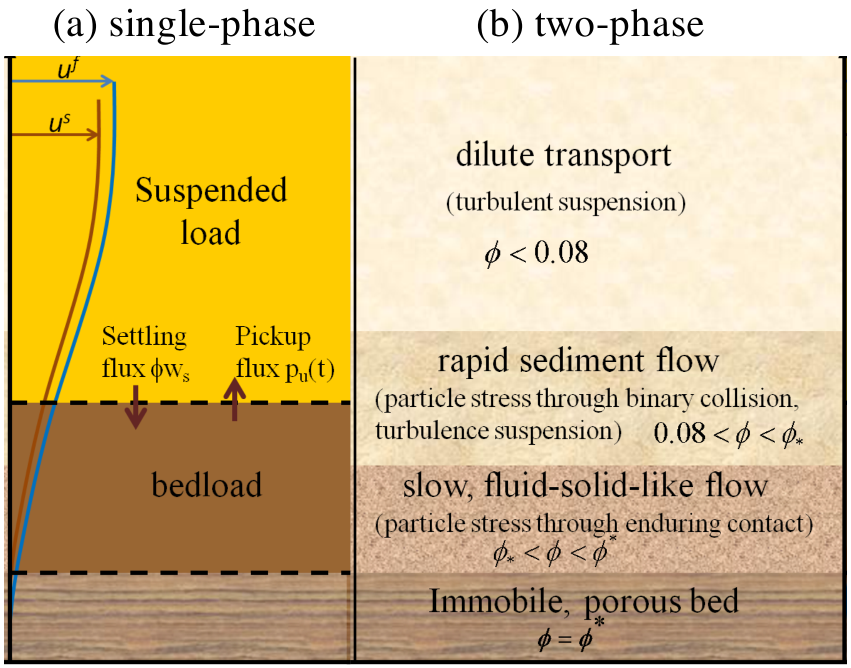


Figure adopted from *https://storm-surge.org/the-science/*

Ortley Beach, Toms River, NJ after Hurricane Sandy. Adopted from *Star Ledger*.

- Studying Sediment transport is essential **for beach erosion and recovery**, however, field evidences suggest that the mechanisms critical in major storm condition were not parameterized properly by state-of-the-art sediment transport models (Foster et al., 2006; Cheng et al., 2016).

Eulerian Two-phase Model for Sediment Transport



Adopted from Yu et al. (2012), *Adv. Water Res.*

Why two-phase model?

- Using two-phase flow equations with closures on interphase momentum transfer (e.g. drag), particle stresses and turbulence-sediment interaction, **full profiles of transport** can be obtained.
- Conventional bedload/suspended load assumptions are not necessary.
- **SedFOAM** (Cheng et al., 2016, *Coastal Engineering*, under revision), an Eulerian two-phase model based on a k-ε turbulence model, is publically available via Community Surface Dynamics and Modeling System (**CSDMS**) model repository maintained by GitHub.
- A CSDMS clinic was hosted on SedFOAM in 2015: https://csdms.colorado.edu/wiki/CSDMS_2015_annual_meeting_Tom_Hsu

SedFOAM (Cheng et al., *Coastal Eng*., in revision)

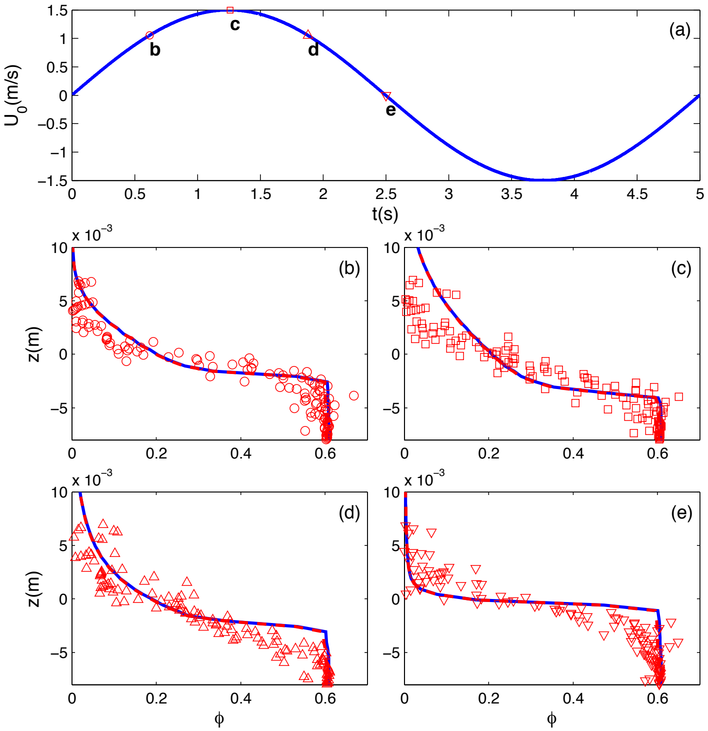
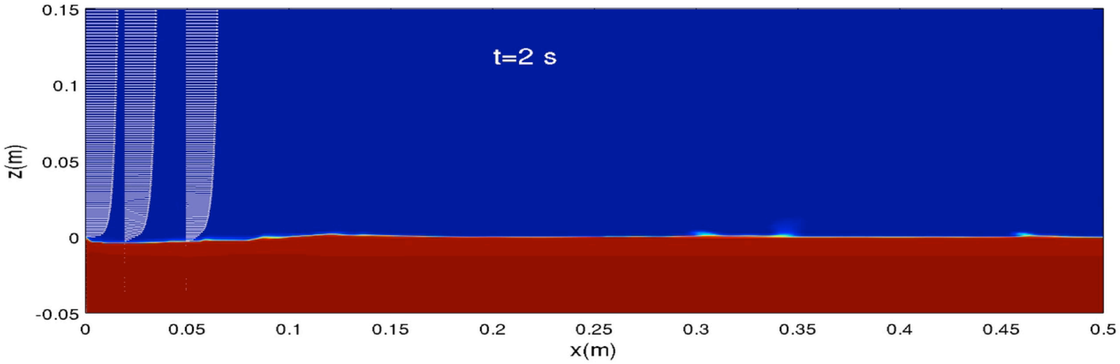


Figure. Modeled (solid curve) and measured (symbols) concentration profiles at four instants in M5010 experiment of O’Donoghue and Wright (2004)

- SedFOAM has been validated with oscillatory sheet flow experiment (O’Donoghue and Wright, 2004)
- It has been used by many researchers for different applications such as scour problems.

