Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
— Two-Phase Continuum Models for Geophysical Particle-Fluid Flows

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

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Content

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2. Turbulence-averaged two-phase modeling of sediment transport
3. Turbulence-resolving two-phase simulation of sediment transport
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Motivation – beach erosion/recovery

Onshore/offshore sediment transport mechanisms

- Wave skewness (e.g., Ruessink et al. 2007).
- Wave boundary layer streaming (e.g., Henderson et al. 2004).
- Wave asymmetry (e.g., Drake & Calantoni 2001).
- Undertow currents (e.g., Gallagher et al. 1998).
- Breaking wave turbulence (e.g., Beach & Sternberg 1996; Sumer et al. 2013).

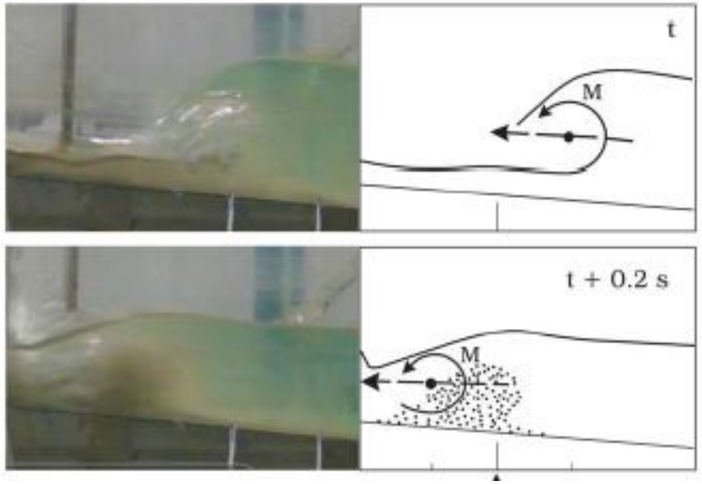
Ruessink and Kuriyama (2008), *GRL:*

"cross-shore sandbar migration on the timescale of years is deterministically forced … unpredictability of sandbar migration results primarily from **model inadequacy during major wave events**."

Hypothesis and Research Question:

- Transport mechanisms critical in major storm condition were not parameterized properly.
- Can nearshore sediment transport be solely parameterized by bottom shear stress (or free-stream velocity just above the wave bottom boundary layer)?

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

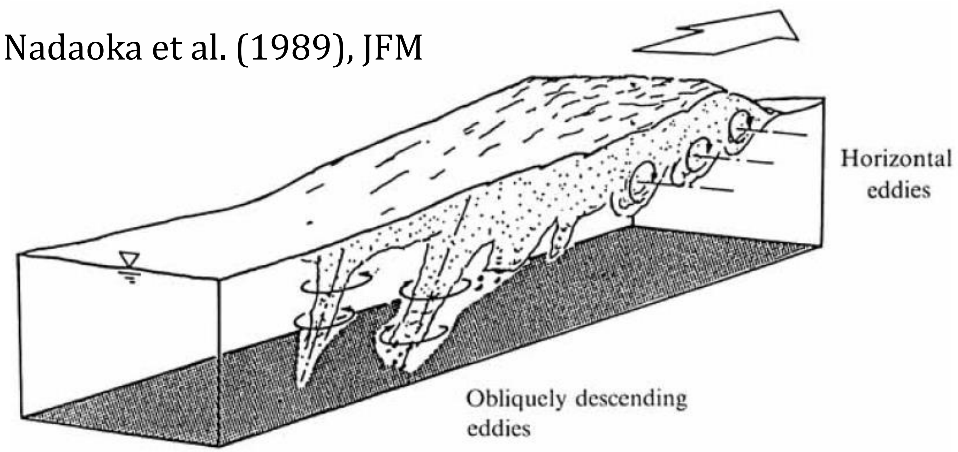


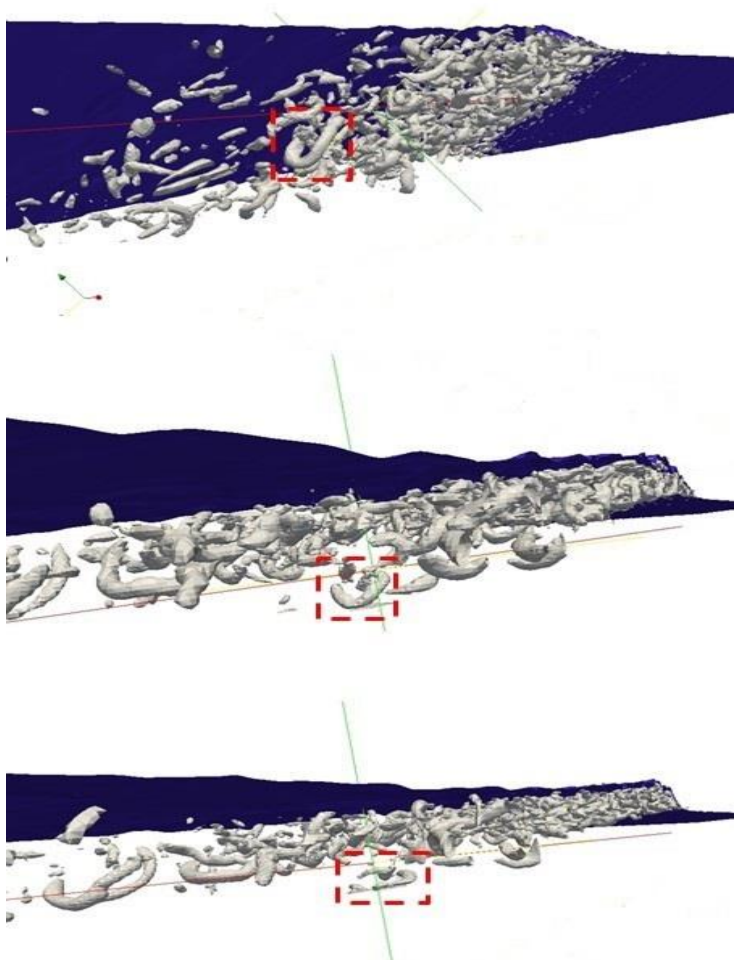
Sediment plume initiated by a plunging breaker. Adopted from flume experiment of Sumer et al. (2013), JGR

Motivation – sediment transport under breaking waves

- Nadaoka et al. (1989) observed horizontal eddies around the wave crest, which further evolve into obliquely descending eddies (ODEs).
- The generation and evolution of coherent structures are observed by PIV (e.g., Ting 2008) and reproduced by 3D Large-Eddy Simulation (e.g., Watanabe et al. 2005; Zhou et al. 2014; Farahani & Dalrymple, 2013).
- Zhou et al. (2014) demonstrated that ODEs are essentially hairpin vortices commonly observed in shear instabilities, and some of them can interact with the bed.

Nadaoka et al. (1989), JFM





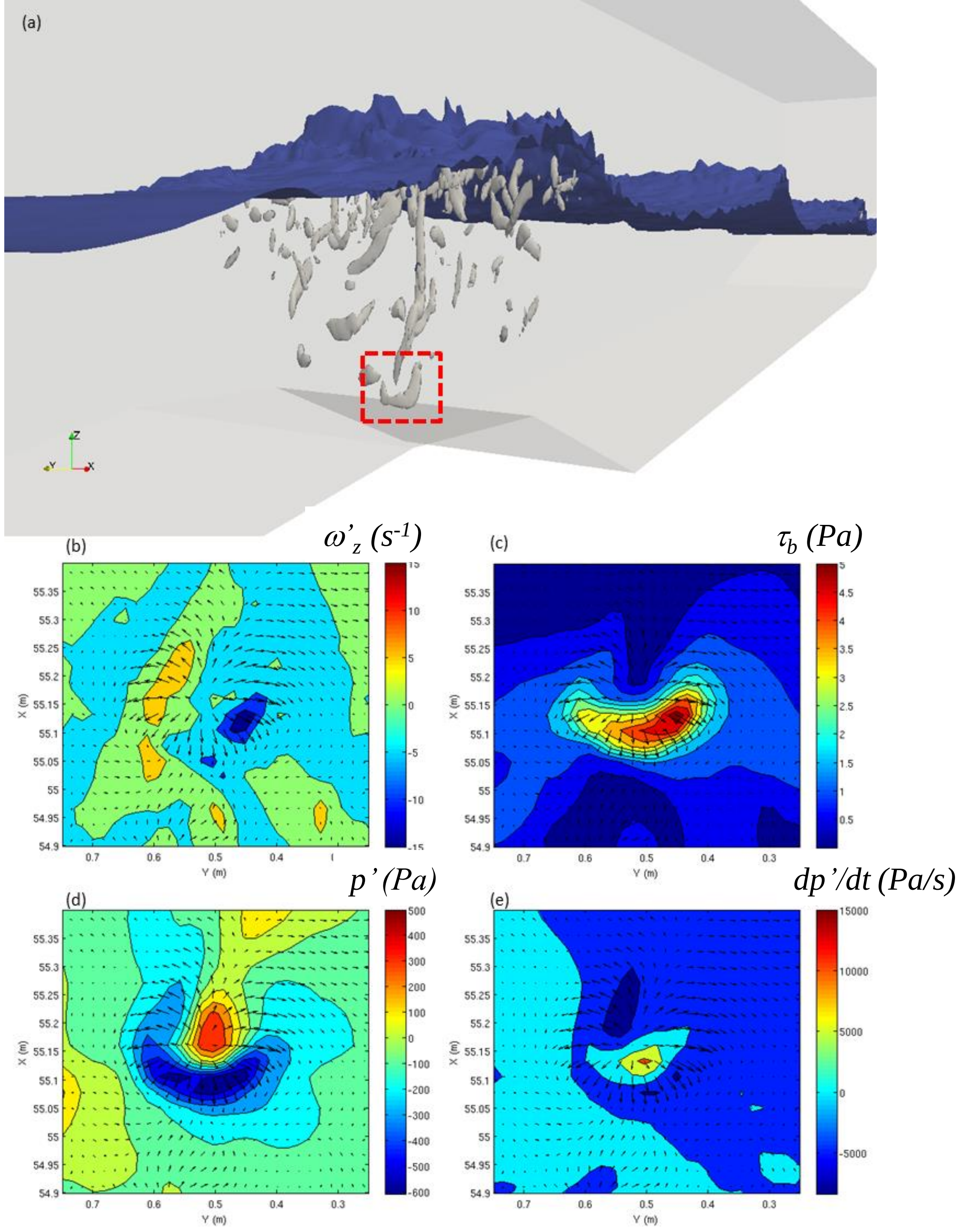
Zhou, Sangermano, Hsu, Ting (2014), JGR - Ocean

Large –eddy simulation of wave-breaking induced turbulent coherent structures and suspended sediment transport on a barred beach – by Z. Zhou, T.-J. Hsu, D. Cox, X. Liu, manuscript in preparation.

Counter-rotating & downburst features of obliquely descending eddies are captured in LES similar to PIV observation reported by Ting (2008), Coastal Eng.

Turbulent coherent structures can induce large bottom shear stress and horizontal pressure gradient.

Need to understand sediment transport driven by concurrent action of large bottom shear stress and large horizontal pressure gradient.



Sand transport - background

1. Transport mode (ripples, sheet flow) and amount of transport are parameterized by the Shields parameter (non-dimensional bottom shear stress).

