Experimental and Numerical Investigation of Grain Shape Effects on Munition Mobility

MR21-1291

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In-Progress Review Meeting

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Project Leads

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Bottom Line Up Front

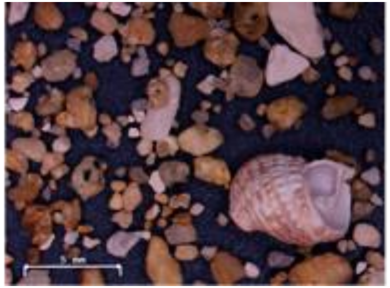
- **Experiments** and **simulations** of **grain shape** effects on **munition mobility**.
- **Experiments finalized**, numerical **code developed** and **validated**.
- **Experimental** program and **coding took longer** than anticipated. Funds spent but **invoicing delayed**.
- **UPRM** catching up on **invoicing**. Remaining funds being used for **graduate student** to finalize analysis and publish results.

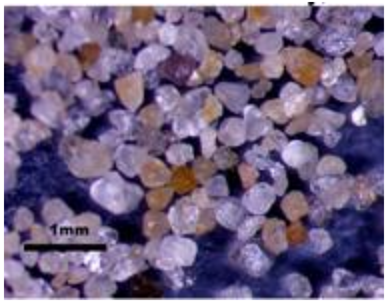
Technical Objective

- This project focuses on **munition mobility** for **irregularly shaped** sand grains.

- Research Objectives:
  - **Quantify** the **role** of **grain shape** and **angularity** on **munition mobility**.
  - **Assess** the validity and/or **propose** modifications to current **predictive models** addressing **munition mobility** for irregularly shaped grains.
  - **Resolve** the physics of **flow entrainment** at the **grain-scale** and characterize its **fundamental differences** for **spherical** vs **irregularly shaped** substrates.

Calcareous sand





Silica sand

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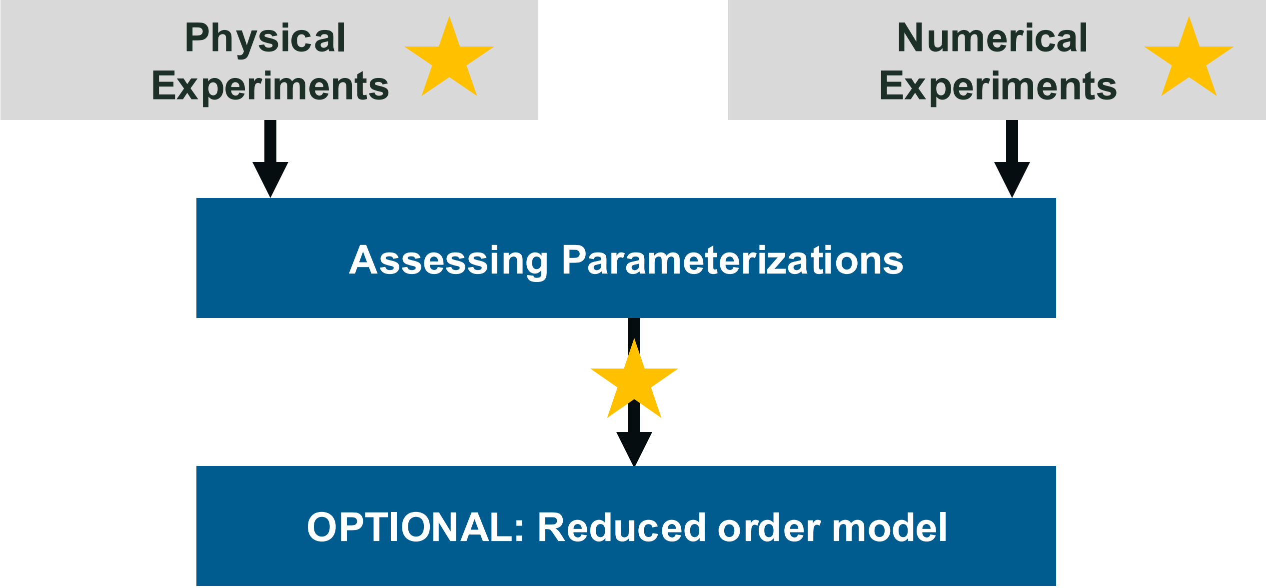
Technical Approach



RESULTS TO DATE

Physical Experiments

Results to Date: Physical Experiments

20mm round

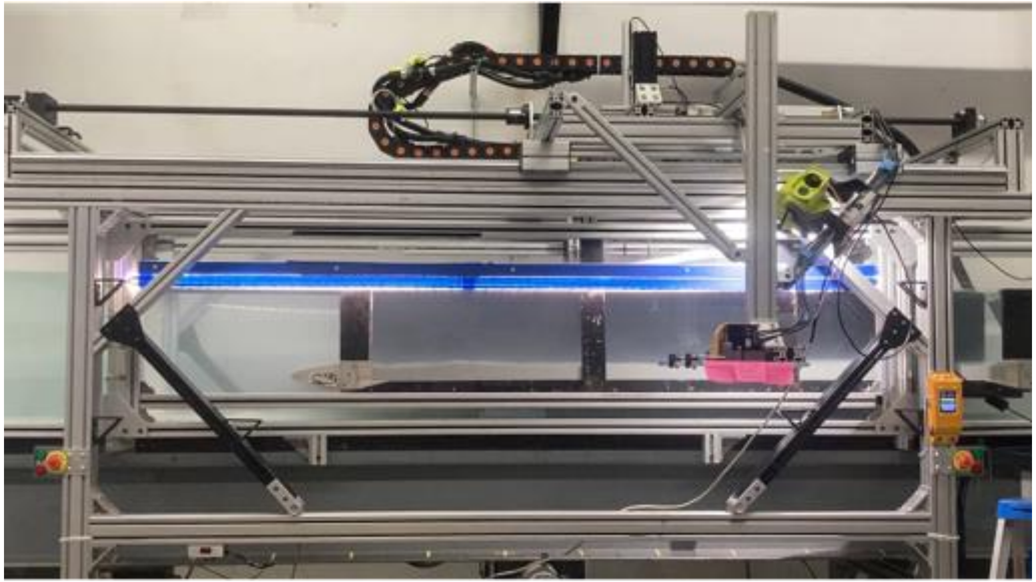
81mm finless

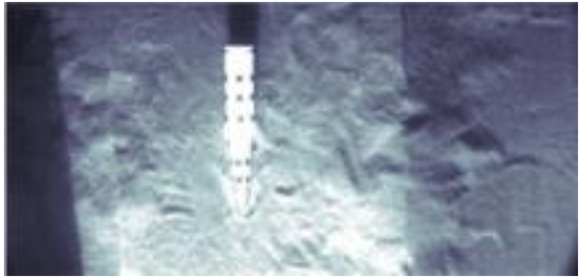
	Calcareous sand Punta Arenas, Vieques	Silica sand Field Research Facility, NC
Specific gravity	2.63 ± 0.01	2.58 ± 0.01
D_{50} (mm)	1.13	0.29
Porosity	37%	38%
Shape factor (2D)	0.85 ± 0.002	0.91 ± 0.001
Angularity index (2D)	0.07 ± 0.001	0.06 ± 0.001
Irregularity (2D)	0.14 ± 0.002	0.11 ± 0.002

★ $$\theta_{2.5} = \frac{f_{2.5} U_0^2}{2(s-1) g D_{50}}$$

$$\theta_m = \frac{U_0^2}{(s_m - 1) g D_m}$$

Results to Date: Physical Experiments

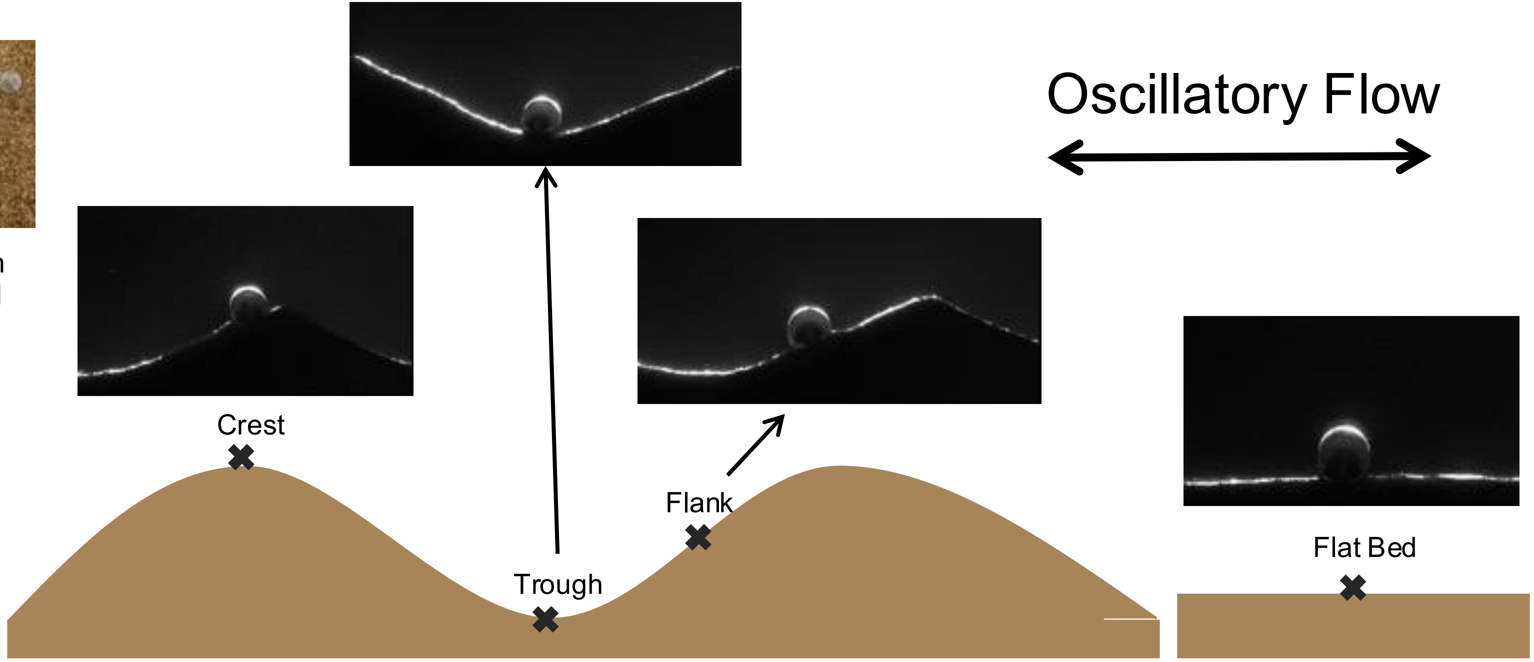




Results to Date: Physical Experiments

81mm finless

20mm round



✖ Position of Munition's center of mass

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Results to Date: Physical Experiments

GRAIN	SURROGATE	RIPPLE LOCATION	ORIENTATION (°)	η (cm)	λ (cm)	U_0 (m/s)	θ_m	$\theta_{2.5}$	s_m/s
SILICA SAND s = 2.58, d_{50} = 0.29 mm (rounded and uniform shapes)	15mm	trough	90	4.4	24.7	0.302	0.38	0.11	1.0
		trough	0	4.1	24.7	0.295	0.36	0.11	1.0
		flank	90	4.1	24.7	0.263	0.28	0.09	1.0
		flank	180	4.3	24.8	0.284	0.33	0.10	1.0
		flank	0	4.1	27.8	0.279	0.32	0.10	1.0
		crest	90	3.9	24.6	0.278	0.33	0.08	1.0
		crest	0	4.1	24.7	0.282	0.33	0.10	1.0
		Rippled Bed Baseline (No Munition)		4.1	24.7	0.284	--	0.10	--
		flat bed	90	flat bed	flat bed	0.272	0.31	0.09	1.0
		flat bed	0	flat bed	flat bed	0.276	0.32	0.10	1.0
CALCAREOUS SAND s = 2.63, d_{50} = 1.13 mm (irregular and heterogeneous shapes)	20mm	trough	90	6.2	30.6	0.459	0.46	0.11	1.0
		trough	0	4.7	35.3	0.456	0.45	0.10	1.0
		flank	90	5.2	30.9	0.468	0.48	0.11	1.0
		flank	180	4.8	27.3	0.44	0.42	0.10	1.0
		flank	0	5.4	33.6	0.427	0.40	0.09	1.0
		crest	90	5.4	34.1	0.439	0.42	0.10	1.0
		crest	0	5.1	32.3	0.429	0.40	0.09	1.0
		Rippled Bed Baseline (No Munition)		4.7	36.6	0.423	--	0.09	--
		flat bed	90	flat bed	flat bed	0.392	0.33	0.08	1.0
		flat bed	0	flat bed	flat bed	0.397	0.34	0.08	1.0
SILICA SAND s = 2.58, d_{50} = 0.29 mm (rounded and uniform shapes)	20mm	trough	90	3.5	29.1	0.446	0.43	0.26	1.0
		trough	0	2.9	32.2	0.414	0.37	0.22	1.0
		flank	90	4.1	29.9	0.404	0.35	0.21	1.0
		flank	180	4	30.9	0.433	0.41	0.24	1.0
		flank	0	4	29.9	0.441	0.42	0.25	1.0
		crest	90	5.1	37.8	0.439	0.42	0.25	1.0
		crest	0	5.2	33.2	0.445	0.43	0.25	1.0
		Rippled Bed Baseline (No Munition)		4.2	28.6	0.442	--	0.25	--

