Novel Eulerian Two-phase Numerical Simulation Tool for Scour Burial of Munitions

MR20-1478

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Final Debrief

January 13, 2026

Project Team

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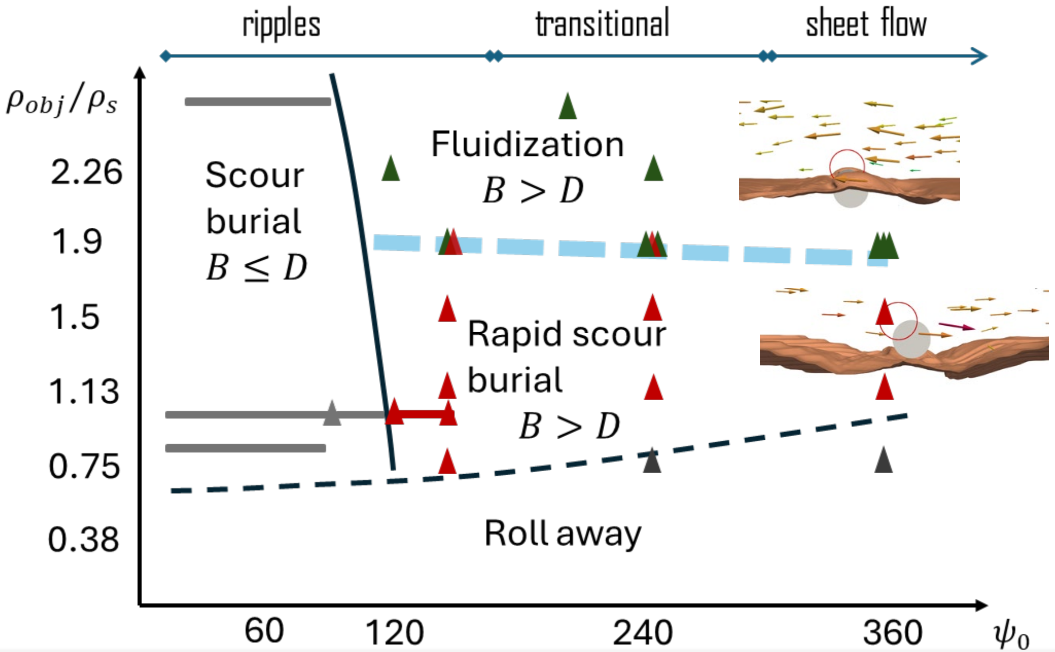
— The two-phase model **SedFoam** has been jointly developed by UD and U. Grenoble since 2015

Bottom Line Up Front

- *The high-fidelity Eulerian two-phase model,* ***SedFoam****, has been successfully developed to simulate self-burial dynamics of UXOs.*
- *We recommend the use of the mobility number ψ_0 and UXO relative density $R = \rho_{obj}/\rho_s$ as primary nondimensional parameters to quantify UXO burial dynamic.*
- *The energetic self-burial processes that may lead to full burials exist when the mobility number $\psi_0 > 120$ (θ_0>0.4) and the relative UXO density $R \gtrsim 1$.*
- *Wave angle and period are of secondary importance in energetic self-burial processes.*
- *Future effort should focus on the effect of initial burial depth and bedforms.*



Technical Objectives

1) The full implementation of a Eulerian two-phase model SedFoam for simulating UXO mobility and self-burial dynamics.
2) Understanding the mechanisms driving full burial and the role of UXO density in controlling the mobility and burial dynamics of UXOs.
3) Carrying out field-relevant scenario simulations to fill the parameter space and provide simulation data to fill data gaps in the data-driven model.

Technical Approach

Task 1:
Improve soil stress closures in SedFoam [5],[6],[13]

Task 2:
UXO-Sediment-Fluid Interaction with 6 degrees of freedom (6DoF) [7]

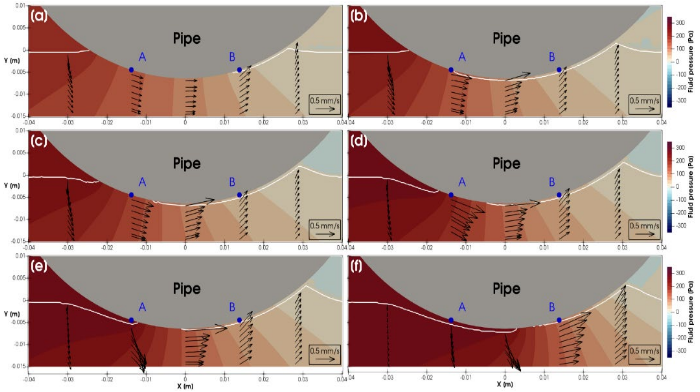
Task 3:
Model Validation with lab experiments
- Sheet flows, ripples, scour [3], [4], [10], [11]
- UXO mobility experiment of Rennie et al. (2017)
- UXO burial experiment of Dimer & Garcia (2007)

Task 4:
Investigating field observed scenarios
- energetic self-burial proccesses
- Effect of UXO density

Task 5:
Simulations to fill data gaps in data-driven models (e.g., Rennie 2017)

Technical Approach

- SedFoam, created in OpenFOAM, solves the water and sediment coupled dynamics using their own mass and momentum equations.
- Avoid artificial separation of sediment transport into bedload and suspended load layers; useful tool to simulate flow-sediment-structure interaction.
- Successful implementation of the capability to simulate object-sediment-fluid interaction with six-degree-of-freedom (6-DoF) [7].