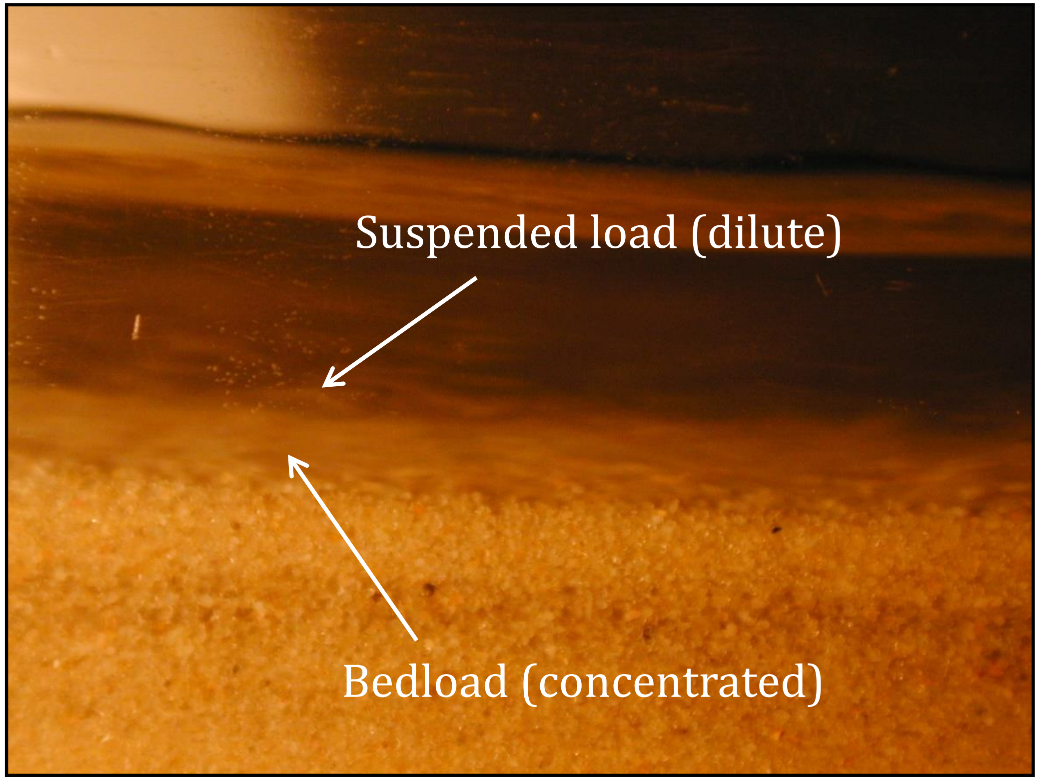
   For waves, Shields parameter is estimated based on peak flow:

$$\theta_w = \frac{u_{*\max}^2}{(s-1)gd}$$

2. Modeled as **bedload** (concentrated region) and **suspended load** (dilute region).
3. Dilute region is resolved but bedload transport and pickup flux are parameterized.

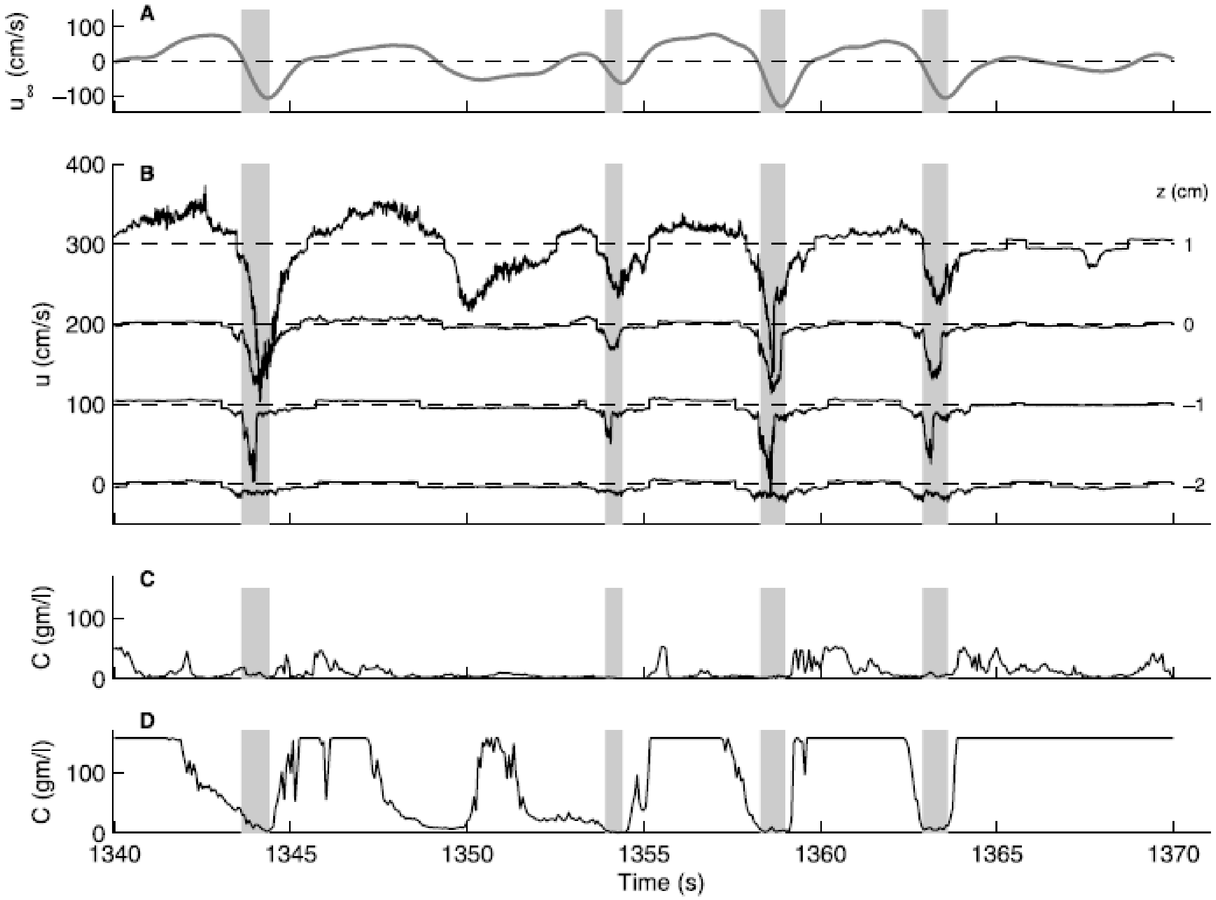
Jenkins, J. T. & Hanes, D. M. 1998 Collisional sheet flows of sediment driven by a turbulent fluid. *J. Fluid Mech.*, 370, 29–52.

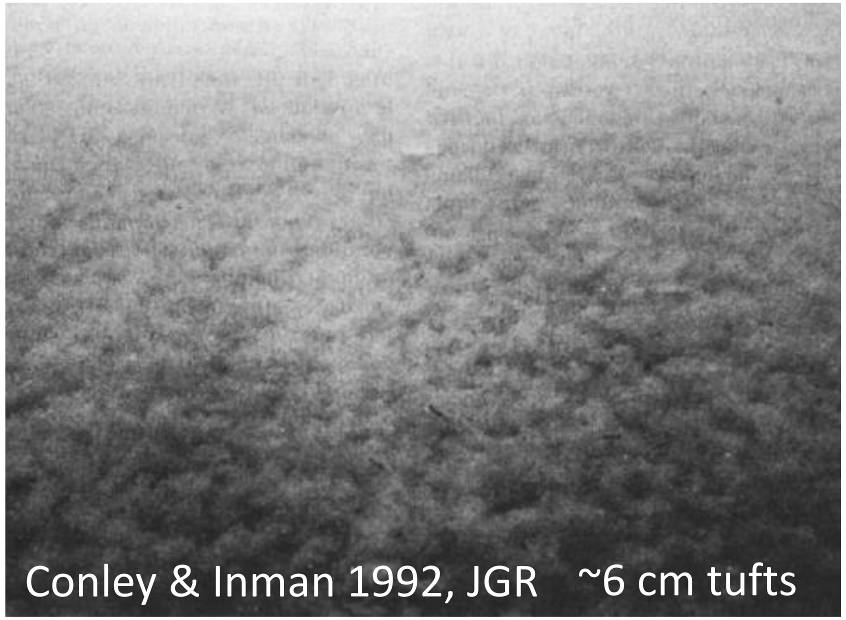
Sheet flow occurs when Shields parameter > 1



Sheet flow with large horizontal pressure gradient

Foster et al. (2006), *JGR-Ocean*: Field evidence of momentary bed failure (plug flow) at Duck, NC, USA:





Sleath (1999), *Cont. Shelf Res.*:

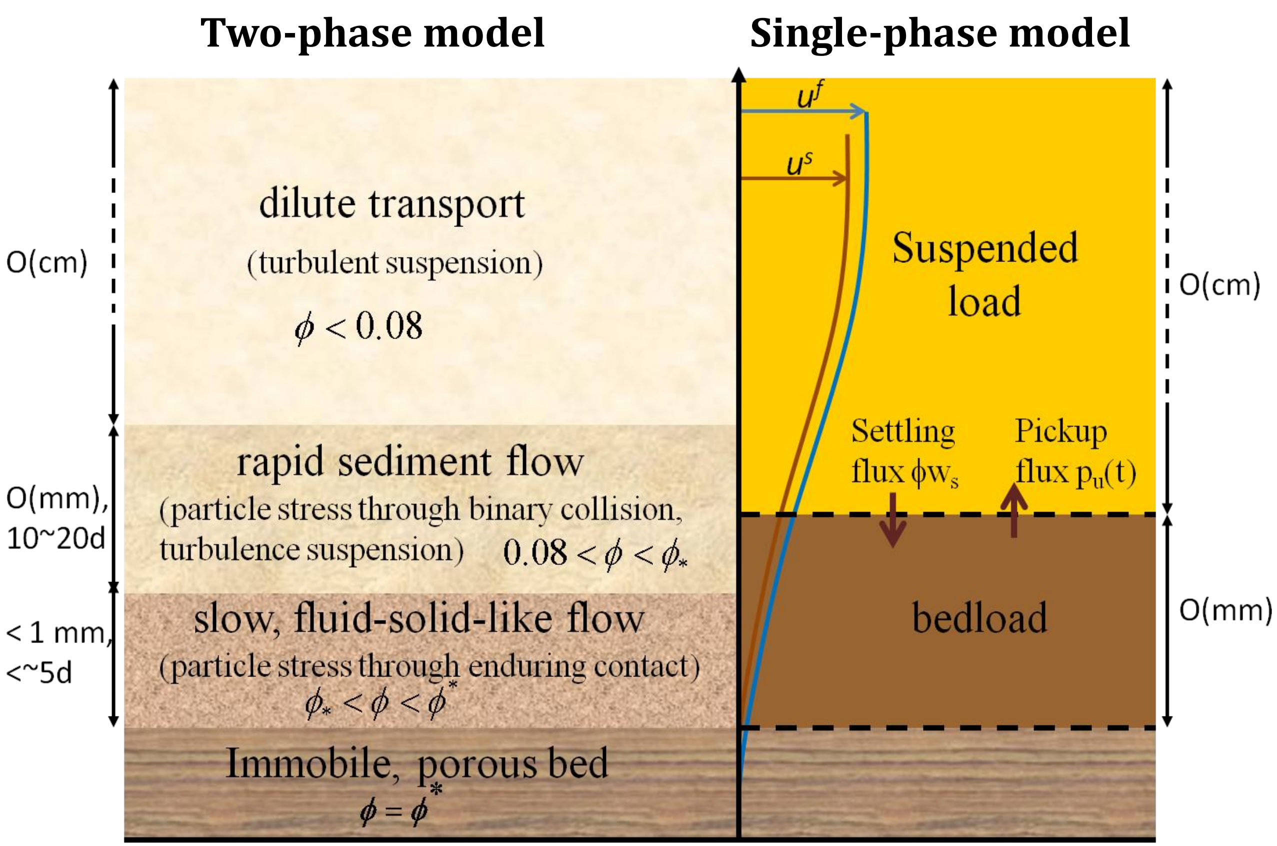
$$\Rightarrow\ S_p = \frac{\partial p/\partial x}{\rho(s-1)g} > 0.33$$

Field evidence suggests that momentary bed failure under intense sheet flow occurs at $S_p > 0.1 \sim 0.2$

To model momentary bed failure, we need to resolve the full profile of sediment transport without bedload/suspended load assumption.

