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MODELING SHEET FLOW UNDER BREAKING WAVES ON A SURF ZONE SANDBAR

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1. Introduction

Wave-driven sediment transport

Sediment suspension under waves, courtesy of Clark Little

Complex mechanisms

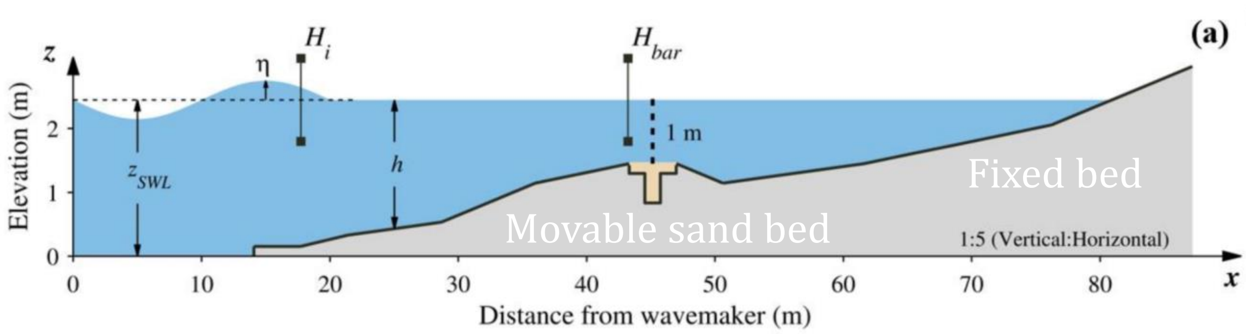
(1) Free surface effects
(2) Boundary layer processes
(3) Unsteady effect on bed shear stress, bedload, and suspended load
(4) Grain properties

Surf zone sandbar

A schematic of surf zone sandbar, courtesy of The COMET program

(1) Sandbar is a prominent feature in the cross shore beach profile undergoing seasonal migration
(2) Act as a natural wave energy dissipater
(3) Sediment transport is driven by wave velocity and acceleration skewness and undertow currents

BARSED experiment (Mieras et al., 2017; Anderson et al., 2017)



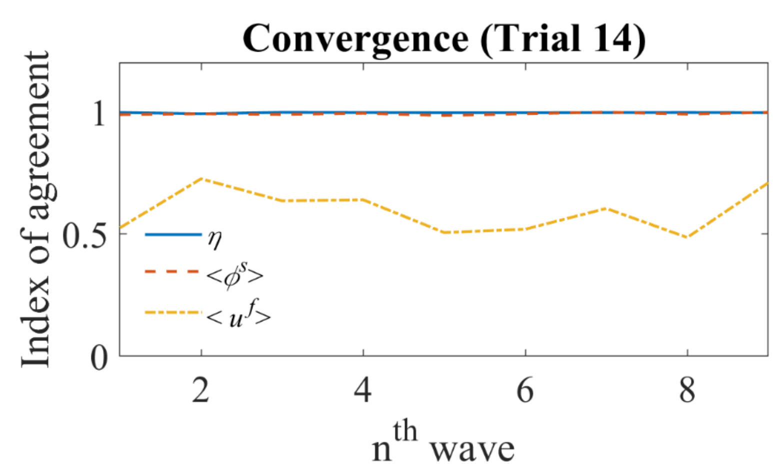
A schematic of the laboratory experiment (Mieras et al., 2017)

HWRL in OSU, Oregon, USA

(1) 104 m (L), 4.6 m (h)
(2) H_{bar} = 0.94 m, T = 7 s (S1T7H60)
(3) h = 1 m at the sediment pit
(4) D_{50} = 170 μm, well-mixed
(5) ADVs, ADPVs, FOBS, CCPs

- **Detailed measurement of sediment transport at the sandbar crest**
  Intra-wave sediment concentration & velocity profiles and pore pressure gradient

- **Ensemble averaged data can be obtained by ensemble-phase-averaging**
  3 trials which have 10, 10, & 9 waves, respectively
  ∴ 29 ensembles (Trials 14, 51, 80)



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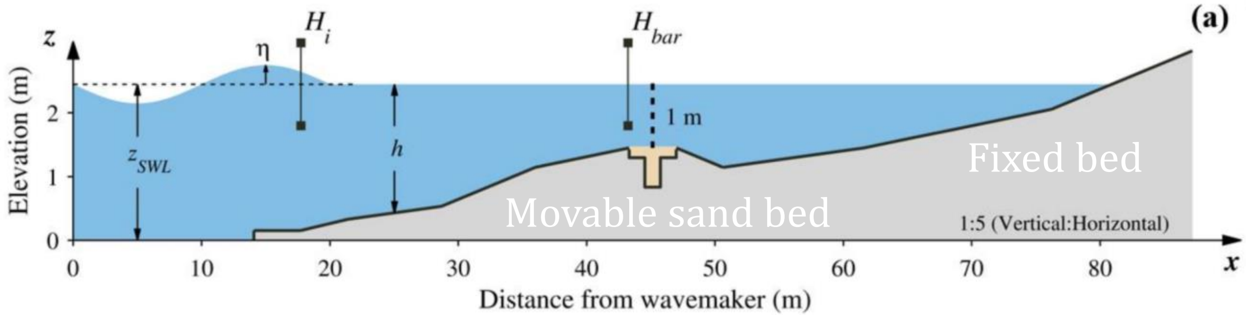


A schematic of the laboratory experiment (Mieras et al., 2017)

Numerical models

Single-phase Navier-Stokes wave model
3D (LES) & 2DV (RANS)

- Evolution of breaking wave turbulence landward of the sandbar crest.
- Performance of different turbulence models can be evaluated

Two-phase sediment transport models with/without free surface
SedFoam & SedWaveFoam