20mm round

Results to Date: Physical Experiments

GRAIN	SURROGATE	RIPPLE LOCATION	ORIENTATION (°)	η (cm)	λ (cm)	U_0 (m/s)	θ_m	$\theta_{2.5}$	s_m/s
SILICA SAND s = 2.58, d_{50} = 0.29 mm (rounded and uniform shapes)	32mm	flat bed	90	flat bed	flat bed	0.292	0.09	0.09	1.6
		flat bed	0	flat bed	flat bed	0.291	0.09	0.09	1.6
	64mm	trough	90	3.5	21.3	0.294	0.1	0.11	0.93
		trough	0	3.4	20.5	0.288	0.09	0.11	0.93
		flank	90	3.2	20.6	0.299	0.1	0.11	0.93
		flank	180	3.4	20.5	0.269	0.08	0.09	0.93
		flank	0	3.4	20.6	0.284	0.09	0.10	0.93
		crest	90	3.55	21	0.293	0.1	0.11	0.93
		crest	0	3.4	20.7	0.296	0.1	0.11	0.93
		Rippled Bed Baseline (No Munition)		3.7	20.9	0.288	--	0.11	--
		flat bed	90	flat bed	flat bed	0.285	0.09	0.1	0.93
		flat bed	0	flat bed	flat bed	0.269	0.08	0.09	0.93
CALCAREOUS SAND s = 2.63, d_{50} = 1.13 mm (irregular and heterogeneous shapes)	81mm	trough	90	3.8	32.5	0.468	0.09	0.11	1.6
		trough	0	4.2	30.5	0.456	0.08	0.10	1.6
		flank	90	3.6	32.3	0.409	0.07	0.08	1.6
		flank	180	4.35	32.25	0.482	0.09	0.11	1.6
		flank	0	4.05	33	0.444	0.08	0.10	1.6
		crest	90	3.35	32.5	0.484	0.09	0.12	1.6
		crest	0	4.55	31.5	0.472	0.09	0.11	1.6
		Rippled Bed Baseline (No Munition)		3.7	20.9	0.288	--	0.11	--
		flat bed	90	flat bed	flat bed	0.446	0.08	0.10	1.6
		flat bed	0	flat bed	flat bed	0.405	0.06	0.08	1.6

81mm finless

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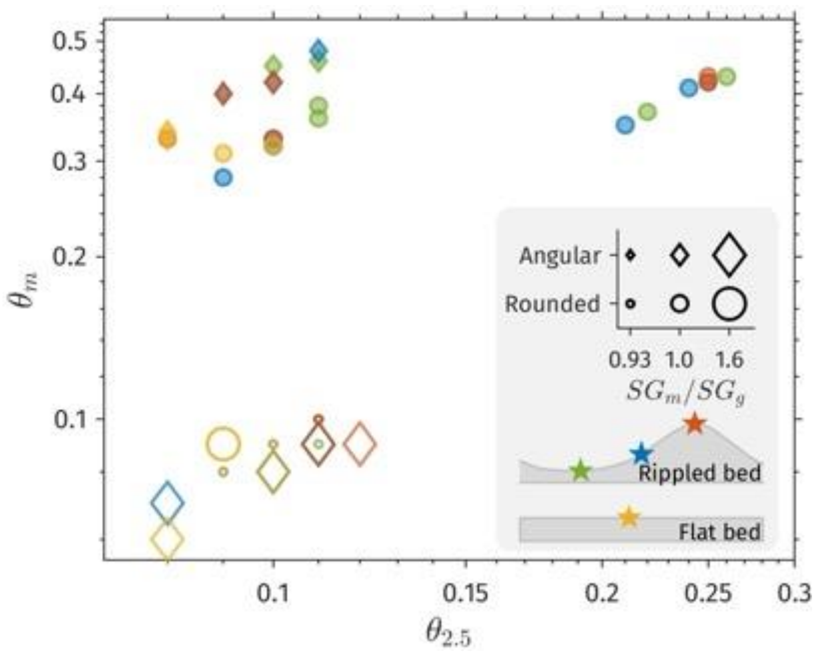
Results to Date: Parameter Space



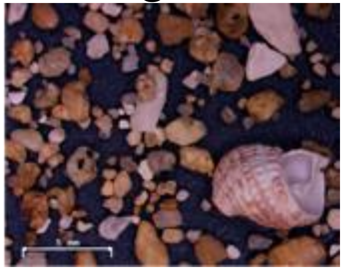
$$\theta_{2.5} = \frac{f_{2.5}\, {U_0}^2}{2(s-1)g\, d_{50}}$$

$$\theta_m = \frac{{U_0}^2}{(s_m - 1)g\, d_m}$$

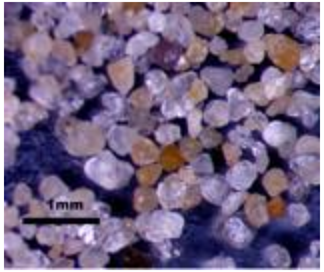
★ 20mm round

☆ 81mm finless

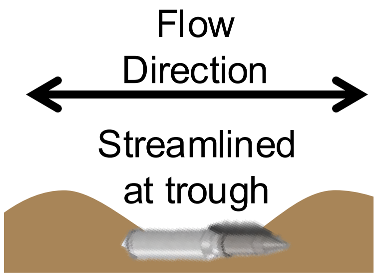
Angular

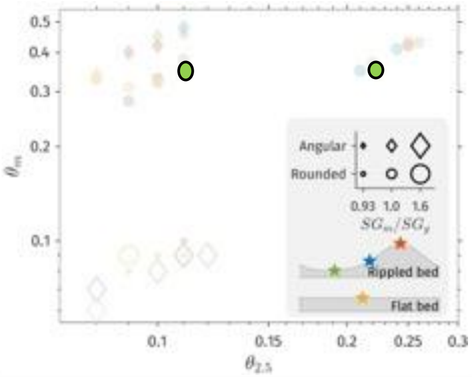


Rounded

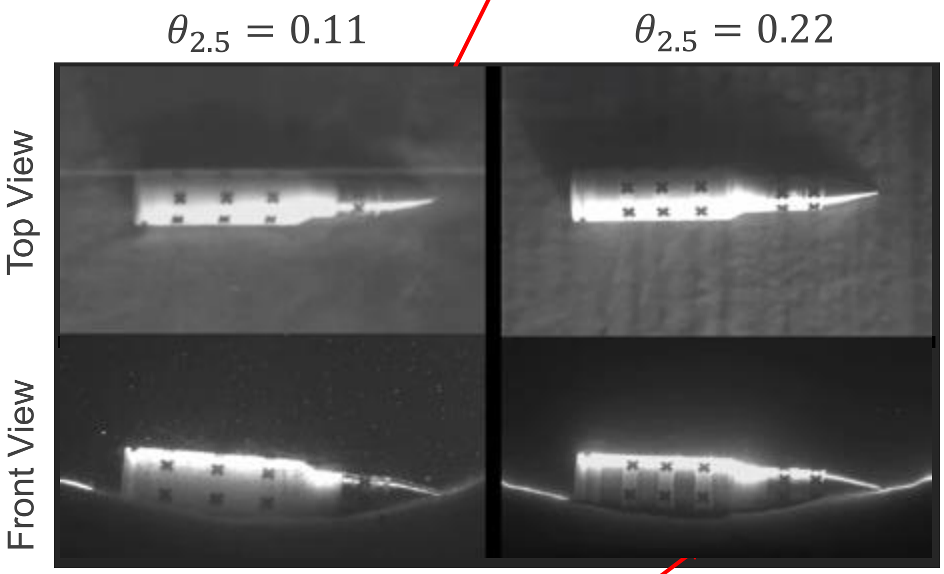


Results to Date: Sediment Mobility

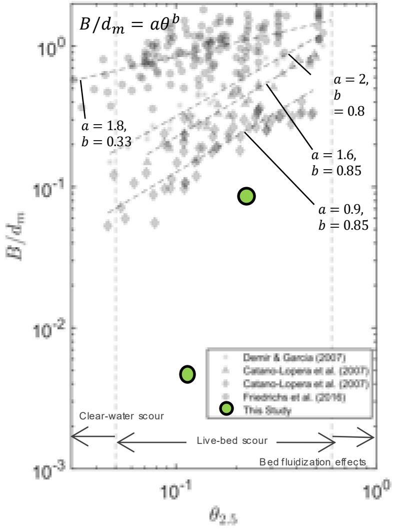




Sediment accumulation



Greater near-bed sediment suspension



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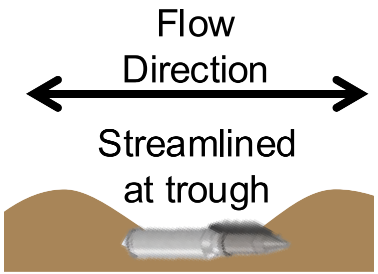
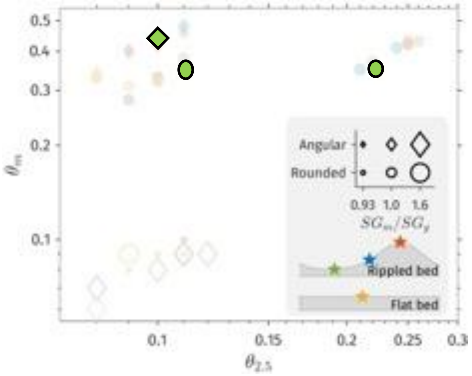
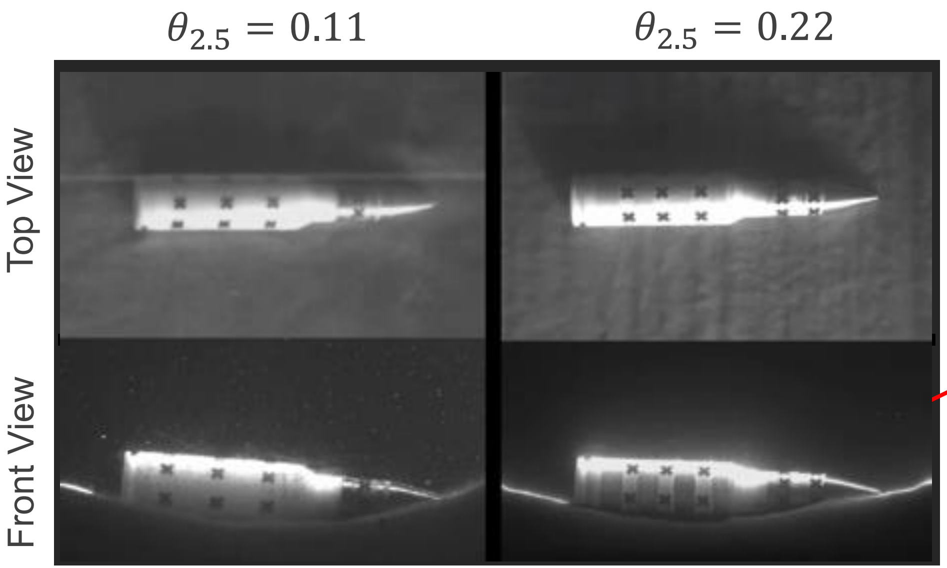
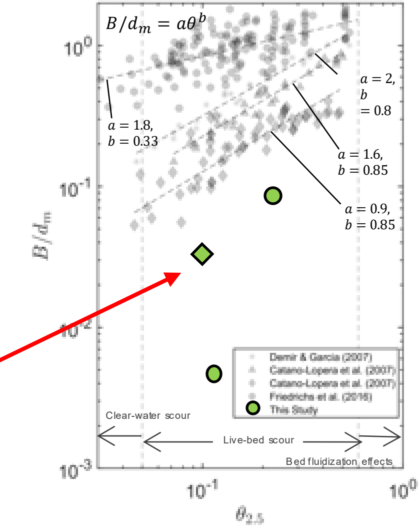
Results: Sediment Mobility and Grain Angularity









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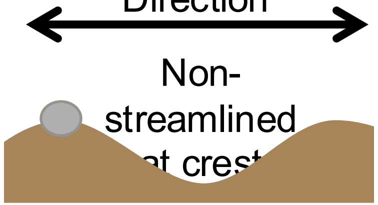
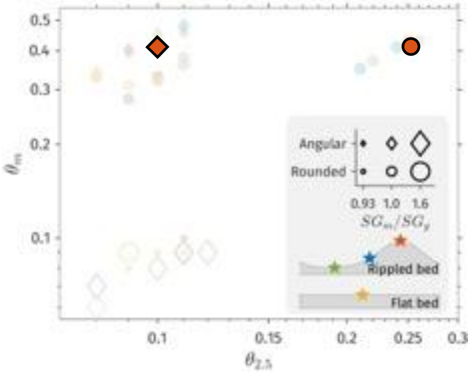
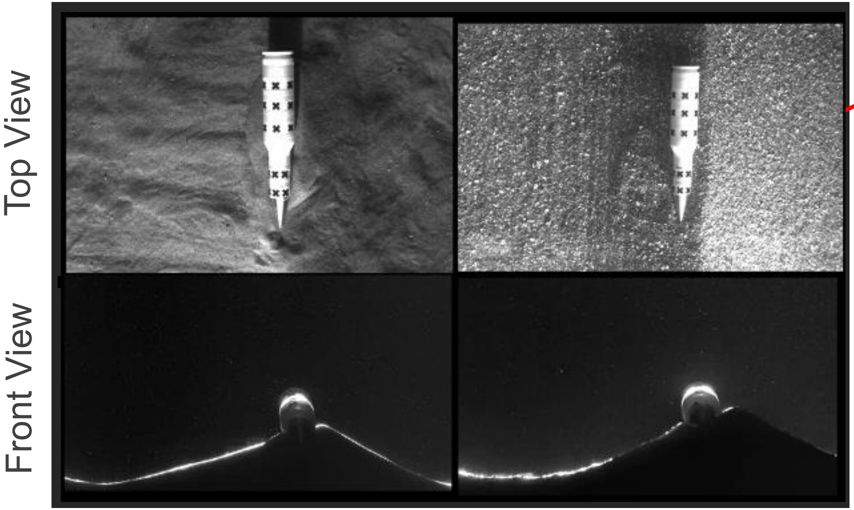
Results: Sediment Mobility and Grain Angularity