Mathematical Formulation

- **Two-phase equations** - fluid & sediment phases (Drew 1980; Jenkins & Hanes 1998).
- **Turbulence closure**
  - Reynolds-averaged model: eddy viscosity with k-ε equations for two-phase flow (e.g., Hsu et al. 2004). Major sediment suspension is due to turbulent diffusion via drag.
  - Turbulence-resolving model: 3D large-eddy simulation (LES) with Smagorinsky closure. Major sediment suspension is expected to be resolved.
- **Particle stresses**
  - Collisional stress is calculated by kinetic theory (Lun et al. 1984).
  - Normal stress due to enduring contact is calculated by Johnson & Jackson (1990).
  - Frictional viscosity of Srivastava and Sundaresan (2003).



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

Numerical Implementation

3D finite volume, open-source, CFD library of solvers, OpenFOAM – revised from twoPhaseEulerFoam, adding the capability we needed, improve the stability of the solver. SedFOAM is publically available via Community Surface Dynamics and System (CSDMS) model repository maintained by GitHub.

Eulerian Two-phase Equations for Sediment Transport

Fluid continuity: $$\frac{\partial(1-\phi)}{\partial t}+\frac{\partial(1-\phi)u_i^f}{\partial x_i}=0,$$

Sediment continuity: $$\frac{\partial\phi}{\partial t}+\frac{\partial\phi u_i^s}{\partial x_i}=0,$$

Fluid momentum: $$\frac{\partial\rho^f(1-\phi)u_i^f}{\partial t}+\frac{\partial\rho^f(1-\phi)u_i^f u_j^f}{\partial x_j}=-\frac{\partial(1-\phi)p^f}{\partial x_i}+\frac{\partial\tau_{ij}^f}{\partial x_j}+\rho^f(1-\phi)g\delta_{i3}+M_i^{fs},$$

Sediment momentum: $$\frac{\partial\rho^s\phi u_i^s}{\partial t}+\frac{\partial\rho^s\phi u_i^s u_j^s}{\partial x_j}=-\frac{\partial\phi p^f}{\partial x_i}-\frac{\partial p^s}{\partial x_i}+\frac{\partial\tau_{ij}^s}{\partial x_j}+\rho^s\phi g\delta_{i3}+M_i^{sf}$$

ϕ: sediment concentration

u_i^f : fluid phase velocity; p^f : fluid pressure

u_i^s: sediment phase velocity

M_i^{fs}, M_i^{sf} : interphase momentum transfer (drag, drift velocity, pressure correction)

$\tau_{ij}^f, \tau_{ij}^s, p^s$: fluid and particle stresses (closures required)

Balance equation for fluid-phase TKE: $\nu^{ft} = C_\mu \frac{(k^f)^2}{\varepsilon^f}$

$$\frac{\partial k^f}{\partial t} + u_j^f \frac{\partial k^f}{\partial x_j} = \frac{R_{ij}^{ft}}{\rho^f}\frac{\partial u_i^f}{\partial x_j} + \frac{\partial}{\partial x_j}\Big[\Big(\nu^f + \frac{\nu^{ft}}{\sigma_k}\Big)\frac{\partial k^f}{\partial x_j}\Big] - \epsilon^f - \frac{2\beta(1-\alpha)\phi k^f}{\rho^f(1-\phi)}$$
$$-\frac{1}{(1-\phi)}\frac{\nu^{ft}}{\sigma_c}\frac{\partial \phi}{\partial x_j}(s-1)g_j.$$

$$\alpha = e^{-B\cdot St}$$

parameterize how well particles can follow the fluid velocity fluctuations

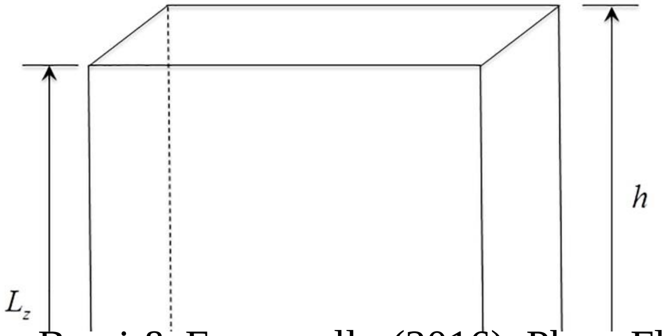
Balance equation for granular temperature, or particle-phase TKE (Hsu, Jenkins & Liu, 2004):

$$\frac{3}{2}\Big[\frac{\partial \phi\rho^s\Theta}{\partial t} + \frac{\partial \phi\rho^s u_j^s\Theta}{\partial x_j}\Big] = \big(-p^{sc}\delta_{ij} + \tau_{ij}^{sc}\big)\frac{\partial u_i^s}{\partial x_j} - \frac{\partial q_j}{\partial x_j} - \gamma_s + J_{int}$$

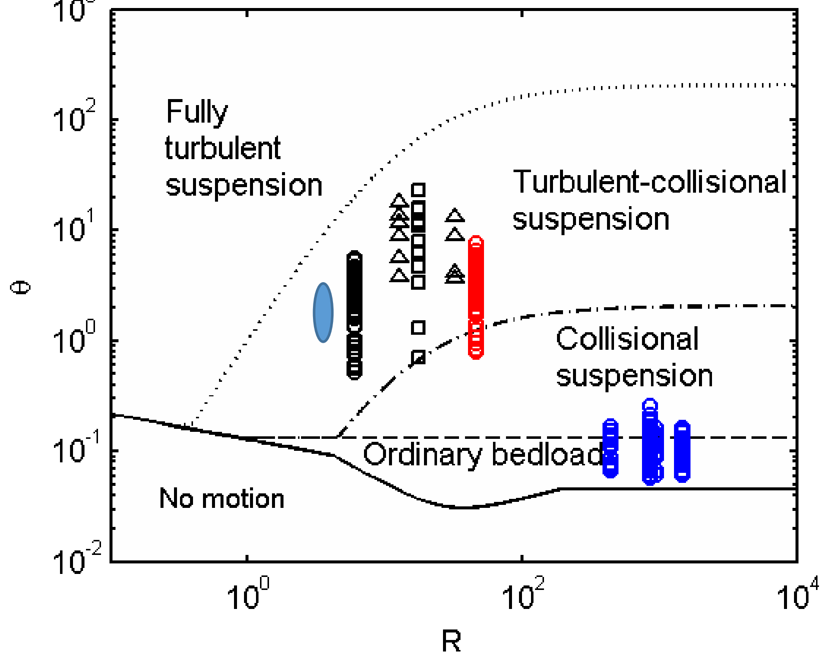
$$J_{int} = \phi\beta(2\alpha k^f - 3\Theta)$$

Sheet flow in steady channel flow – Turbulence-averaged modeling

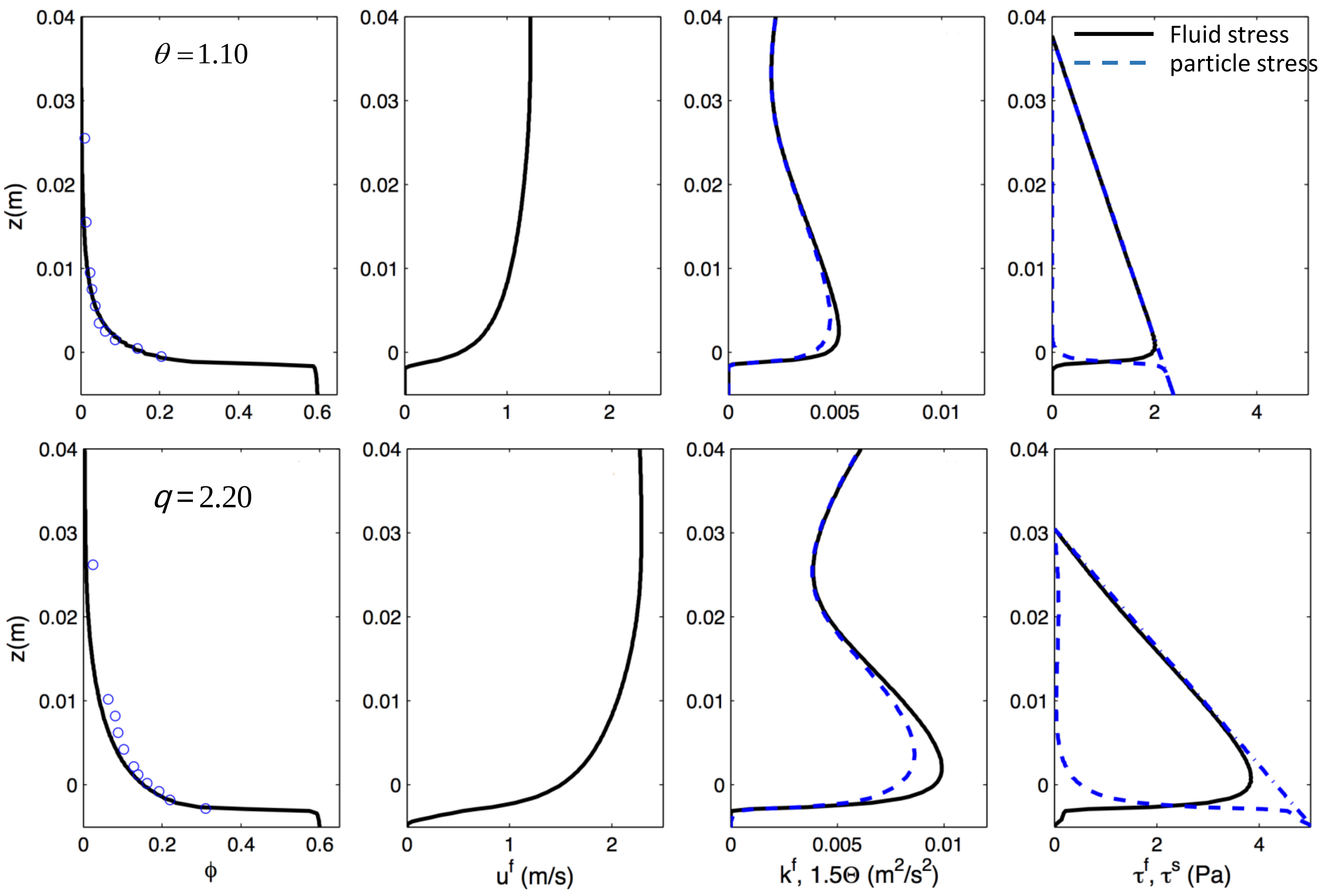
Turbulence-averaged 1DV simulation
L_x=L_y=1 grid point length
L_z=15 cm, h_b=5 cm, Δz=0.25 mm



