



SEED: Crawler Mobility

MR24-4562

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US Army ERDC

In-Progress Review Meeting

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Project Team



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Bottom Line Up Front

- Despite many struggles, the team was able to prove out concepts, highlighting potential serious operability questions in capability with crawlers
- Initial pathways have been established to evaluate hydrodynamic performance and geotechnical stability

Technical Objective

- Amphibious Crawlers have been identified as a platform of *high utility* for sensing in the surfzone environment. Concept has been around since early 1970's, historically having limited success, though recent platforms have demonstrated capability in limited environments, while failing in two key mechanisms:
 - Hydrodynamic – investigated through CFD FSI
 - geotechnical – using acoustic methods to identify bottom type forward of vehicle for eventual avoidance

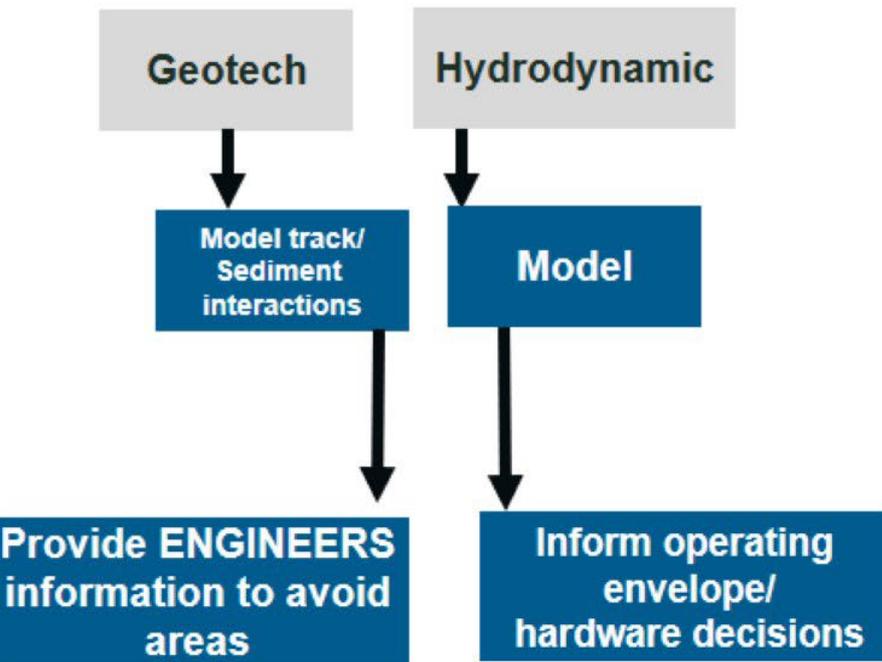


Hydrodynamic failure in Duck NC



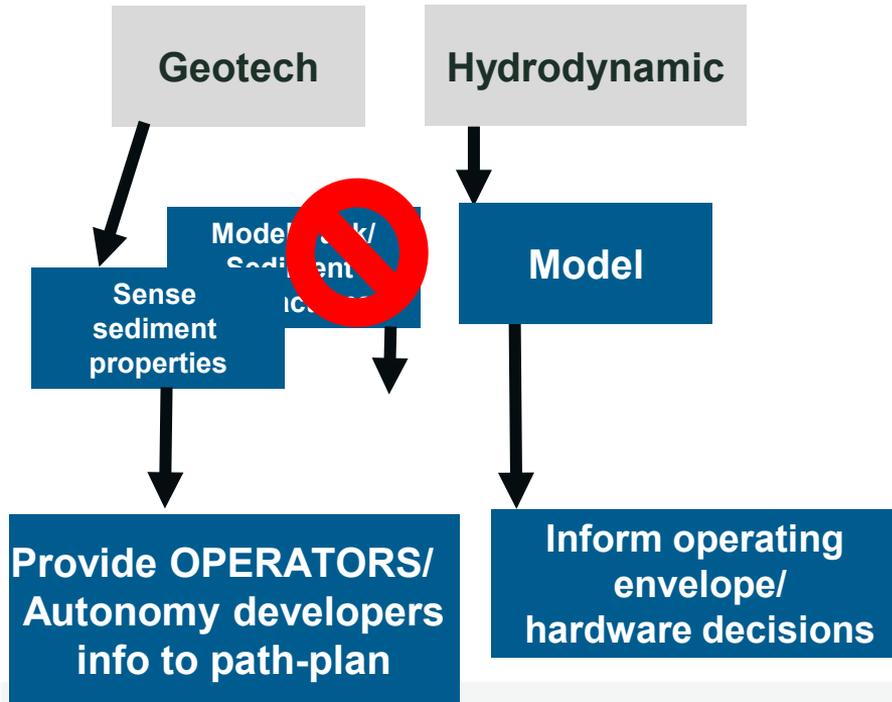
Geotechnic failure in San Diego Bay, CA

Technical Approach



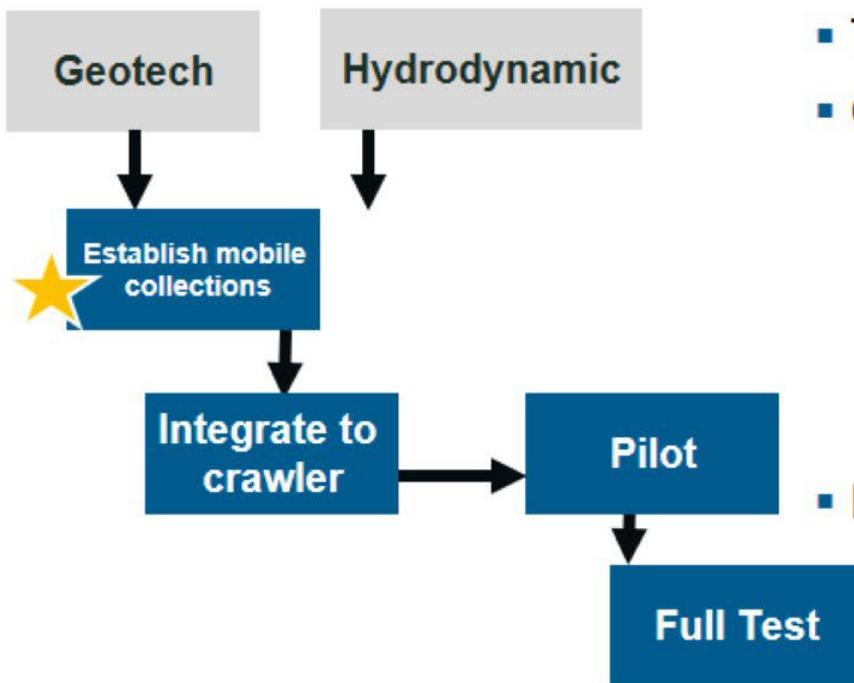
- Two lines of investigation
- Geotechnical
 - Rescoped to focus on sensing areas of soft sediment rather than explore/model track/sediment interactions
- Hydrodynamic
 - Use wave model to force CFD model to explore hydrodynamic forcing

Technical Approach - Geotechnical



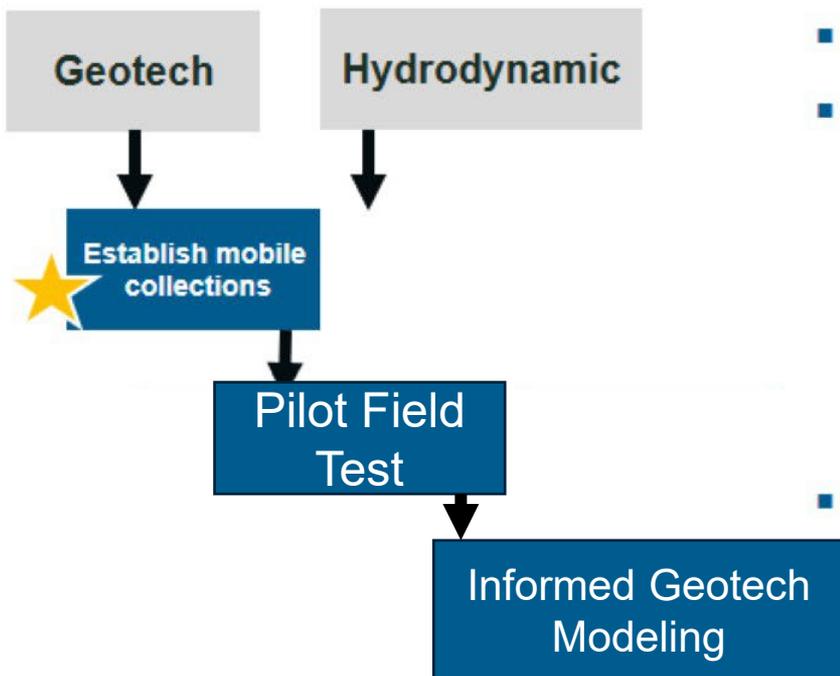
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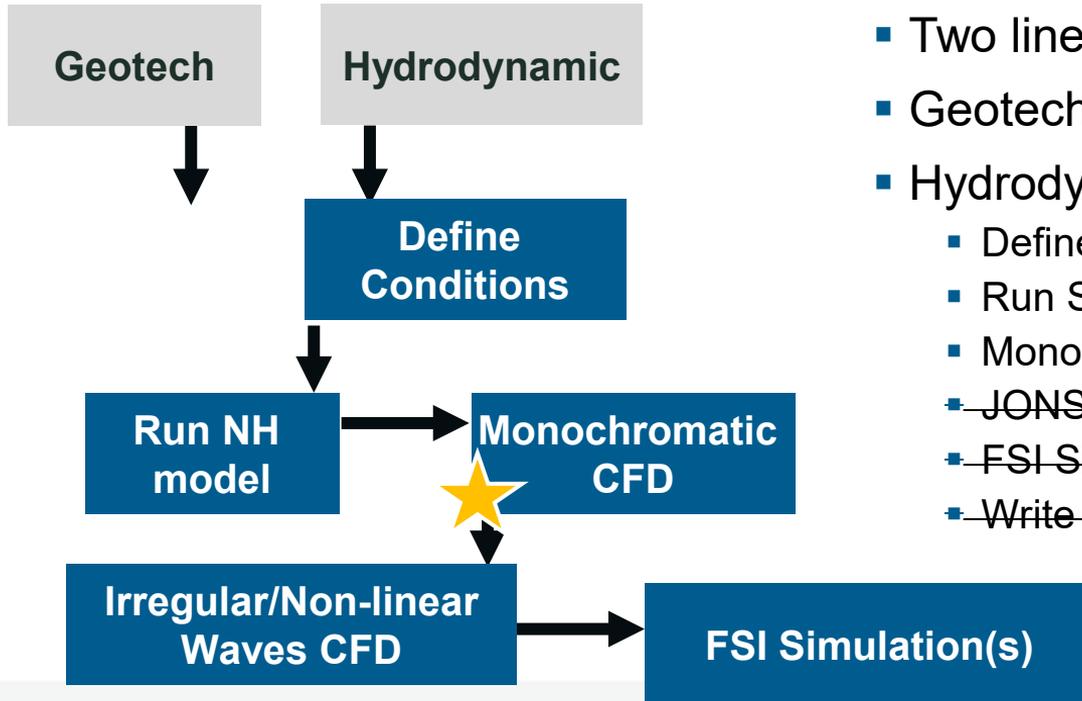
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 - Contract partner
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 - Integrate to crawler
 - Pilot test (FRF Sound) - march
 - Full test (may)
- Hydrodynamic