Tsai et al. (2022) [13] Onset of scour via piping

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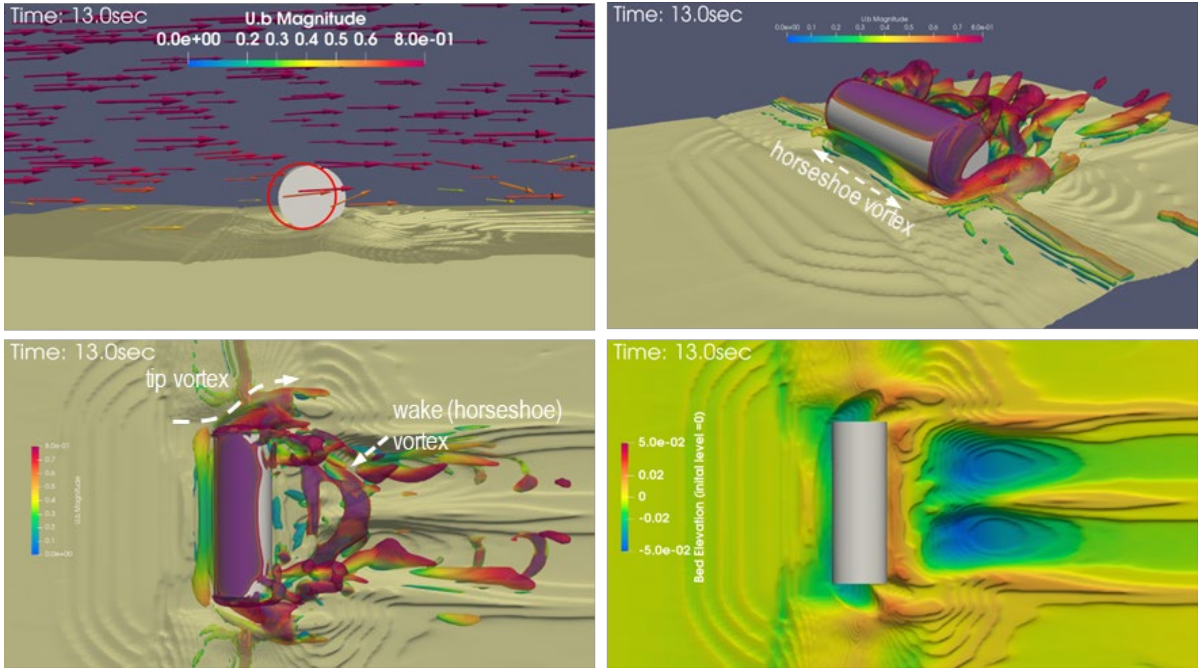
Results - mobility and initial burial driven by accelerating currents

- Successful validation for UXO mobility and initial burial driven by a unidirectional accelerating current (Rennie et al. 2017).
- Flow separations and resulting tip vortices and lee-wake vortex cause major scour developments that prevent further object movement.



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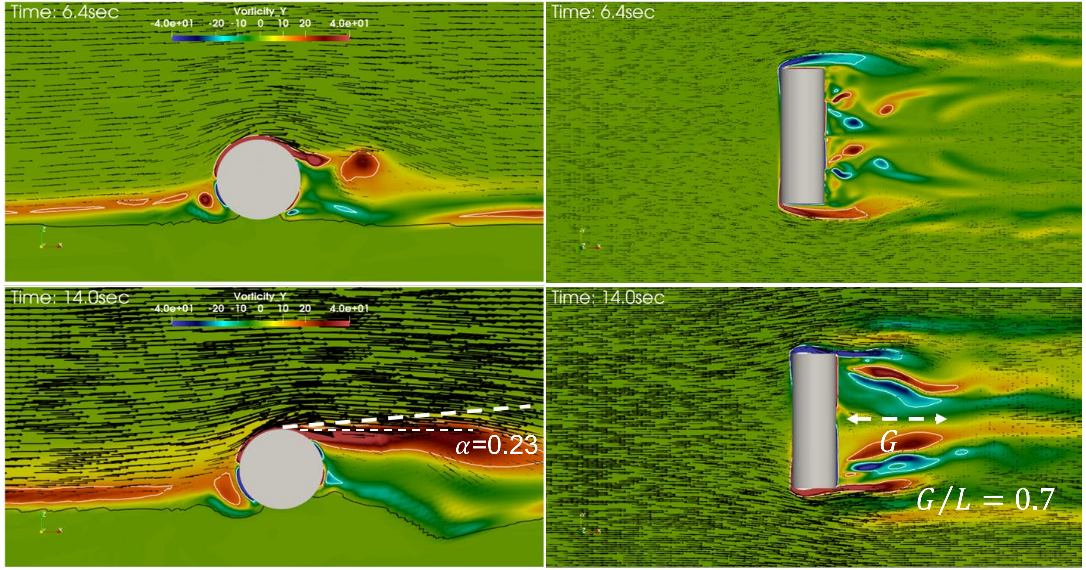
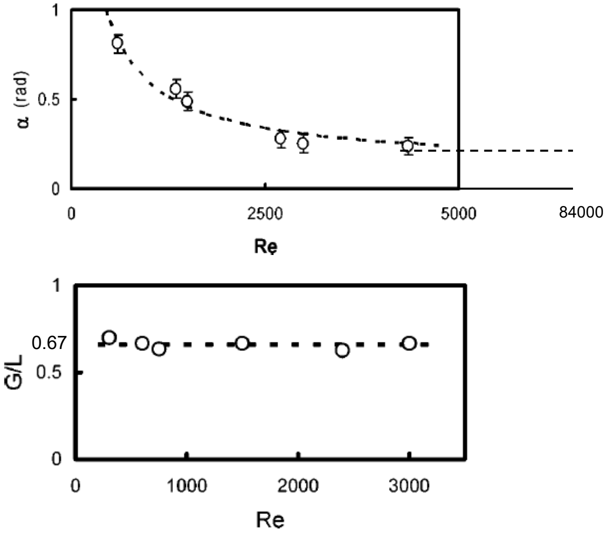
Results - mobility and initial burial driven by accelerating currents

- Resolved vortices characteristics are similar to laboratory experiment of Testik et al. (2005) and large-eddy simulation of Smith and Foster (2007).





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Results – self-burial driven by waves

- Successful validation for UXO self-burial driven by oscillatory flow with the laboratory experiments of Dimer and Garcia (2007) and Cataño-Lopera et al. (2007).
  - Scour burial – a slow process that occurs in several stages; does not reach full burial; UXO density unimportant; exists when the far-field Shields parameter $0.02 < \theta_0 < \theta_1$.
    According to Dimer and Garcia (2007) $\theta_1 \approx 0.4$.
  - Burial by fluidization – reach full burial in a short amount of time
    One laboratory observation by Cataño-Lopera et al. (2007) at $\theta_0 = 0.74$, $\rho_{obj} = 7850\,kg/m^3$
    $\theta_0 > \theta_1 = 0.6$ (Friedrichs et al. 2016)

Table 1. Experimental Conditions

Test number	Uw (cm/s)	Period (sec)	Initial burial and bed condition	KC number	Far field Shields parameter θ_0	Final burial depth (Bd)
1	20	6	0.05D/Flat	14.0	0.047	0.15D
2	30	6	0.03D/Flat	20.9	0.093	0.26D
3	40	6	0.03D/Flat	27.9	0.155	0.41D
4	50	6	0.04D/Flat	34.9	0.230	0.65D
5	60	6	0.04D/Flat	41.9	0.320	0.78D
6	70	6	0.02D/Flat	48.8	0.424	>1.00D
7	80	6	0.03D/Flat	55.8	0.541	>1.00D
8	40	9	0.04D/Flat	41.9	0.139	0.45D
9	25	4	0.03D/Flat	11.6	0.077	0.27D
⋮	⋮	⋮				

Dimer and Garcia (2007)

Hypothesis: When the **local** Shields parameter θ (or mobility number ψ) exceeds the sheet flow criteria, a unique burial process, called "rapid scour burial" exists that can also lead to full burial; θ_1 can be as low as 0.4.

