MODELING THE EFFECTS OF OBJECT-INDUCED RESONANT TURBULENCE ENHANCEMENT OF SEAFLOOR OBJECT SCOUR AND BURIAL

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Abstract

As fluid flows around a seabed object, the object-induced turbulence intensifies sediment dynamics around and near the object as compared to the far field, which may enhance object scour at various points along the object as well as its overall burial. Empirical models of object scour and burial based on far-field parameterizations (e.g. Shields number) currently need to be tuned to specific object properties and environmental conditions and commonly exhibit high predictive uncertainties. Appalachian State's Applied Fluids Laboratory is working to improve existing object scour and burial models through the introduction of an amplification factor derived from a linear combination of dynamic turbulent kinetic energy (TKE) production components. The components correspond to resonance length scales representative of emergent turbulent structures (e.g. horseshoe and shed/wake vortices) as governed by the geometry of the object, instantaneous burial depth, orientation to flow, and forcing conditions. Using the open source computational fluids dynamics model OpenFOAM, we generate stress gradient fields and other diagnostics for a suite of simulations spanning a range of controls for steady and oscillatory flows to produce a "look-up" table of TKE production components. In the future, sediment entrainment and transport probabilities would be coupled to each TKE component and summed to yield a scalar amplification factor with associated uncertainties that can be applied to traditional equilibrium scour and burial depth predictions. We intend to present initial results of the calibration and validation of model predictions with available datasets and compare scour and burial depth predictions to those from traditional methods. Our goal is to provide the seafloor sciences community with a fast and effective improvement to the prediction of object scour and burial for a wide range of applications.

1.0 Theory

Seafloor object scour and burial models in use today are based on an empirical approach originally developed by Whitehouse [1] for scour around marine structures. Subsequent work by Trembanis et al. [2], Elmore et al. [3], Rennie et al. [4], Friedrichs [5], Demir and García [6] and others has led to parameterized community models for free objects such as unexploded ordinance (UXO), that must be tuned to specific forcing regimes, object geometries and material properties, and environmental conditions. These models continue to yield high uncertainties due to scarcity of data across a vast multi-dimensional parameter space, as well as the intrinsic complexity of the problem, including the effects of object geometry and orientation to flow on scour and burial processes.

Turbulent structures form near a sea bed object (Figure 1) at characteristic length scales governed by the size and shape of the object, its orientation to flow, as well as forcing conditions. As is well known, the distribution and intensity of resonant structures are not only the primary drivers behind scour and burial rates predicted by existing parametric models but enhance or suppress sediment scour and subsequent object burial. We seek to refine existing models using an *amplification factor* that modifies equilibrium burial depths (equation 1) predicted by existing parameterized models based a *turbulence sourcing function* (TSF, see right panel) that encapsulates the effects of object shape, orientation, and instantaneous burial depth. Instead of employing numerically intensive approaches (e.g. Jenkins et al., 2007), we seek a simple correlation between TSF and either the enhancement or suppression of B_{eq} and the rates of scour and burial. Using the open source CFD model OpenFOAM [7] for steady flows, we quantify the location and intensity of stress and related diagnostics relative to a baseline condition. Future work will include refinement for object orientation, instantaneous burial depth, and combined wave /current forcing, as well as sediment coupling probabilities from literature.