Technical Approach - Geotechnical



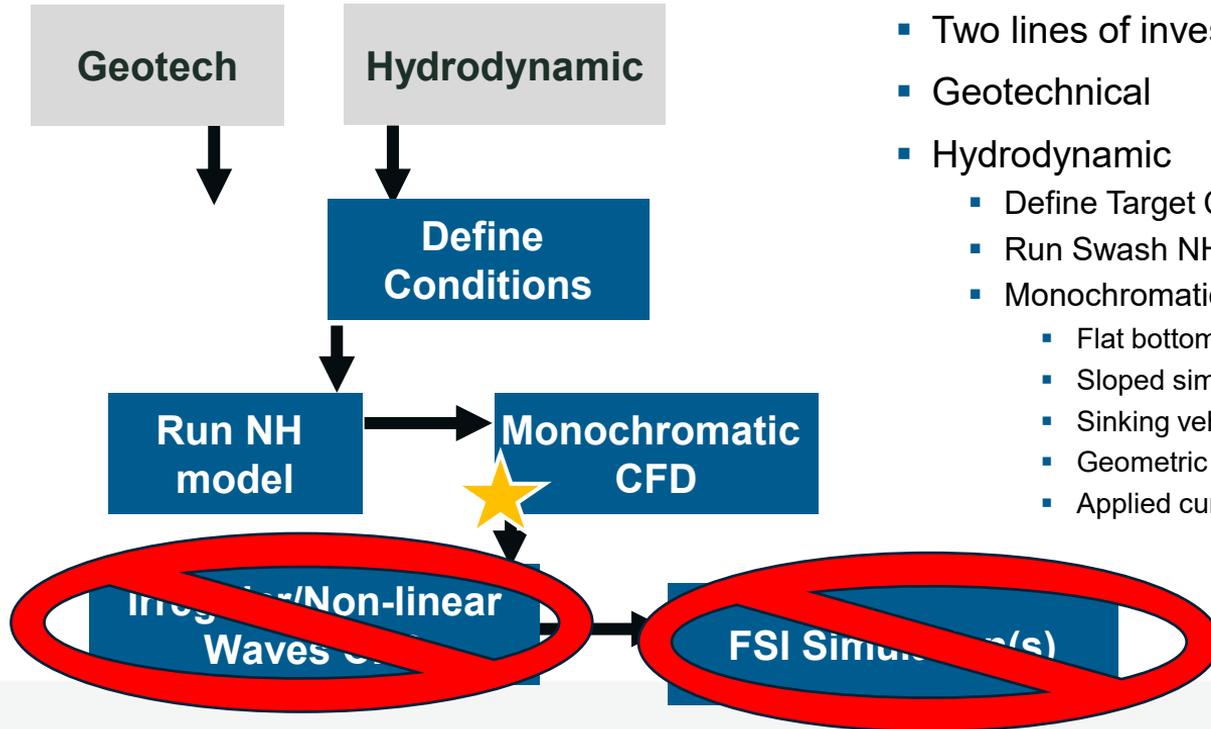
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- Hydrodynamic

Technical Approach - Hydrodynamic



- Two lines of investigation
- Geotechnical
- Hydrodynamic
 - Define Target Conditions
 - Run Swash NH Model
 - Monochromatic CFD
 - ~~JONSWAP/Non-linear CFD~~
 - ~~FSI Simulations~~
 - ~~Write paper~~

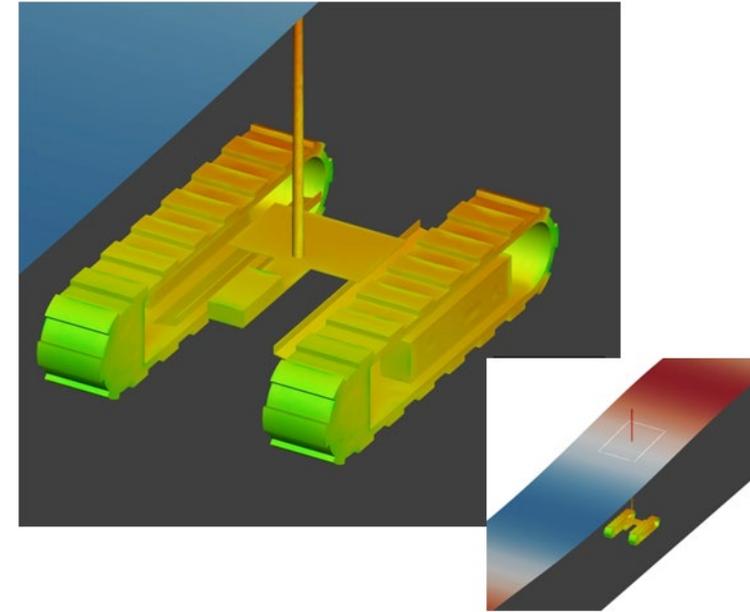
Technical Approach - Hydrodynamic



- Two lines of investigation
- Geotechnical
- Hydrodynamic
 - Define Target Conditions
 - Run Swash NH Model
 - Monochromatic CFD
 - Flat bottom
 - Sloped simulations
 - Sinking vehicle
 - Geometric variations
 - Applied currents

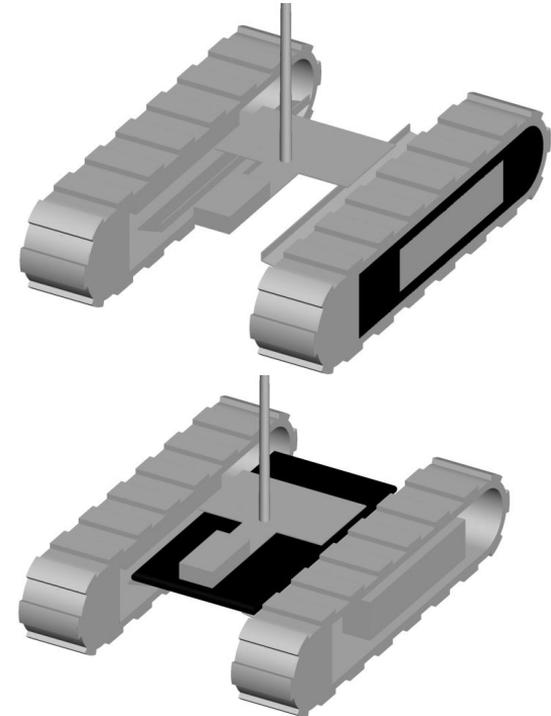
Technical Approach – Hydrodynamic Modeling

- Numerical simulations of the vehicle in the surf zone were conducted to evaluate forces on the vehicle and determine operational envelope
- Commercial code STARCCM+ was used for these simulations
- Simulation approach, including model geometry development and wave field generation, and main results are presented



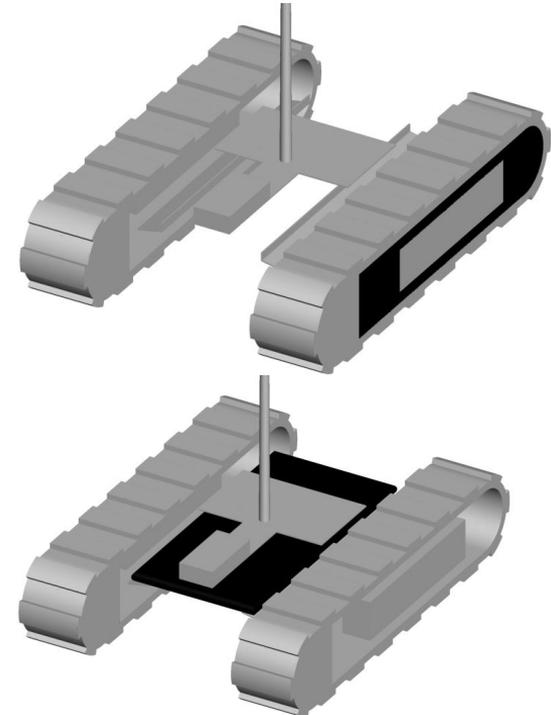
Technical Approach – Model geometry

- Vehicle geometry was based on available CAD model, genericized crawler modeled from GSIQ platform
- Four main structures were maintained in the model: tracks including battery packs, central instrumentation plate, and mast
- Modifications to the tracks to include covers and plate to increase its areas were considered
- Sinkage of the tracks into the sub-surface was considered for stationary vehicle
 - Sinking cannot be imposed to moving vehicle