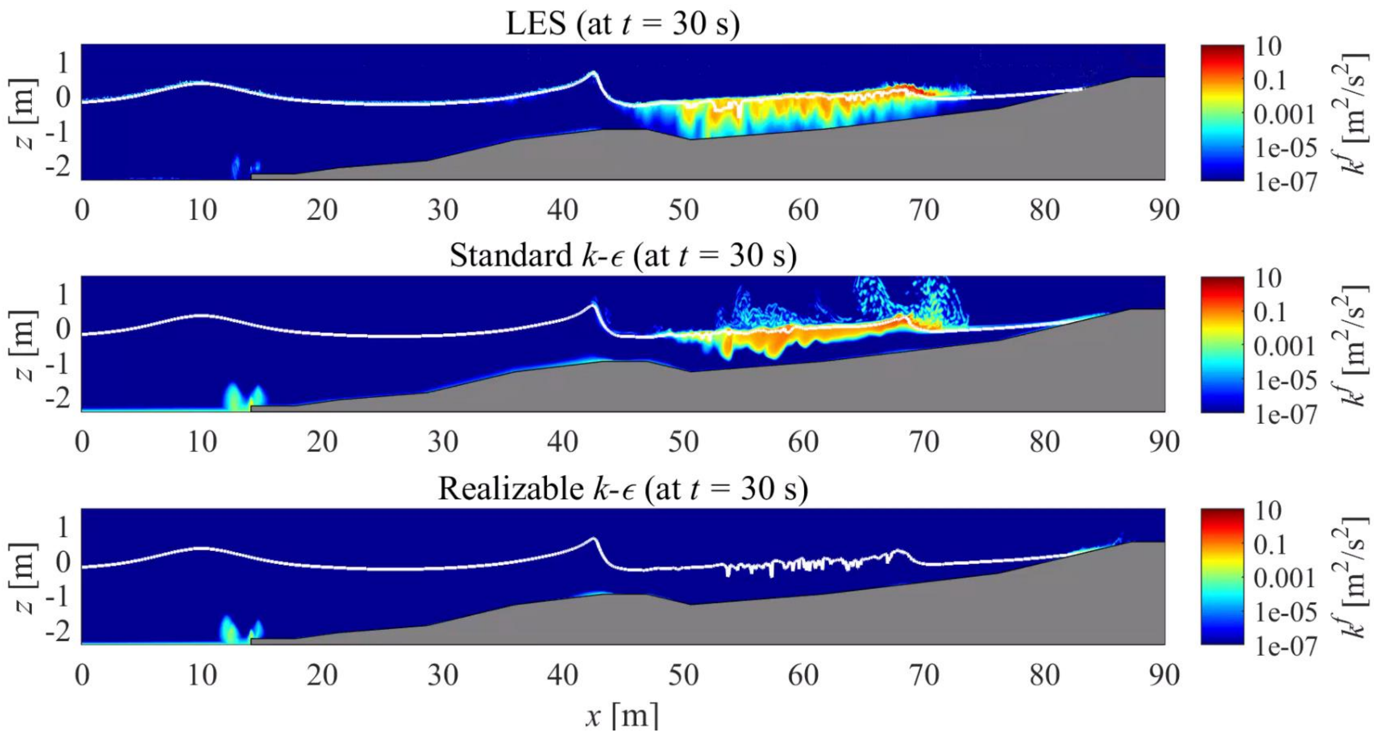
- Examine various sediment transport mechanisms under breaking waves
- Isolate the free surface effect on sediment transport (e.g., streaming)

Single-phase (air-water mixture) Navier-Stokes wave model investigation

(1) 3D LES model with a standard Smagorinsky closure

(2) 2DV RANS model with a standard $k-\epsilon$ closure

(3) 2DV RANS model with a realizable $k-\epsilon$ closure



- All three models show returning TKE at later stage
- Standard $k-\epsilon$ does a better job at transition stage
- Spreading rate of TKE is much higher in standard $k-\epsilon$

Single-phase (air-water mixture) Navier-Stokes wave model investigation

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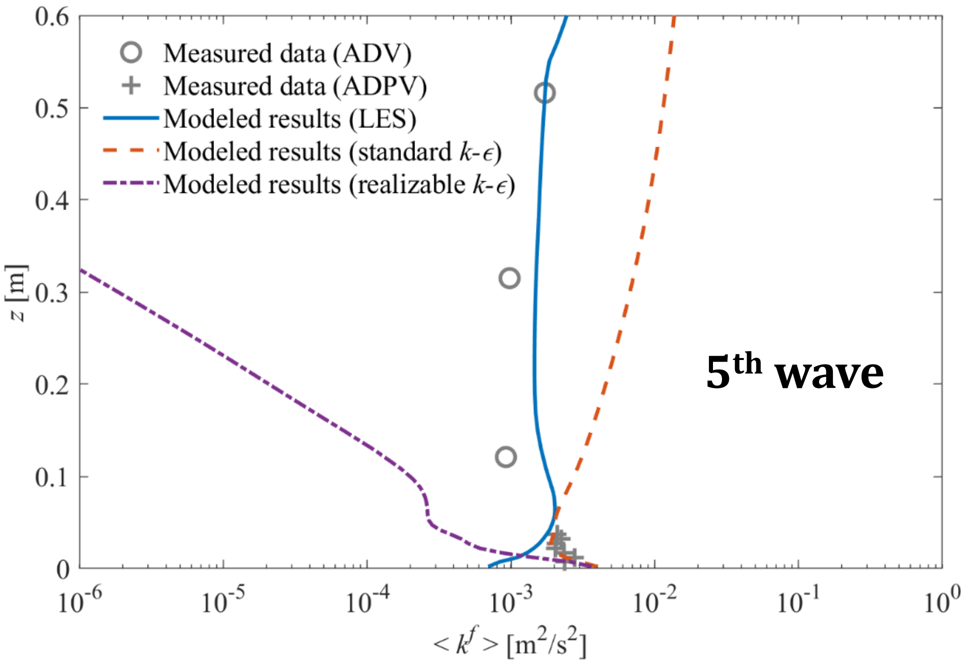
Model-data comparison of wave-averaged TKE



- **High-pass filtering** with 0.5 Hz cutoff frequency is applied to measured velocity before calculating TKE
- Phase-spanwise-average is applied for LES model results
- TKE for 5th wave is selected for RANS models
- Standard $k - \epsilon$ closure overpredicts TKE at the later stage (after 6th wave)
- Realizable $k - \epsilon$ closure agree with LES results only at later stage

Single-phase (air-water mixture) Navier-Stokes wave model investigation
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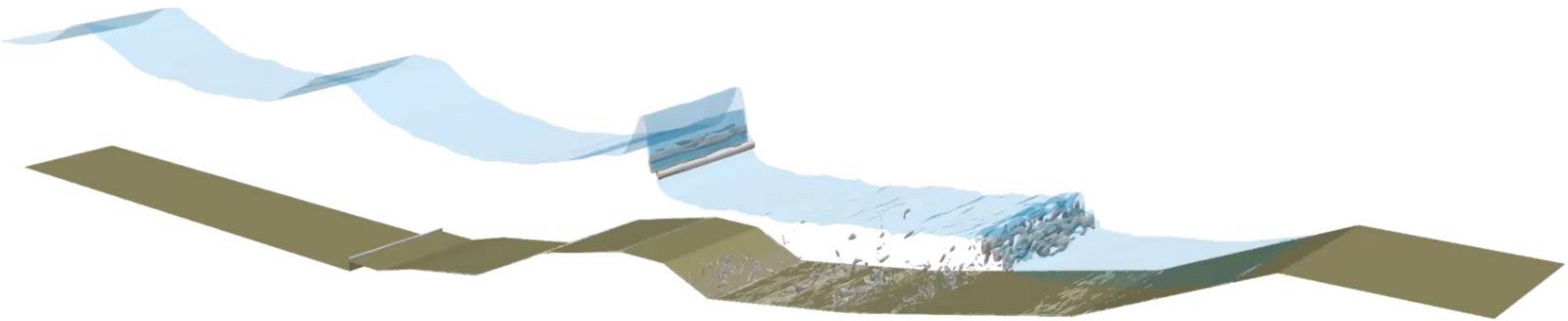
Turbulent coherent structure (TCS) using $\lambda_2 = -50$ (LES results)