Enhanced equilibrium burial depth

Equilibrium burial depth from traditional methods

$$B_{eq} = \alpha B_{eq,0} \qquad (1)$$

Amplification factor

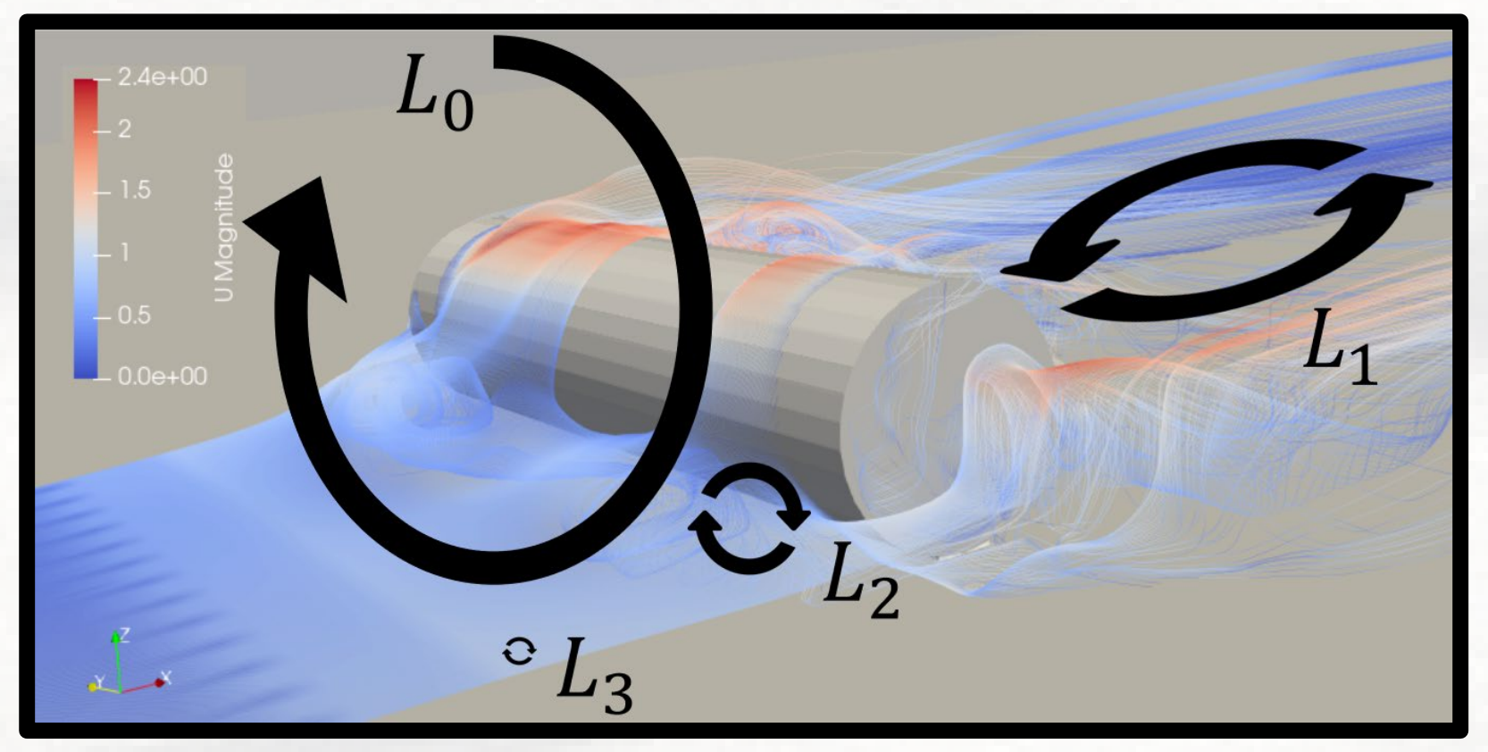


Figure 1: Resonant turbulent structures that emerge depending on object shape, size, orientation to flow, instantaneous burial depth, and forcing conditions..

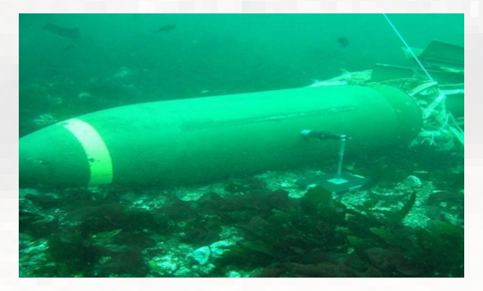
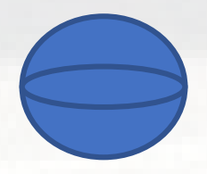
L_0 :	Large scale eddies of the scale of the boundary layer thickness that emerge primarily during flow reversal and burst events • Lead to large-scale mobilization and transport. We do not model these effects here.
L_1 :	Eddies on the scale of the object diameter that emerge primarily as shed structures from the top and sides of the object. • Responsible for diffusive near-object transport and downstream mobilization / bedforms.
L_2 :	Eddies on the scale of a fraction of the object diameter (e.g. bound and horseshoe structures). • Direct near-object mobilization / redistribution and transport. Can dominate near-object dynamics during clear-water scour.
L_3 :	Microscale turbulent stress on the scale of the grain diameter (e.g. far-field dynamics).

