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Modeling of munition dynamic due to turbulent flow and scour

Yalan Song, Zilong Li, Tong Qiu and ***Xiaofeng Liu***

Department of Civil and Environmental Engineering, Pennsylvania State University

SERDP • ESTCP
SYMPOSIUM
2018 | Enhancing DoD's Mission Effectiveness

Underwater UXO – Burial and Mobility

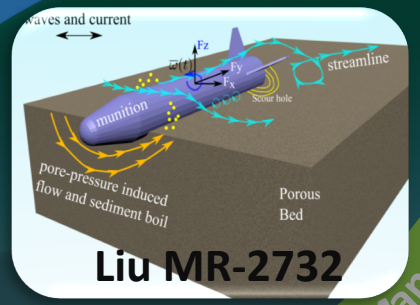
Munitions Response – Site Management

Bryan Harre - Keynote

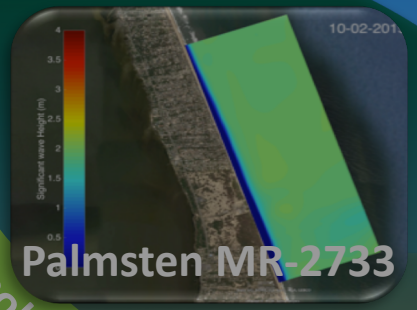
Munitions Mobility

Management Needs

Management Needs



Liu MR-2732



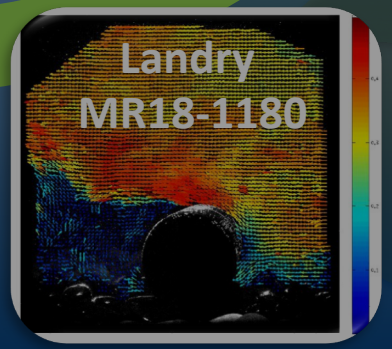
Palmsten MR-2733

Management Tools

Management Tools

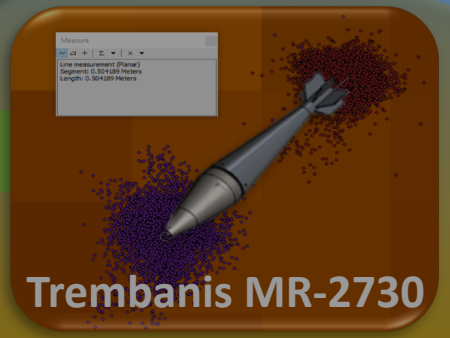
Simulation & Prediction

Laboratory Measurements



Landry MR18-1180

Puleo MR-2503

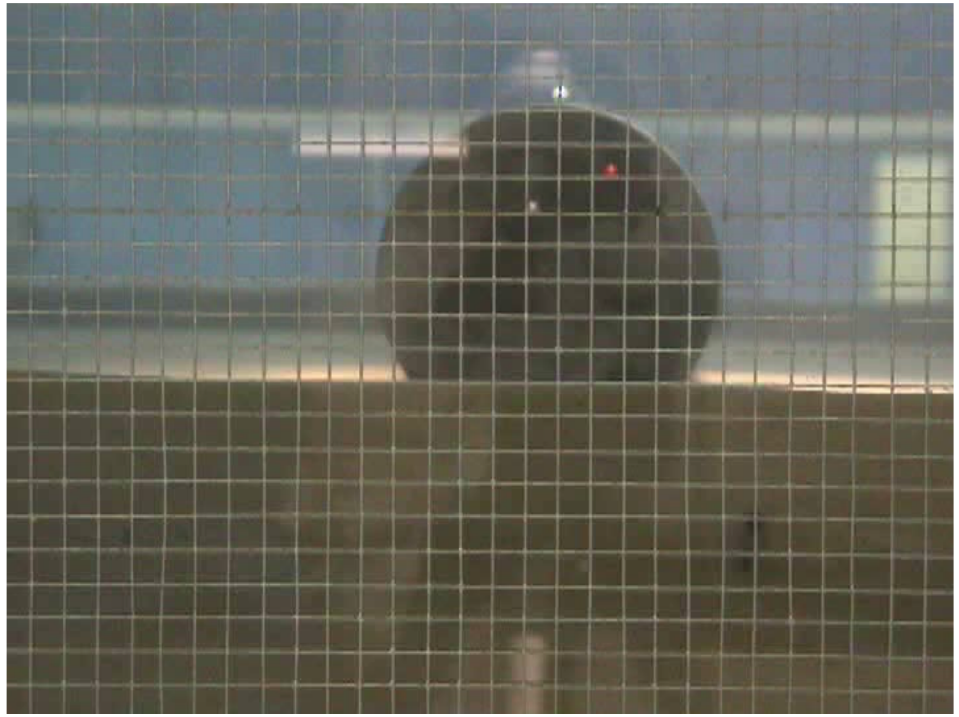


Trembanis MR-2730

Field Observations

Technical background

- Coupled system: flow, sediment bed, and munition



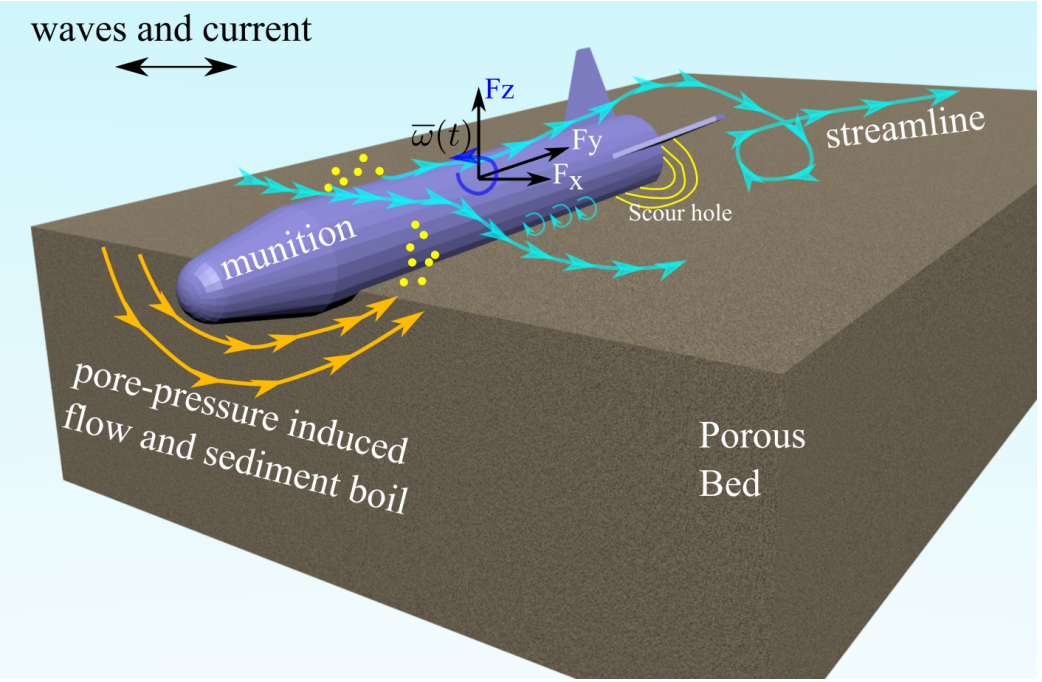
Hydrosystems Lab, University of Illinois

Key physical processes:

- Turbulent flow
- Sediment transport (erosion and scour)
- Liquefaction (pore-pressure build-up)
- 6-DoF rigid body motion (munition)
- Granular sediment movement

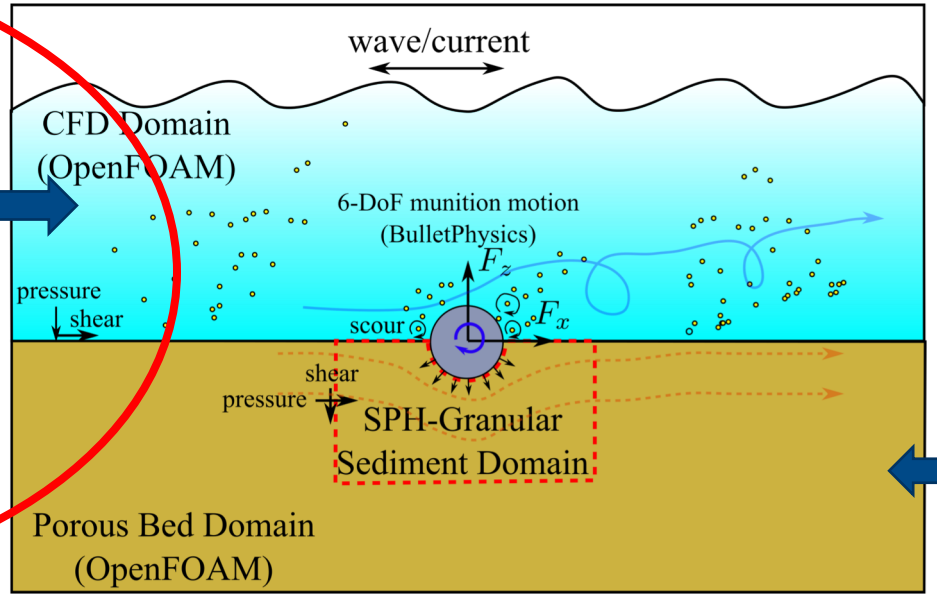
Technical objective

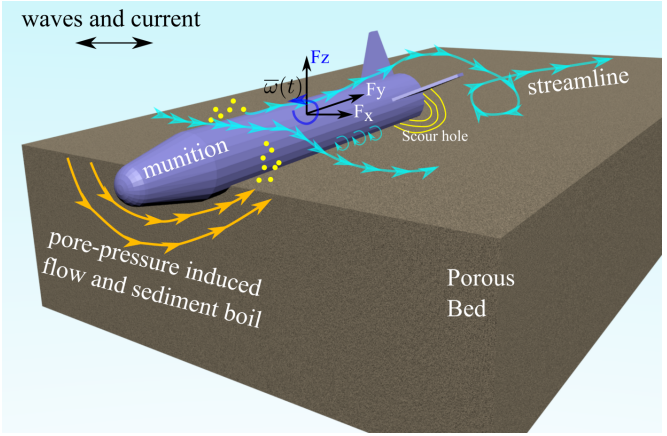
To build a 3D computer model to understand the mechanisms and identify key parameters of the initiation of motion, transport, and burial of underwater munitions.