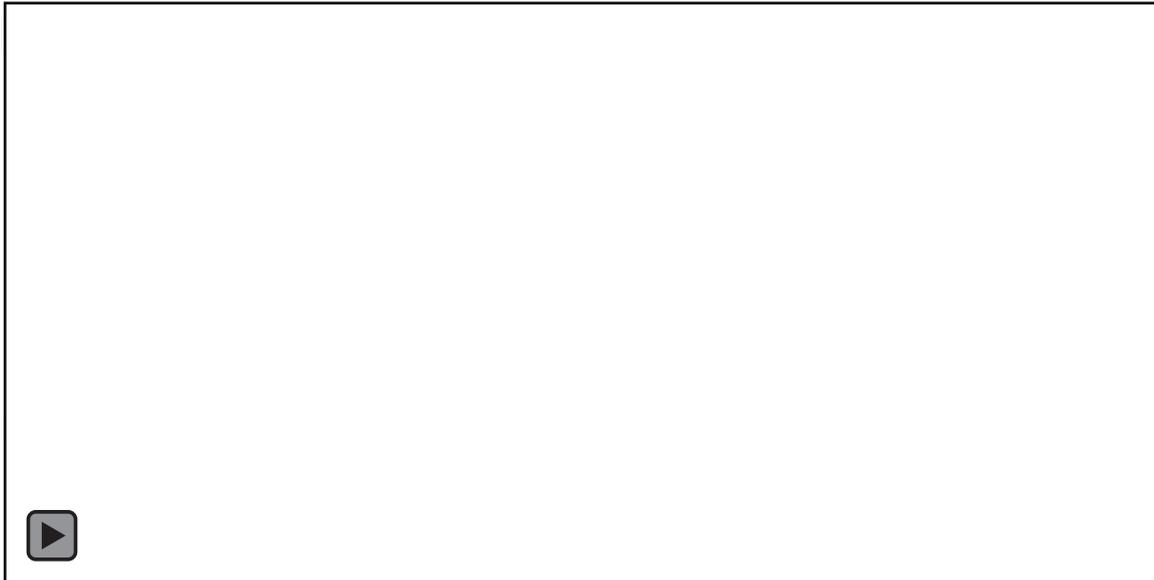
Technical Approach – Model geometry

- Initial approach considered the vehicle as a multibody free to move in one or multiple directions
 - Vertical and horizontal motions
 - Pitch with a pivot axis normal to the track face
- Independent motion of the tracks is not supported by the software
 - They can only advance as a rigid body in the initial configuration
- Contact model in STARCCM+ is not very advanced
 - Spring-type contact model difficult to relate to vehicle dynamics
- Ultimately, fixed geometry was used



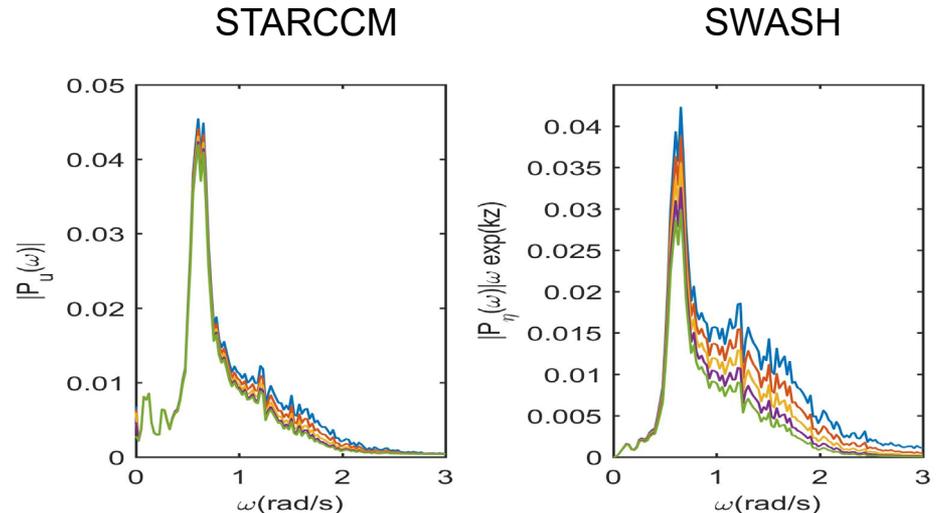
Technical Approach – Wave modeling

- Initial approach considered full bathymetry of surf zone and wave field generated by SWASH solver as boundary condition
- First approach:
 - Superposition of analytical monochromatic waves based on water surface elevation
 - Poor fidelity to SWASH field
 - Not enough attenuation with depth
 - Overestimation of low frequency components



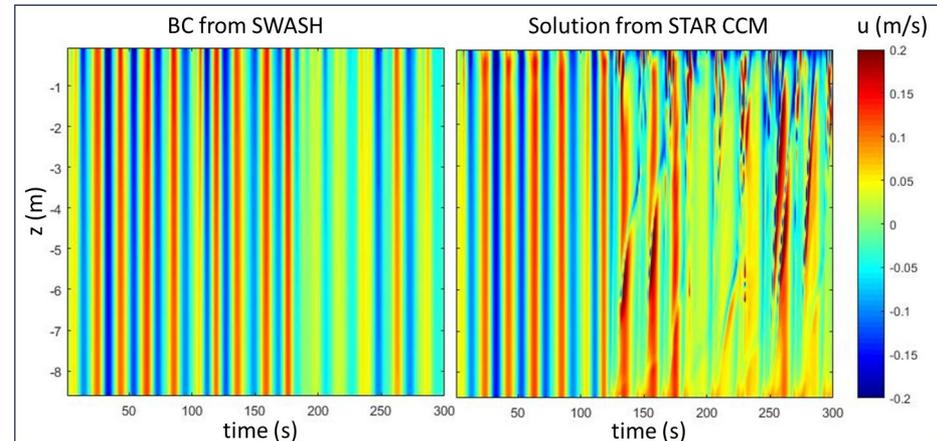
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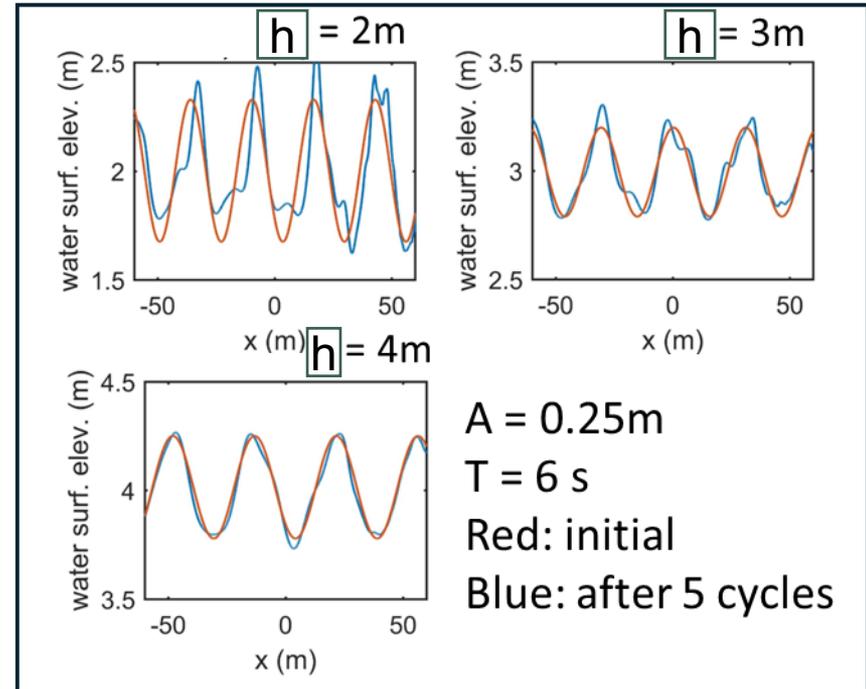
Technical Approach – Wave modeling

- Table with velocity components as function of time and depth
 - Good initial agreement, reflections from slope and breaking region affect wavefield
- In general, full wavefield is more expensive to run, exposes vehicle to limited wave conditions due to time constraints on the simulation (fewer wave cycles)
- Reflections from bottom features are difficult to mitigate and limit the time extent of the simulation
- Monochromatic waves allow a more systematic study of forces on the vehicle



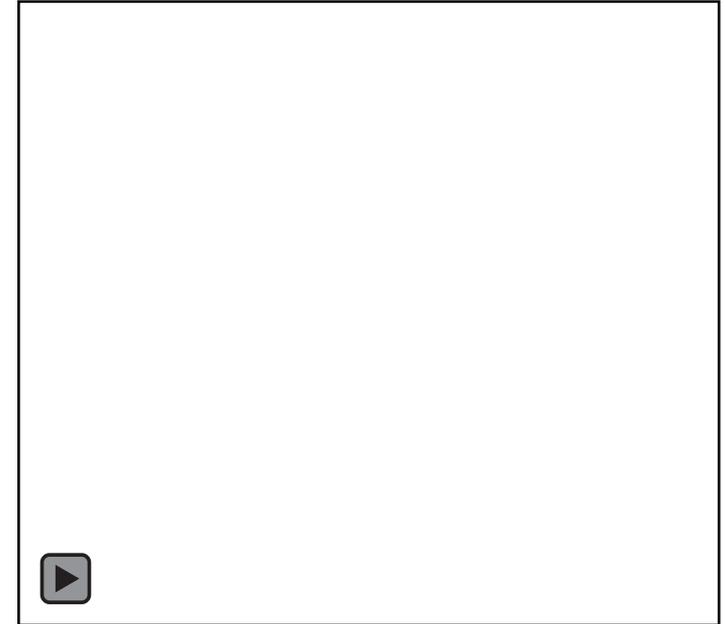
Technical Approach – Wave modeling

- Monochromatic waves were used to determine forces on vehicle, varying
 - Depth
 - Wavelength
 - Amplitude
 - Bottom Slope
- Sinusoidal wave shape cannot be maintained for all conditions
 - Worse for longer waves and shallower cases
 - Wave evolution needs to be included in force description



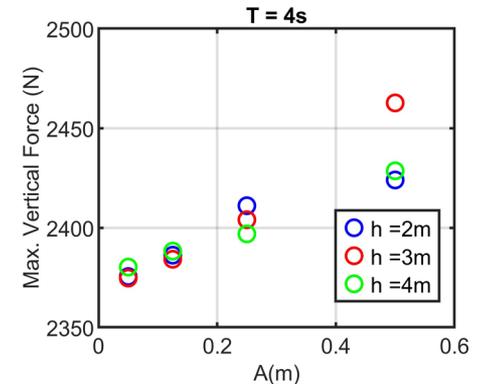
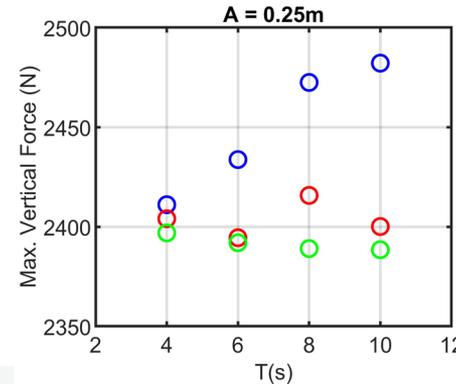
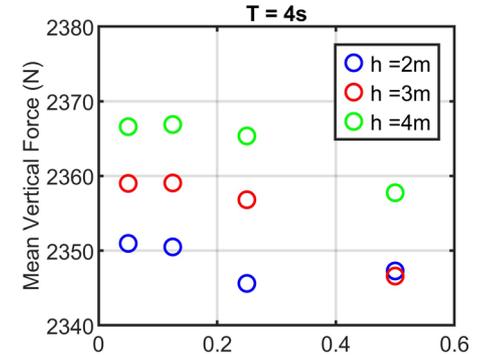
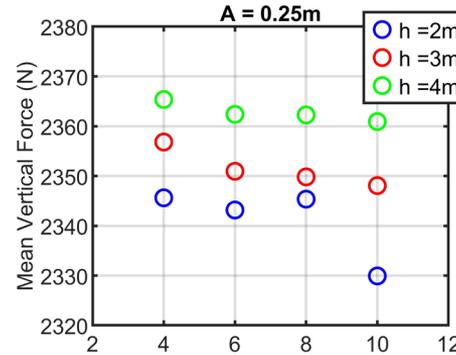
Technical Approach – CFD details