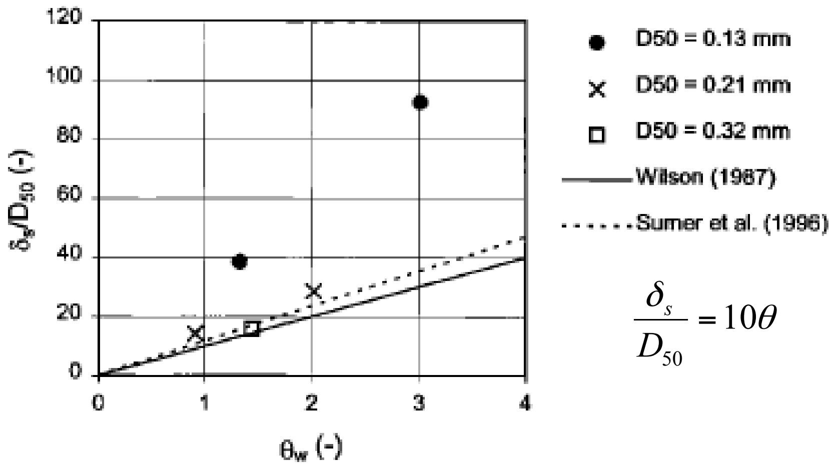


Movie. Scour downstream an apron, u_f=3.69 cm/s, d=0.25 mm

Why turbulence-resolving:

- In turbulence-averaged models, closure of turbulence-sediment interactions is highly empirical.
- For oscillatory sheet flow:
  - Turbulence-averaged two-phase model works reasonably well for **medium to coarse sand**.
  - Most existing models including turbulence-averaged two-phase model fail to predict enhanced transport thickness for **fine sand** (i.e., sand with $d_{50} < 0.15$ mm)

How can we do a better job for fine sand?



$$\frac{\delta_s}{D_{50}} = 10\theta$$

Dohmen-Janssen et al. (2001), *JGR*.

Hypothesis:

1. Turbulence-sediment interactions are critical for fine sand.
2. Typical wave conditions in coastal environment are transitionally turbulent (especially during flow reversal).

→ A turbulence-resolving simulation approach is needed

Filtered Eulerian two-phase flow equations:

☐ Mass Conservation Equations

$$\frac{\partial \rho^f(1-\bar{\phi})}{\partial t}+\frac{\partial \rho^f(1-\bar{\phi})\bar{u}_i^f}{\partial x_i}=0,$$

$$\frac{\partial \rho^s\bar{\phi}}{\partial t}+\frac{\partial \rho^s\bar{\phi}\bar{u}_i^s}{\partial x_i}=0,$$

ρ^f, ρ^s	fluid and sediment density
$\bar{\phi}$	filtered sediment concentration
$\bar{u}_i^f, \bar{u}_i^s$	filtered fluid and sediment velocities

☐ Momentum Equations

$$\frac{\partial \rho^f\left(1-\bar{\phi}\right)\bar{u}_i^f}{\partial t}+\frac{\partial \rho^f\left(1-\bar{\phi}\right)\bar{u}_i^f\bar{u}_j^f}{\partial x_j}=-(1-\bar{\phi})\frac{\partial \bar{p}^f}{\partial x_i}+\frac{\partial \bar{\tau}_{ij}^f}{\partial x_j}+\rho^f(1-\bar{\phi})g\delta_{i3}+\bar{M}_i^{fs},$$

$$\frac{\partial \rho^s\bar{\phi}\bar{u}_i^s}{\partial t}+\frac{\partial \rho^s\bar{\phi}\bar{u}_i^s\bar{u}_j^s}{\partial x_j}=-\bar{\phi}\frac{\partial \bar{p}^f}{\partial x_i}-\frac{\partial \bar{p}^s}{\partial x_i}+\frac{\partial \bar{\tau}_{ij}^s}{\partial x_j}+\rho^s\bar{\phi}g\delta_{i3}+\bar{M}_i^{sf}.$$

- Fluid and sediment momentum coupling are dominated by **drag force**: M_i^{fs}, M_i^{sf}.
- Fluid stresses are modeled with sub-grid turbulence model (Germano, 1991).
- Particle stresses due to collisions and frictions are modeled with kinetic theory for granular flow and frictional stress models (Ding and Gidaspow, 1990; Srivastava and Sundaresan, 2003).

Sub-grid model:

Turbulence-resolving: Eulerian two-phase equations are solved in 3D with a domain size sufficiently larger than the largest eddies and high numerical resolution (on the order of grain size).

➡ Large eddies/structures are directly **resolved**, and effect of small eddies/structures on large scale motions are **modeled** with sub-grid closures:

For fluid and particle sub-grid stress:

$$\overline{u_i^f u_j^f} - \overline{u}_i^f \overline{u}_j^f = -2\nu_{sgs}^f S_{ij}^f \qquad \nu_{sgs}^f = C_s(\Delta)^2\left|S^f\right| \qquad \text{where, } \left|S^f\right| = \sqrt{2S_{ij}^f S_{ij}^f} \qquad \Delta = \left(\Delta_x \Delta_y \Delta_z\right)^{1/3}$$

The coefficient C_s is determined using a dynamic procedure (Germano, 1991), and similar closures are used for **sediment sub-grid stress**.