1.1 Turbulence Sourcing Function

We classify seabed objects into four types as shown below. We suggest the use of a "TKE sourcing function (TSF)," such as the ratio of object volume to surface area, that maps normalized object geometry to the potential for TKE production.

$$TSF = f(Cf, Af, Bf) \qquad (2)$$

Complexity factor (e.g. n_{edges}/n_{sides})
Asymmetry factor (e.g. COM/h)
Bulk factor (e.g. $L_0 A/V$)

Representative Object		Prelim TSF*	Seabed Objects	
Half-sphere		0.49		Rockan and Manta mines
Square Pyramid		0.73		
Cylinder*		1.00		Cylindrical mines, UXO, structures, etc.
Sphere		1.31		Spherical mines and structures
Rectangular solid		2.54		

** Normalized to cylinder*

2.0 OpenFOAM Configuration and Automation

Mesh Characteristics
– Finest resolution: 0.001 m
– Grossest resolution: 0.5 m
– Cells between refinement layers: 4
– Domain: 8x8x5 m, 16x16x10 cells

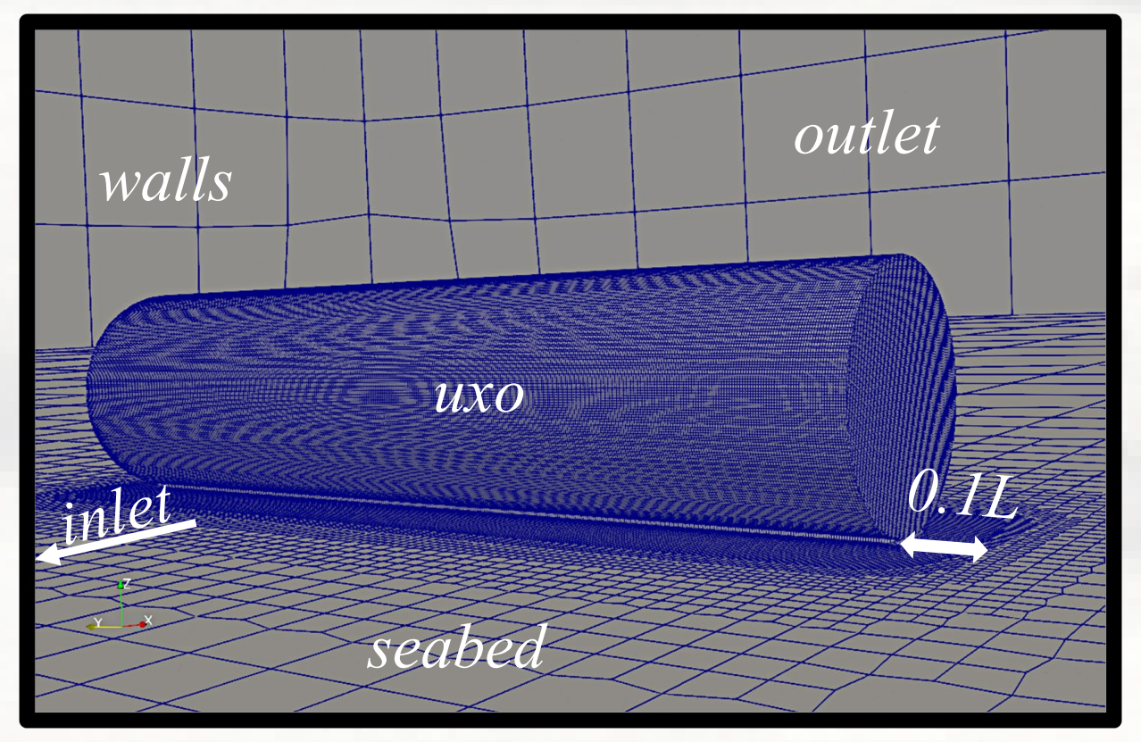
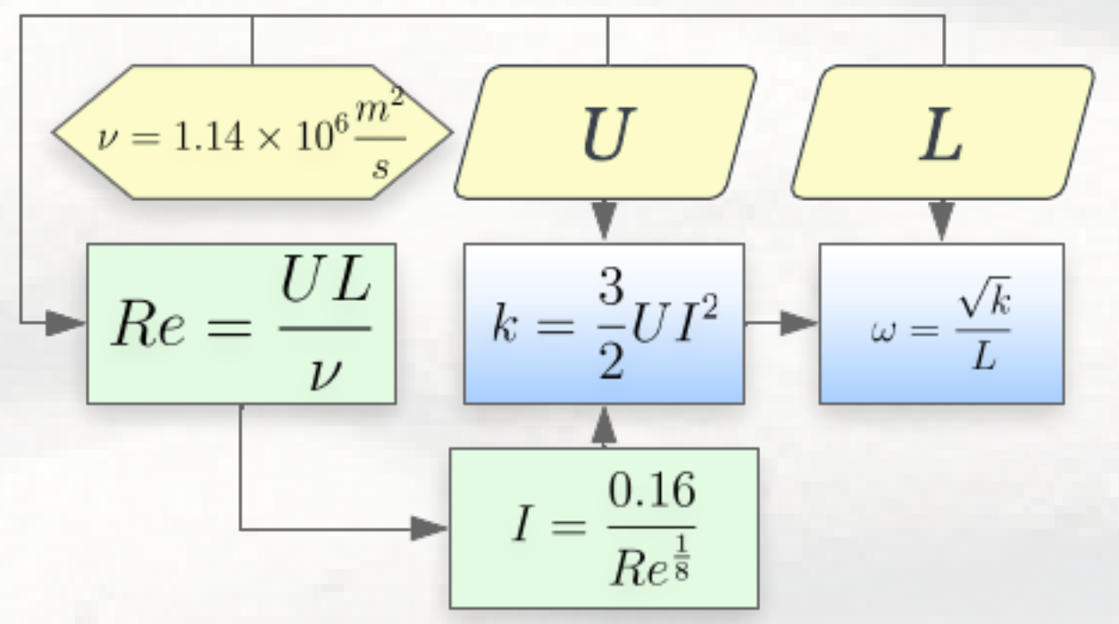