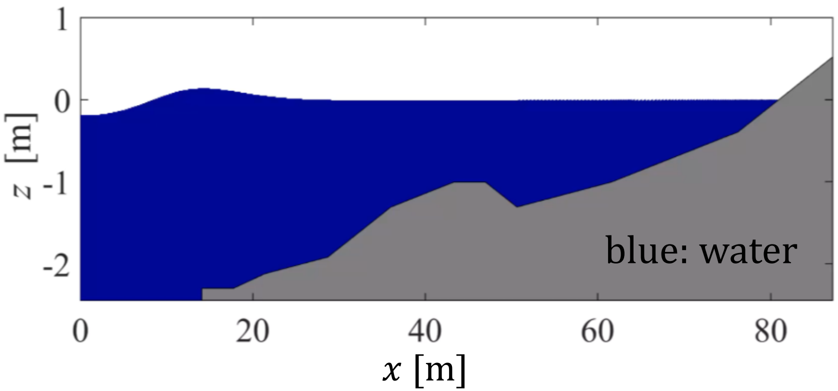


- Wave-breaking turbulence approaches the bed landward of the bar crest.
- In this case, sediment transport at the bar crest may be mainly driven by wave velocity skewness, horizontal pressure gradient (acceleration skewness), and streaming

Free surface resolving two-phase Eulerian sediment transport model

InterFoam/waves2Foam

Jacobsen et al. (2011, *IJNMF*; 2014, *Coast. Eng.*)

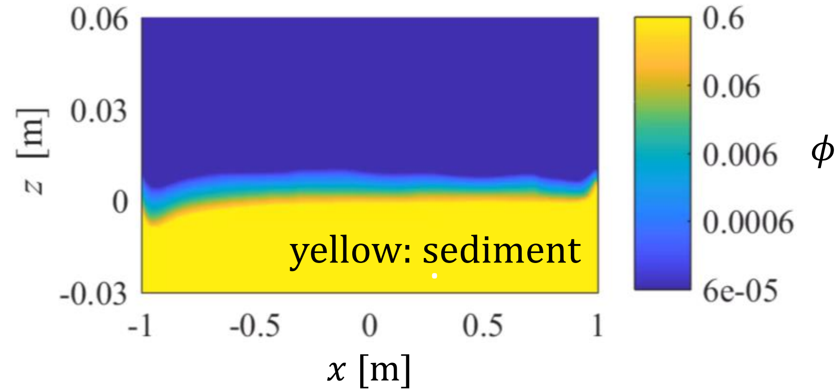


Capability

(1) Wave generation/absorption
(2) Surface evolution
(3) Wave shoaling and breaking
(4) Boundary layer process

SedFoam

Cheng et al. (2017, *Coast. Eng.*)



Capability

(1) Two-phase sediment transport model
(2) Full profile of sediment transport
(3) Sheet flow; scour around structures

SedWaveFoam

- Only standard $k - \epsilon$ turbulence model is available

Reynolds-averaged Mass Conservation Equations

Air phase (immiscible)

$$\frac{\partial \phi^a}{\partial t} + \frac{\partial \phi^a u_i^a}{\partial x_i}$$

+

Water phase (immiscible)

$$\frac{\partial \phi^w}{\partial t} + \frac{\partial \phi^w u_i^w}{\partial x_i}$$

Dispersed sediment phase (miscible)

$$\frac{\partial \phi^s}{\partial t} + \frac{\partial \phi^s u_i^s}{\partial x_i}$$

where ϕ is the volumetric concentration, satisfying $\phi^a + \phi^w + \phi^s = 1$

Air-water mixture phase (of two immiscible fluids)

$$\frac{\partial \phi^f}{\partial t} + \frac{\partial \phi^f u_i^f}{\partial x_i}$$

Dispersed sediment phase

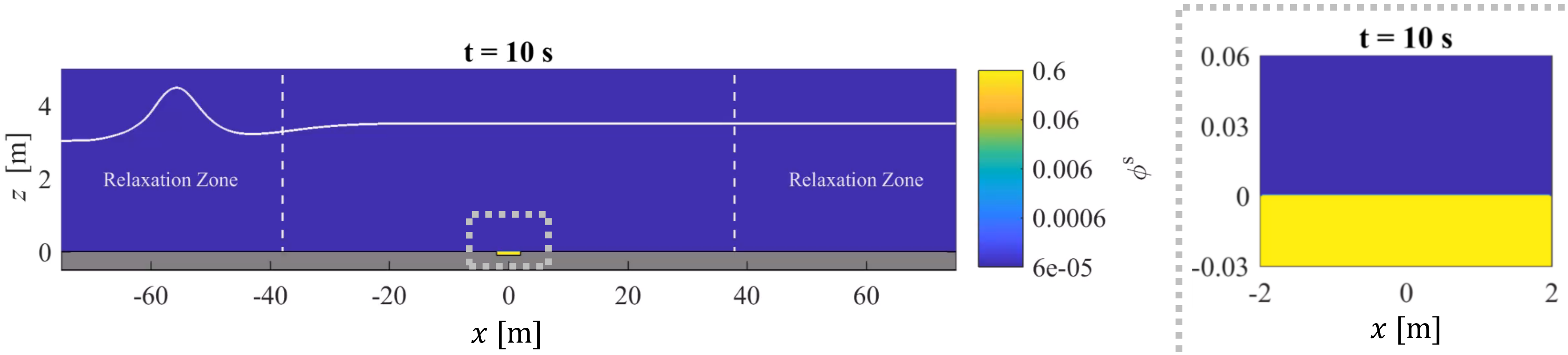
$$\frac{\partial \phi^s}{\partial t} + \frac{\partial \phi^s u_i^s}{\partial x_i}$$

where $\phi^f = \phi^a + \phi^w$ and $u^f = (u^a \phi^a + u^w \phi^w)/\phi^f$

- Air-water interface is tracked by interface compression method (Berberović et al., 2009; Klostermann et al., 2013).
- Diffusion and excessive flux at the air-water interface is constrained.

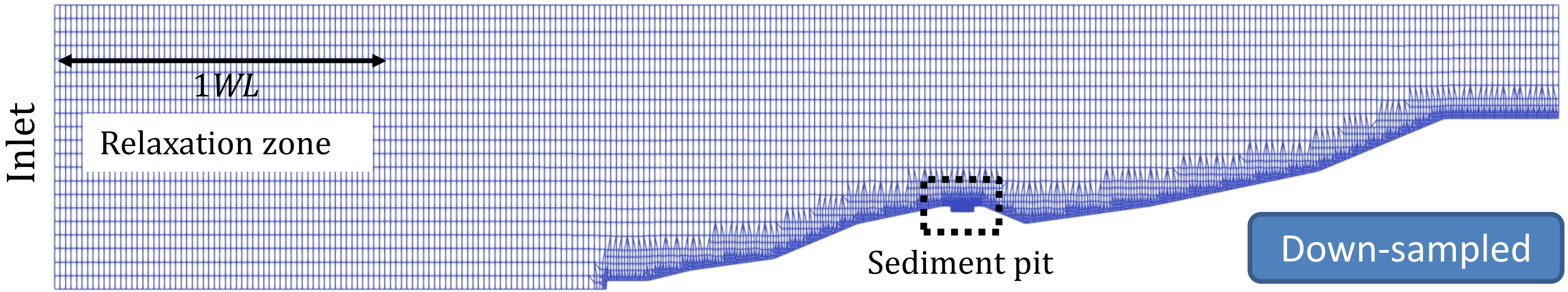
First paper of SedWaveFoam is recently published in JGR: Oceans