For sub-grid contribution of drag:

Ozel et al. (2013): mesoscale structures of sediment particles such as **streamer** and **clusters**, may not be resolved by the mesh size, and they can have a dramatic effect on the overall sediment dynamics.

The effect of unresolved mesoscale structure can be accounted by a sub-grid drag correction:

$$\overline{\phi(u_i^f - u_i^s)} = \left(1 + K\right)\overline{\phi}(\overline{u}_i^f - \overline{u}_i^s)$$

The coefficient K depends on grid size and sediment concentration, and it's determined by using a dynamic procedure (Ozel et al., 2013).

Model Validation - Sheet flow in steady channel flow

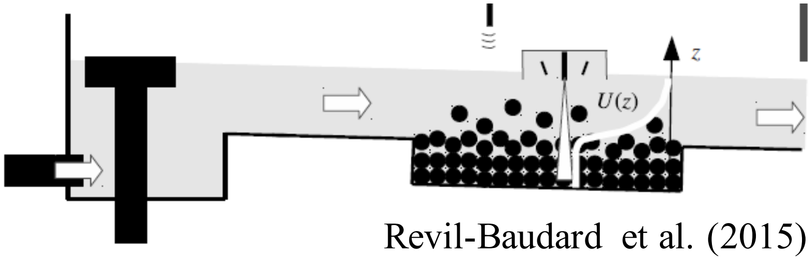
LEGI experiment (Revil-Baudard et al., 2015, *JFM*):

Colocated two-component velocities (u, w) and sediment concentration (ϕ) are measured.

Flow condition: $u_* = 5$ cm/s, $h = 0.13$ m

Sediment properties: $s = 1.192$, $d = 3$ mm, $W_s = 5.59$ cm/s

Shields parameter: $\theta = \dfrac{u_*^2}{(s-1)gd} \approx 0.5$



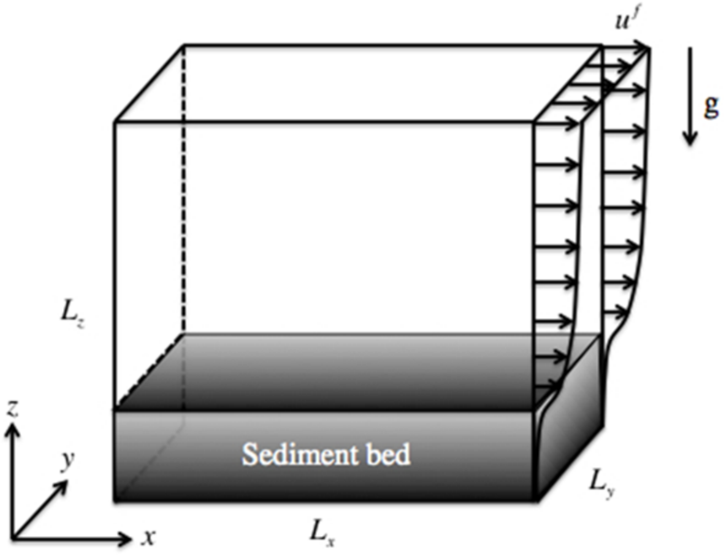
Revil-Baudard et al. (2015)

Numerical simulation:

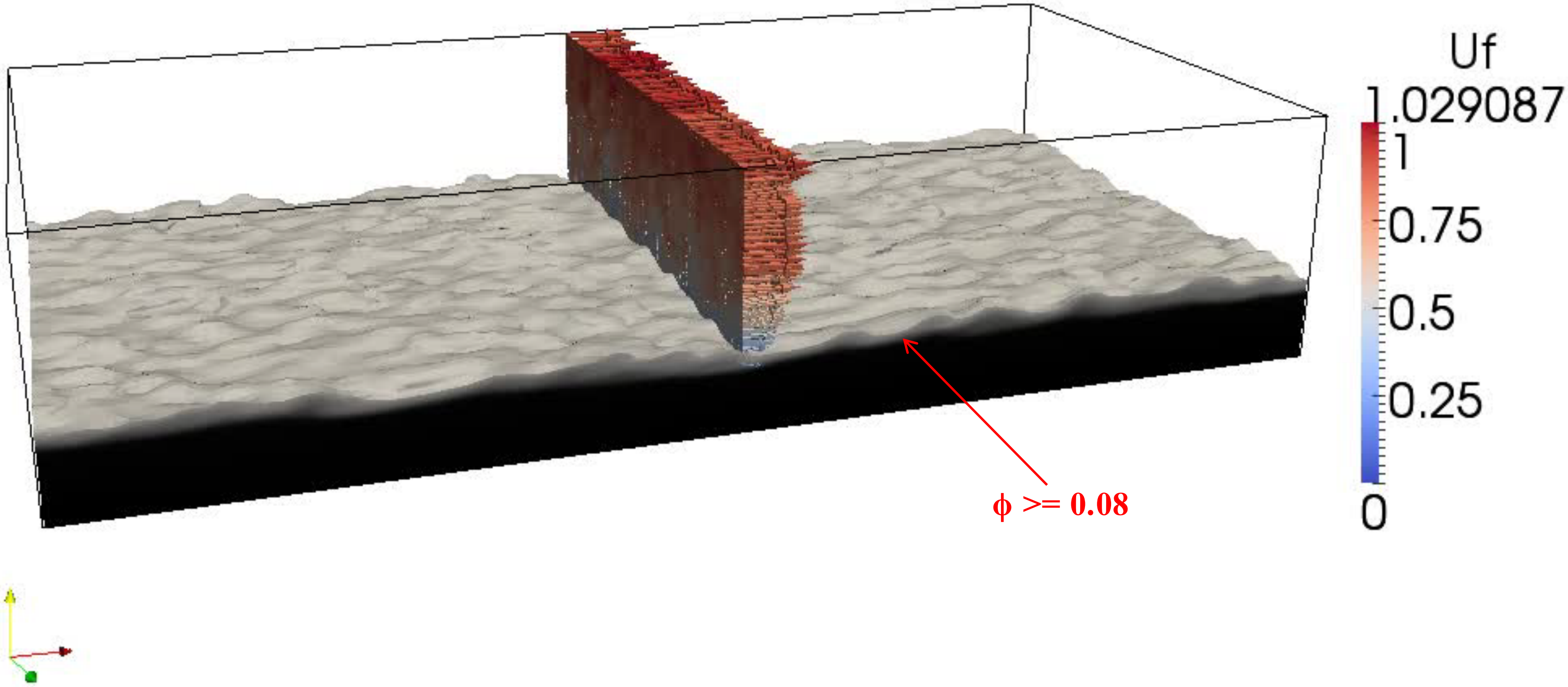
$L_x = 0.844$ m $L_y = 0.422$ m $L_z = 0.175$ m ($z_b = 0.045m$)