- Simulations were conducted at full scale
- Second order discretization
- Volume of Fluid (VOF) is used to represent the multiphase flow
- SST turbulence model used
 - Grid size near the solid was refined until required conditions for the turbulence model were met
- Inlet/outlet BCs were placed far away from vehicle to avoid reflections affecting the flow in its vicinity



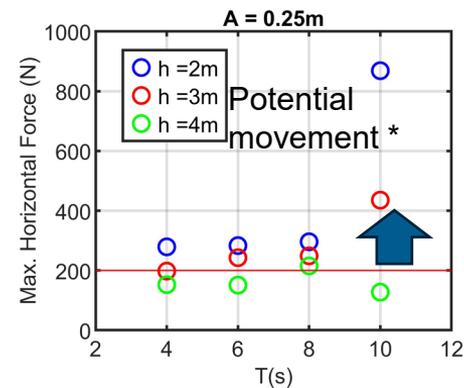
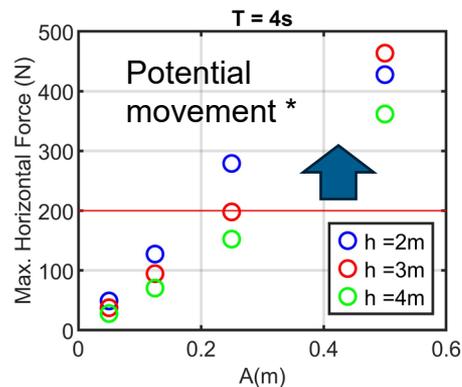
Results – Vertical forces, flat bottom

- Initial characterization with base geometry (no track covers, small plate)
- Wave period 4-10 s, $A=0.25$ m
- Also, $A=0.05-0.5$ m at $T = 4$ s
- Mean from 2330 to 2370 N – neutrally buoyant vehicle weight is 238 to 242 kg
 - Actual weight ~280kg
 - Force includes hydrostatic component (buoyancy)
 - No anticipated movement with 4-10s wave
- Max force increase with decreasing depth
- Mean slightly decreases with depth and period, but less noticeably than for long. forces



Results – Longitudinal forces, flat bottom

- Mean force is zero
 - Imposing a current causes a mean value for the forces
 - Advancing vehicle requires propulsion to overcome generated drag
- Amplitude quadratic with wave amplitude
- Force increase with decreasing depth for moderate amplitude waves
- Long waves show increased force, due to deformation of wave
- Shallow conditions ($h < 3$ m) and large amplitude waves ($A > 0.3$ m) show potential for wave induced motion



*Simplified frictional coefficient of 0.5

Results – Partially sunken vehicle

- Previous results used fully closed surfaces for vehicle, which required fluid gap with bed
 - Provides accurate measure of buoyancy
 - Increases solid surface exposure to fluid flow unrealistically
 - Includes spurious forces on track
- By generating a mesh for which the vehicle becomes part of the BC, the flow around it can be better characterized
 - But, hydrostatic components cannot as easily be separated
- Simulations for flat conditions and on a 1:10 slope were conducted with new geometry (including track covers and larger plate)
- Fixed geometry, effect of vehicle motion is considered by superimposing a uniform velocity of 0.75 m/s to wave field

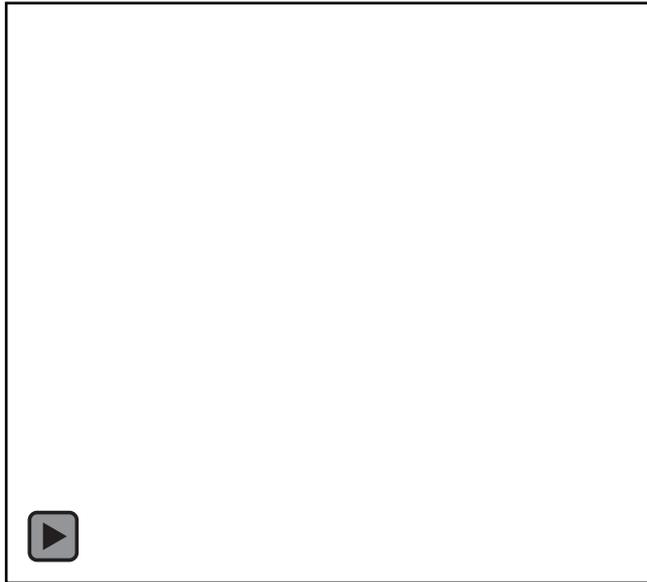
Results – Partially sunken vehicle

Flow field and pressure distribution with and without current

$A = 0.5 \text{ m}$

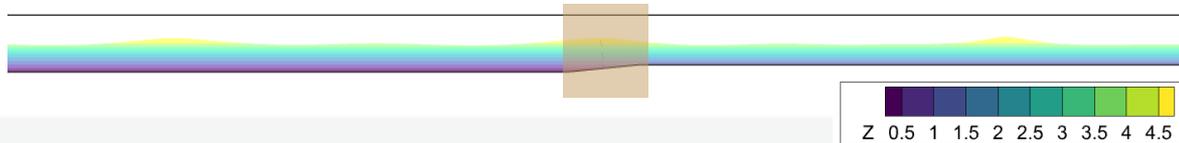
$h = 4 \text{ m}$

$T = 10 \text{ s}$



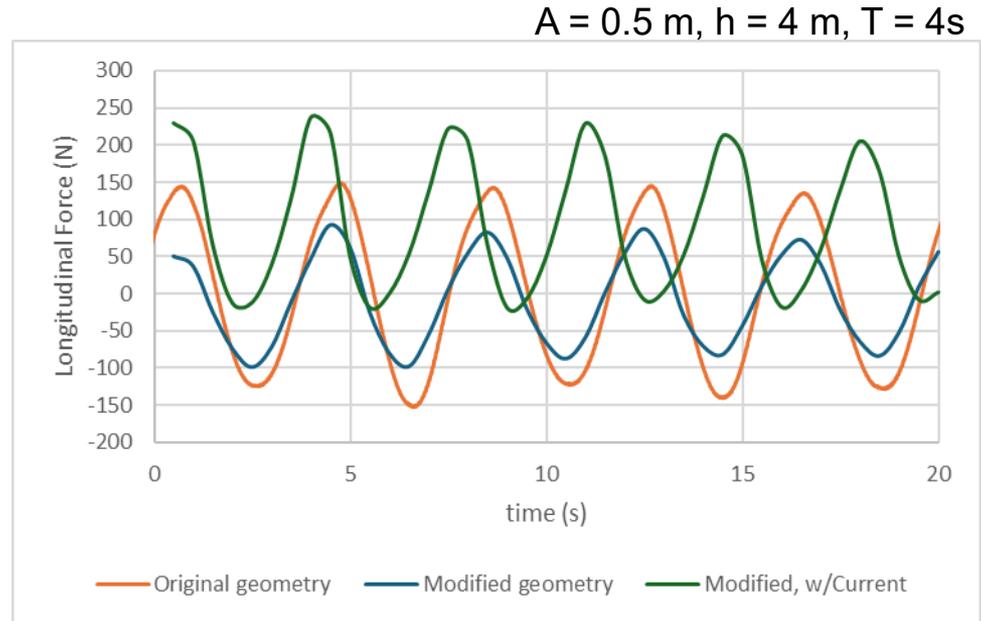
Results – Partially sunken vehicle

- Slope 1:10 also simulated
 - Sloped section 10 m in length
 - Depth reported at center of the slope
 - Wave dispersion will be slightly affected by deeper/shallower conditions away from slope
- Imposed current aligns well with bathymetry



Results – Partially sunken vehicle

- Horizontal forces
- Track covers reduce drag, offsetting drag from larger instrumentation plate
 - Current (equivalent to vehicle motion) result in a non-zero mean drag, and overall increase in maximum value
 - Similar results observed for other flow conditions
 - Full set of data still being analyzed
- Vertical forces are not as easy to compare due to difficulties separating hydrostatic and hydrodynamic components



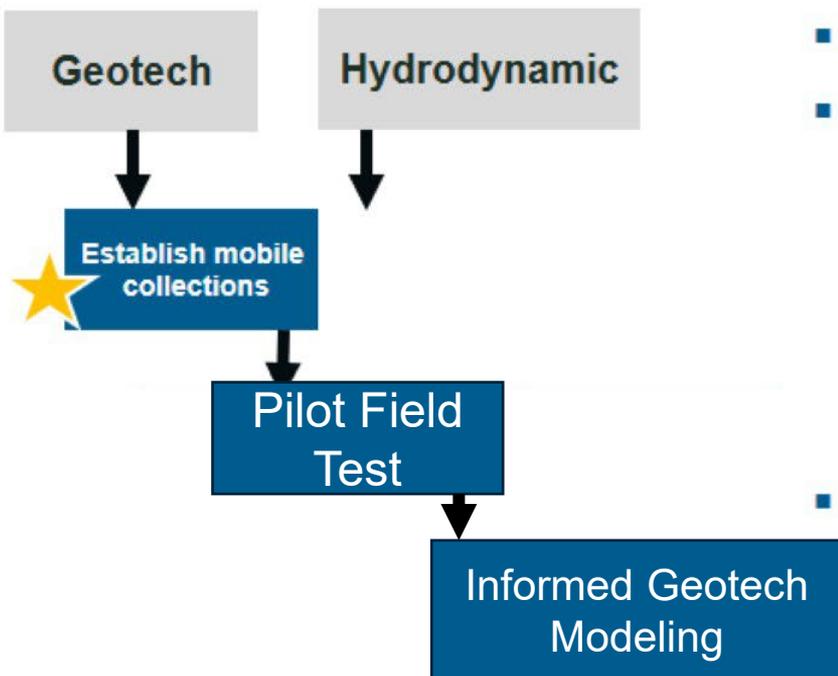
Side fairings reduce drag by 30% in this simulation