Comprehensive modeling framework

- 3D scour model for the turbulent flow and sediment transport





- SPH granular sediment solver for the saturated sediment domain

Hydrodynamic force

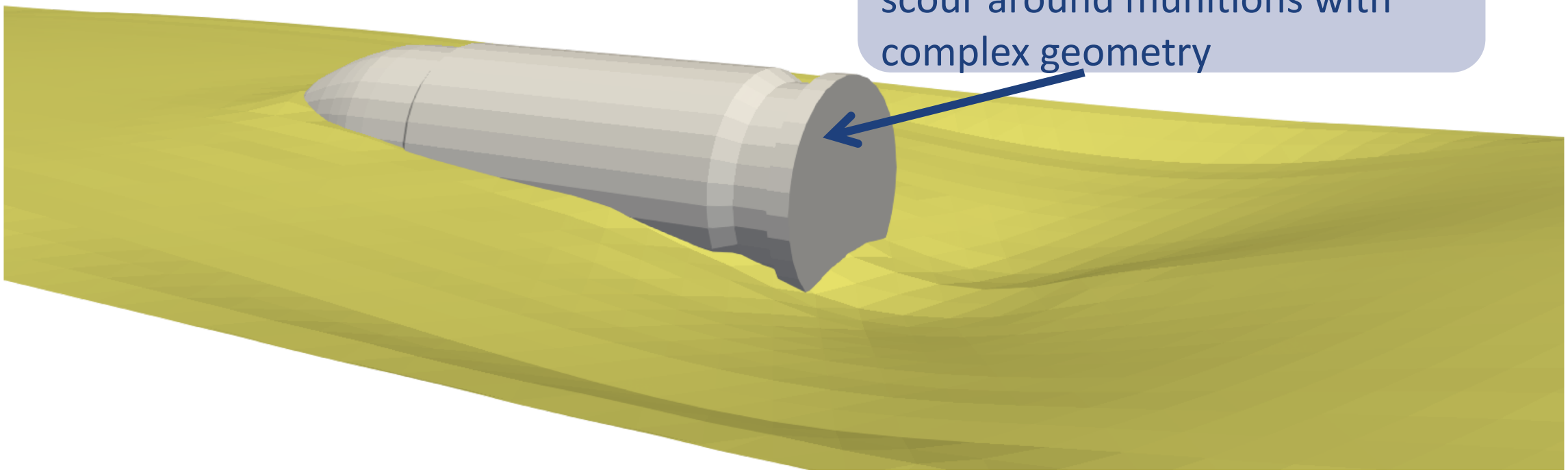
New Position

- Munition 6-DoF motion solver for the motion of munition

Sediment force

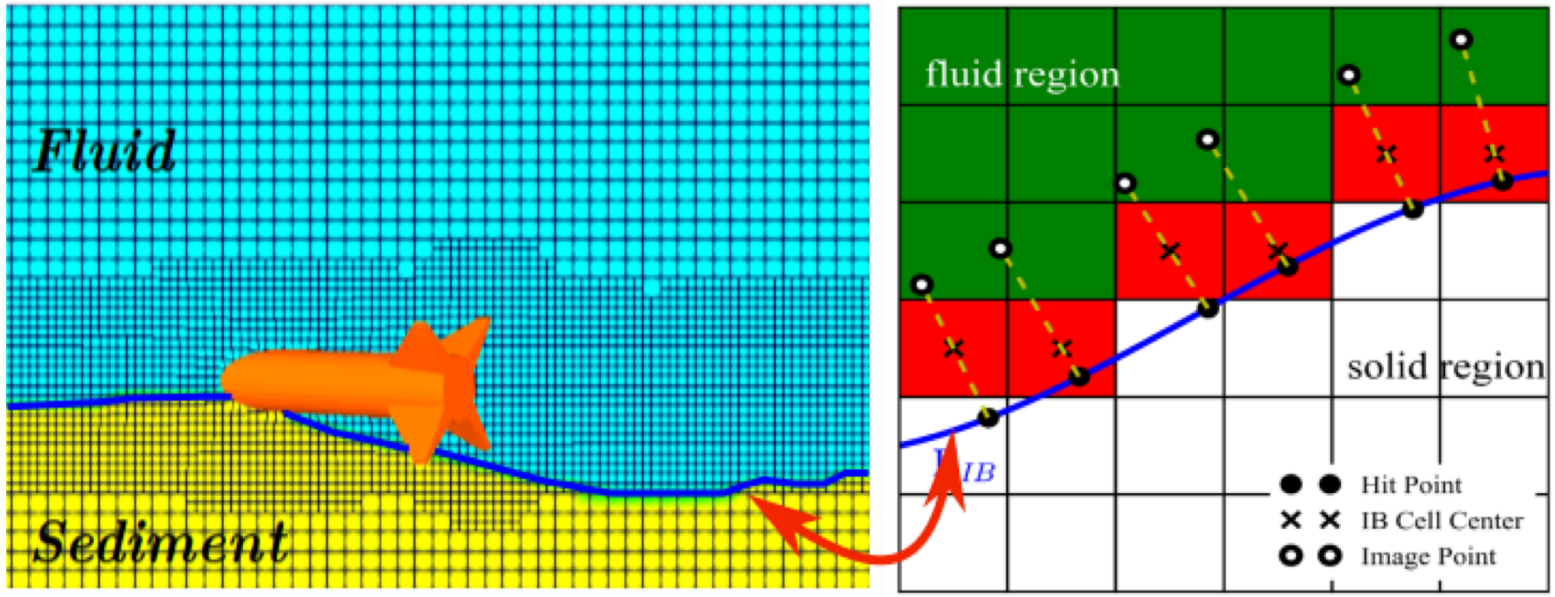
New Position

3D scour model



Very difficult for traditional mesh deformation method for scour around munitions with complex geometry

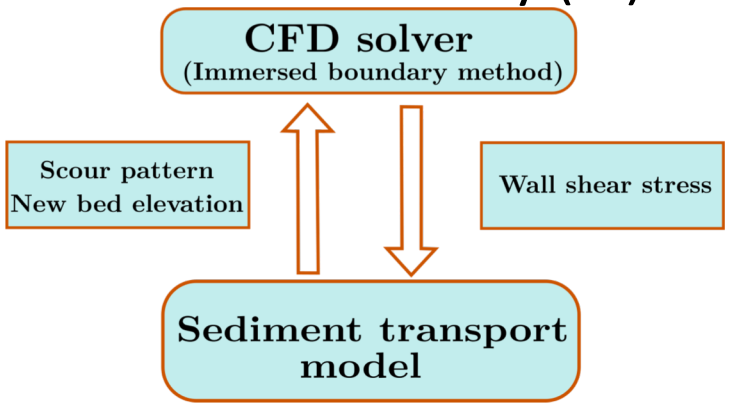
3D scour model: : immersed boundary method



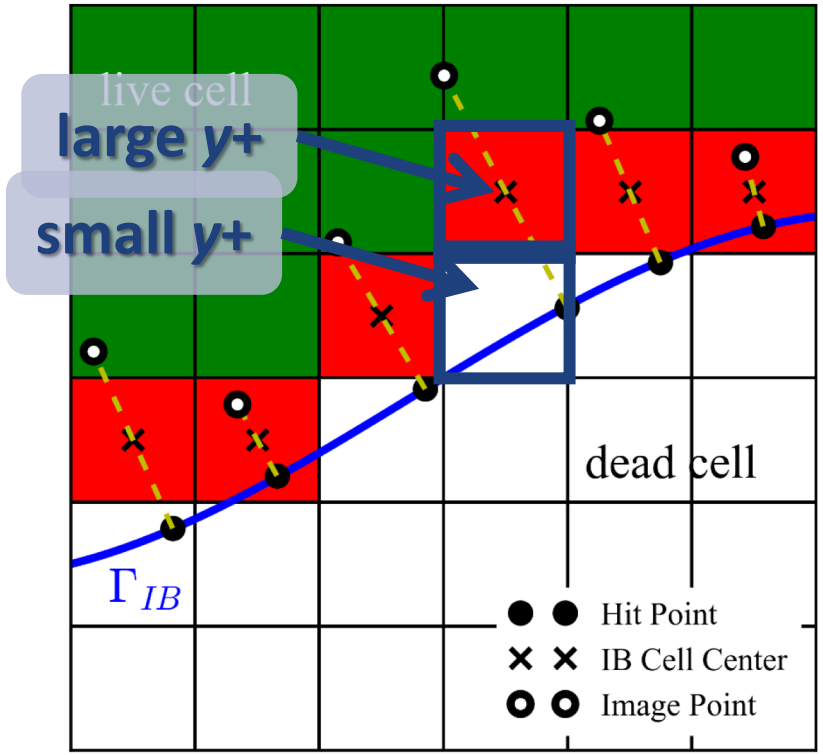
schematic of IB method:

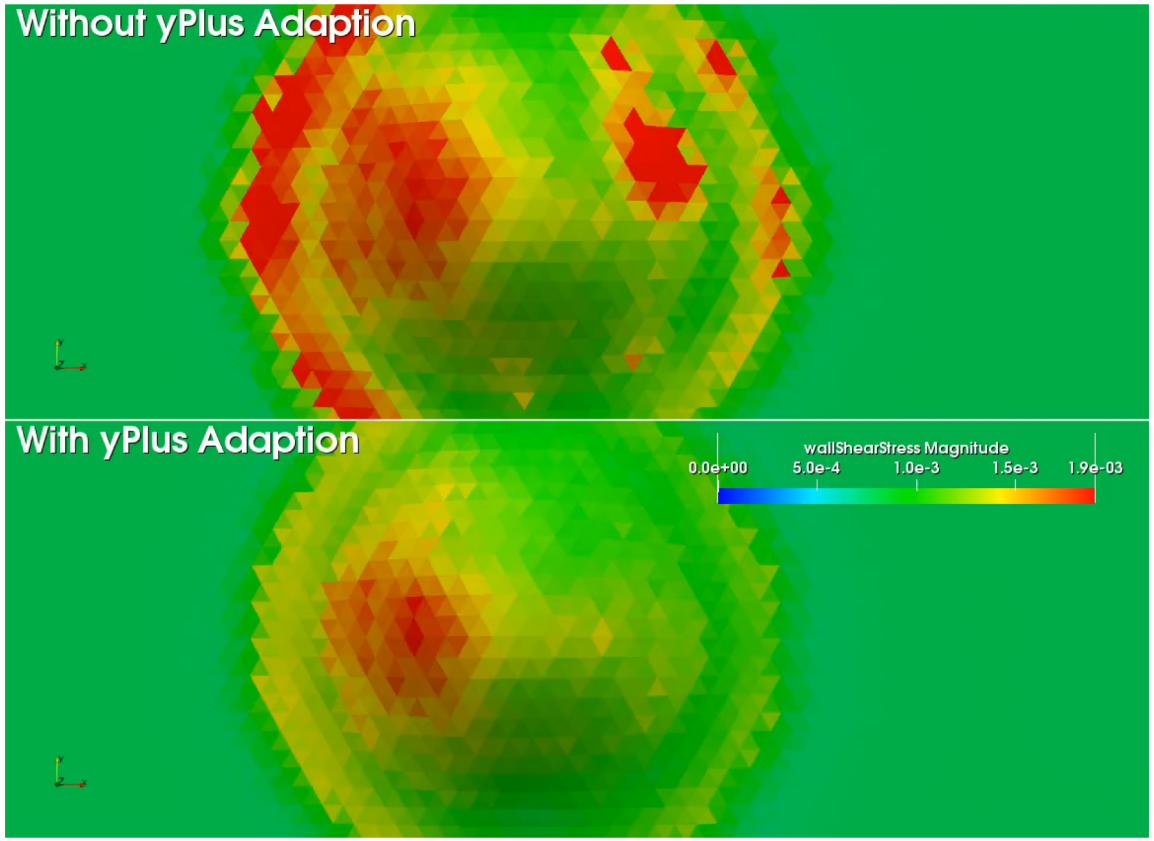
IB cells (red filled)
live cells (green filled)
dead cell (white filled)
Immersed interface (blue curve).

➢ Sediment bed is modeled as an immersed boundary (IB)