$\Delta x = \Delta y = 6.6$ mm $\Delta z = 0.4 \sim 2.2$ mm

Domain size and grid resolution are verified by velocity fluctuation correlation and energy spectrum.



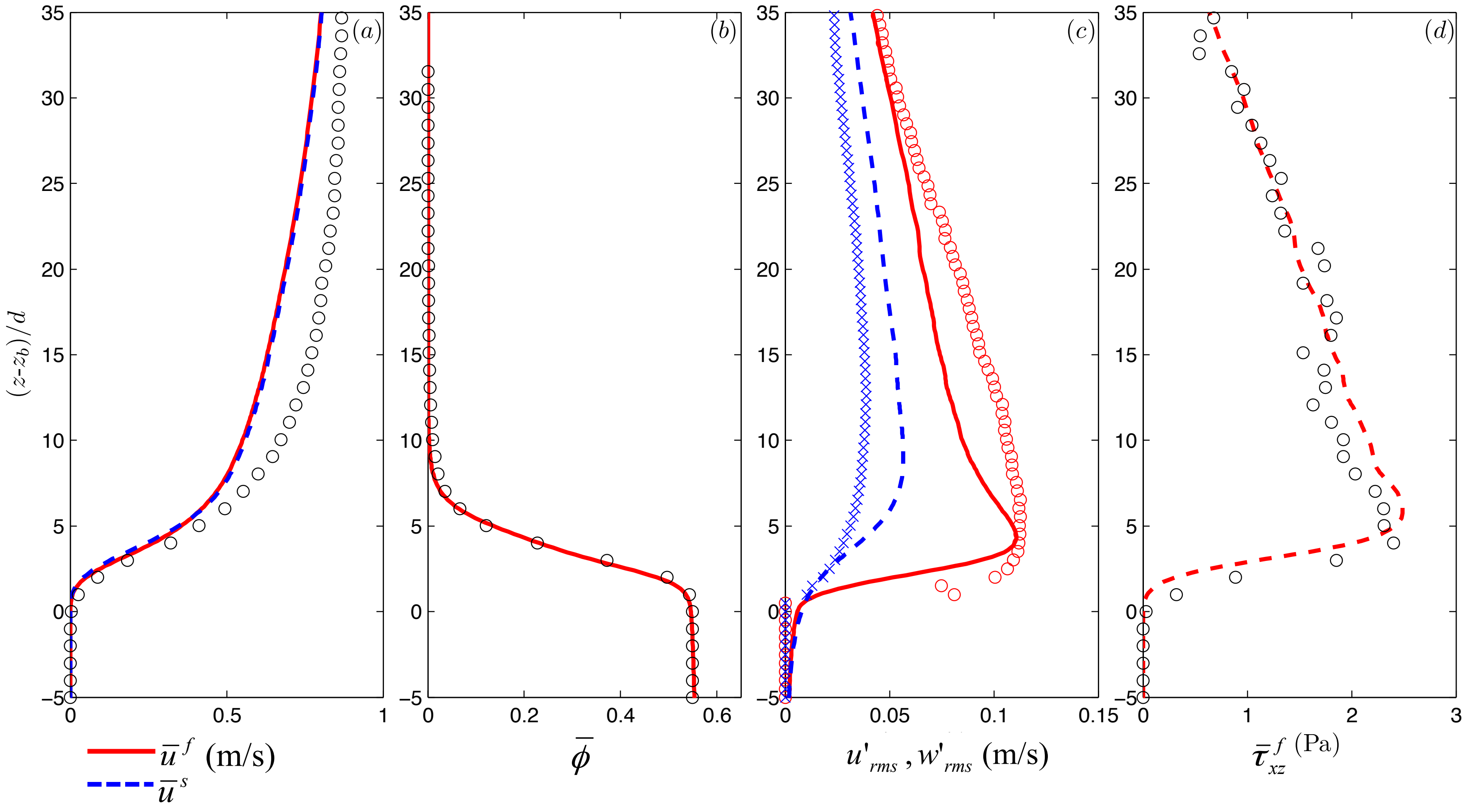
3D view- Sheet flow in steady channel flow



φ >= 0.08

Ensemble-averaged flow statistics

Symbols: measure data (Revil-Baudard et al., 2015, *JFM*)
Curves: simulation results



