Atmospheres, Oceans, Earths – Unifying Perspectives on Geophysical and Environmental Multiphase Flows

The role of turbulent coherent structures on the frontal features and evolving seabed

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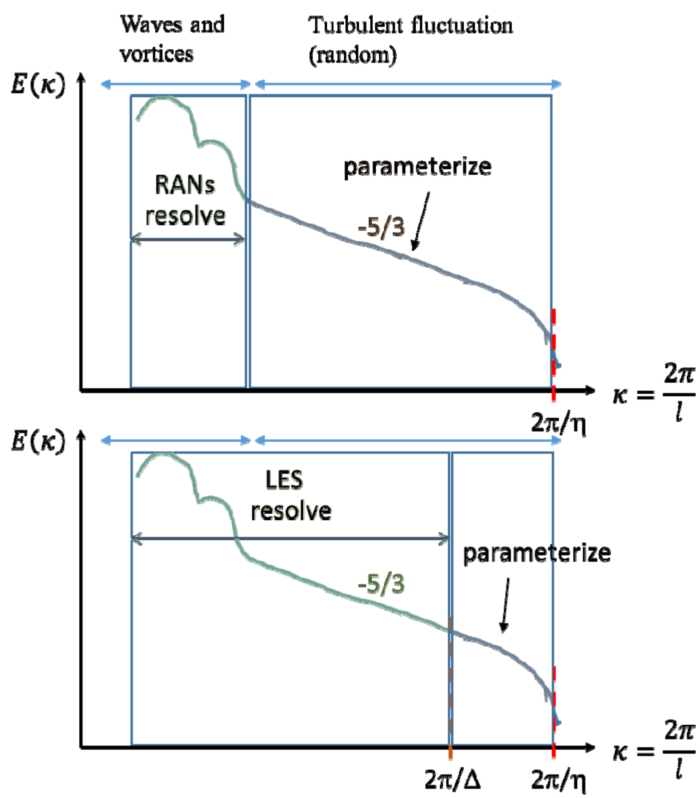
Problem Statement



- The Reynolds-averaged (turbulence-averaged) methodology has been the most popular/affordable modeling approach for coastal & estuarine processes.
- The main assumption of a Reynolds-averaged methodology is to model the effect of turbulent fluctuations via a “diffusion” process.
- For shear flows with relatively simple configurations, turbulent diffusion seems to work well.
- When the flows of interest are more complex (e.g., instabilities, primary vortices in flow separation, and highly 3D configurations), the Reynolds-averaged closure assumption becomes ambiguous.

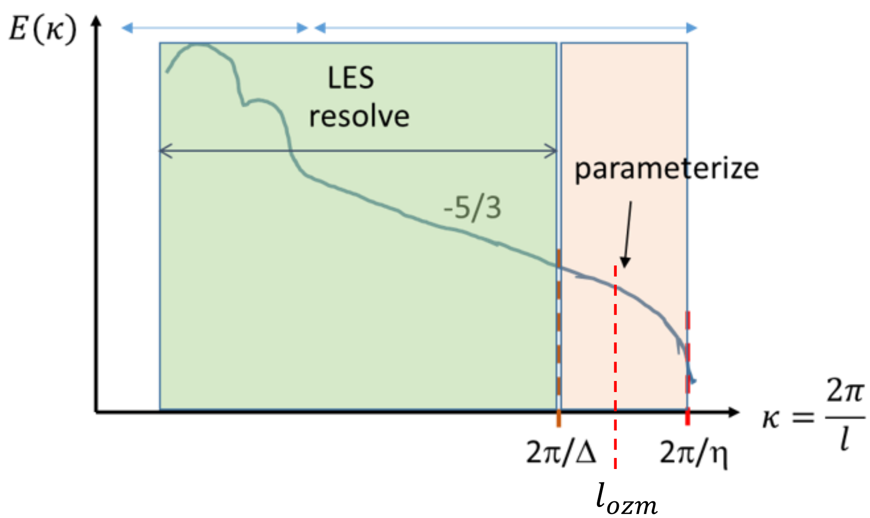
  ⇒ Turbulence-resolving methodology, such as large-eddy simulation (LES), is a more appropriate choice, in spite of the higher computational cost.

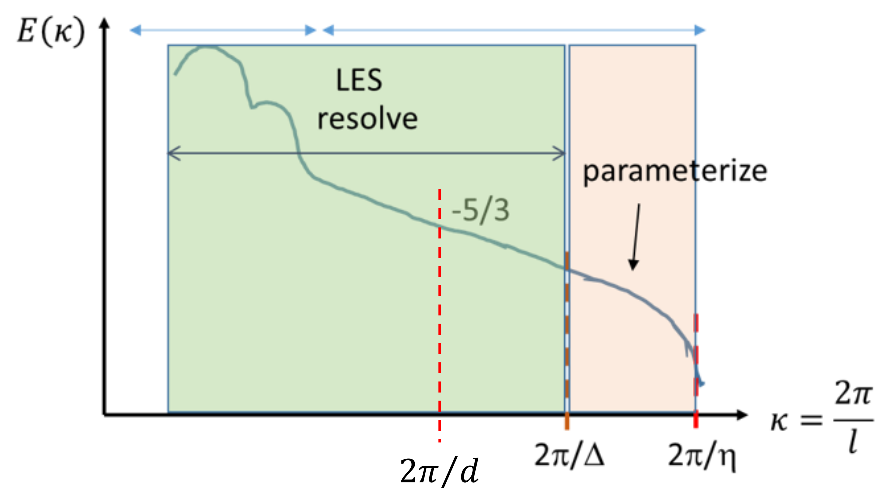
- For stratified flow, or particle-laden flows, turbulent diffusion is even more questionable, even for large-eddy simulations due to the interaction between carrier flow, density stratification, and particles:

  i. Filter size Δ > Ozmidov scale $l_{ozm} = \sqrt{\varepsilon / N^3}$: unresolved stratification effect of turbulence.

  ii. Filter size Δ > particle size d: unresolved micro-structure effect (*Ozel et al. 2013, IJMF)*.

  iii. Filter size Δ < particle size d, the so-called finite size effect (*Balachandar 2009, IJMF*; *Mathieu et al. 2021, J. Fluid Mech.*).





Modified from Mathieu et al. (2021)

Objective

This presentation will discuss the following problems that require resolving a large part of turbulent coherent structures (a RANS model does not work):

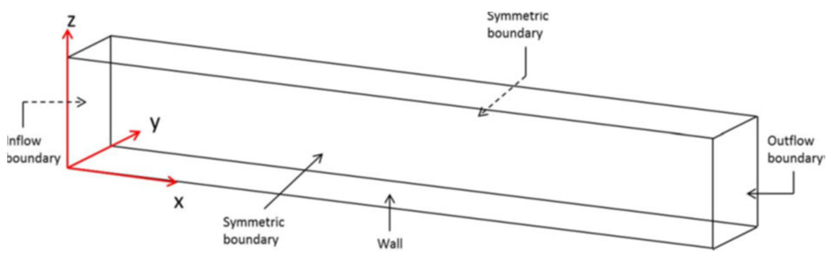
1. Lobe and cleft instabilities at a field-scale river plume front (NHWAVE by Fengyan Shi)

2. Wave-driven sheet flows - Phase-lag effect and net transport rate of fine sand (SedFoam by Antoine Mathieu)

3. Scour around a vertical pile (SedFoam by Benjamin Tsai)

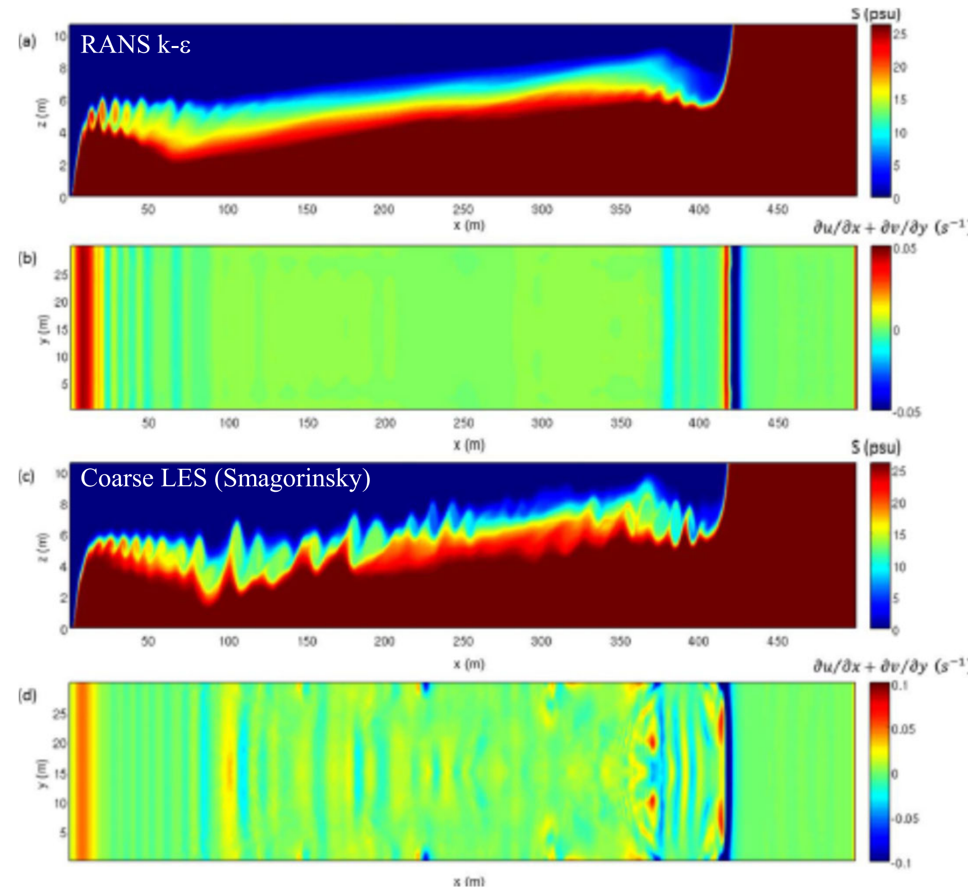
1. Lobe-and-cleft instabilities at river plume fronts

NHWAVE solves the 3D salt-stratified density varying flow with Boussinesq approximation in terrain- and surface-following (σ-) coordinate *(Shi et al. 2016, Estuaries and Coasts; Zhou et al. 2018, JGR:Oceans)*.



