CSDMS 2016 Annual Meeting, May 17~29, 2016

Modeling Coastal Processes Using OpenFOAM

Zheyu Zhou[1], Xiaofeng Liu[2], Tian-Jian Hsu[3]

[1] PhD Candidate, University of Delaware, Civil & Environmental Engineering
[2] Assistant Professor, Penn State University, Civil & Environmental Engineering
[3] Associate Professor, University of Delaware, Civil & Environmental Engineering

CSDMS
COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

Collaborators

Daniel Cox, Oregon State University

Francis Ting, South Dakota State University

B. Mutlu Sumer, Jørgen Fredsøe, Erik D. Christensen, Technical University of Denmark

Anders W. Nielsen, Bjarne Jensen, DHI

Acknowledgement

National Science Foundation – OCE, CMMI, OISE

Office of Naval Research – Littoral Geosciences & Optics

U.S. Army Corps of Engineers

XSEDE and **UD HPC Center** for computing resources

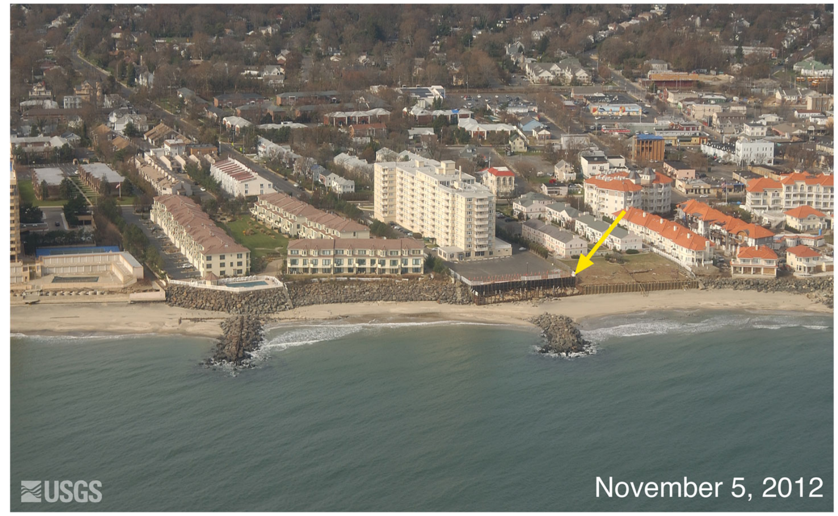
Motivation

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**."

Pre-and Post- Harricane Sandy photo comparison of Long Branch, NJ



http://coastal.er.usgs.gov/hurricanes/sandy/photocomparisons/newjersey.php

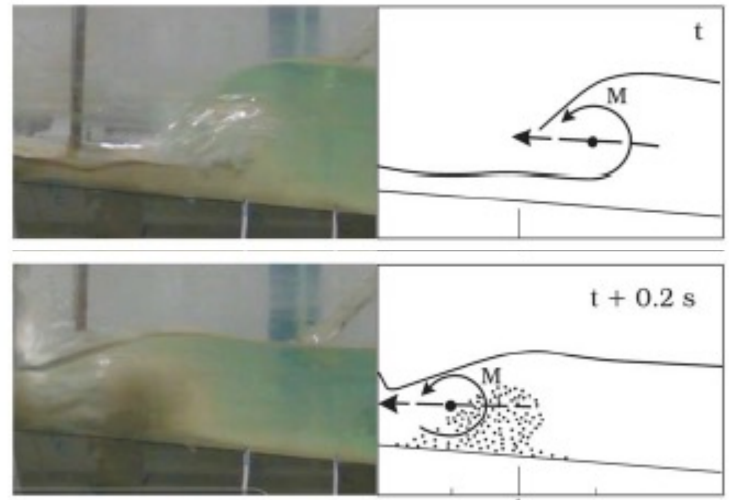
Local Scour around coastal infrastructures

- Key mechanisms that can trigger unexpected large local scour around structures in the coastal zone that may lead to multi-hazard scenarios during extreme windstorms/tsunami impact.
- Enhanced erosion by upward-directed pore pressure gradient and momentary bed failure are currently missing.

localized scour after extreme events. Tonkin et al. (2013); FEMA (2011)

Hypothesis and Research Questions

- Transport mechanisms critical in major storm condition were not parameterized properly.
- Wave-breaking-induced turbulent coherent structures play a key role in the resulting sediment transport.
- Seabed responses need to be explicitly included in sediment transport modeling.



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

Content

1. Introduction of OpenFOAM. (Liu)
2. Large-eddy simulation for wave breaking and suspended sand transport. (Zhou)
3. Demonstration of other coastal related applications: scour, seedbed response, particle transport, and density currents. (Liu)
4. Hands on demonstration for simulating solitary wave breaking over a sloping beach using OpenFOAM (interFoam solver). (Zhou)

Introduction of OpenFOAM

- OpenFOAM is an open source multi-physics modeling platform written in C++
  - www.openfoam.com
  - www.openfoam.org
- FOAM stands for "**F**ield **O**peration **A**nd **M**anipulation"
- OpenFOAM is not limited to fluid dynamics
  - It is a generic modeling platform
  - It can be used to solve (m)any differential equation(s)

User levels

- Fact: OpenFOAM is powerful but quite complicated
- How well should I know the details about OpenFOAM?
  - Basic usage: run simulations with existing solvers
  - Intermediate: make minor changes to suit your needs
  - Advanced: make major changes, create new solvers, libraries, boundary conditions, utilities, etc.

Fundamental of OpenFOAM

- Basic elements:
  - Mesh: Discrete representation of physical domain
  - Data definition: velocity, pressure, concentration, etc
  - Discretization of equations: how to discretize the governing equations (such advection-diffusion equation)
  - Solution of linear system: [A][**x**]=[b]
- OF uses C++ Object-Oriented programming
  - As a user: you should be aware of this
  - As a developer: you should know the details

How are equations solved in OF?

- A partial differential equation is essentially a group of differential operations on a field (concentration, velocity, pressure, etc.)

Mathematical Language:

$$\frac{\partial k}{\partial t} + \nabla\bullet(\mathbf{u}k) - \nabla\bullet[(\nu+\nu_t)\nabla k] = \nu_t \left[\frac{1}{2}(\nabla\mathbf{u} + \nabla\mathbf{u}^T)\right]^2 - \frac{\epsilon_o}{k_o} k$$

Pseudo-Natural Language in OF:

```
solve
(
    fvm::ddt(k)
  + fvm::div(phi, k)
  - fvm::laplacian(nu() + nut, k)
== nut*magSqr(symm(fvc::grad(U)))
  - fvm::Sp(epsilon/k, k)
);
```

$$\Downarrow$$

$$[A]\,[x] = [b]$$

How are equations solved in OF?

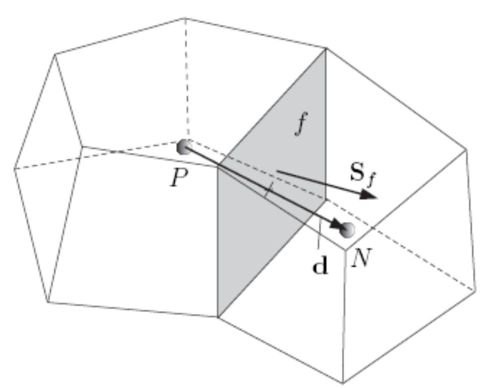
Term description	Implicit / Explicit	Text expression	fvm::/fvc:: functions
Laplacian	Imp/Exp	$\nabla^2\phi$	`laplacian(phi)`
		$\nabla \bullet \Gamma\nabla\phi$	`laplacian(Gamma, phi)`
Time derivative	Imp/Exp	$\frac{\partial\phi}{\partial t}$	`ddt(phi)`
		$\frac{\partial\rho\phi}{\partial t}$	`ddt(rho,phi)`
Second time derivative	Imp/Exp	$\frac{\partial}{\partial t}\left(\rho\frac{\partial\phi}{\partial t}\right)$	`d2dt2(rho, phi)`
Convection	Imp/Exp	$\nabla \bullet (\psi)$	`div(psi,scheme)*`
		$\nabla \bullet (\psi\phi)$	`div(psi, phi, word)*`
			`div(psi, phi)`
Divergence	Exp	$\nabla \bullet \chi$	`div(chi)`
Gradient	Exp	$\nabla\chi$	`grad(chi)`
		$\nabla\phi$	`gGrad(phi)`
			`lsGrad(phi)`
			`snGrad(phi)`
			`snGradCorrection(phi)`
Grad-grad squared	Exp	$\lvert\nabla\nabla\phi\rvert^2$	`sqrGradGrad(phi)`
Curl	Exp	$\nabla \times \phi$	`curl(phi)`
Source	Imp	$\rho\phi$	`Sp(rho,phi)`
	Imp/Exp†		`SuSp(rho,phi)`

How are equations solved in OF?

- OF uses finite volume method for spatial discretization
- The core is the Gauss theorem $\int_V \nabla \star \phi \; dV = \int_S d\mathbf{S} \star \phi$

Advection $$\int_V \nabla \bullet (\rho \mathbf{U} \phi) \; dV = \int_S d\mathbf{S} \bullet (\rho \mathbf{U} \phi) = \sum_f \mathbf{S}_f \bullet (\rho \mathbf{U})_f \phi_f = \sum_f F \phi_f$$

Laplacian $$\int_V \nabla \bullet (\Gamma \nabla \phi) \; dV = \int_S d\mathbf{S} \bullet (\Gamma \nabla \phi) = \sum_f \Gamma_f \mathbf{S}_f \bullet (\nabla \phi)_f$$



How are equations solved in OF?

- Spatial discretizaiton needs boundary conditions (B.C.)
- OF provides a rich selection of B.C.s
  - Generic: fixed value, fixed gradient, mixed
  - Physical: inlet, outlet, no slip, slip, etc.
  - Others: symmetry, periodic, empty, processor (for parallel computation), etc.
- If not enough, then write your own B.C.
  - e.g., suspended sediment B.C. on the bottom

How are equations solved in OF?

- OF also provides temporal discretization schemes

Scheme	Description
Euler	First order, bounded, implicit
localEuler	Local-time step, first order, bounded, implicit
CrankNicholson	Second order, bounded, implicit
backward	Second order, implicit
steadyState	Does not solve for time derivatives

Example: Euler scheme

$$\frac{\partial}{\partial t}\int_V \rho\phi \, \mathrm{d}V = \frac{(\rho_P \phi_P V)^n - (\rho_P \phi_P V)^o}{\Delta t}$$

backward scheme

$$\frac{\partial}{\partial t}\int_V \rho\phi \, \mathrm{d}V = \frac{3\,(\rho_P \phi_P V)^n - 4\,(\rho_P \phi_P V)^o + (\rho_P \phi_P V)^{oo}}{2\Delta t}$$

How are equations solved in OF?

- Now what?
  - After the discretization, we get an algebraic system of equations: $[A]\,[x] = [b]$
  - OF provides linear equation solvers

From `fvSolution` file

```
solvers
{
    p PCG
    {
        preconditioner    DIC;
        tolerance         1e-06;
        relTol            0;
    };

    U PBiCG
    {
        preconditioner    DILU;
        tolerance         1e-05;
        relTol            0;
    };
}
```

Linear system solver choices

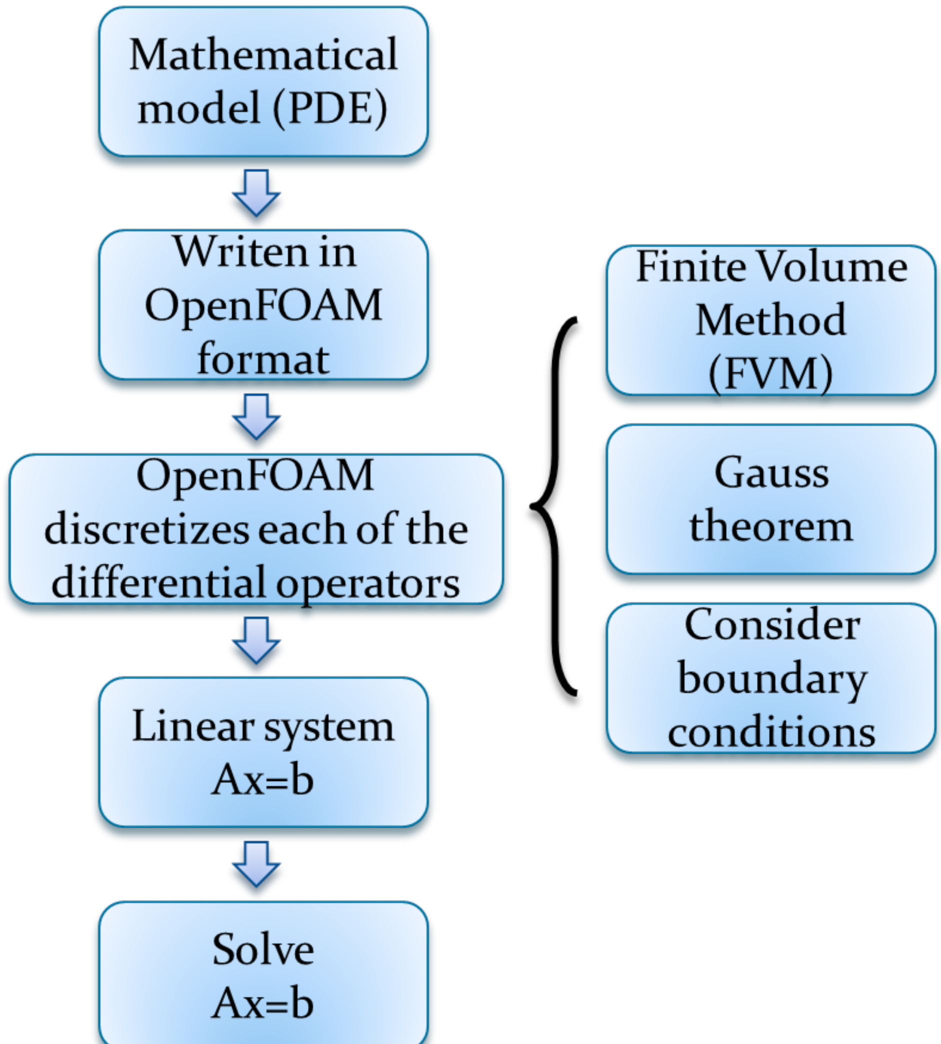
Solver	Keyword
Preconditioned (bi-)conjugate gradient	`PCG/PBiCG`†
Solver using a smoother	`smoothSolver`
Generalised geometric-algebraic multi-grid	`GAMG`

†`PCG` for symmetric matrices, `PBiCG` for asymmetric

Options for preconditioners

Preconditioner	Keyword
Diagonal incomplete-Cholesky (symmetric)	`DIC`
Faster diagonal incomplete-Cholesky (`DIC` with caching)	`FDIC`
Diagonal incomplete-LU (asymmetric)	`DILU`
Diagonal	`diagonal`
Geometric-algebraic multi-grid	`GAMG`
No preconditioning	`none`

Summary of OF workflow

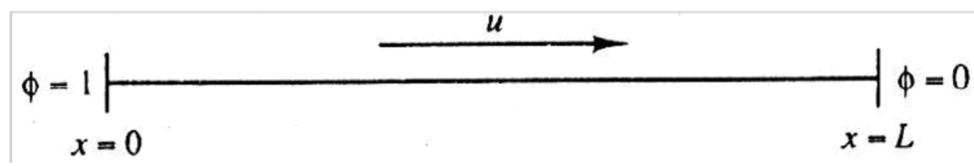


Example – steady 1D advection-diffusion

Governing equation, B.C., I.C.. u = 0.1 m/s, L = 1 m, Γ = 0.1 kg/(m.s)

$$\underbrace{\frac{d}{dx}(\rho u \phi)}_{\text{convection term}} = \underbrace{\frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right)}_{\text{diffusion term}}$$

$$\phi(x=0) = 1, \qquad \phi(x=L) = 0$$

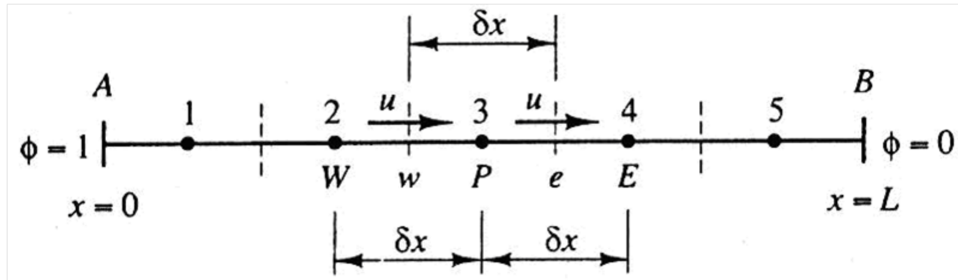


In OF, the solver looks like:

```
fvScalarMatrix TEqn
(
      fvm::ddt(rho, T)
    + fvm::div(rho*phi, T)
    - fvm::laplacian(DT, T)
);
```

Example – steady 1D advection-diffusion

Mesh



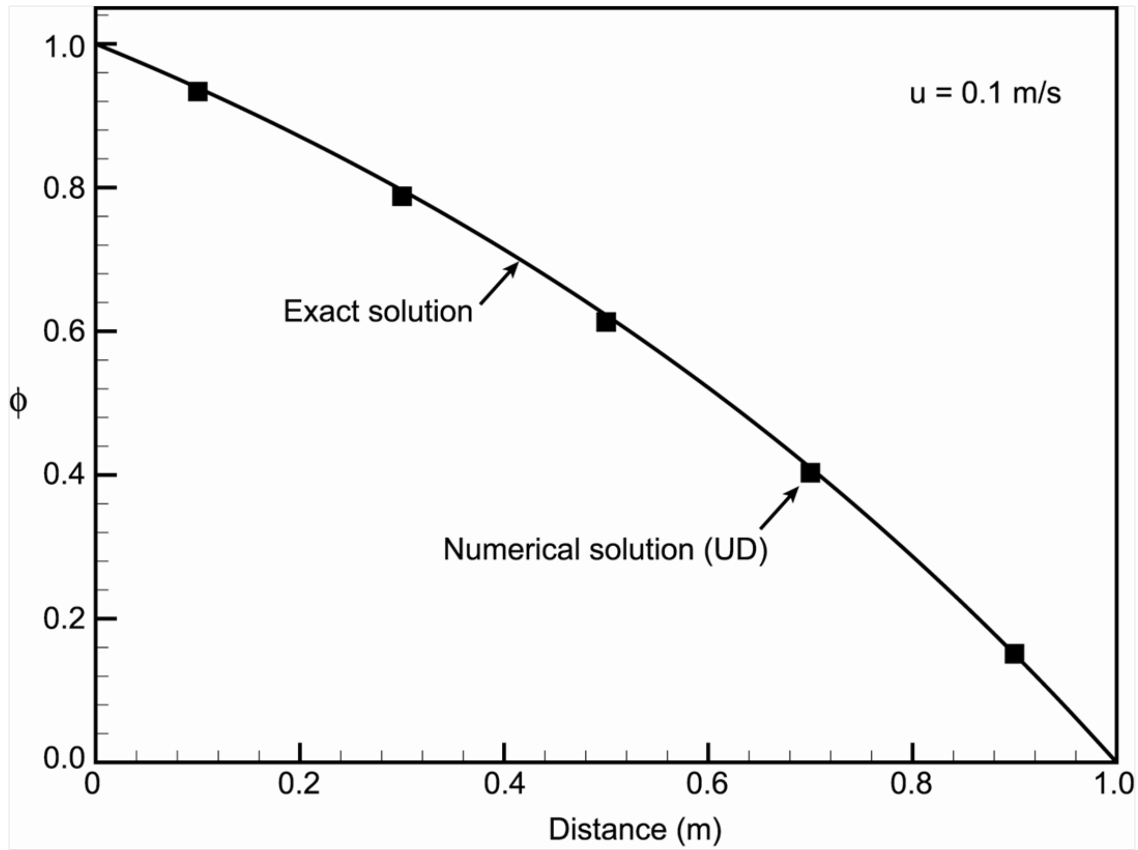
$$[A]\,[x] = [b]$$

$$\begin{bmatrix} 1.55 & -0.45 & 0 & 0 & 0 \\ -0.55 & 1.0 & -0.45 & 0 & 0 \\ 0 & -0.55 & 1.0 & -0.45 & 0 \\ 0 & 0 & -0.55 & 1.0 & -0.45 \\ 0 & 0 & 0 & -0.55 & 1.55 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{bmatrix} = \begin{bmatrix} 1.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Example – steady 1D advection-diffusion

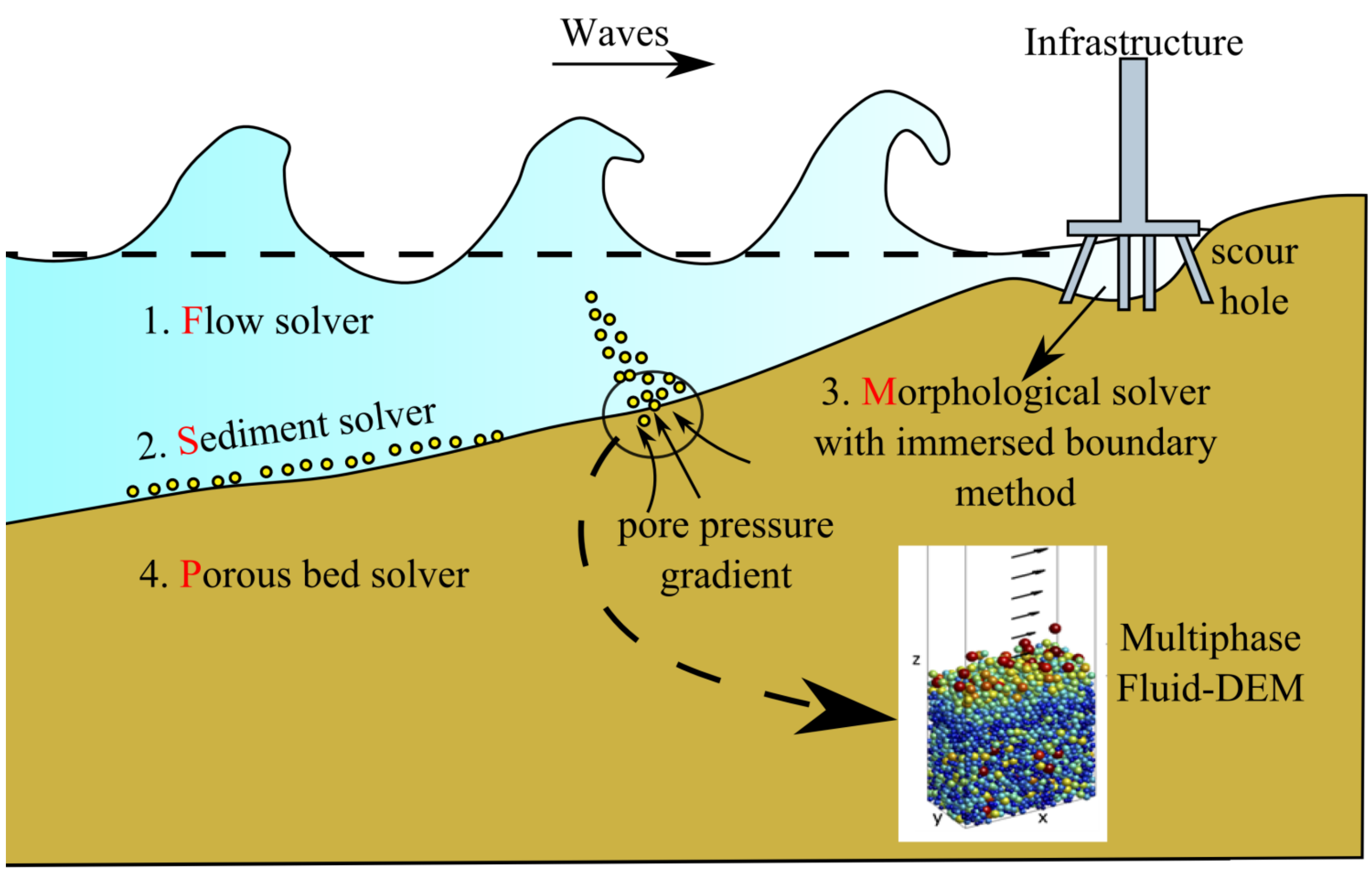
Solving the linear equations, we get the solution:

$$\begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{bmatrix} = \begin{bmatrix} 0.9421 \\ 0.8006 \\ 0.6276 \\ 0.4163 \\ 0.1579 \end{bmatrix}$$