Berzi & Fraccarollo (2016), Phys. Fluids



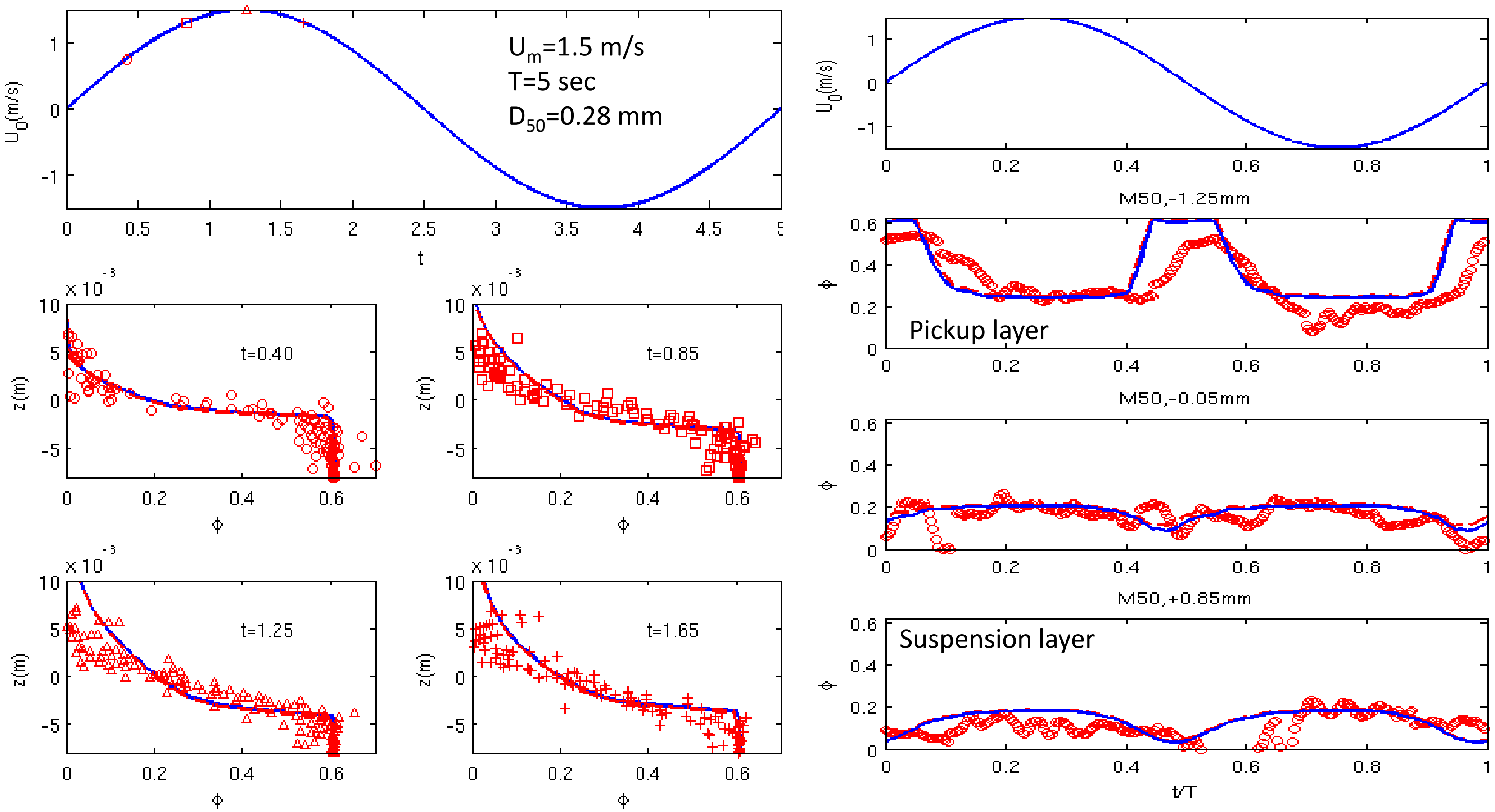
Fine sand, d=0.13 mm, s=2.65   Sumer et al. (1996), *J. Hydraulic Eng.*



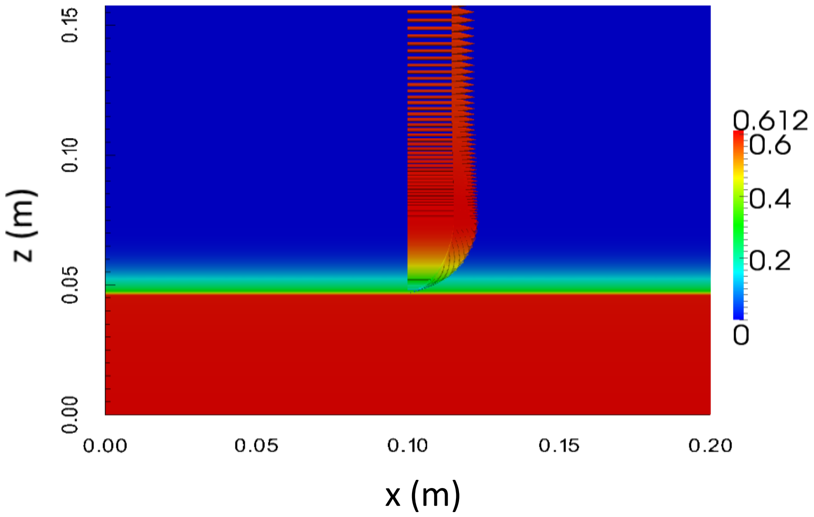
Model Validation – 2DV Turbulence-averaged modeling

Oscillating water tunnel (U-tube) sheet flow experiment of O'Donoghue & Wright (2004), *Coast. Eng.*

$$\theta_w = \frac{u_{*w}^2}{(s-1)gd} = 2.1 \ \text{(Turbulent-collisional suspension)} \quad S_p = \frac{\partial p/\partial x}{\rho(s-1)g} = 0.12$$



Sediment concentration at flow peak

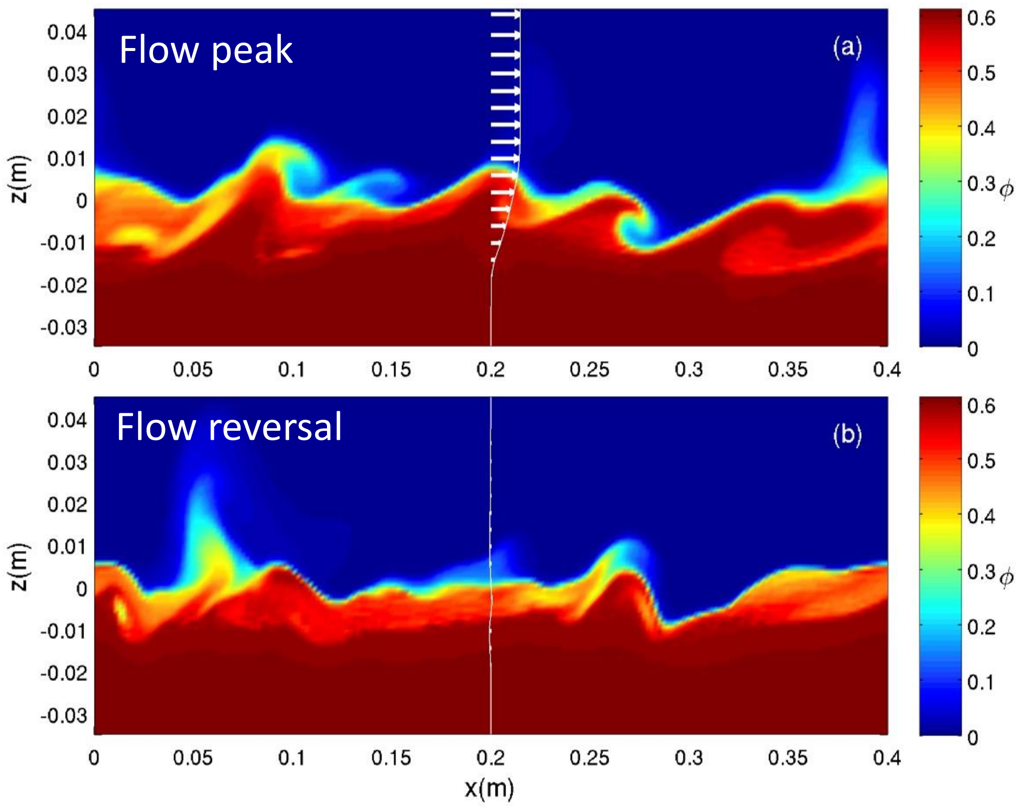


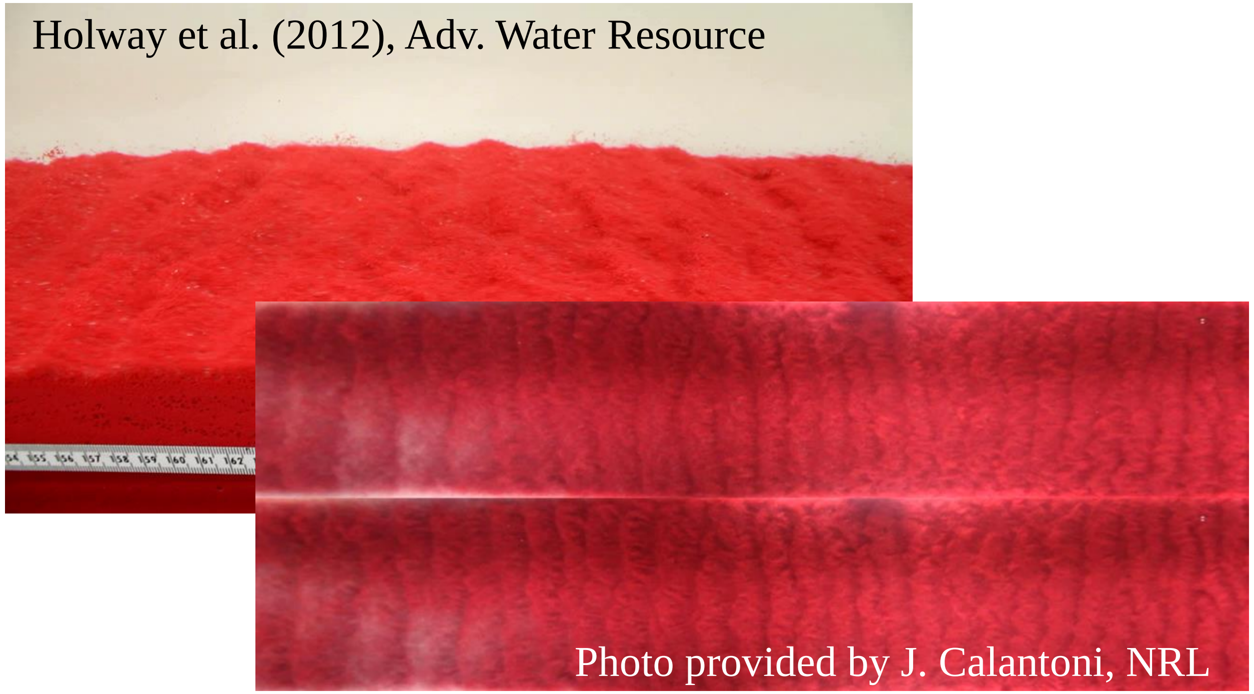
As expected, turbulence-averaged sheet flow in a u-tube is homogeneous in the streamwise direction. The numerical model can reproduce this (no numerical issue).