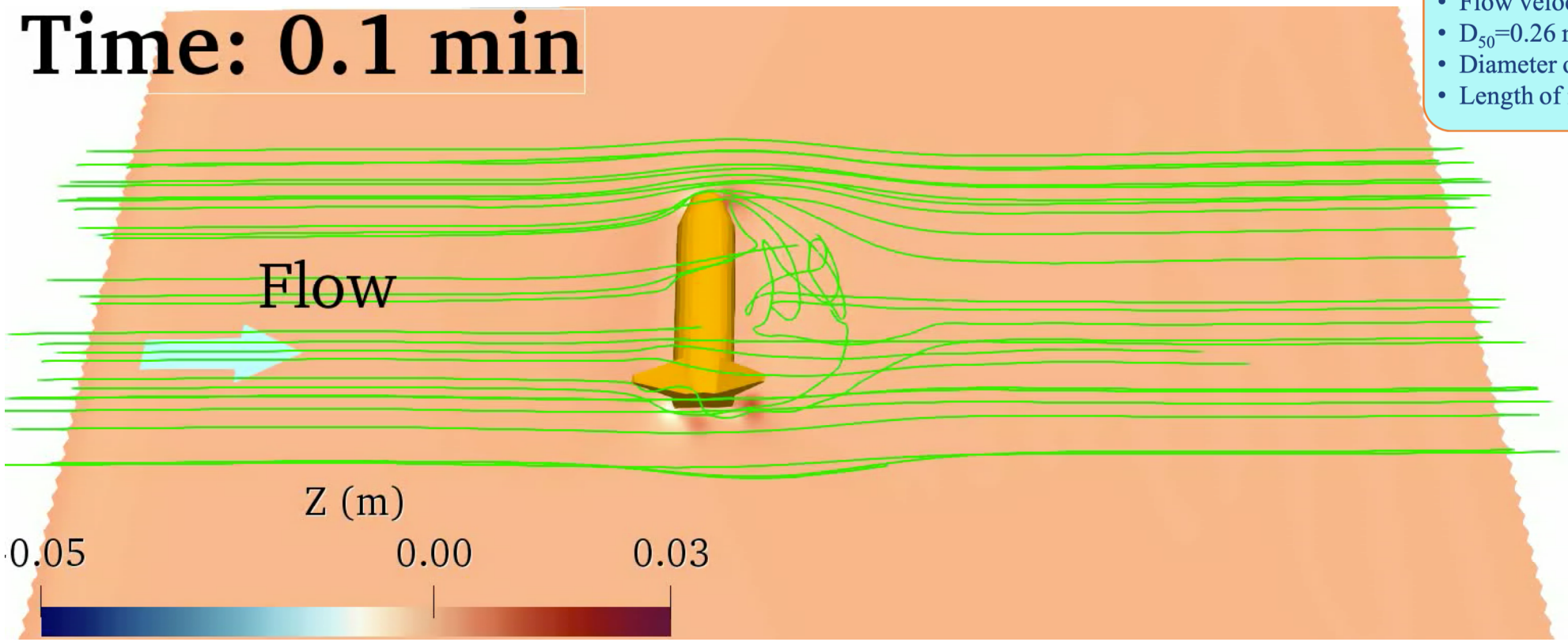
y^+-adaptive IB wall function





Scour model results: scour around a UXO with fins

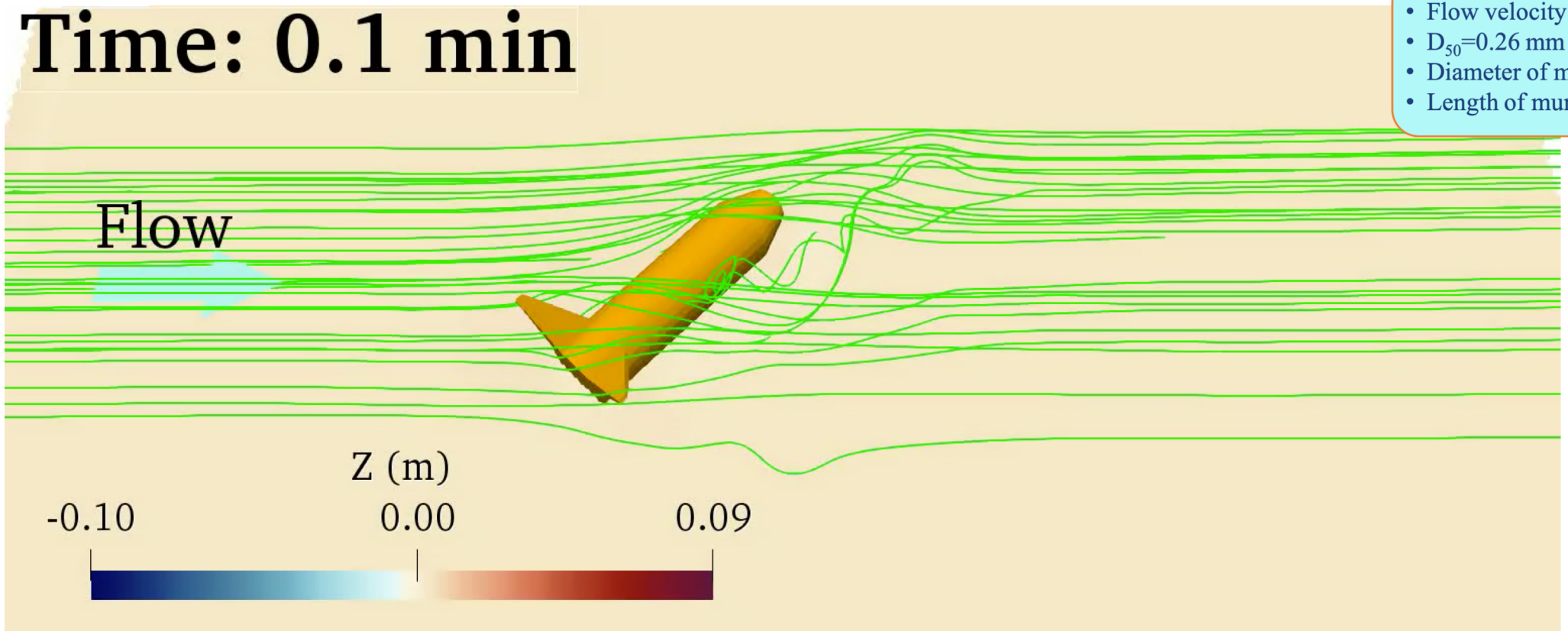
90°



- Flow velocity: 0.5 m/s
- D_{50}=0.26 mm
- Diameter of munition: 0.396 m
- Length of munition: 0.732 m

Scour model results: scour around a UXO with fins

135°



- Flow velocity: 0.5 m/s
- D_{50}=0.26 mm
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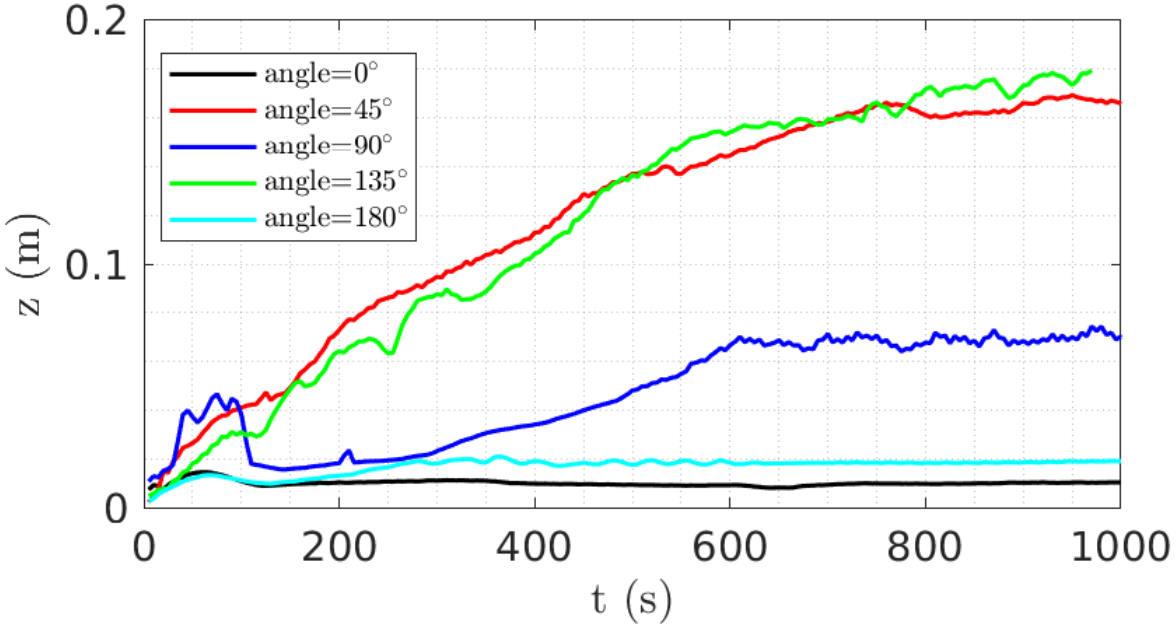
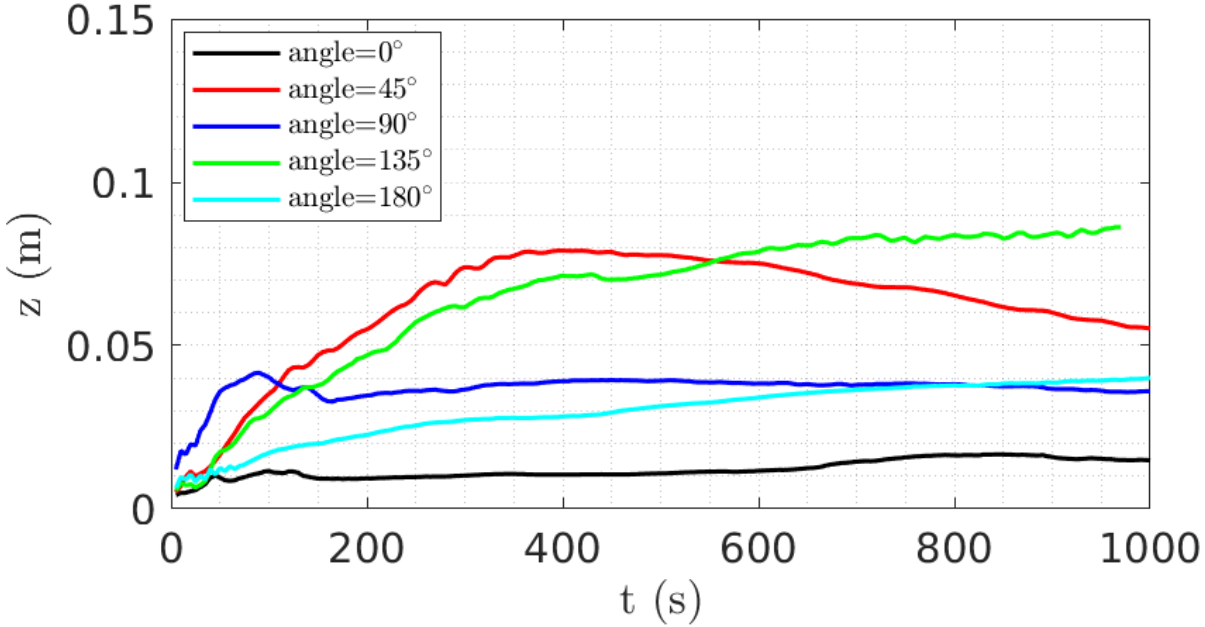
Scour analysis

- ***Deposition depth***



- ***Scour depth***



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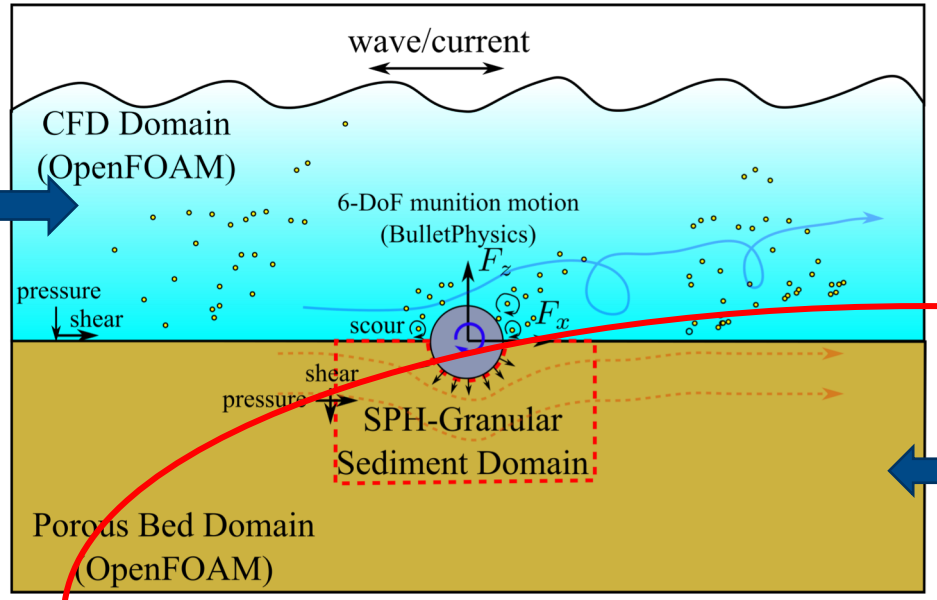

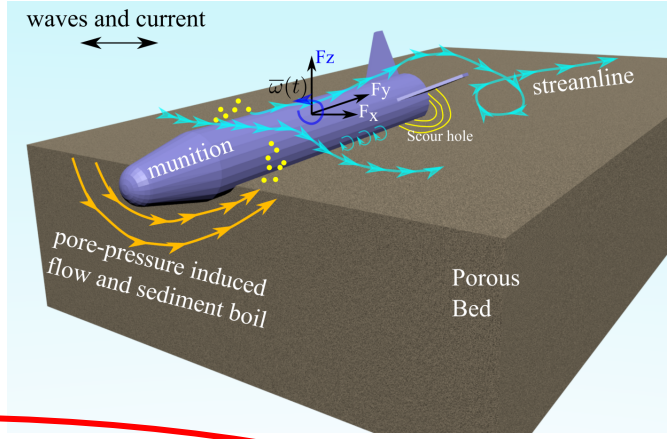

Hydrodynamic force

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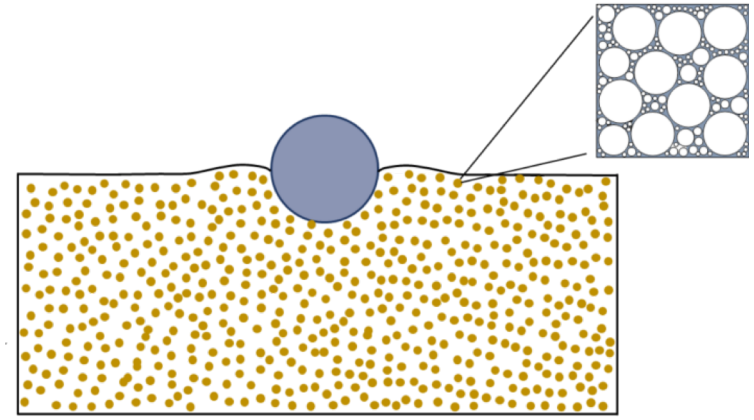
Smoothed particle hydrodynamics granular model