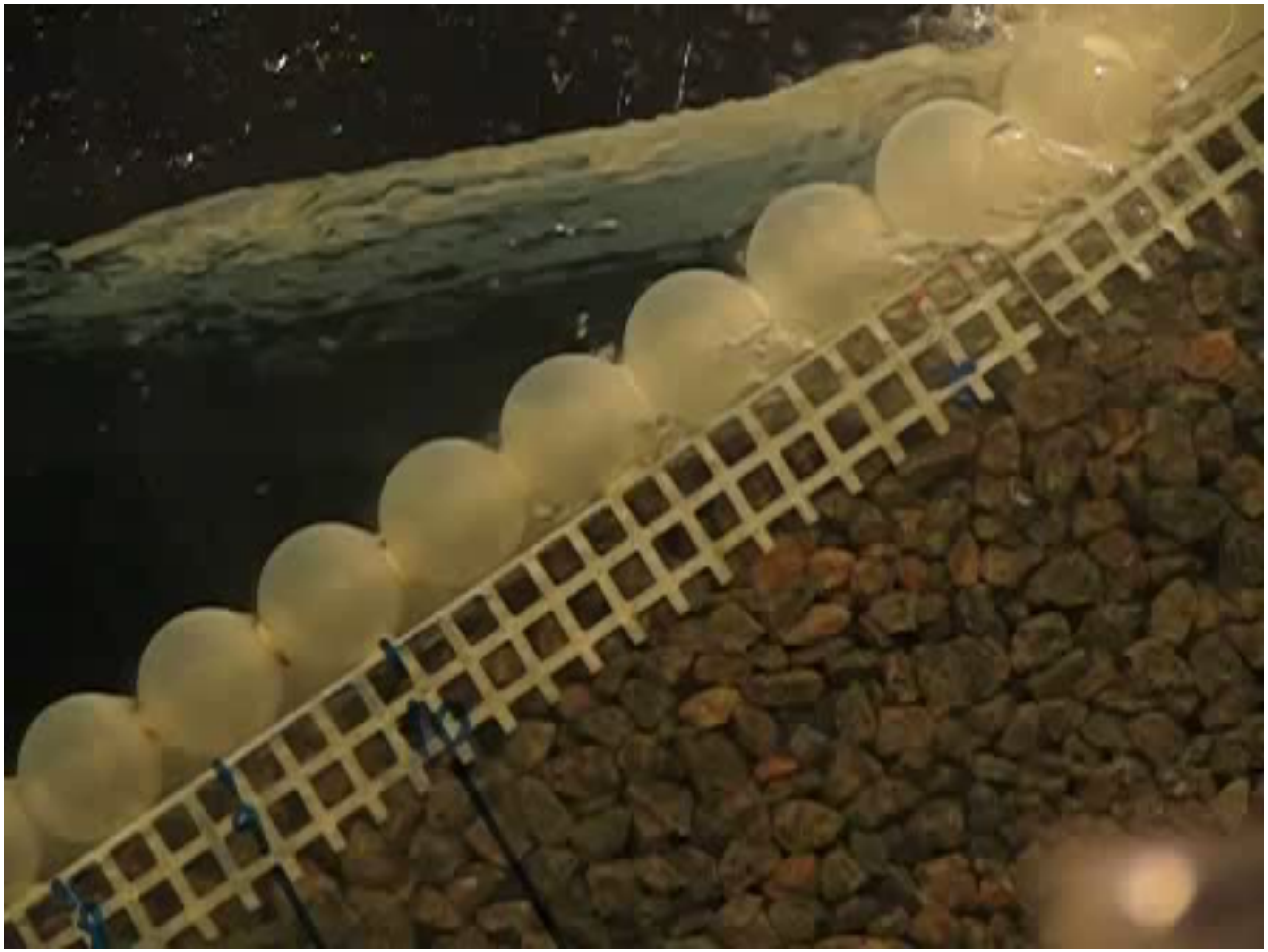
Coastal related applications

- Scour protection
- Seabed response
- Particle transport
- Gravity currents and sediment plumes

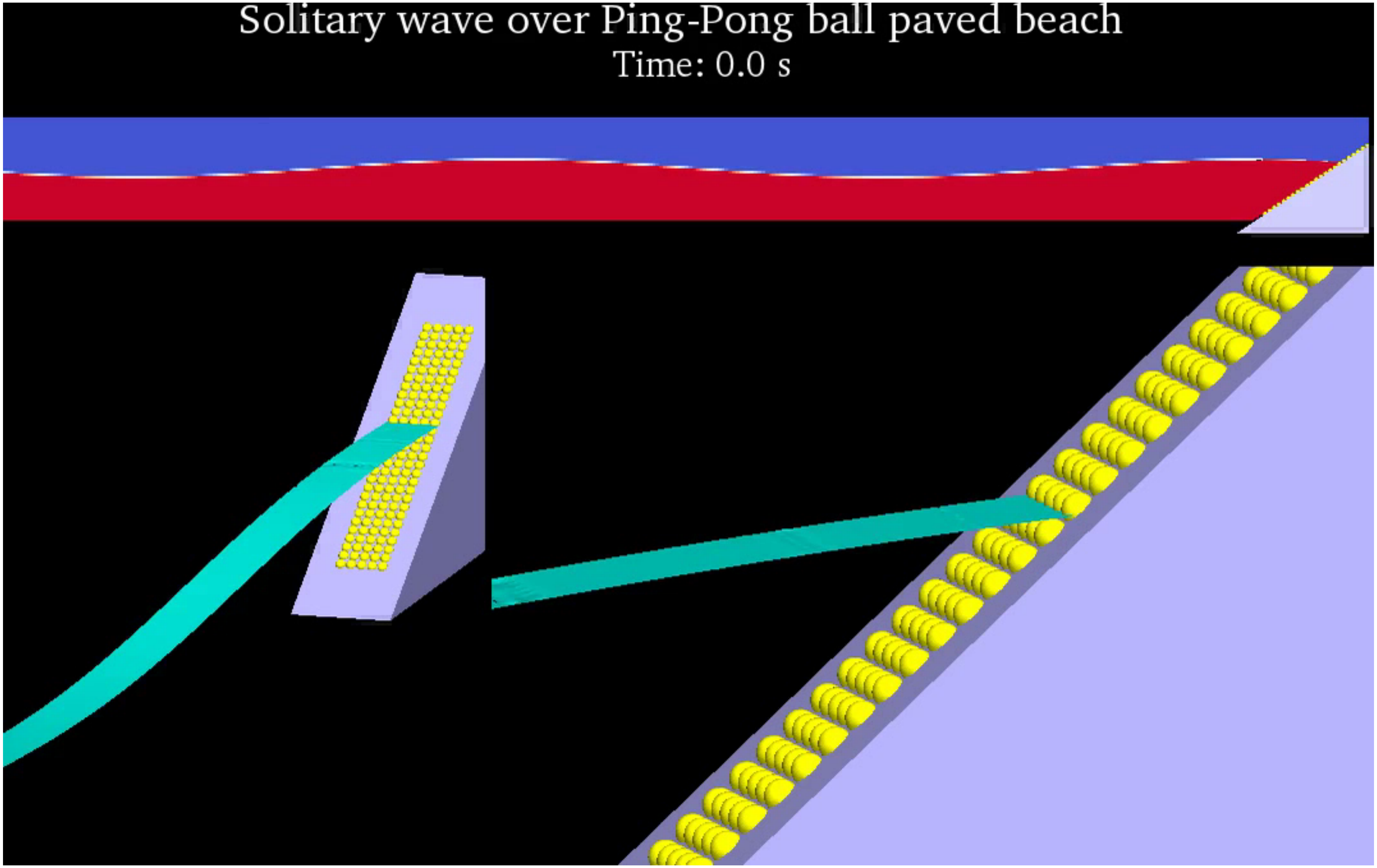


Lab experiment in a wave flume

Flow penetration, turbulence, and effect of armor units (Ping-Pong balls)



Courtesy of Bjarne Jensen, Ph.D., formerly at DTU, now at DHI

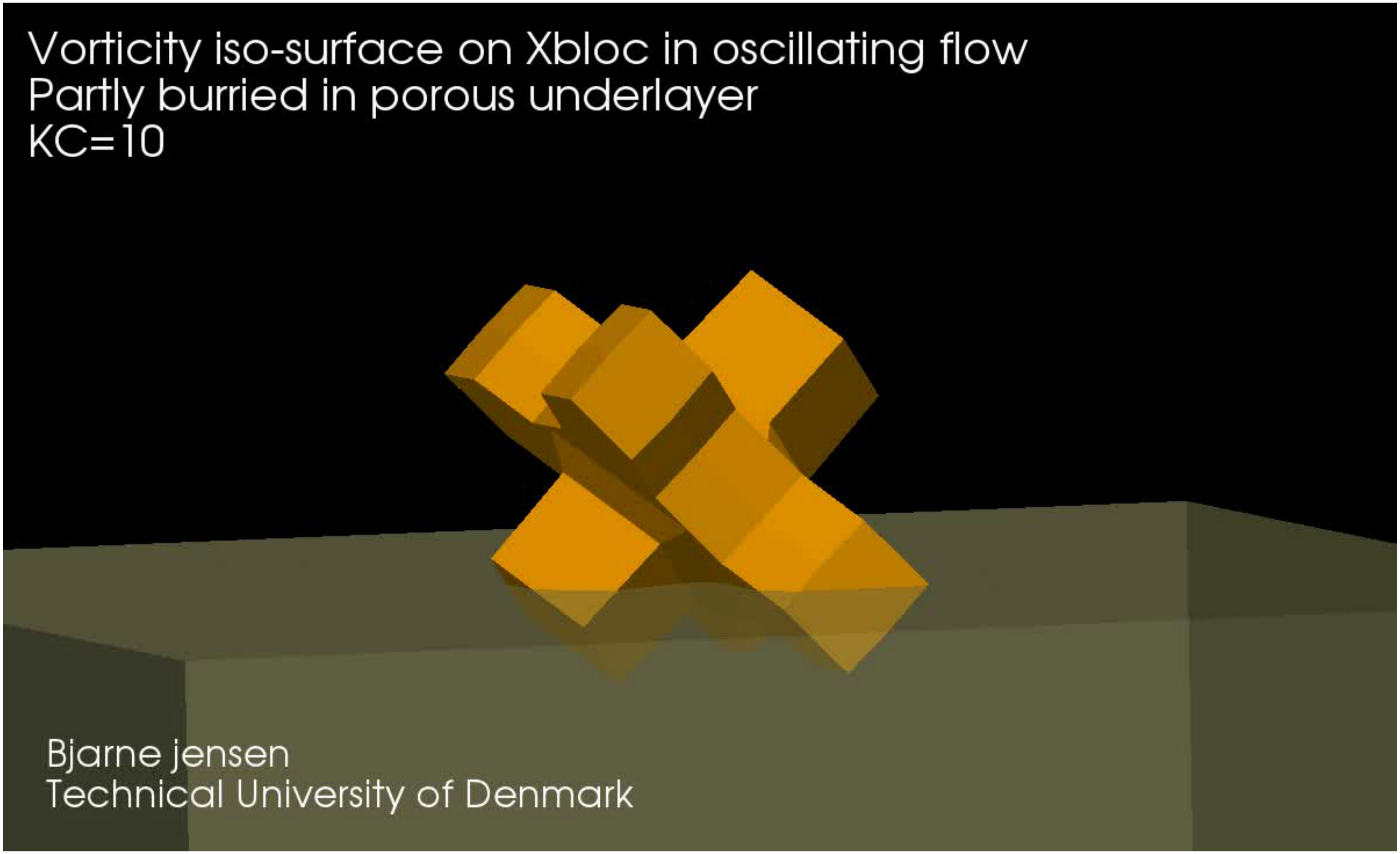


Jensen et al., 2016, under review

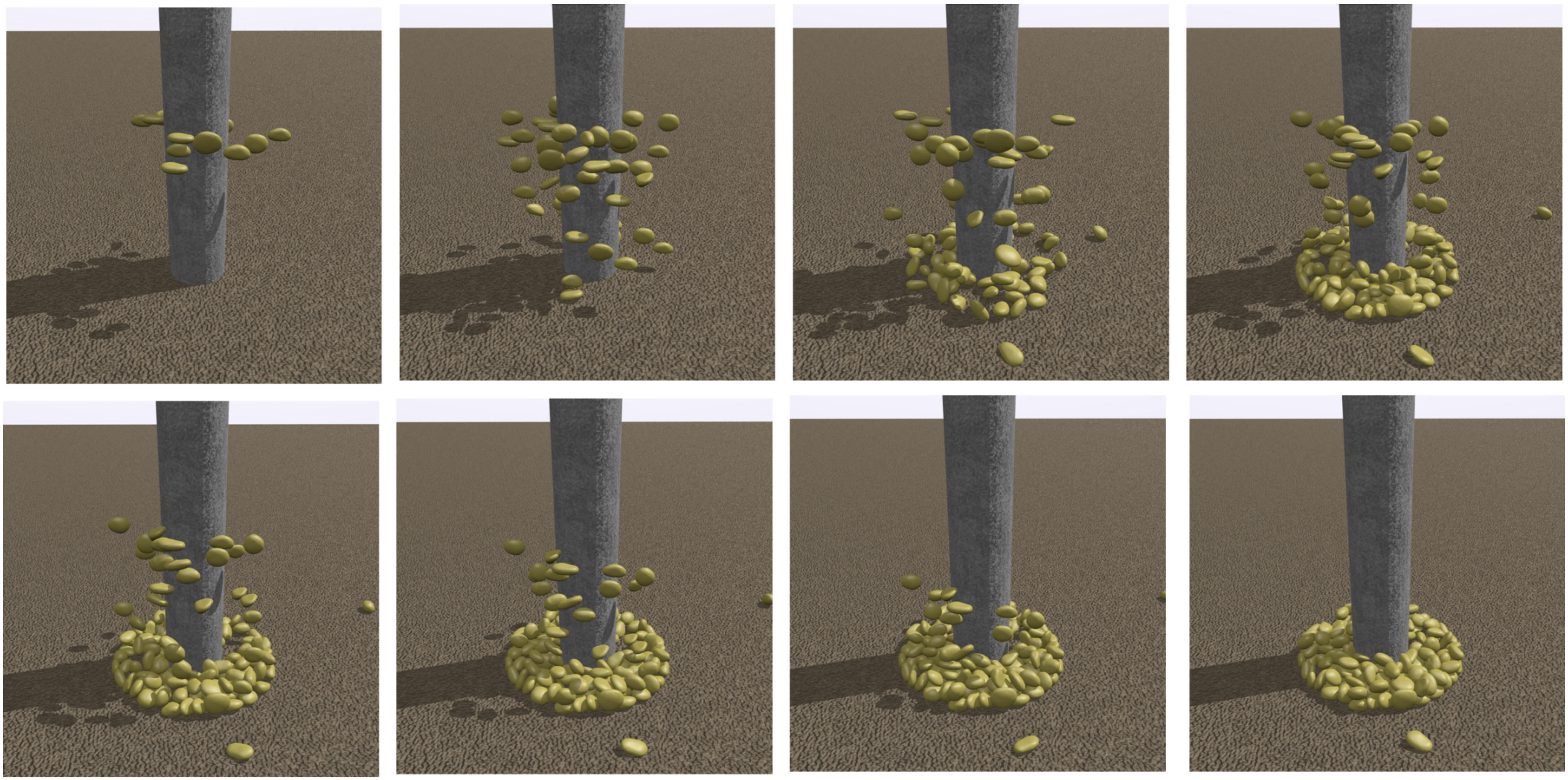
Concrete Armor Block on Porous Bed under ***Waves***

- Concrete armor units for coastal protection
- Xbloc data and drawings courtesy by Delta Marine
Consultants (DMC)

Concrete Armor Block on Porous Bed under ***Waves***

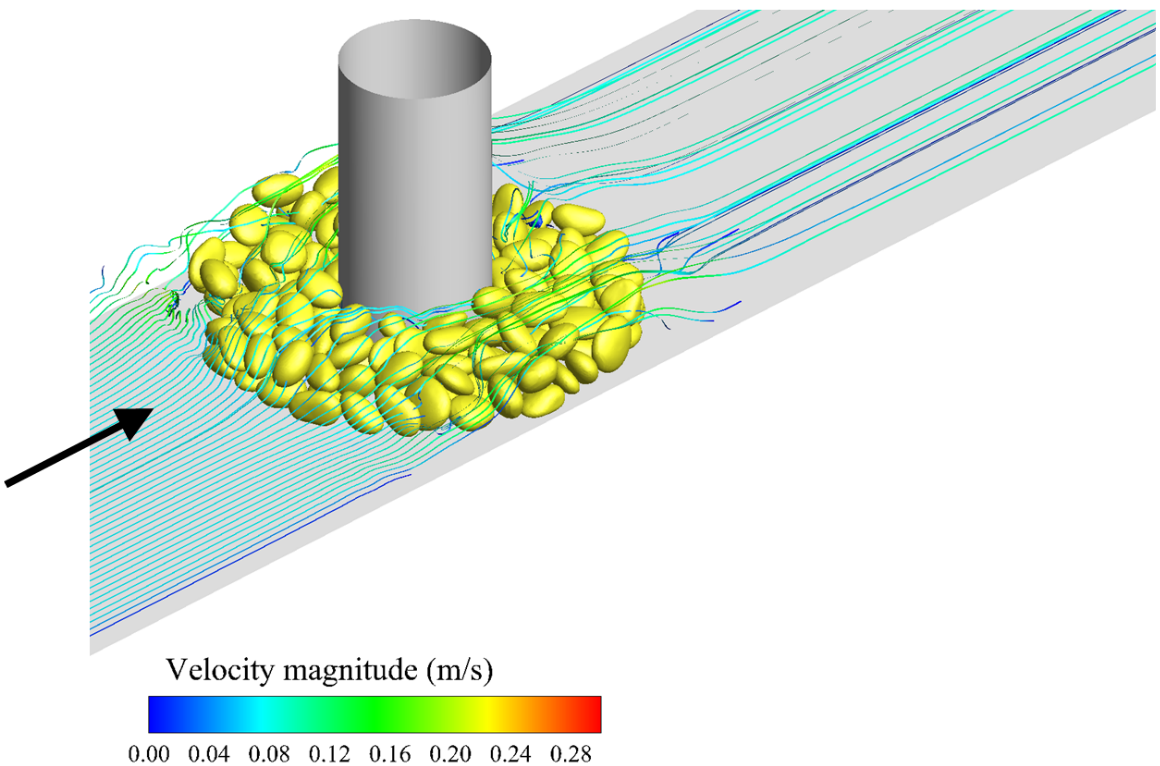


Scour protection

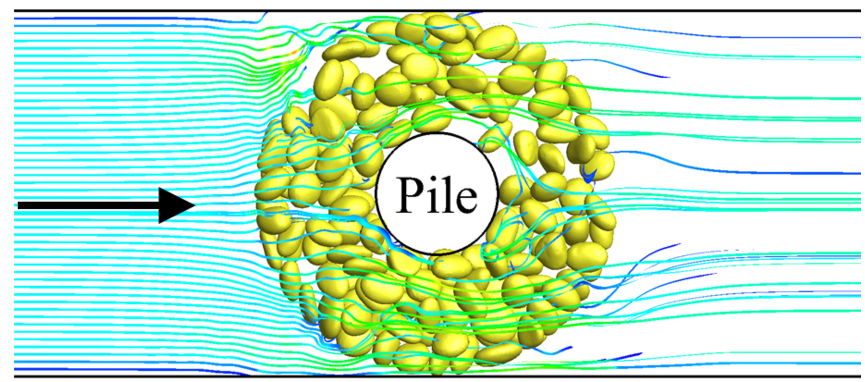


Rock arrangement using *BulletPhysics* (not part of OF)