Figure 2: Example of our mesh near a 4:1 cylinder

Initial Conditions
– Turbulent kinetic energy (k)
– Specific rate of dissipation (*omega*)
– Turbulent viscosity (*nut*) = 0
– Pressure (p) = 0
– Flow velocity (U)



$$\nu = 1.14 \times 10^{6} \frac{m^2}{s}$$

U

L

$$Re = \frac{UL}{\nu}$$

$$k = \frac{3}{2} U I^2$$

$$\omega = \frac{\sqrt{k}}{L}$$

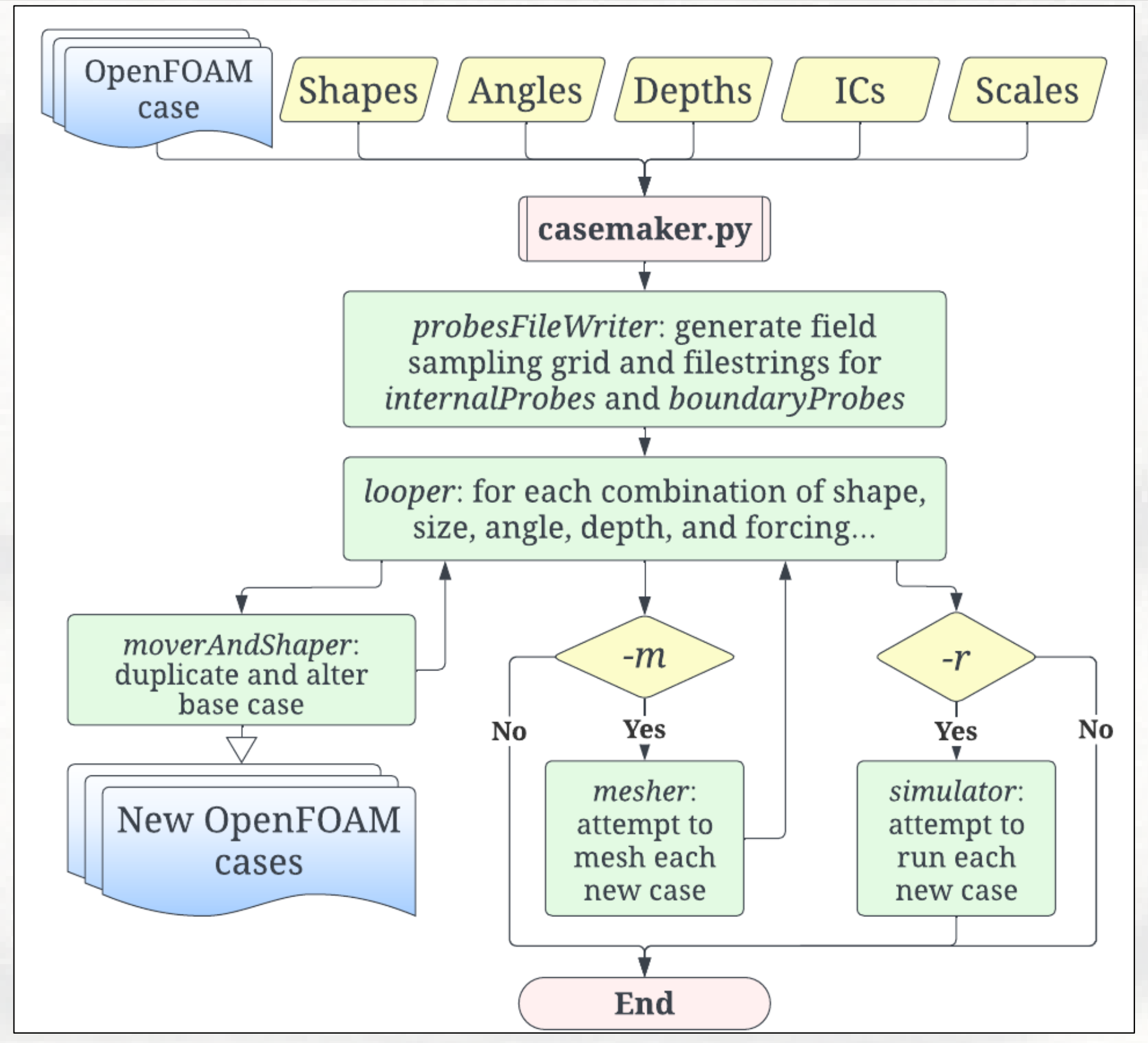
$$I = \frac{0.16}{Re^{\frac{1}{8}}}$$

Simulation Characteristics
- Time step: 0.005 s
- Simulation duration: 5 s
- Data write interval: 0.25 s
- Solver: SIMPLE algorithm
- Typical run time: ~ 11 hours
- Typical simulation size: ~ 350 GB

Automation
The script *casecopier.py* can duplicate a base OpenFOAM case for each combination among a set of forcing conditions, object shapes, sizes, flow respective rotation angles, and burial depths.

Boundary Conditions

	k	***omega***	***nut***	***p***	***U***
inlet	fixedValue	fixedValue	Calculated	zeroGradient	fixedValue
outlet	inletOutlet	inletOutlet	Calculated	fixedValue	inletOutlet
walls	Slip	Slip	Calculated	Slip	Slip
seabed	kqRWallFunction	omegaWallFunction	nutkWallFunction	zeroGradient	noSlip
uxo	kqRWallFunction	omegaWallFunction	nutkWallFunction	zeroGradient	noSlip



OpenFOAM case

Shapes

Angles

Depths

ICs

Scales

casemaker.py

probesFileWriter: generate field sampling grid and filestrings for *internalProbes* and *boundaryProbes*