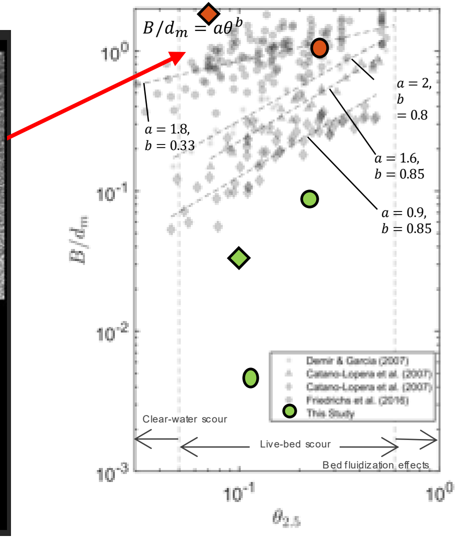




Rounded $\theta_{2.5} = 0.25$

Angular $\theta_{2.5} = 0.10$





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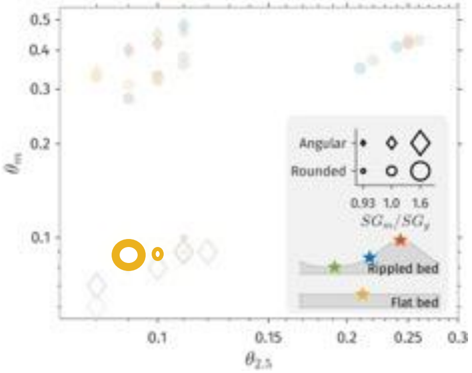
Results to Date: Relative Density

Flow Direction

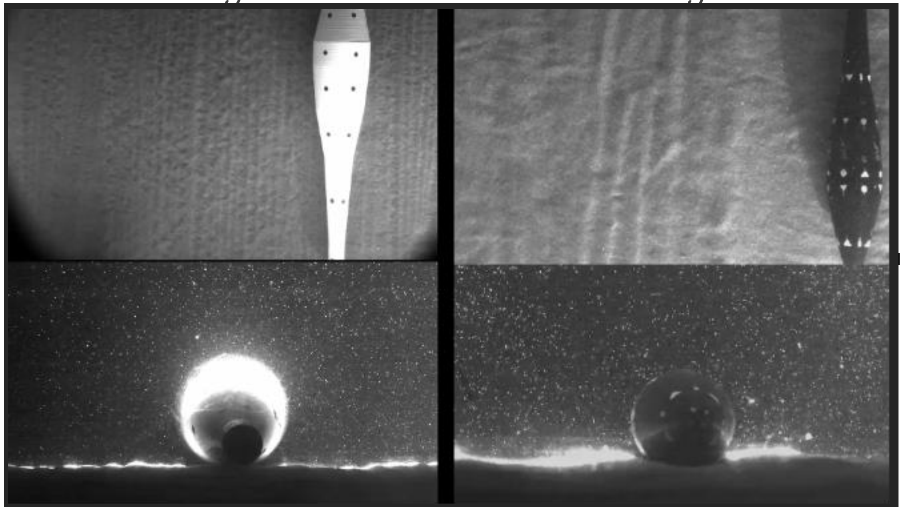
Non-streamlined flat bed

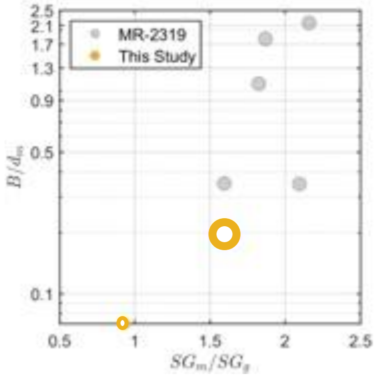


$SG_m/SG_g = 0.93$ $SG_m/SG_g = 1.6$

Top View

Front View

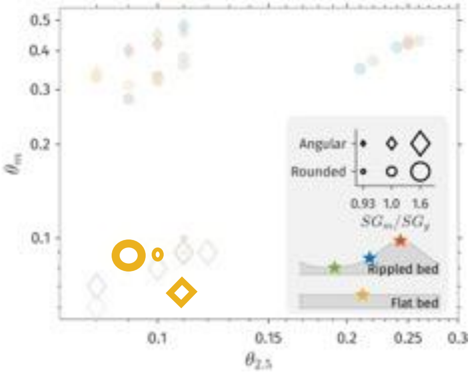




Results: Relative Density and Grain Angularity

Flow Direction

Non-streamlined flat bed

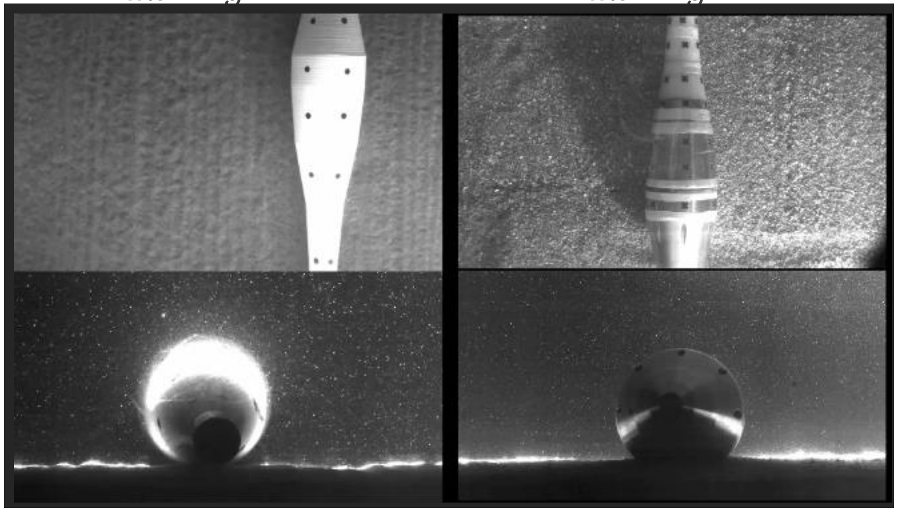


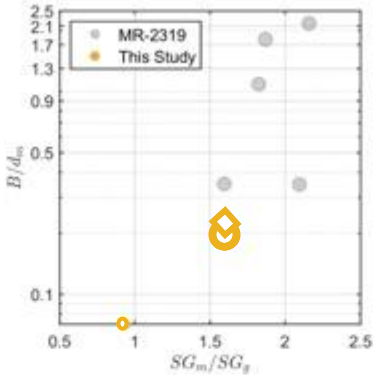
Rounded $SG_m/SG_g = 0.93$

Angular SG_m/SG_g =1.6

Top View

Front View





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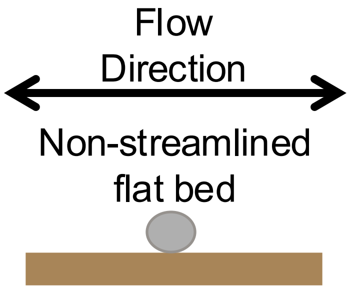
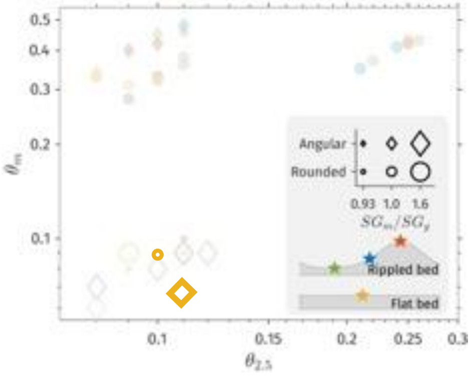
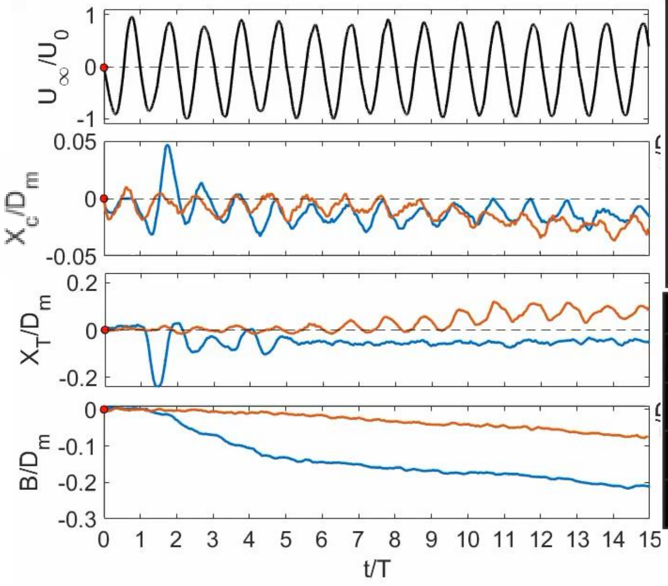
Results: Relative Density and Grain Angularity

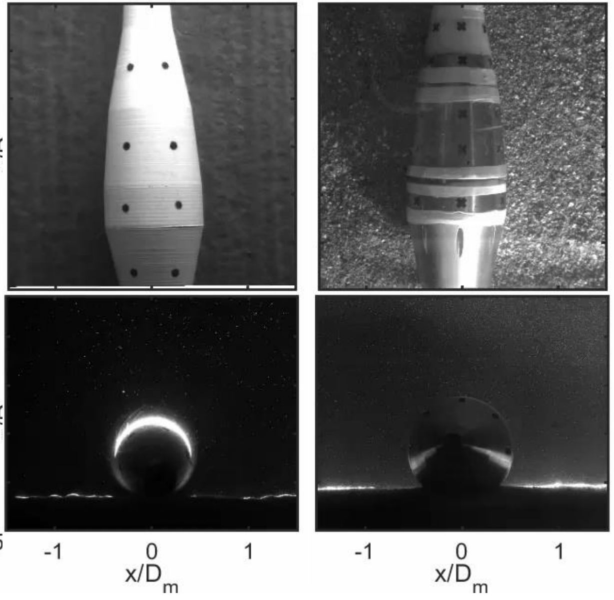






Rounded

Angular



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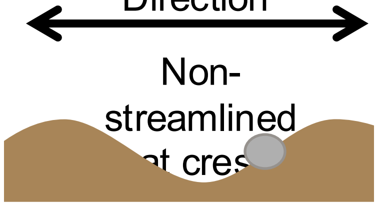
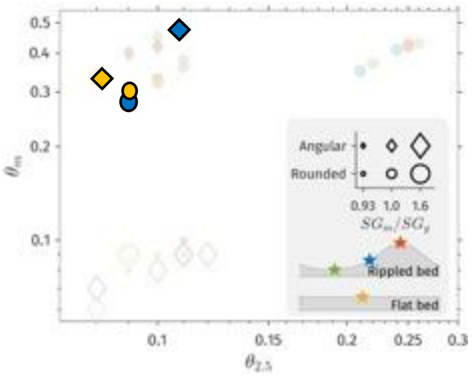
Results: Munition Mobility and Grain Angularity



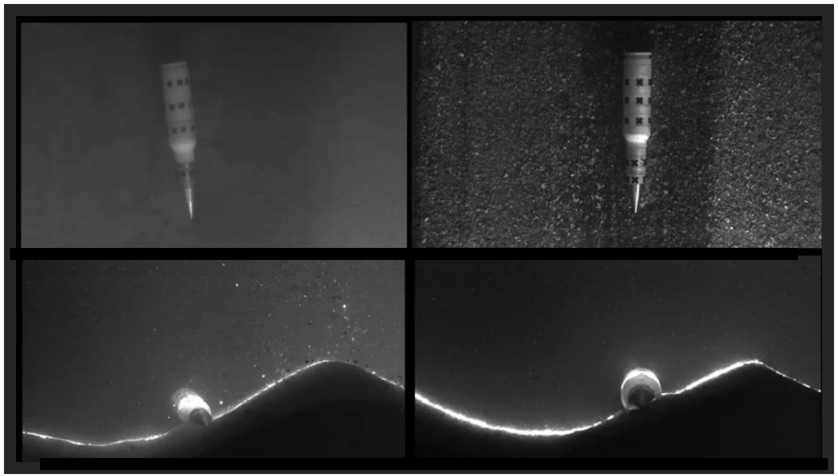


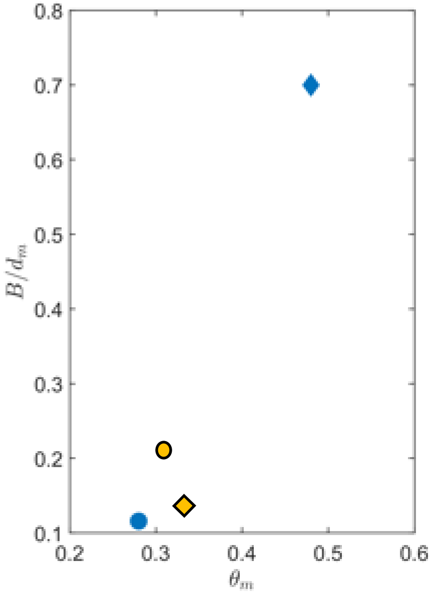
Rounded
$\theta_m = 0.28$

Angular
$\theta_m = 0.48$

Top View

Front View





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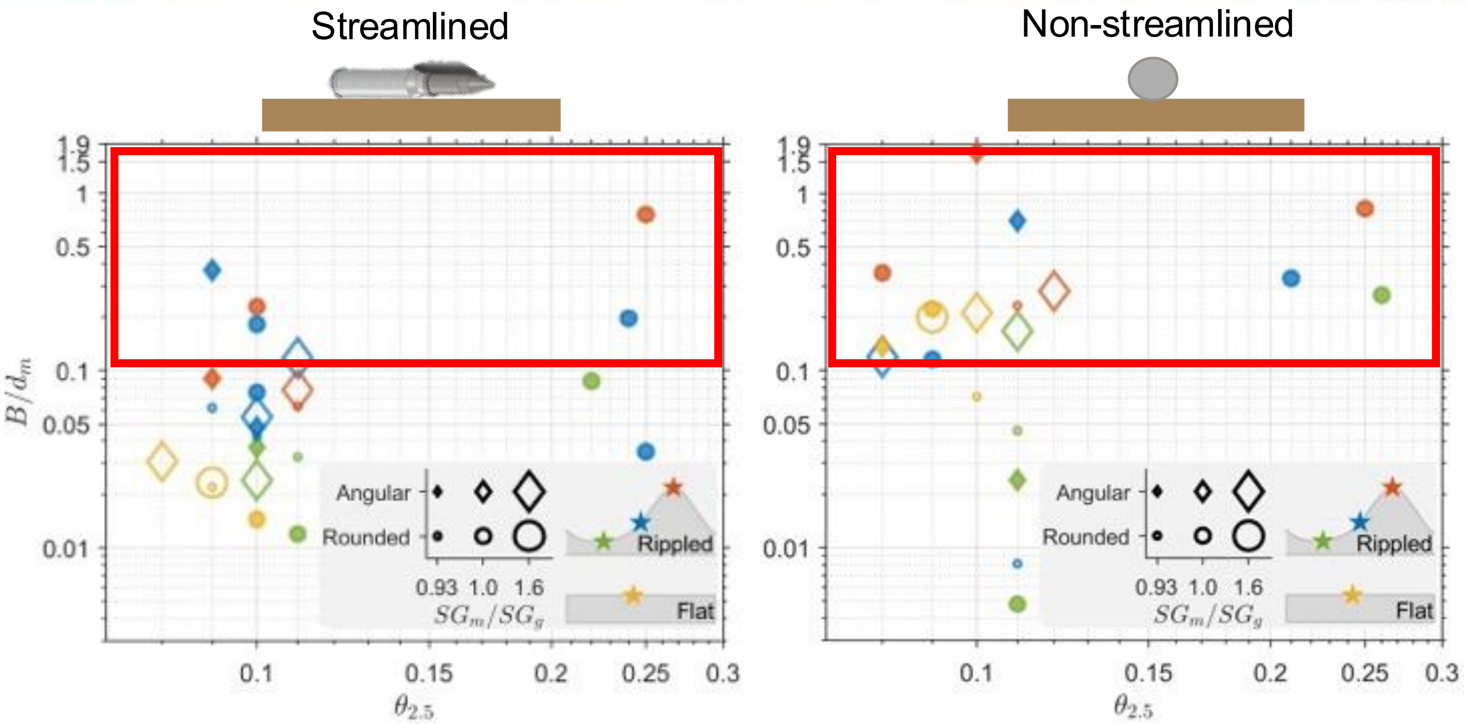
Results to Date: Summary