Kim et al. (2018): A numerical study of sheet flow under monochromatic nonbreaking waves using a free surface resolving Eulerian two-phase flow model



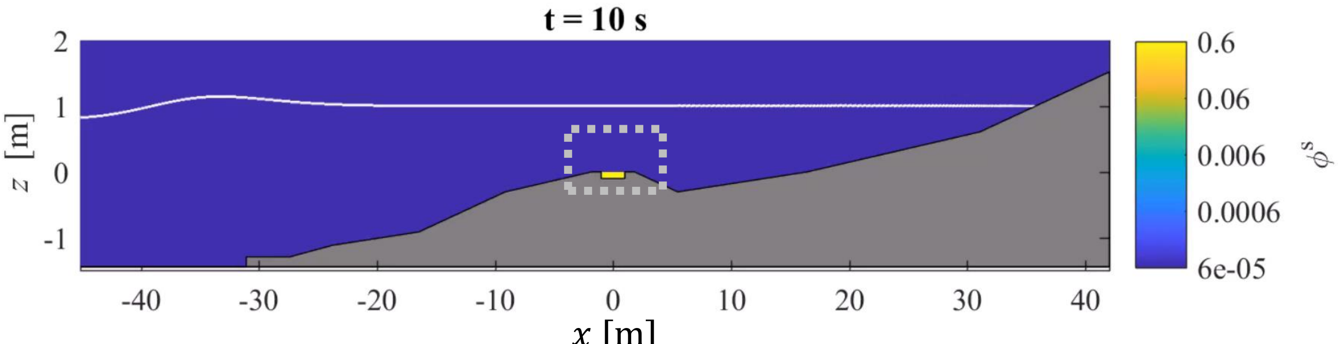
- Detailed **model validation** with the large wave flume data (Dohmen-Janssen & Hanes, 2002) of sheet flow under **monochromatic nonbreaking** surface waves
- **Enhanced onshore sediment transport** under surface waves associated with progressive wave streaming is due to a **wave-stirring mechanism**
- Source code and case setup are available at: https://github.com/sedwavefoam/sedwavefoam

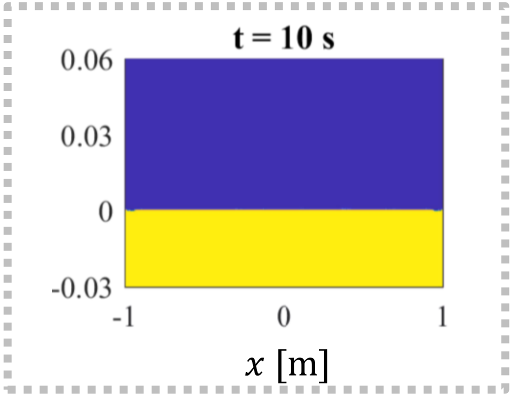
2D numerical flume of 131 (x) x 5 (z) m with a sediment pit of 2.5 (x) x 0.1 (z) m



2 mm < Δx < 16 mm, 1 mm < Δz < 8 mm → N = 4.6 million grid points

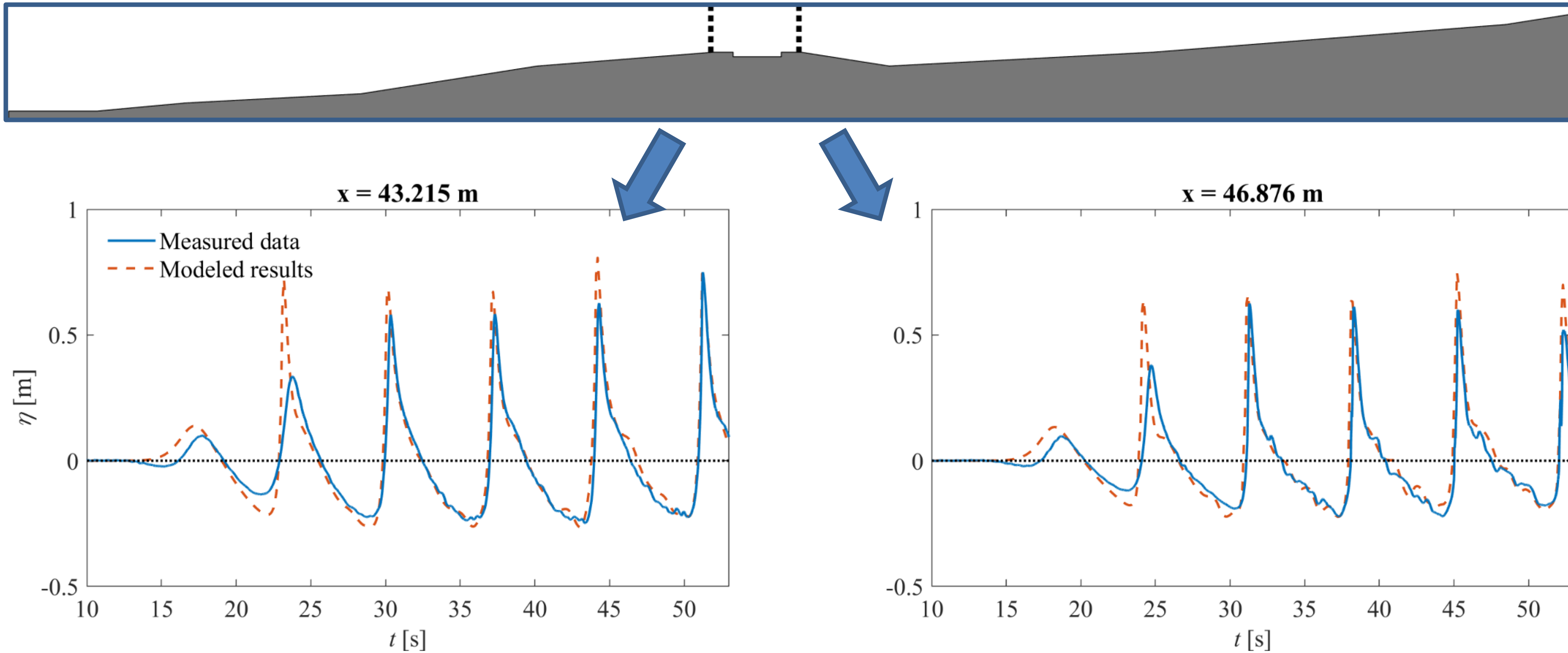
SedWaveFoam concurrently resolves free surface wave field and sediment transport





Yellow (sediment), Blue (air-water mixture), White curve (air-water interface)

Time series of wave height (η) around sediment pit



- Model results agree well with the measured data ($IA \geq 0.93$ & NRMSE $\leq 0.8\%$)
- Zero-up crossing of η (or pressure in measured data) is used for ensemble-averaging