looper: for each combination of shape, size, angle, depth, and forcing…

moverAndShaper: duplicate and alter base case

New OpenFOAM cases

-m

mesher: attempt to mesh each new case

-r

simulator: attempt to run each new case

End

References

[1] Whitehouse, R. 1998. Scour at Marine Structures. London, England: Thomas Telford Publications

[2] Trembanis, A. C., Friedrichs, C. T., Richardson, M. D., Traykovski, P., Howd, P. A., Elmore, P. A., & T.F. Wever. 2007. IEEE Journal of Oceanic Engineering, 32(1), 167–183.

[3] Elmore, P.A., S.E. Bradford, K.M. Duvieilh, M.D. Richardson, 2009, The Deterministic Mine Burial System, NRL/FR/7440--09-10,146.

[4] Rennie, S.E., A. Brandt, and C.T. Friedrichs. 2017. Ocean Engineering 131 (2017) 282–294.

[5] Friedrichs, C. 2018. Simple Parameterized Models for Predicting Mobility, Burial and Re-exposure of Underwater Munitions, SERDP Project MR-2224, May 2018

[6] Demir, S.T., García, M.H., 2007. Experimental Studies on Burial of Finite-Length Cylinders under Oscillatory Flow. J. Waterway, Port, Coastal, Ocean Eng. 133, 117–124.

[7] Weller, H. *et al.*, *OpenFOAM v11*. (OpenFOAM Foundation, United Kingdom, 2023).

[8] Jenkins, S.A., D.L. Inman, M.D. Richardson, T.F. Wever, J. Wasyl. Scour and Burial Mechanics of Objects in the Nearshore, IEEE Journal of Oceanic Engineering, 32(1), 167–183.