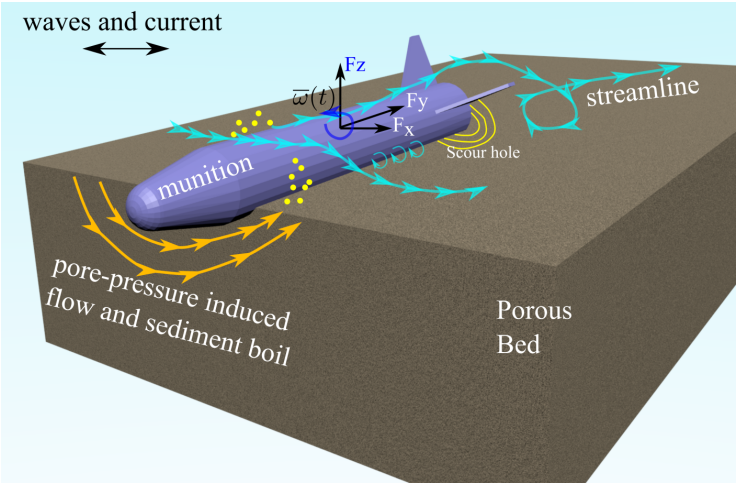
Saturated sediment is modeled with the Herschel-Bulkley-Papanastasiou (HBP) model

- Viscous – Plastic
- Shear thinning or thickening



To model munition motion:

- Force and moment on munition
- 6-degree of freedom motion



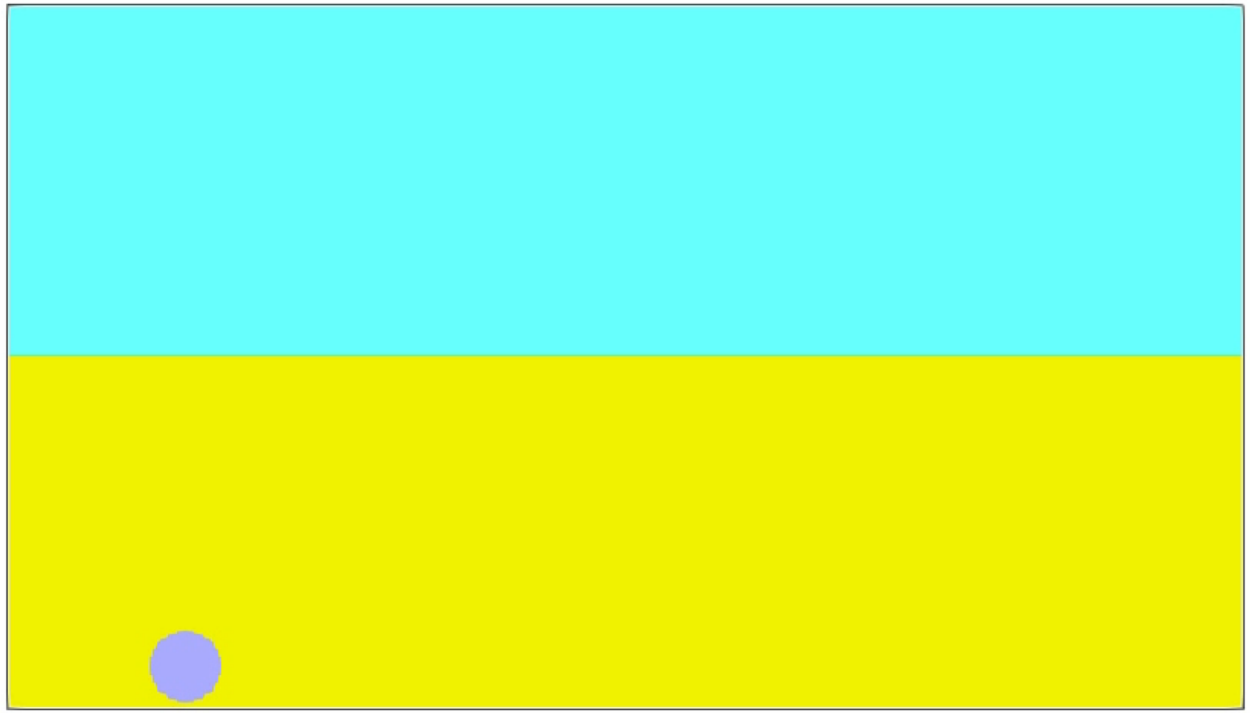
Munition mobility demonstration

Density effect

Munition on bed under oscillatory shaking

frequency = 3 Hz, amplitude = 5 cm

$$\frac{\rho_{munition}}{\rho_{water}} = 1.2, \ \frac{\rho_{sediment}}{\rho_{water}} = 2.65$$

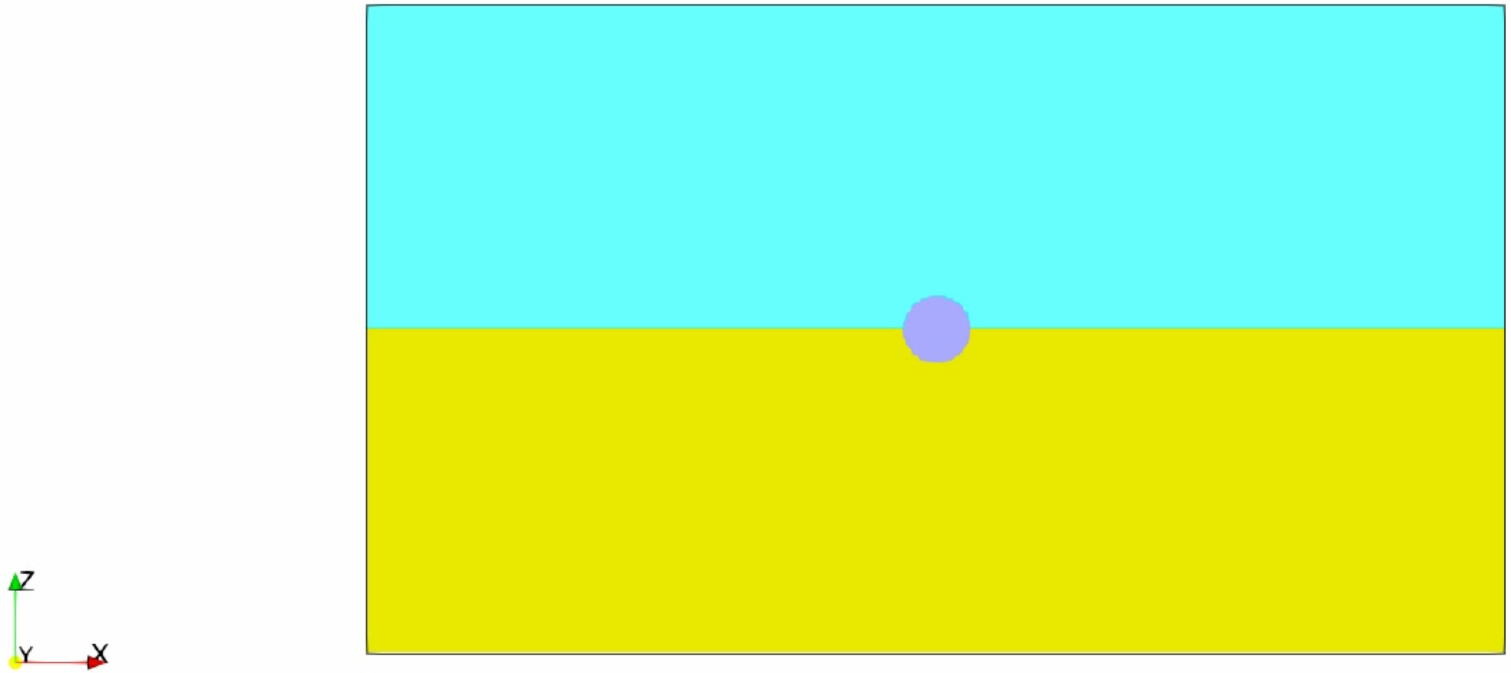


Density effect

Munition on bed under oscillatory shaking

frequency = 3 Hz, amplitude = 5 cm

$$\frac{\rho_{munition}}{\rho_{water}} = 4.0, \quad \frac{\rho_{sediment}}{\rho_{water}} = 2.65$$

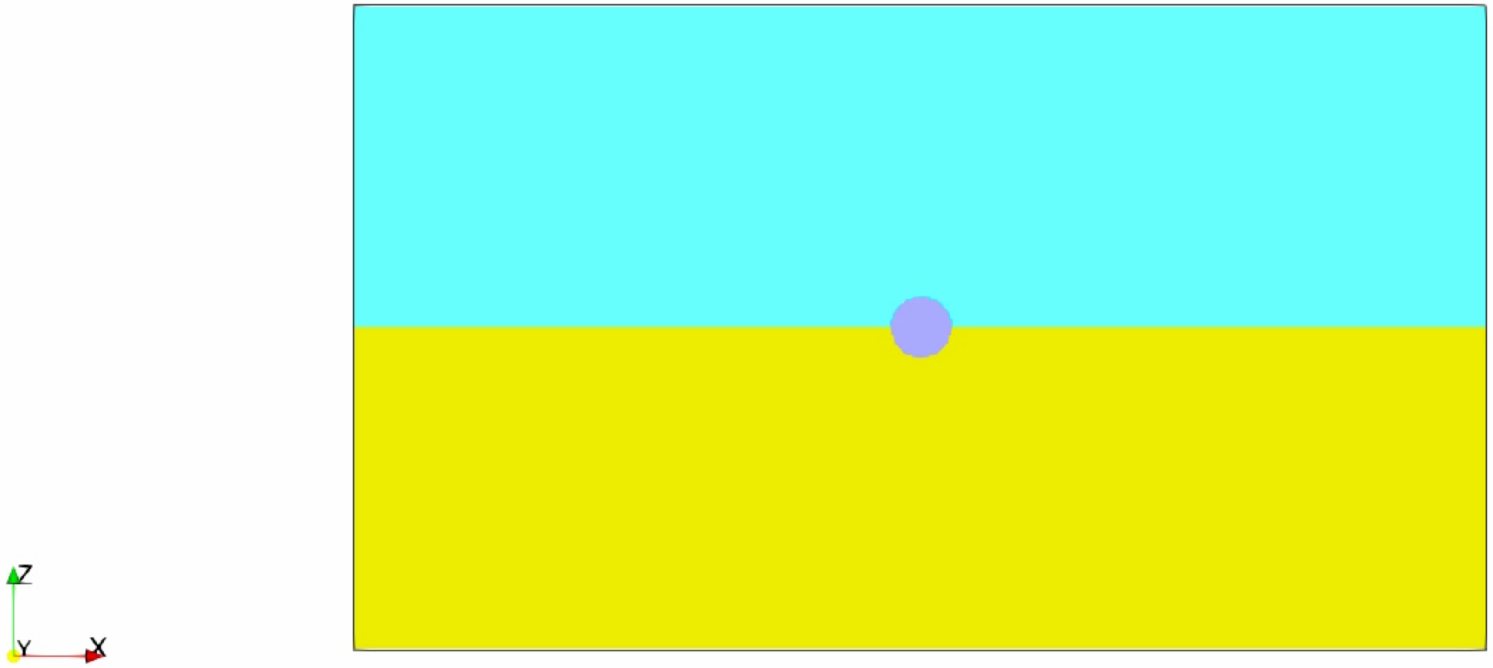


Density effect

Munition on bed under oscillatory shaking

frequency = 3 Hz, amplitude = 5 cm

$$\frac{\rho_{munition}}{\rho_{water}} = 7.8, \quad \frac{\rho_{sediment}}{\rho_{water}} = 2.65$$