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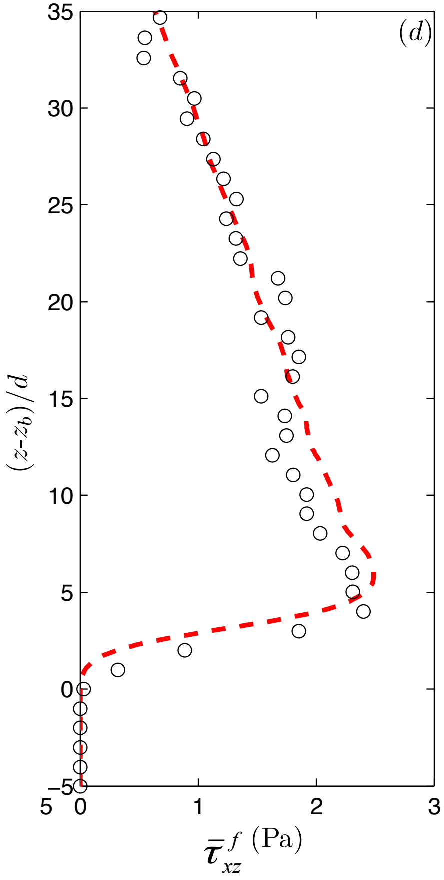

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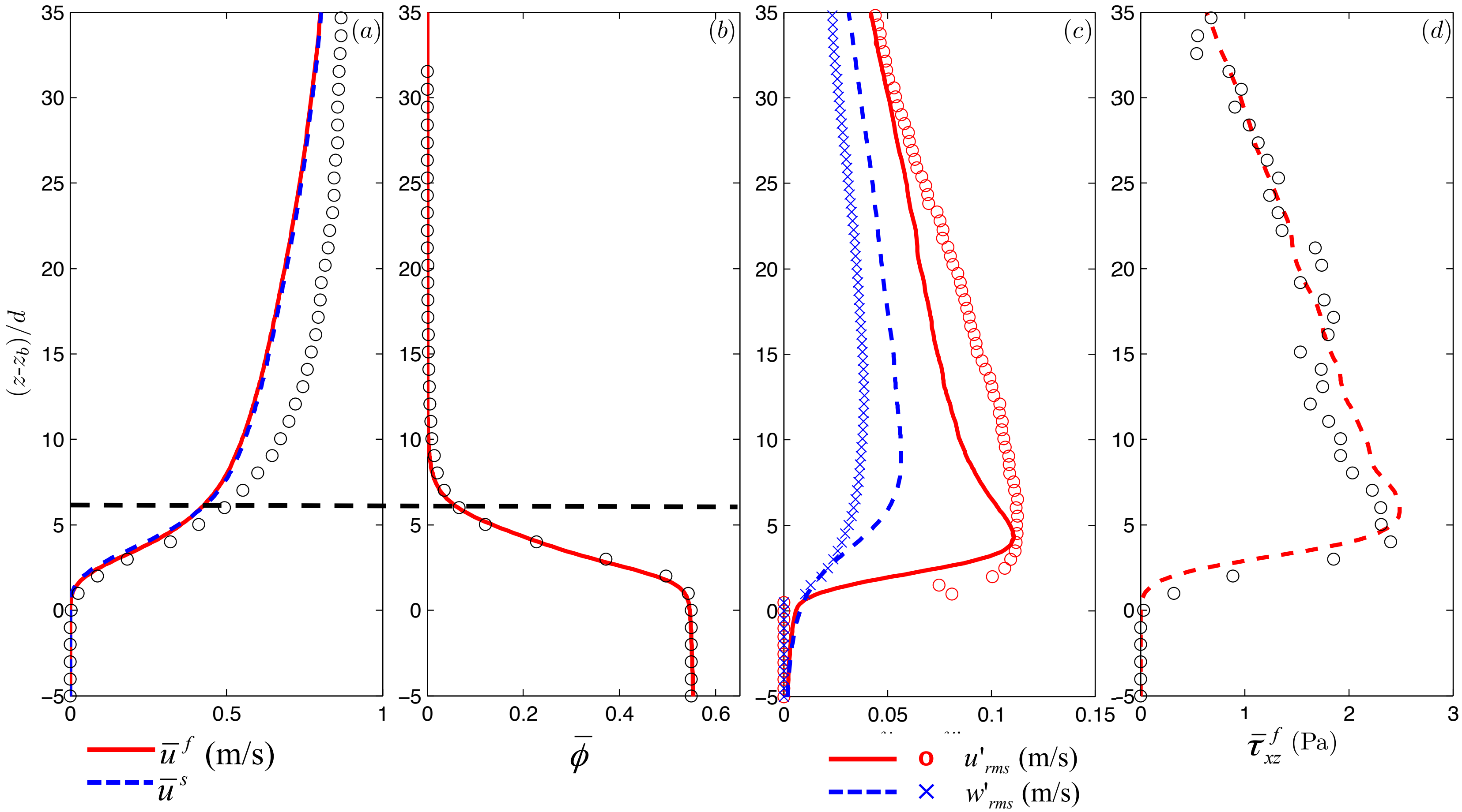