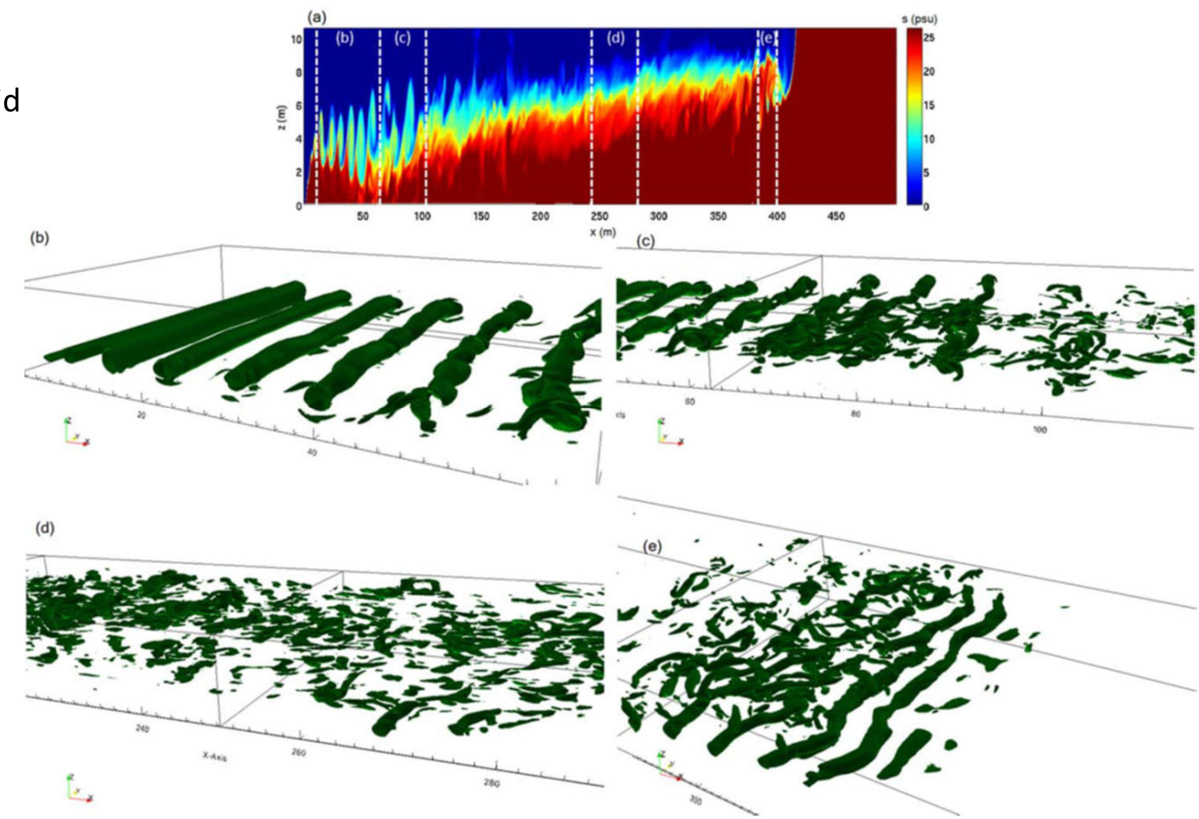
- For laterally uniform domain (statistically 2D), RANS and coarse grid LES ($\Delta \approx 3l_{ozm}$) are statistically similar;
  - ➢ LES shows (under-resolved) Kelvin Helmholtz instabilities at the bottom of density current but RANS model show a smooth transition
  - ➢ The mix layer depth and other bulk features of the density current between these two simulations are similar.

Medium resolution $\Delta \approx 0.5\,m > \; l_{ozm} \approx 0.2\,m$



- For laterally uniform domain (statistically 2D) high resolution LES with $\Delta \approx l_{ozm}$
  - ➢ Resolve shear instabilities and their evolution into smaller structures
  - ➢ The front is less turbulent without much features.

High resolution,
Smagorinsky sub-grid
$\Delta \approx 0.16\ m \approx l_{ozm}$



- Realistic river plume shows lobe-and-cleft like frontal features

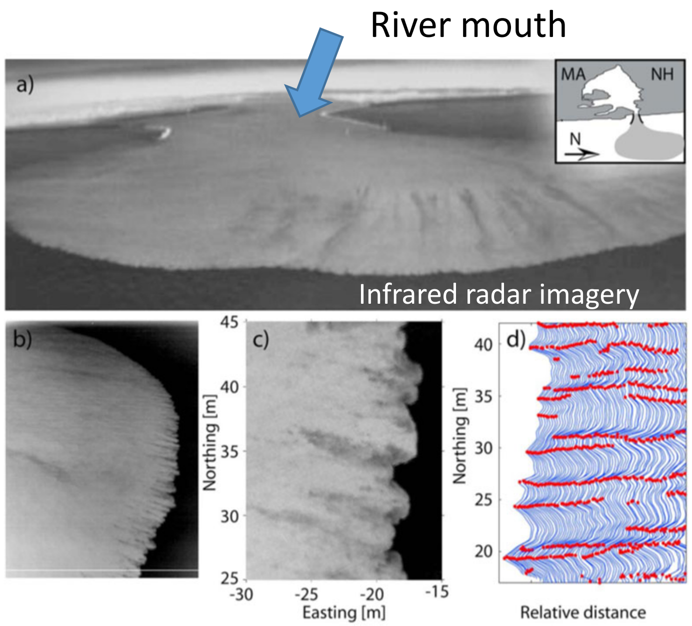


Fig.2 in Horner-Devine and Chickadel (2017) GRL; https://doi.org/10.1002/2017GL072997

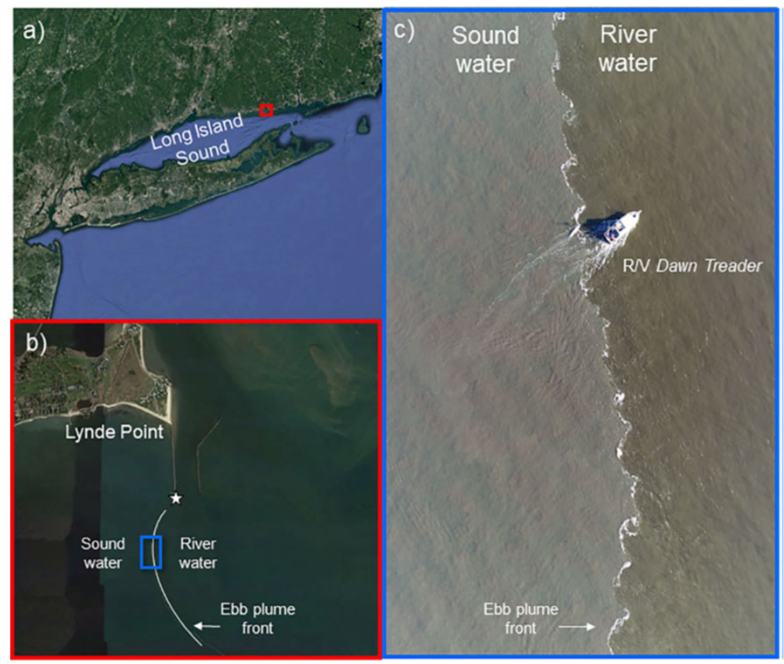
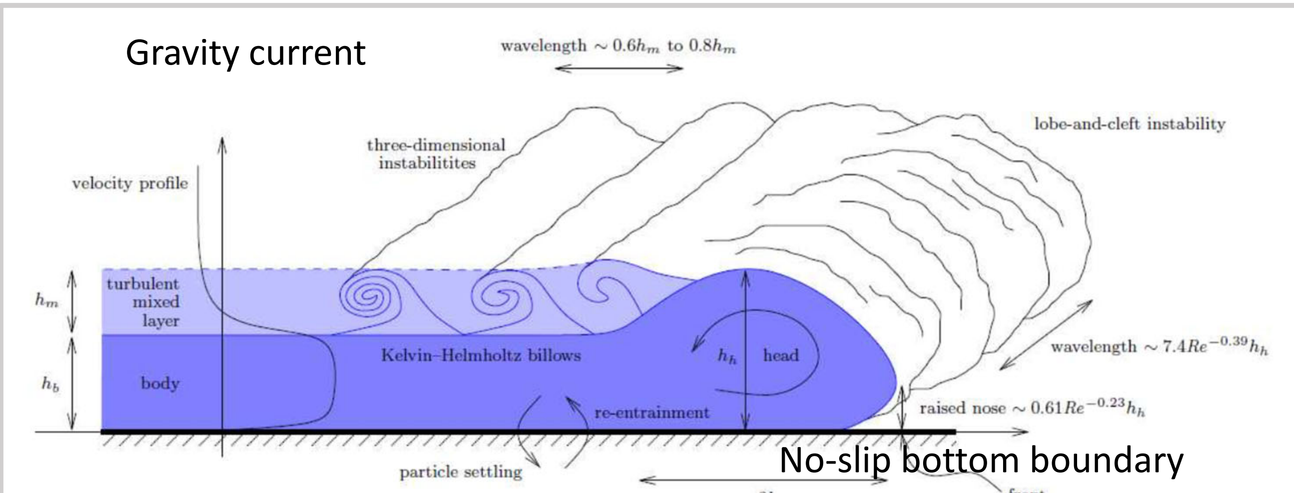


Fig.1 in Simpson, Shi, Jurisa, Honegger, Hsu, Haller (2022) J. Geophys. Res: Oceans. https://doi.org/10.1029/2021JC017799

- Classic explanation for lobe-and-cleft instability cannot be applied to explain those observed at the front of a river plume



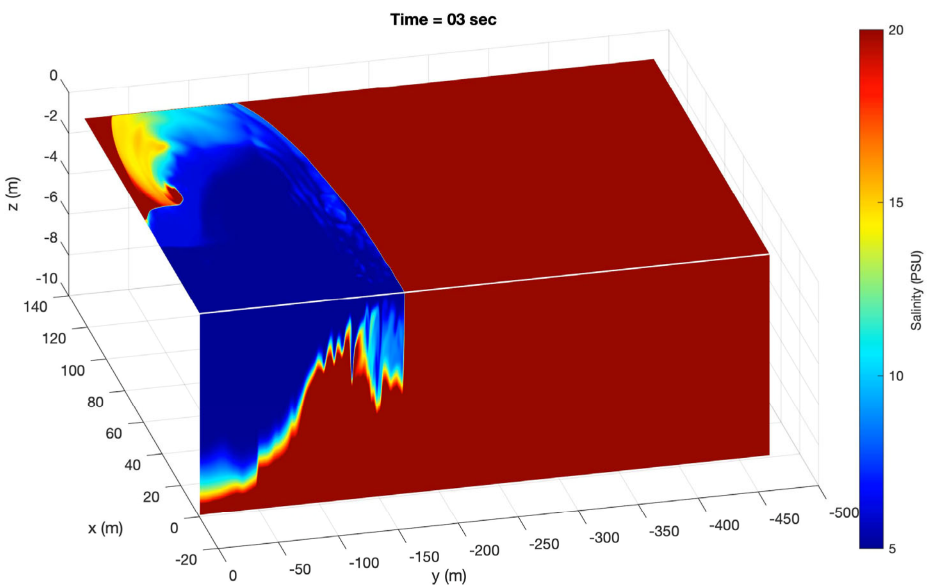
Slim (2006), PhD Thesis, Univ. Cambridge.

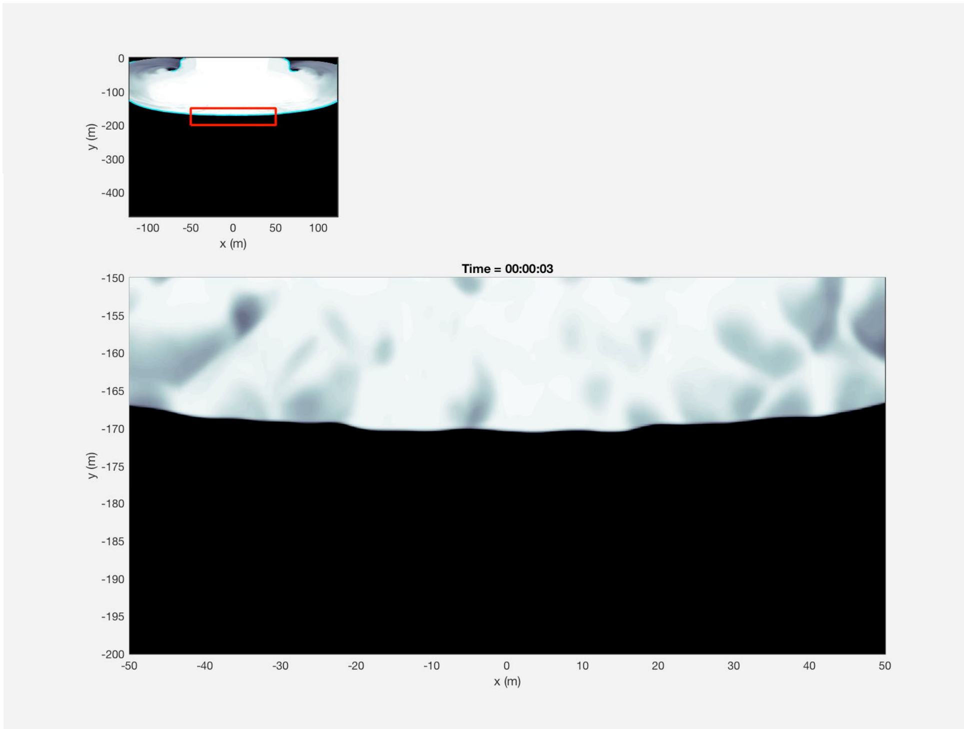
Causes:

- no-slip bottom boundary and Rayleigh-Taylor instability *(Simpson, 1972, JFM; Hartel et al. 2000, JFM)*

⇒ We test the hypothesis that lateral spreading is the key mechanism driving lobe-and-cleft features at a river plume front using NHWAVE via eddy-resolving simulations.