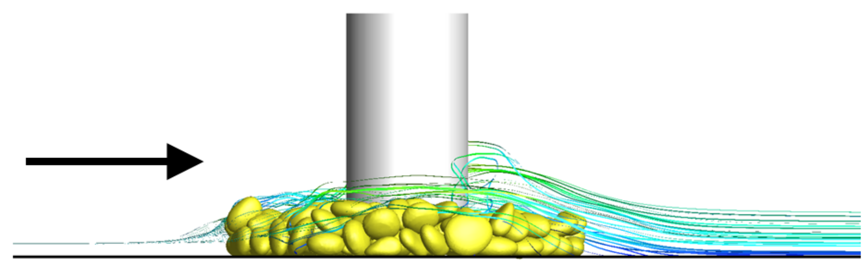
Scour protection



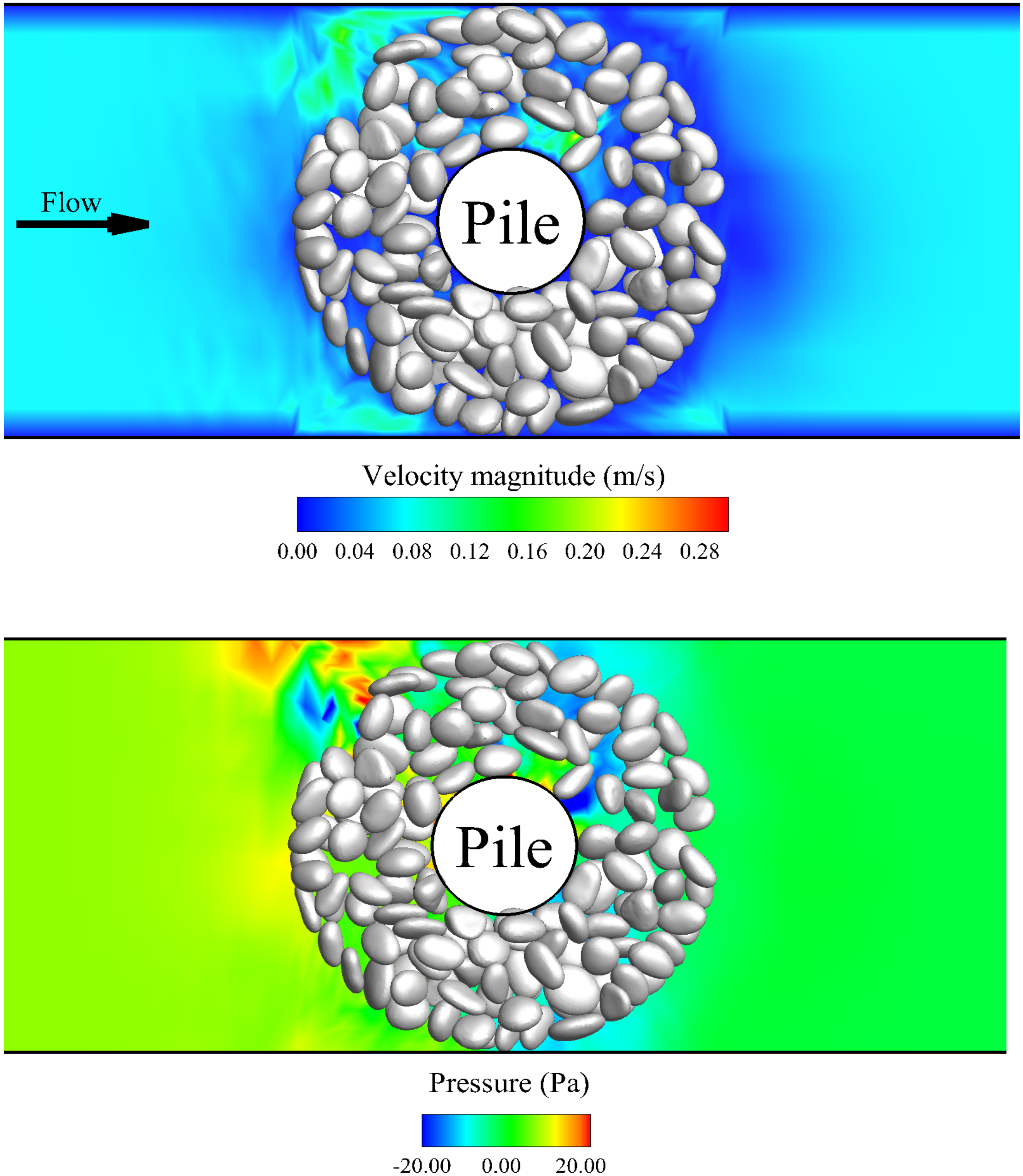
Top view



Side view

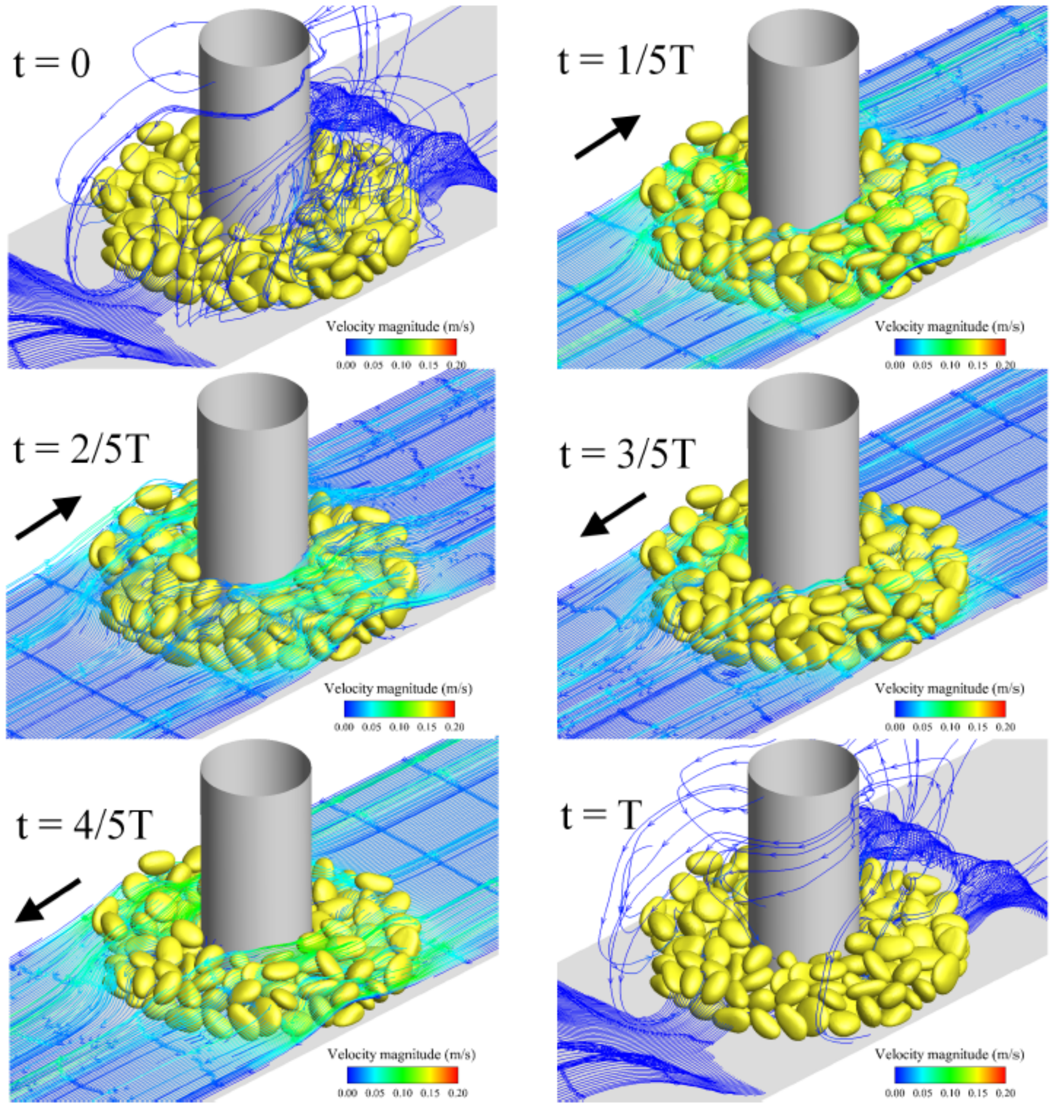


Unidirectional flow



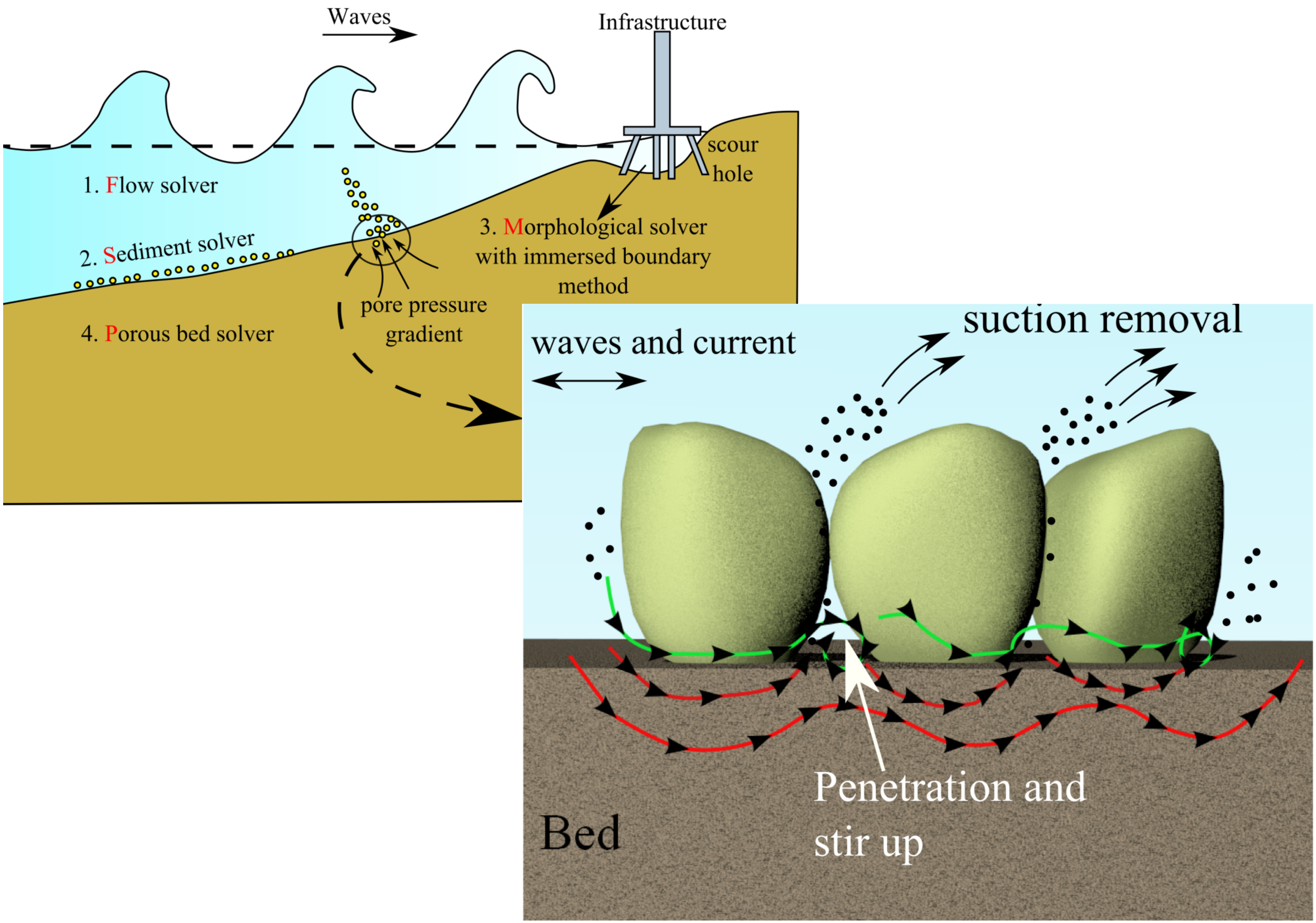
Flow
Pile
Velocity magnitude (m/s)
0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28
Pile
Pressure (Pa)
-20.00 0.00 20.00

Scour protection

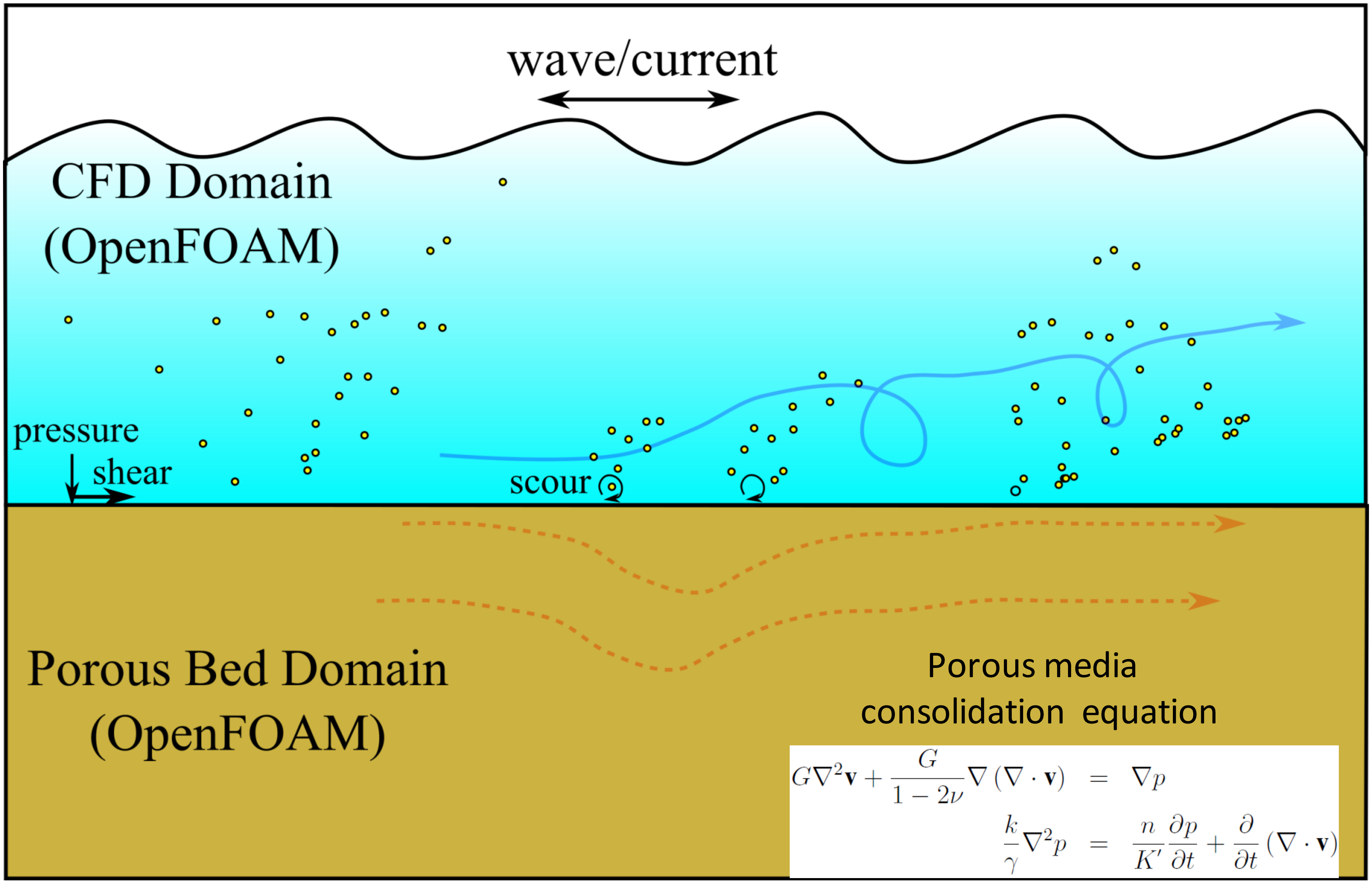


Oscillatory flow

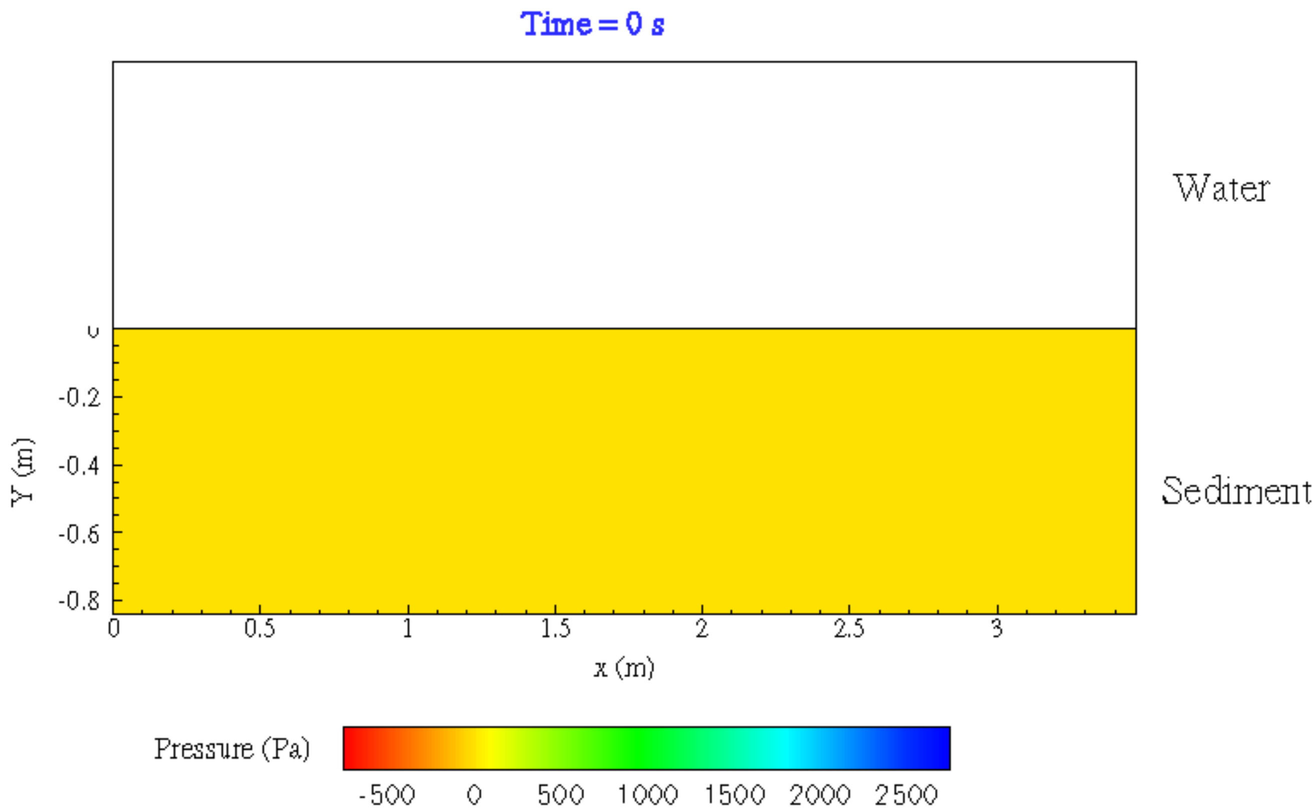
Seabed response



Seabed response



Seabed response

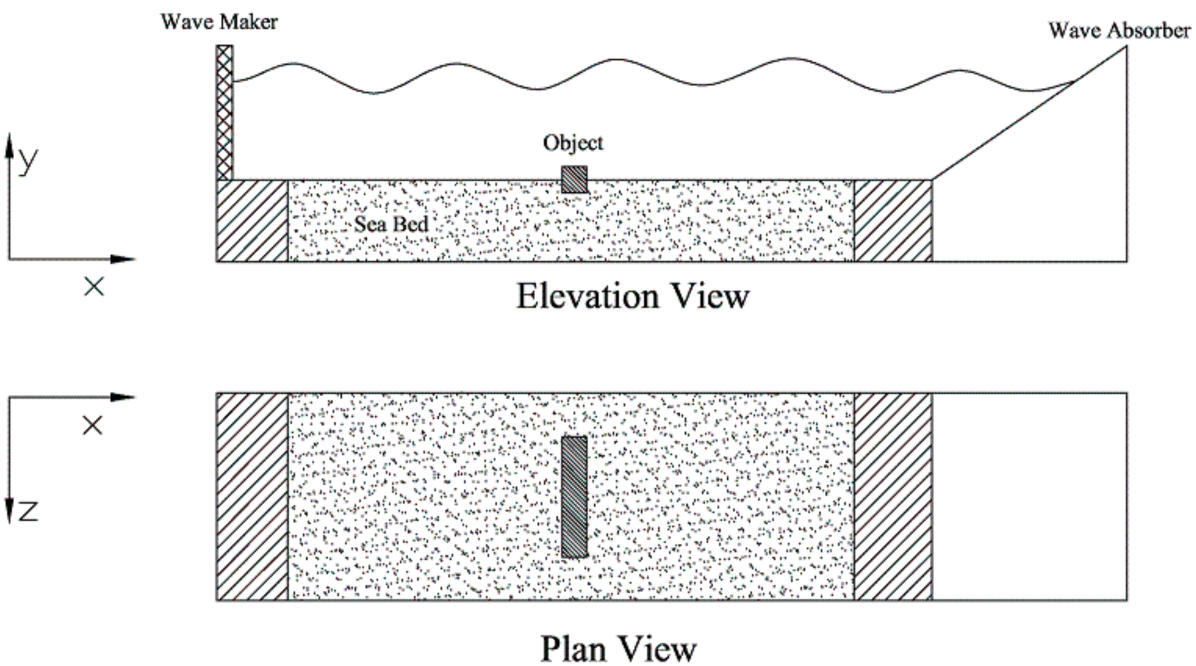


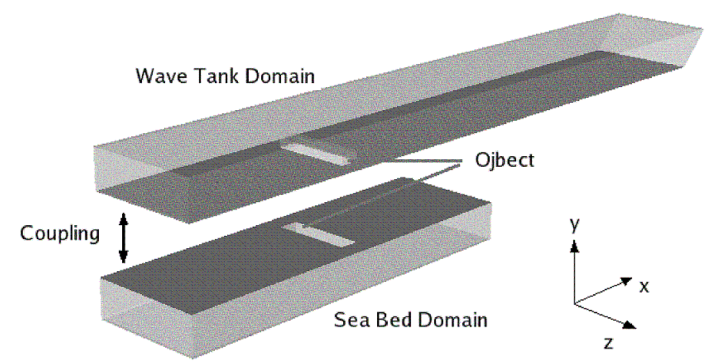
Liu and García (2007)

Seabed response

The wave tank is 40m long and 3m wide. The water depth in the tank is 1m. An object (which is represented by a box of dimensions 2mX0.5mX0.5m is half buried in the sand.

Wave period = 3s
Wave length = 10m
Wave height = 0.4m

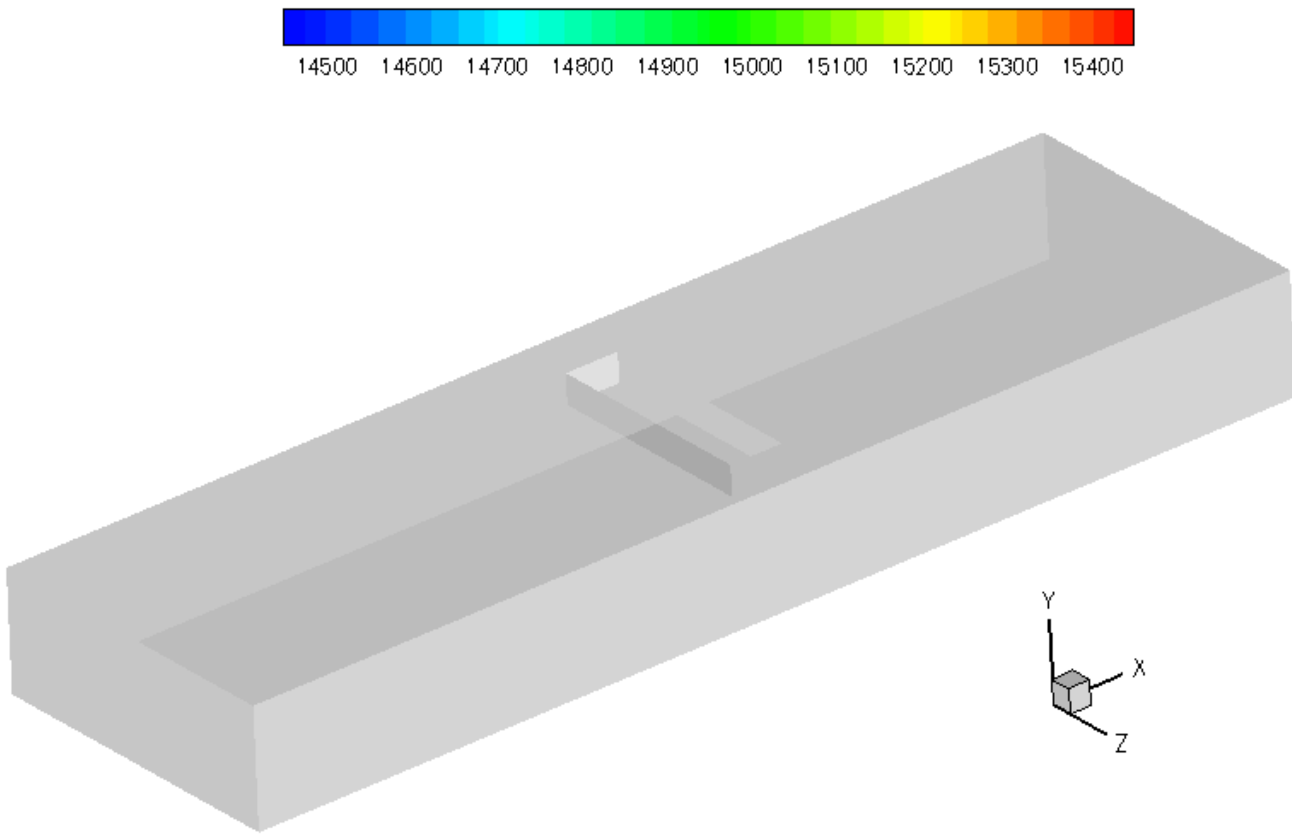




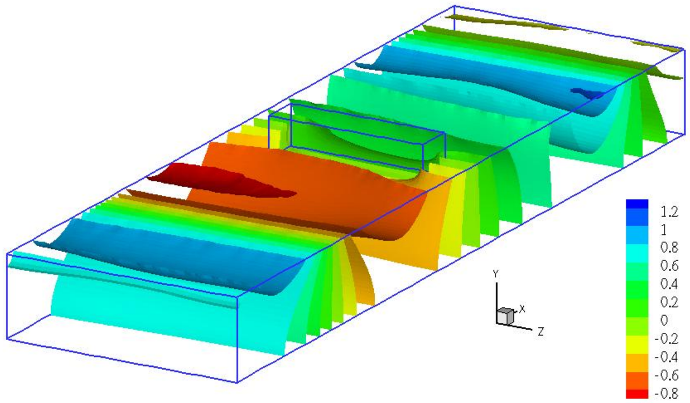
3D view

Liu and García (2007)