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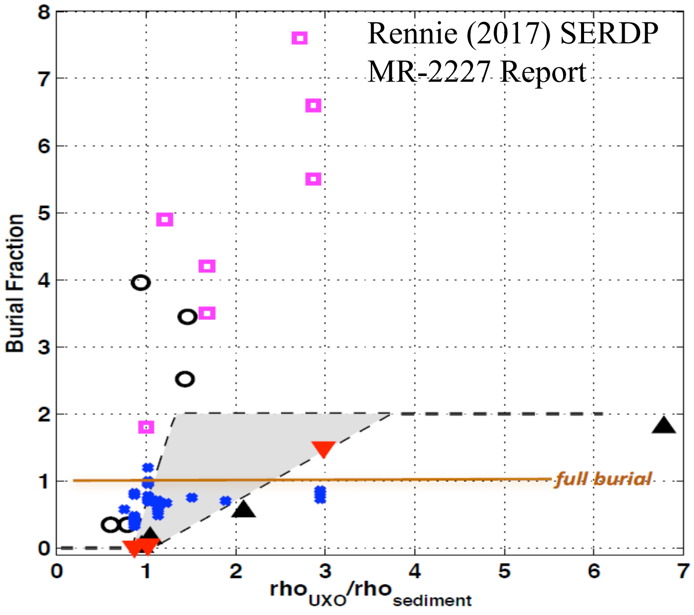
Results – self-burial driven by waves

Research Questions

1. What are the major differences in burial features between the "rapid scour burial" and the "burial by fluidization"?

2. What is the role of UXO density in these two energetic self-burial processes?



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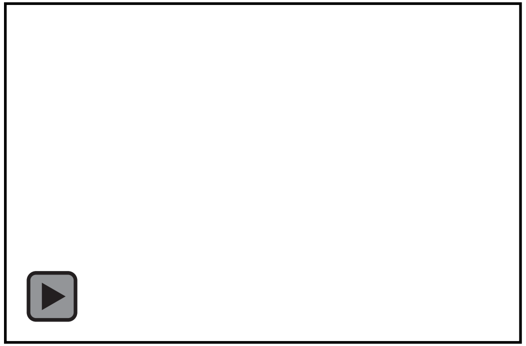
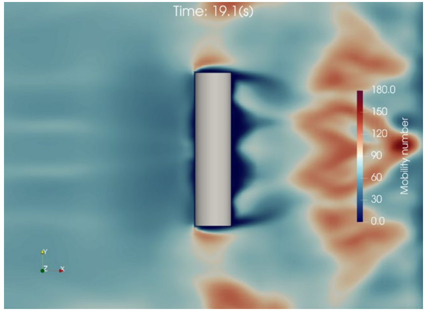
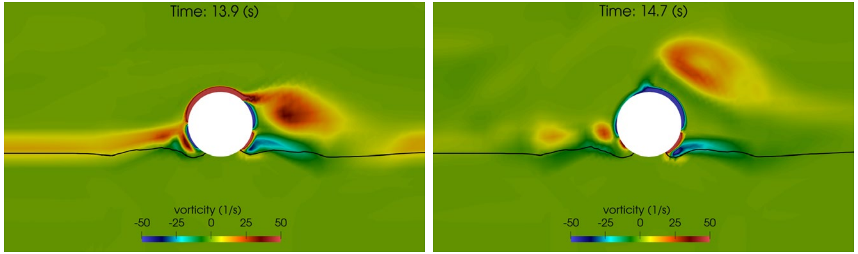
Results – scour burial

	ρ_{obj} (kg/m^3)	U_w (m/s)	T (sec)	θ_0	ψ_0	KC	B/D predictor	Attack angle (°)	Burial behavior
Case 1	2700	0.6	6	0.32	89	42	0.84	90	Scour Burial

} Dimer and Garcia (2007)







- At lower far-field Shields parameter of $\theta_0 = 0.32$, the model predicts the first stage of scour occurring at t=15~20 sec, consistent with laboratory observation (t=25 sec).
- Local mobility number only reach to $\psi \approx 120$, below sheet flow criteria of 158.
- Simulated vortex pattern is consistent with similar laboratory experiment of Testik et al. (2005) for oscillatory flow at a lower Reynolds number.

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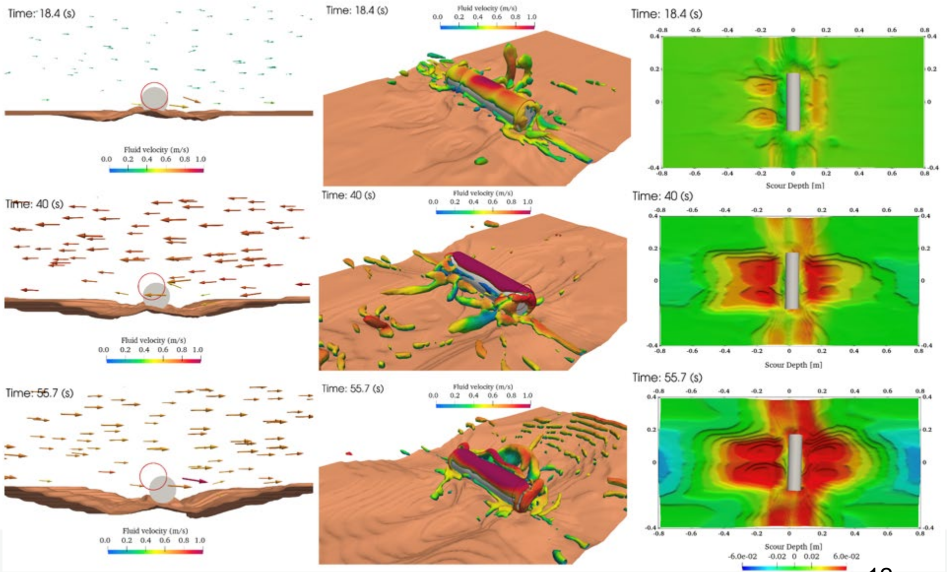
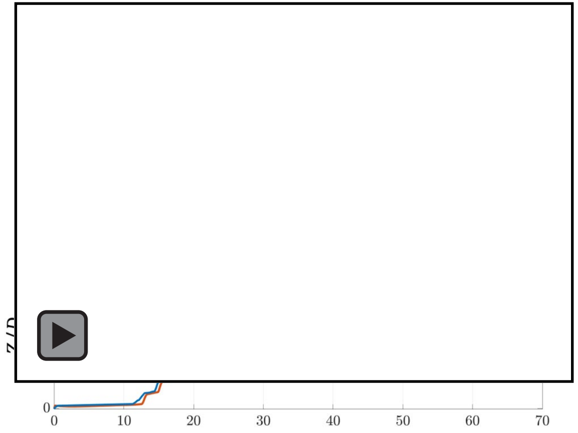
Results – rapid scour burial