Momentary bed failure in sheet flow

When we reduce the period to T=1.8 sec…

$$\theta = 2.8 \qquad S_p = 0.32$$

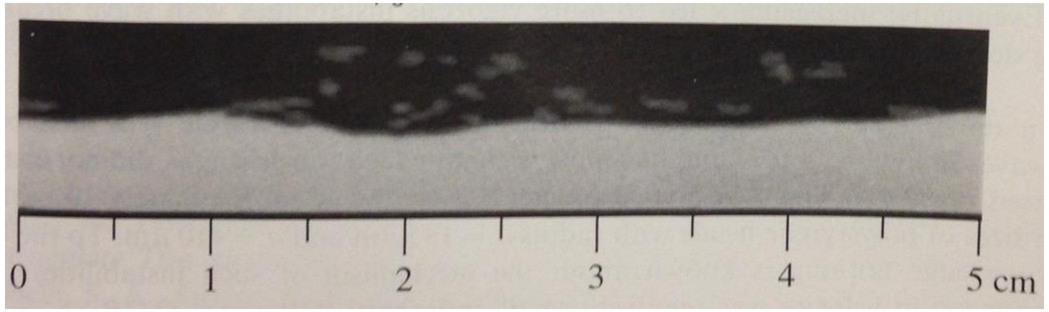




Holway et al. (2012), Adv. Water Resource

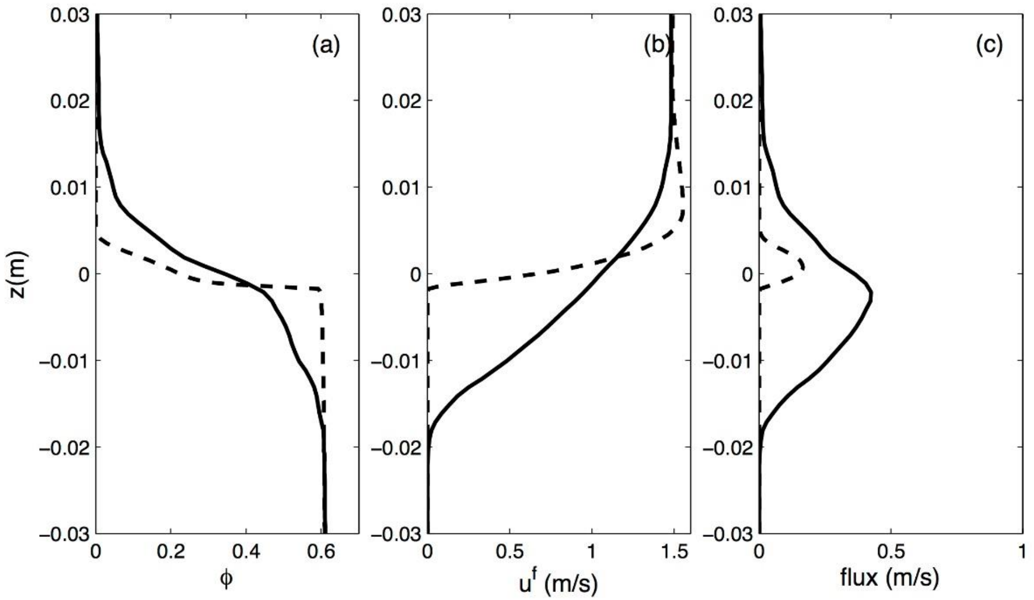
Photo provided by J. Calantoni, NRL

Schaflinger, Acrivos & Stibi (1995), *Int. J. Multiphase Flow*
Mouilleron & Charru (2002), *J. Fluid Mech.*:
- Bed instability occurs when mobile layer thickness is large.



Adopted from Schaflinger et al. (1995)

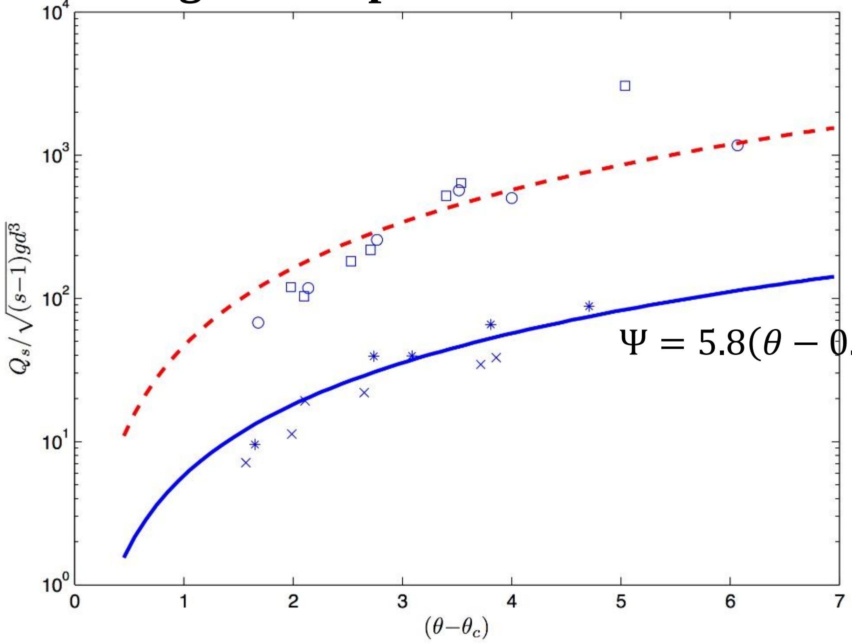
At flow peak: (a) Sediment conc (b) flow velocity (c) sediment flux



2DV model
1DV model

Instability and billows enhance sheet flow layer thickness by about 5 times. Instantaneous transport flux is enhanced by about 5 times.

Half-wave-averaged transport rate

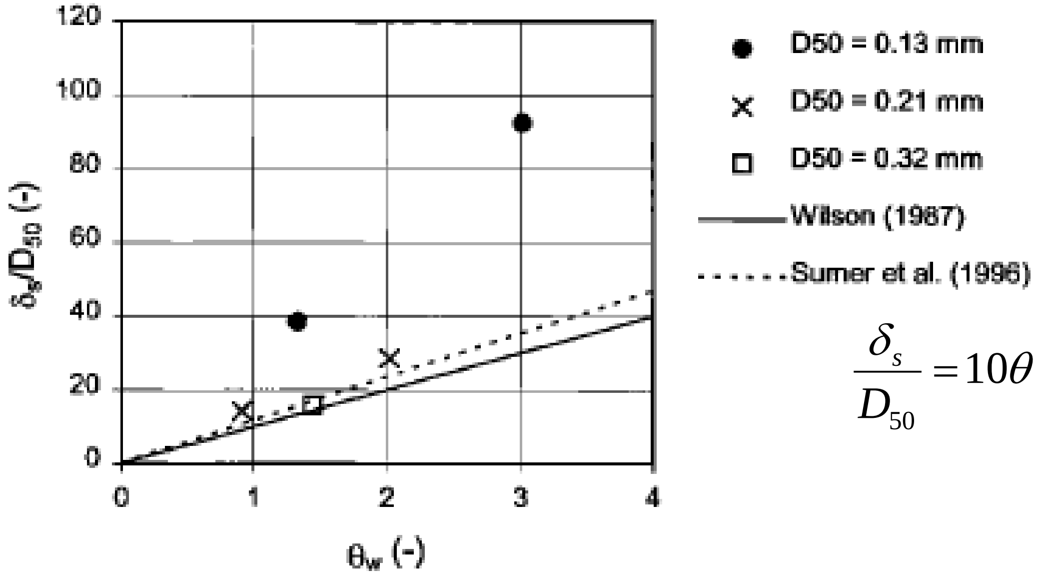


$\Psi = 5.8(\theta - 0.05)^{1.65}$

To better resolve the evolution and dissipation of billows, a 3D turbulence-resolving simulation approach is needed

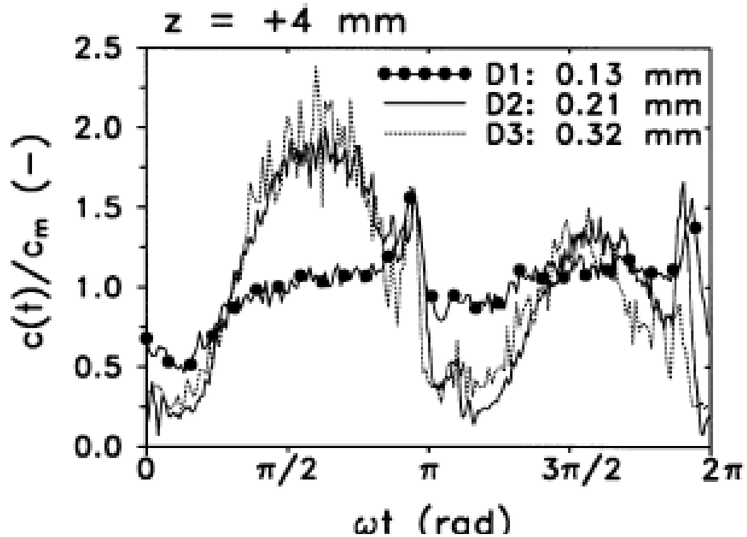
Other challenges: The scaling law to estimate sheet layer thickness is much larger for fine sand.

Dohmen-Janssen et al. (2000), *JGR.*

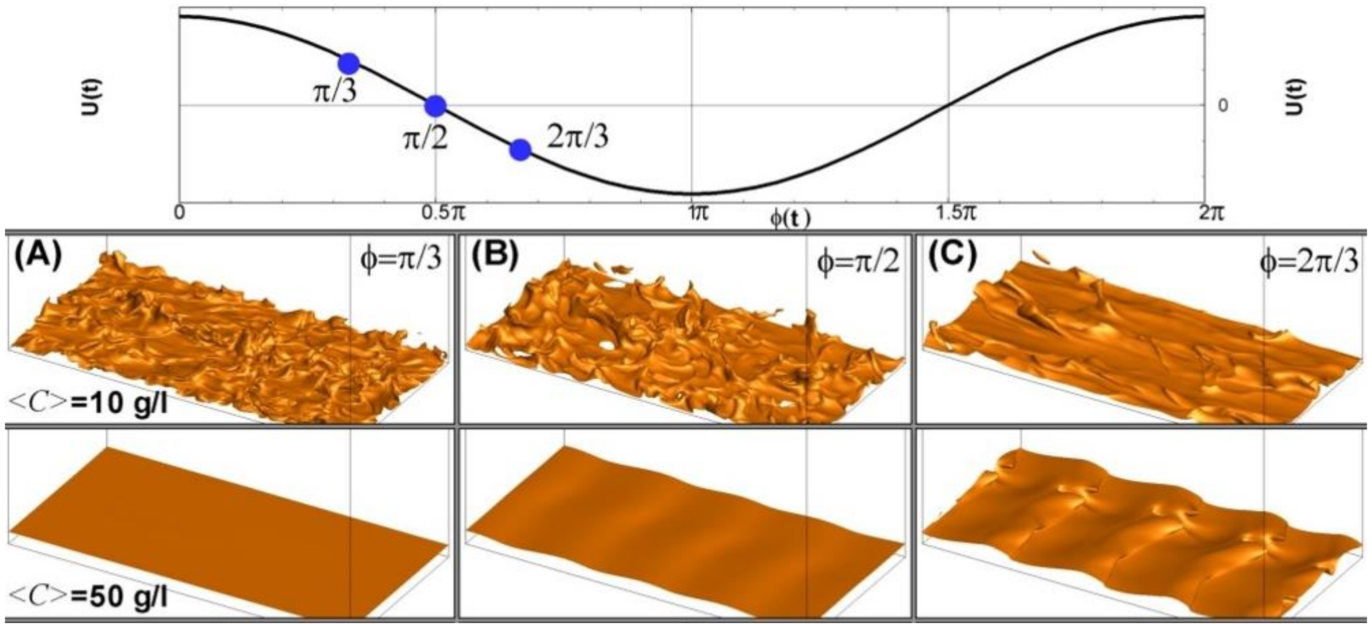


$$\frac{\delta_s}{D_{50}} = 10\theta$$

Dohmen-Janssen et al. (2001), *Coast. Eng.*



- Reynolds-averaged two-phase model cannot reproduce observed features for fine sand (i.e., sand with D_{50}<0.15 mm).
- We suspect flow is transitionally turbulent and flow becomes more energetic during reversal. A turbulence-resolving simulation approach is needed (e.g., Ozdemir et al. 2010, *JFM*.).