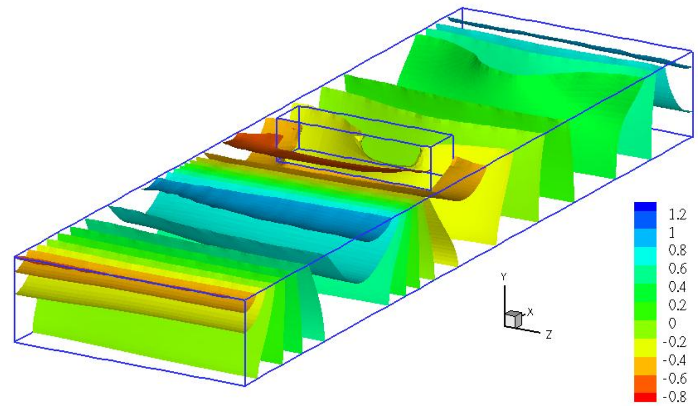
Seabed response



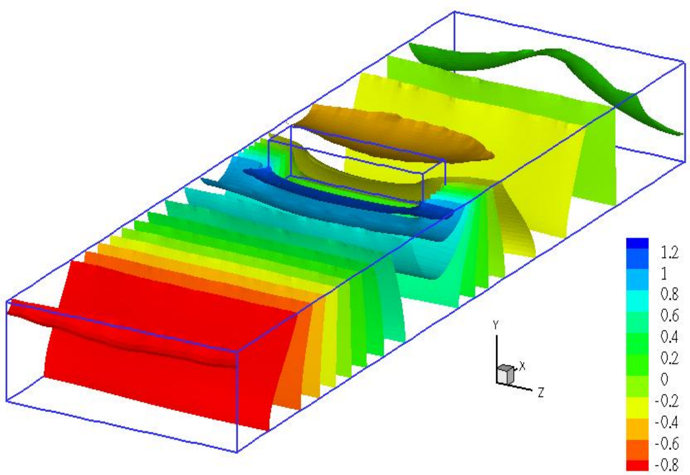
Liu and García (2007)



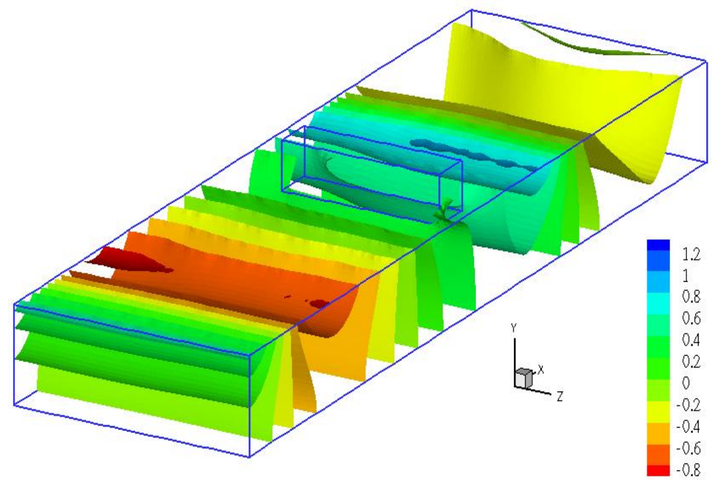
$t = t_0 + \frac{T}{4}$



$t = t_0 + \frac{T}{2}$



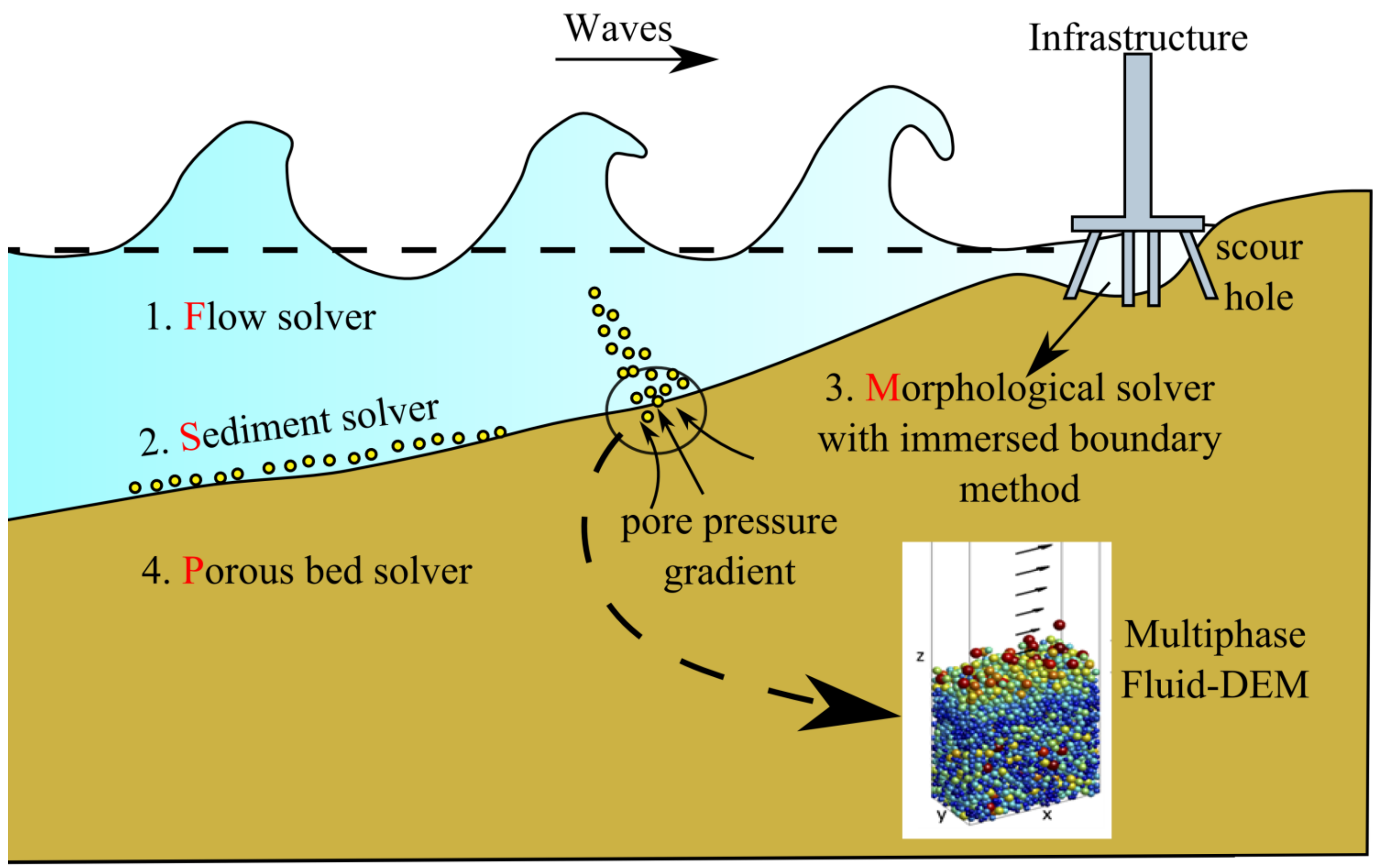
$t = t_0 + \frac{3T}{4}$



$t = t_0 + T$

Pore pressure in one period

Lagrangian particle transport



Lagrangian particle transport

- OF provides capabilities to do Lagrangian particle tracking for sediment
- Another alternative: CFDEM = OpenFOAM for fluid solver + LAMMPS for particle DEM
- Example equation for a particle

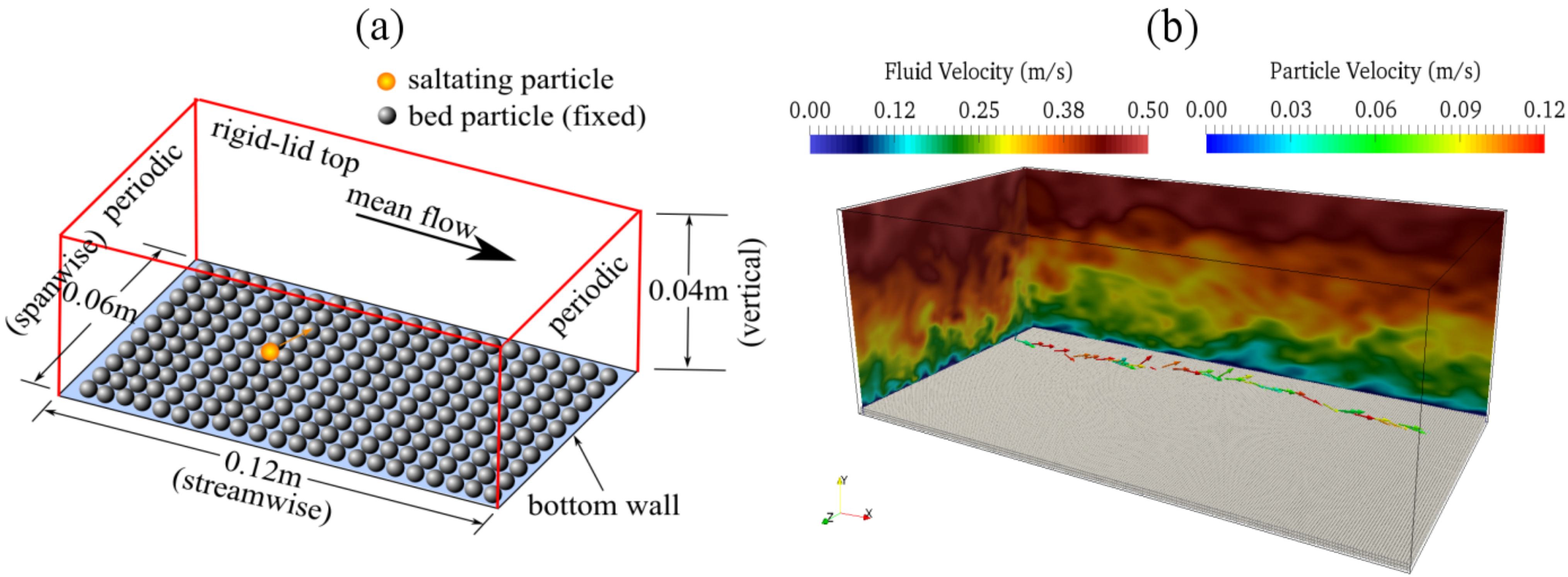
$$m_i \frac{d\boldsymbol{u}_{\boldsymbol{p},i}}{dt} = \boldsymbol{f}_{\boldsymbol{pf},i} + \sum_{j=1}^{k_i} \boldsymbol{f}_{\boldsymbol{c},ij} + m_i \boldsymbol{g}$$

$\boldsymbol{f}_{\boldsymbol{pf},i}$: fluid-particle coupling force

$\boldsymbol{f}_{\boldsymbol{c},ij}$: particle contact force

Lagrangian particle transport

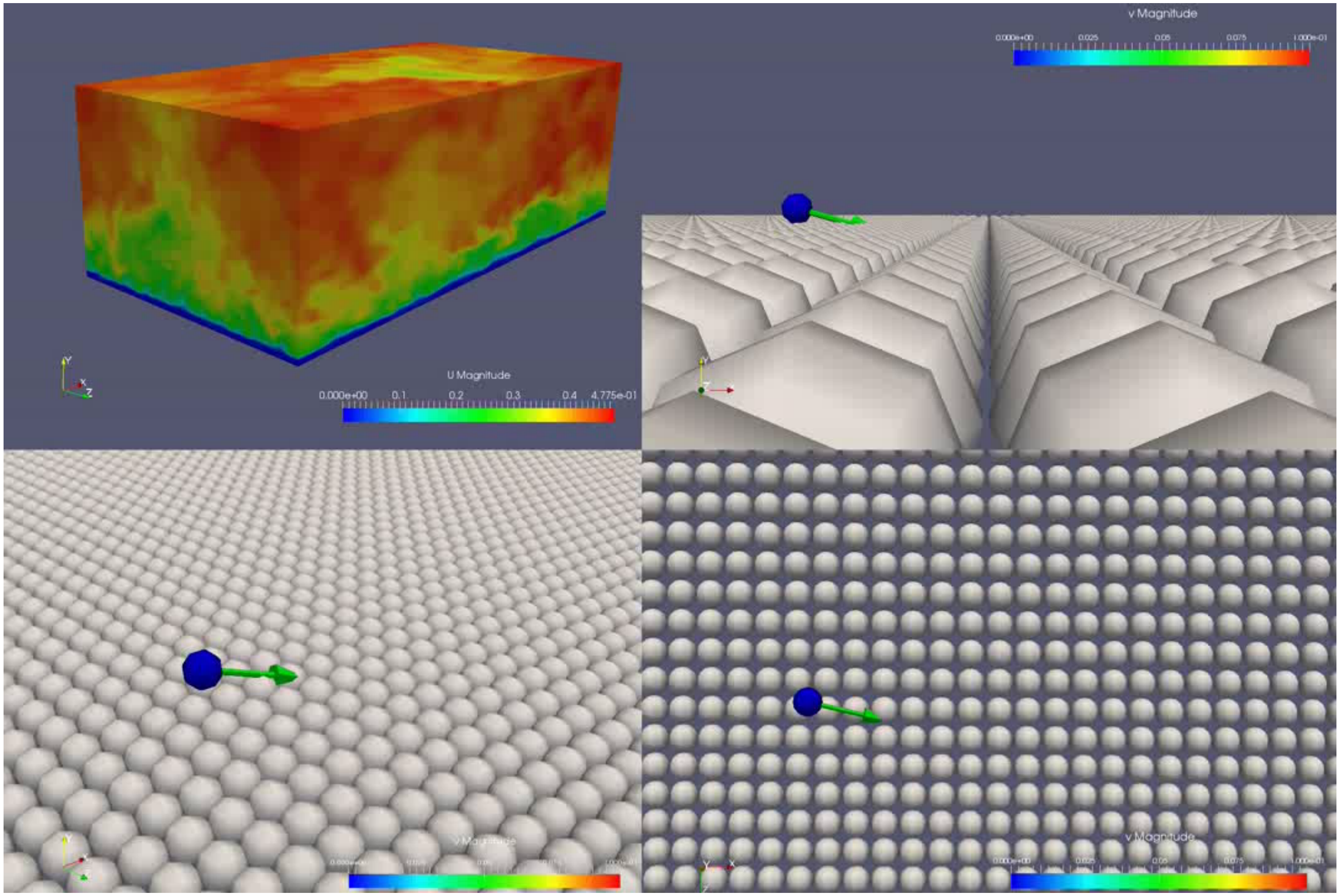
Single particle saltation in unidirectional flow



Liu et al., 2016, submitted

Lagrangian particle transport

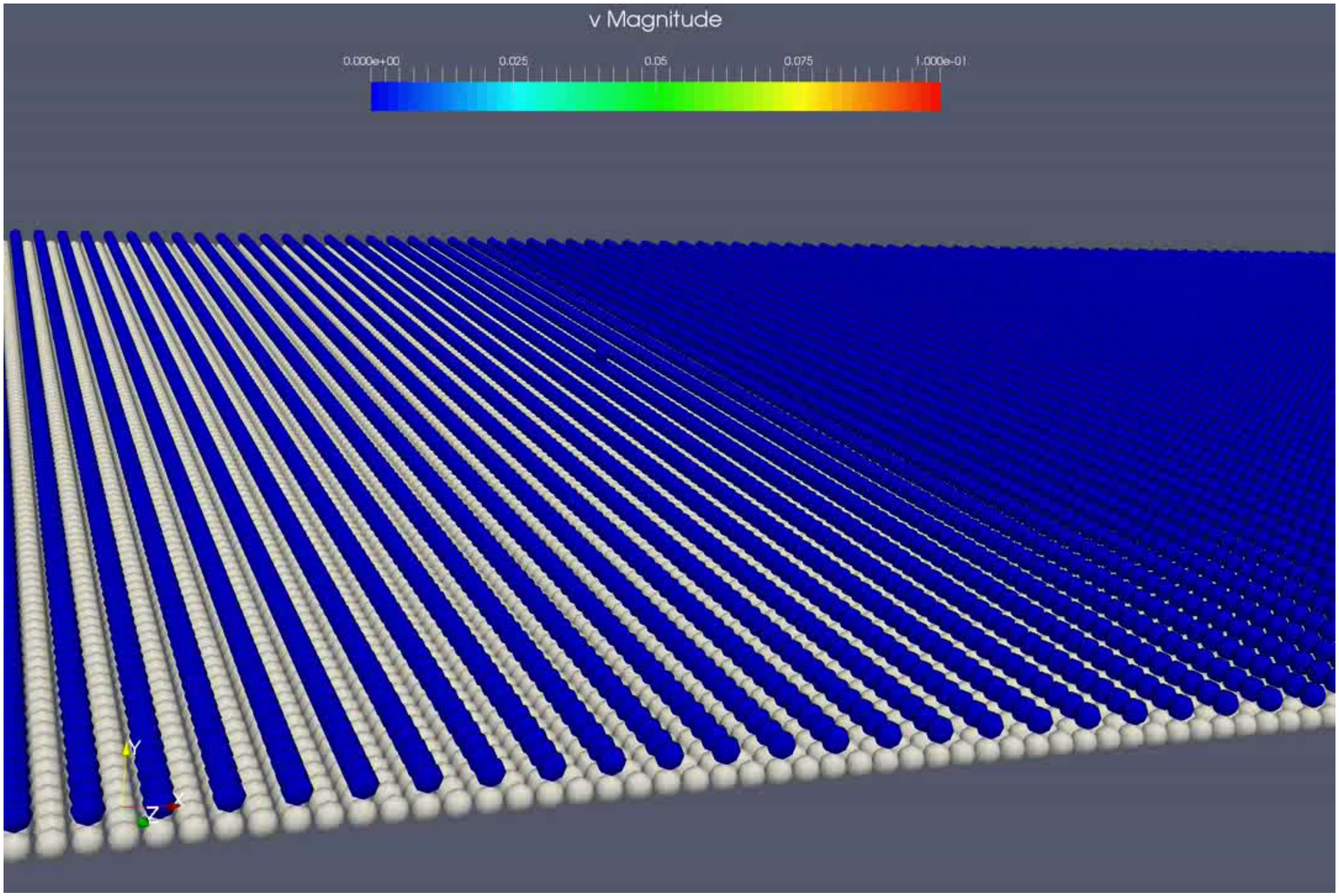
Single particle saltation in unidirectional flow



Liu et al., 2016, submitted

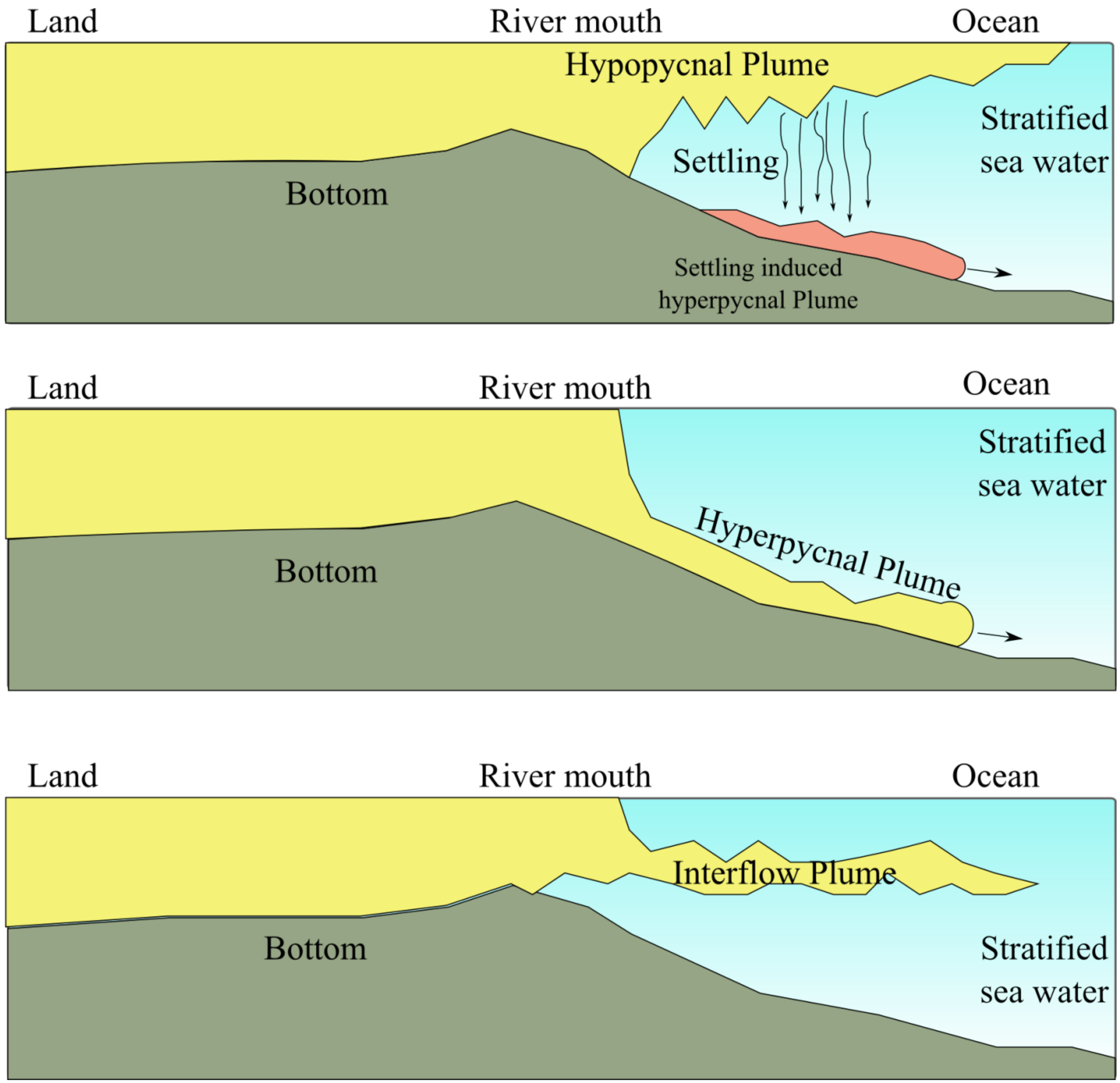
Lagrangian particle transport

Multiple particles (bedload) in unidirectional flow



Liu et al., 2016, submitted

Gravity current and sediment plume



Gravity current and sediment plume

- A customized solver, *gravityCurrentFoam,* which solves:
  - N-S equations with Boussinesq approximation

$$\nabla \cdot \mathbf{u} = 0,$$

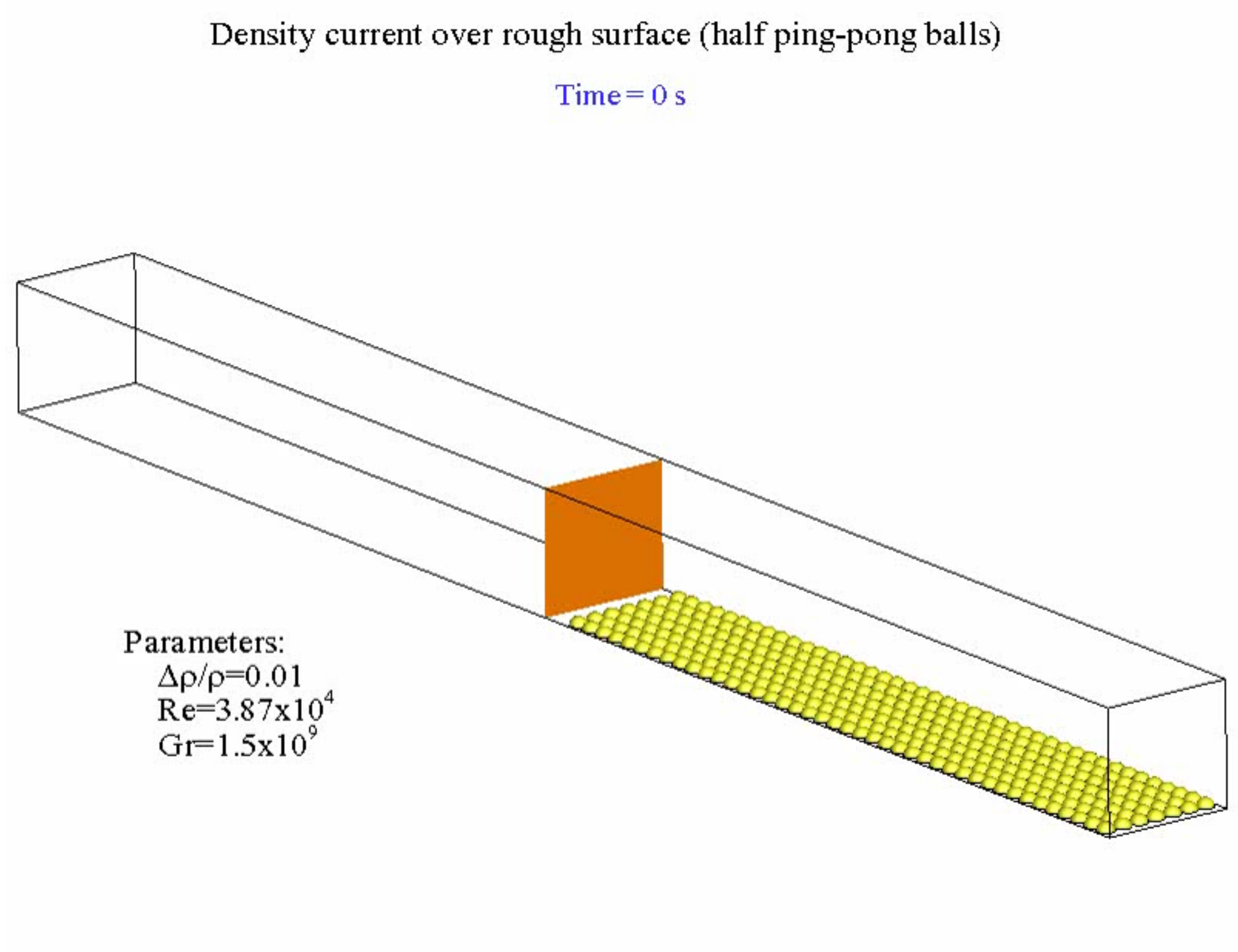
$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \overline{C}\delta + \nabla \cdot \left[\left(\frac{1}{\sqrt{G_r}} + \nu_{sgs} \right) \nabla \mathbf{u} \right] + \mathbf{F},$$