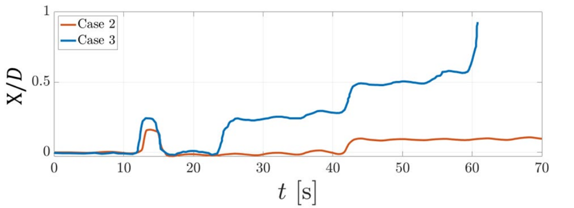
	ρ_{obj} (kg/m^3)	U_w (m/s)	T (sec)	θ_0	ψ_0	KC	B/D predictor	Attack angle (°)	Burial behavior
Case 2	2700	0.7	6	0.42	121	49	1	90	Rapid Scour Burial
Case 3	2700	0.8	6	0.54	158	56	1.17	90	Rapid Scour burial

Dimer and Garcia (2007)

Case 3

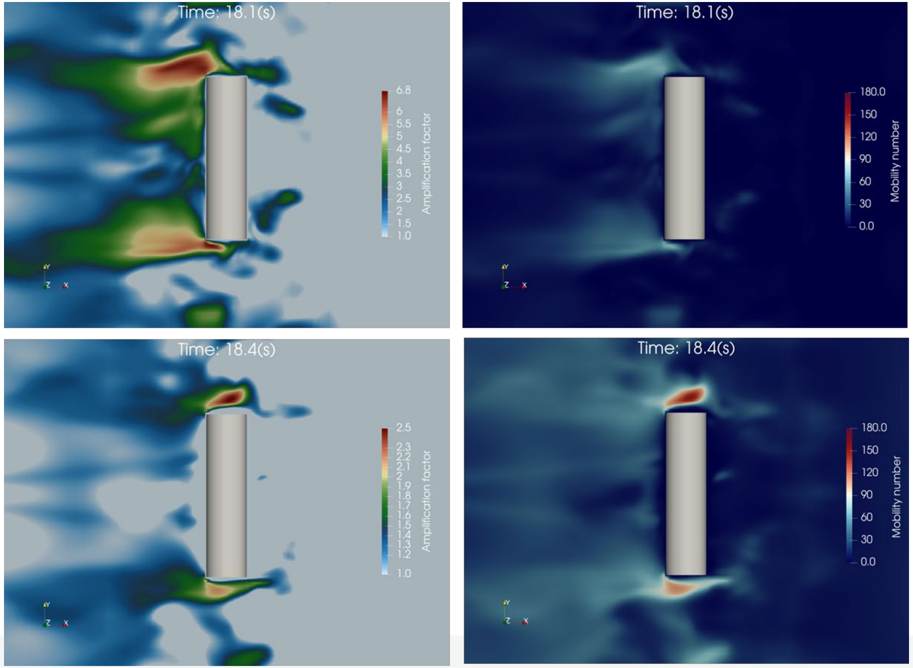




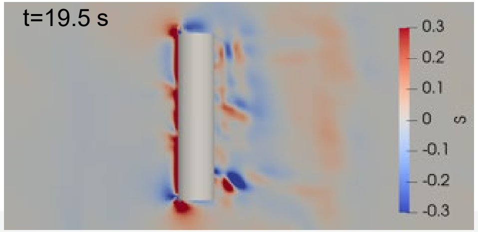


Results – rapid scour burial

Amplification factor $\frac{U}{U_0}$ Mobility number $\psi = \frac{U^2}{(s-1)gd}$



- The presence of short cylinder enhances local flow velocity near the two end corners via flow separations and tip vortices.
- Rapid scour burial occurs when the local mobility number near the UXO ($\psi = 180$) exceeding sheet flow criteria ($\psi > \psi_0 = 158$).
- We are also looking into the generation of momentary bed failure $|S| = \frac{|\partial p/\partial x| + |\partial p/\partial y|}{(\rho_s - \rho)g}$>0.2



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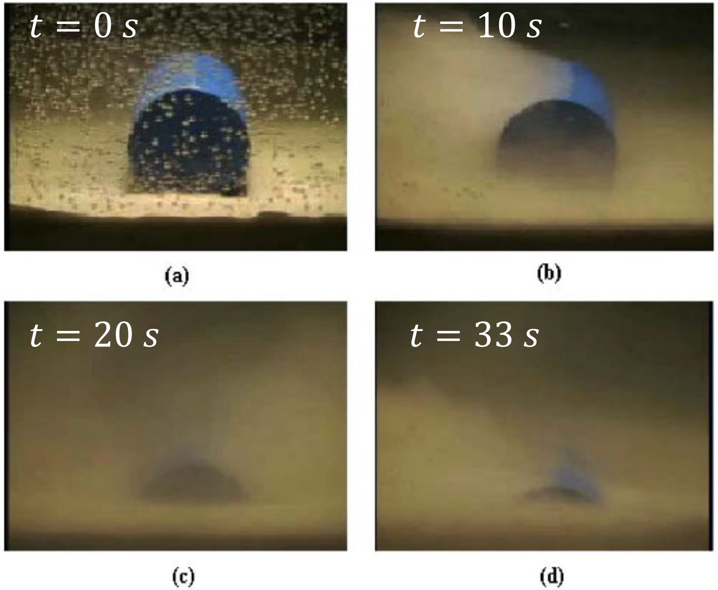
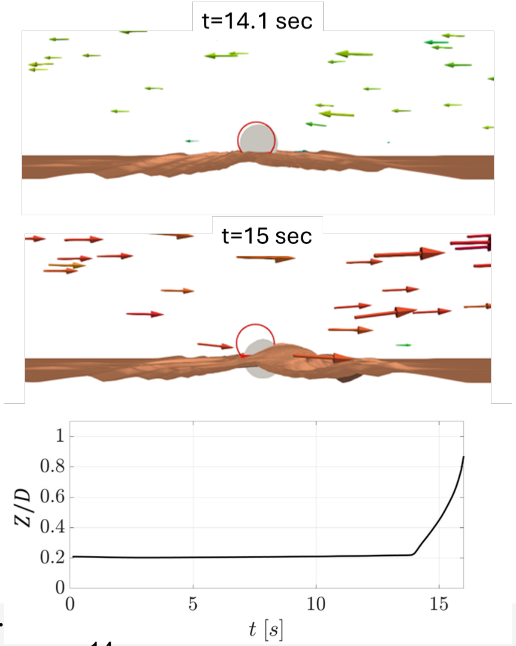
Results – burial by fluidization