Summary and Future Research – Hydro modeling

- Current results show that CFD can provide forces and moments on the vehicle under different wave and slope conditions
 - Stability currently limited to comparison of hydrodynamic forces to reduced weight component in direction normal to the bed
 - Tangential components would require traction model for vehicle
 - CFD can successfully predict forces changes with geometry modifications
 - Can be used to reduce drag, increase downward forces for stability, etc.
 - Current capabilities in solver limits range of possible simulation scenarios
 - Separation of hydrostatic and hydrodynamic forces
 - Forces prediction, simulation of moving vehicle
 - Contact and traction model

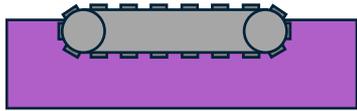
* DOD HPC lost data on sloped simulations that we will try to re-run for annual meeting and final report

Technical Approach - Geotechnical

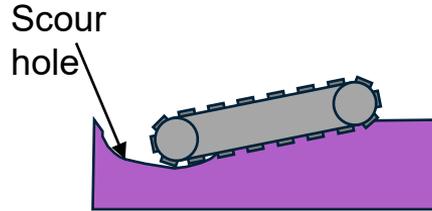


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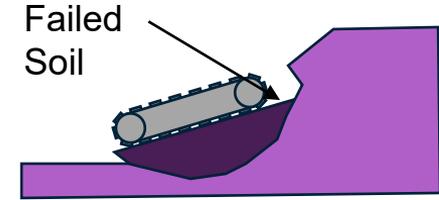
Results – Geotech Modes of Failure



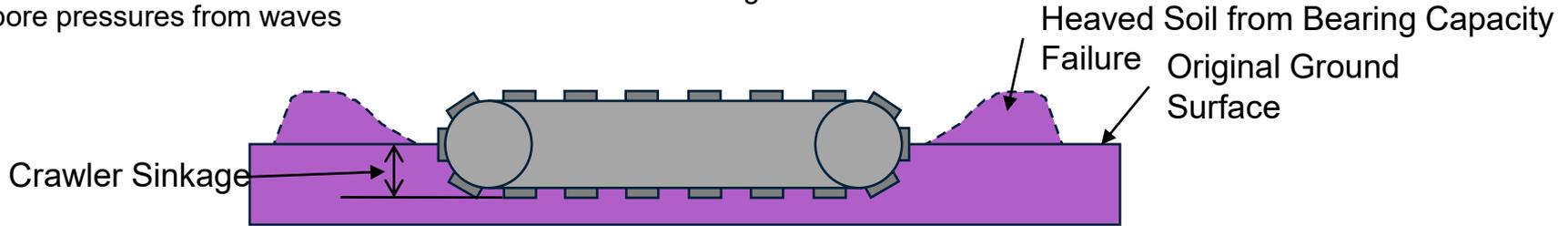
Liquefaction Failure –
Crawler sinks into the sediment due to severe reduction in soil bearing capacity due to increased pore pressures from waves



Scour Failure – Current and wave action removes sediment from around the crawler leading to bearing capacity failure from reduced bearing area

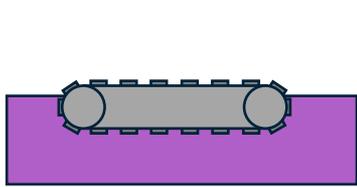


Slope Failure – Dune or sandbar fails due to weight of crawler

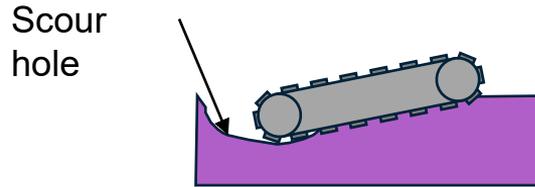


General Bearing Capacity Failure –
Case considered for this framework

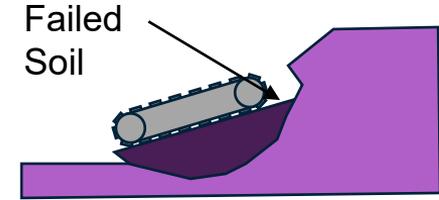
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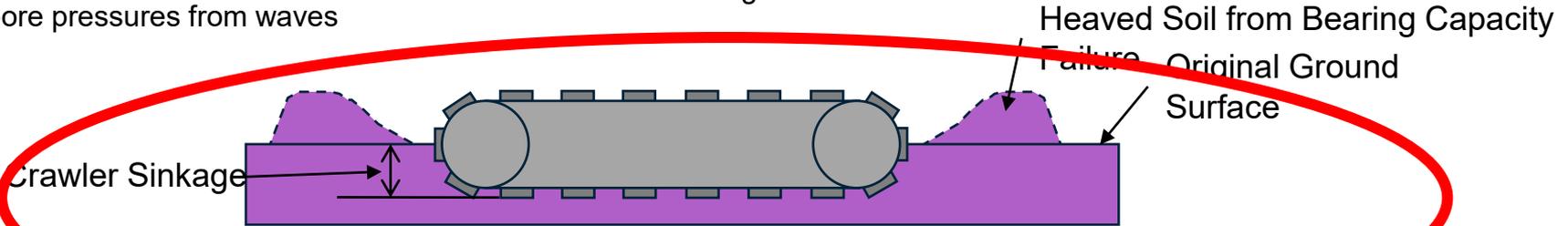
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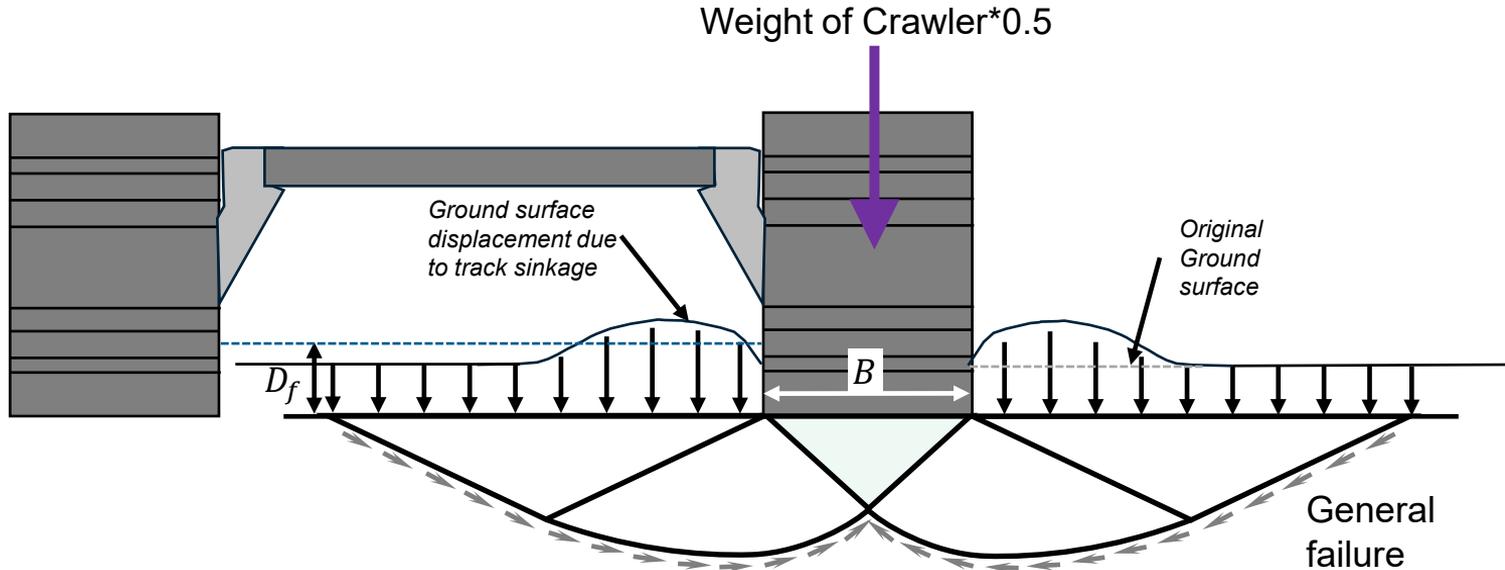


Slope Failure – Dune or sandbar fails due to weight of crawler



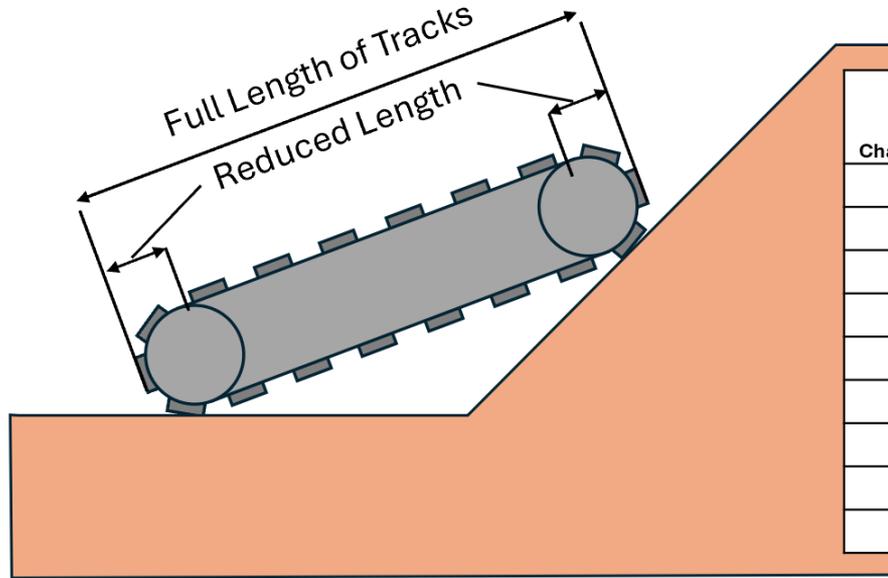
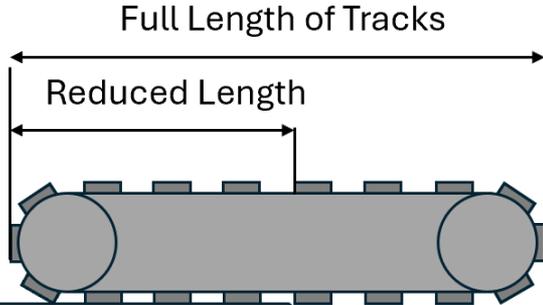
General Bearing Capacity Failure – Case considered for this framework