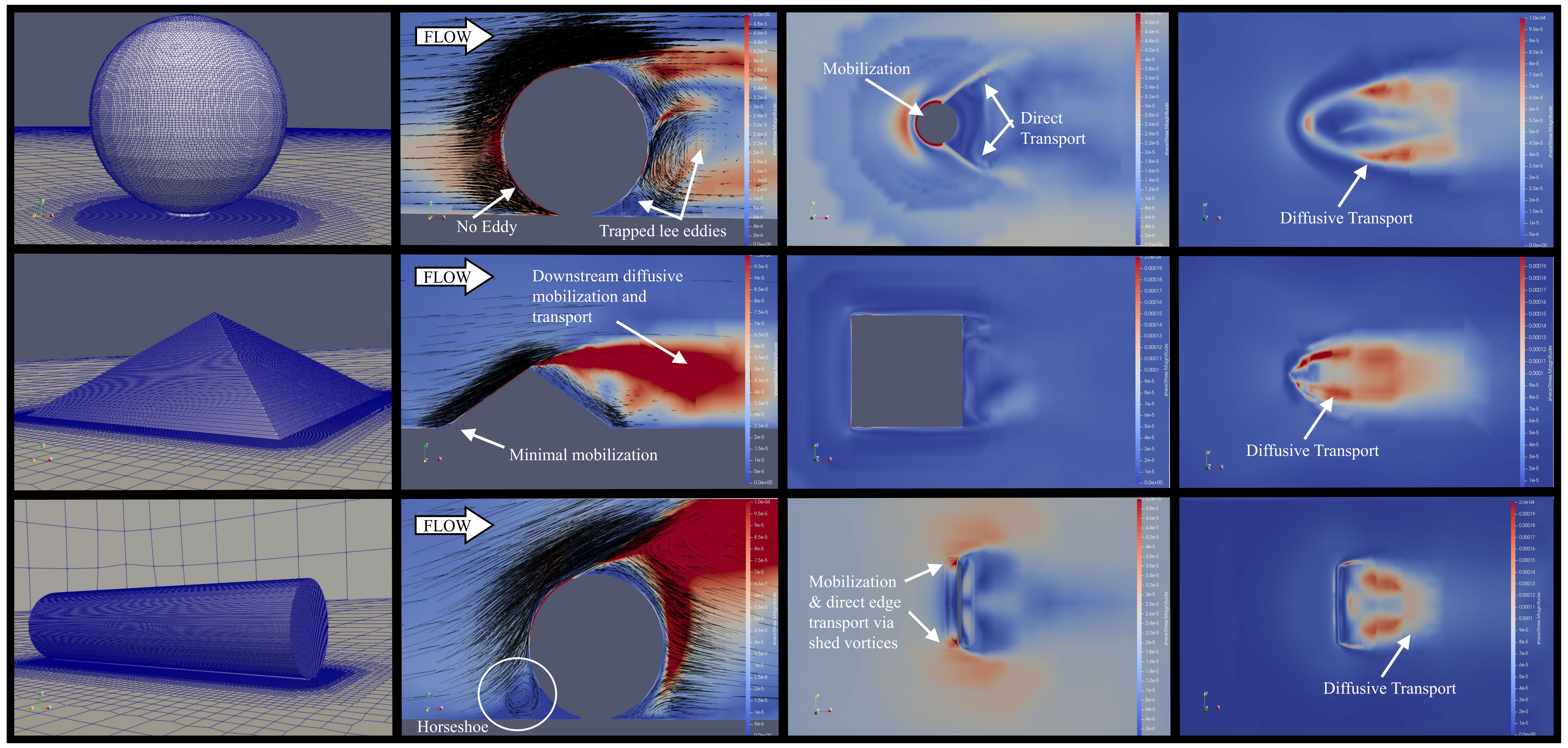
3.0 Results to Date

Mesh — Center Slice — Top-down: At Base — Top-down: At Top

Sphere
R=0.10m
TSF=1.31

Pyramid
H=0.10m
L=0.24m
TSF=0.73

Cylinder
D=0.10m
L=0.40m
TSF=1.00



We delineate emergent turbulent structures (quantified here via the maximum stress) above and below the center point of the object (See Figure 3). We simplify otherwise highly complex dynamics:

- ➢ Turbulence induced **below** the object center point will more likely couple **directly** to the seabed, mobilizing sediment near the object and either
  - reorganize sediment distribution near the object (e.g. mass-conserved scour pits), and/or
  - transport sediment away from the object
- ➢ Turbulence induced **above** the object center point will couple to the seabed sediment **diffusively**, transporting sediment entrained near the object (due to direct coupling) downstream, removing mass from around the object and (potentially) forming downstream bedforms.
  - Fine sediments would more easily mobilize and couple diffusively.

Plotting the mean (over θ) of the maximum stress as a function of preliminary TSF for the objects tested suggests that the TSF may be a strong predictor of scour enhancement or suppression (Figure 4).
- Recall, TSF does not encapsulate sediment coupling.