- Grain angularity generally dominates over $\theta_{2.5}$
- θ_m and S_m/S_g dominate over grain angularity

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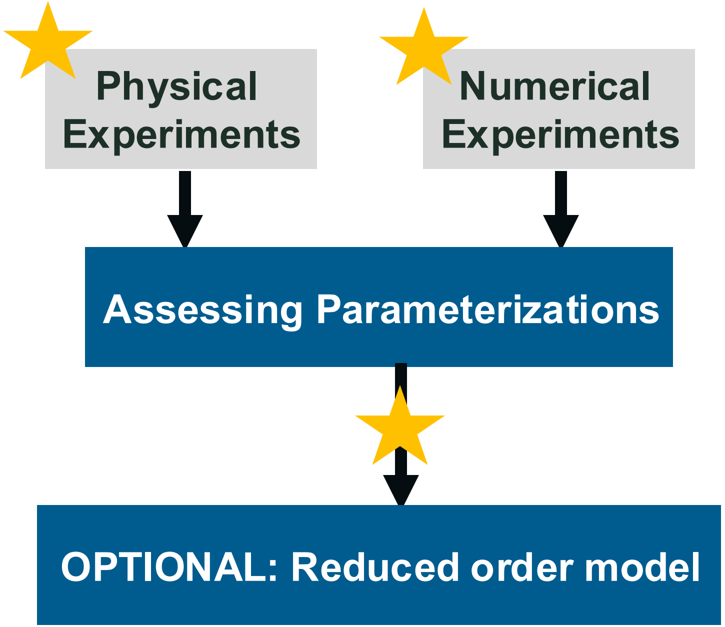
Next Steps

- Finalize analysis and submit reports.
- Utilize results from experimental program to **assess parameterizations** of munition mobility for irregularly shaped grains.
- Gather knowledge gained through the experimental and numerical programs to **publish results**.



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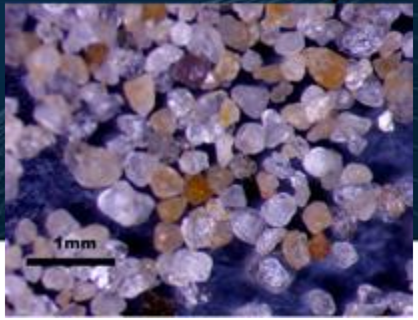
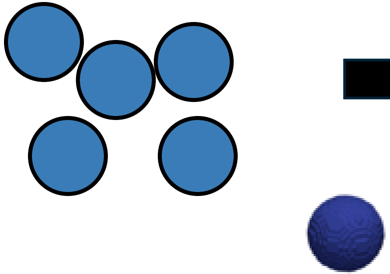
RESULTS TO DATE

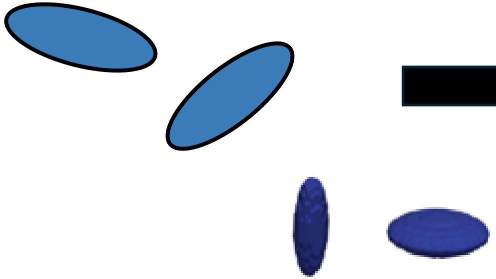
Numerical Experiments

Particle shapes





Simple spherical



Spheroidal particle

Angular particle

	Sphere	Cube	Octahedron
Corey Shape Factor	1	1	0.71
Sphericity	1	0.81	0.82

- Decrease in sphericity and increase in angularity leads to lower settling velocity
- Flow separation is more likely to occur for non-spherical

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Effect of bed with octahedrons

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{1}{Re_\delta}\frac{\partial^2 U_i}{\partial x_j^2} + \Pi(t) \quad ; \quad \frac{\partial U_i}{\partial x_i} = 0$$

oscillatory forcing

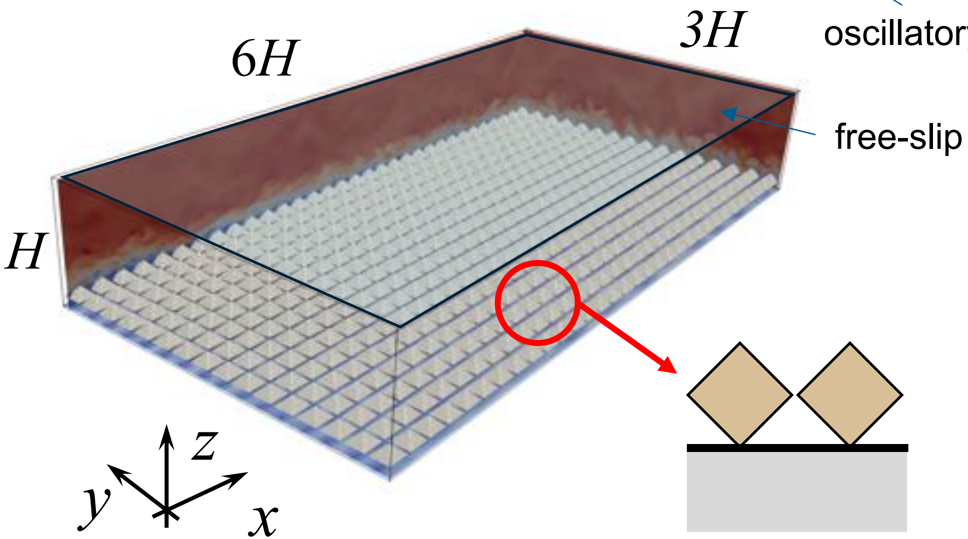
$$Re_\delta = \frac{U_0 \delta}{\nu}$$

Stokes layer depth

$$\delta = \sqrt{\frac{2\nu}{\omega}}$$

$$Re_\delta = 90,\ 190,\ 765,\ 1200 \qquad \frac{\delta}{H} = 0.17$$

Laminar → **Turbulent**

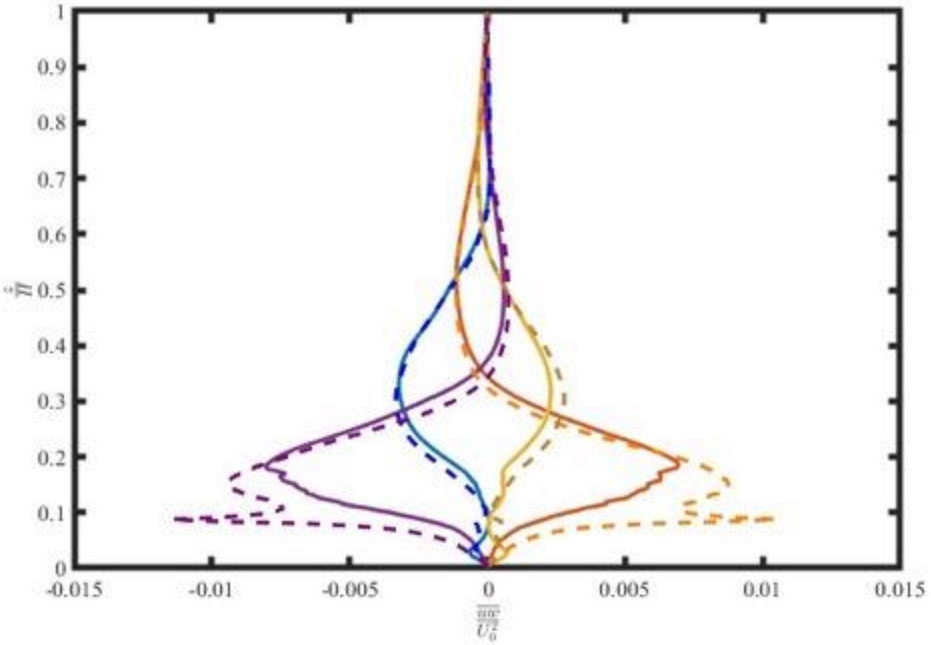


Second-order centered finite-difference scheme with staggered Cartesian grid. Third-order Runge-Kutta method with fractional-step (Orlandi, 2000)

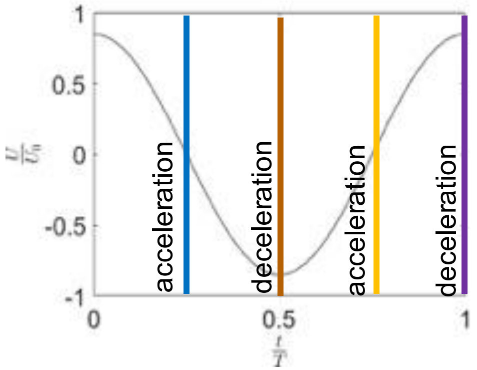
Bed particles with Immersed Boundary method & applied B.C. (Orlandi & Leonardi, 2006)

Reynolds Stresses

$Re_\delta = 1800$



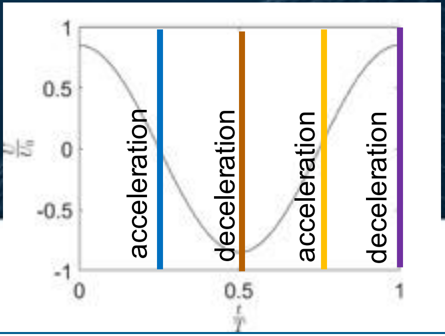
$$\frac{\delta}{H} = 0.17$$



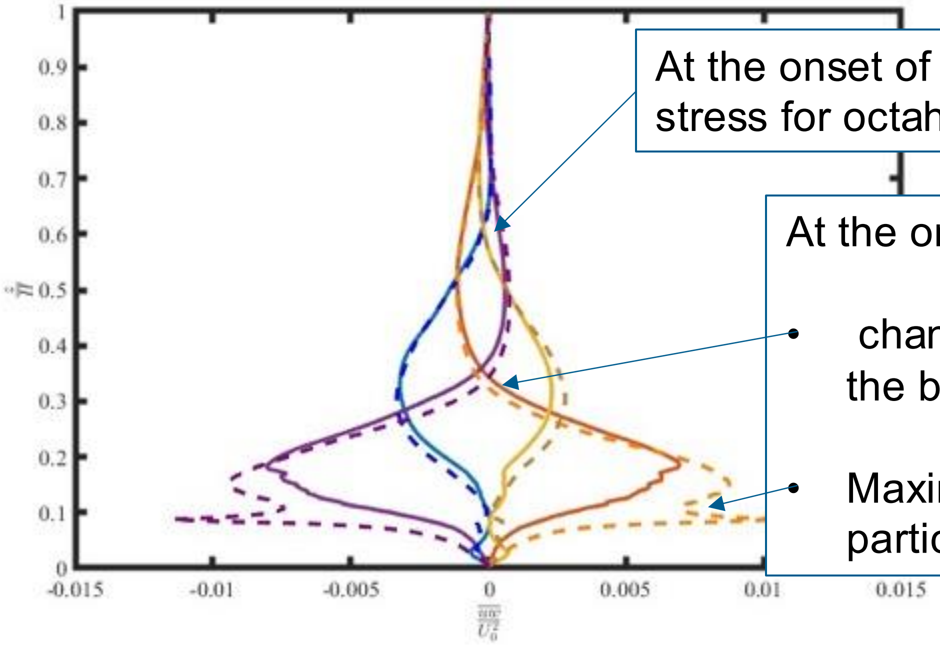
Legend

———	Spherical particles
– – – – – –	Octahedral particles

Reynolds Stresses



$Re_\delta = 1800$



At the onset of acceleration, changing sign of Reynolds stress for octahedral and spherical collapse at same height.

At the onset of deceleration:

- changing sign of Reynolds stress occurs closer to the bed for octahedral particles than for spherical.
- Maximum Reynolds stress is higher for octahedral particles due to angularity.