Evidence of attenuated fluid turbulence by sediments

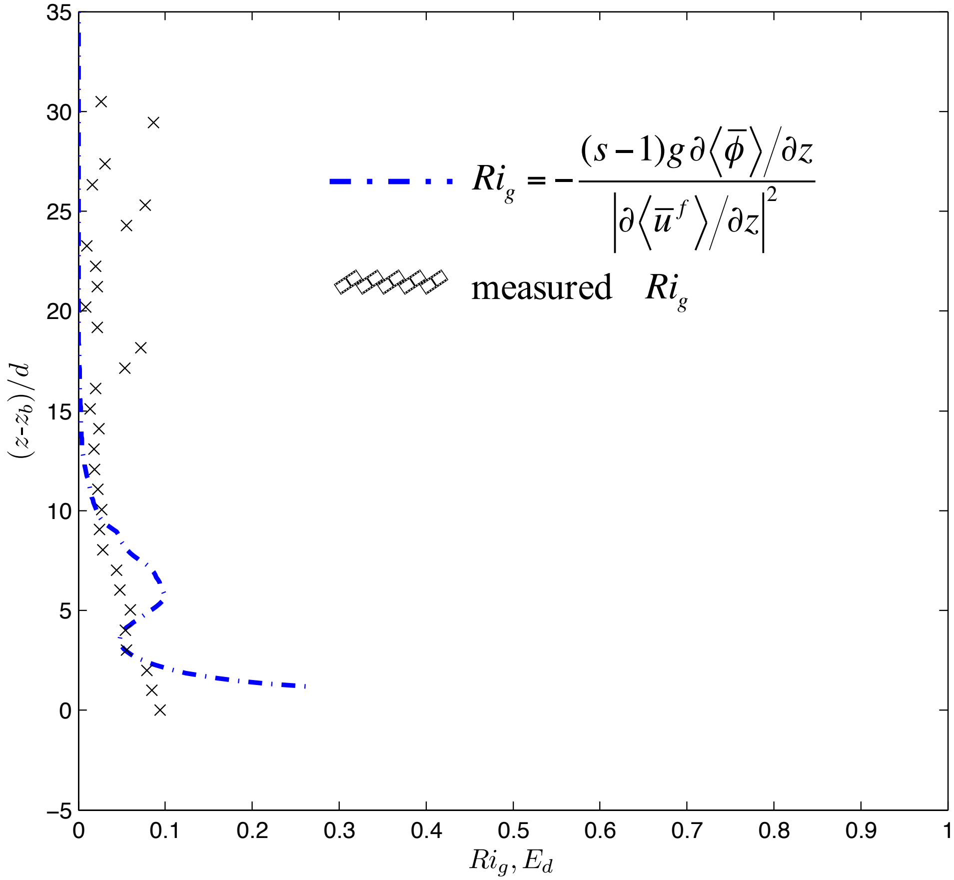
Rough-wall log law velocity profile:

$$\langle \overline{u}^f \rangle (z) = \frac{u_*}{\kappa} \ln\left(\frac{z - z_b}{z_0} \right)$$

Reduction of von Karman constant:

Measured: **κ= 0.23**
Modeled: **κ= 0.2**
< Clear fluid: κ= 0.41

Sediment-induced **density stratification** can damp fluid turbulence



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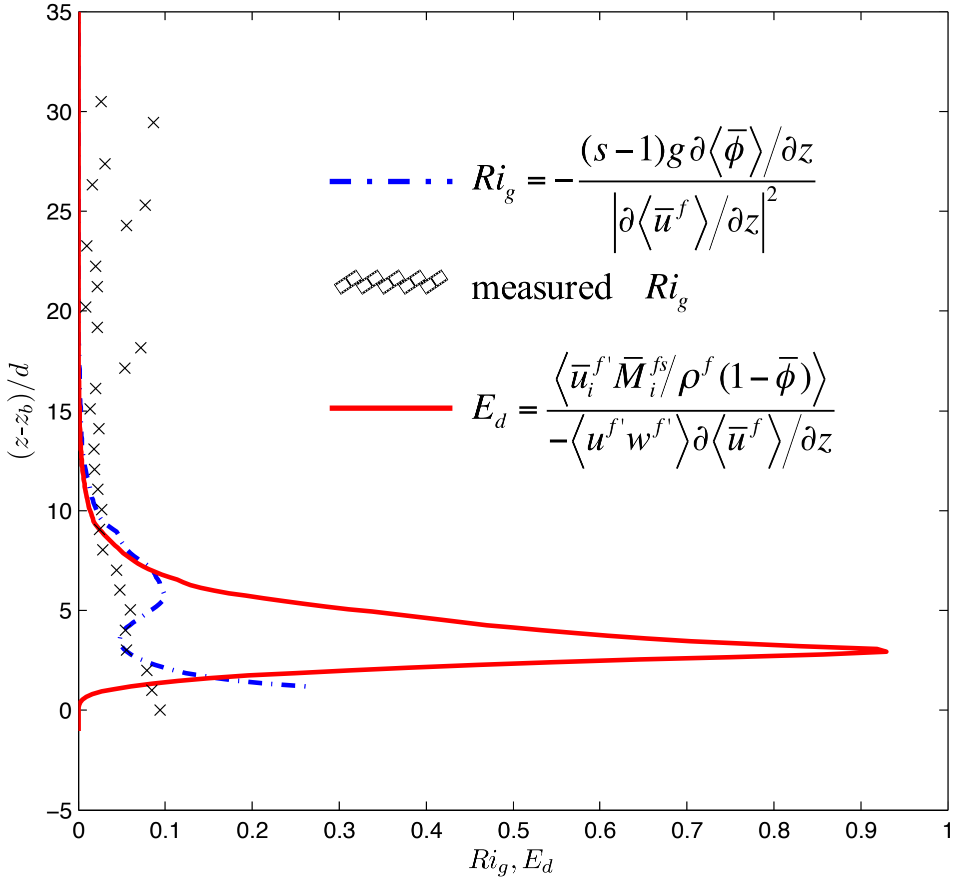
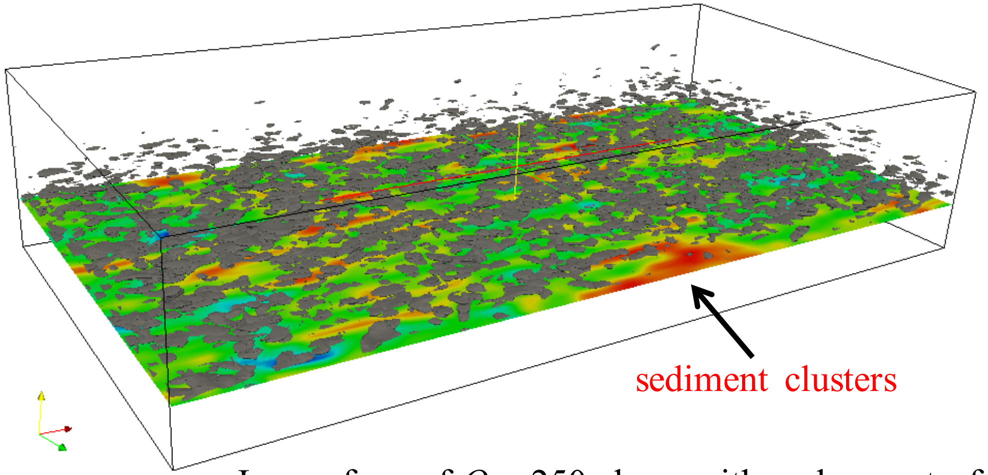
Sediment-induced **density stratification** can damp fluid turbulence, however, it's playing a minor role comparing to **drag induced turbulence damping effect** for this flow condition and sediment (W_s/u_*=1.1).