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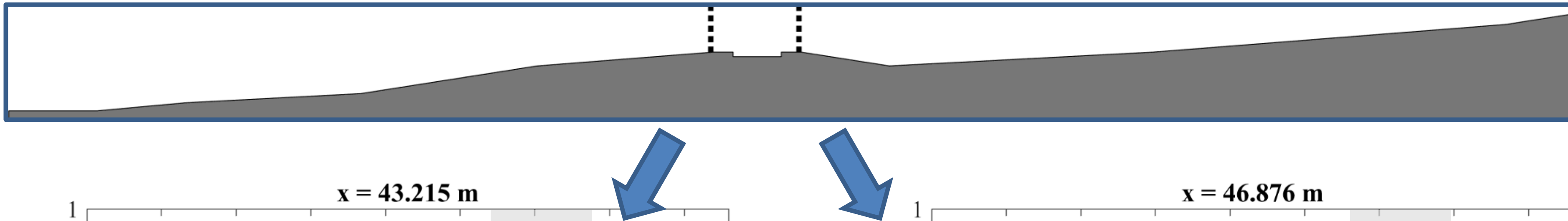
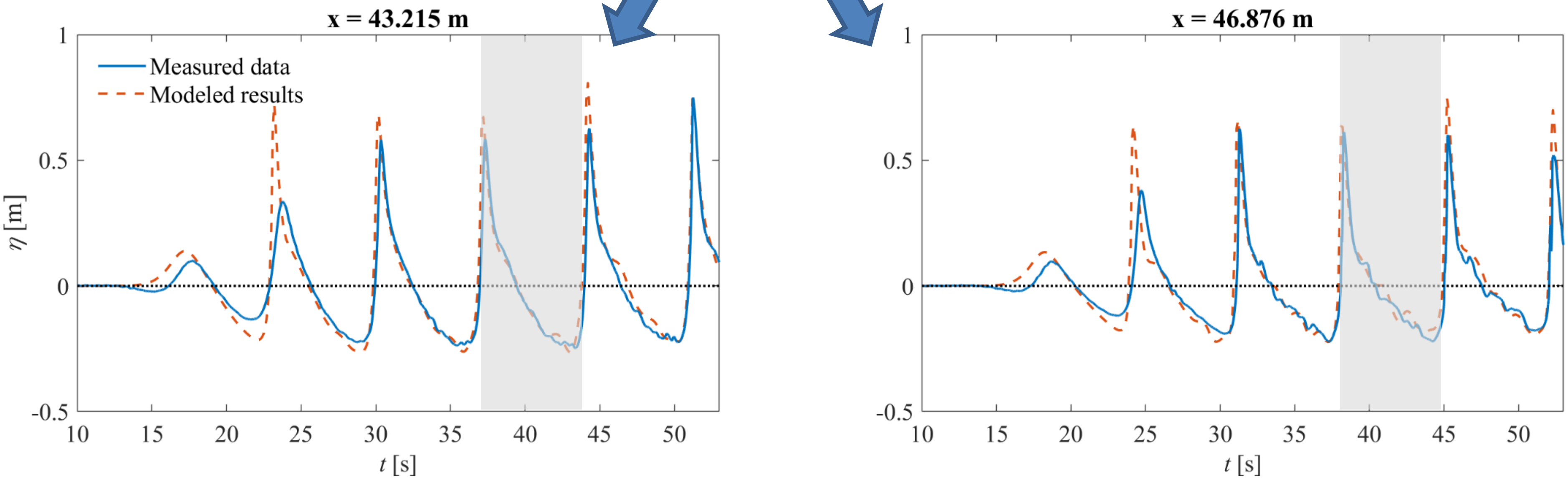
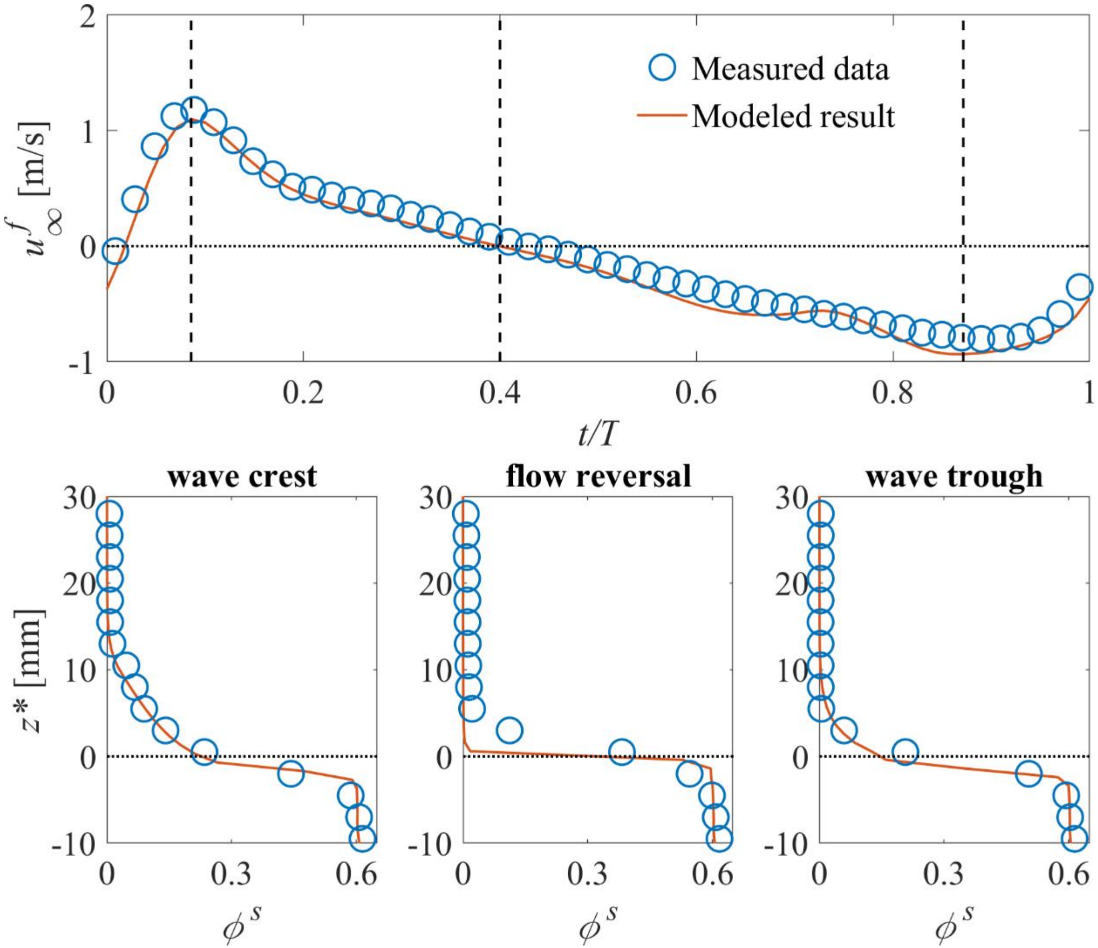