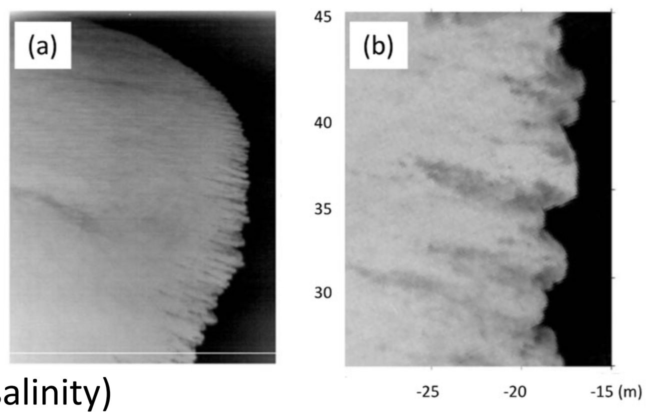
- Δ_x = 0.15625m, Δ_y = 0.3125m
- DOMAIN W=480M, L=600M
- DEPTH: 6-10m, Δ_z=0.075-0.125m
- BACKGROUND SALINITY 25 PSU
- INPUT FLOW VELOCITY: 0.8 m/s; SALINITY: 5 PSU
- Standard Smagorinsky closure



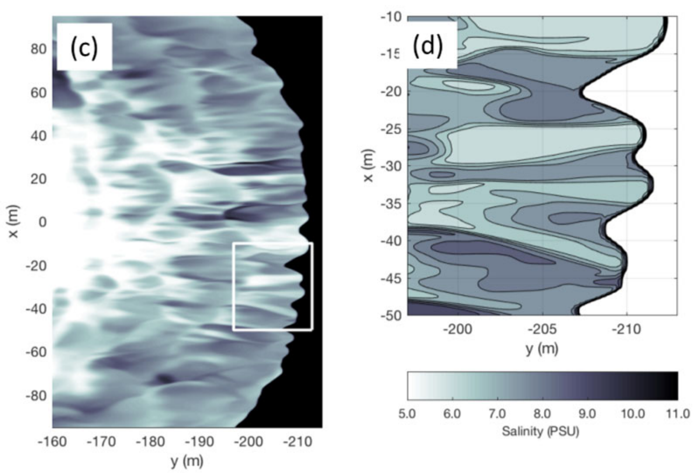


Observed (temperature)

Horner-Devine and Chickadel (2017)



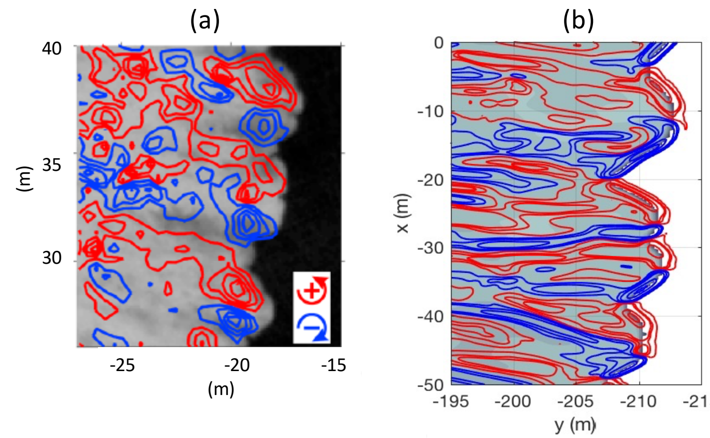
Modeled (surface salinity)



- Lobe-cleft geometry:

  Observed lobe wave length ≈ 3~5 m; Modeled lobe wave length ≈ 6~10 m

  Observed lobe amplitude ≈ 1~2 m; Modeled lobe amplitude ≈ 2.5 m

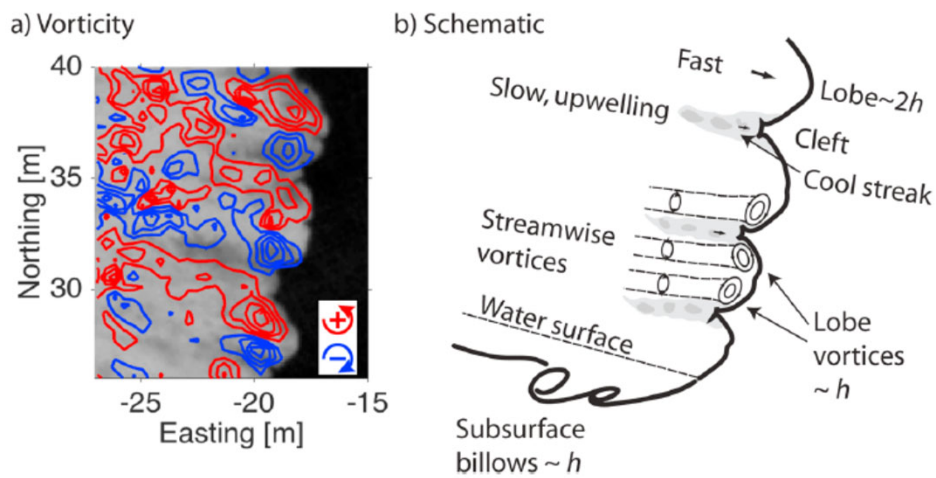


- Observed plume depth *h=1.5~2 m;* Modeled plume depth *h=3 m (central region).*

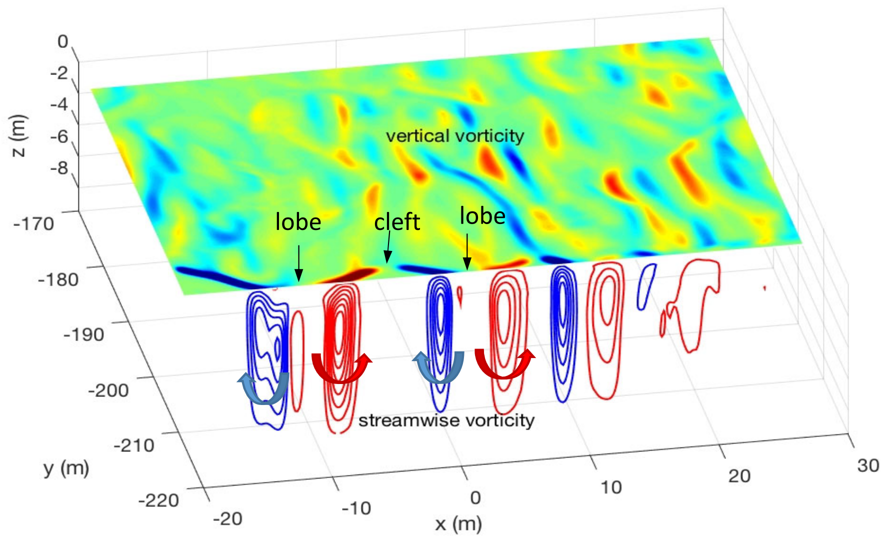
  Modeled: $l/h = 2{\sim}3$.

  Observed: $l/h = 2.5$.

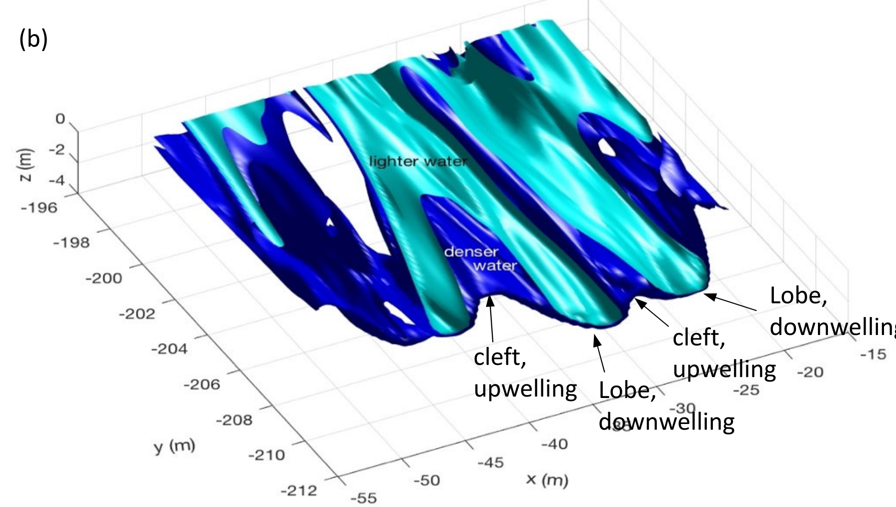
- Horner-Devine and Chickadel (2017) hypothesized that the lobe vortices are caused by pair of streamwise vortex tubes bending upward at the front.
- Cleft is associated with upwelling of cool and saltier (denser) water while the lobe is associated with downwelling.
- Simulation results show a consistent pattern.



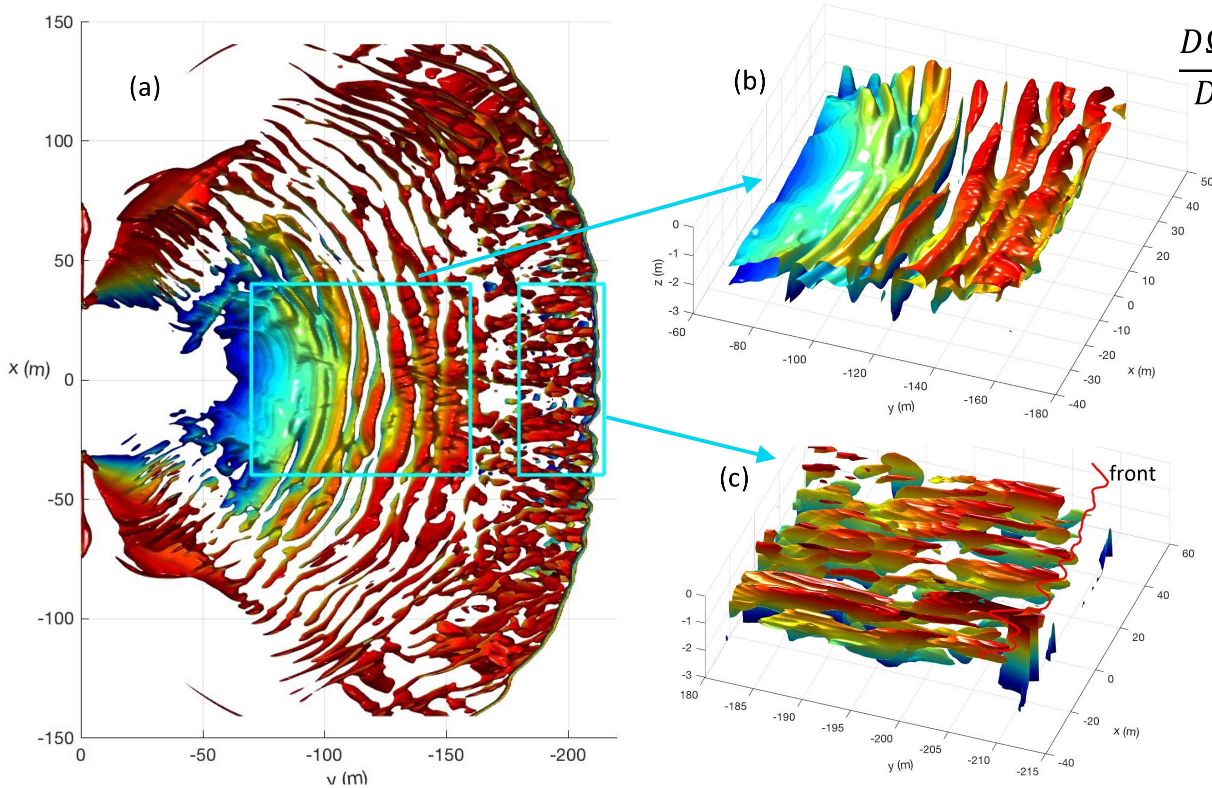
(a)