  - Advection-diffusion equation for concentration

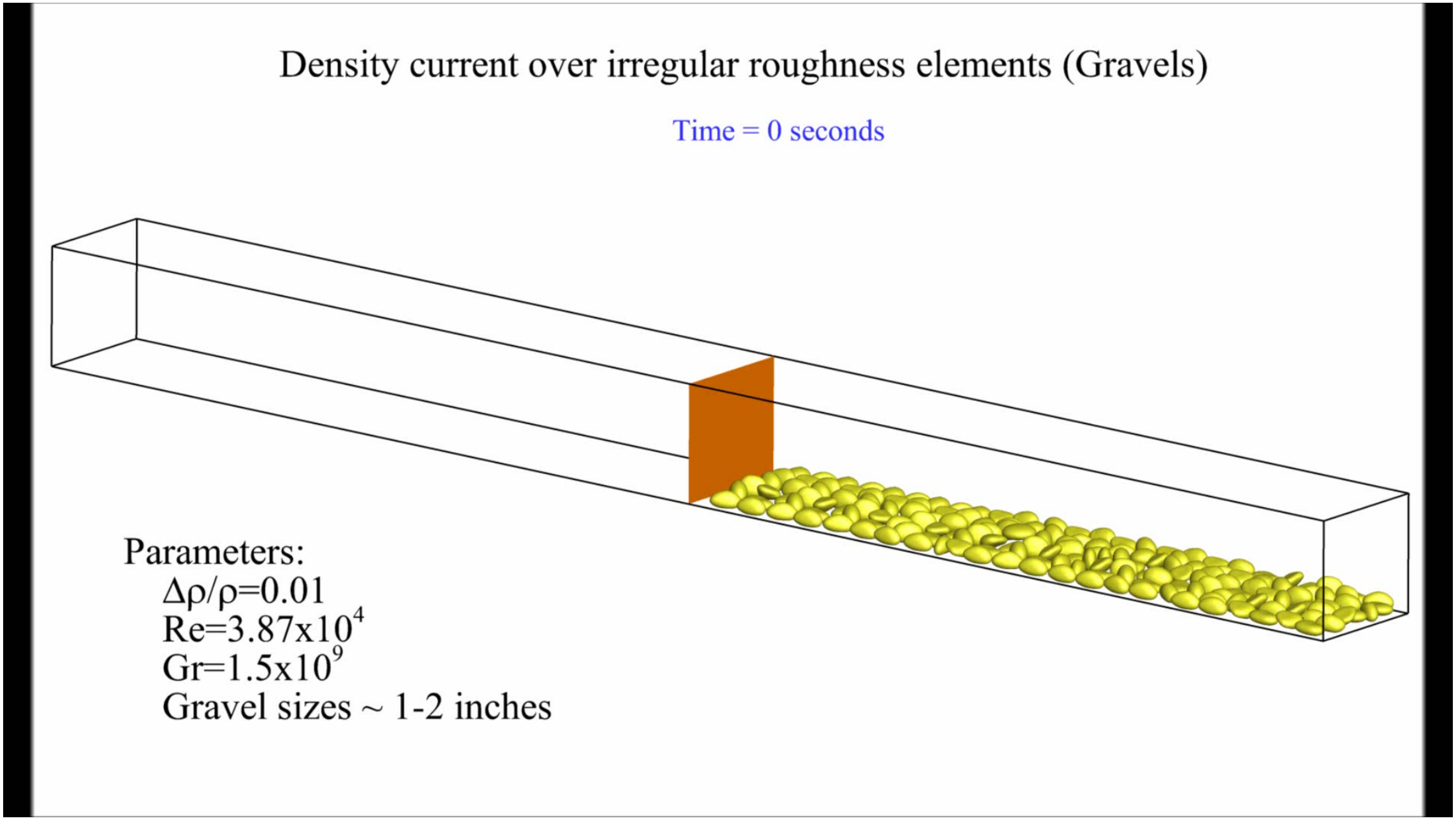
$$\frac{\partial \overline{C}}{\partial t} + \nabla(\mathbf{u}\overline{C}) = \nabla \cdot \left[\left(\frac{1}{\sqrt{G_r} S_c} + \alpha_{sgs} \right) \nabla \overline{C} \right] + S_r,$$

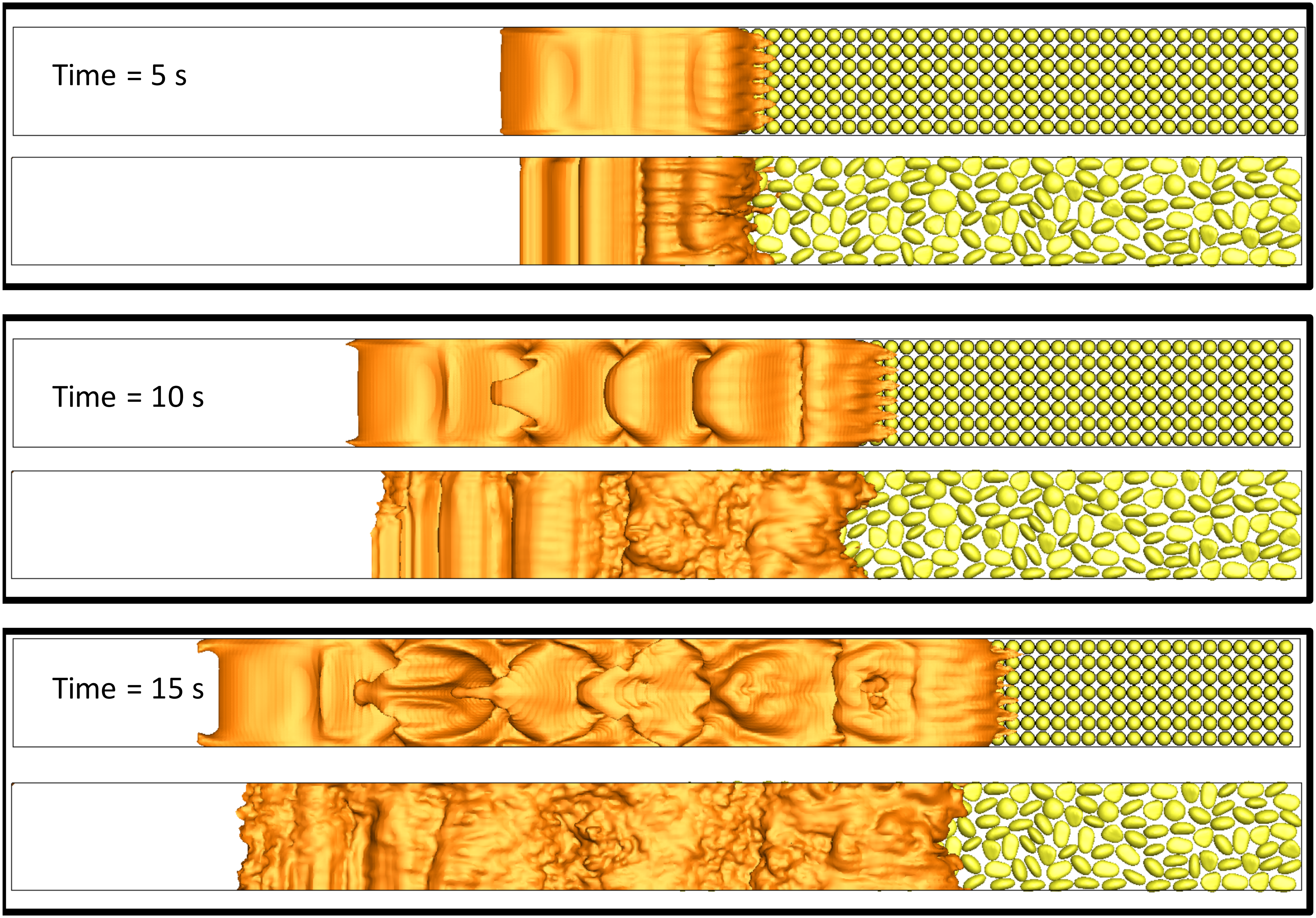
Jiang and Liu (2016), under review

Gravity current and sediment plume



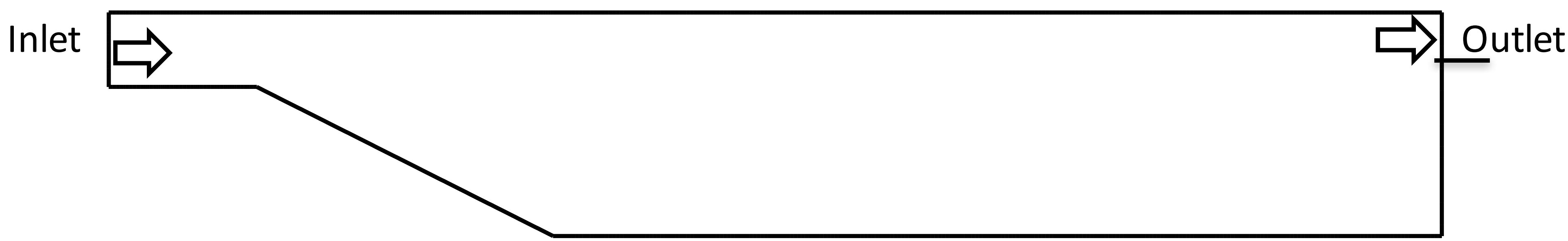
Gravity current and sediment plume



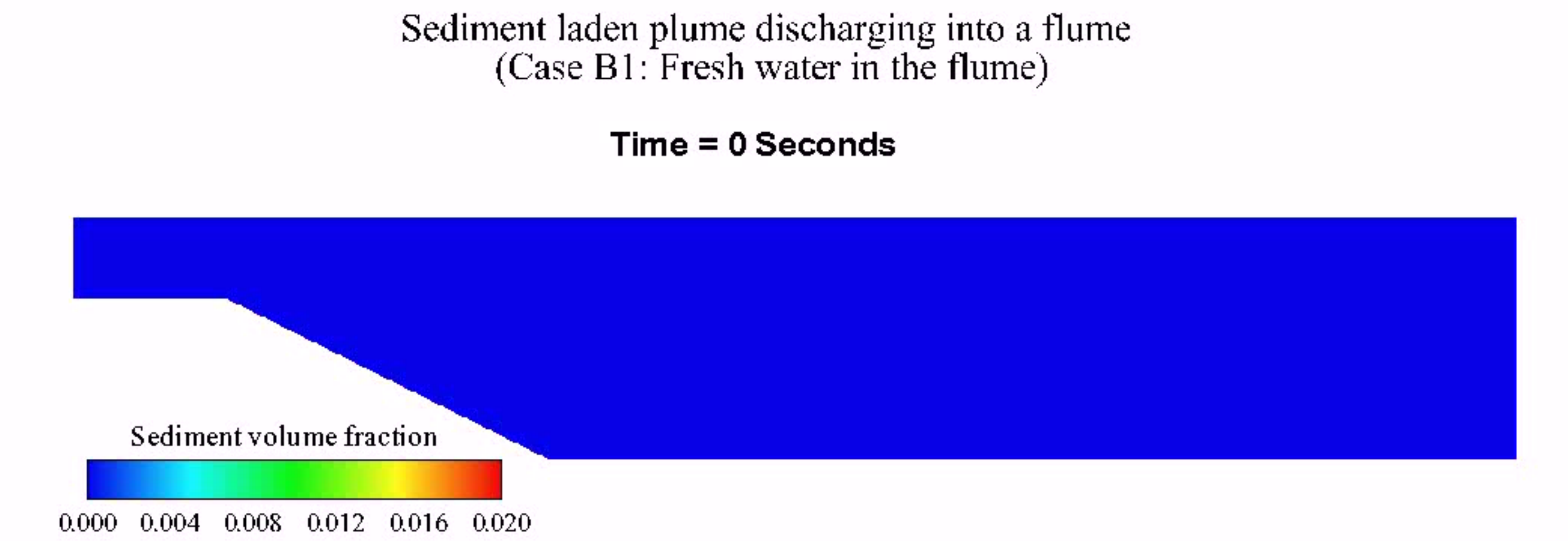

Time = 5 s
Time = 10 s
Time = 15 s

Gravity current and sediment plume

- Sediment laden plume discharging into a flume



Simulation case: Underflow only



Sediment laden plume discharging into a flume
(Case B2: Salty water in the flume. Both overflow and underflow appear.)

Time = 0 Seconds

Sediment laden plume discharging into a flume
(Case B3: Salty water in the flume. Reduced settling velocity. Only overflow appears.)

Time = 0 Seconds

More recent simulations

- The inlet sediment concentration is 0.7 kg/m^3
- The salinity is 8 ppt

Figure. Instantaneous sediment concentration distribution

Rouhnia, Strom and Liu, River Flow 2016

More recent refined simulations

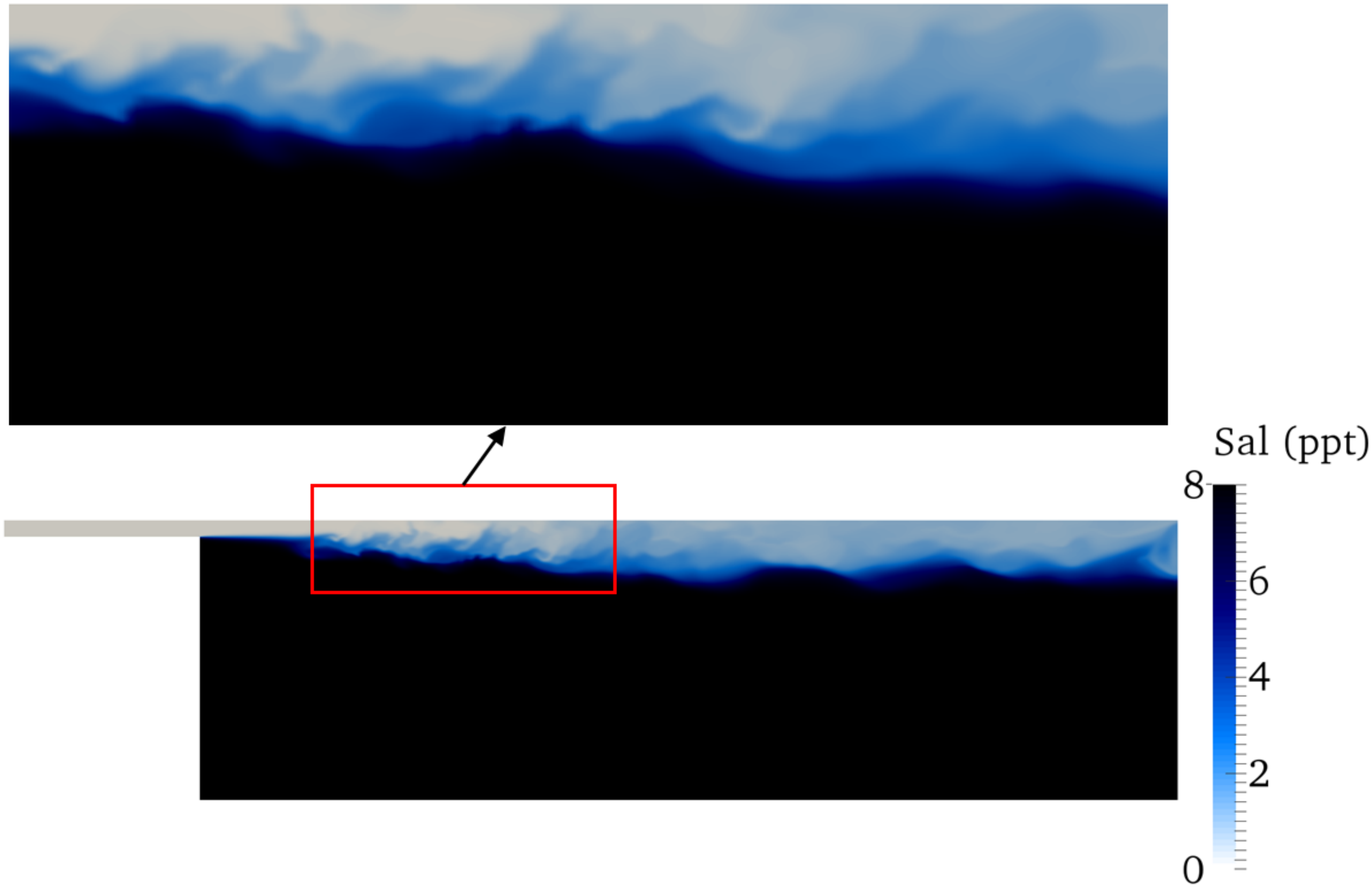


Figure: An instantaneous salinity concentration distribution

Rouhnia, Strom and Liu, River Flow 2016

More recent refined simulations

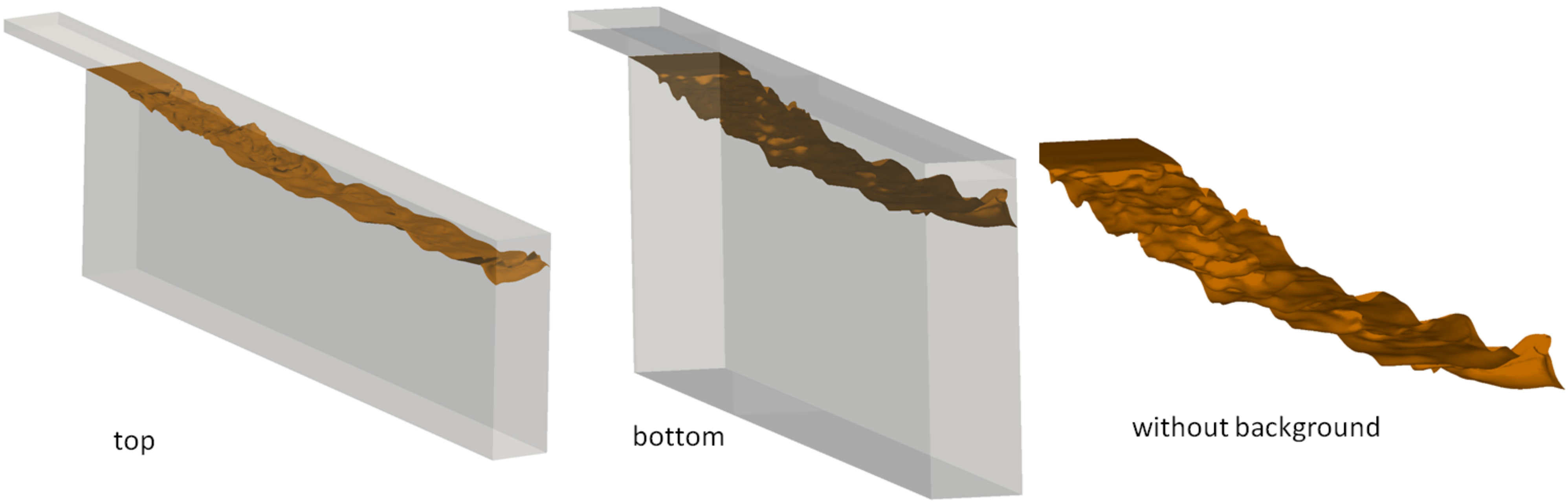
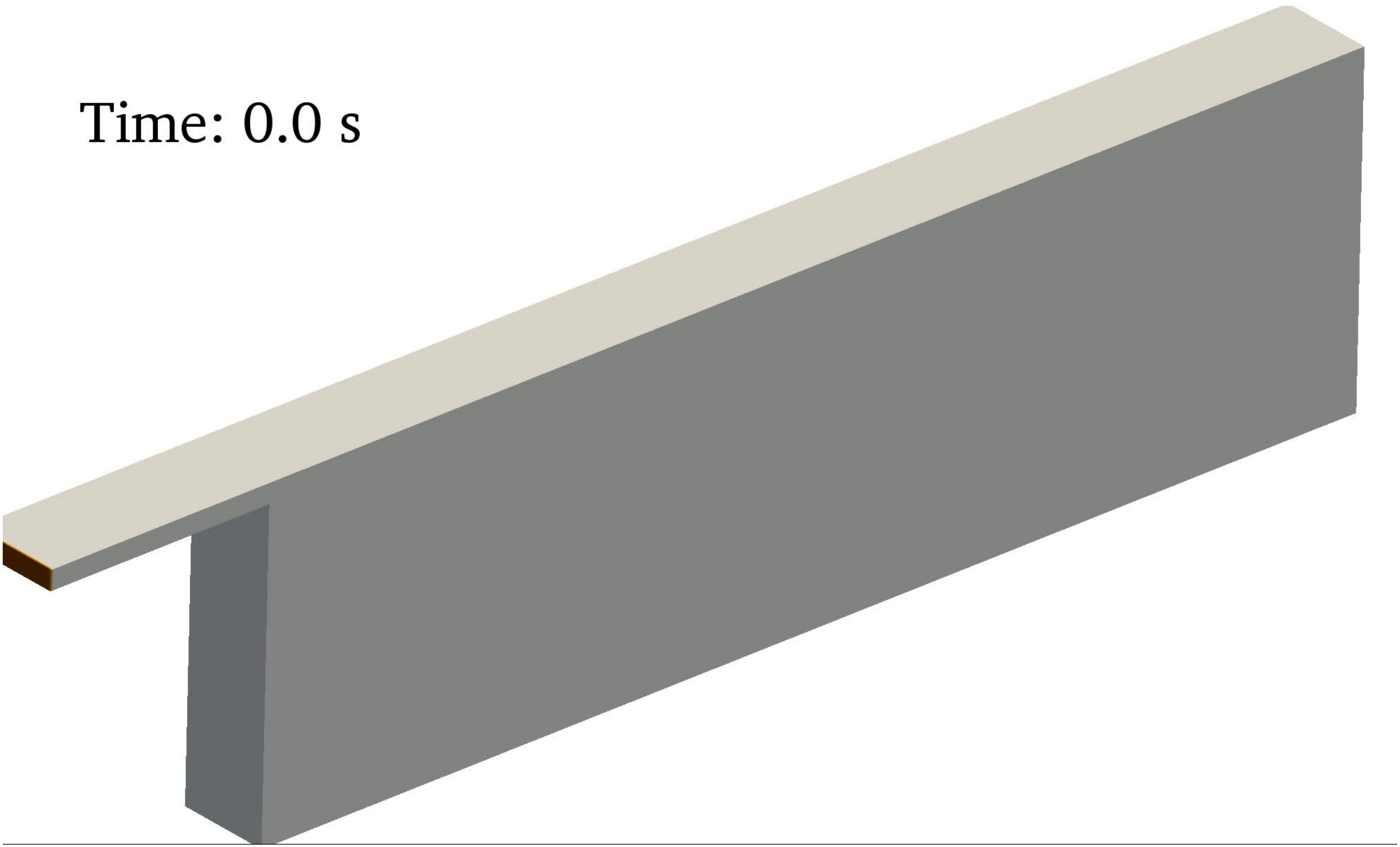
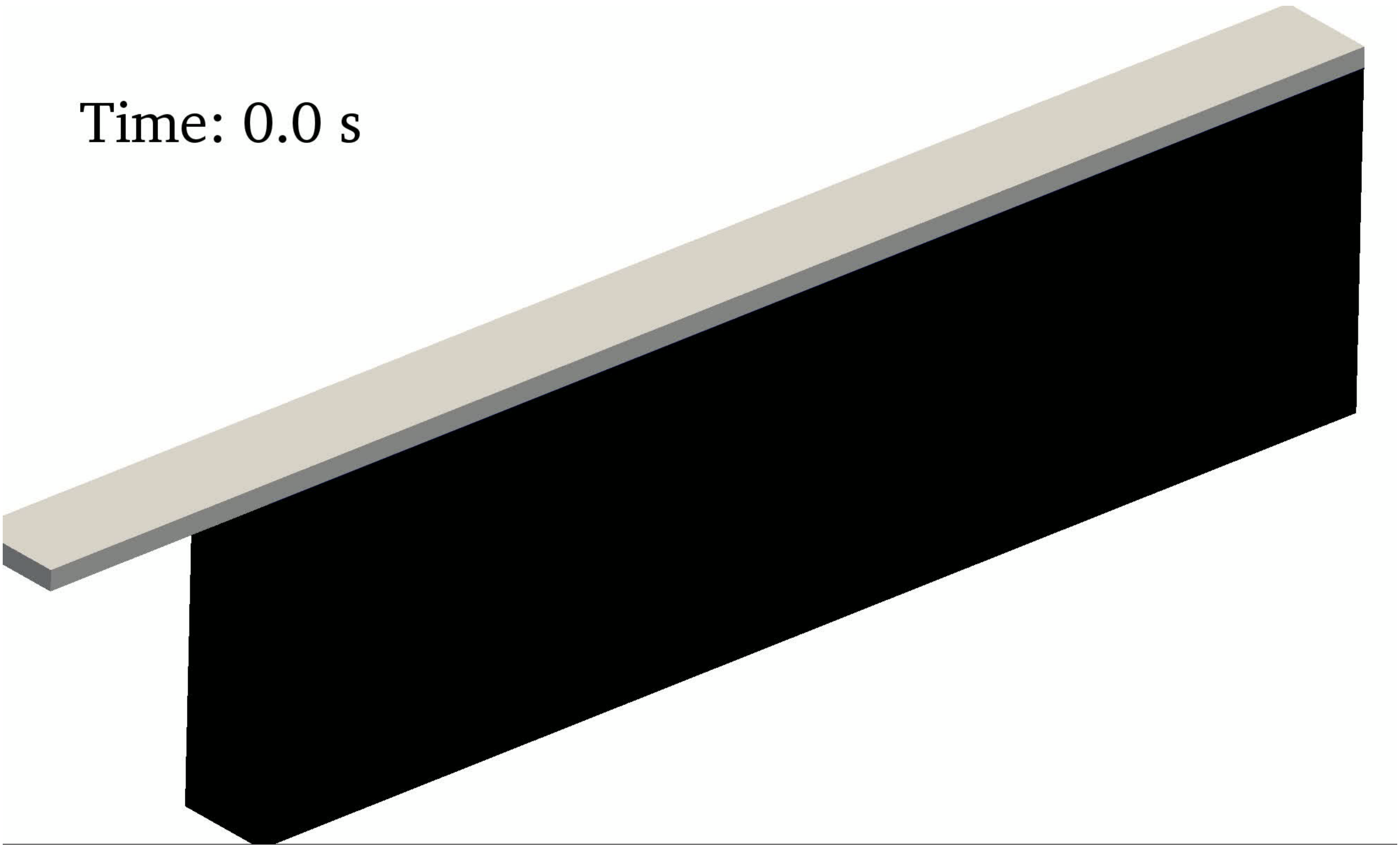