	ρ_{obj} (kg/m^3)	U_w (m/s)	T (sec)	θ_0	ψ_0	KC	B/D predictor	Attack angle (°)	Burial behavior
Case 4	7850	0.88	3.6	0.74	192	62	1.37	90	Fluidization

} Cataño-Lopera et al. (2007)



Adopted from Cataño-Lopera et al. (2007) IEEE Oceanic Eng.



- Model reproduces the main features of burial by fluidization:
  - Rapid burial occurs in a few wave periods.
  - Leave no notable scour hole.

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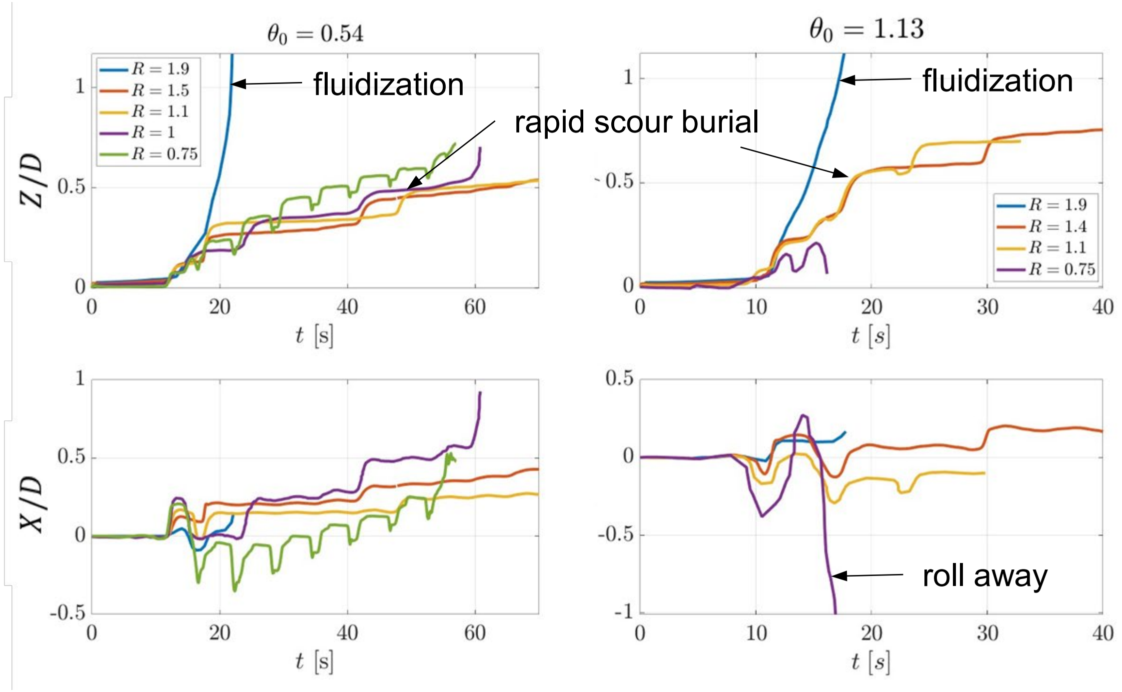
Results – Effect of UXO density

- In energetic flow ($\theta_0 > 0.4{\sim}0.5$):
  - ➢ rapid scour burial may be common.
  - ➢ burial by fluidization also require high UXO density ($R \gtrsim 1.9$).
  - ➢ When the UXO density is too low ($R < 0.75{\sim}1$), it tends to roll away, and self-burial is unlikely.