Results – Simplified Bearing Capacity Based Trafficability



- Terzaghi's bearing capacity equation as modified by Vesic was used to calculate the bearing capacity of the crawler over different soil types and profiles.
- The soil surcharge load is taken as D_f

Results – Track Area reduction

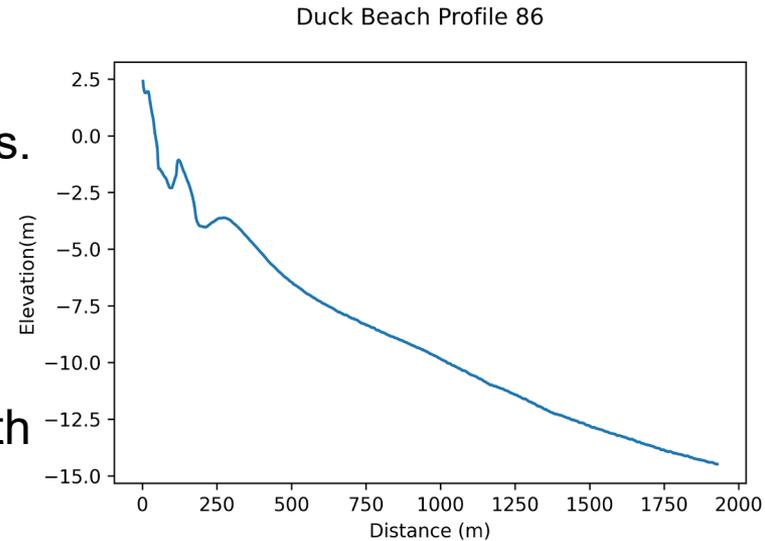


Change in Slope (°)	Reduction Factor
5	0.9
10	0.8
15	0.55
20	0.4
25	0.45
30	0.3
35	0.25
40	0.2
45	0.1

- The track length is changed using a track length reduction factor, between 0.1 and 0.9.
- The reduction factor is based on the difference in ground slope between measurement points.

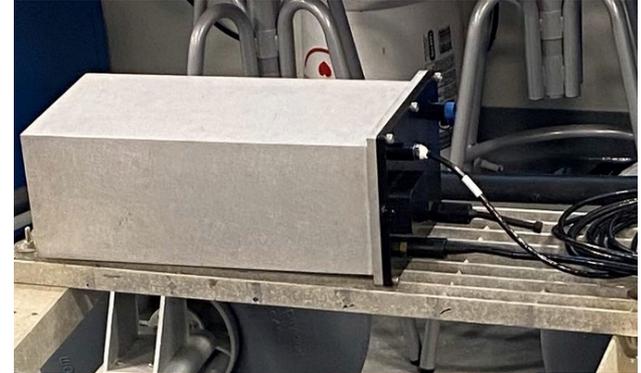
Analysis on Typical beach profiles

- Extract bathymetry: over 150 beach and nearshore profiles at FRF site.
- The beach profiles were converted to change in slope for the trafficability analysis.
- Penetrometer deployments were used to estimate the seabed strength parameters.
- Additionally, a soft fine-grained sediment (silt or clay) is also considered. Soil strength data is then taken from a different site but applied to the beach profiles.



Pilot Field effort

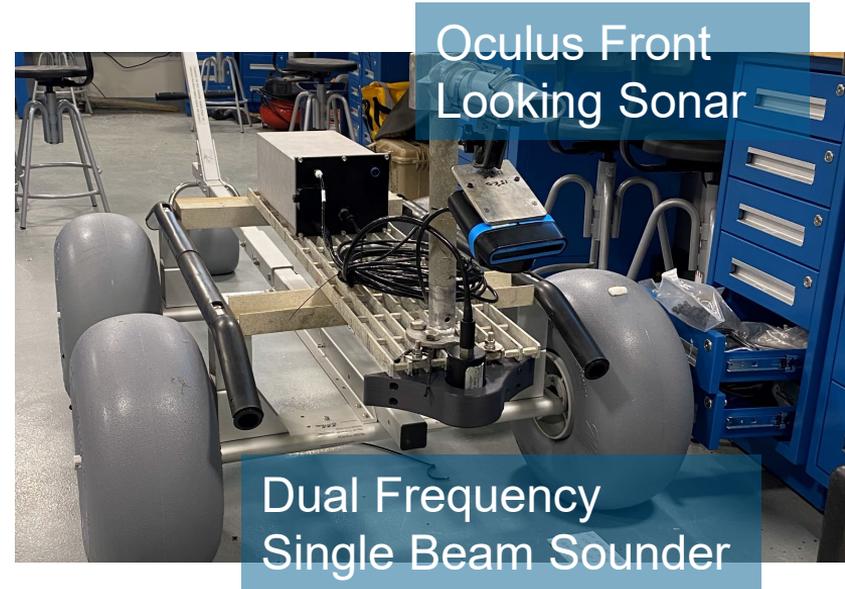
- Developed payload box
 - Self-powered
 - Data compute and driver software for
 - Multi-frequency Sonar (sub bottom sensing)
 - Forward look sonar
- Drove crawler down to sound
 - Fried motor on the way to the sound
 - Repair cost was \$150k



Picture of broken crawler

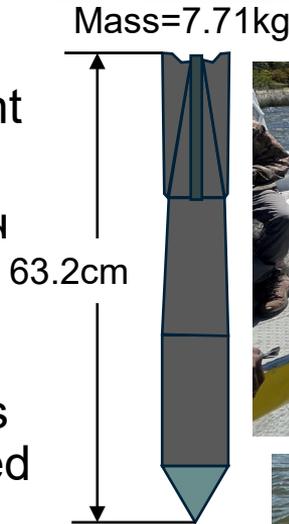
Pilot Field effort

- Target:
 - Assess framework performance using USACE crawler in the sound and in the beach-nearshore zone
 - Compare mobility as well as sinkage depth with framework results
- Alternate
 - Deploy sonars from alternate platforms
 - Use an instrumented cart as “crawler” surrogate

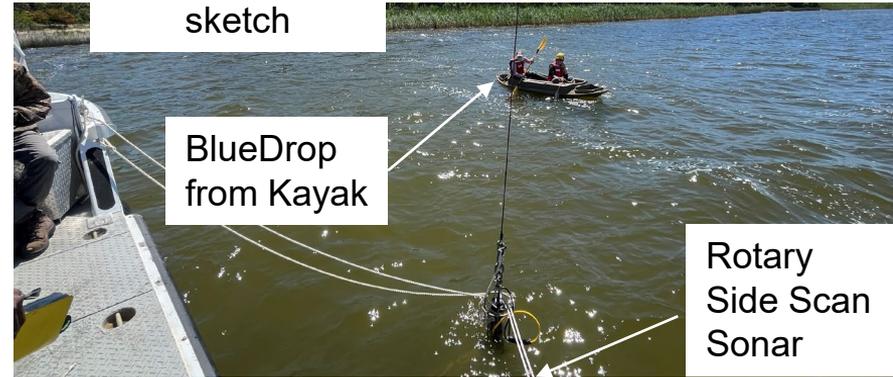


Field Framework Spring 2025

- Selected two different sites, based on perceived difference in sediment strength while walking.
- At each site the buggy was pushed through the area after an initial set side scanning.
- Penetrometer (PFFP) deployments and sediment coring was conducted to assess the sediment properties.
- A final round of side scan imagery was taken after sampling and PFFP measurements.

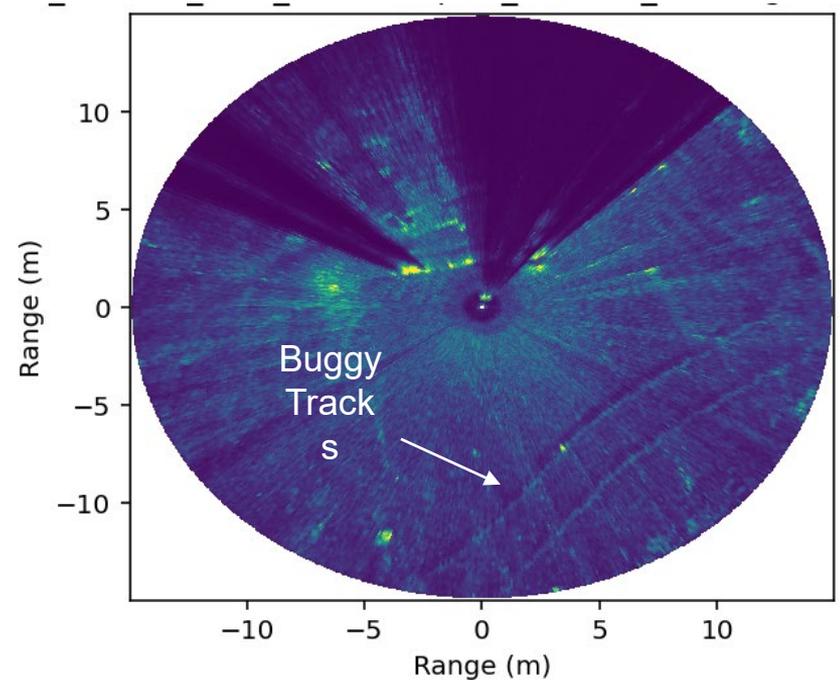
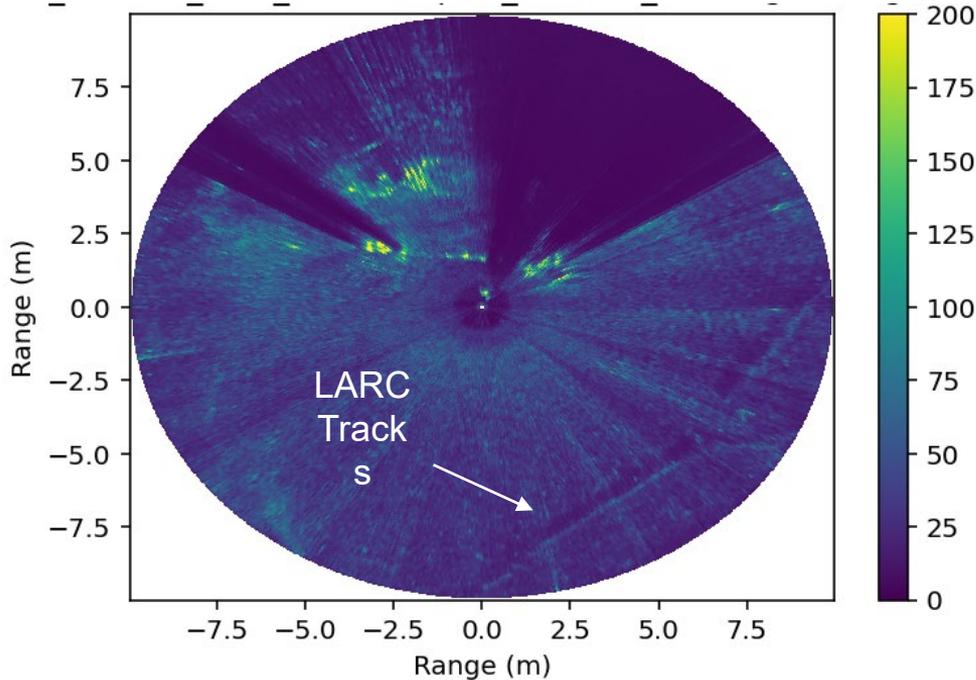