Figure: The interface between the plume and the ambient fluid represented by the iso-surface of the the sediment concentration (=0.45 kg/m^3)

Rouhnia, Strom and Liu, River Flow 2016

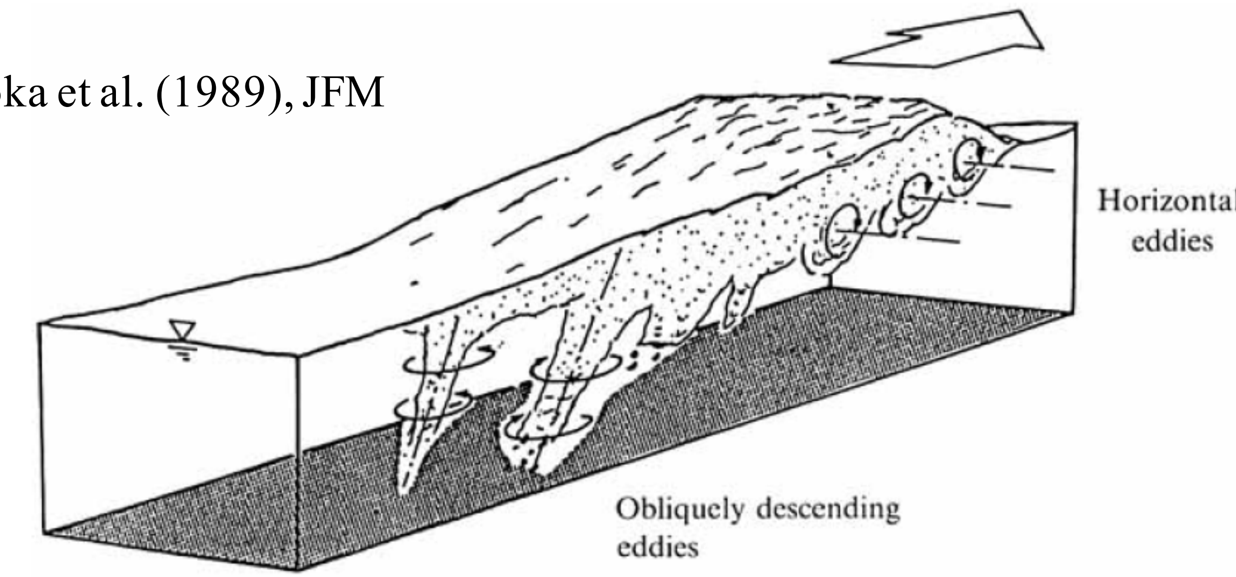

Time: 0.0 s


Time: 0.0 s

Sediment transport under breaking waves

- Nadaoka et al. (1989), laboratory wave flume observation – horizontal eddies around the wave crest evolve into **obliquely descending eddies** (ODEs). These ODEs may approach the bed and enhance sediment transport.
- Similar and more detailed wave flume observations were reported, e.g., Ting (2006,2008), Huang et al. (2010a,b), Ting and Nelson (2011).

Adopted from Nadaoka et al. (1989), JFM



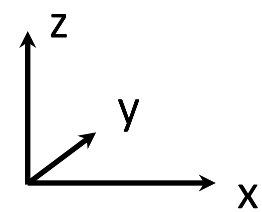
- Research Question:
  1. Can the generation and evolution of ODEs be reproduced by 3D Large-Eddy Simulation?
  2. What are the effects ODEs on the seabed and the resulting sediment transport?

3D Large Eddy Simulation Approach

• Solving 3D filtered incompressible Navier-Stokes equation for water phase and air phase:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_i \frac{\partial \bar{u}_j}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \upsilon \frac{\partial^2 \bar{u}_i}{\partial x_j x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_i u_j} - \bar{u}_i \bar{u}_j\right) + g_i$$



• Volume of fluid (VOF) to track the water-air interface:

$$\rho = \alpha_1 \rho_1 + (1 - \alpha_1)\rho_2$$

$$\frac{\partial \alpha_1}{\partial t} + \frac{\partial}{\partial x_j}\left(\alpha_1 \bar{u}_{1i}\right) = 0$$

✔$_1$: volume fraction of water phase
✗$_1$: water density

$1 - \alpha_1$: volume fraction of air phase

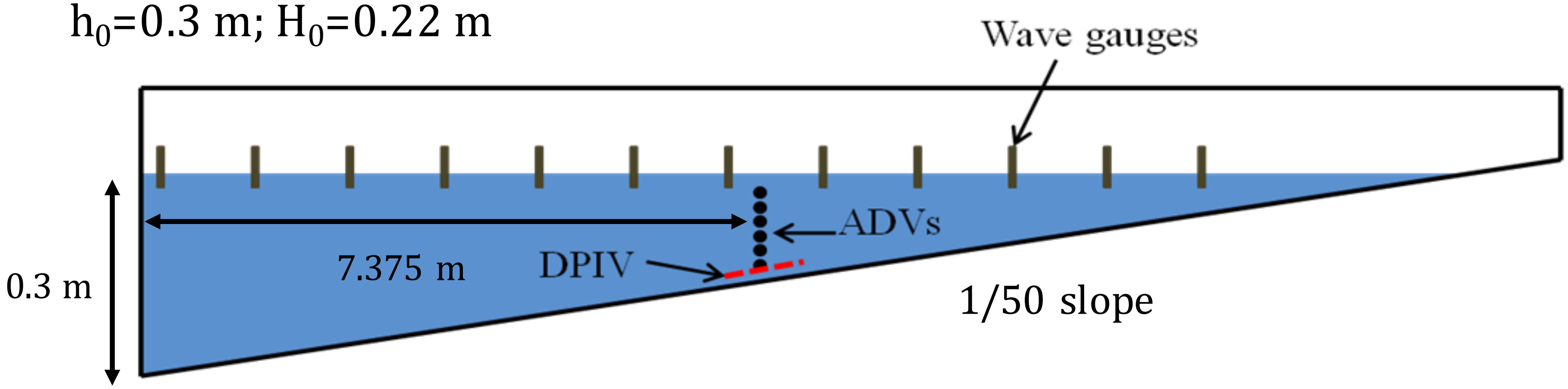
• Sub-grid stress $\tau_{ij} = \bar{u}_i \bar{u}_j - \overline{u_i u_j}$ is calculated with Dynamic Smagorinsky closure (Germano 1991; Lilly 1992).

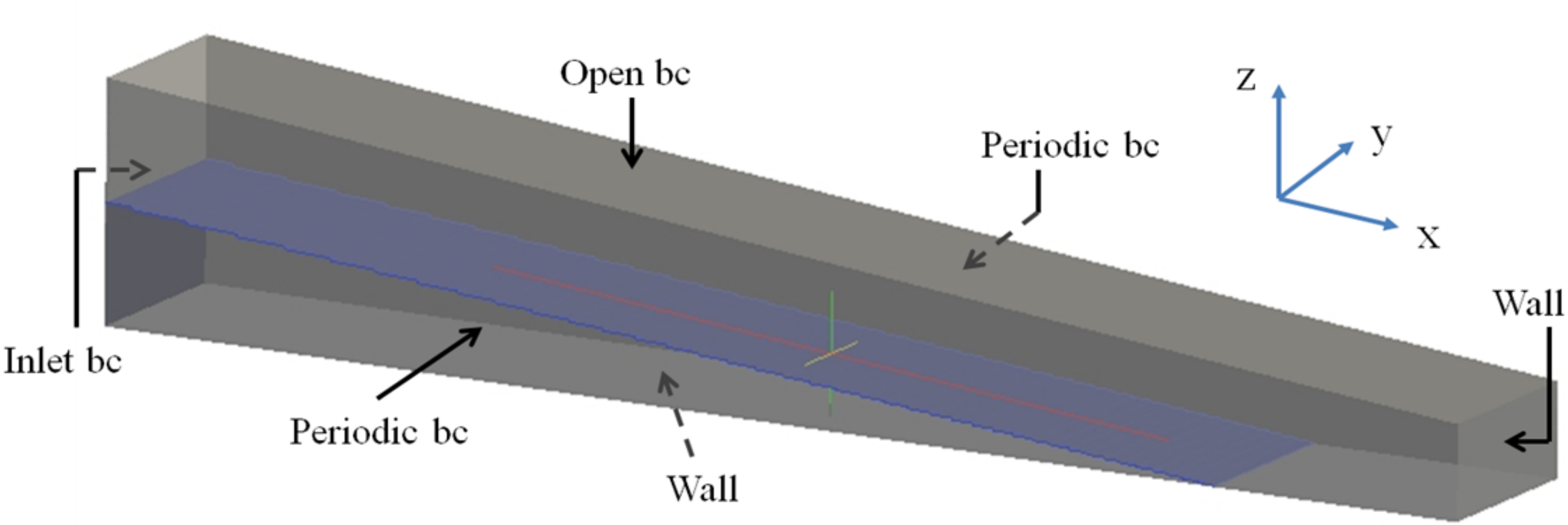
• The numerical implementation is based on an open source CFD C++ library of solvers, called OpenFOAM (specifically, interFOAM, *Klostermann, et al. 2012*). The solver is based on a finite volume scheme and fully parallelized with MPI.

I. Solitary wave breaking over a sloping planar beach

– Ting (2006, 2008, Coastal Eng.) Solitary wave breaking over a 1/50 sloping beach.

h_0=0.3 m; H_0=0.22 m





– use 15.5 million (2427×80×80 in x, y, z) grid points.
Δx_{max}=11.5 mm (Δx_{min}=4.6 mm); Δy=7.5 mm; Δz_{max}=7.5 mm (Δz_{min}=3 mm)

Free-surface elevation - validation

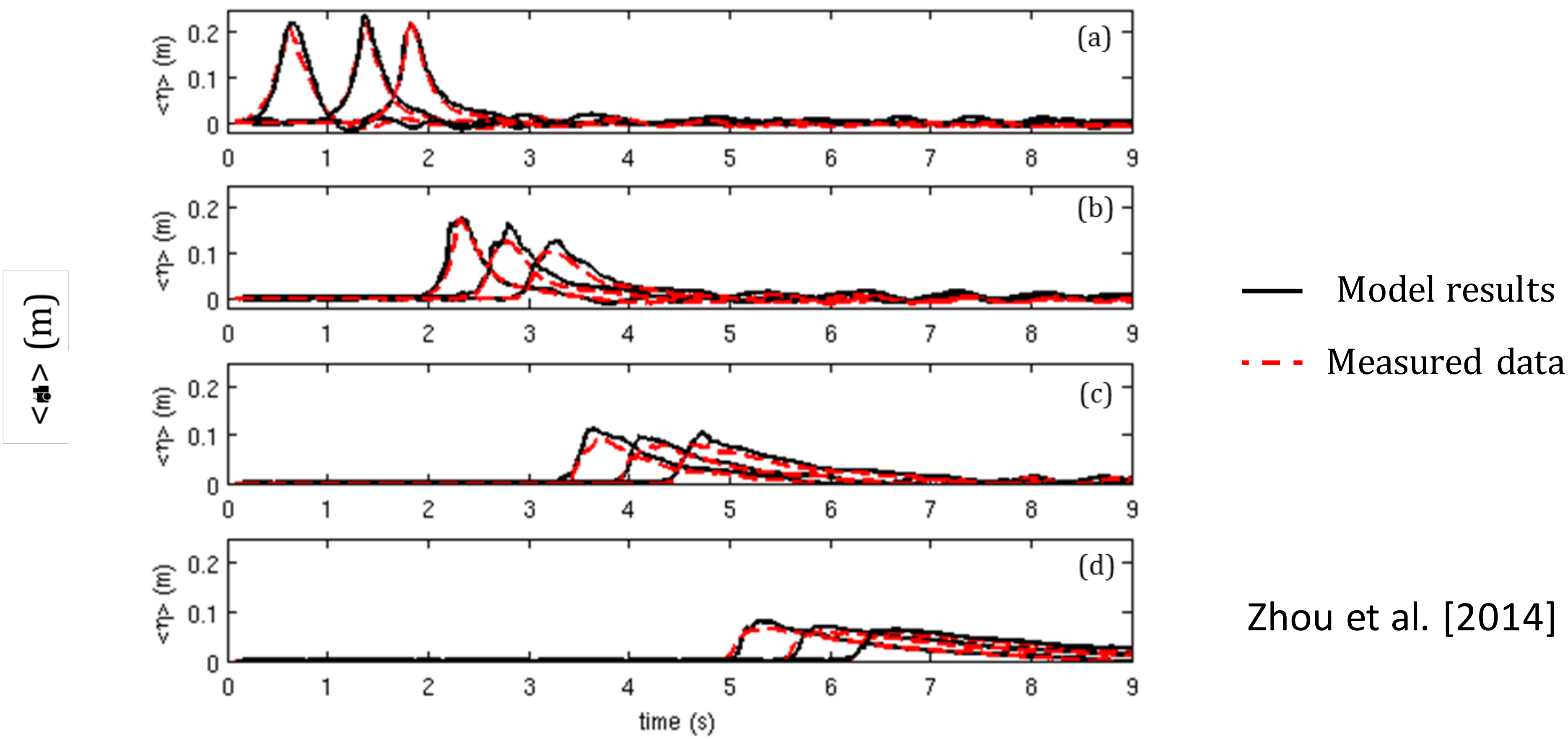
Measured data: ensemble-average over 5 identical runs (Ting, 2006)

Numerical simulation: Spanwise average over 0.6 m flume width (80 grid points; ~5 eddy size)

$$\eta = \langle \eta \rangle + \eta' \quad u_i = \langle u_i \rangle + u_i'$$

< >: represents ensemble average or spanwise average

' : represents "turbulent" fluctuations



Zhou et al. [2014]

Turbulence-averaged velocities and RMS velocity fluctuations - validation

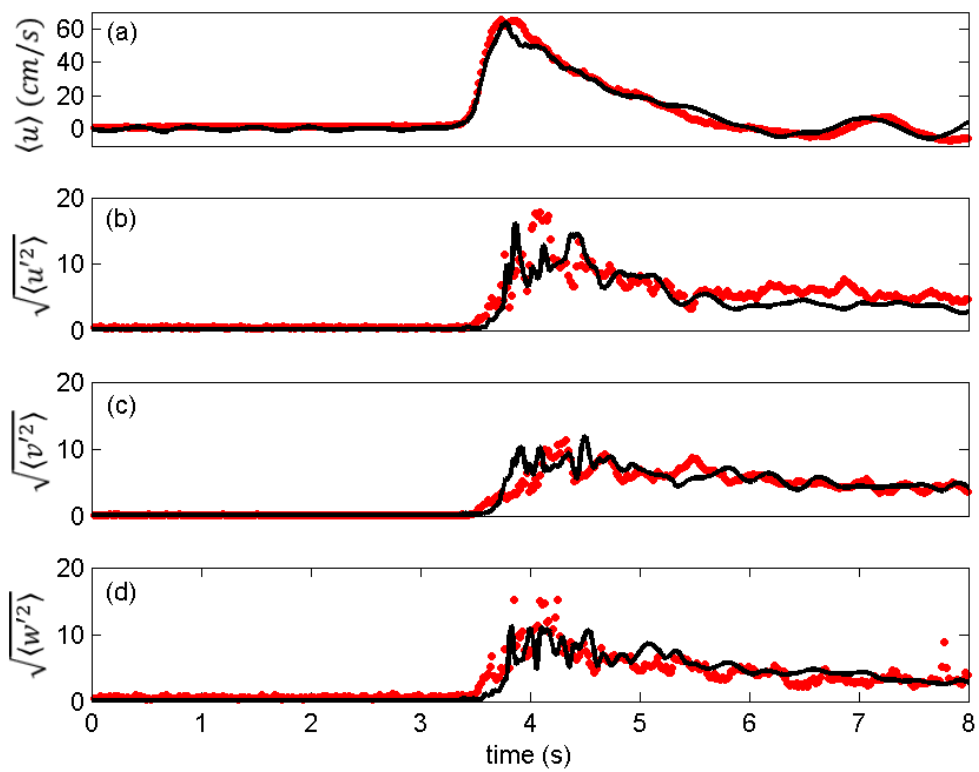
Measured data: ensemble-average over 29 identical runs (Ting, 2006)

Numerical simulation: Spanwise average over 0.6 m flume width (80 grid points; ~5 eddy size)

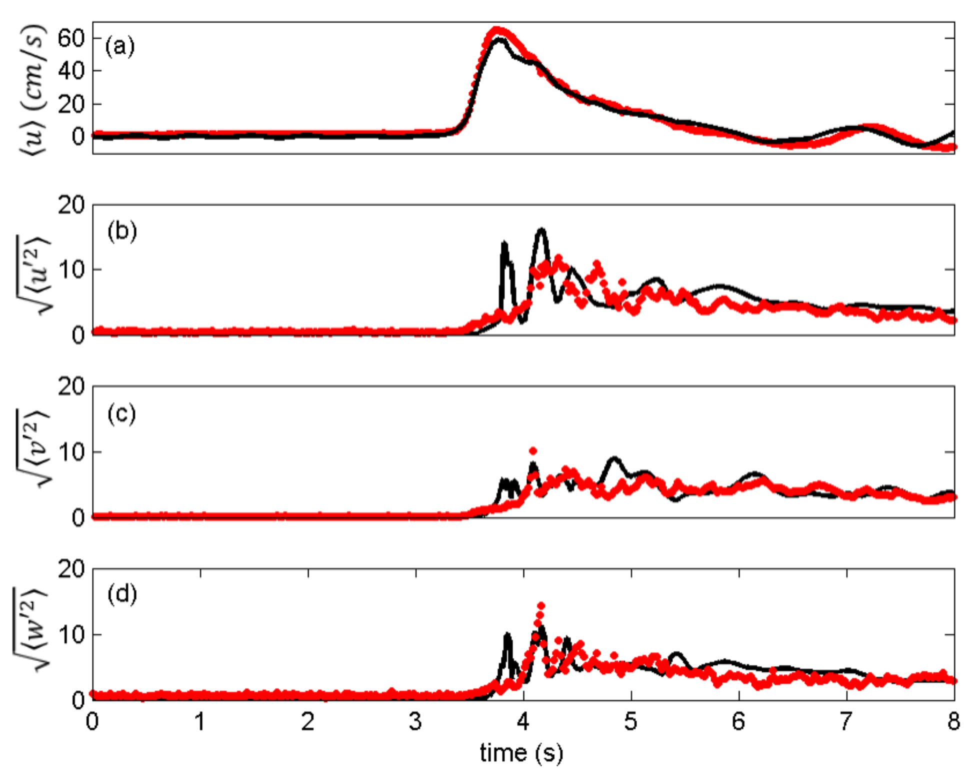
x=7.325 m; local depth=15.25cm

Measured data (red dashed line)
Model results Dyn Smagorinsky (black solid line)

z=11 cm above the bed (near surface)



z=7 cm above the bed (middle water depth)