(b)



- Origin of lobe-and-cleft



K-H instabilities

Lateral variability

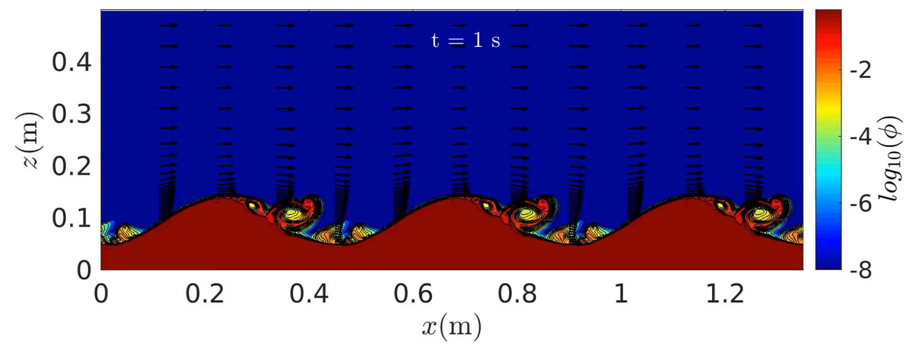
$$\frac{D\Omega_y}{Dt} = \boldsymbol{\Omega_x \frac{\partial v}{\partial x}} + \Omega_y \frac{\partial v}{\partial y} + \Omega_z \frac{\partial v}{\partial z} + \frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial z}\frac{\partial P}{\partial x} - \frac{\partial \rho}{\partial x}\frac{\partial P}{\partial z}\right)$$

- Lateral spreading is the key to generate streamwise vortex tubes and convert 2D instabilities into 3D flow structures!

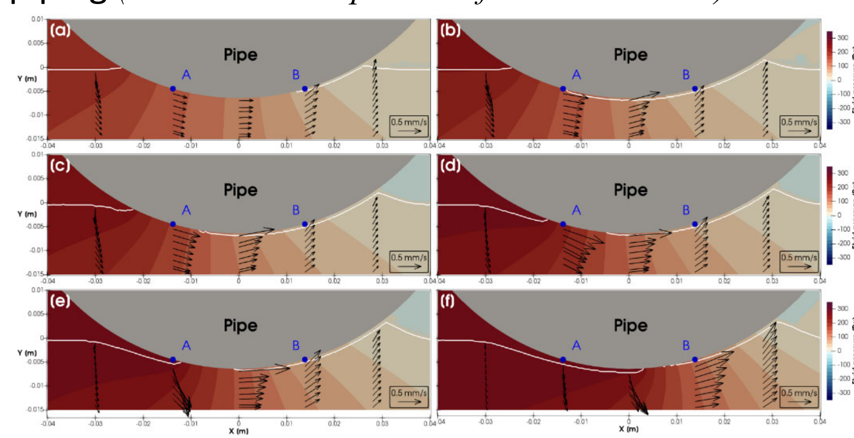
What is SedFoam?

- SedFoam is an open-source Eulerian two-phase model for sediment transport applications created in the OpenFOAM (Cheng et al. 2017, Coastal Eng.; Chauchat et al. 2017, GMD).
- SedFoam solves water and sediment phases by their own mass and momentum equations and with inter-phase coupling terms (e.g., drag, pressure gradient)
- Particle stress due to
  - shear-driven collision (kinetic theory or mu(I) rheology).
  - quasi-static frictional contact (Johnson & Jackson 1987, JFM; Srivastava & Sundaresan 2003, Powder Tech.) and dilatancy (Montella et al 2021, JFM).
- The two-phase framework can avoid the artificial separation of transport into bedload and suspended load layers.
- Earlier version based on a Reynolds-averaged approach that includes k-ω or k-ε turbulence closure;
- Recently, it has been extended with 3D large-eddy simulation methodology (dynamic Smagorinsky closure) with or without finite size correction (Mathieu et al. 2020, 2022, J. Fluid Mech.).

SedFoam 2DV RANS simulation of ripple evolution
(Salimi-Tarazouj et al. 2021, JGR-Earth Surface)



SedFoam 2DV RANS simulation of onset of scour via piping *(Tsai et al.. European J. of Mech. B/Fluids)*



Model Formulation

Filtered mass and momentum equations for fluid and sediment (particle) phases:

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

ϕ: sediment concentration

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

Fluid and sediment velocities $\tilde{u}_i^f = \frac{\overline{(1-\phi)u_i^f}}{(1-\bar{\phi})}, \quad \tilde{u}_i^s = \frac{\overline{\phi u_i^s}}{\bar{\phi}},$

Fluid momentum
$$\frac{\partial\rho^f(1-\bar{\phi})\tilde{u}_i^f}{\partial t} + \frac{\partial\rho^f(1-\bar{\phi})\tilde{u}_i^f\tilde{u}_j^f}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\tilde{\Sigma}_{ij}^f + \sigma_{ij}^{f,sgs}\right) - \bar{M}_i + \Phi_i^{f,sgs} + (1-\bar{\phi})(\rho^f g_i + f_i^v),$$

Particle momentum
$$\frac{\partial\rho^s\bar{\phi}\tilde{u}_i^s}{\partial t} + \frac{\partial\rho^s\bar{\phi}\tilde{u}_i^s\tilde{u}_j^s}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\tilde{\Sigma}_{ij}^s + \sigma_{ij}^{s,sgs}\right) + \bar{M}_i + \Phi_i^{s,sgs} + \bar{\phi}(\rho^s g_i + f_i^v)$$

ρ^f, ρ^s: fluid and particle density

p^f: fluid pressure

$\bar{M}_i$: filtered momentum exchange (drag and pressure gradient, etc)

$\tilde{\Sigma}_{ij}^f$, $\tilde{\Sigma}_{ij}^s$: filtered fluid stress (molecular viscosity) and particle stresses (Kinetic theory of granular flow + frictional/contact stress)

$\sigma_{ij}^{f,sgs}$, $\sigma_{ij}^{s,sgs}$: Fluid and particle sub-grid stress (dynamic Lagrangian model)

$\Phi_{ij}^{f,sgs}$, $\Phi_{ij}^{s,sgs}$: other sub-grid contribution in fluid and particle phases (neglected here as our filter/grid size is similar to particle size)

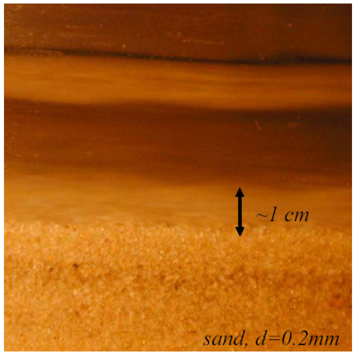
f_i^v: flow forcing (unidirectional current, sine waves, Stokes 2nd (skewed) waves, or Saw-tooth (asymmetric) waves.

2. Phase-lag effect and net transport of fine sand driven by nonlinear waves

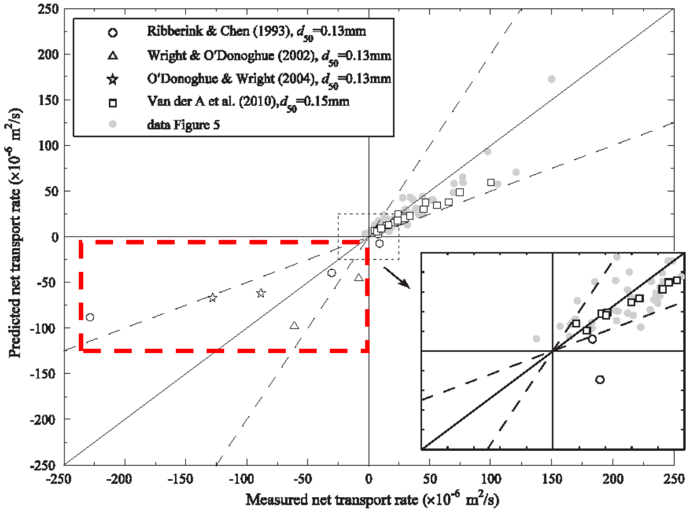
- Sheet flow is a dominating mode of sand transport in the surf zone

  Shields parameter (normalized bed shear stress): $\theta = \frac{\tau_b}{(\rho^s - \rho^w)gd} > 1$

- Unique sheet flow ($\theta > 1$) characteristics for fine sand driven by oscillatory flow:

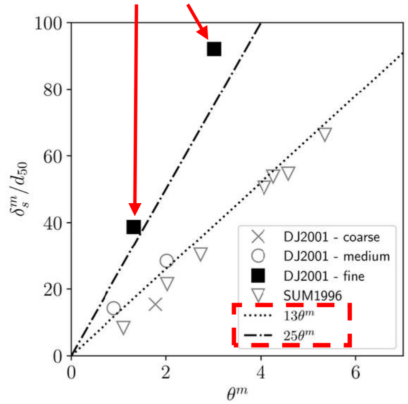


i. Net offshore transport is obtained for fine sand ($d < 0.15\ mm$) when driven by onshore velocity-skewed flows; attributed to phase-lag effect due to small settling velocity (e.g., Dohman-Janssen et al. 2001, Coastal Eng.; van der A et al. 2013, Coastal Eng.).



van der A et al. (2013, Coastal Eng.)

ii. Normalized sheet flow layer thickness is much larger for fine sand ($d = 0.15\ mm$)

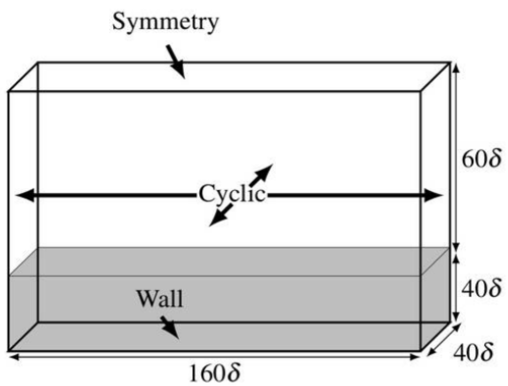


iii. These unique features cannot be reproduced by 1DV RANS k-ε type models (Kranenburg et al. 2014, Adv. Water Resources)

- Hypothesis: Unique fine sand features are caused by flow instabilities, not just due to small settling velocity.
- Conduct 3D LES for oscillatory sheet flow for medium and fine sand

Case	Wave	d_{50} (μm)	Period T (s)	Velocity amp U_m $(\frac{m}{s})$	Re_w	Re_δ	Reference
M512	Sine	280	5	1.5	1.8×10^6	1890	O'Donoghue & Wright (2004) Coastal Eng.
F512	Sine	150	5	1.5	1.8×10^6	1890	O'Donoghue & Wright (2004) Coastal Eng.
M5010	Skew	280	5	1.5	1.8×10^6	1890	O'Donoghue & Wright (2004) Coastal Eng.
F5010	Skew	150	5	1.5	1.8×10^6	1890	O'Donoghue & Wright (2004) Coastal Eng.
M706015	Asy	270	6	1.3	1.6×10^6	1790	van der A et al. (2010) Coastal Eng.
F706015	Asy	150	6	1.3	1.6×10^6	1790	van der A et al. (2010) Coastal Eng.