TSF may effectively represent the effects of object shape on equilibrium burial depth. Here, $\alpha^* = \partial_\theta \tau_{object} / \partial_\theta \tau_{ff}$ ranges from ~0.7 to ~1.5 over the range of proposed TSF tested (Figure 5). The overall amplification factor (future work) will be a function of α^* and will include sediment coupling, object density, and combined waves and currents:

$$\alpha = f\left(\alpha^*, \frac{\theta}{\theta_c}, KC, \frac{D}{d_{50}}, \rho_{obj}, \ldots\right) \qquad (3)$$

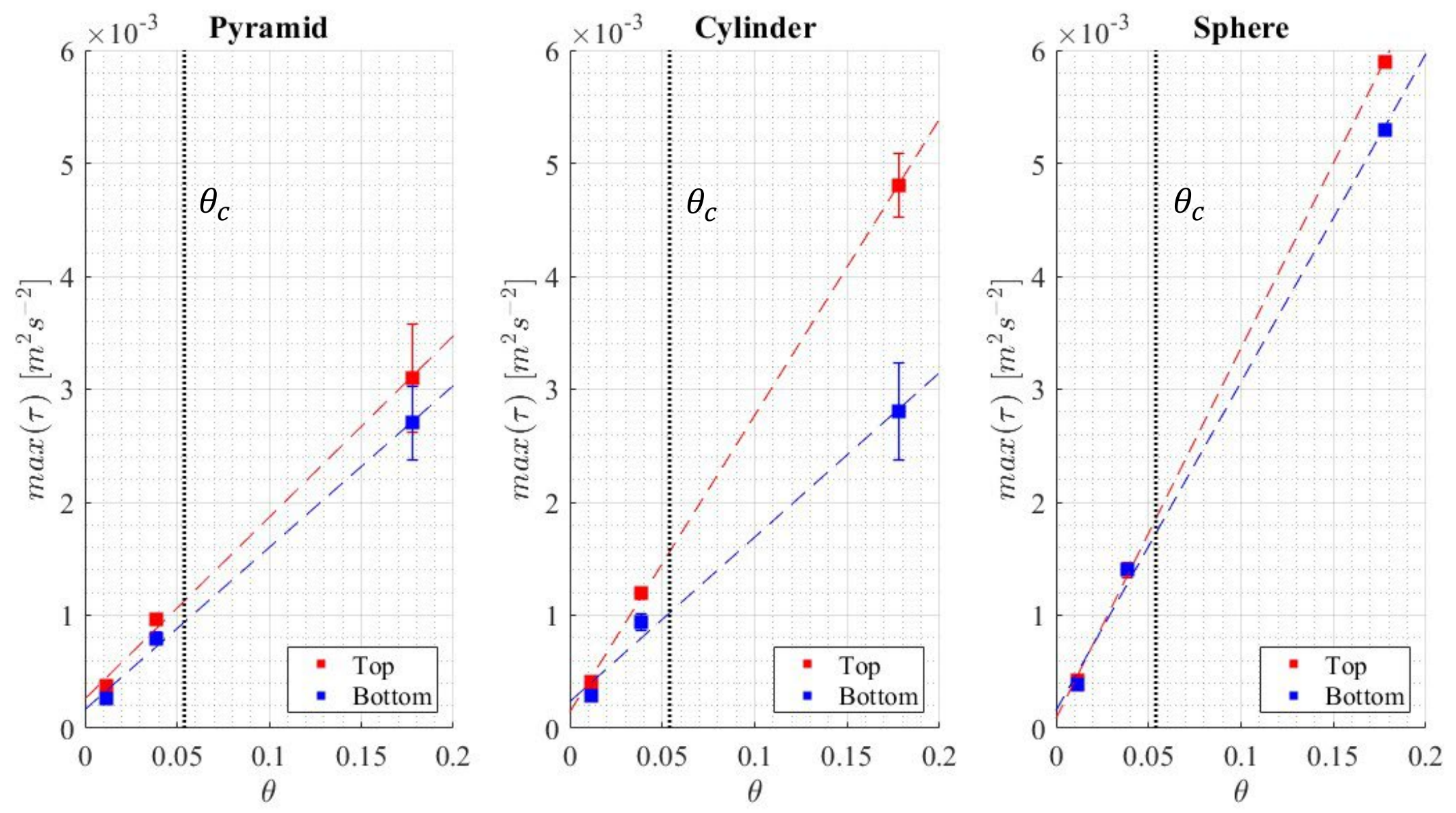


Figure 3: The maximum stress above (red) and below (blue) the center points of the square pyramid (LEFT), cylinder (CENTER) and sphere (RIGHT) as a function of far-field Shields parameter.