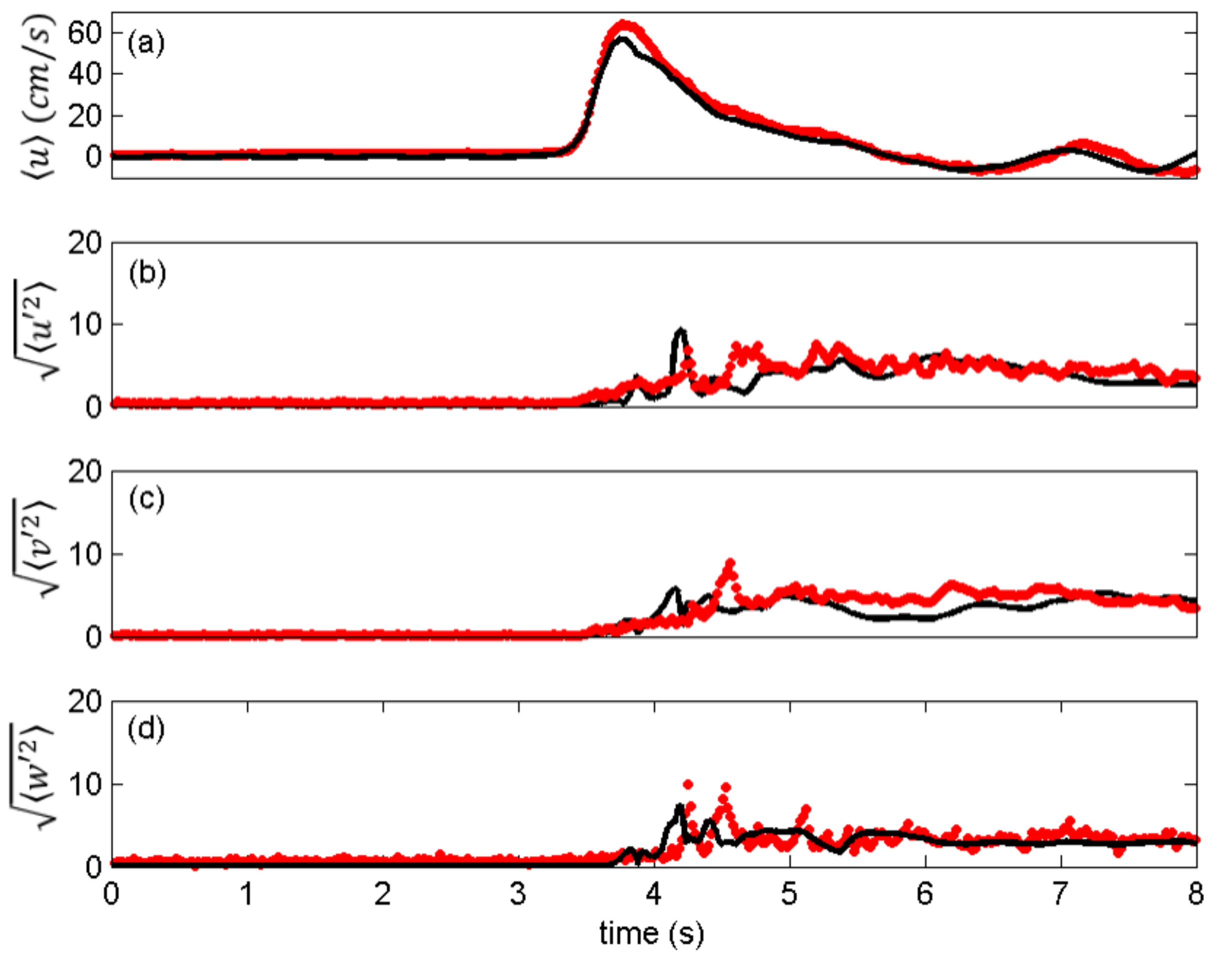
Turbulence-averaged velocities and RMS velocity flucutations - validation

x=7.325 m; local depth=15.25cm

z=3 cm above the bed (near bed)

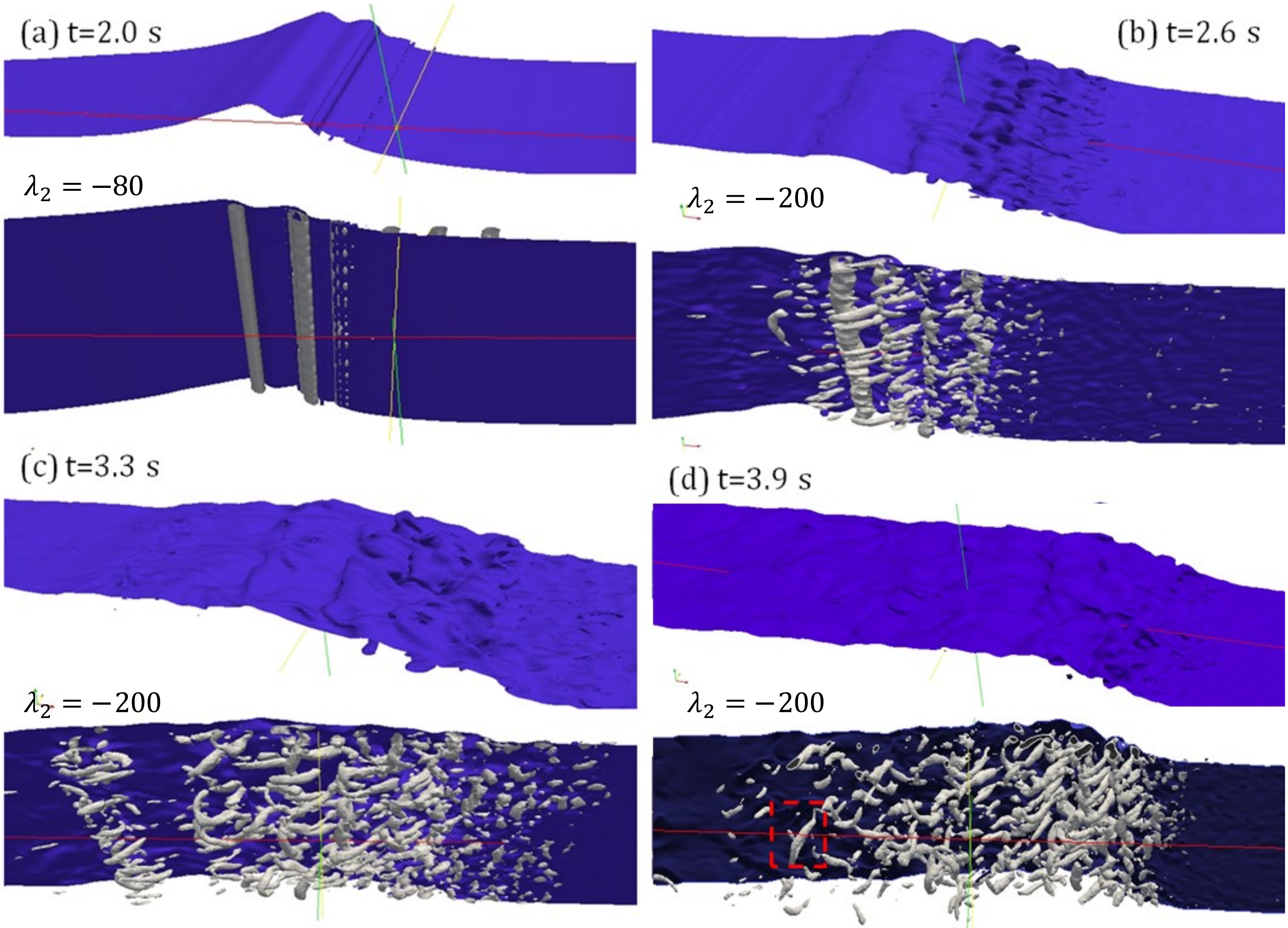
Measured data

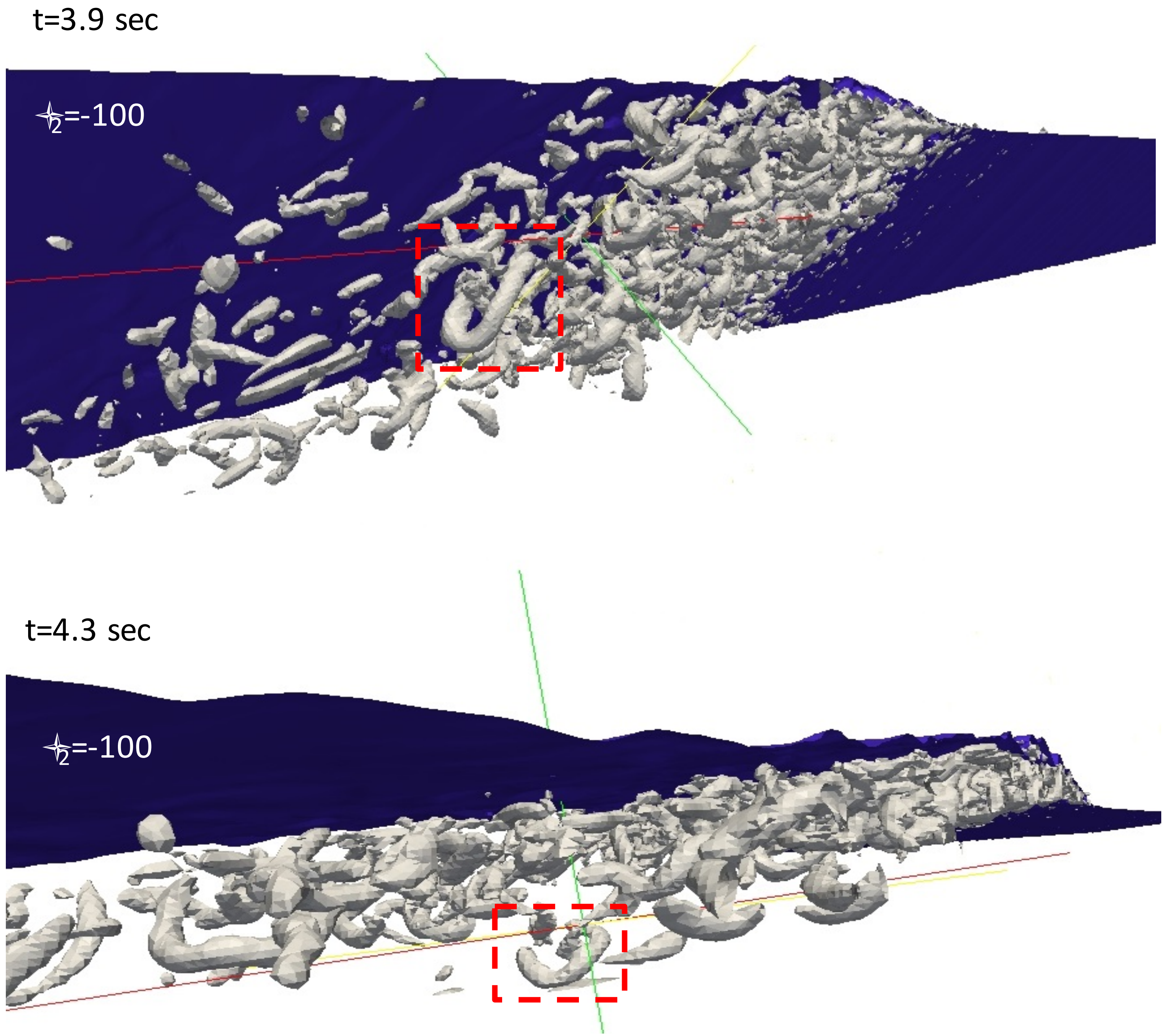
Model results Dyn Smagorinsky



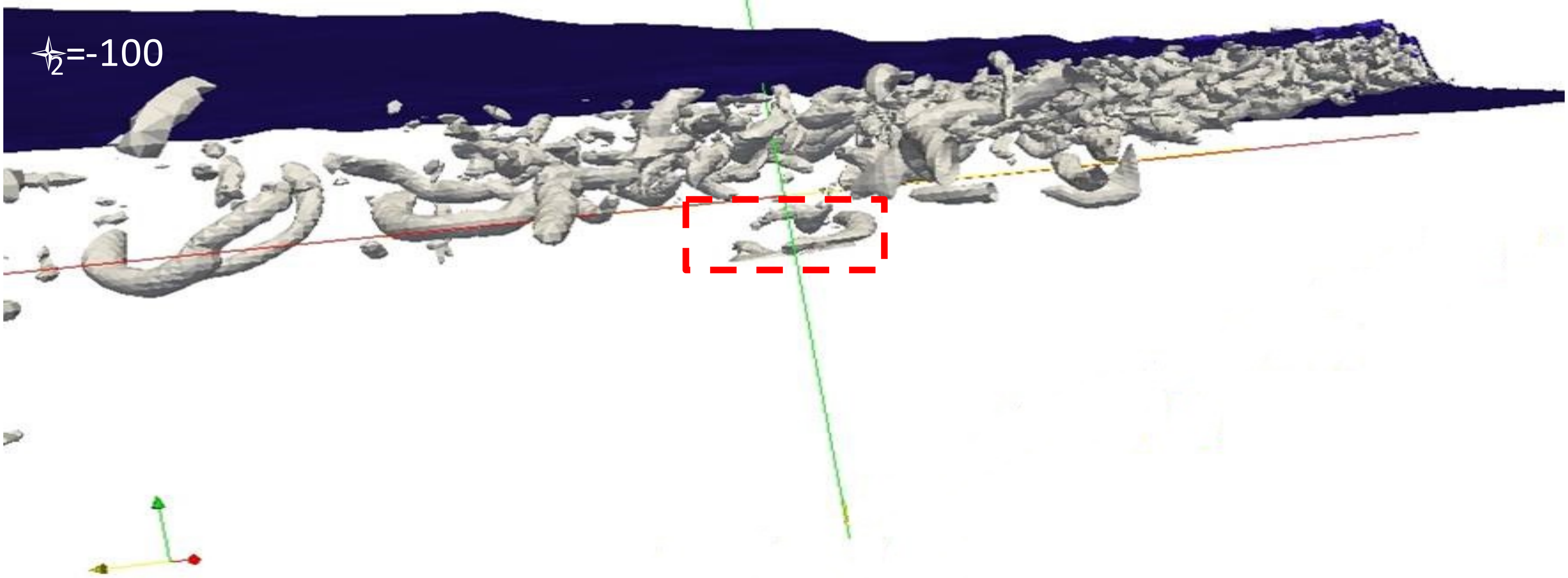
Generation and evolution of turbulent coherent structures

λ_2-method (Jeong & Hussain 1995, JFM): the eigenvalues of the symmetric tensor $S^2+\Omega^2$ with S and Ω : the symmetric and anti-symmetric parts of the velocity gradient tensor.

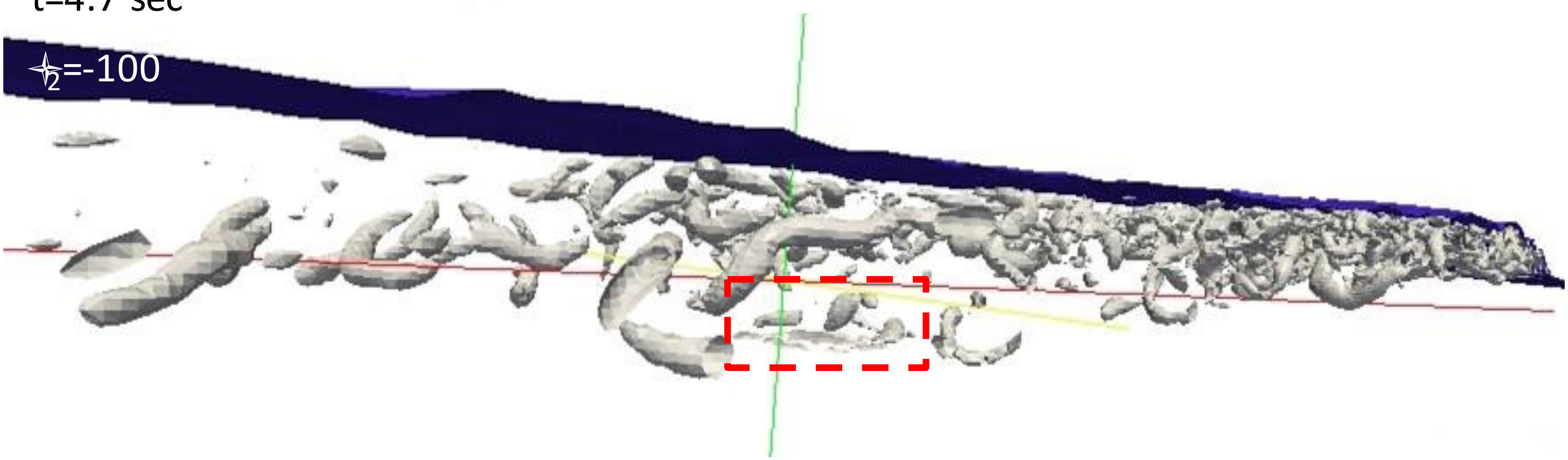



t=3.9 sec
=-100
t=4.3 sec
=-100

t=4.5 sec

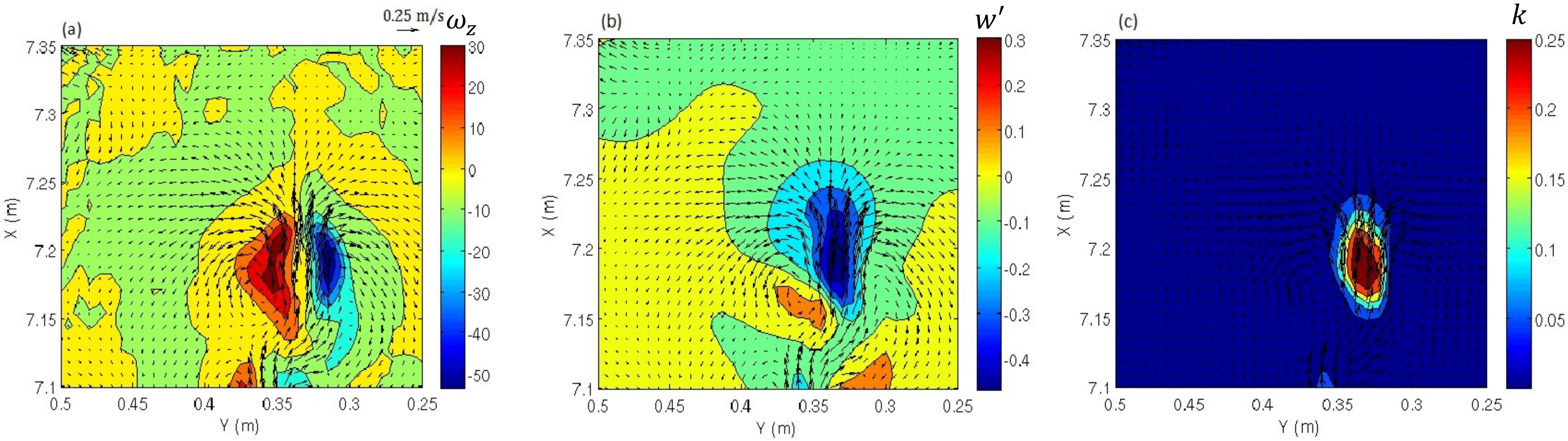


t=4.7 sec

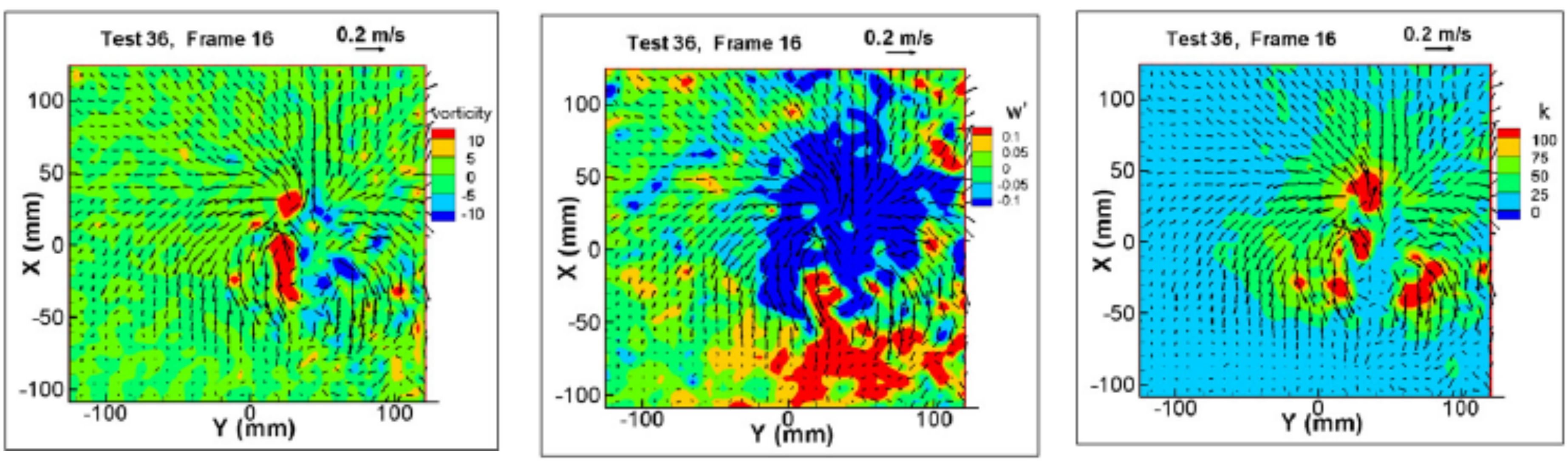


The Structure of ODEs – comparsion with PIV data of Ting (2008)