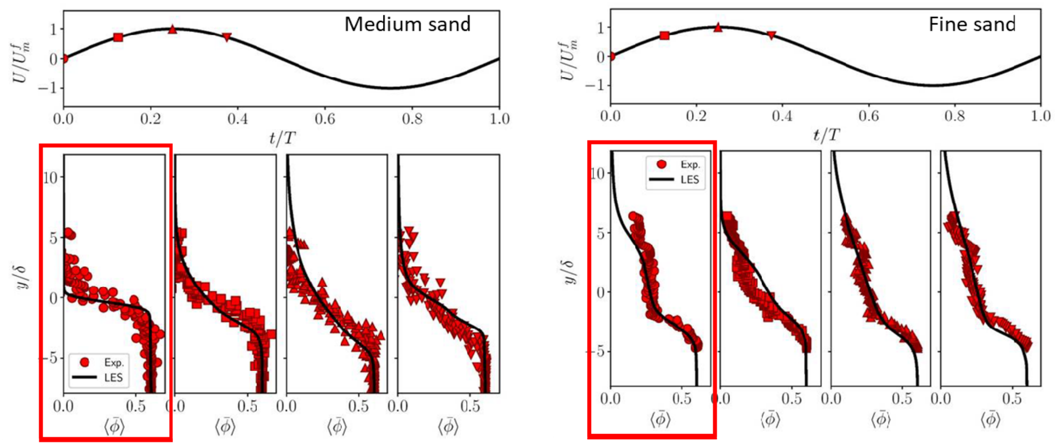
(*Mathieu et al. 2022; J. Fluid Mech.; Mathieu et al, in preparation for Coastal Eng.*)



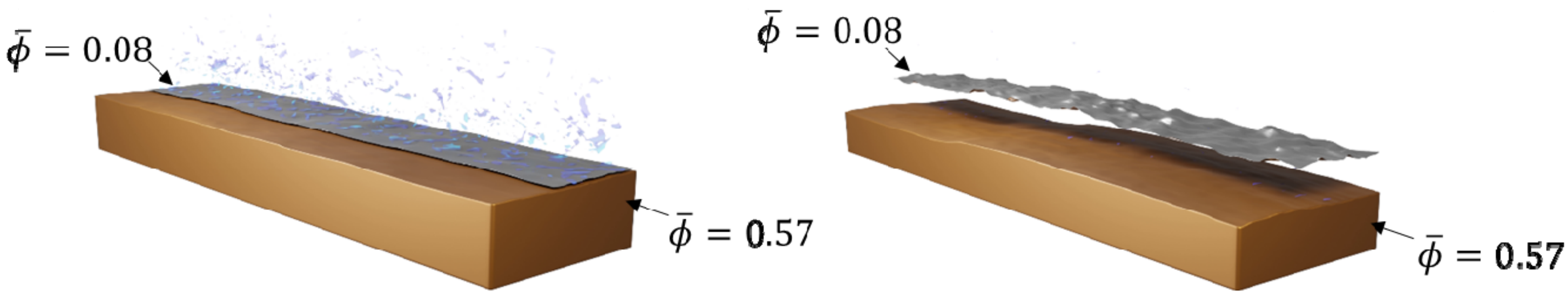
Mesh	Number of cells	Δ_x^+	Δ_z^+	Δ_y^+ (bed)
$200 \times 260 \times 92$	4,784,000	110	60	25

- Unique features are due to nonlinear interaction between instabilities, turbulent eddies and sediment.

Flow reversal

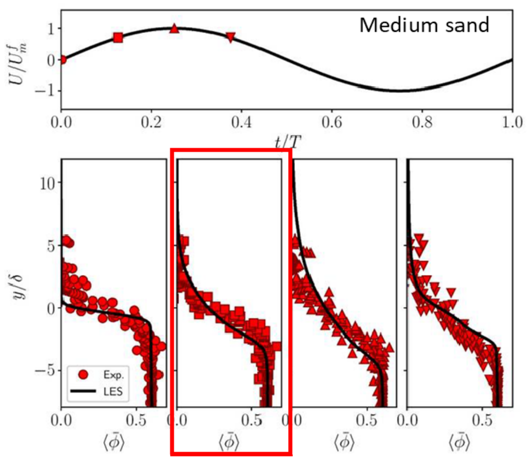


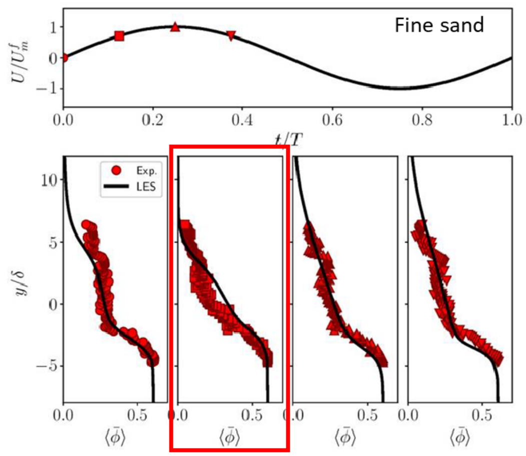
- For medium sand (M512), nearly all sediment particles are settled to the bed. Some turbulence remain in the boundary layer.
- For fine sand (S512), significant amount of sediment particles remain suspended. No turbulence seen in the boundary layer.



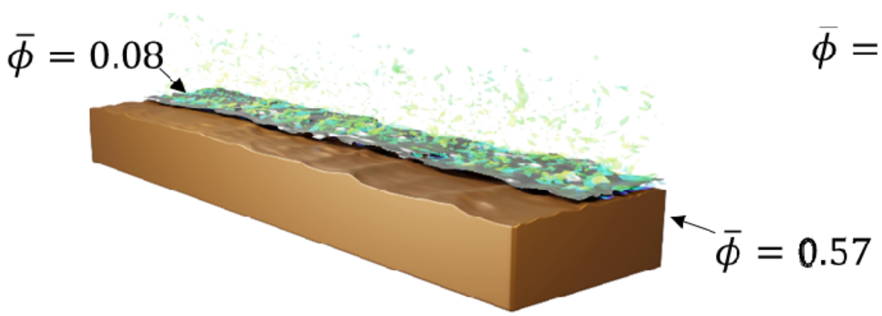
- Unique features are due to nonlinear interaction between instabilities, turbulent eddies and sediment.

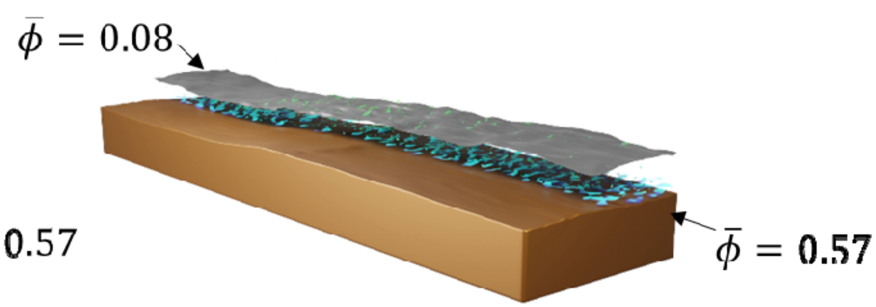
Flow acceleration





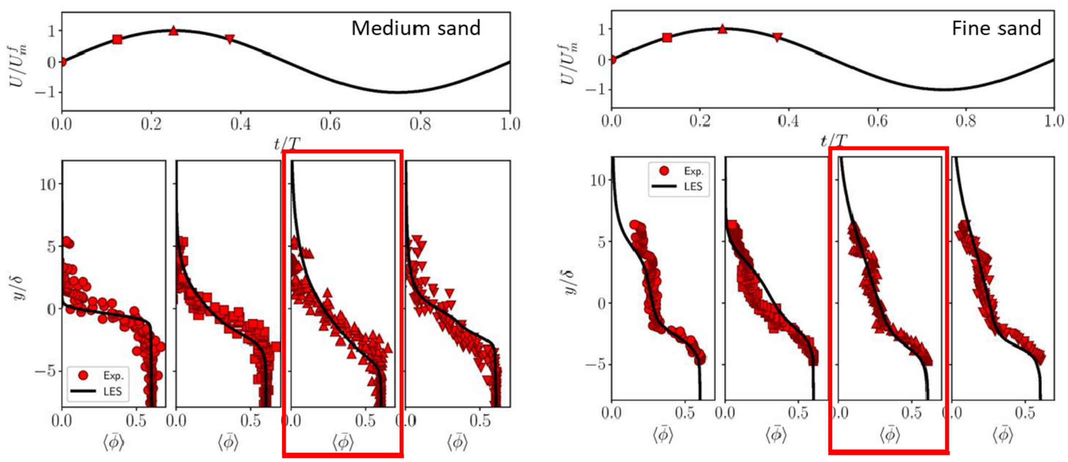
- Small instabilities are observed.
- Fine sand particles are remain suspended and instabilities are observed in the sediment layer.

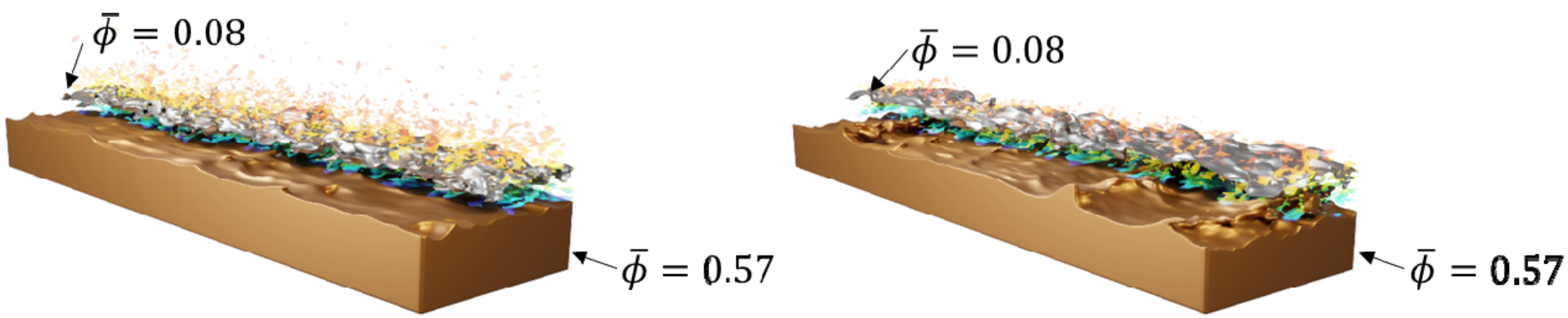




- Unique features are due to nonlinear interaction between instabilities, turbulent eddies and sediment.