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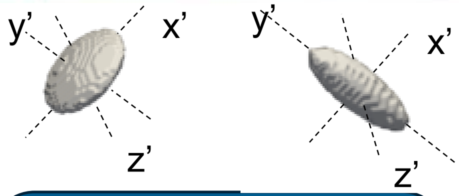
Non-spherical particle dynamics



Ensure correct particle orientation → Particle – fluid coupling → Particle angular kinematics

$$\beta_0 = cos(\frac{\phi}{2})cos(\frac{\theta}{2})cos(\frac{\psi}{2}) + sin(\frac{\phi}{2})sin(\frac{\theta}{2})sin(\frac{\psi}{2})$$

$$\beta_1 = sin(\frac{\phi}{2})cos(\frac{\theta}{2})cos(\frac{\psi}{2}) - cos(\frac{\phi}{2})sin(\frac{\theta}{2})sin(\frac{\psi}{2})$$

$$\beta_2 = cos(\frac{\phi}{2})sin(\frac{\theta}{2})cos(\frac{\psi}{2}) + sin(\frac{\phi}{2})cos(\frac{\theta}{2})sin(\frac{\psi}{2})$$

$$\beta_3 = cos(\frac{\phi}{2})cos(\frac{\theta}{2})sin(\frac{\psi}{2}) - sin(\frac{\phi}{2})sin(\frac{\theta}{2})cos(\frac{\psi}{2})$$

$$\boldsymbol{M_f} + \int_{CS} \boldsymbol{r} \times (\boldsymbol{\sigma_{ij}}) \cdot \boldsymbol{dA}$$

$$=$$

$$\frac{\partial}{\partial t}\int_{CV} \boldsymbol{r} \times \vec{V} \rho d\forall + \int_{CS} \rho \boldsymbol{r} \times \vec{V}(\vec{V_n} \cdot \boldsymbol{dA})$$

$$I'_{x_1x_1}\frac{d\omega'_{x_1}}{dt} - \omega'_{x_2}\omega'_{x_3}(I'_{x_2x_2} - I'_{x_3x_3}) = N'_{x_1},$$

$$I'_{x_2x_2}\frac{d\omega'_{x_2}}{dt} - \omega'_{x_3}\omega'_{x_1}(I'_{x_3x_3} - I'_{x_1x_1}) = N'_{x_2},$$

$$I'_{x_3x_3}\frac{d\omega'_{x_3}}{dt} - \omega'_{x_1}\omega'_{x_2}(I'_{x_1x_1} - I'_{x_2x_2}) = N'_{x_3},$$

$$I_i = \rho \int r^2 dV$$

$$m_p \frac{d\boldsymbol{v}_p}{dt} = \int_S \boldsymbol{T} \cdot \boldsymbol{n} dS$$

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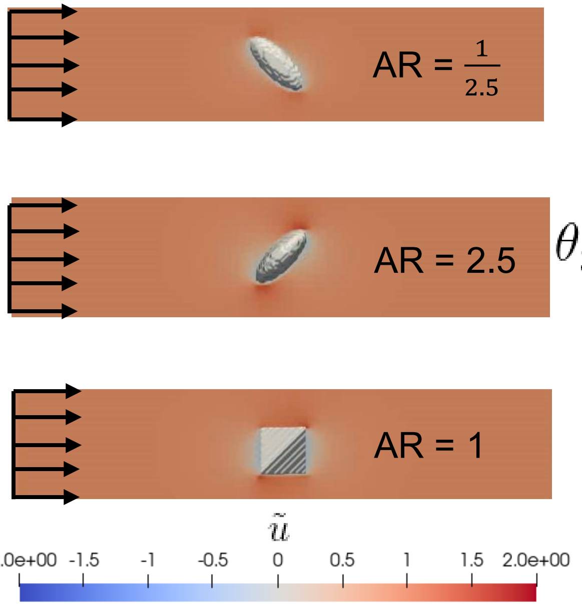
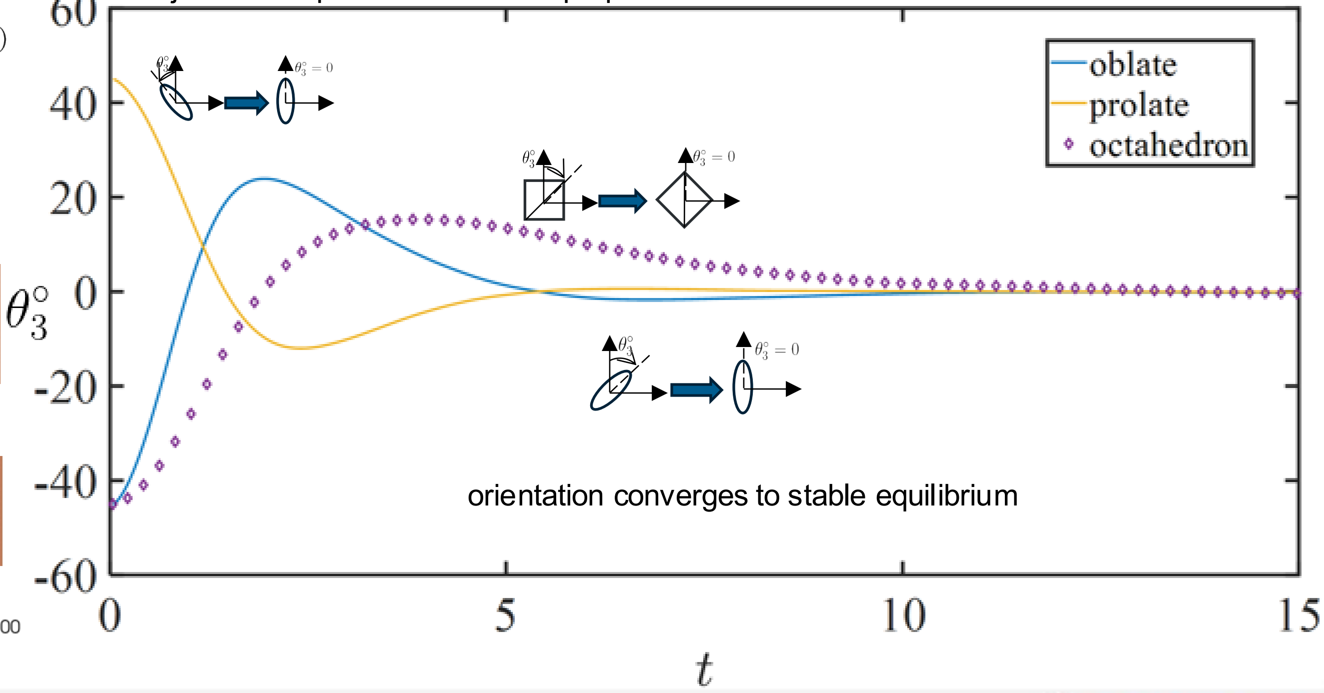
Particle rotation (translation constrained)

Uniform inflow, $Re = 100$

$I_{z(prolate)} < I_{z(oblate)} < I_{z(octahedron)}$



major axes of particles stabilizes perpendicular to the flow direction



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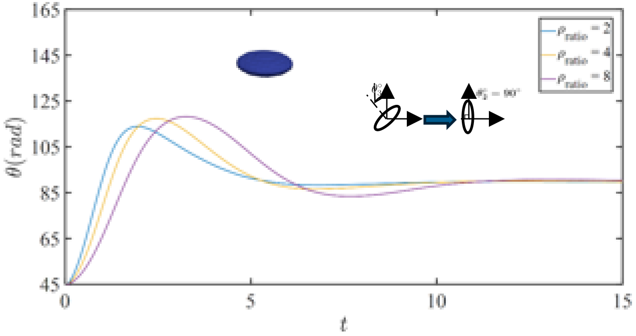
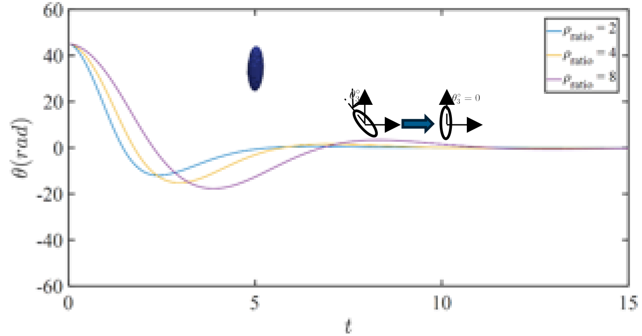
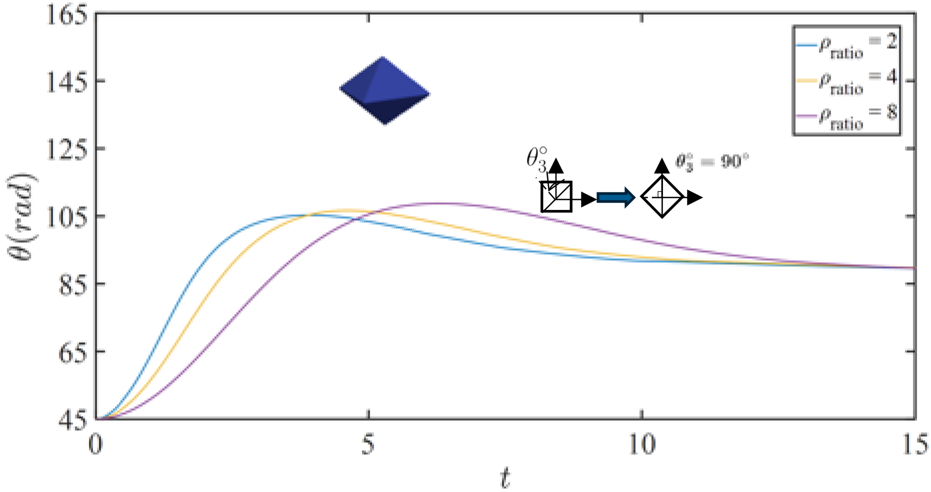
Density ratios



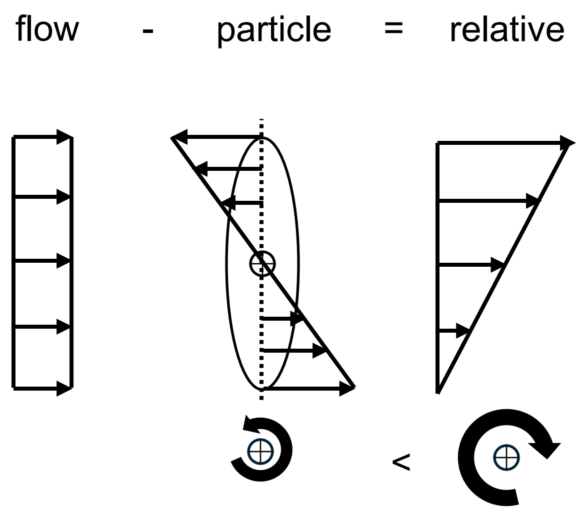




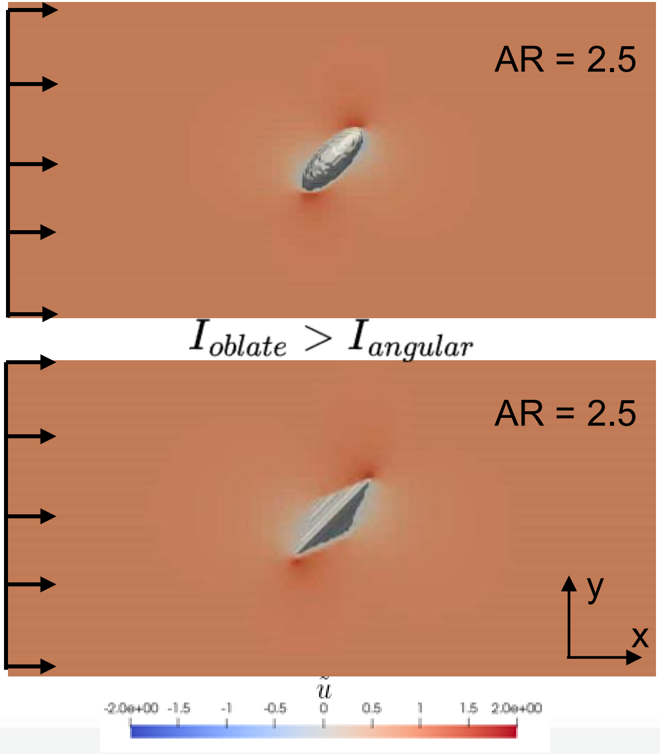
With increasing density ratio, amplitude increases

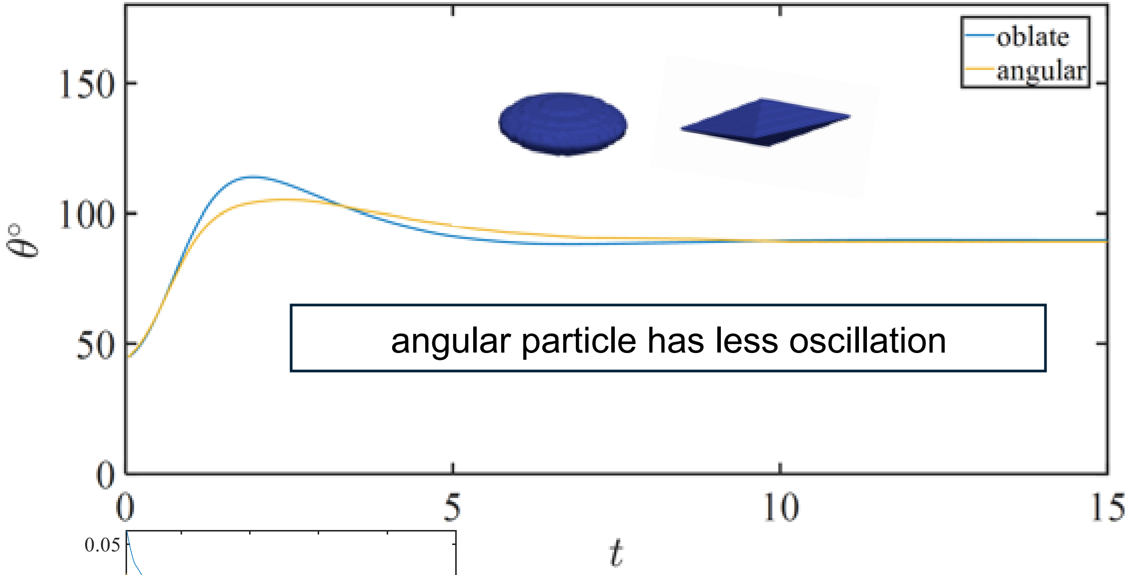
$$\rho_{ratio} = \frac{\rho_{particle}}{\rho_{fluid}}$$