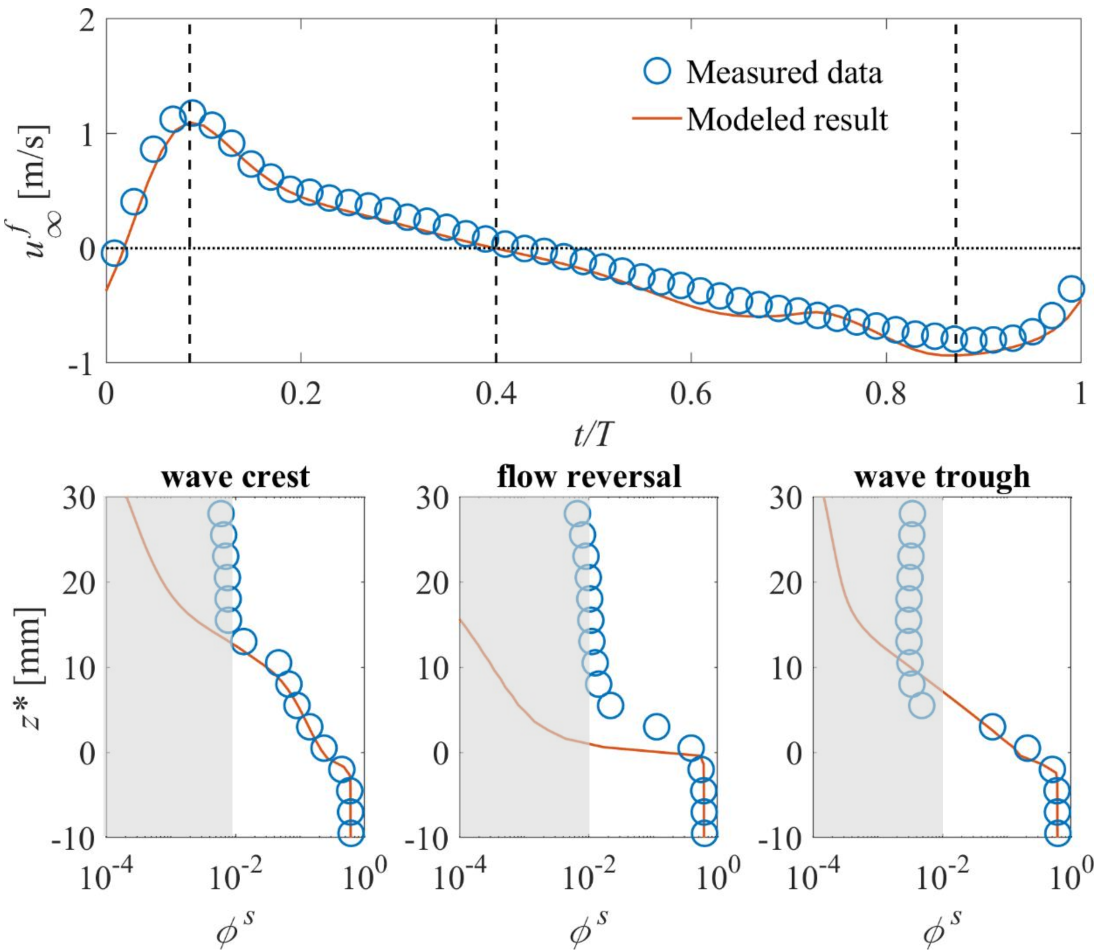
- Model results agree well with the measured data ($IA \geq 0.93$ & NRMSE $\leq 0.8\%$)
- Zero-up crossing of η (or pressure in measured data) is used for ensemble-averaging
- **4th wave** is selected for the model validations (no effect from the retuning TKE)

Free stream velocity and sediment concentration profiles (z^* = 0 is the bed location)



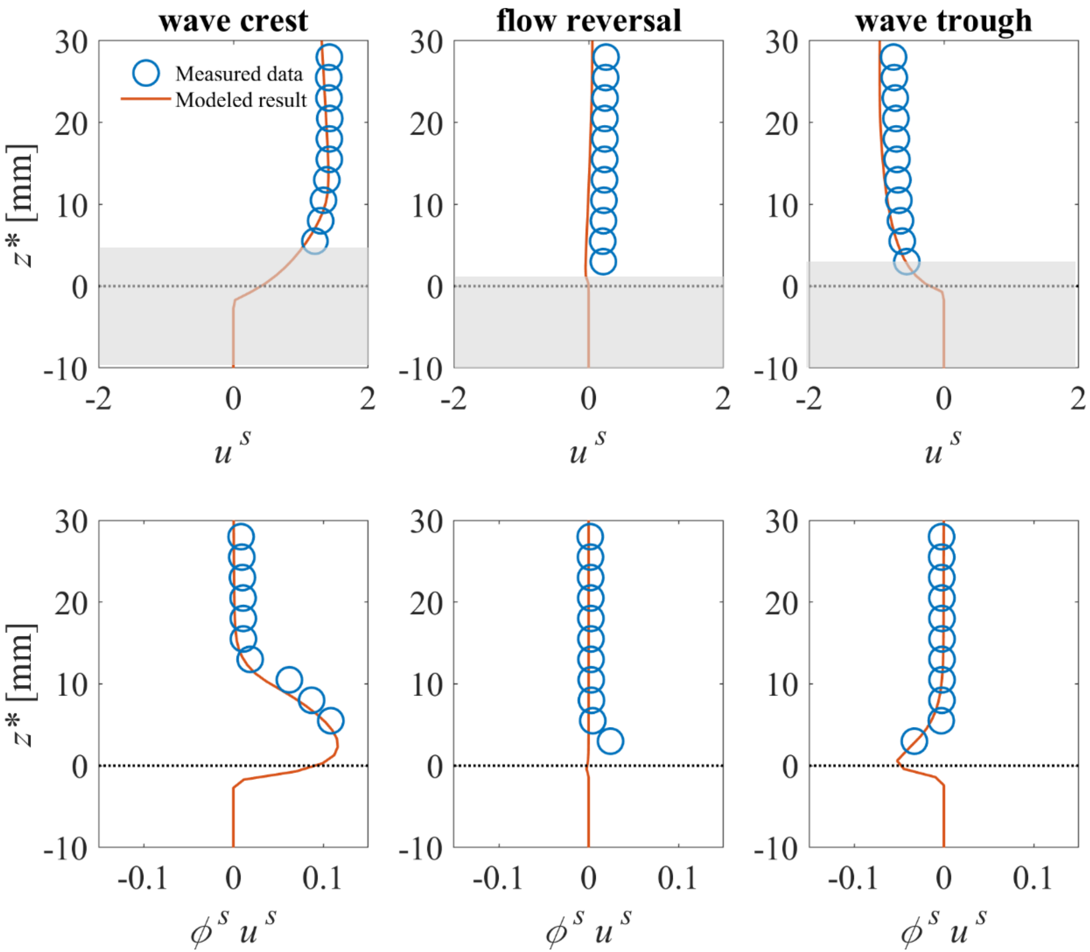
- Free stream velocity and sediment concentration profiles are predicted well ($IA \geq 0.99$, NRMSE $\leq 0.6\%$)
- Notable discrepancy at the flow reversal may be attributed to smoothed data from CCP sensors $\delta_{s,\min} \approx 5$ mm (Lanckrit et al., 2013)

Free stream velocity and sediment concentration profiles (z^* = 0 is the bed location)