Turbulence-resolving Eulerian Two-Phase Model for Sediment Transport

Eulerian two-phase equations are solved in 3D with a domain size sufficiently larger than the largest eddies and high numerical resolution (~1 mm).

For fluid sub-grid stress:

Smagorinsky closure $\nu_{sgs} = \left(C_s \Delta\right)^2 |S|$ with C_s =0.1

$\Rightarrow$ We have tried to determine C_s via a dynamic procedure using a test filter but we get some very small or negative value of ν_{sgs}.

$\Rightarrow$ There is no sediment impact explicitly included in the sub-grid closure. More sophisticated sub-grid closure will be tested in the future.

For particle sub-grid stress:

Only kinetic theory of granular flow is incorporated. Effects of fluid agitation is ignored. The particle phase sub-grid turbulence (Simonin et al. 2002) is also ignored at this point.

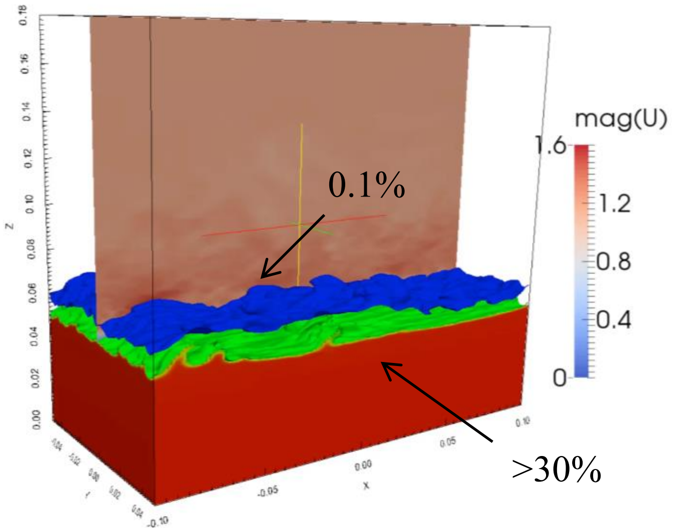
3D turbulence-resolving Eulerian two-phase simulation

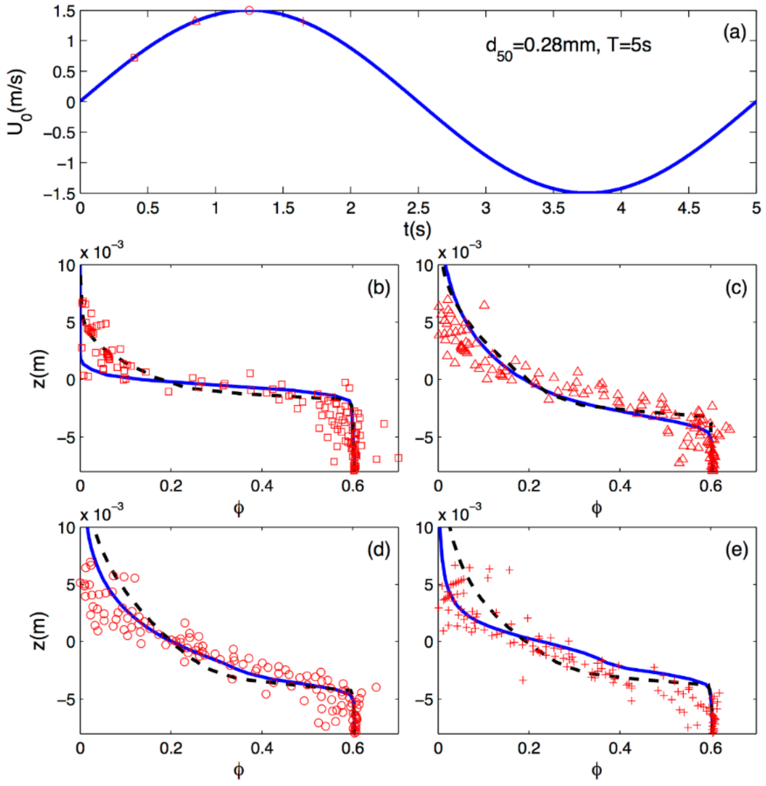
oscillatory sheet flow: O'Donoghue & Wright (2004), medium sand $d = 0.28$ mr

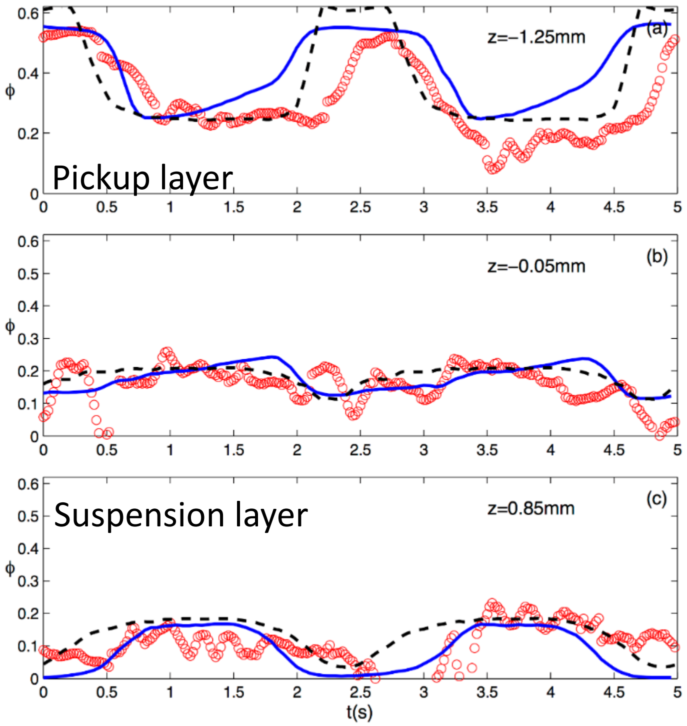
Domain size: $L_x \times L_y \times L_z = 0.2\text{m} \times 0.1\text{m} \times 0.18\text{m}$

Domain discretization: $N_x \times N_y \times N_z = 132 \times 132 \times 240$

Grid sizes: $\Delta_x = 1.5$ mm $\Delta_y = 0.75$ mm $\Delta_{z\min} = 0.45$ mm



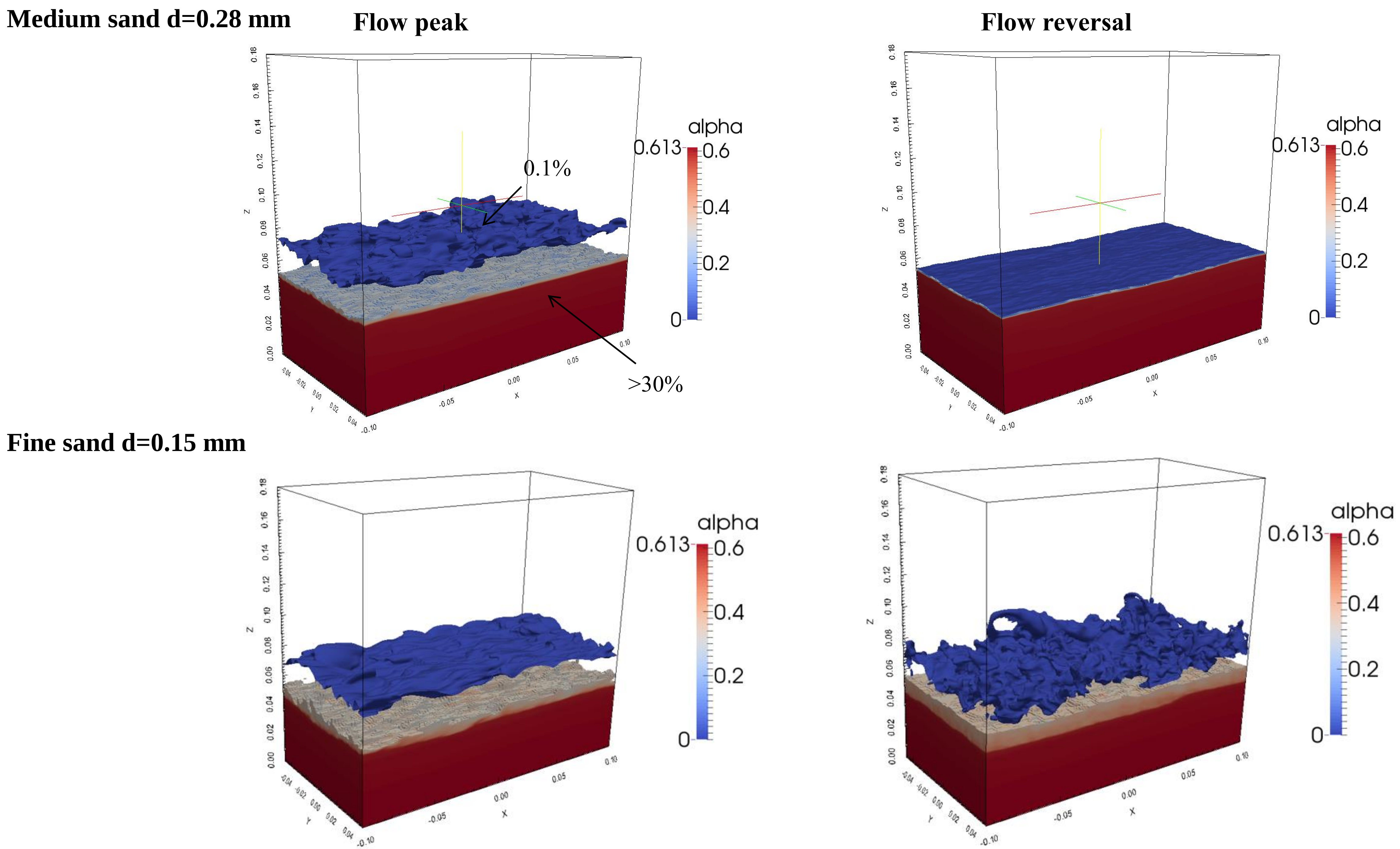




symbols measured data

LES results

RANS results (Cheng et al. 2015)