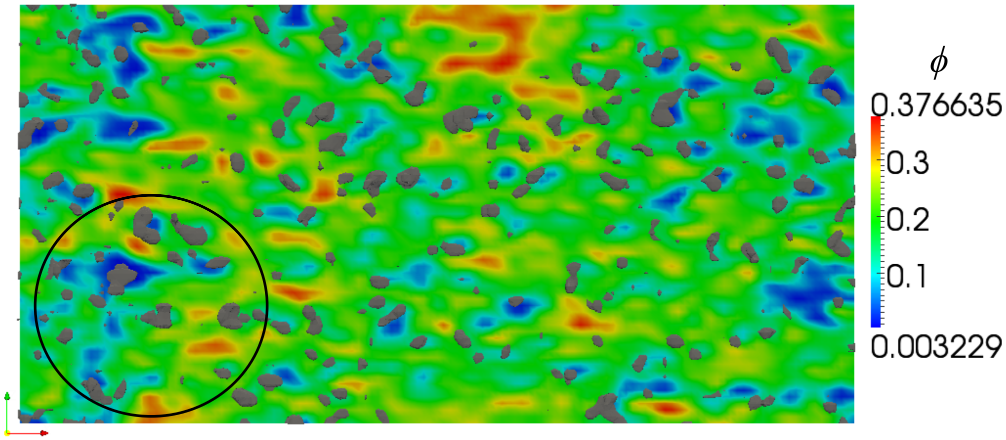
Preferential concentration

Heavy particles are preferentially biased to regions of **high strain rate** and **low vorticity** (Wang and Maxey, 1993), and second invariant Q is used to identify these regions (Chakraborty et al., 2005):

$$Q = \frac{1}{2}(|\Omega|^2 - |S|^2)$$



Iso-surface of $Q = 250$ along with a plane cut of sediment concentration at $(z-z_d)/d=4$, $<\phi>=0.2$



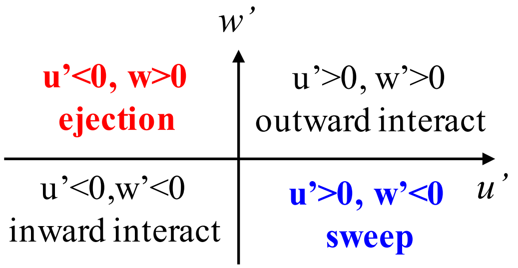
Plane-view of $Q = 250$ (gray color) and concentration fields.

$Q>0$ → low ϕ

Similar phenomenon are also reported by Cheng et al. (2015, *Computers & Geosciences*).

Intermittency

Turbulent motions:



w’

u’<0, w>0

ejection

u’>0, w’>0

outward interact

u’<0,w’<0

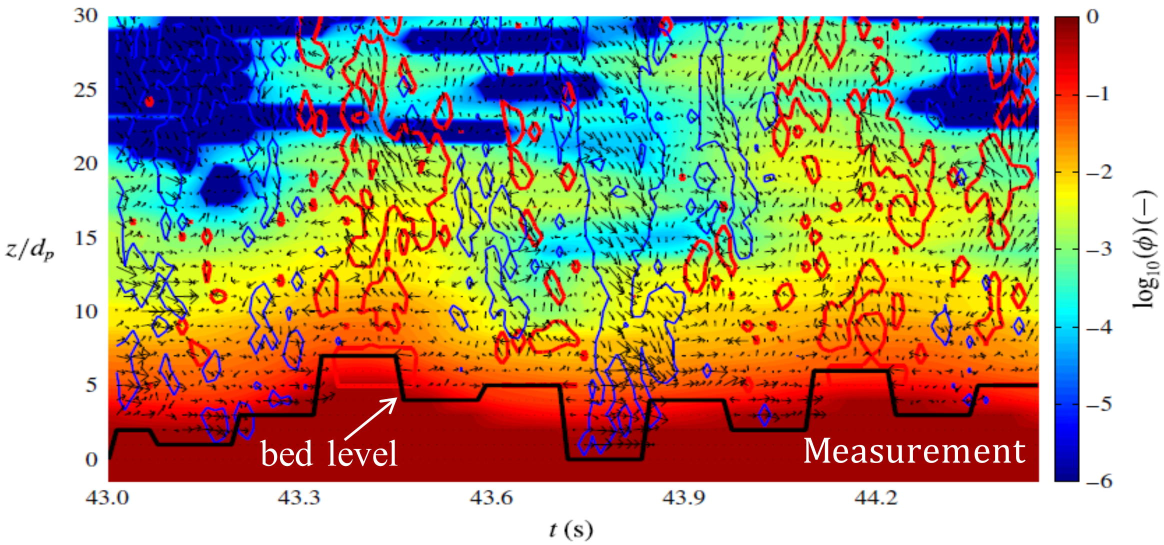
inward interact

u’>0, w’<0

sweep

u’