Flow crest

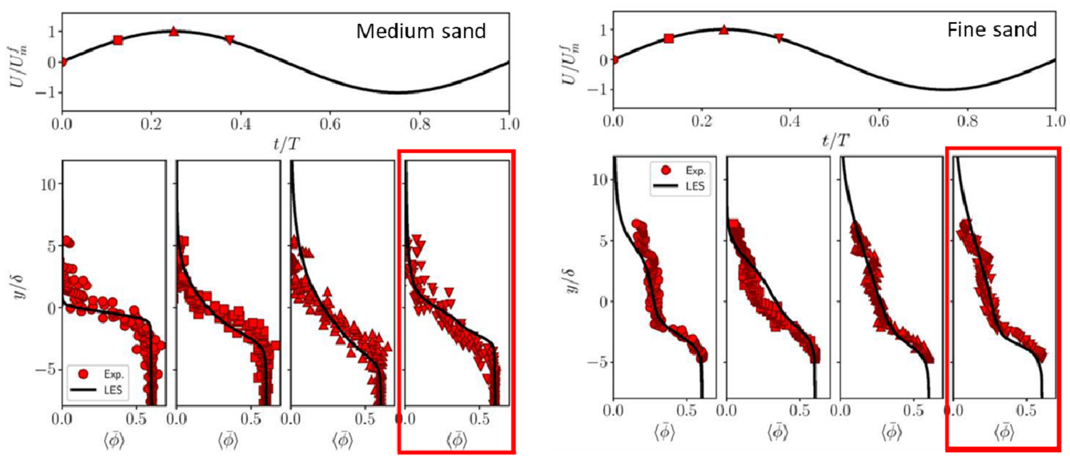




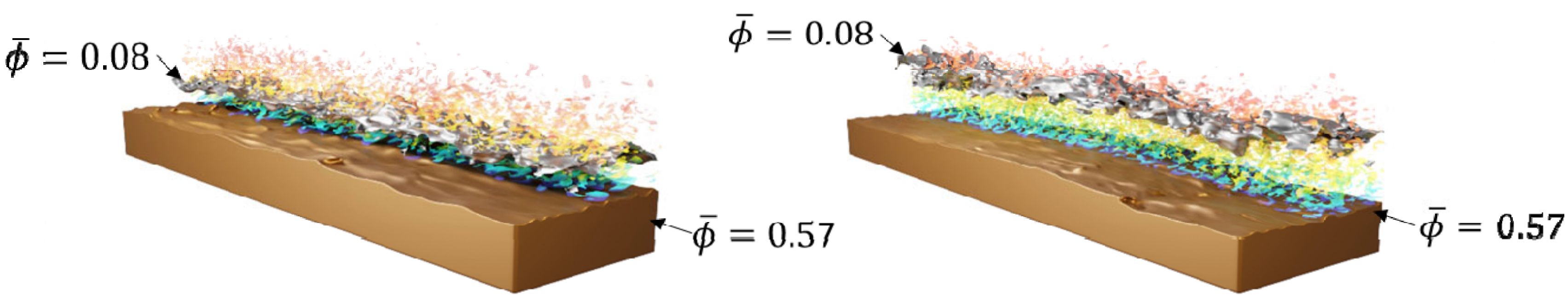
- During flow crest, instabilities transitioned to turbulence and drove large sediment suspension.
- Sheet flow layer thickness for fine sand is larger than that of medium sand.

- Unique features are due to nonlinear interaction between instabilities, turbulent eddies and sediment.

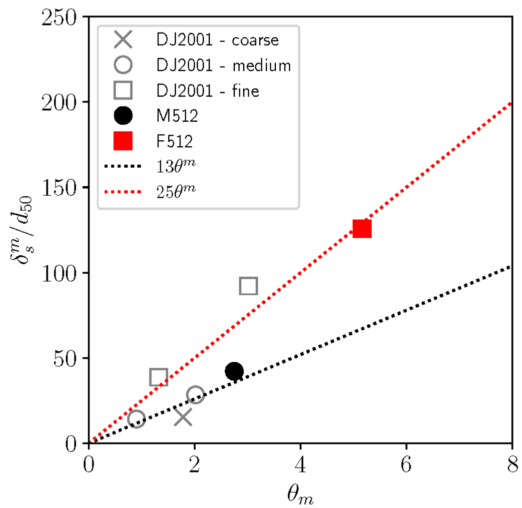
Flow deceleration

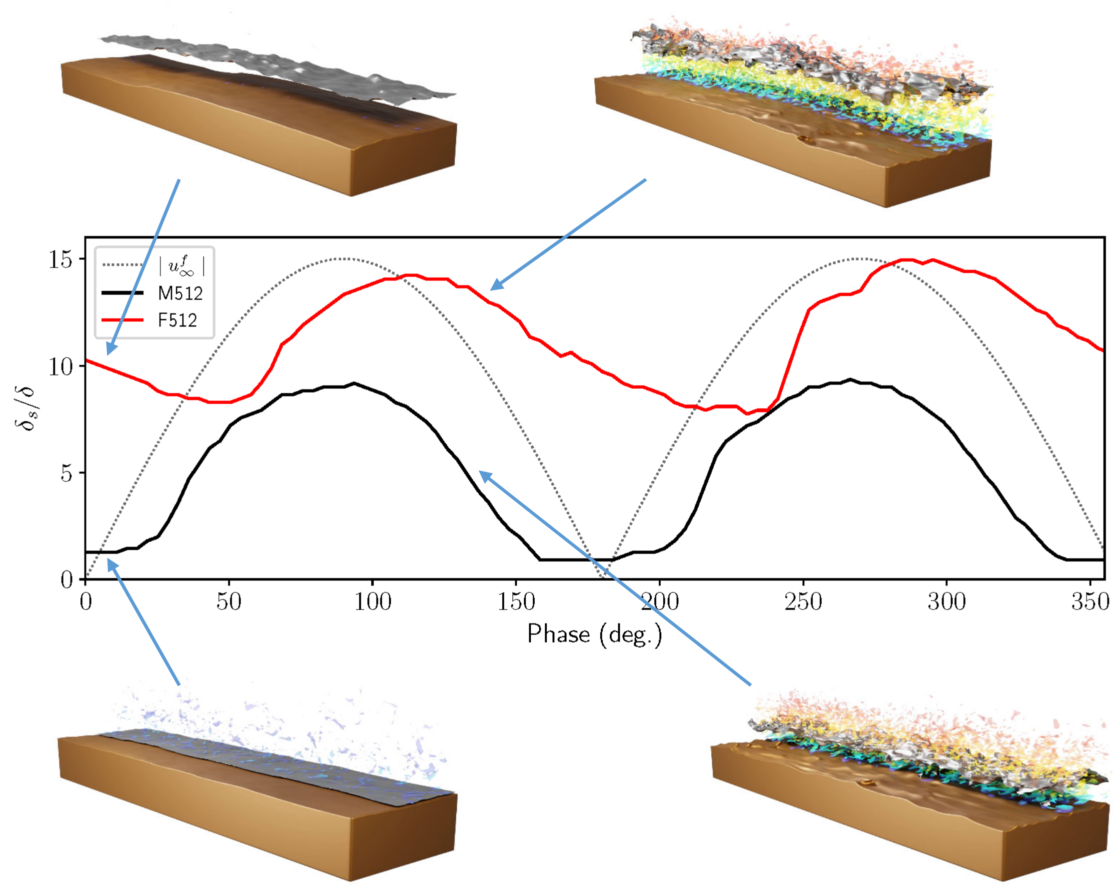


- During deceleration, flows remain turbulent and keep sediment suspended.
- Sheet flow layer thickness for fine sand is clearly larger than that of medium sand.

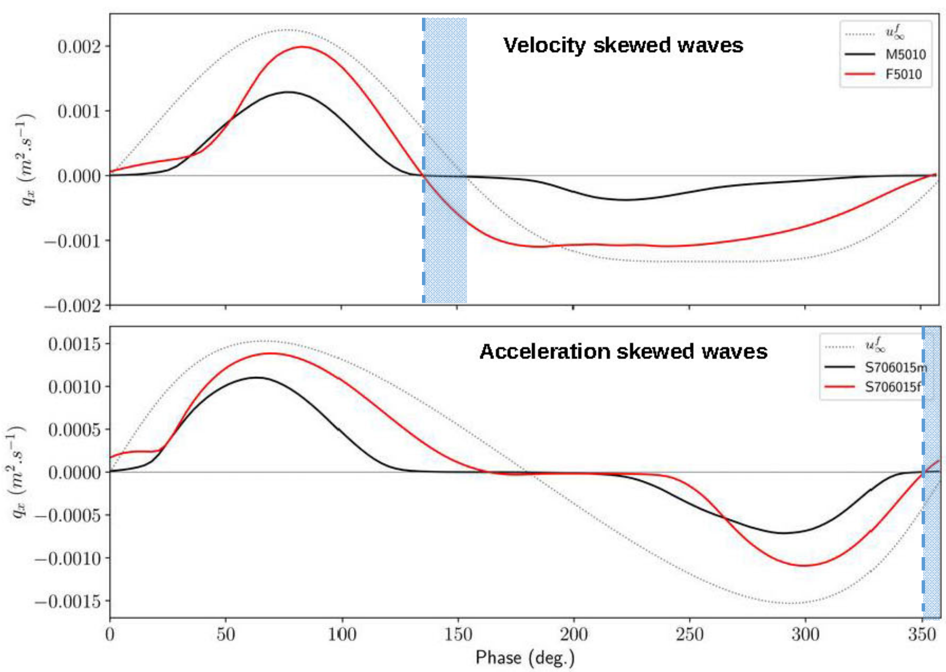


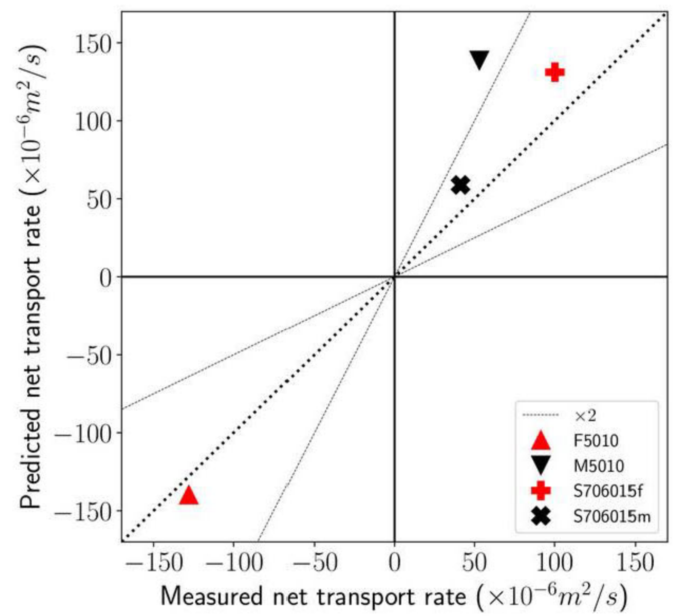
- The phase-lag effect for fine sand is not only due to its small settling velocity but also caused by **enhanced sheet flow layer thickness due to flow instabilities** during flow reversal and early stage of flow acceleration.