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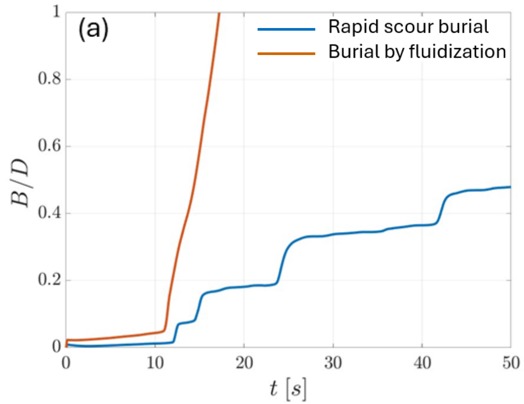
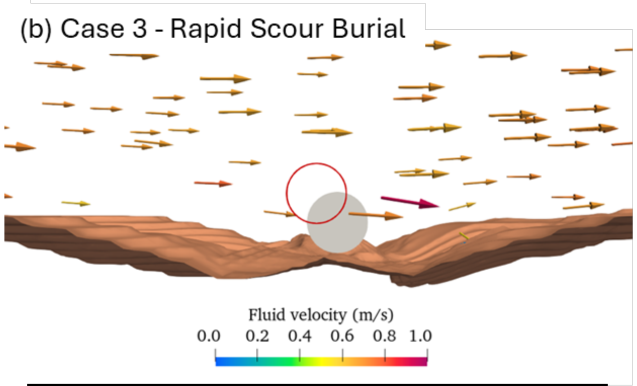
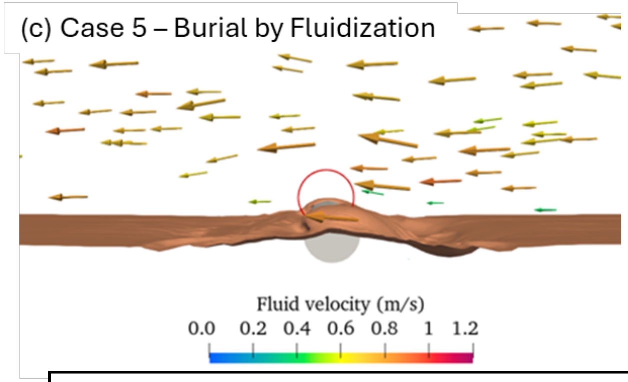
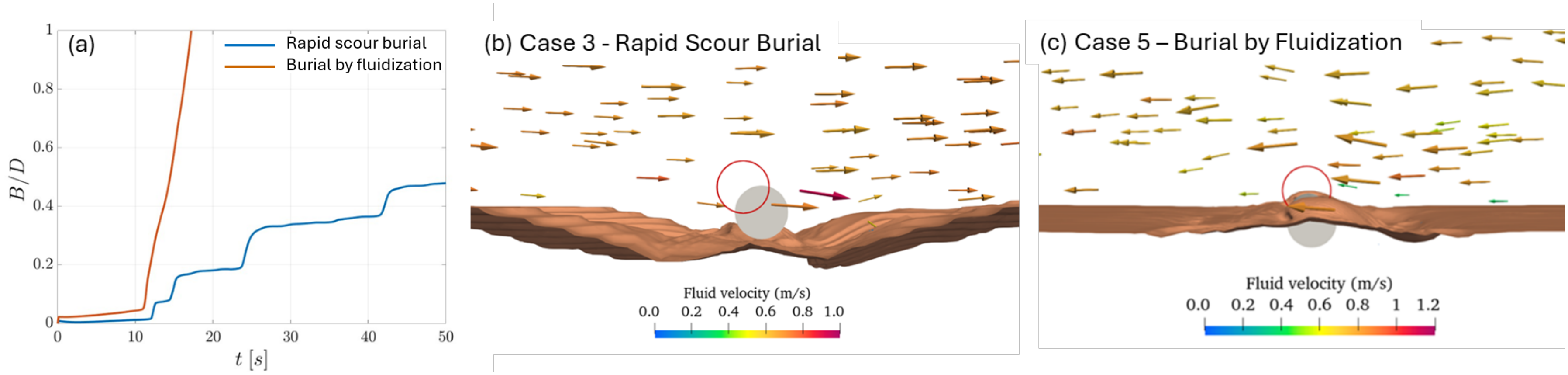
Results – rapid scour burial vs burial by fluidization







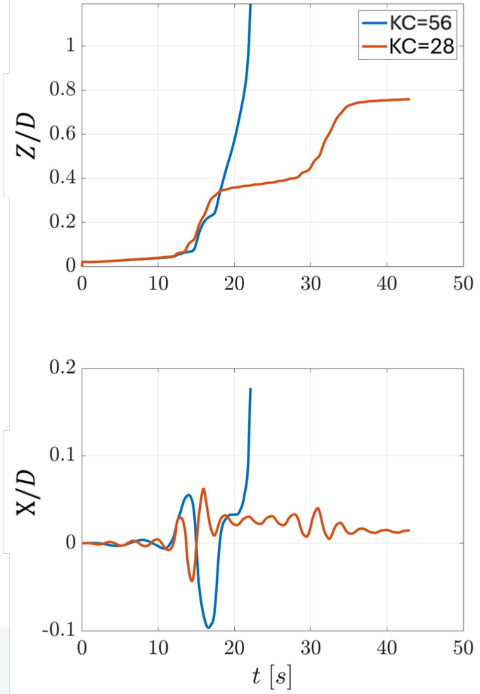
Results – rapid scour burial vs burial by fluidization



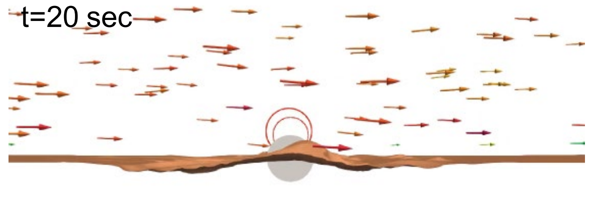
- Rapid scour burial takes minutes and leaves a scour hole, while burial by fluidization takes a few wave periods without leaving a notable scour hole.
- Both occur in energetic flows, but fluidization further requires high UXO density.
- Both can cause full burial in a short amount of time.

Results – Effect of Wave Period (KC number)

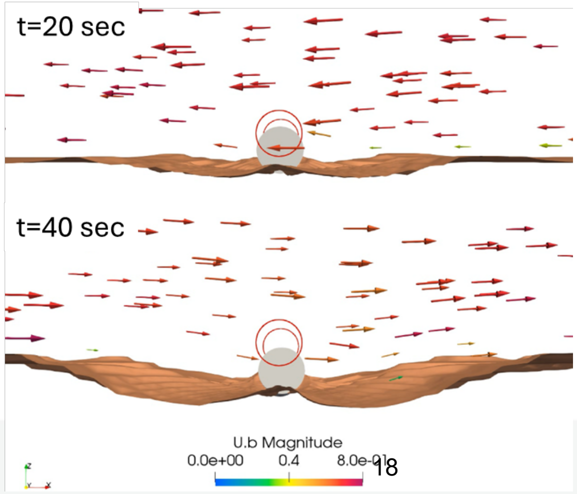
Mobility number $\psi_0 = 158$
Relative UXO density $R = 1.9$



KC=56, $\theta_0 = 0.54$ Burial by fluidization



KC=28, $\theta_0 = 0.65$ Rapid scour burial



- Vortex intensity of a smaller period (smaller KC) wave is weaker and burial mode shifts to rapid scour burial.
- This cannot be explained by the far-field Shields parameter θ_0 based on boundary layer turbulence as θ_0 increases for smaller wave period.
- We recommend the use of far-field mobility number ψ_0 and KC for parameterizing burial dynamics.