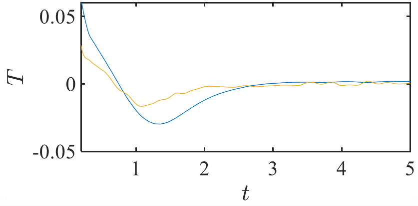
Stability



Angular particle with aspect ratio







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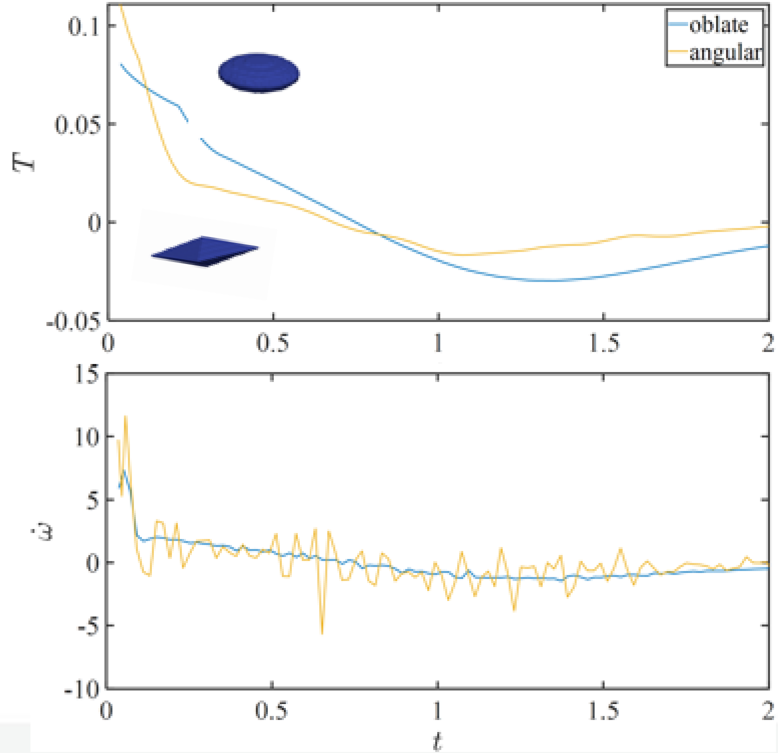
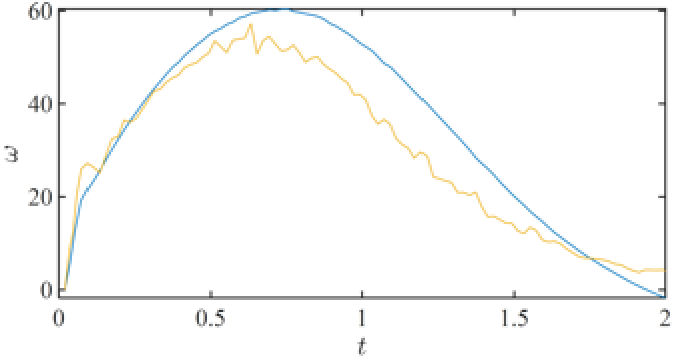
Angular particle with aspect ratio



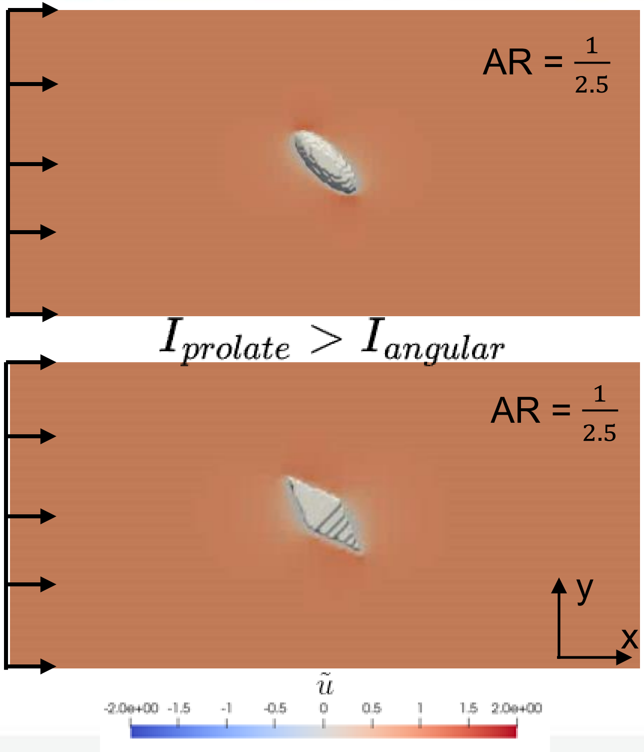
The angular oblate has lower torque and angular acceleration.

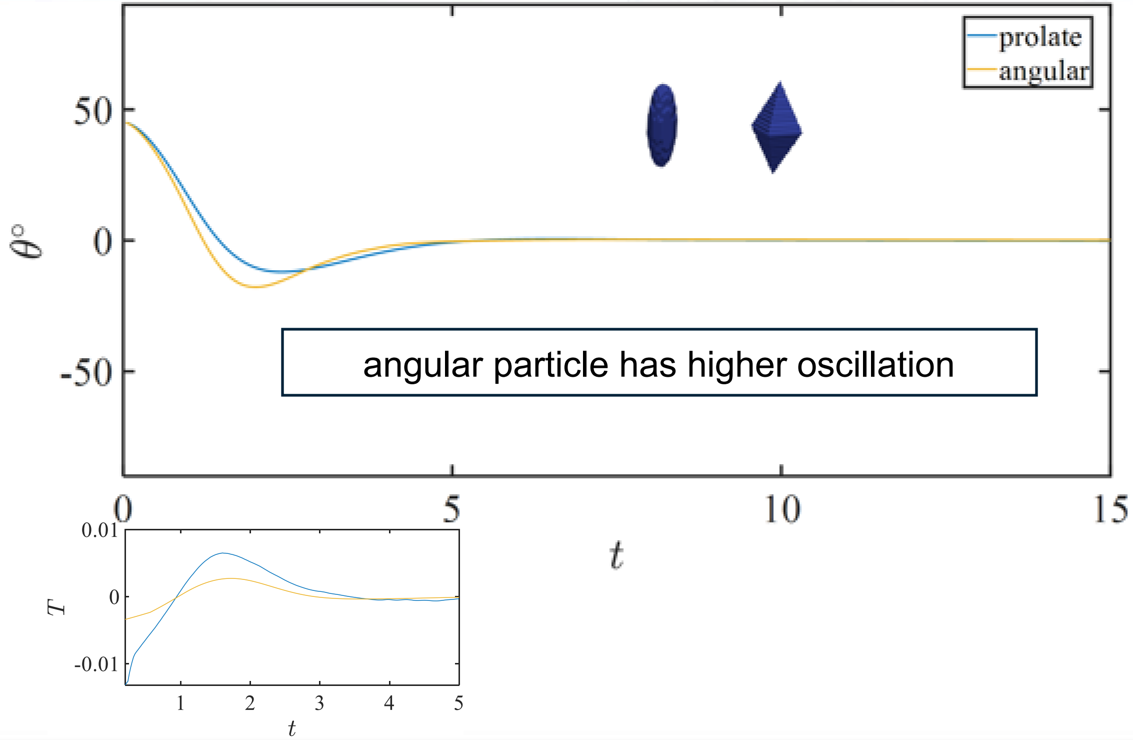
$$\frac{I_{smooth}}{I_{angular}} \approx 1.8$$

This results to lower magnitude of angular velocity and lower oscillation amplitude.

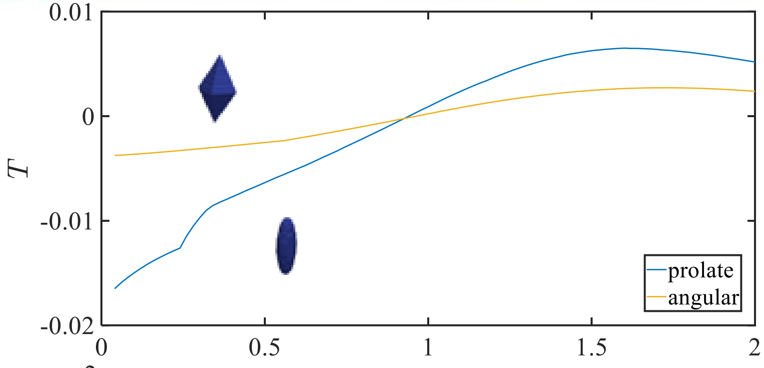


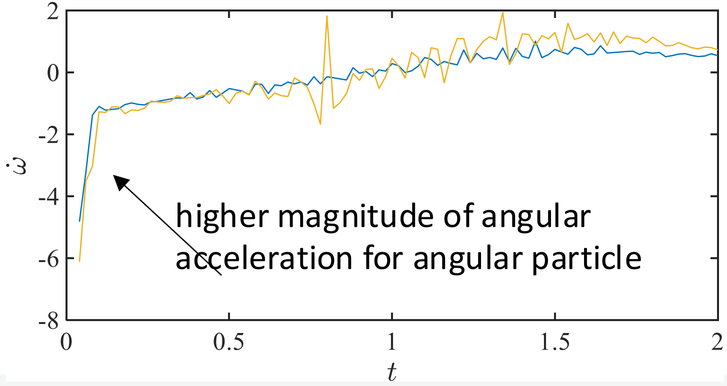
Angular particle with aspect ratio





Angular particle with aspect ratio



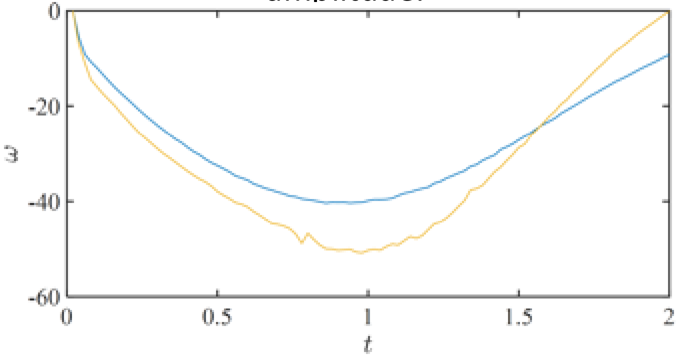


Torque is higher in magnitude for smooth prolate but the **resulting acceleration** of the angular prolate is higher due to differences in moment of inertia.

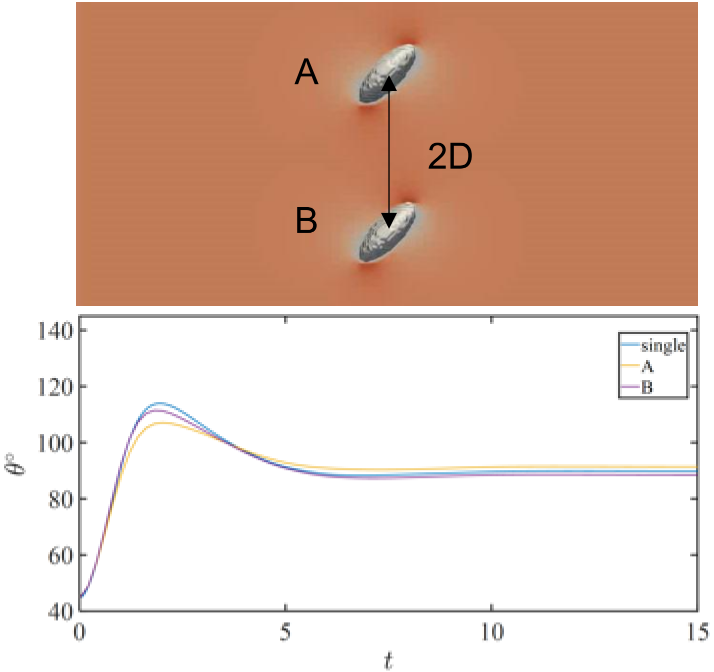
$$\frac{I_{smooth}}{I_{angular}} \approx 2.7$$

$$\frac{d\omega}{dt} = \frac{T}{I_z}$$

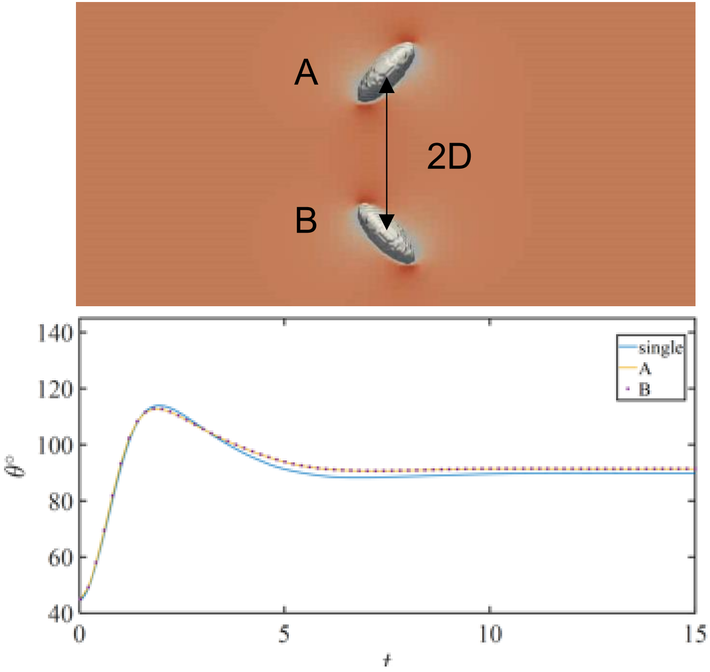
This results to higher magnitude of angular velocity and higher oscillation amplitude.