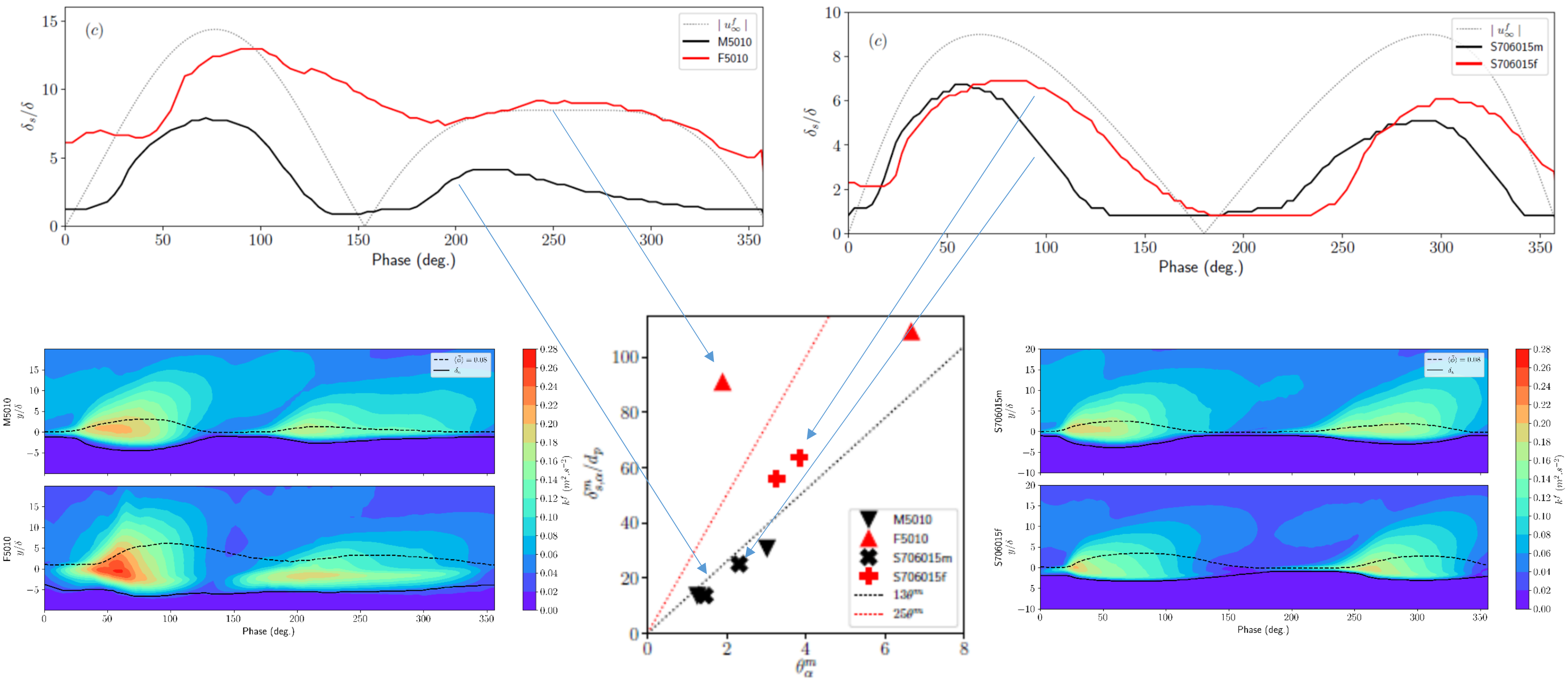




- LES SedFoam is used to simulate net transport driven by nonlinear waves and captures:
  - A strong phase-lag effect of fine sand driven by onshore velocity-skewed oscillatory flow leads to a net offshore transport
  - A moderate phase-lag effect of fine sand driven by onshore acceleration-skewed oscillatory flow enhances net onshore transport



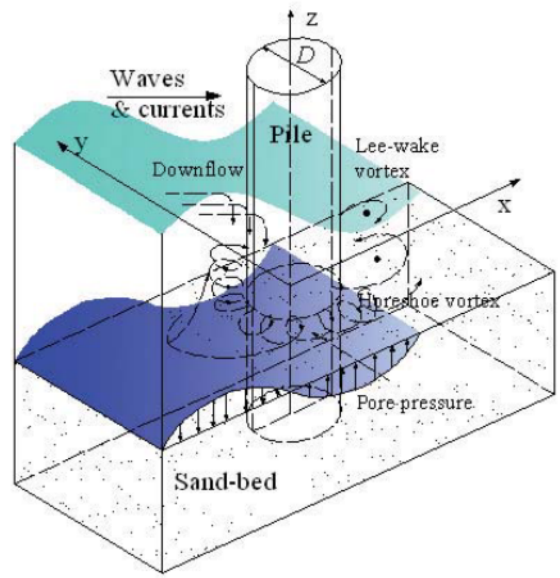


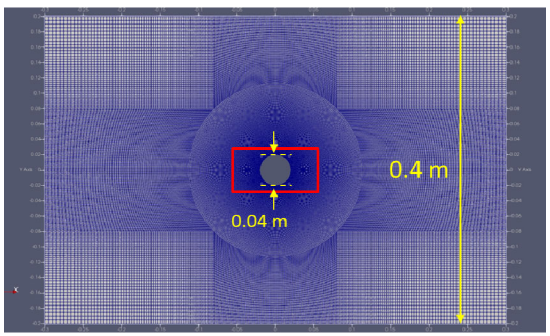


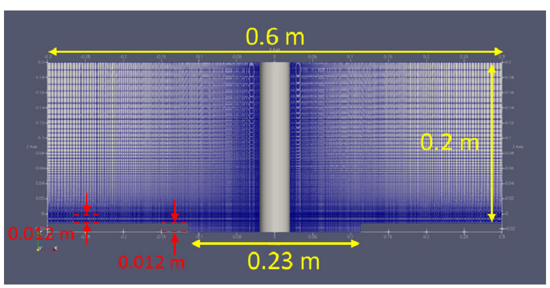
(c)
$|u^f_\infty|$
M5010
F5010
δ_s/δ
Phase (deg.)
(c)
$|u^f_\infty|$
S706015m
S706015f
δ_s/δ
Phase (deg.)
M5010 y/δ
F5010 y/δ
Phase (deg.)
k^f $(m^2.s^{-2})$
$\delta^m_{s,\alpha}/d_p$
θ^m_α
M5010
F5010
S706015m
S706015f
$13\theta^m$
$25\theta^m$
S706015m y/δ
S706015f y/δ
Phase (deg.)
k^f $(m^2.s^{-2})$

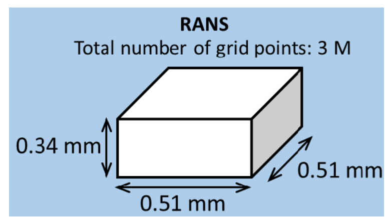
3. Scour around a vertical pile driven by an oscillatory flow

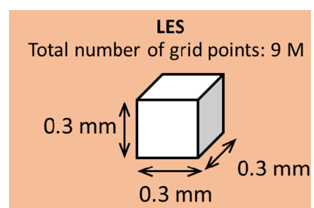
- To understand the importance of concurrently resolving primary vortices and turbulent coherent structures in scour (LES vs. RANS k-ω closure).
- Sumer et al. (1997, J. Fluid Mech.; 2013, J. Waterway, Port, Coastal, Ocean Eng.) report measured bottom shear stress, scour depth, and flow pattern around a circular pile for a series of rigid bed and sand bed ($d_{50} = 0.17\ mm$) wave flume experiments.









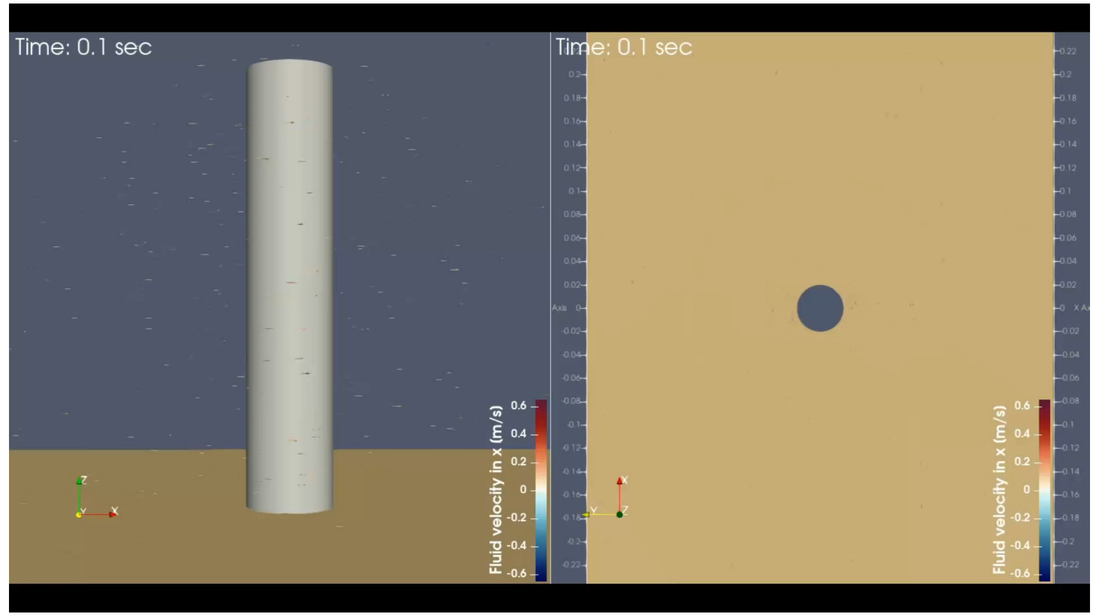


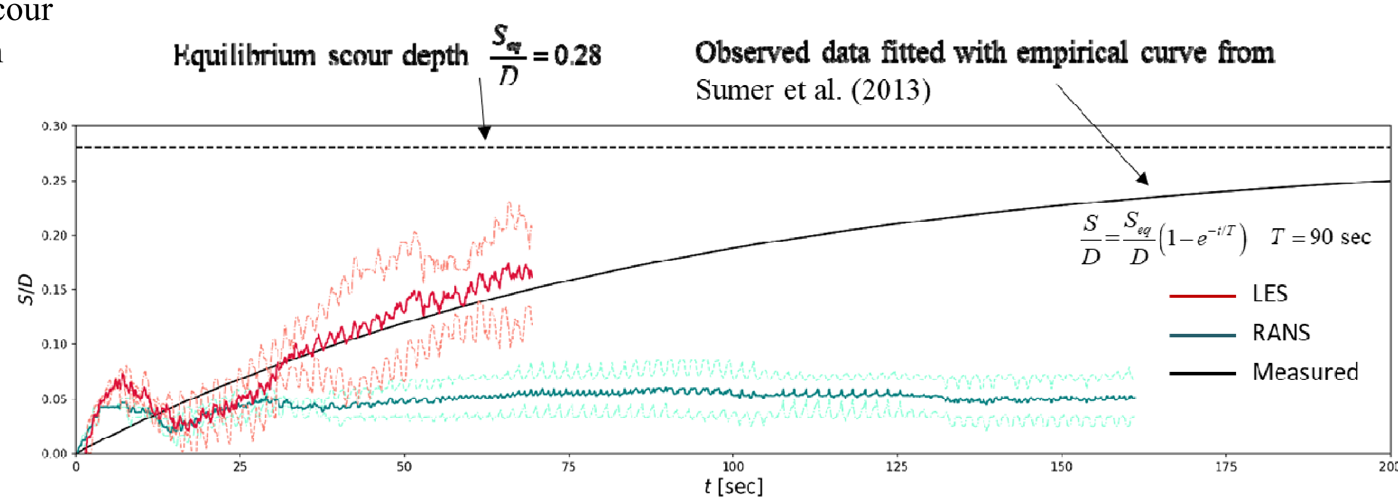
- SedFoam LES for the experiment of Sumer et al. (2013)

  $U = 0.225\ m/s \quad T = 1.79\ s \quad D = 0.04\ m$

  $KC = \dfrac{UT}{D} = 10 \qquad d_{50} = 0.17\ mm, \theta \approx 0.1$

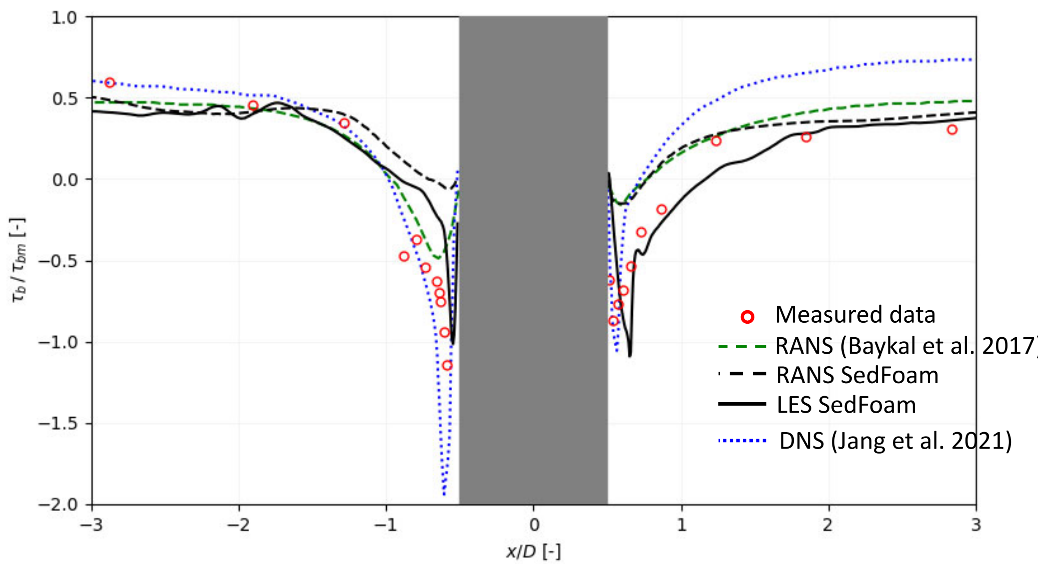
  - SedFoam LES is able to predict measured temporal evolution of scour depth that agrees well with measured data.
  - SedFoam RANS $k - \omega$ closure significantly under-predicts scour depth around a circular pile in oscillatory flows.