Simulation results at t=3.9 sec, xy-plane FOV at z=9 cmab

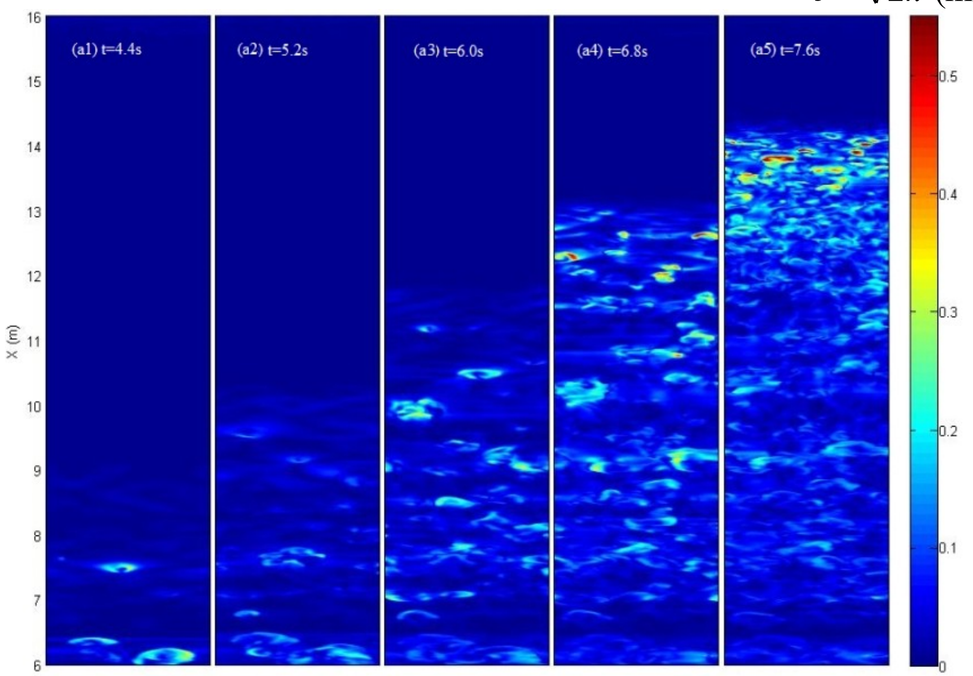


Measured PIV data (Ting 2008, Coastal Eng.), xy-plane FOV at z = 7 cmab

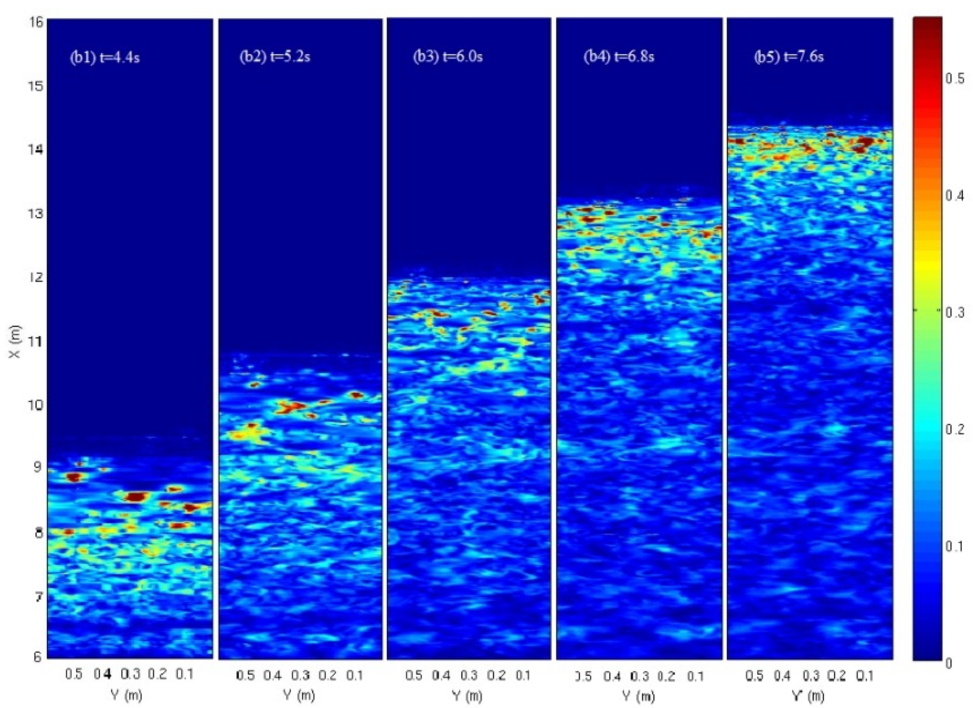


20 cm

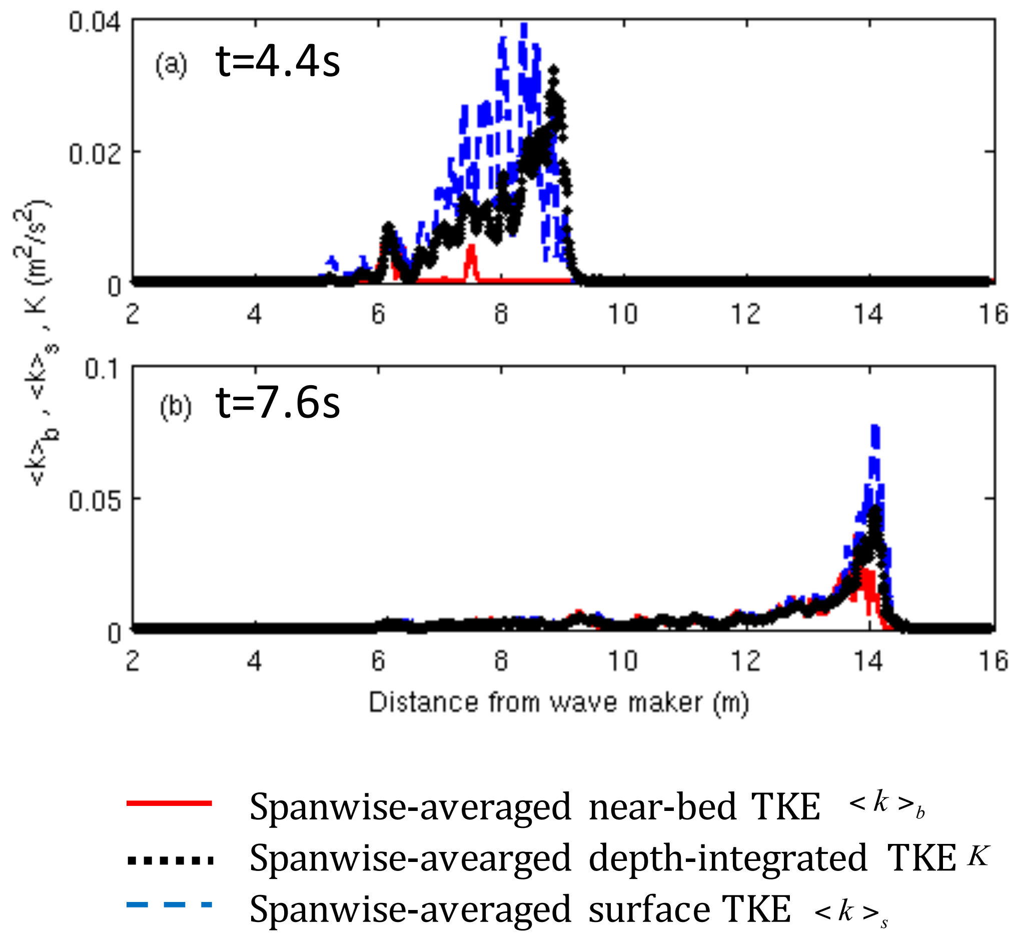
Near bed instantaneous turbulent intensity $\sqrt{2k}$ (m/s)



Near surface instantaneous turbulent intensity



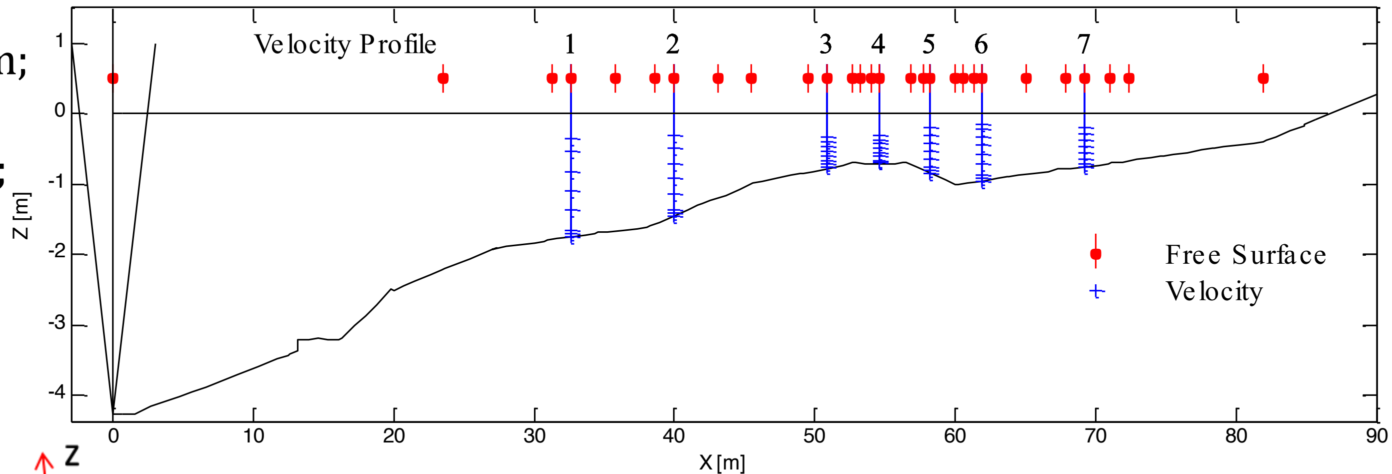
Fate of obliquely descending eddies

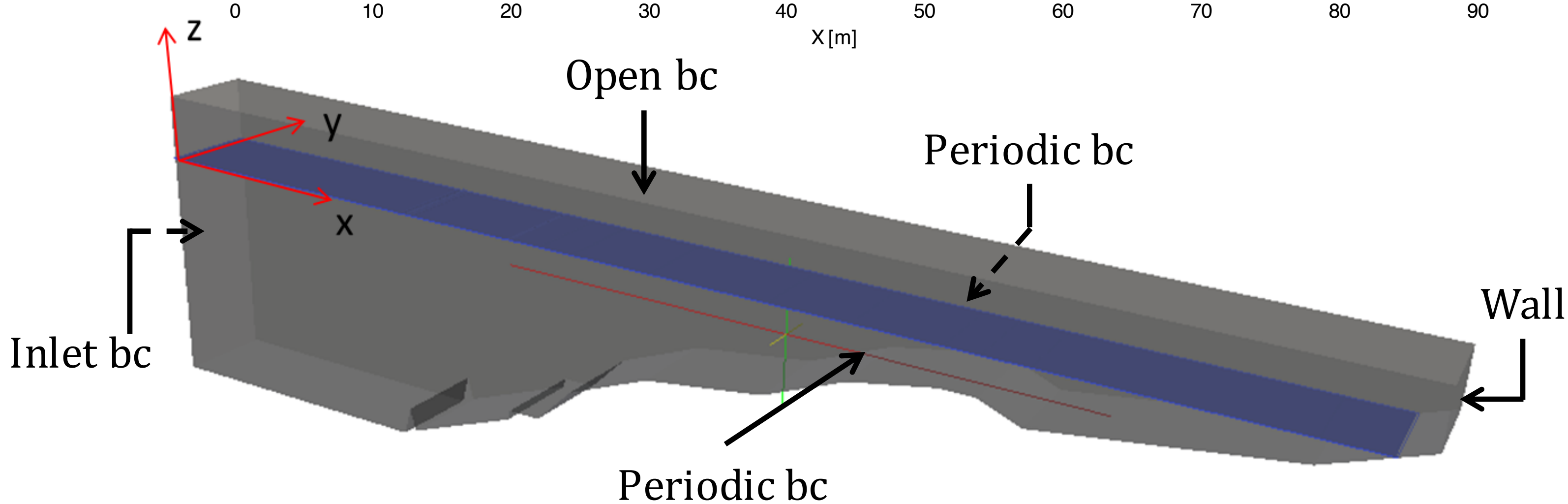


II. Periodic waves breaking over a near proto-type scale barred beach

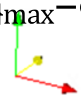
– Scott et al. (2005, Meas. Sci. Technol.) Large-scale laboratory experiment of periodic waves breaking over a fixed barred beach (bathymetry approximated the bar geometry for the average profile of the DUCK94 field experiment at a 1:3 scale)

L_{flume} =104 m;
h_0=4.252 m;
H_0=0.515 m;
T = 4.0 sec



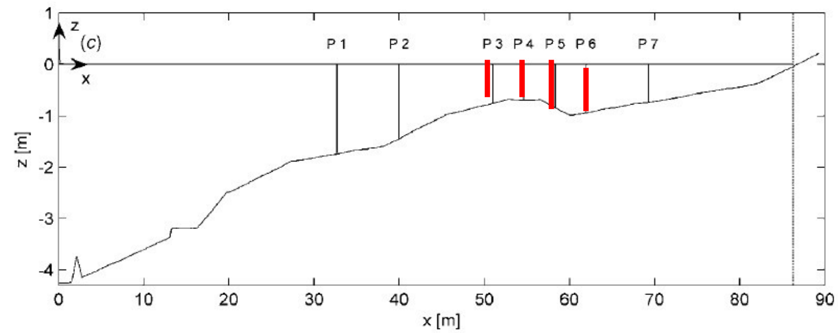


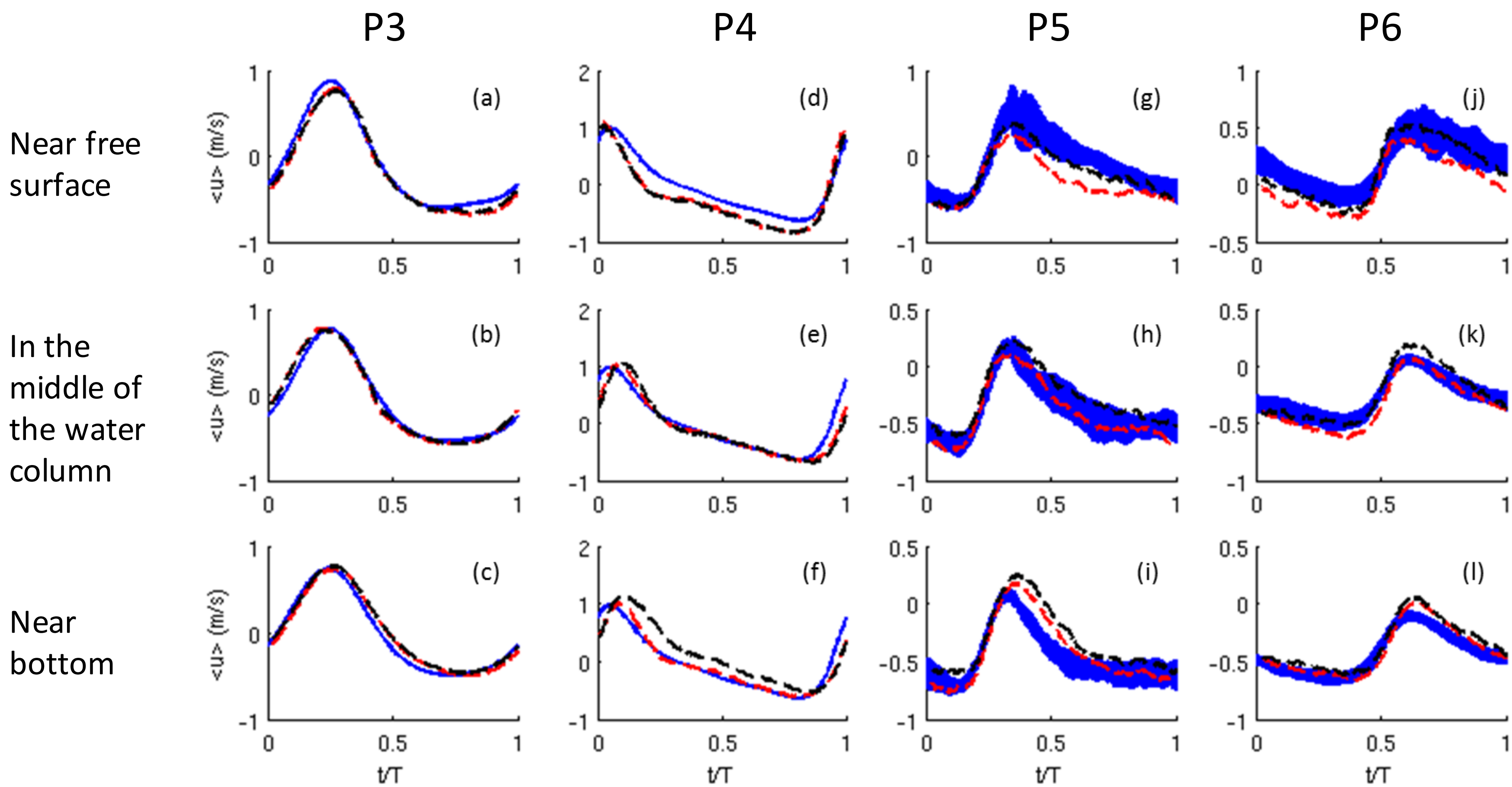
– use 28.3 million (2888×96×102 in x, y, z) grid points.
Δx_{max}=8.0 cm (Δx_{min}=1.5 cm); Δy=1.8 cm; Δz_{max}=5.35 cm (Δz_{min}=0.97 cm)



Model validation

Turbulence-averaged velocities





measured data — LES results; spanwise-averaged 40^{th} wave to 44^{th} wave

Zhou et al. [2016], submitted to JGR

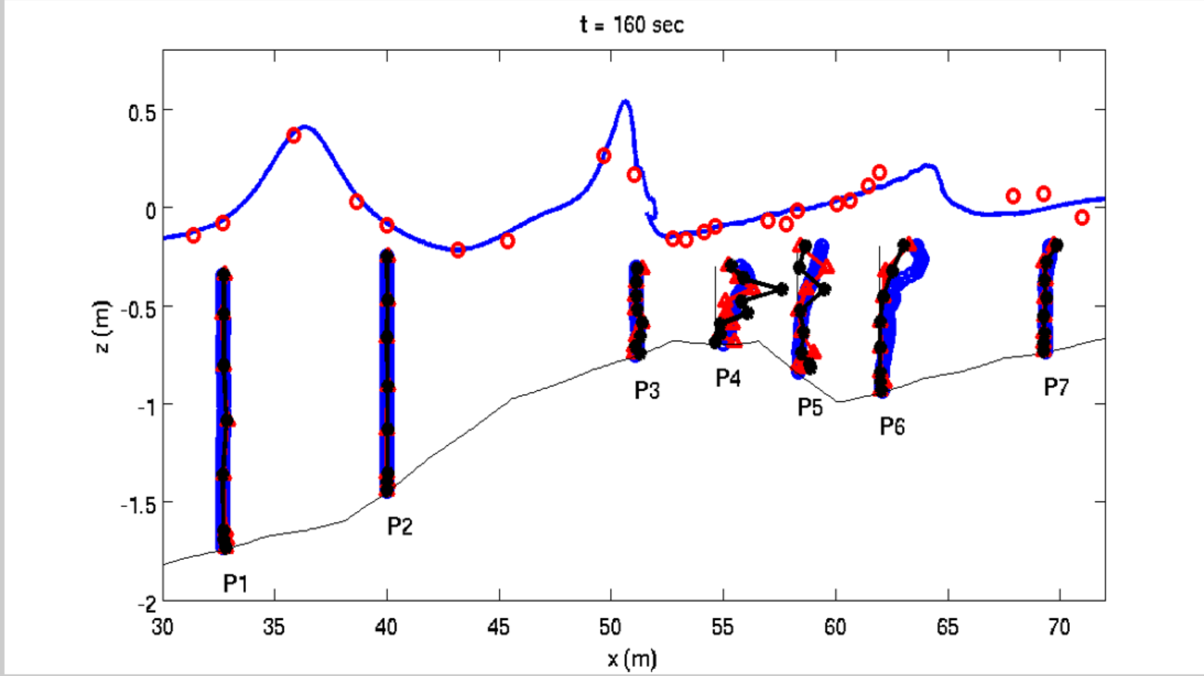
Sediment with $D_{50} = 0.17mm$ has been added at the bar crest in the simulation of Scott et al. (2005)

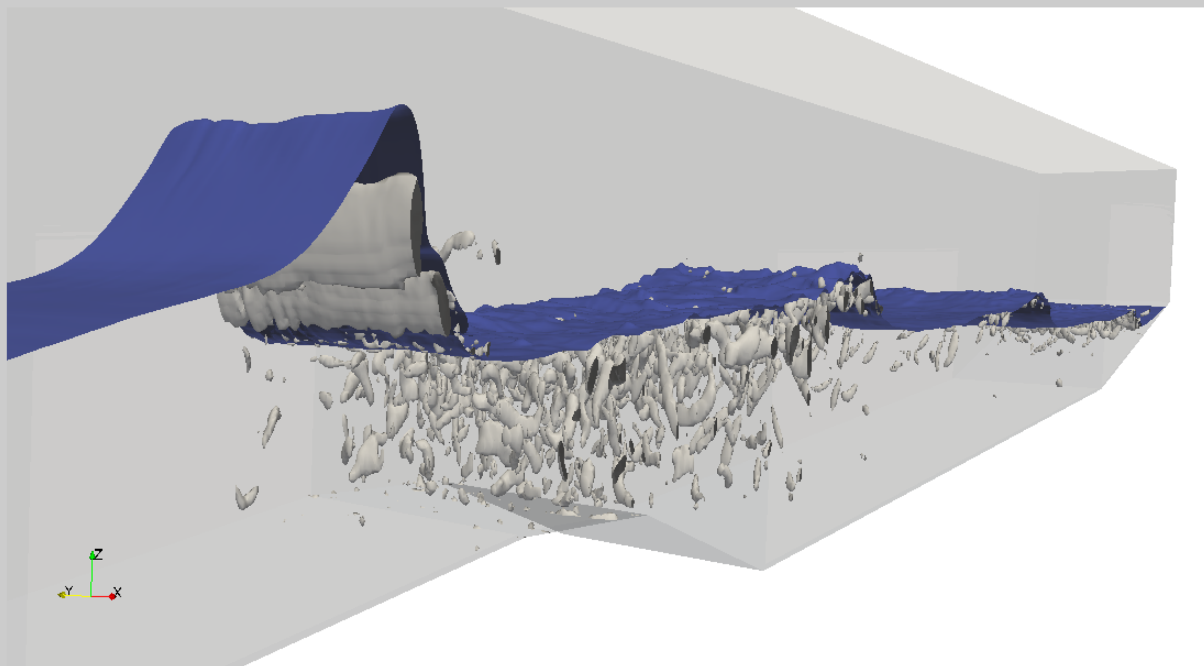
— Free surface in LES

o Measured free surface (with ensemble averaging)

Δ * measured TKE (with ensemble averaging)

O LES results; spanwise-averaged and averaged over $40^{th} \sim 50^{th}$ wave



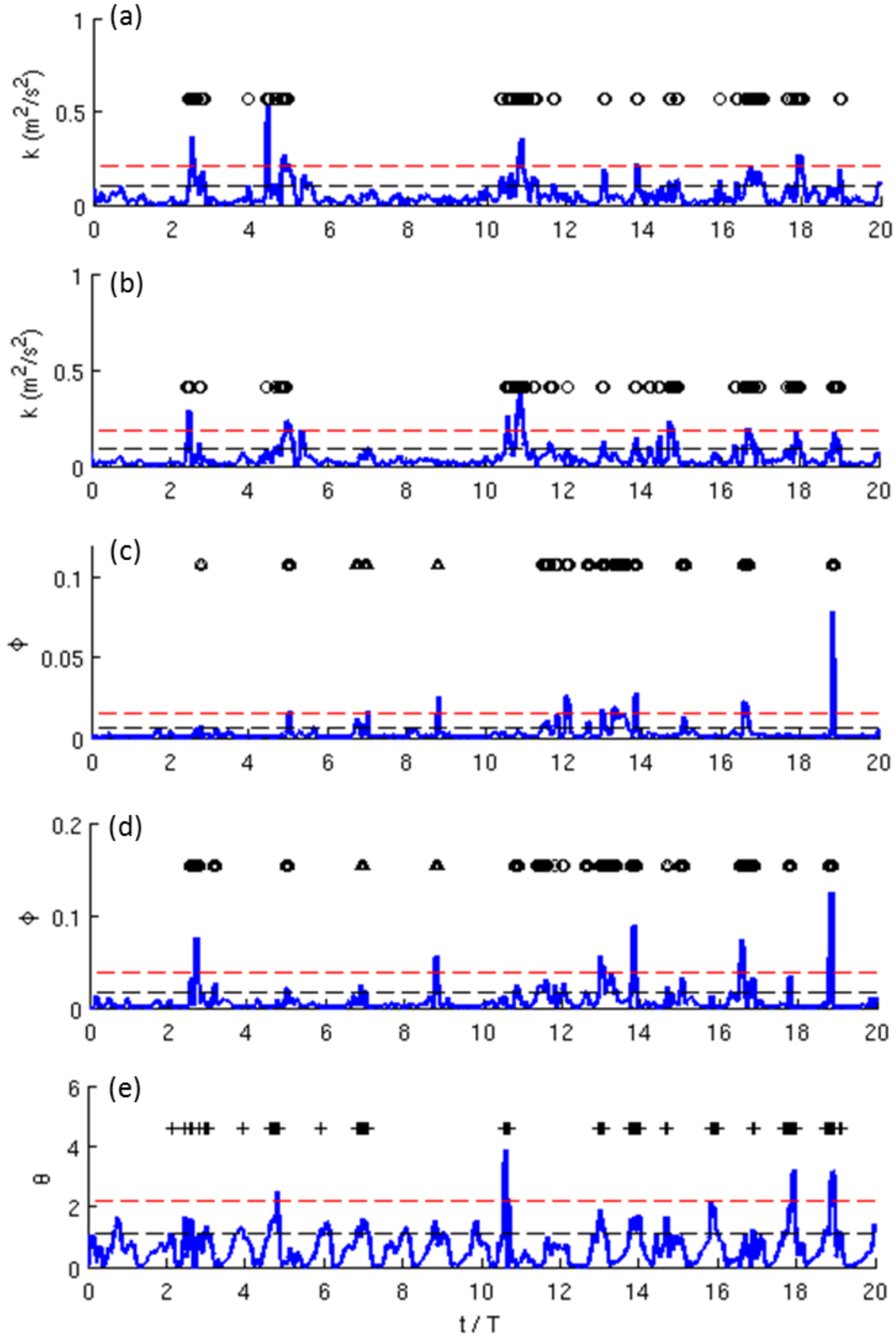


Blue iso-surface: free surface

Grey iso-surface: turbulent coherent structure with $\lambda_2 = -15$

Yellow iso-surface: sediment plume with $\phi = 0.2\%$

Intermittency of breaking wave turbulence and sediment suspension



1) Coherent suspension events account for only <u>10%</u> of the record but account for about 50% of the sediment load.
2) <u>60~70%</u> of coherent bottom stress events are associated with surface-generated turbulence.
3) <u>Nearly all</u> the coherent sand suspension events are associated with coherent turbulence events due to wave-breaking turbulence approaching the bed.