Density effect

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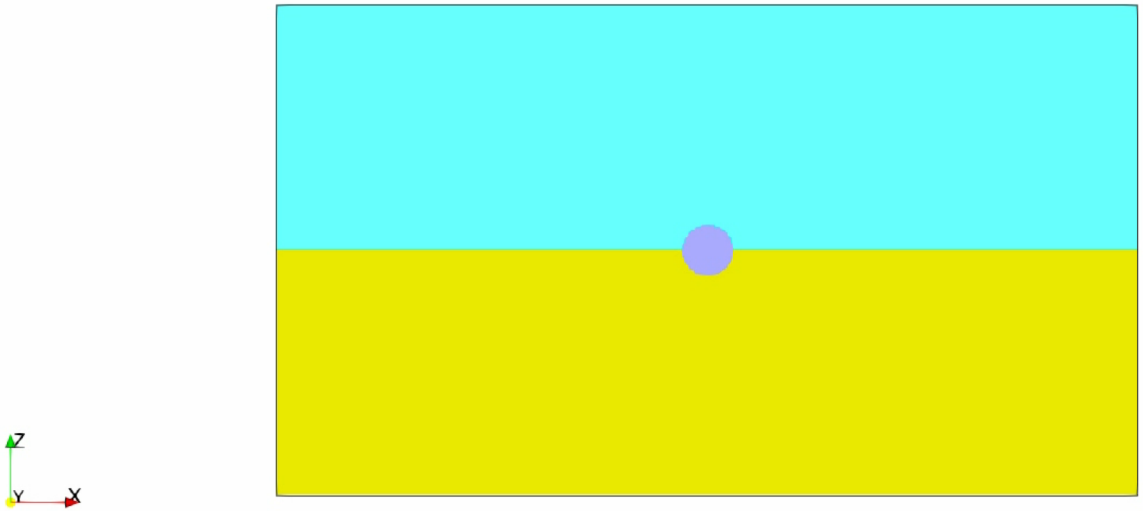
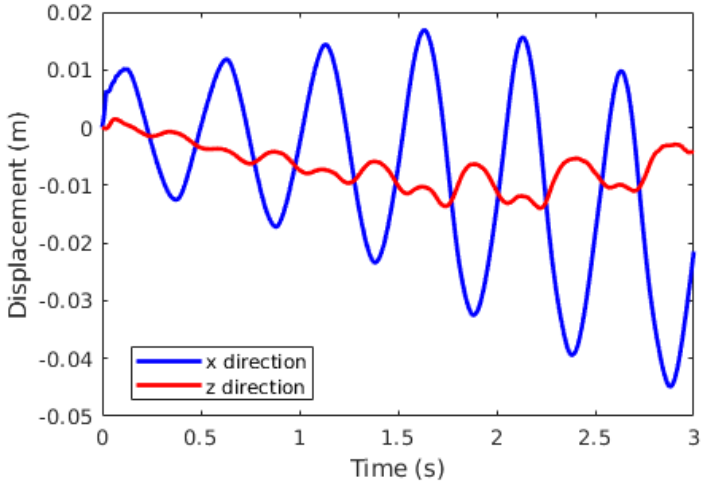
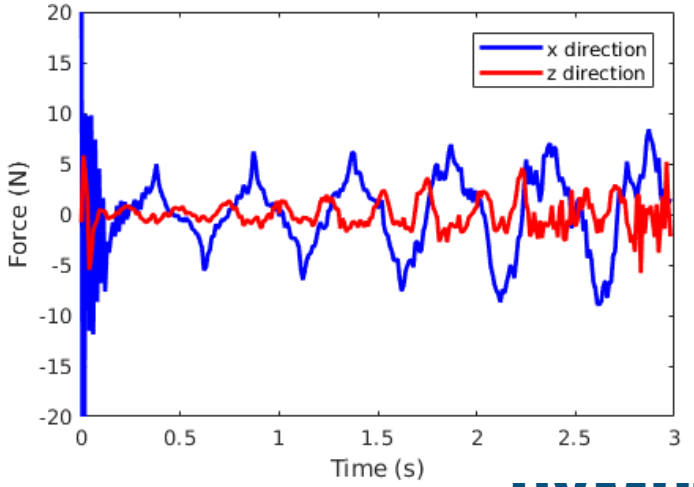
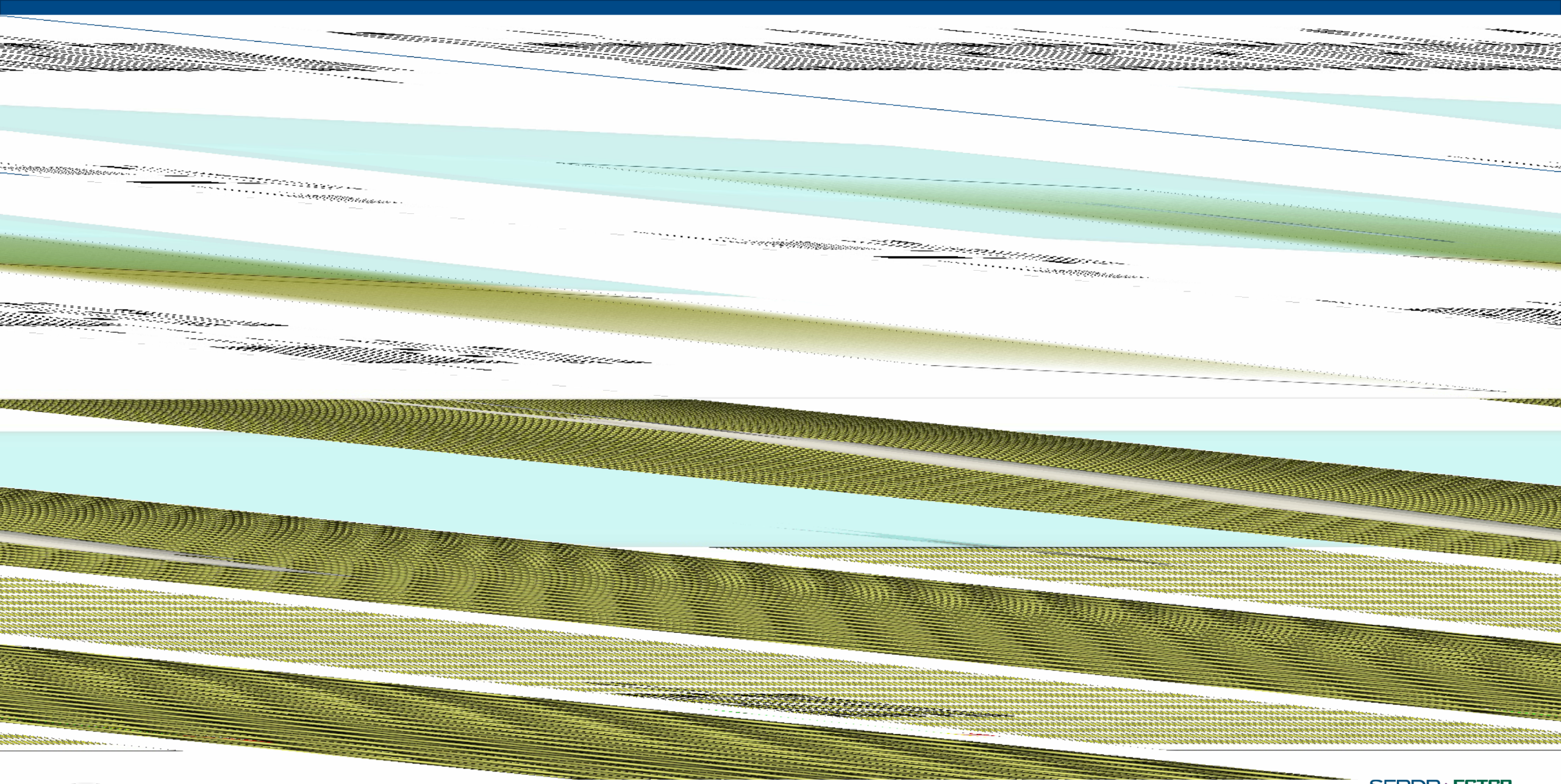
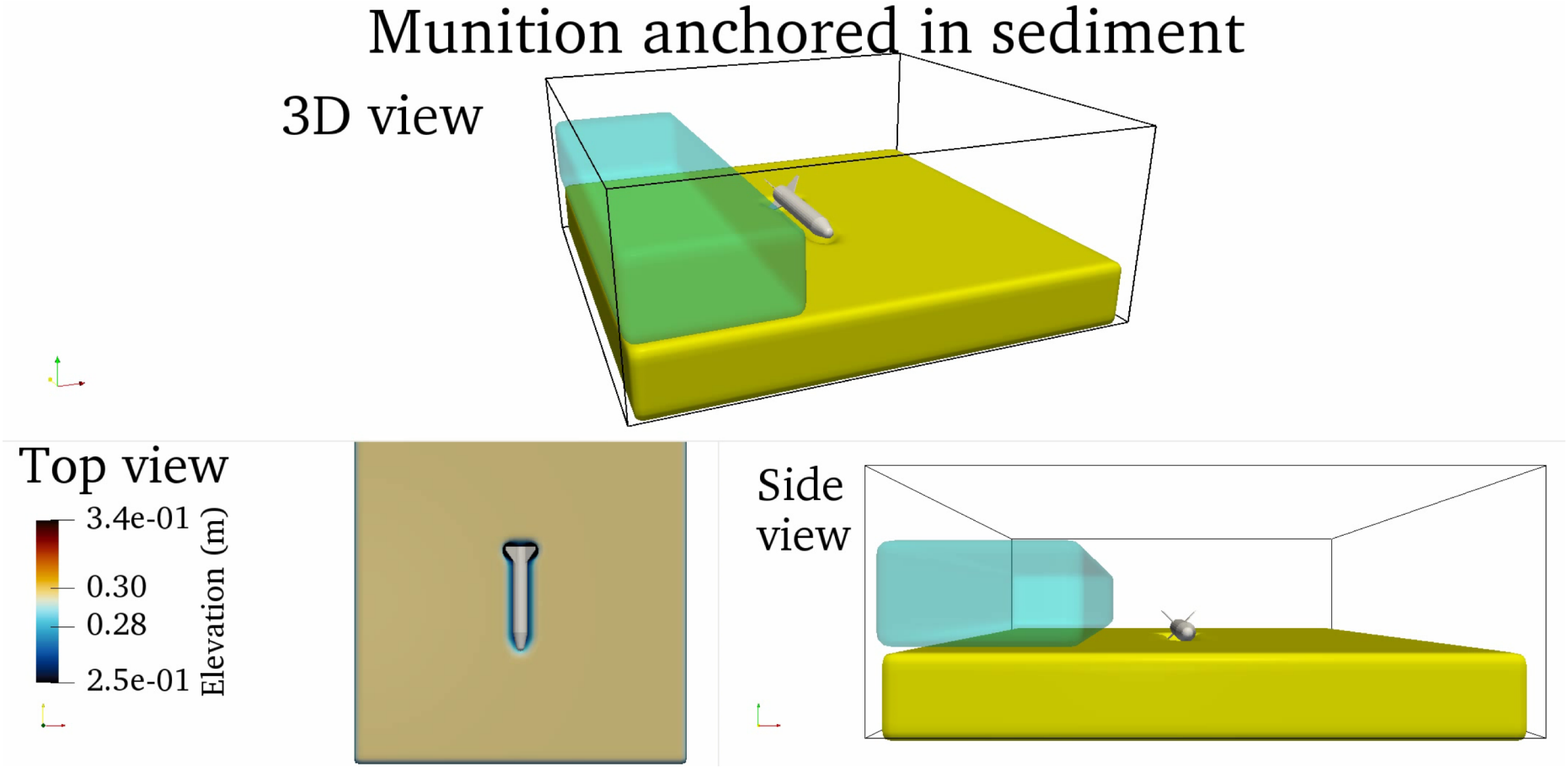