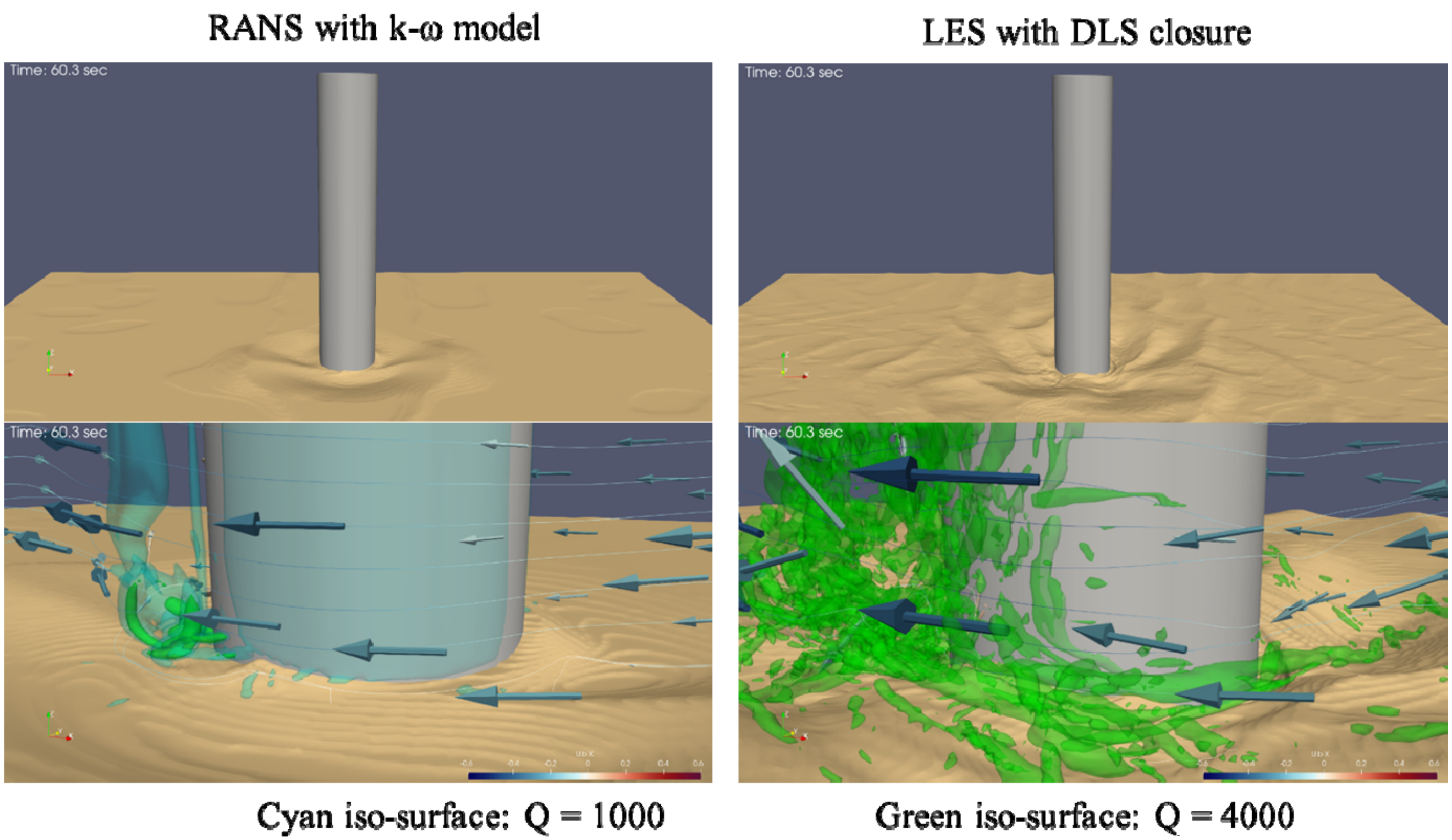


- Under-predicted scour depth in RANS $k - \omega$ closure is due to an under-prediction of bottom shear stress near the pile, consistent with earlier studies (Baykal et al. 2017, Coastal Eng.)
- The present SedFoam LES and a recent DNS (Jang et al. 2021, Phys. Fluids) are able to predict the increase of bottom shear stress similar to the measured data.

Sumer et al. (2013) at KC=10



- Under-prediction of bed shear stress near the pile in RANs model is due to significant under-prediction of horseshoe vortices.



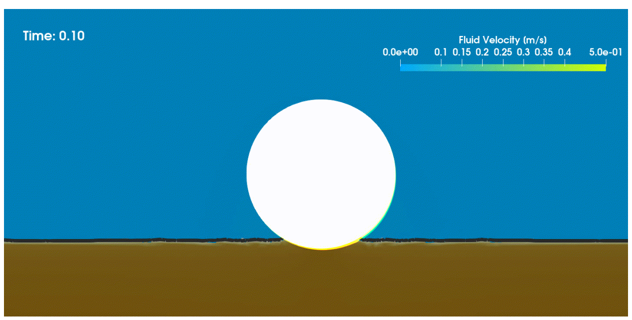
Concluding Remarks

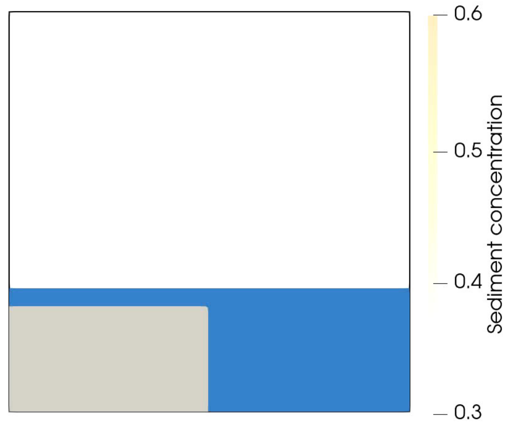
- For certain coastal processes, “diffusion” may not be the best solution:

  The next generation numerical models for certain coastal processes should be based on turbulence-resolving simulation approaches to tackle these nonlinear processes.

- Future work - SedFoam

  1) Bedform simulations.
  2) Coupled object movement (6DoF) with fluid and sediment phase.
  3) Capability to solve air-water interface.





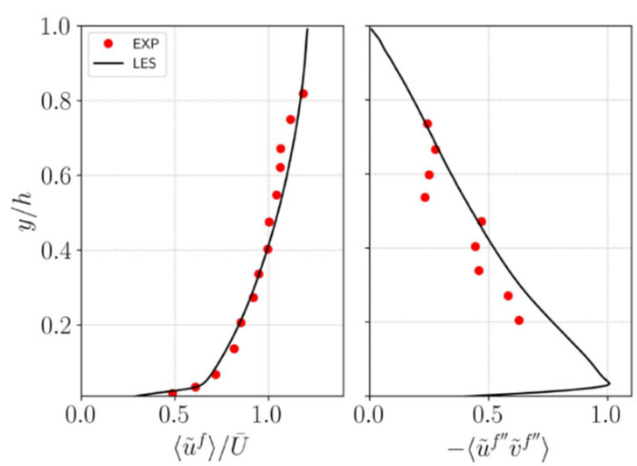
$d = 0.5\ mm;\ \theta \approx 0.1$

2. A chicken and egg problem! (Best 1992, *Sedimentology*; Hsu, 2022, *J. Fluid Mech.*)

Bedforms can be generated by boundary layer turbulent coherent structures from a completely flat bed; see the recent fully-resolved simulations (Scherer, Uhlmann, Kidanemariam, Krayer, 2022 On the role of turbulent large-scale streaks in generating sediment ridges. *J. Fluid Mech*. 930, A11.)

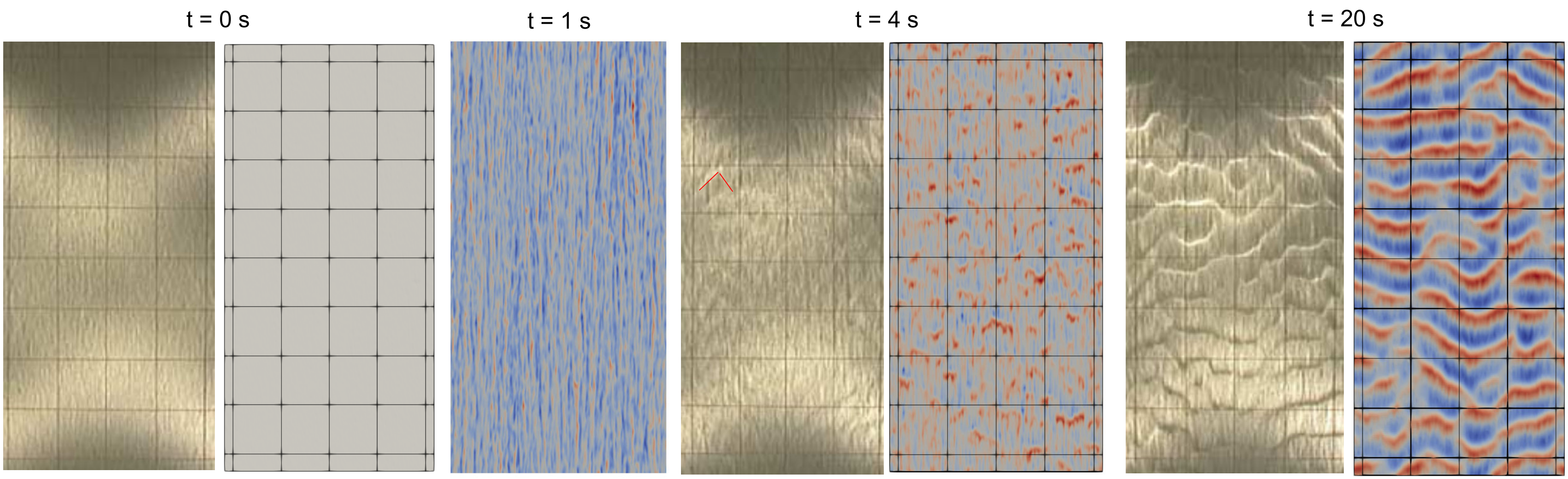
- We are validating SedFoam LES for the initiation of bedforms driven by a unidirectional current reported by Venditti and Church (2005, *J. Geophys. Res. Earth Surface*).

$Re = 76{,}000;\ h = 0.152\ m; \overline{U} = 0.5\ m/s$



$d_{50} = 0.5\ mm;\ \theta \approx 0.1$

- Simulation results reveal that bedforms can be initiated from a completely flat bed by resolved turbulent coherent structures which drives small, flow-parallel sand ridges (see t=1 s). These small ridges later evolve into cross-hatch pattern similar to measured data.
- SedFoam LES is able to predict the pattern of bed features evolving from flat bed, small 3D bedforms, and large 2D bedforms similar to observation.



- Bedform initiation by an oscillatory flow ($U_m = 0.48\frac{m}{s}, T = 5\ sec$) https://youtu.be/ZJlKwaWm9jw