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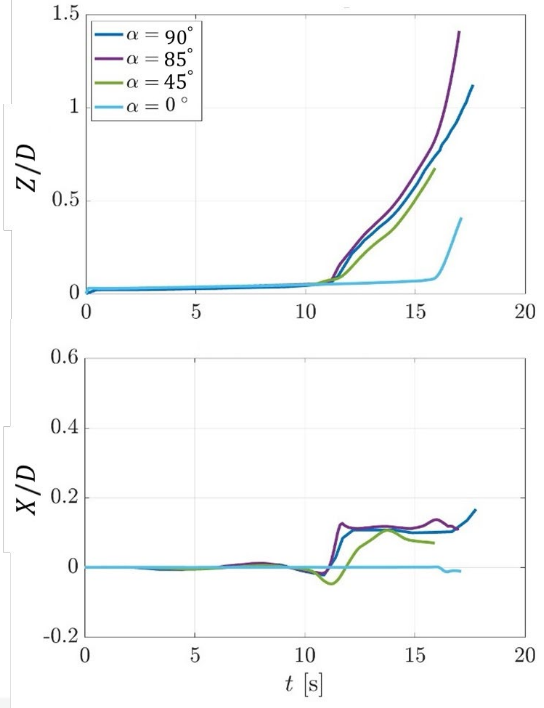
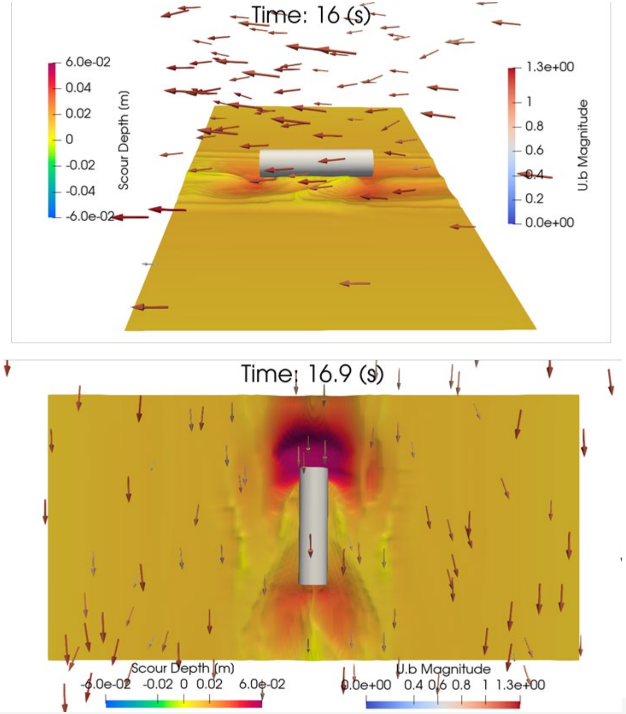
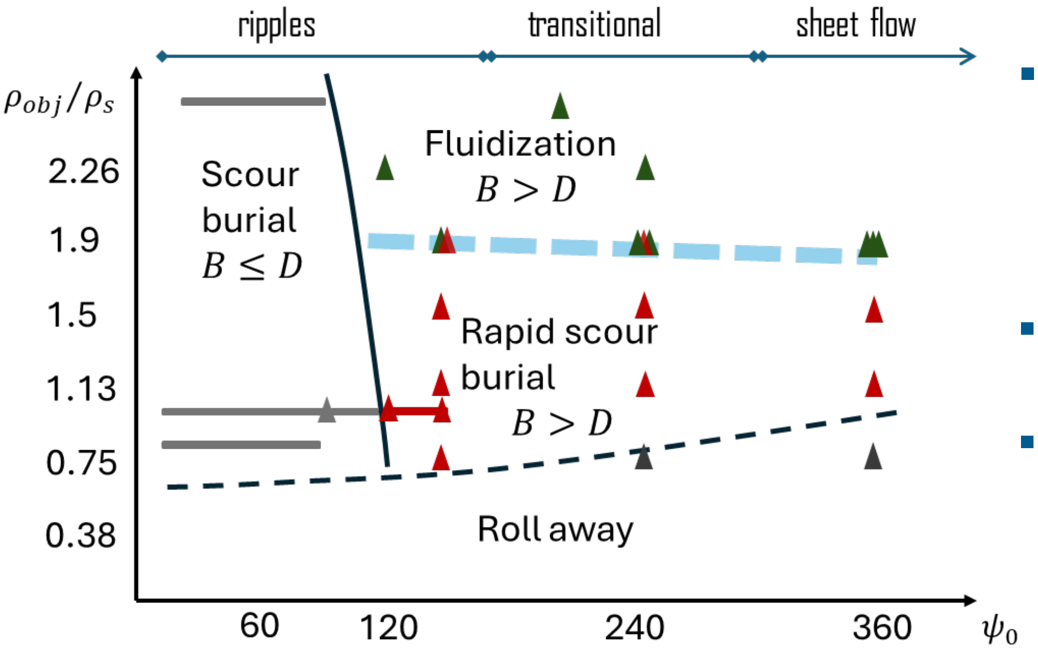
Results – Effect of wave angle of attack





- Burial by fluidization is insensitive to a variation of angle of attack up to about 45° from normal incidence.
- Changing the angle of attack by 90° from normal incidence causes a delay of the occurrence of burial by fluidization.

Synthesis



- *The energetic self-burial processes that may lead to full burials occur when the mobility number $\psi_0 > 120$ ($\theta_0 \gtrsim 0.4$) and the relative UXO density $R = \rho_{obj}/\rho_s \gtrsim 0.75\sim1.0$.*
- *Wave angle is of minor importance in energetic self-burial processes.*
- *This diagram is mainly developed for negligible Initial burial depth. For energetic burial process, initial burial depth may be of minor importance.*

Next Steps

- Archiving model setup files (for each run) and simulation data; making them easily accessible to other researchers.
- Wrapping up two manuscripts to be submitted in early 2026 regarding fate of UXOs driven by unidirectional accelerating currents and UXO burial dynamics driven by oscillatory flows.

Technology Transfer

- Through collaboration with NRL, we provide simulation data to enhance the data-driven probabilistic modeling framework UnMES (Rennie 2017).
- Define the importance of key physical parameters and develop parameterizations to predict the fate of UXO useful for munition site management (Final Report).
- In addition to journal publications, research findings have been presented in SERDP/ESTCP symposiums (oral presentation in 2022; posters in 2021, 2023, 2024), IPR 2022~2024, 2023 Munition in the Underwater Environment Workshop, oral presentations in 2024 Ocean Science Meeting, 2024 AGU Fall Meeting, 6th Symposium of Two-phase Flow Modelling for Sediment Dynamics in Geophysical Flows.
- Most updated version of SedFoam is publicly available at
  - https://sedfoam.github.io/sedfoam/
  - https://github.com/SedFoam/sedfoam

  Tutorial cases for UXO burial will be made available in early 2026.