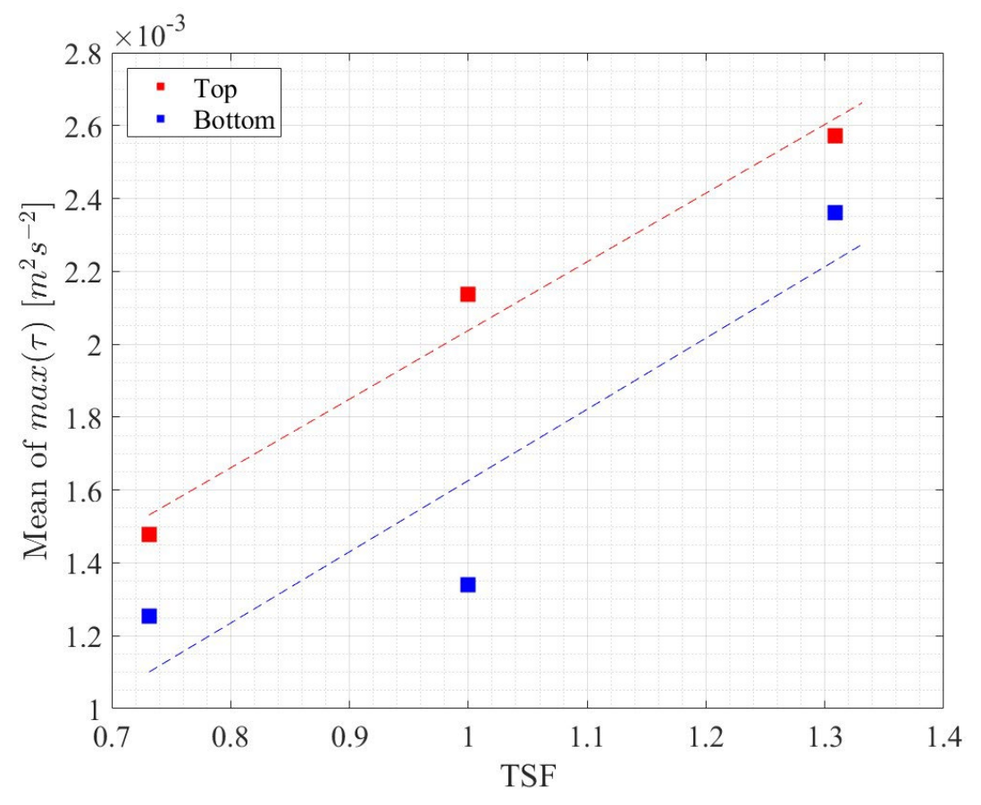


Figure 4: Average over θ of the maximum stress above (red) and below (blue) the center points of the objects as a function of their preliminary TSF.

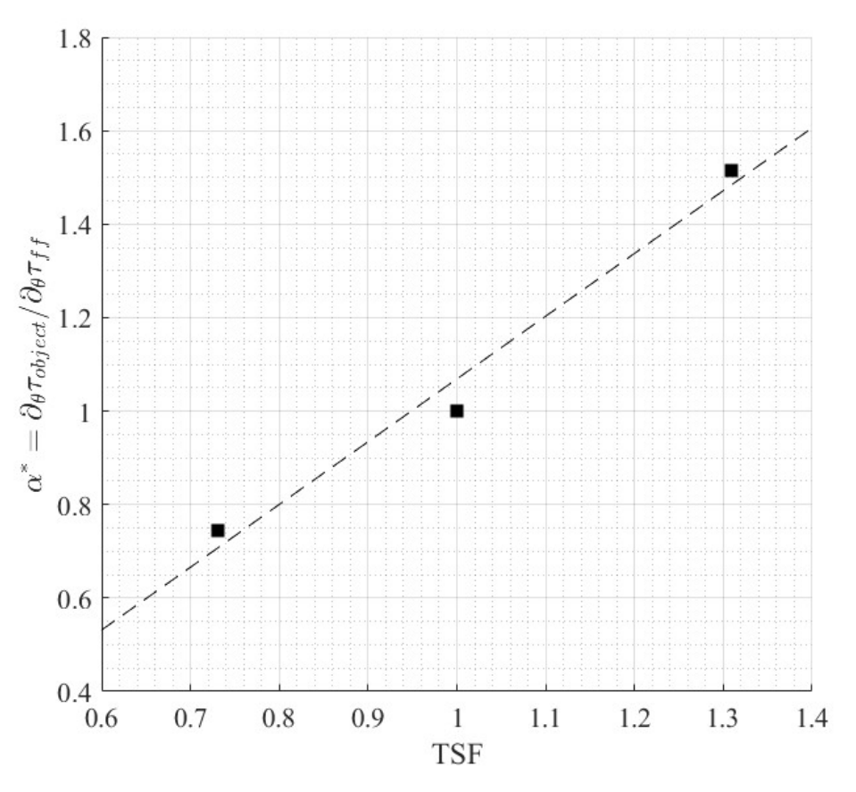


Figure 5: The rate of increase in stress as forcing increases indicates object sensitivity to turbulence production and likelihood for scour enhancement.