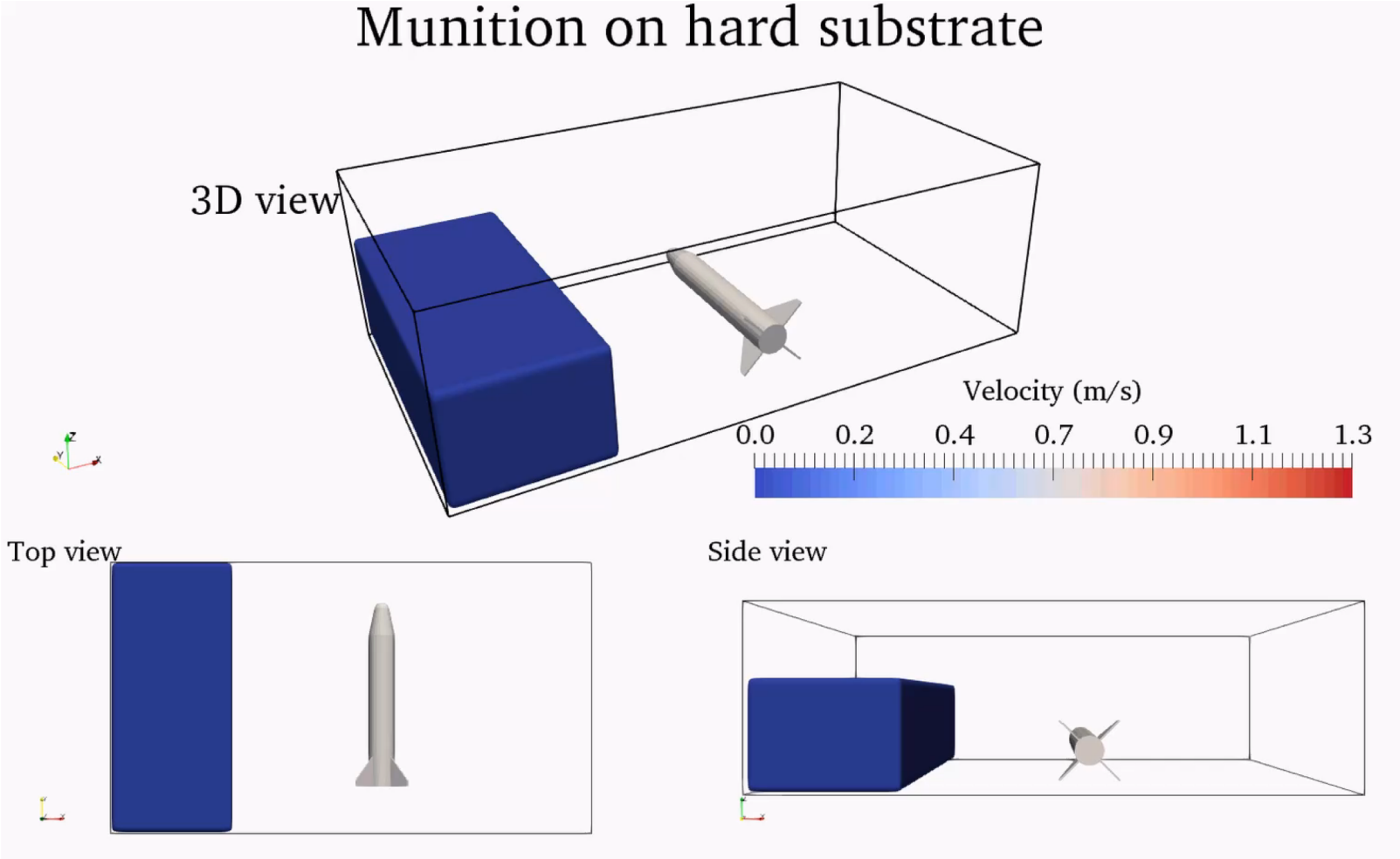




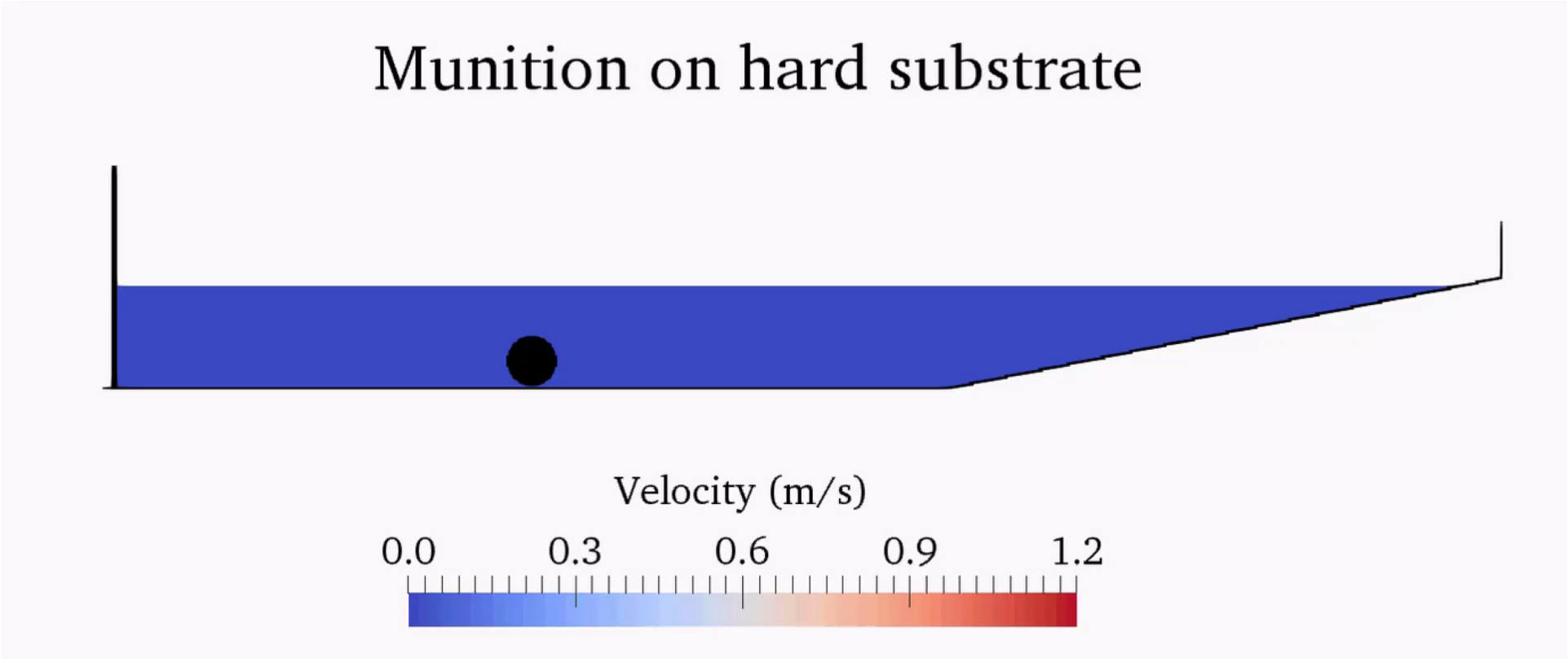
Munition mobility



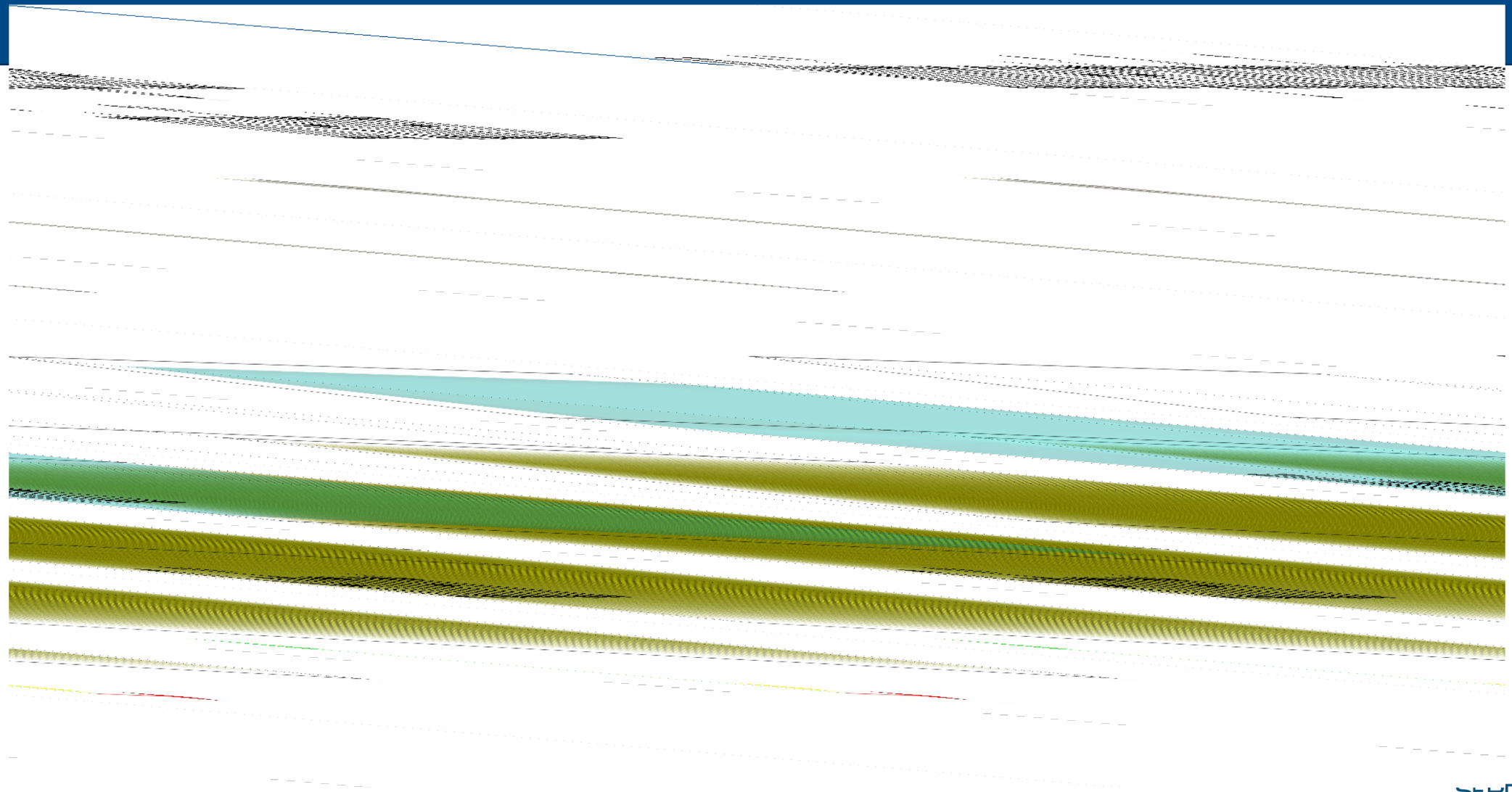
Munition mobility



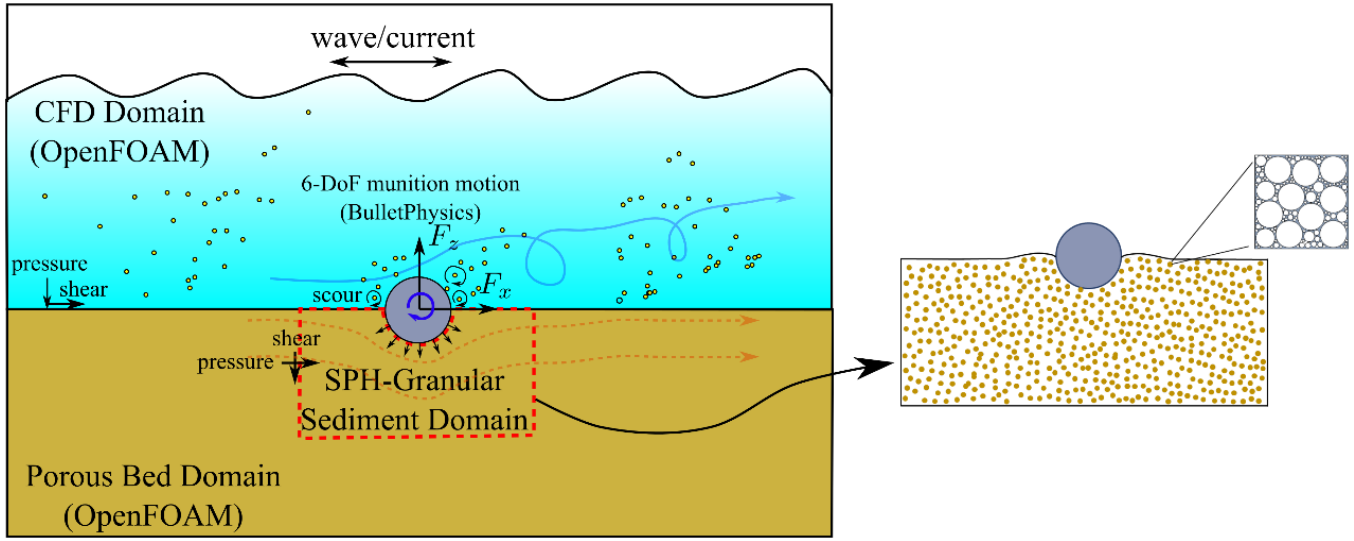
Munition mobility

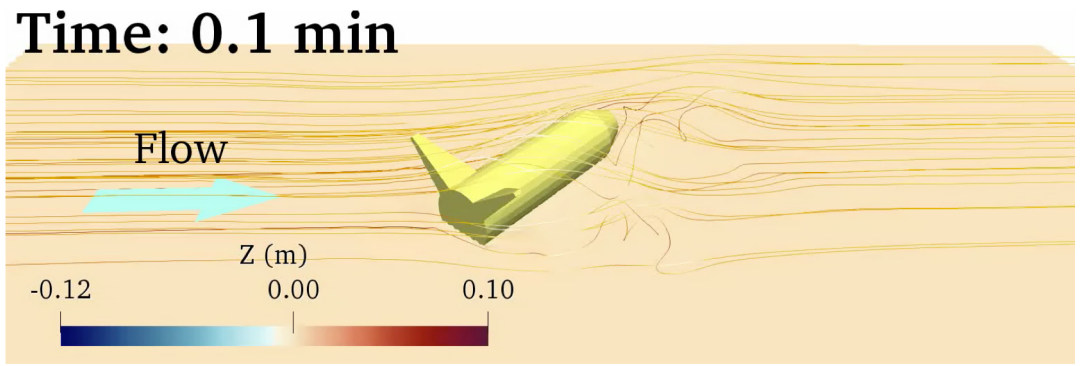


Munition entry



Summary

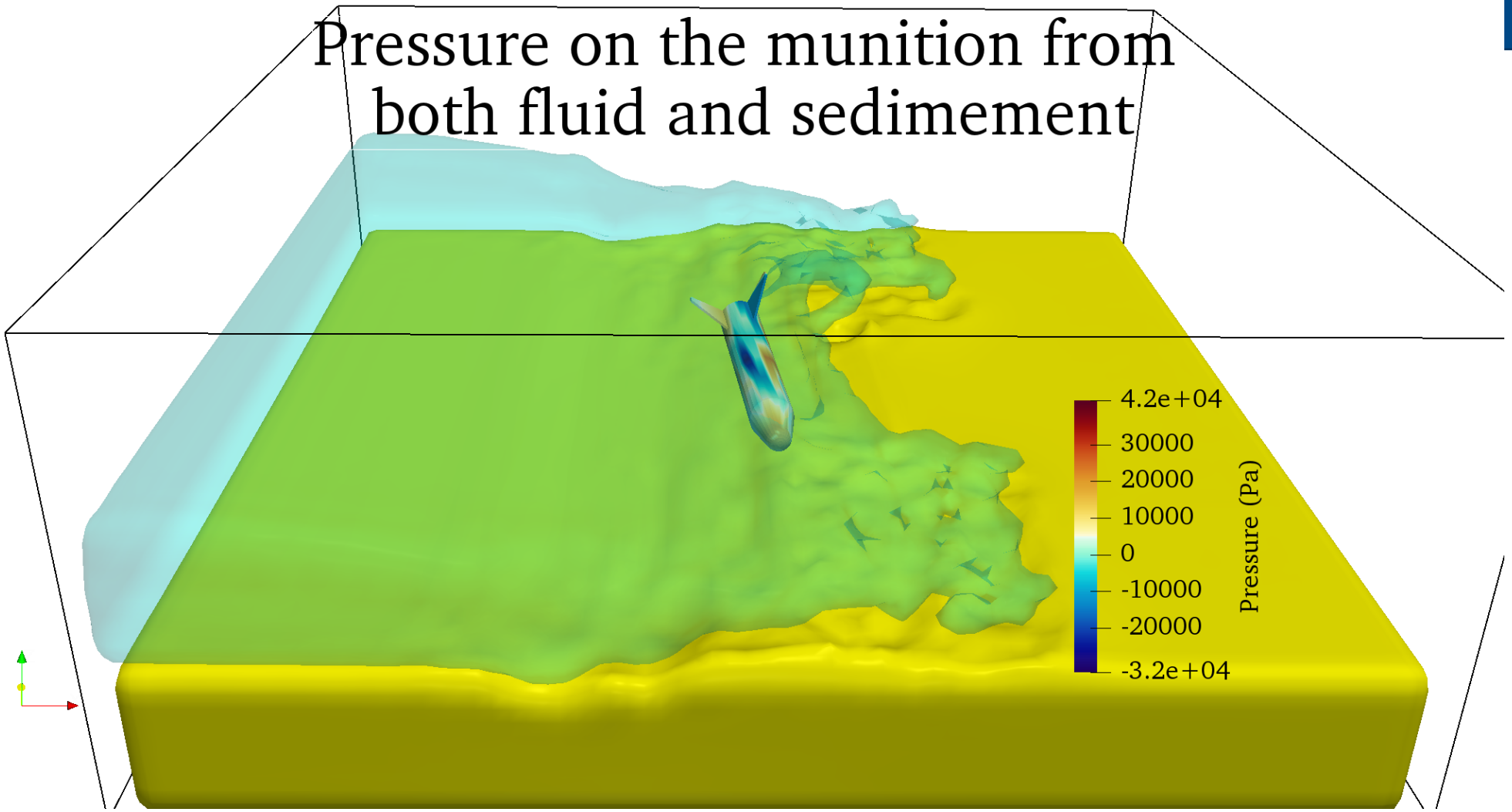

wave/current
CFD Domain
(OpenFOAM)
6-DoF munition motion
(BulletPhysics)
F_z
F_x
pressure
shear
scour
shear
pressure
SPH-Granular
Sediment Domain
Porous Bed Domain
(OpenFOAM)


Time: 0.1 min
Flow
Z (m)
-0.12
0.00
0.10

Water velocity (m/s)
0.00
1.00
2.15
Bed elevation (m)
0.21
0.25
0.33