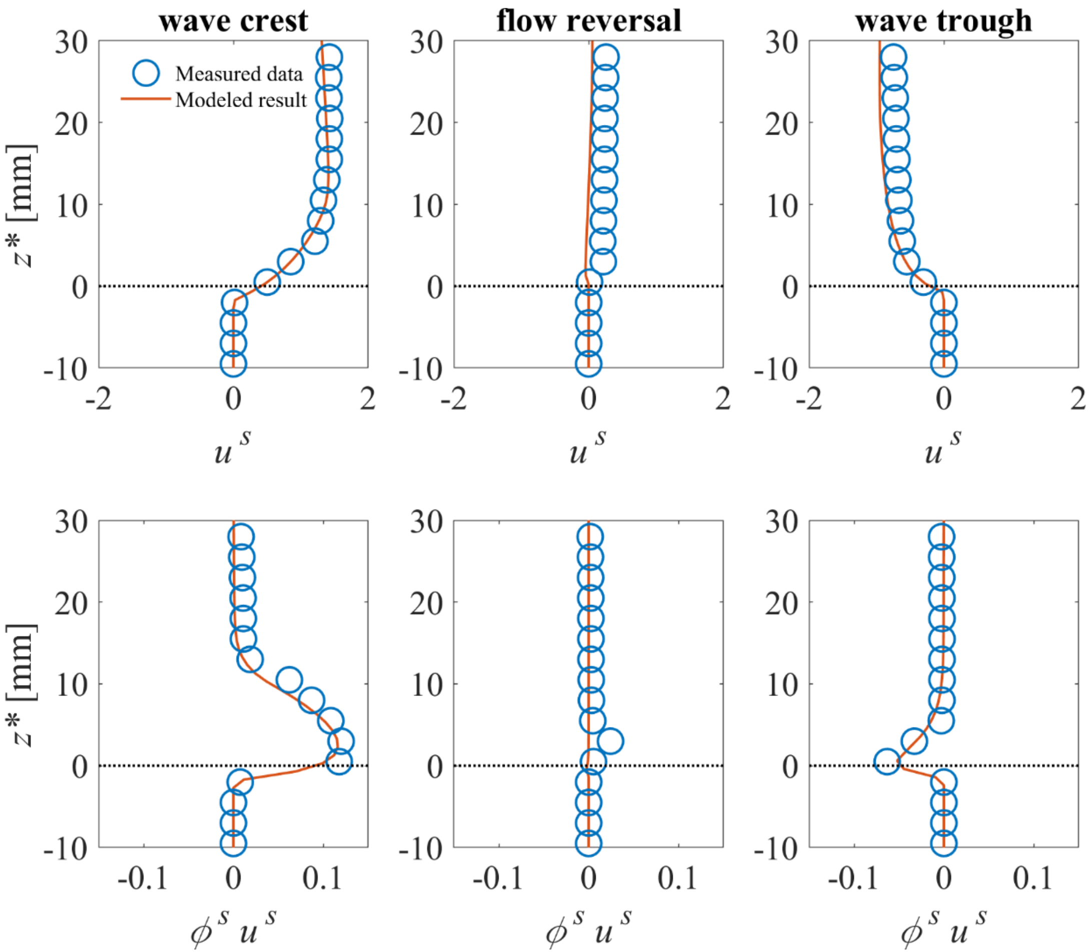
- Free stream velocity and sediment concentration profiles are predicted well ($IA \geq 0.99$, NRMSE $\leq 0.6\%$)
- Notable discrepancy at the flow reversal may be attributed to smoothed data from CCP sensors $\delta_{s,\min} \approx 5$ mm (Lanckrit et al., 2013)
- Uncertainties of the sediment properties in the wave flume ($\phi^s < 10^{-2}$)
  → looks like a washload
  → not used for transport rate

Vertical profiles of velocity (u^f) and sediment flux ($\phi^s u^s$)



- In general, good agreements are obtained (NRMSE < 1.3%)
- Velocity in the sheet flow layer could not be measured
- Model results are used to cover the missing velocities in the measured data

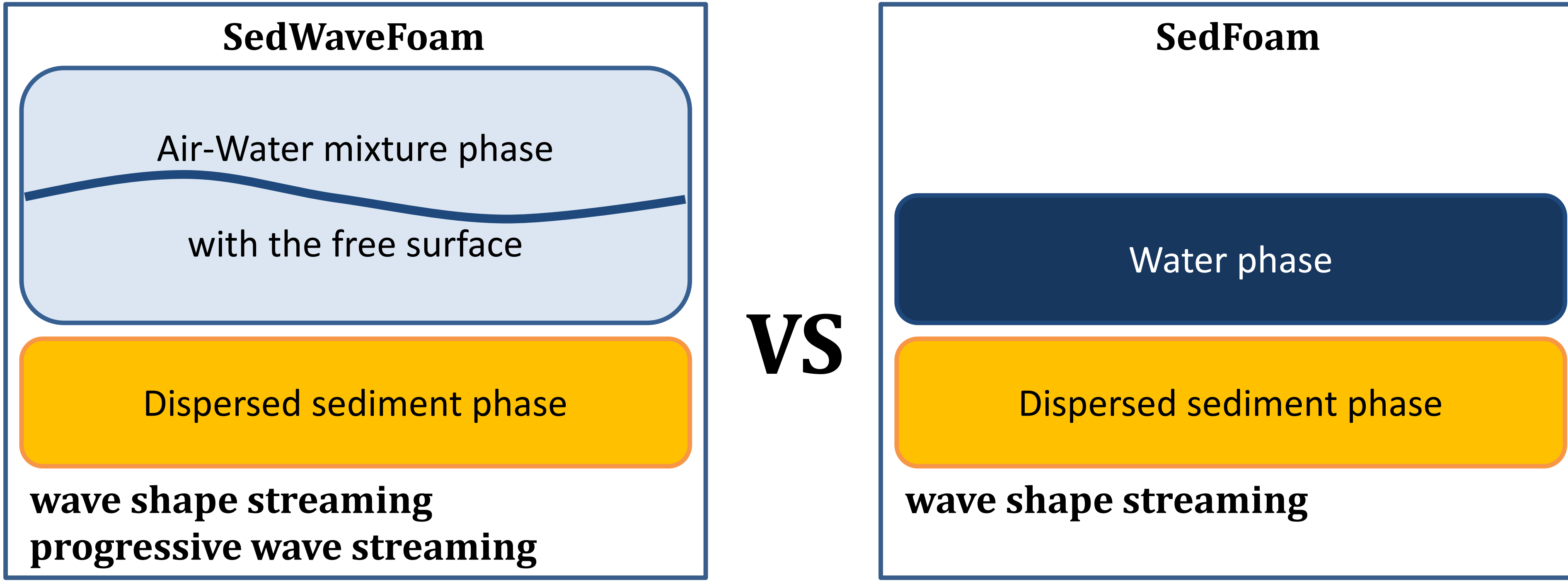
Vertical profiles of velocity (u^f) and sediment flux ($\phi^s u^s$)



- In general, good agreements are obtained (NRMSE < 1.3%)
- Velocity in the sheet flow layer could not be measured
- Model results are used to cover the missing velocities in the measured data