BlueDrop PFFP sketch



Rotary Sonar Results

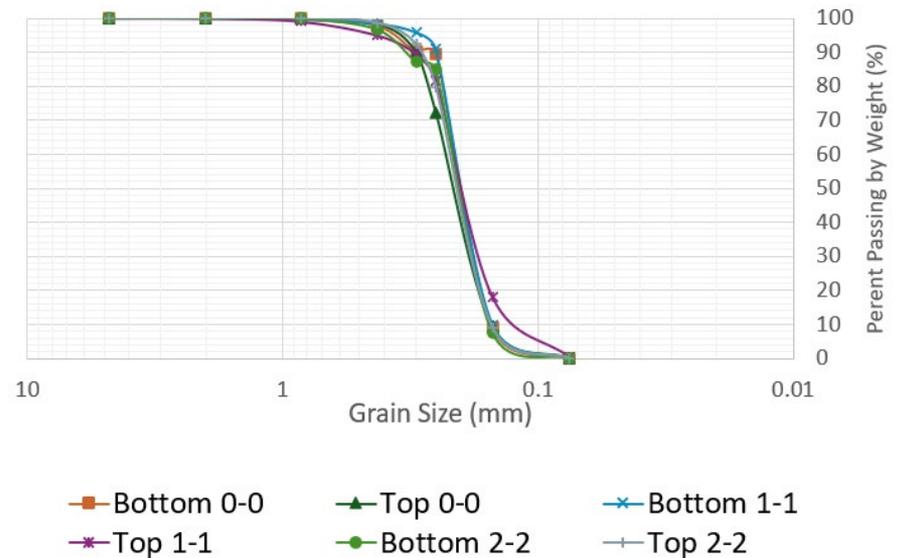
- Rotary side scan sonar clearly displayed tracks, i.e., sinkage of the surrogate vehicle during motion.
- It is concluded that acoustic surveying and observations of mobility (as initially planned) would provide information suitable to validate the predicted sinkage.



Sediment Sampling Results

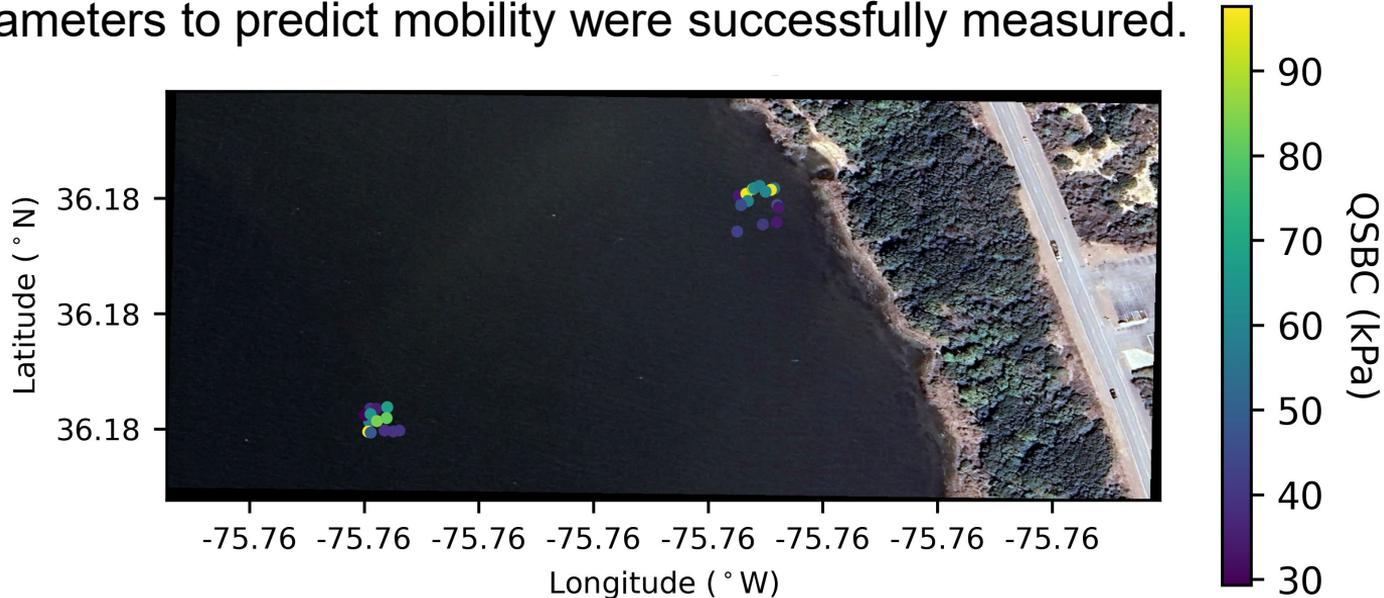
- Sediment across the two sites shows very little variation.
- Samples consist of almost entirely fine sand with less than 1% fines.
- All samples classify as SP (Poorly graded sand).

FRF Sound Side Crawler Experiment Gradation Results



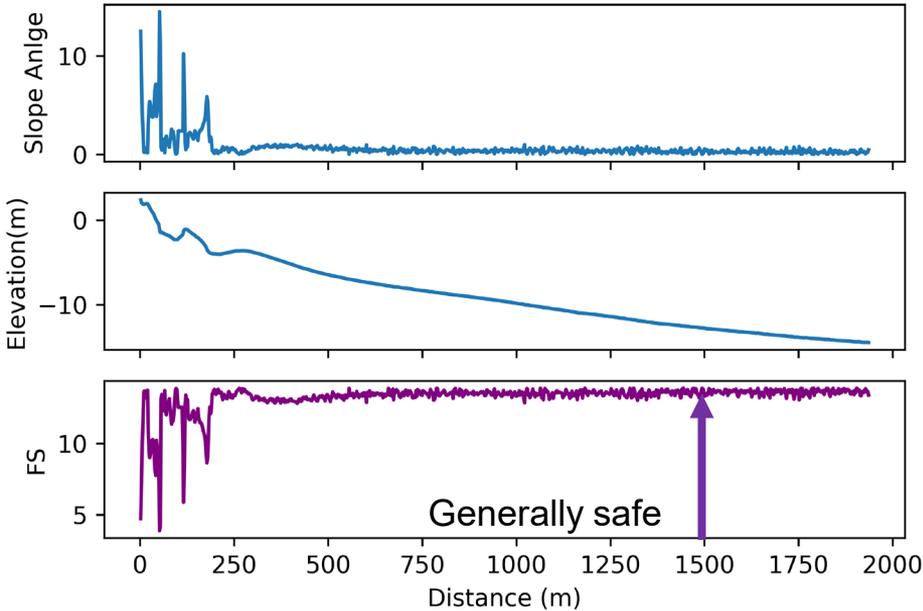
Spatial Variability in Bearing Capacity

- Quasi Static Bearing Capacity (QSBC) ranges between 29kPa and 97 kPa with an average of 56 kPa, representing noticeable spatial variability on the small-scale.
- Ranges and averages are almost identical between the two sites.
- Key input parameters to predict mobility were successfully measured.



Mobility Prediction

Duck Beach Profile and Crawler FS 86

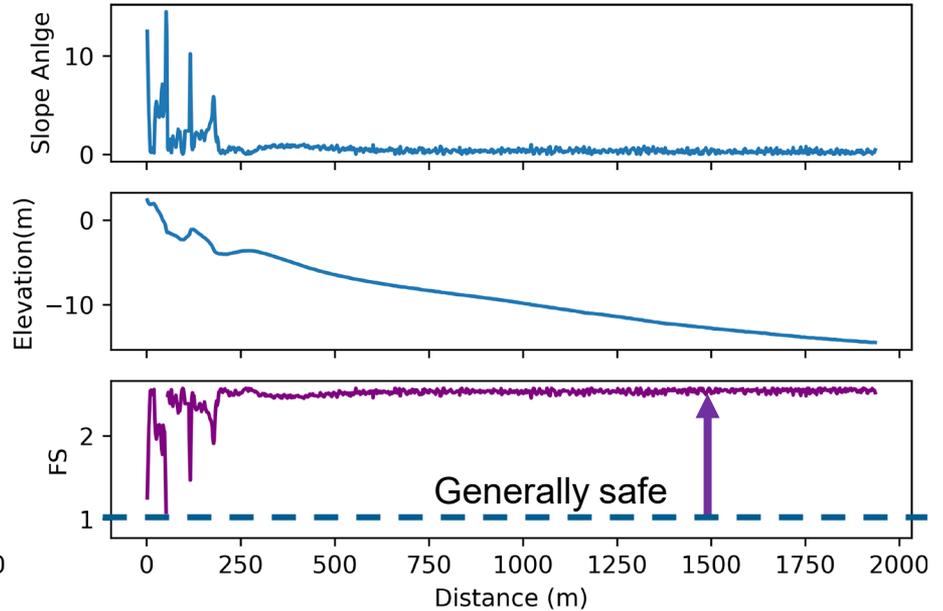


Results for coarse grained soil (sand).