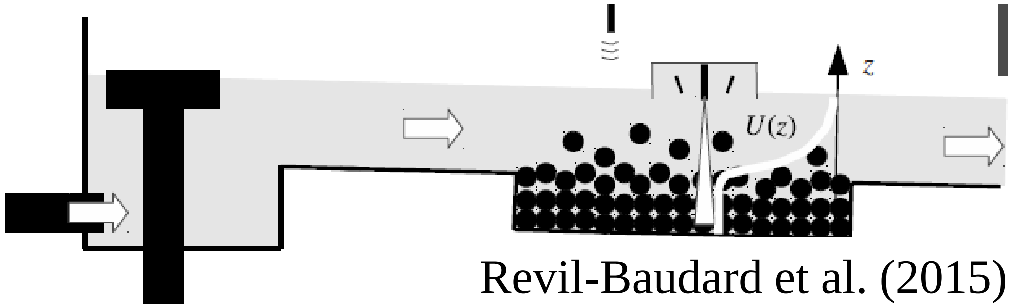

Medium sand d=0.28 mm
Flow peak
Flow reversal
Fine sand d=0.15 mm
alpha
0.613
0.6
0.4
0.2
0
0.1%
>30%
Z
X
Y

Model Validation (more rigorous)- Sheet flow in steady channel flow

Revil-Baudard, Chauchat, Hurther, Barraud (2015), J. Fluid Mech.:

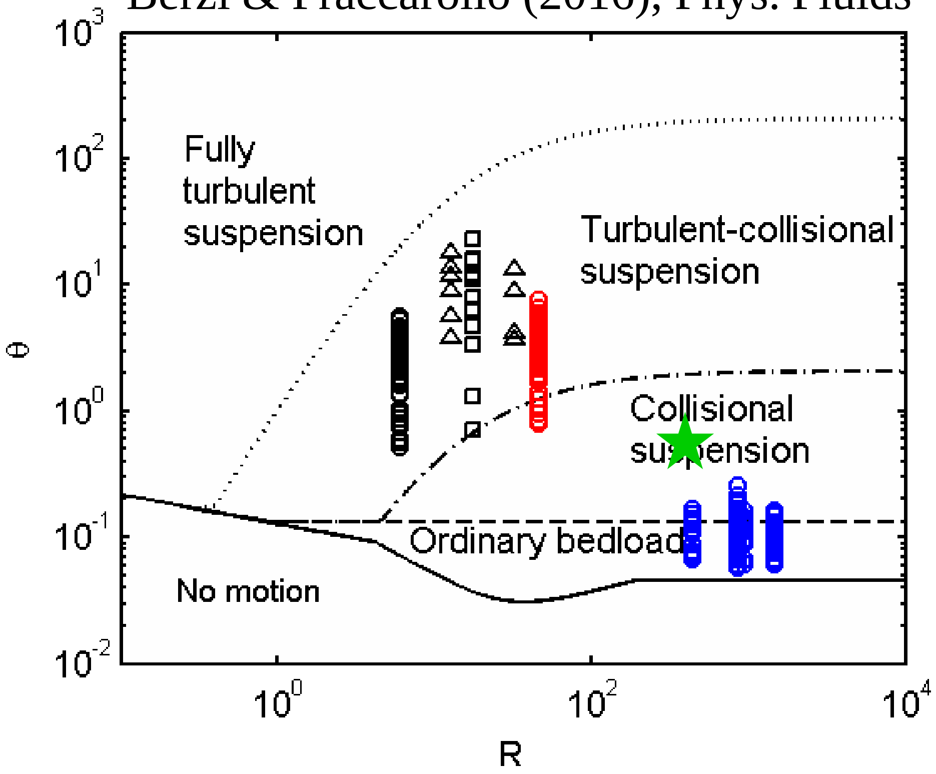
$u_* = 5\,\mathrm{cm/s}$, h= 0.124 m, d= 3 mm, ρ^s=1192 kg/m^3

$W_s = 5.59\,\mathrm{cm/s};\ \theta = 0.5;\ W_s/u_* = 1.1$



Revil-Baudard et al. (2015)

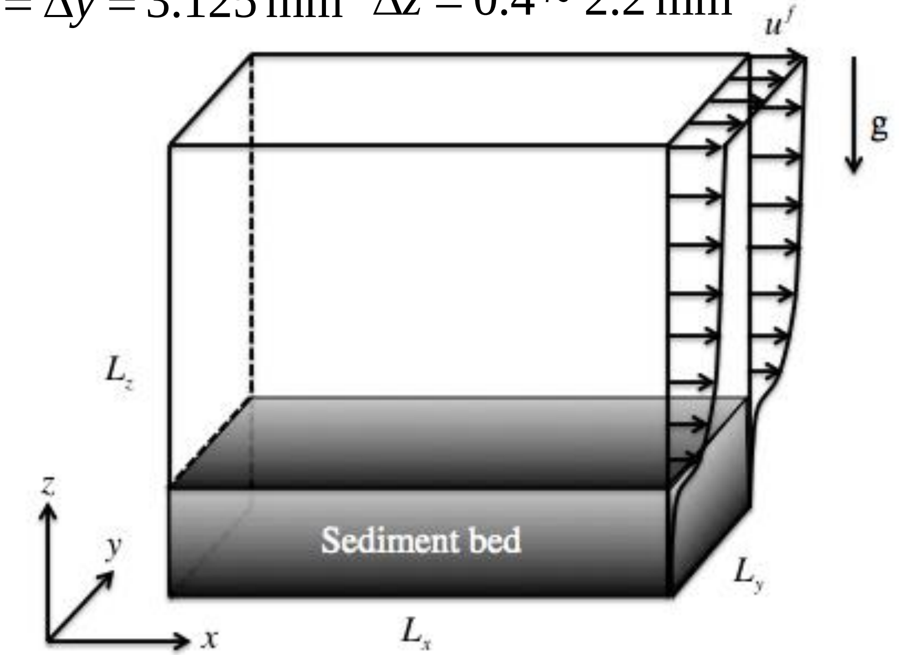
Berzi & Fraccarollo (2016), Phys. Fluids



In the numerical simulation:

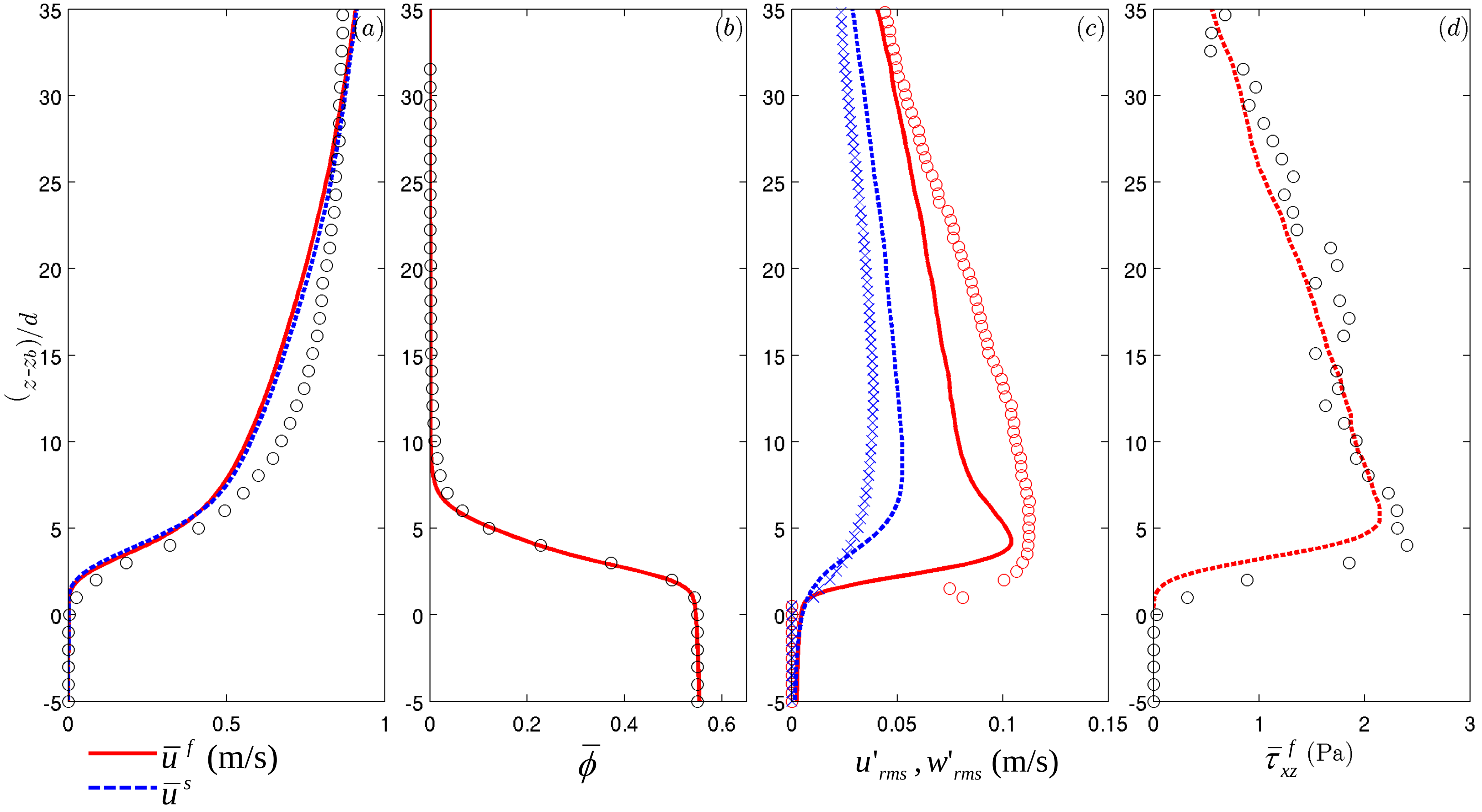
$L_x = 0.8\,\mathrm{m}\quad L_y = 0.4\,\mathrm{m}\quad L_z = 0.168\,\mathrm{m}$

$\Delta x = \Delta y = 3.125\,\mathrm{mm}\quad \Delta z = 0.4 \sim 2.2\,\mathrm{mm}$