→ full profile of sediment flux

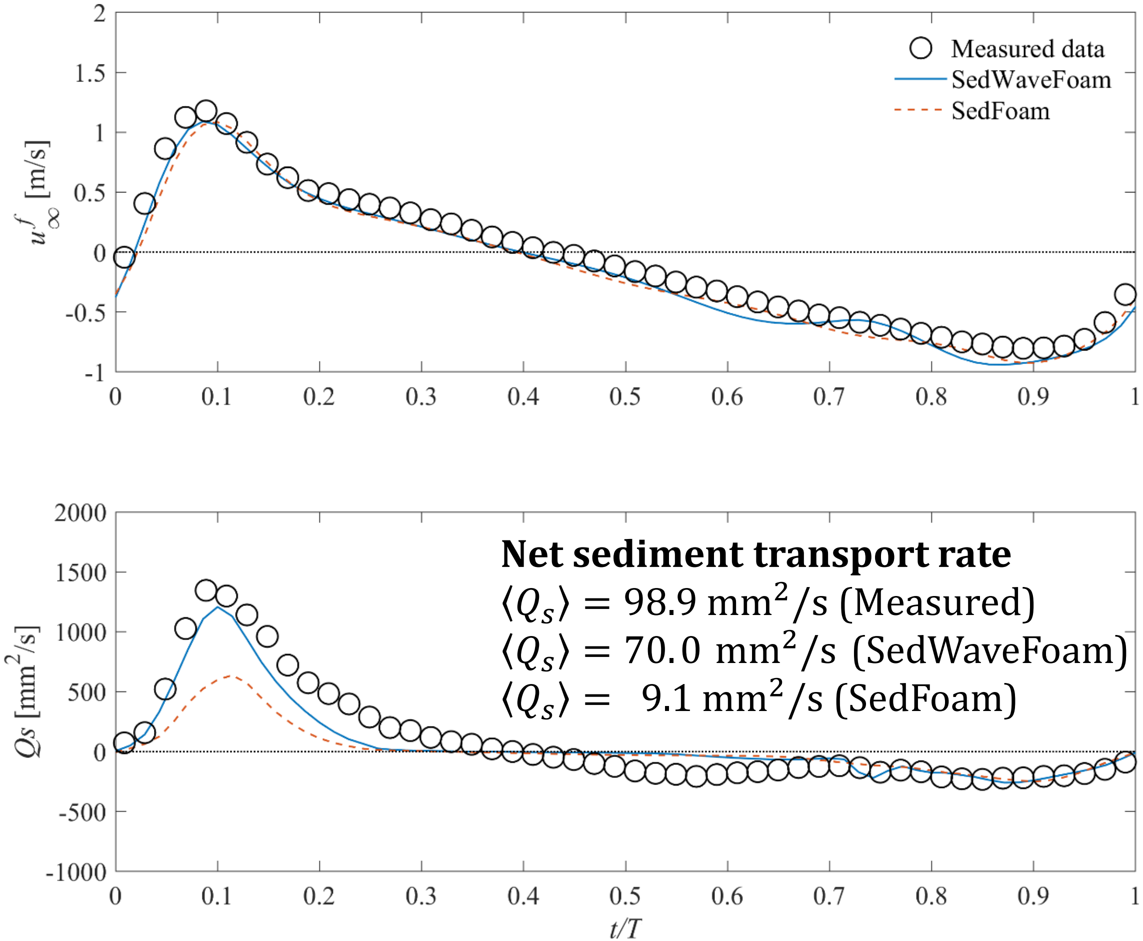
1DV SedFoam (to model U-tube) is adopted to isolate the free surface effect



SedWaveFoam – SedFoam = progressive wave streaming + other free surface effects

- Same vertical grid size is applied with the 0.15 m domain size (> WBBL) for SedFoam
- To drive the flow in SedFoam, $f_{\text{ext}} = \rho^f \, \partial u^f / \partial t$ is calculated from SedWaveFoam

Time series of free stream velocity (u^f_∞) and sediment transport rate ($Q_s = \int \phi^s u^s dz$)



- Both models are under very similar flow conditions
- Better prediction of the sediment transport rate is obtained by SedWaveFoam
- Progressive wave streaming-induced sediment transport rate
  (SedWaveFoam – SedFoam)
  $\langle Q_{\text{pws}} \rangle = 60.9 \text{ mm}^2/\text{s}$
- Nielsen and Callaghan (2003)'s method works reasonably well in predicting $\langle Q_{\text{pws}} \rangle$
  $\langle Q_{\text{pws}} \rangle = 78.3 \text{ mm}^2/\text{s}$

Summary

1. The fully coupled model, SedWaveFoam, has been developed to study sediment transport under various realistic surface waves
2. A comprehensive validation for sheet flow driven by breaking was carried out
3. The mechanism of progressive wave streaming driving the enhanced sediment transport under surface waves can be revealed by utilizing SedWaveFoam and SedFoam

Future works

1. Refine the simulation to better understand free surface effects on sediment transport
   - Identify the role of wave breaking turbulence, wave streaming current, and horizontal pressure gradient on sediment transport
2. Investigate wave breaking turbulence and sediment transport in the inner-surf zone and swash zone (e.g., dune erosion)

Thanks


Tom Hsu
aka my advisor


Hungry
Charlie


Ryan
from Texas


Jack Puleo
with smile
SAND

Single-phase Navier-Stokes wave model investigation

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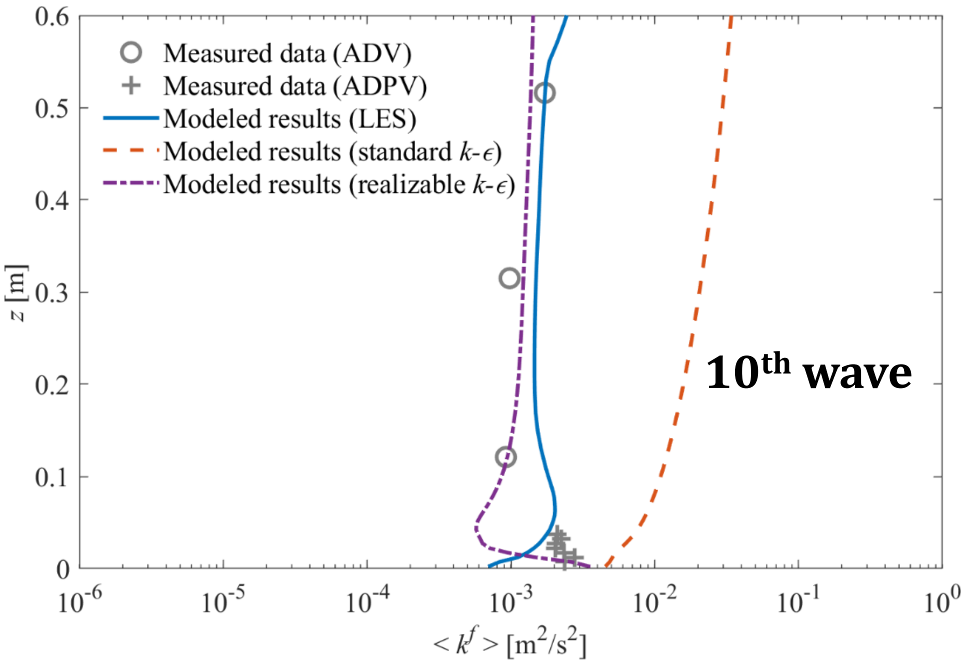

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