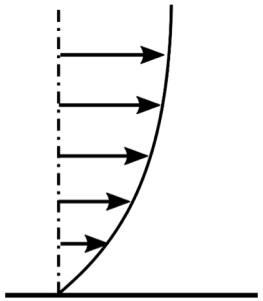
Backup slides

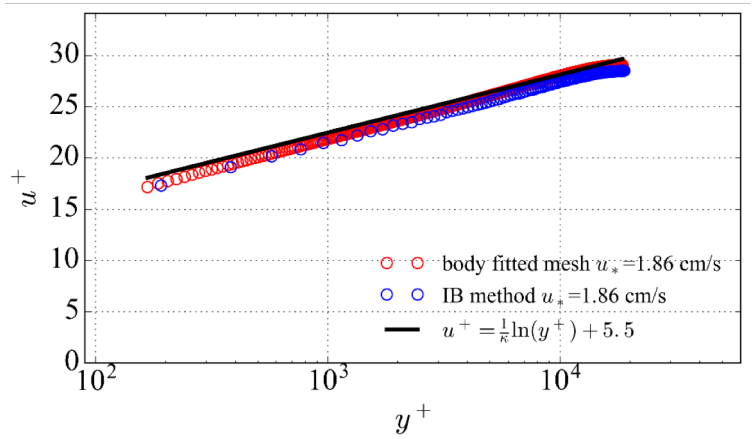
Pressure distribution on munition

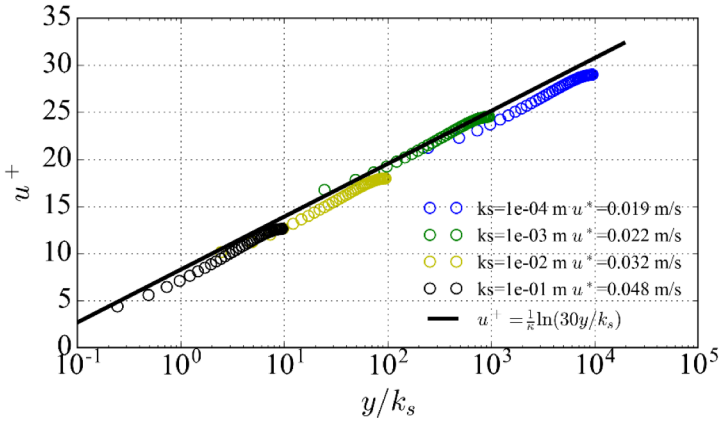


Validation of hydrodynamic part

1D

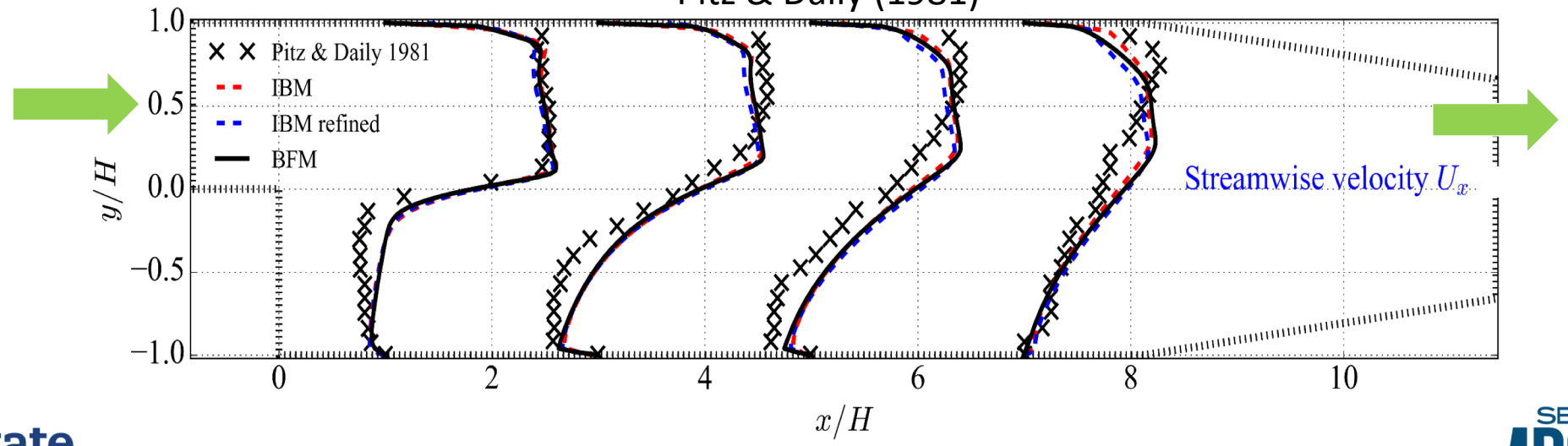






2D

Pitz & Daily (1981)



Basic concept of SPH

- Integral representation of a field function:

$$\langle f(\mathbf{x})\rangle = \int_{\Omega} f(\mathbf{x}')W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'$$

- Smoothing function should satisfy:
  - Normalization condition

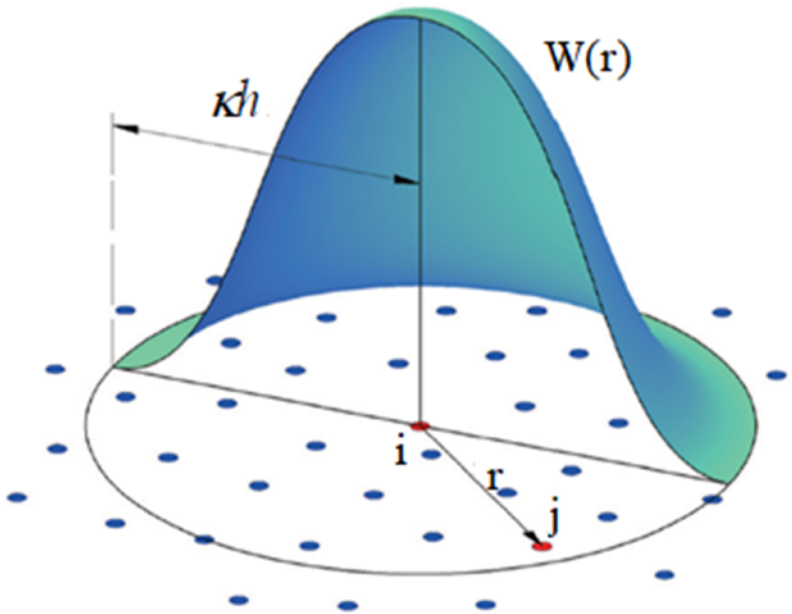
$$\int_{\Omega} W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}' = 1$$