Backup slides

MR-1478: Novel Eulerian Two-phase Numerical Simulation Tool for Scour Burial of Munitions

Performers: *T.-J. Hsu, J. Zhang, M. Nouri, A. Mathieu, Univ. Delaware; J. Chauchat, E. Montella, C. Bomany, Univ. Grenoble Alpes.*

Technology Focus

Create a next-generation numerical simulation tool for studying burial dynamics of munitions based on SedFoam framework

Research Objectives

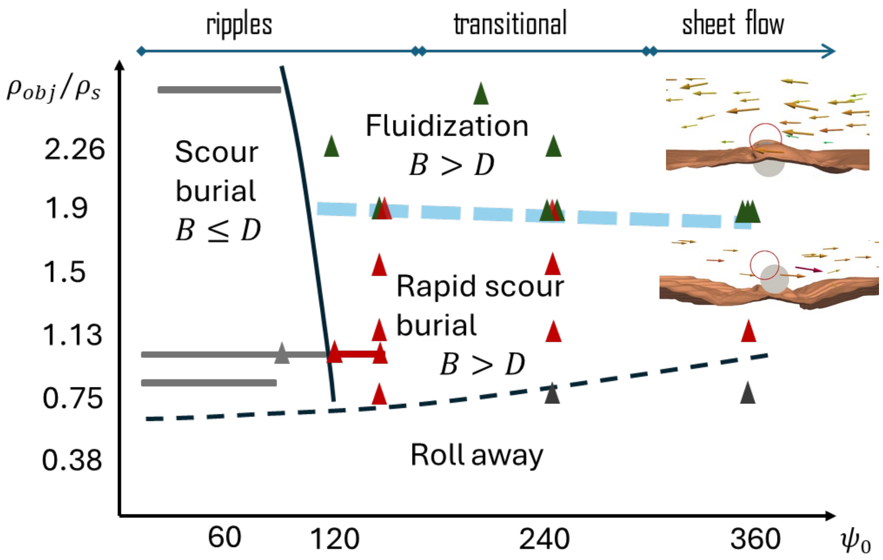
- *Full implementation of SedFoam for simulating UXO mobility and burial dynamics.*
- *Study energetic burial processes of UXO that may lead to full burial.*
- *Carrying out field-relevant scenario simulations to fill data gaps in the data-driven model.*

Project Progress and Results

- *We recommend the use of the mobility number ψ_0, relative UXO density, and the KC number to describe self-burial dynamics.*
- *The energetic self-burial processes that may lead to full burials exist when the mobility number $\psi_0 > 120$ (θ_0>0.4) and the relative UXO density $\rho_{obj}/\rho_s \gtrsim 1$.*

Technology Transition

- *Findings inform data-driven model; simulation data and model set-up are available to other researchers.*



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Plain Language Summary

- What problem are you addressing?

Energetic and high-density UXO self-burials often cause full burial which is essential information for munition site management. This study investigates the effect of wave intensity and munition density on the energetic UXO self-burial processes.

- What are you trying to achieve and how are you doing it?

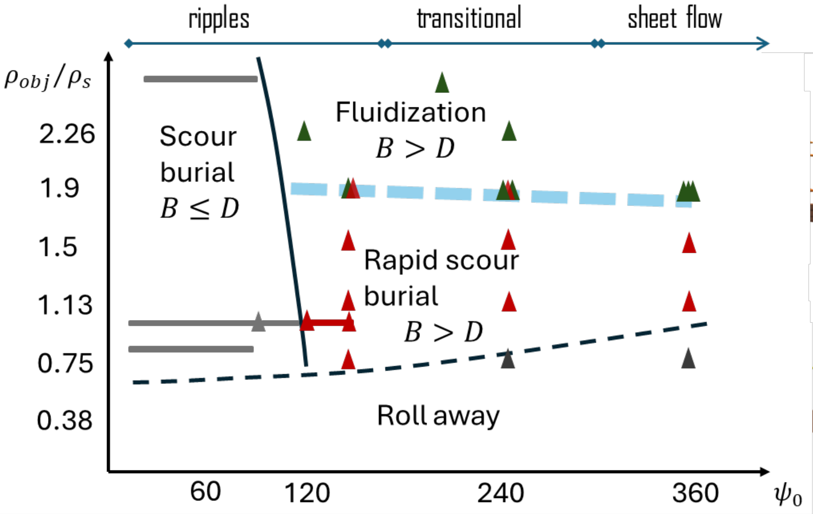
Limited field data prevents a holistic understanding of energetic self-burial processes for a wide range of UXO density. This study uses a high-fidelity two-phase model SedFoam to provide simulation data and fill data gaps.

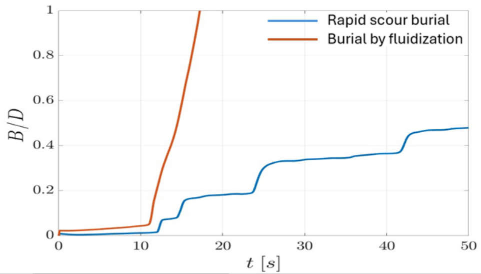
- What are the expected outcomes and how is it advancing existing knowledge?

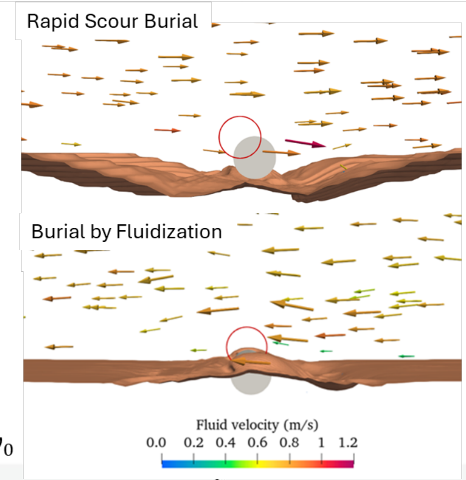
We confirm the existence of "rapid scour burial" regime and investigate the critical UXO density needed for "burial by fluidization". Both processes lead to full burial. Extensive simulation data provides a regime diagram defining the occurrence of these energetic self-burial processes.

Impact to DoD Mission

- We investigate energetic self-burial processes of munitions that lead to full burial. Findings can be a significant cost-saving for munition site mitigation.
- Simulation results allow the development of a regime map and enhancement to data-driven predictive tool UnMES widely used by DoD researchers and munition site managers.







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