Wallace (2016), *Ann. Rev. Fluid Mech.*



(Revil-Baudard et al., 2015, *JFM*)

— Ejection

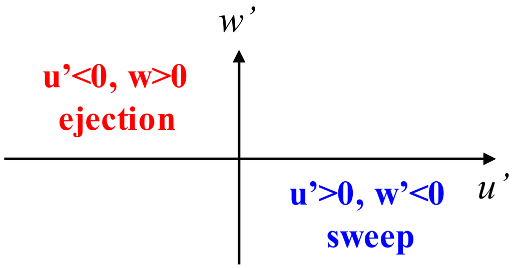
- Increase of bed level

— Sweep

- Drop of bed level

Intermittency

Turbulent motions:



u'<0, w>0
ejection

u'>0, w'<0
sweep

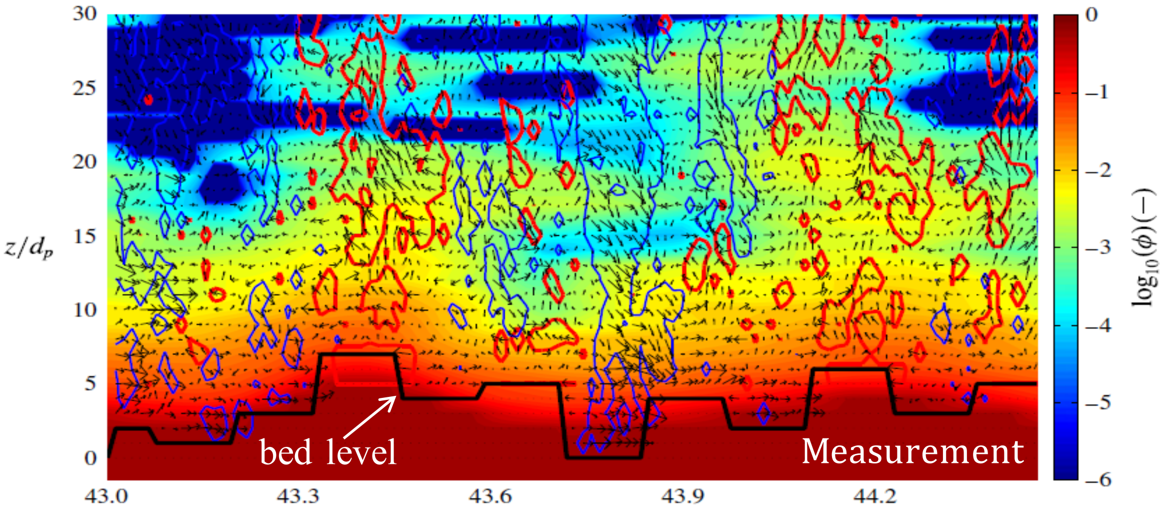
Wallace (2016), *Ann. Rev. Fluid Mech.*

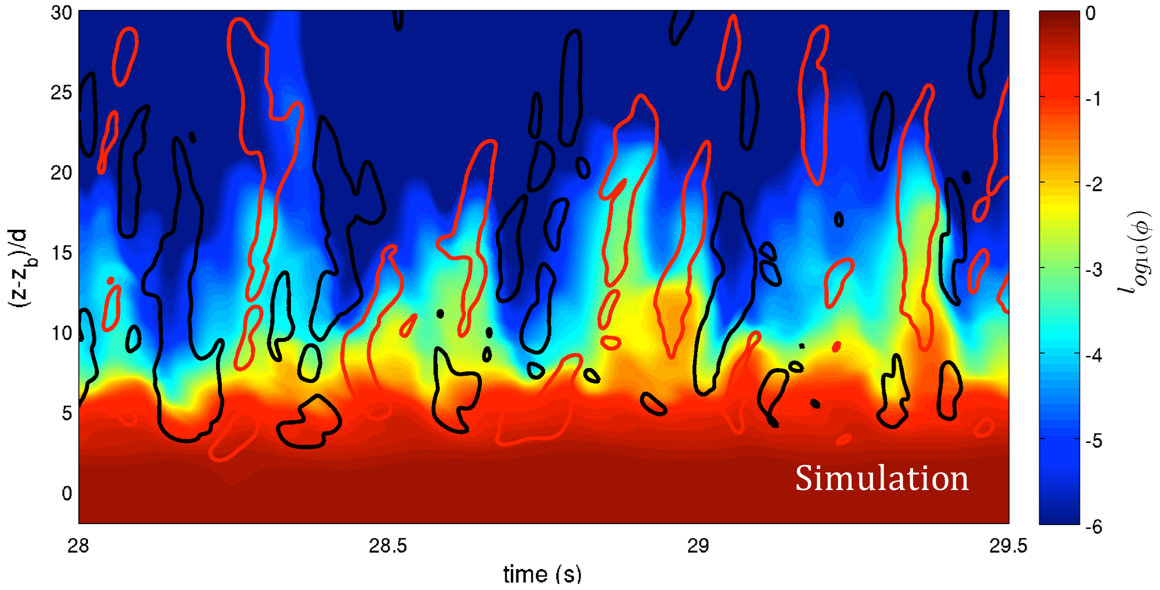
— Ejection

Increase of bed level

— Sweep

Drop of bed level





Concluding Remarks

Findings:

- Turbulence-resolving two-phase Eulerian model is developed and validated with LEGI steady sheet flow experiment.
- Drag-induced turbulence attenuation becomes more important than the density stratification in LEGI experiment.
- Model is able to capture sediment preferential concentration.

Further investigations:

- Streamwise velocities and sediment suspension is under-predicted in the dilute region.
- The inward/outward interaction events are under-predicted by our model (not reported).
- More quantitative analysis of bed intermittency are needed.

Thank you!

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