  - Delta function property

$$\lim_{h\to 0} W(\mathbf{x}-\mathbf{x}',h) = \delta(\mathbf{x}-\mathbf{x}')$$

  - Compact support condition

$$W(\mathbf{x}-\mathbf{x}',h) = 0 \qquad when\ |\mathbf{x}-\mathbf{x}'| > kh$$



Particle approximation in SPH method

Liquid phase model

- Governing equations (Continuity and momentum):

$$\frac{D\rho}{Dt} = -\rho \frac{\partial v^{\alpha}}{\partial x^{\alpha}}$$

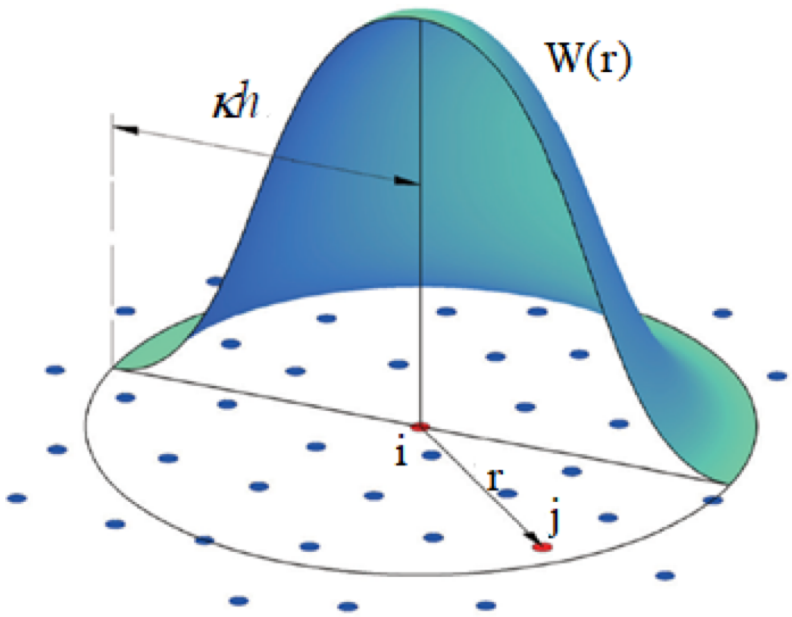
$$\frac{Dv^{\alpha}}{Dt} = \frac{1}{\rho}\frac{\partial \sigma^{\alpha\beta}}{\partial x^{\beta}} + g^{\alpha}$$

- Translated into SPH form:
  - Continuity

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j (v_i^{\alpha} - v_j^{\alpha}) \frac{\partial W_{ij}}{\partial x_i^{\alpha}}$$

  - Momentum

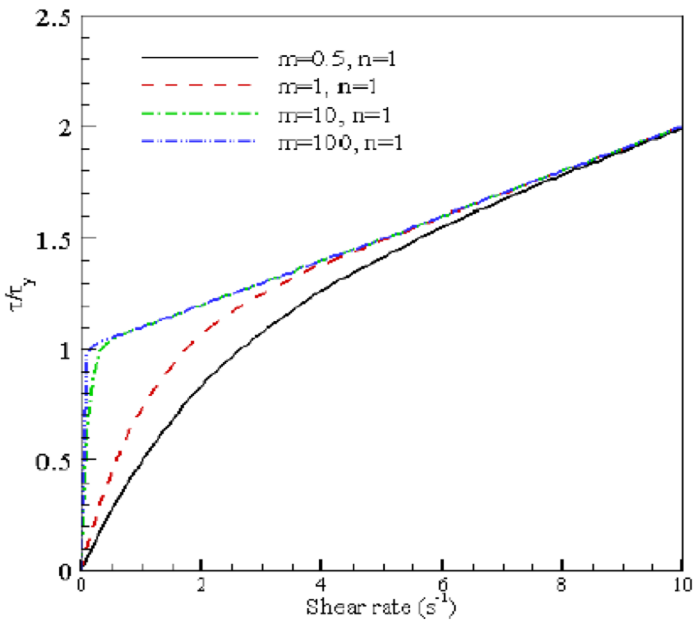
$$\frac{Dv_i^{\alpha}}{Dt} = \sum_{j=1}^{N} \left(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_j^{\alpha\beta}}{\rho_j^2}\right) \frac{\partial W_{ij}}{\partial x_i^{\beta}} + g_i^{\alpha}$$



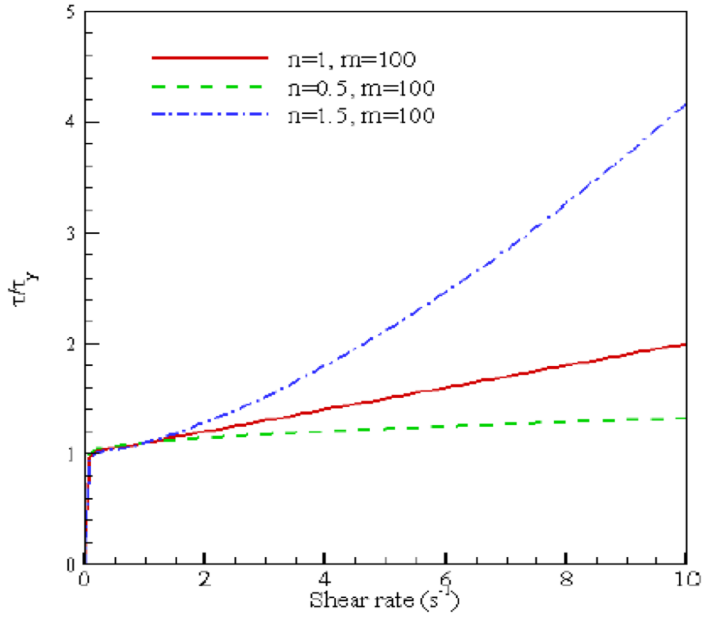
Particle approximation in SPH method

Sediment phase model

- Sediment constitutive equation:
  - Herschel-Bulkley-Papanastasiou (HBP): $\phi_1 = \frac{|\tau_y|}{\sqrt{\mathrm{II}_D}}\left[1 - e^{-m\sqrt{\mathrm{II}_D}}\right] + 2\mu\left|4II_D\right|^{\frac{n-1}{2}}$
    - Viscous – Plastic (m exponential growth)
    - Shear thinning or thickening (n power law)



(a)



(b)

Yield criteria

- Drucker-Prager (DP) yield criterion:

$$\sqrt{J_2} - |\tau_y| = 0$$

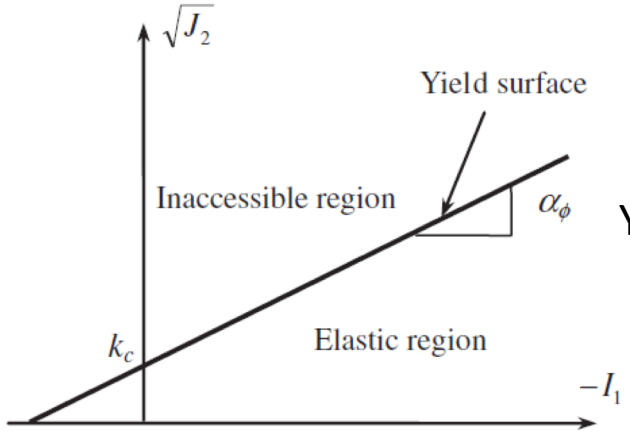
- Apply the yield criterion:

$$|\tau_y| = -\alpha I_1 + \kappa$$

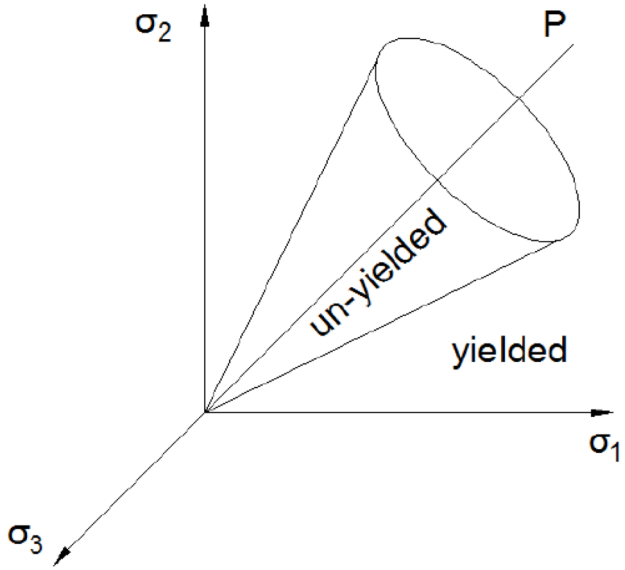
- Yielding occurs when:

$$-\alpha I_1 + \kappa \le 2\mu\sqrt{II_D}$$

$$a = -\frac{2\sqrt{3}\sin(\phi)}{3-\sin(\phi)} \qquad \kappa = \frac{2\sqrt{3}\cos(\phi)}{3-\sin(\phi)}$$



Yield criteria in $(-I_1, \sqrt{J_2})$ plane



Drucker-Prager (DP) yield surface in principal stress space

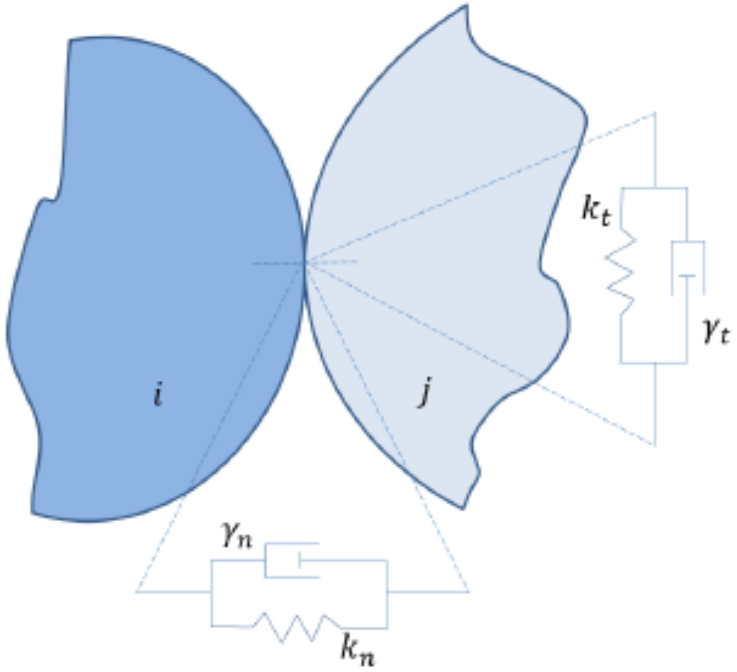
6-DoF motion and DEM contact

- 6-DoF rigid body dynamics:
  - Force balance: $$M\frac{d\boldsymbol{V}}{dt}=\sum_{k\in BPs}m_k\boldsymbol{f}_k$$
  - Inertial equation: $$I\frac{d\boldsymbol{\Omega}}{dt}=\sum_{k\in BPs}m_k\left(\boldsymbol{r}_k-\boldsymbol{R}_0\right)\times\boldsymbol{f}_k$$
- DEM contact:
  - Normal force:

$$\mathbf{F}_{n,ij}=\mathbf{F}_n^r+\mathbf{F}_n^d=k_{n,ij}\delta_{ij}^{3/2}\mathbf{e}_{ij}^n-\gamma_{n,ij}\delta_{ij}^{1/2}\dot{\delta}_{ij}\,\mathbf{e}_{ij}^n$$

  - Tangential force:

$$\mathbf{F}_{t,ij}=\mathbf{F}_t^r+\mathbf{F}_t^d=k_{t,ij}\delta_{ij}^{t}\mathbf{e}_{ij}^t-\gamma_{t,ij}\delta_{ij}^{t}\dot{\delta}_{ij}\,\mathbf{e}_{ij}^t$$



Collision between particles in DEM