Particles in tandem

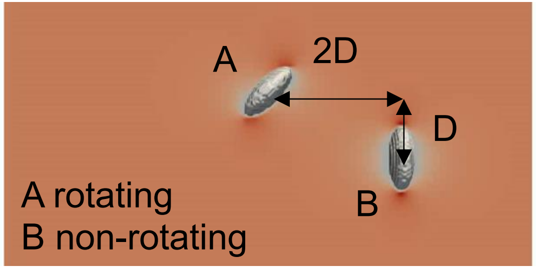


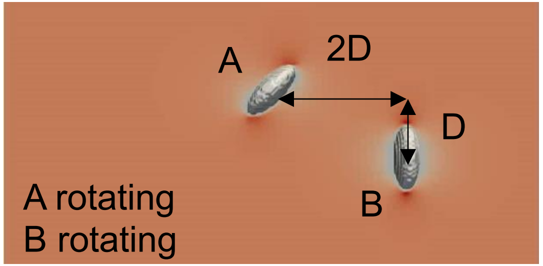
Both particles experience damping.
A is damped more than B

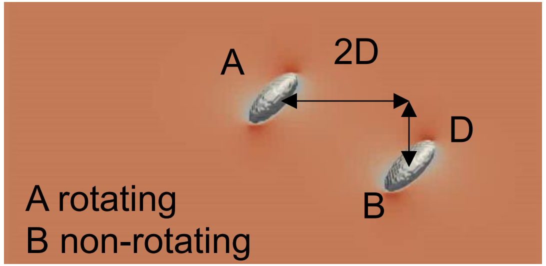


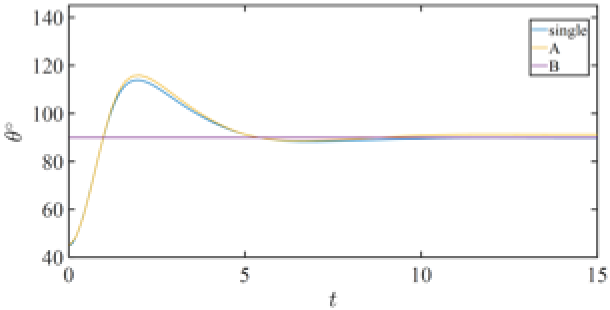
Similar damping due to symmetry. (B is multiplied by -1 for visualization)

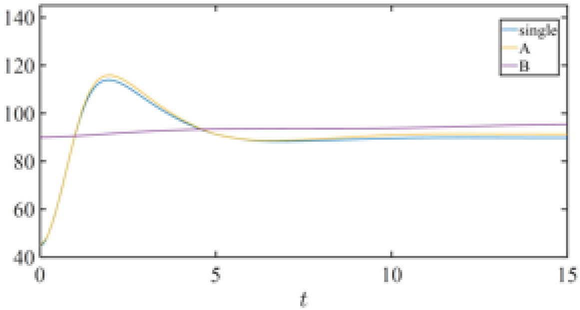
Particles in tandem

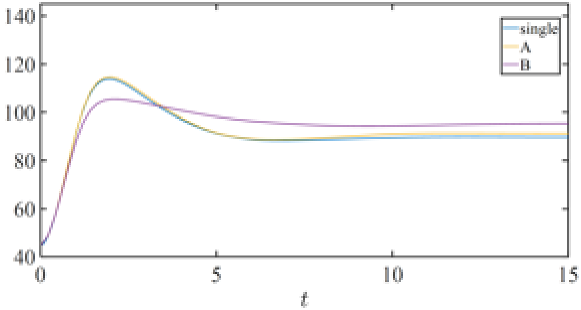












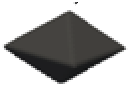
Oscillations amplified due to presence of B.

Similar effect when B is rotating.

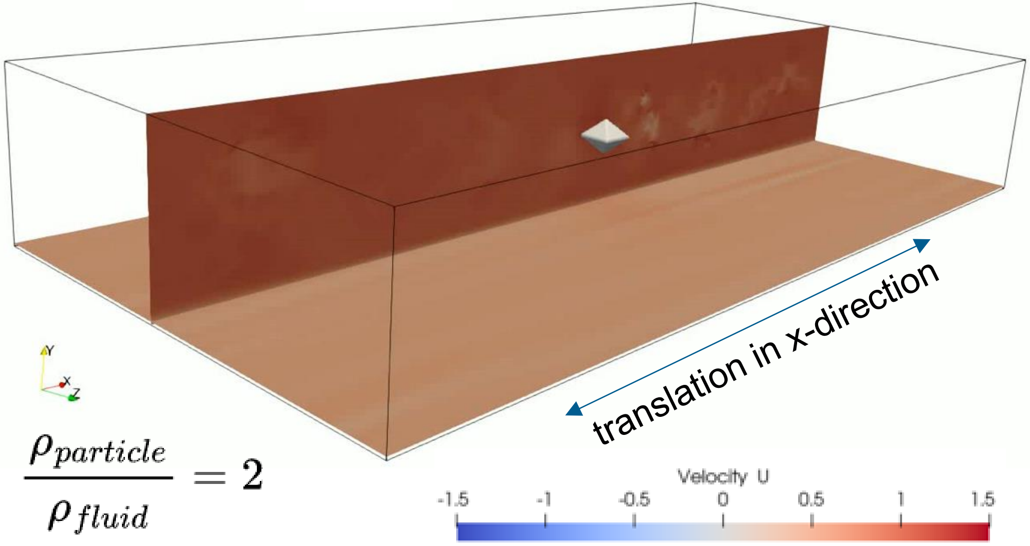
Minimal effect on A when B is initially 45°. Initial orientation of the B matters.

Particle rotation with translation in oscillatory flow

Octahedron



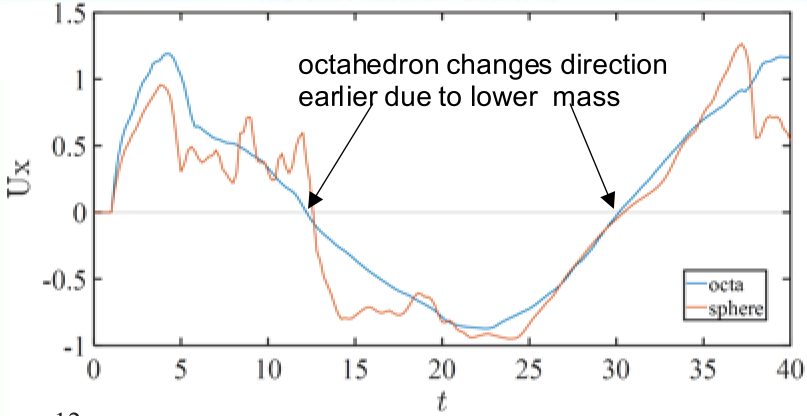
$Re_\delta = 1800$

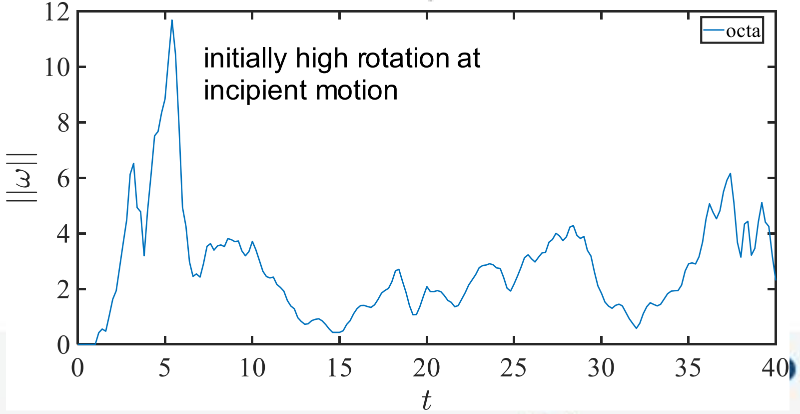


$$\frac{\rho_{particle}}{\rho_{fluid}} = 2$$

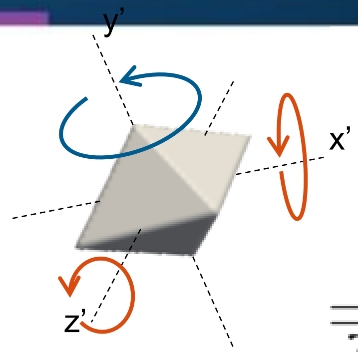
$$\frac{\delta}{H} = 0.17$$

* ω in radians/ time unit





Tumbling and spinning

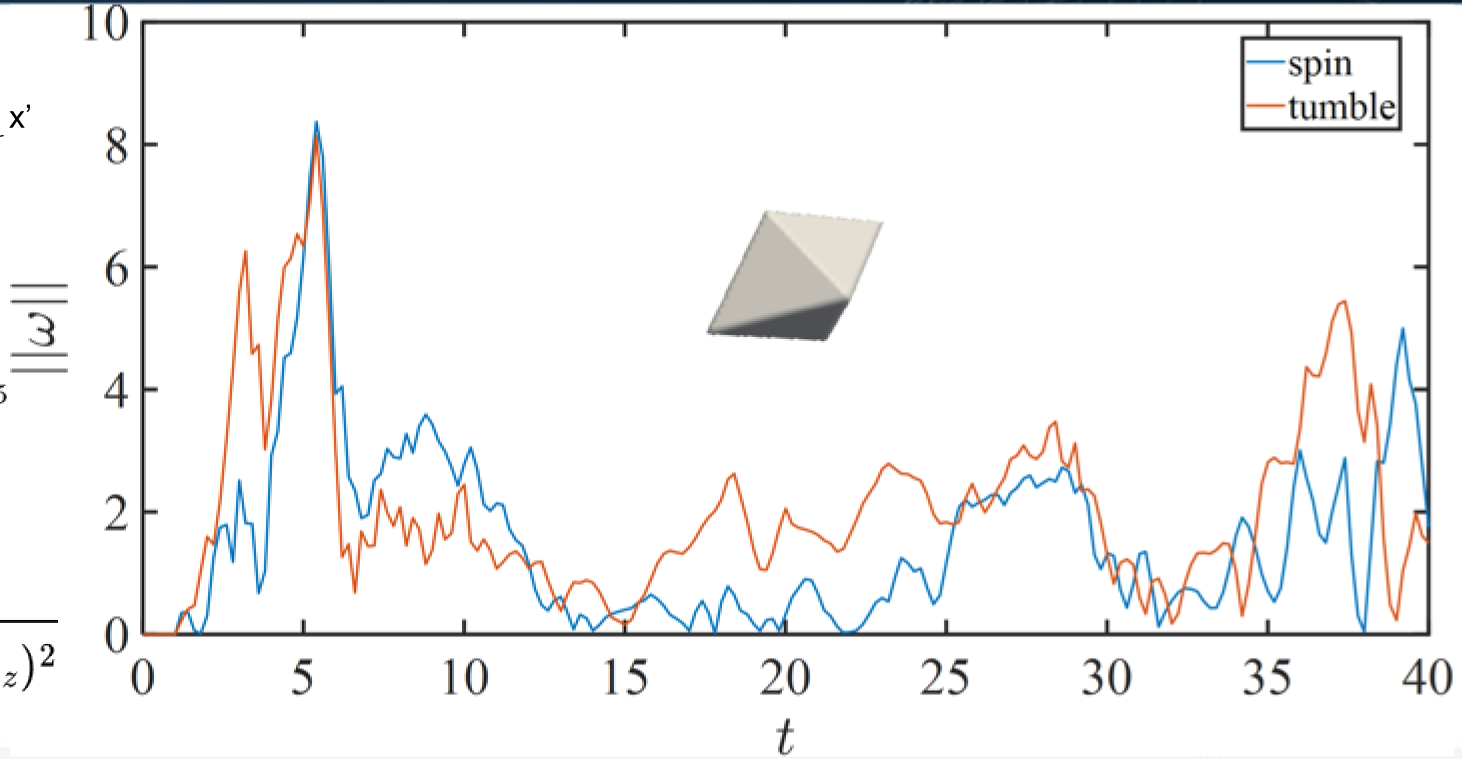


$$I_z = I_x = 5.12 \times 10^{-5}$$

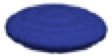
$$I_y = 7 \times 10^{-5}$$

$$\omega_s = |\omega_y|$$

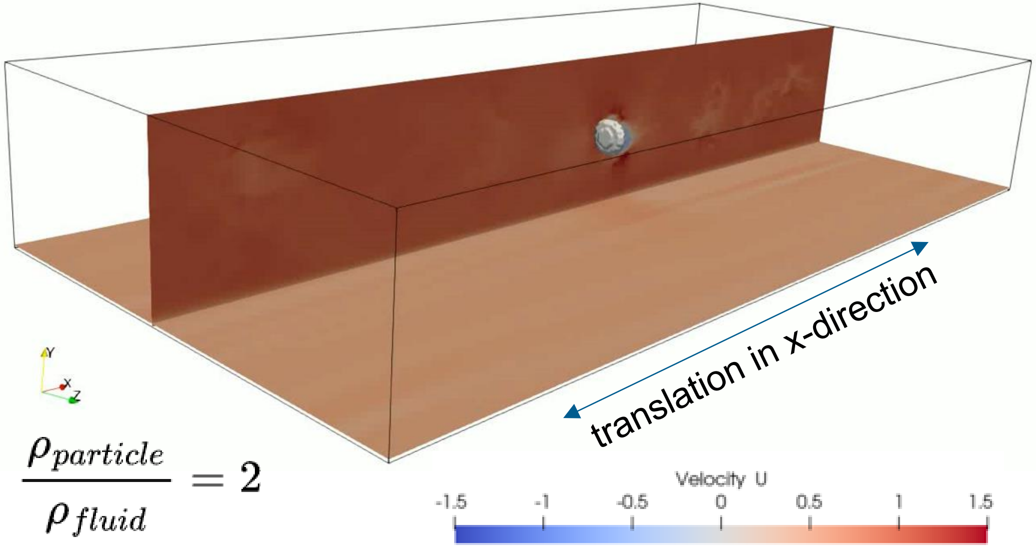
$$\omega_t = \sqrt{(\omega_x)^2 + (\omega_z)^2}$$