Ensemble-averaged flow statistics

Symbols: measure data
Curves: simulation results

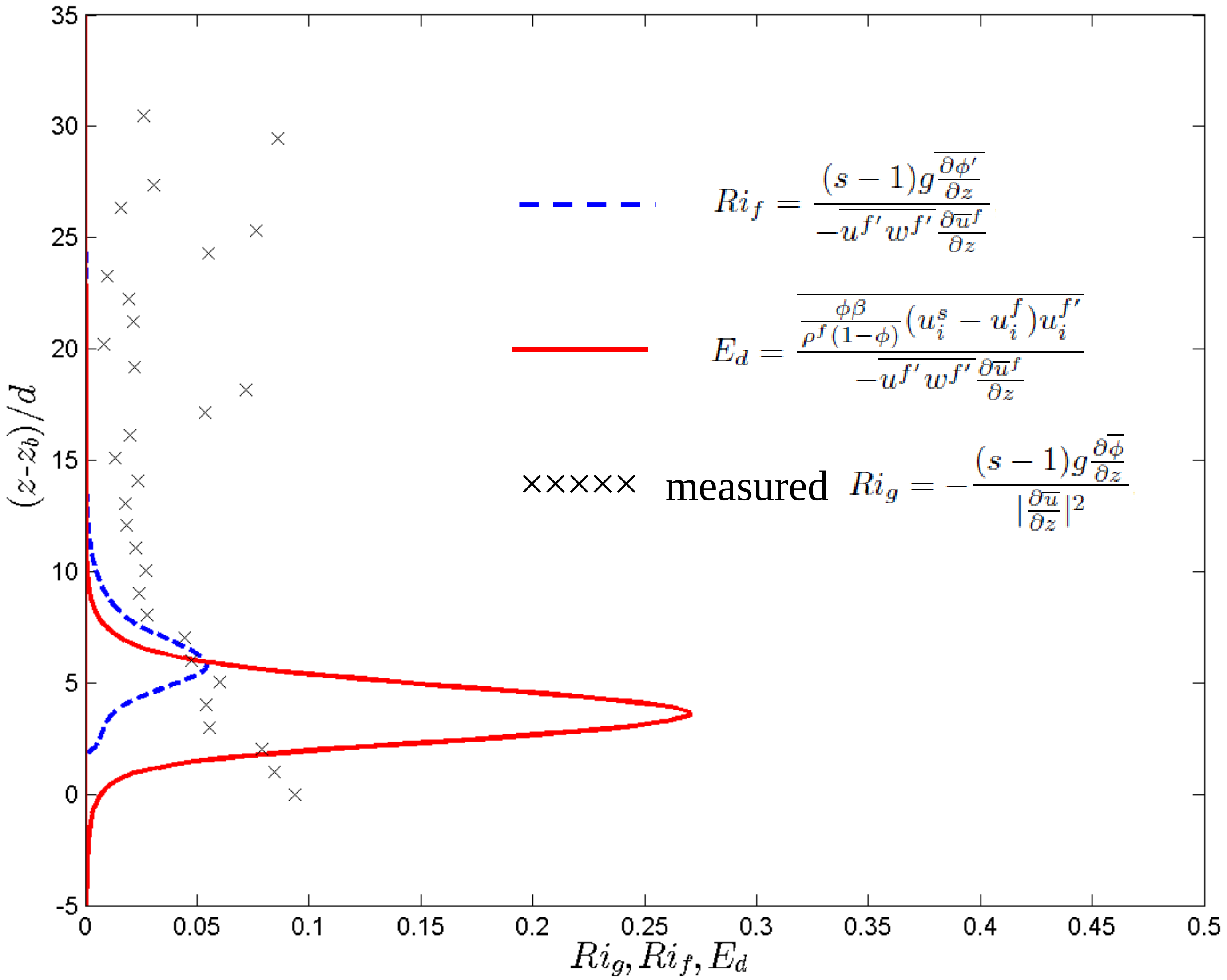


Evidence of attenuated fluid turbulence by sediments

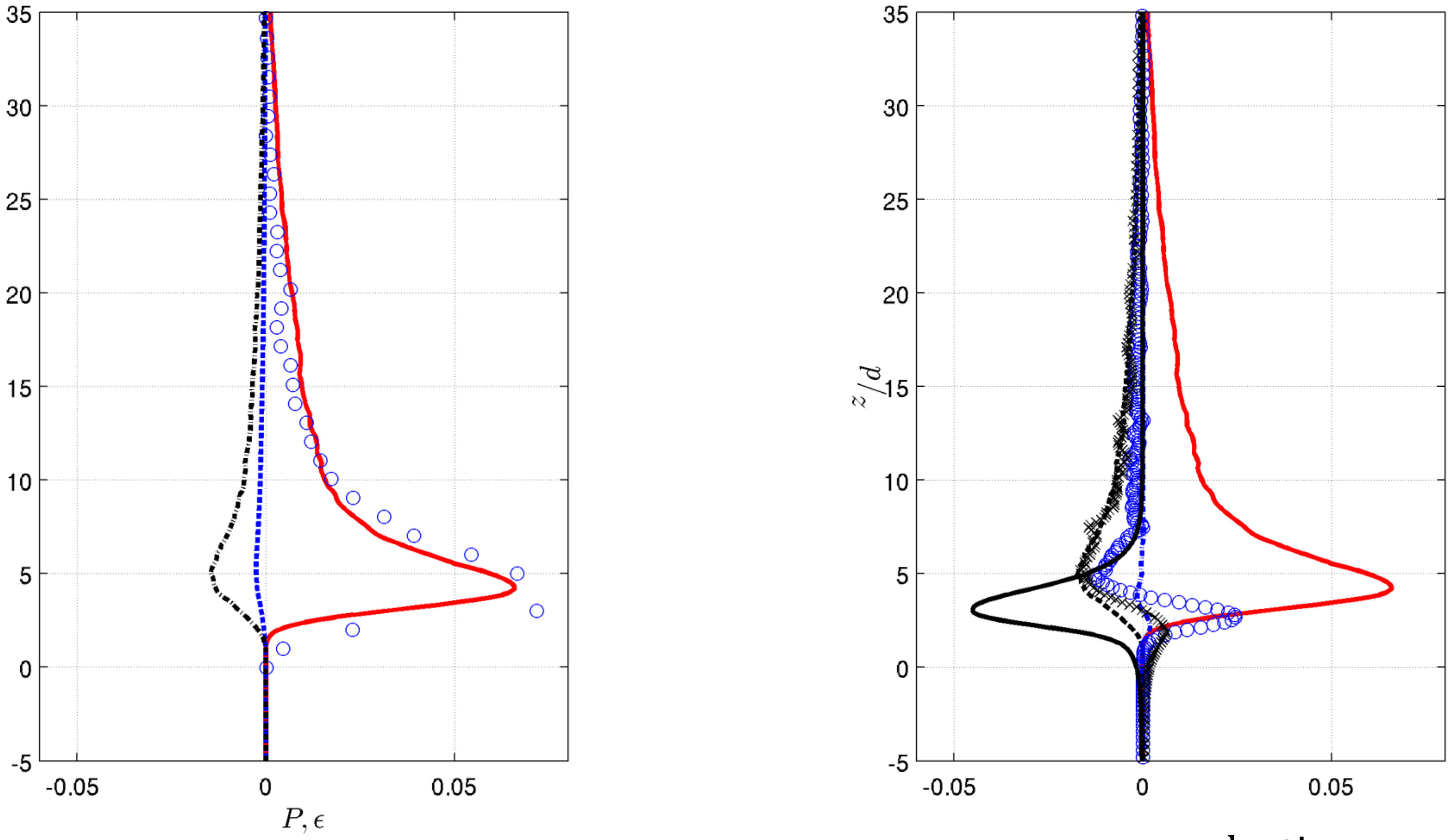
$$\bar{u}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z-\Delta}{z_0}\right)$$

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

For the present flow condition and particle properties ($W_s/u_*=1.1$), most of the turbulence attenuation is due to drag. Sediment-induced density stratification plays a minor role.



Turbulence kinetic energy budget



o o o o Measured production

Modeled production

Modeled subgrid turb dissipation

Model resolved turb dissipation

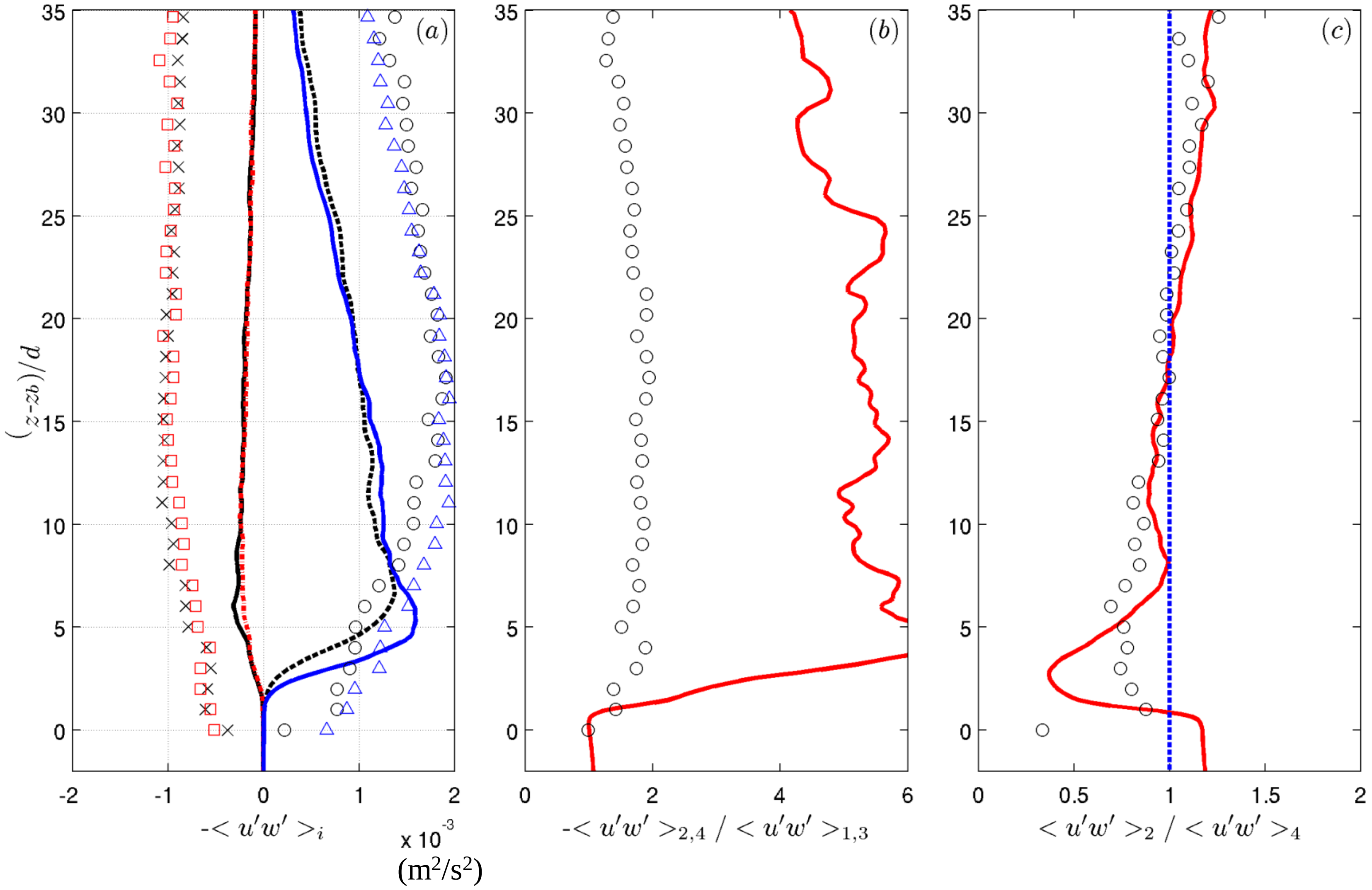
production

turbulent dissipation

Dissipation due to drag

Others are pressure transport (x), advection (o) and diffusion

Sweeps (Q4), ejections (Q2), outward/inward (Q1/Q3) interactions



- Model is able to predict the dominant components, i.e., ejections and sweeps
- Model under-predict inward and outward interactions

Future work

- **Refine the 3D LES Eulerian two-phase model for sediment transport (more sophisticated sub-grid fluid turbulence stress, particle phase sub-grid turbulence stress, drift velocity). More detailed validation (e.g., Carpart & Fraccarollo 2011, GRL; Berzi & Fraccarollo 2015, PRL).**
- Study wave-driven bedforms: generation, evolution, migration and annihilation.
- Expand SedFOAM for Euler-Lagrangian (coupled CFD-DEM) model for sediment transport. Armoring, winnowing, grain shape effect, etc.