Sinkage = 5cm

Friction Angle = 30°

Duck Beach Profile and Crawler FS 86



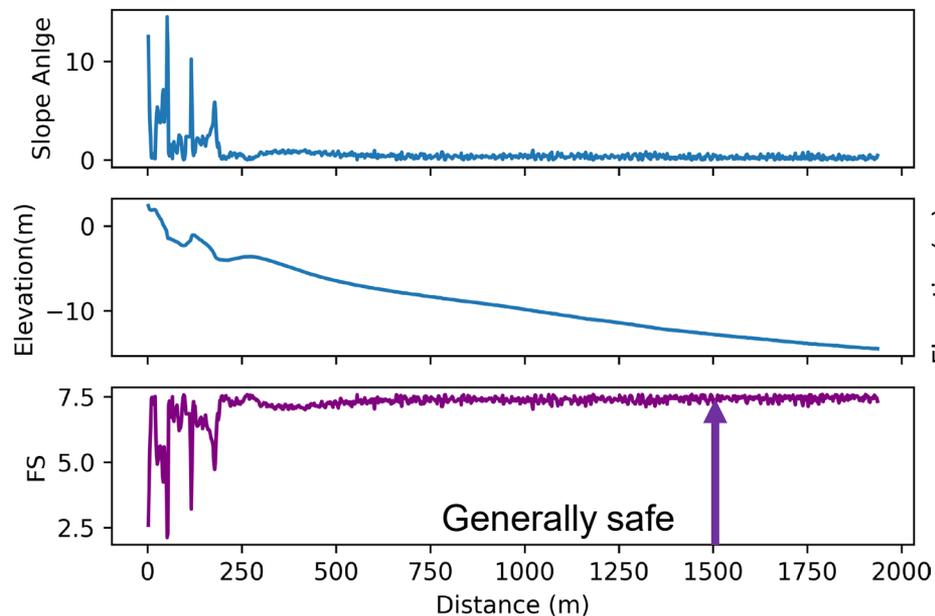
Results for fine grained soil (silt or clay).

Sinkage = 20cm

Undrained Strength (S_u) = 0.75kPa

Mobility prediction – + Weight Extended

Duck Beach Profile and Crawler FS 86



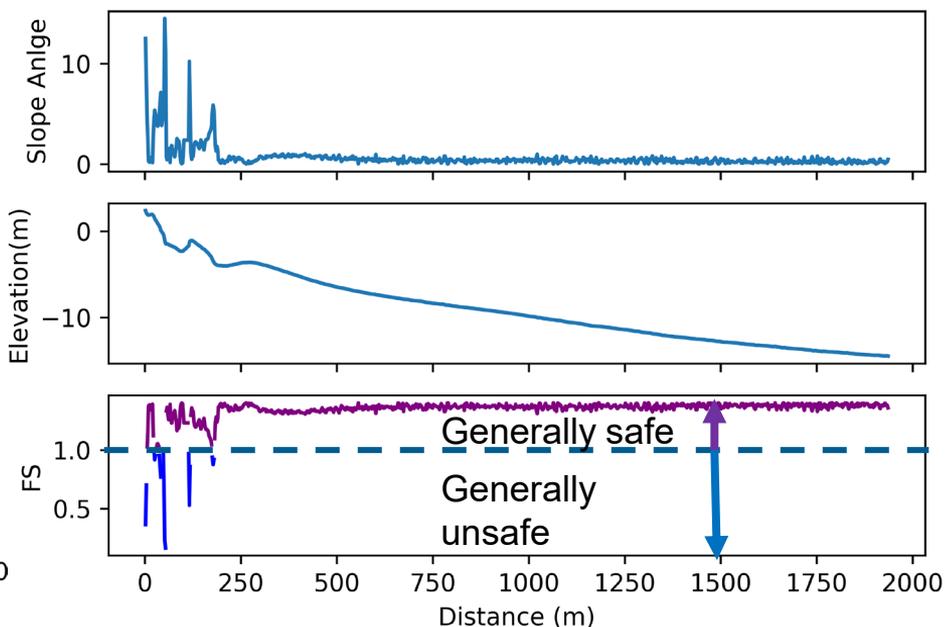
Results for coarse grained soil (sand).

Sinkage = 5cm

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Crawler weight extended to 500kg

Duck Beach Profile and Crawler FS 86



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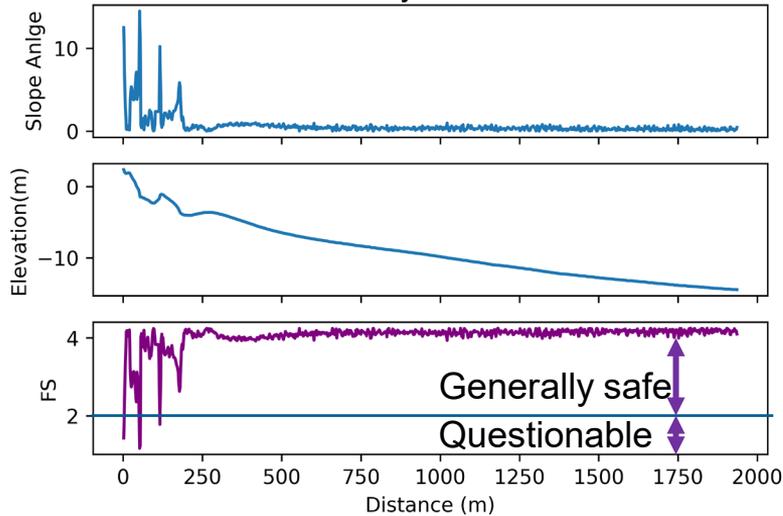
Sinkage = 20cm

Undrained Strength (S_u) = 0.75kPa

Crawler weight extended to 500kg

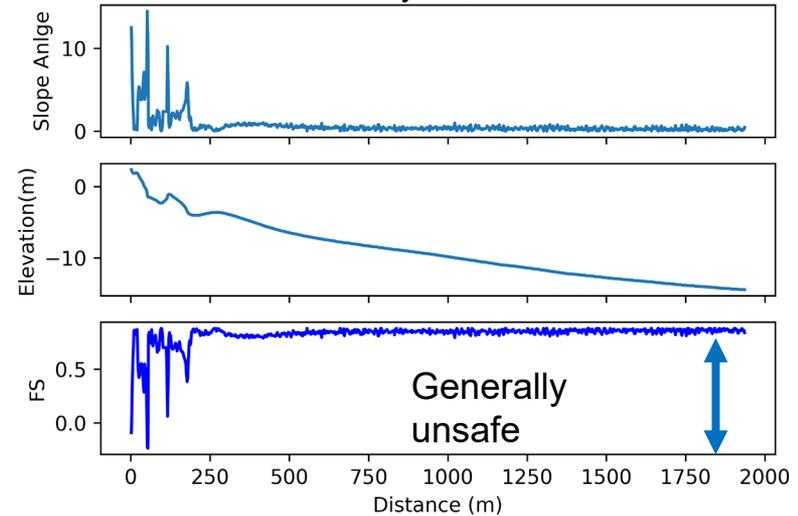
Mobility Prediction – + shortened track

Duck Beach Profile and Crawler FS 86
January 14, 2021



Results for coarse grained soil (sand).
Sinkage = 5cm
Friction Angle = 30°

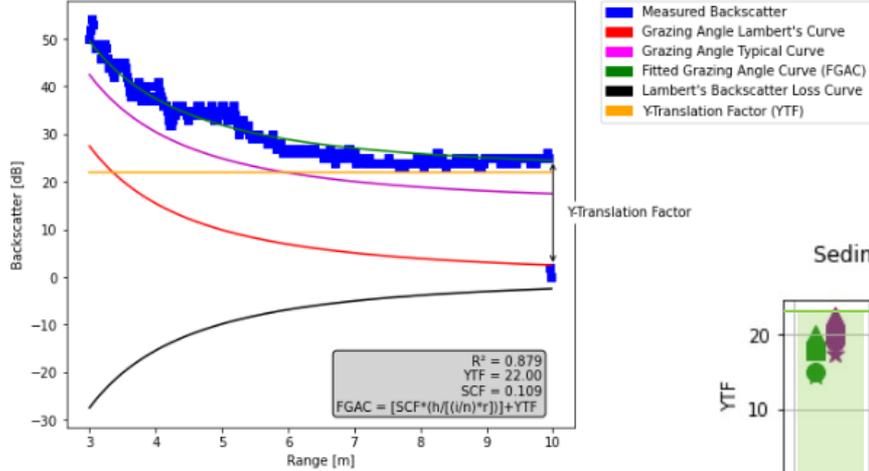
Duck Beach Profile and Crawler FS 86
January 14, 2021



Results for fine grained soil (silt or clay).
Sinkage = 20cm
Undrained Strength (S_u) = 0.75kPa

Feasibility exploration

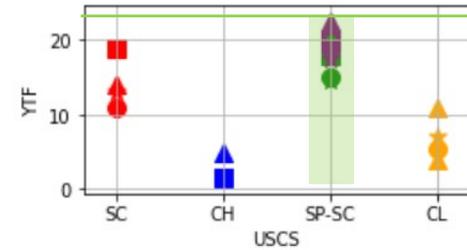
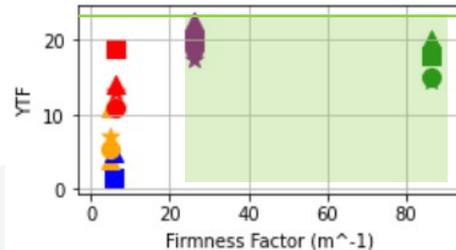
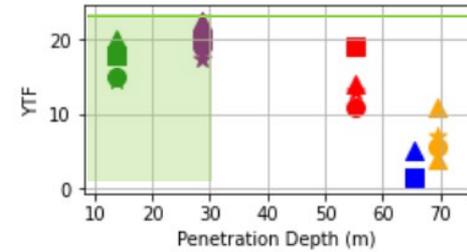
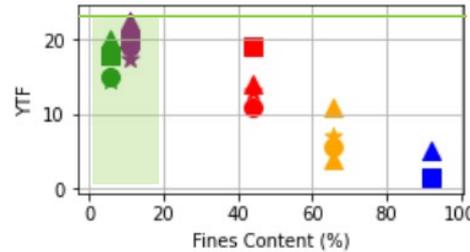
['May22,2025,12-45-43_Duck_Site1-1_10m_initial.smb', 'row means for sediment type: ', 'gravel']



- Rotary side scan data was used in Lambert's curve backscatter vs distance model
- Results are tested against framework developed in SERDP MR21-1265.

- Results suggest reasonable agreement with other sites characterized by sandy, stiff soils.
- Penetration depth may be overestimated from layering at FP site.

Sedimentology Comparisons for Y-Translation Factor



Future Work

- Hydrodynamic
 - Re-run missing simulations
 - Drive conditions with random sea's
 - Extend to
 - larger wave conditions (longer domains/runtimes)
 - Different orientations
 - Free body motions (allows ability to look at accumulated motion)
- Geotechnical
 - Functional crawler re-collecting FLS data
 - Multiple environments ranging from hard to soft bottom