Particle rotation with translation in oscillatory flow

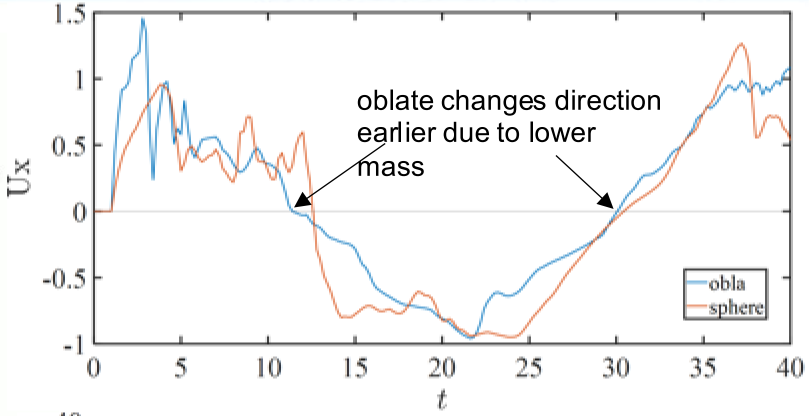
Oblate 

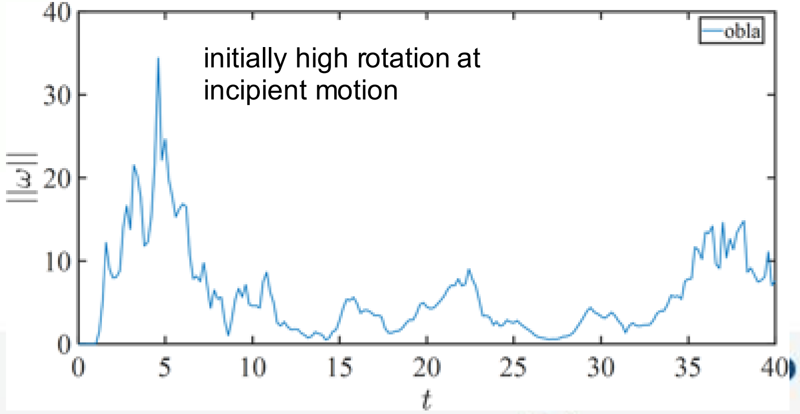
$Re_\delta = 1800$



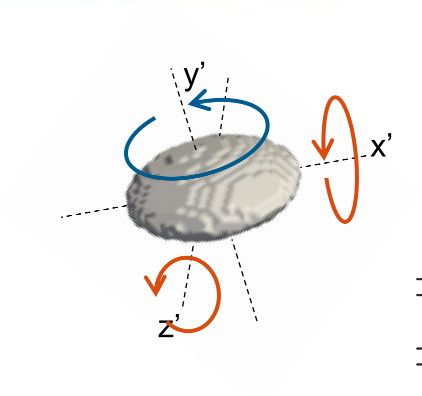
$$\frac{\rho_{particle}}{\rho_{fluid}} = 2$$

* ω in radians/ time unit





Tumbling and spinning

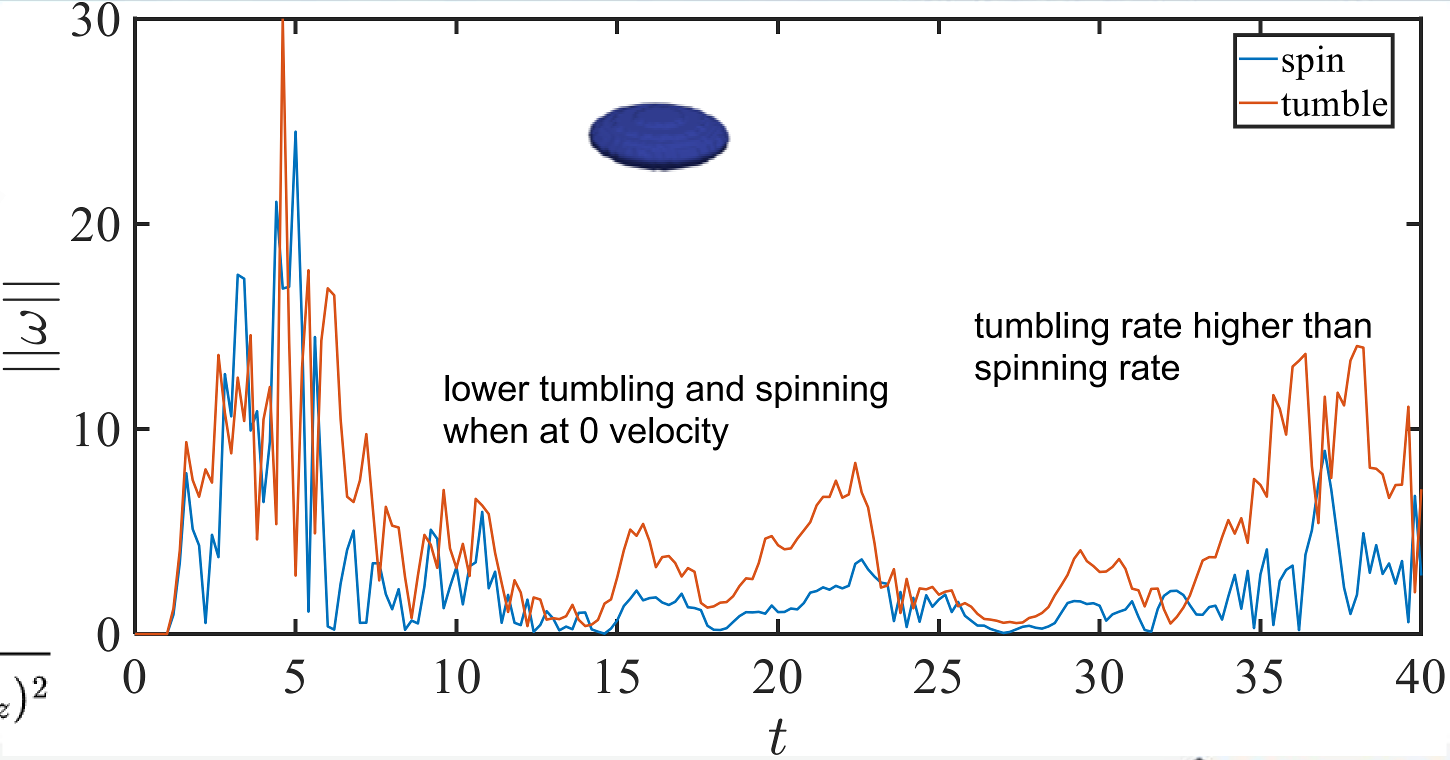


$$I_z = I_x = 2.45 \times 10^{-5}$$

$$I_y = 4.19 \times 10^{-5}$$

$$\omega_s = |\omega_y|$$

$$\omega_t = \sqrt{(\omega_x)^2 + (\omega_z)^2}$$



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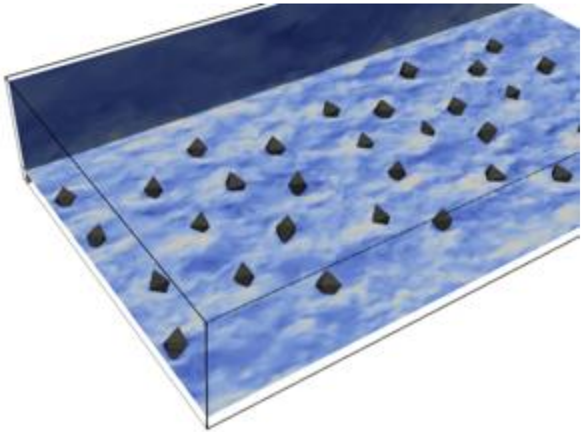
Summary

- Angular particles contribute to higher roughness in the bed leading to higher Reynolds stresses.
- Position and initial orientation of the particles has significant effect on the rotation kinematics.
- Implementing angularity on particles with different aspect ratios have different effects on the kinematics.
- Oblate particles experience higher tumbling than spinning. (combined effects of wake and ratio of moment of inertia of the axes)
- Particle rotation is minimum when particle is changing directions in oscillatory flow.



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Next Steps

- Simulate particles with geometry obtained from experimental campaign in Vieques
- Carry out sensitivity analysis to the shape and position of the particles to deduce reduced order models
- Compare simulation results with particles vary with regular and irregular shape

Technology Transfer (FY24)

- Ciri, U., Rodriguez-Abudo, S. and S. Leonardi, 2024, *Comparison between shear-driven and pressure-driven oscillatory flows over ripples*, **J. of Fluid Mech**. doi:10.1017/jfm.2024.931.
- Tubije, J. M. B., Ciri, U., Rodriguez-Abudo, S., & Leonardi, S., 2024, *Numerical investigation of angular particle dynamics*. **TACCSTER Meeting**, Austin, TX.
- Rodriguez-Abudo, S. and T. Santiago, 2024, *Fluid-Sediment-Object Interaction Under Oscillatory Flow*, 77th Annual **APS-DFD Meeting**, Salt Lake City, UT.
- Ciri, U., Rodriguez-Abudo, S. and S. Leonardi, 2024, *Numerical simulations of oscillatory flow over rough beds with different shapes and angularity*, 77th Annual **APS-DFD Meeting**, Salt Lake City, UT.
- Tubije, J. M. B., Ciri, U., Rodriguez-Abudo, S., & Leonardi, S., 2024, *Numerical investigation of angular particle dynamics*. 77th Annual **APS-DFD Meeting**, Salt Lake City, UT.
- Rodriguez-Abudo, S. and S. Leonardi, 2024, *Experimental and Numerical Investigation of Grain Shape Effects on Munition Mobility*, **SERDP Symposium,** Washington DC.

Technology Transfer: Transition Plan

- The knowledge gathered through this study seeks to inform the way current efforts, such as the Underwater Munitions Expert System (Rennie, 2017), predict mobility, burial and re-exposure of underwater munitions in tropical settings. We will share the data with the relevant experts and pursue enhancements as appropriate.
- All PIV data and PIV-derived quantities will be accessible to the program office, colleagues, and relevant repositories.

Issues

- **Experimental program** and **coding took longer** than anticipated.
  - Instrumentation and personnel issues.
- Funds on track to be fully spent by Jan. 2026 but **UPRM invoicing delayed**.

BACKUP MATERIAL

MR-1291: Experimental and Numerical Investigation of Grain Shape Effects on Munition Mobility

Performers:

Sylvia Rodríguez-Abudo, University of Puerto Rico - Mayaguez
Stefano Leonardi, University of Texas – Dallas

Technology Focus:

Munition mobility for irregularly shaped sand grains.

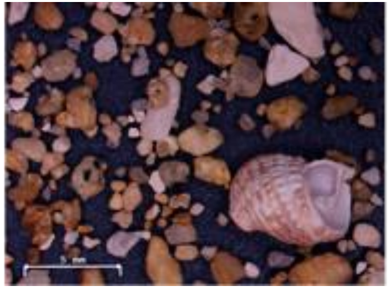
Research Objectives:

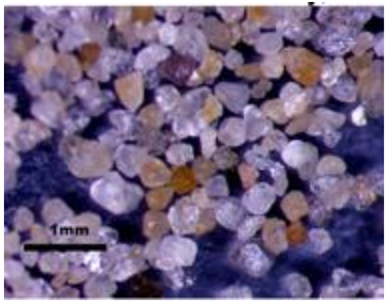
- **Quantify** the **role** of **grain shape** and **angularity** on munition **mobility.**
- **Assess** the validity and/or **propose** modifications to current **predictive models** addressing **munition mobility** for irregularly shaped grains.
- **Resolve** the physics of **flow entrainment** at the **grain-scale** and characterize its **fundamental differences** for **spherical** vs **irregularly shaped** substrates.

Project Progress and Results

Full-scale experiments completed. Analysis underway. Numerical code for non-spherical particles developed and validated.

Calcareous sand





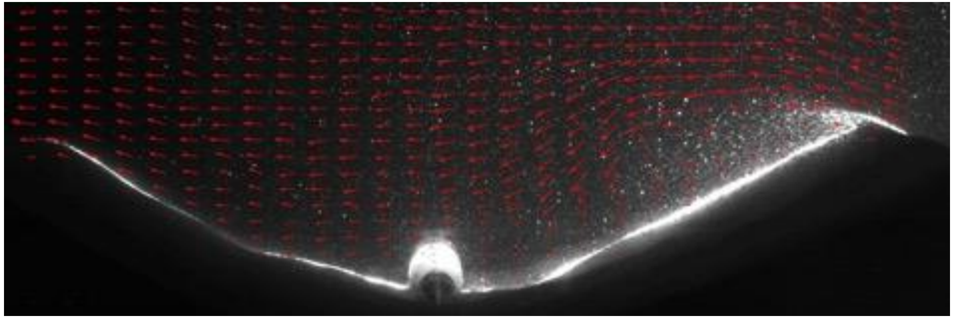
Silica sand

Plain Language Summary

- This project focuses on munition mobility for irregularly shaped sand grains.
- We have undertaken full-scale laboratory observations of munition mobility on silica (regular shape) and calcareous (irregular shape) sands. Numerical code has been developed to assess the physics of flow around irregularly shaped particles.
- The knowledge gathered through this study seeks to inform the way current efforts, such as UNMES, predict mobility, burial and re-exposure of underwater munitions in tropical settings.

Impact to DoD Mission

A numerical approach to study flow around irregularly-shaped particles and their interaction has been developed and validated. The experimental campaign suggests significantly more burial for irregular grains, typical of calcareous sand in the tropics.



The code can be used for several applications involving flow-particle interactions. Results of the experimental work will help better inform tracking and predictions of munition mobility.

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Action Items

- The team is behind on various QPR and interim reports. Will work on those ASAP to close the project appropriately.

Publications (FY24)

- Ciri, U., Rodriguez-Abudo, S. and S. Leonardi, 2024, *Comparison between shear-driven and pressure-driven oscillatory flows over ripples*, **J. of Fluid Mech**. doi:10.1017/jfm.2024.931.
- Tubije, J. M. B., Ciri, U., Rodriguez-Abudo, S., & Leonardi, S., 2024, *Numerical investigation of angular particle dynamics*. **TACCSTER Meeting**, Austin, TX.
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Literature Cited

- Orlandi P. & Leonardi S. (2006). DNS of turbulent channel flows with two- and three-dimensional roughness. Journal of Turbulence 7, 1-22.
- Orlandi & Leonardi (2008) DNS of 3D turbulent rough channels: parametrization and flow physics. J. Fluid Mech., vol. 606, 399-415, (https://doi.org/10.1017/S0022112008001985).

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