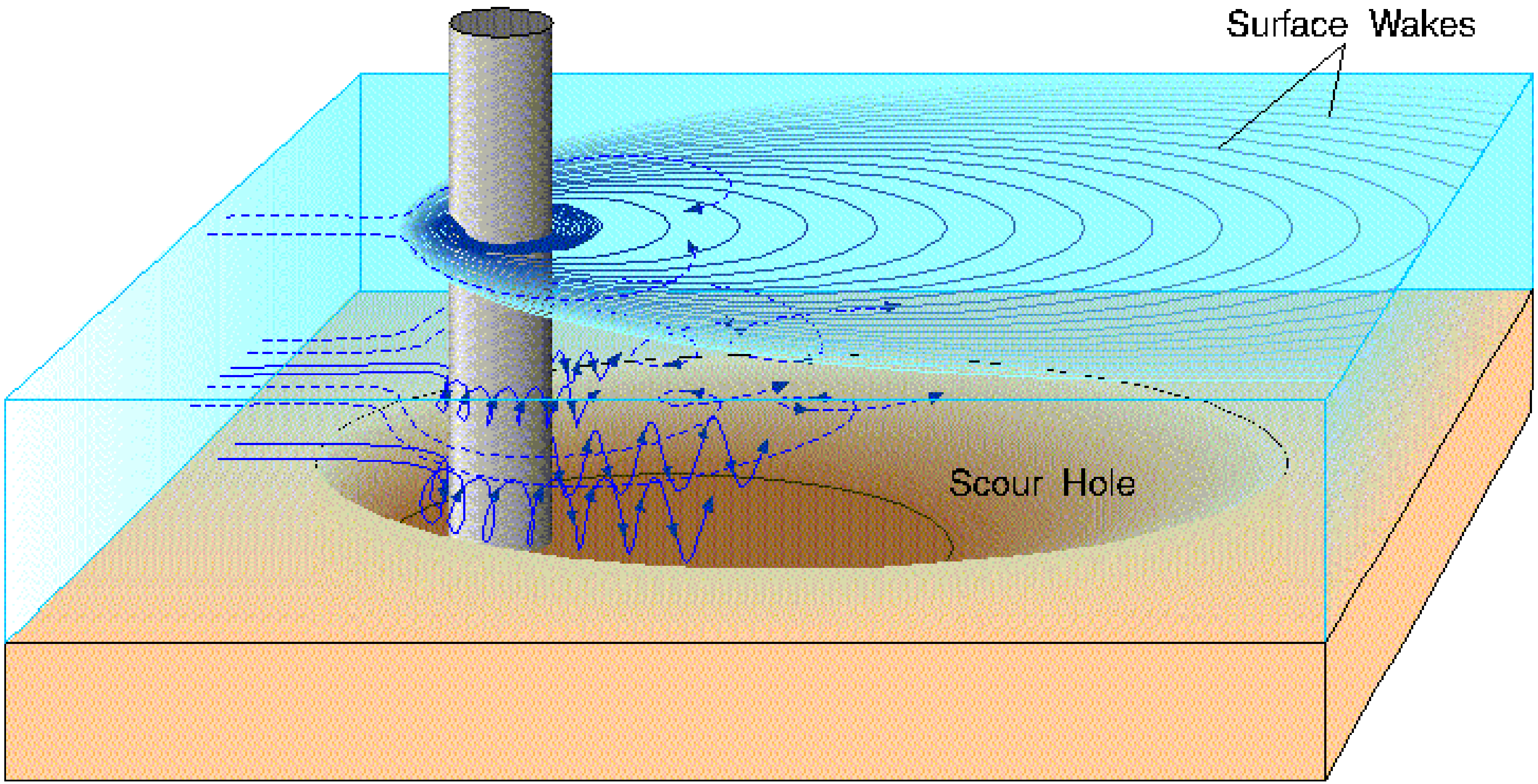
Development of FDOT SERF and RETA Design Equations for Coastal Scour when a Single Vertical Pile is Subjected to Wave Attack

FDOT Project No. BDV34-977-12, Tim Holley, P.E., Senior Drainage Design Engineer, Project Manager

University of North Florida
Taylor Engineering Research Institute
1 UNF Drive, Building 4, Room 1501
Jacksonville, FL 32224

PI: Raphael Crowley, Ph.D., P.E., Associate Professor in Coastal and Port Engineering, r.crowley@unf.edu

Background – Local Scour



Local Scour Illustration

Background – RETA/SERF

Alternative scour design method:

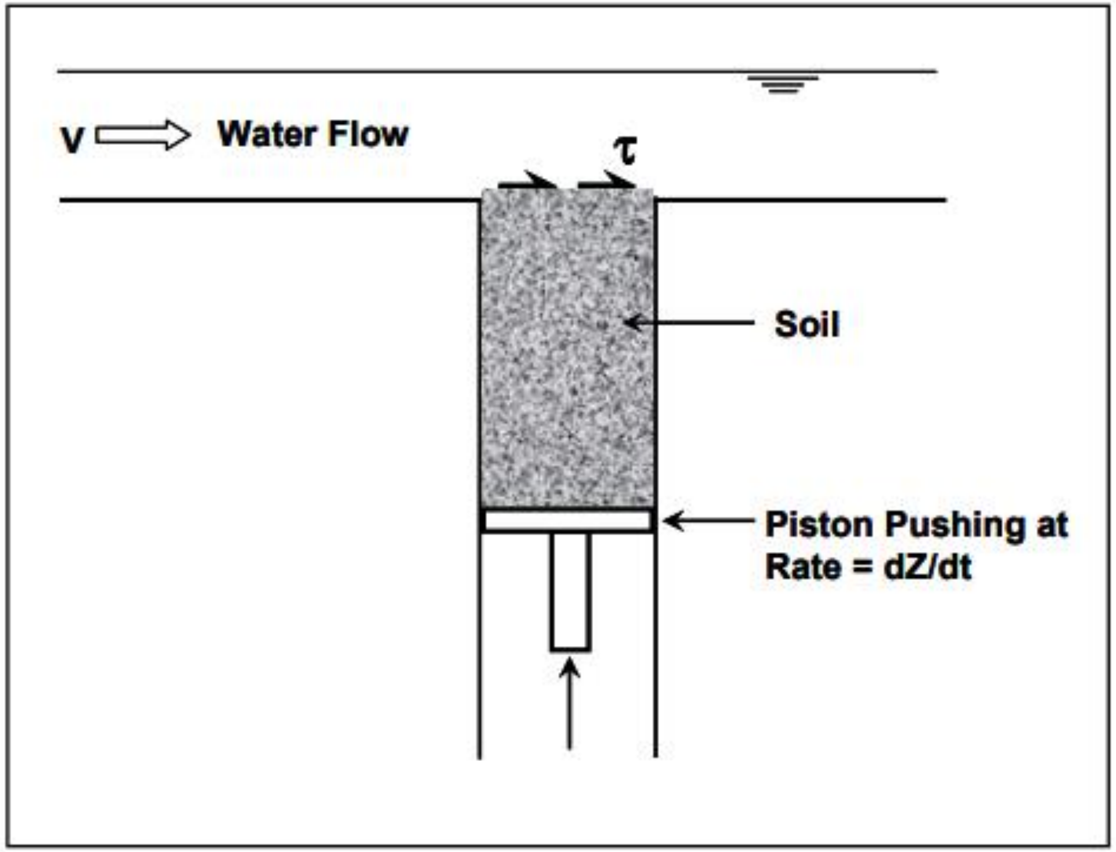
1. Develop conservative hydrograph to get flow as a function of time

2. Use hydrograph to estimate bed stresses in the field as a function of time

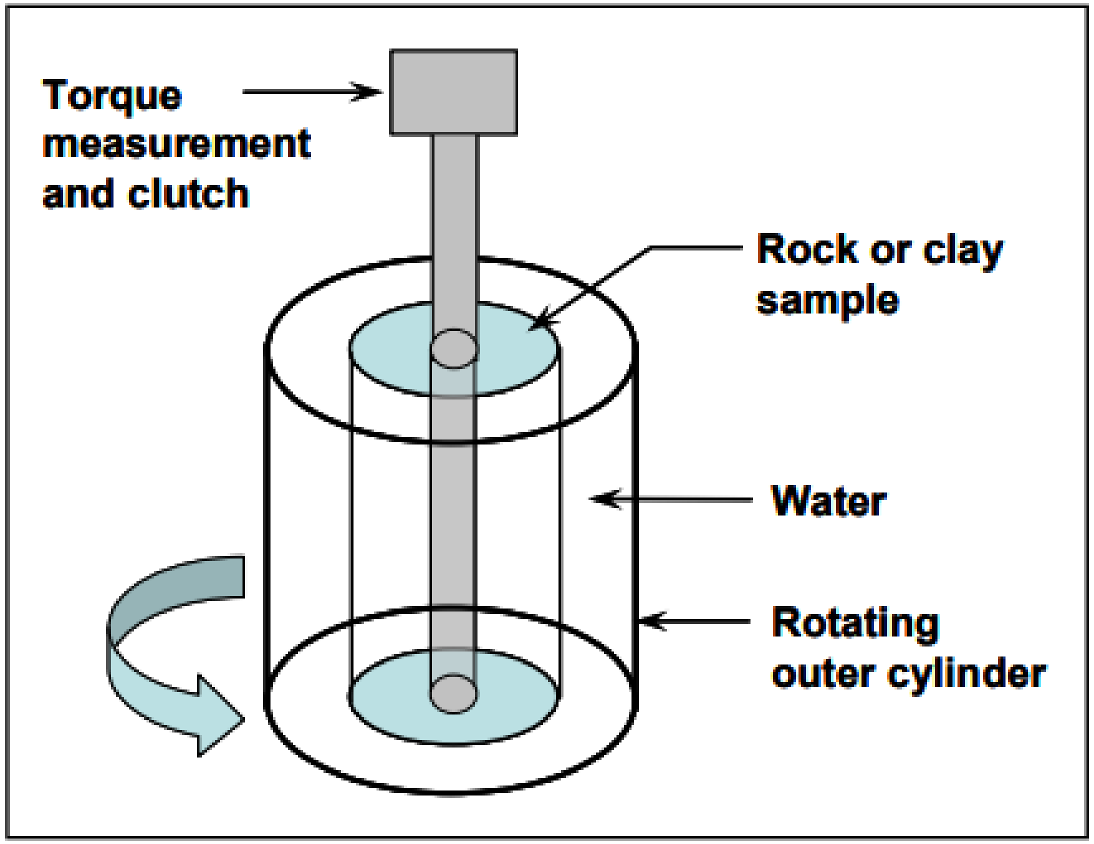
3. Collect soil sample and subject it to erosion testing; this gives relationship between stress and erosion

4. Each stress from (2) corresponds to an erosion rate from (3). Add the erosion rates together to get total scour depth over bridge's lifetime.

Background – RETA/SERF



Piston-style erosion test (SERF)



Rotational-Style Erosion Test (RETA)

Background – SERF/RETA Steady Flow Equation

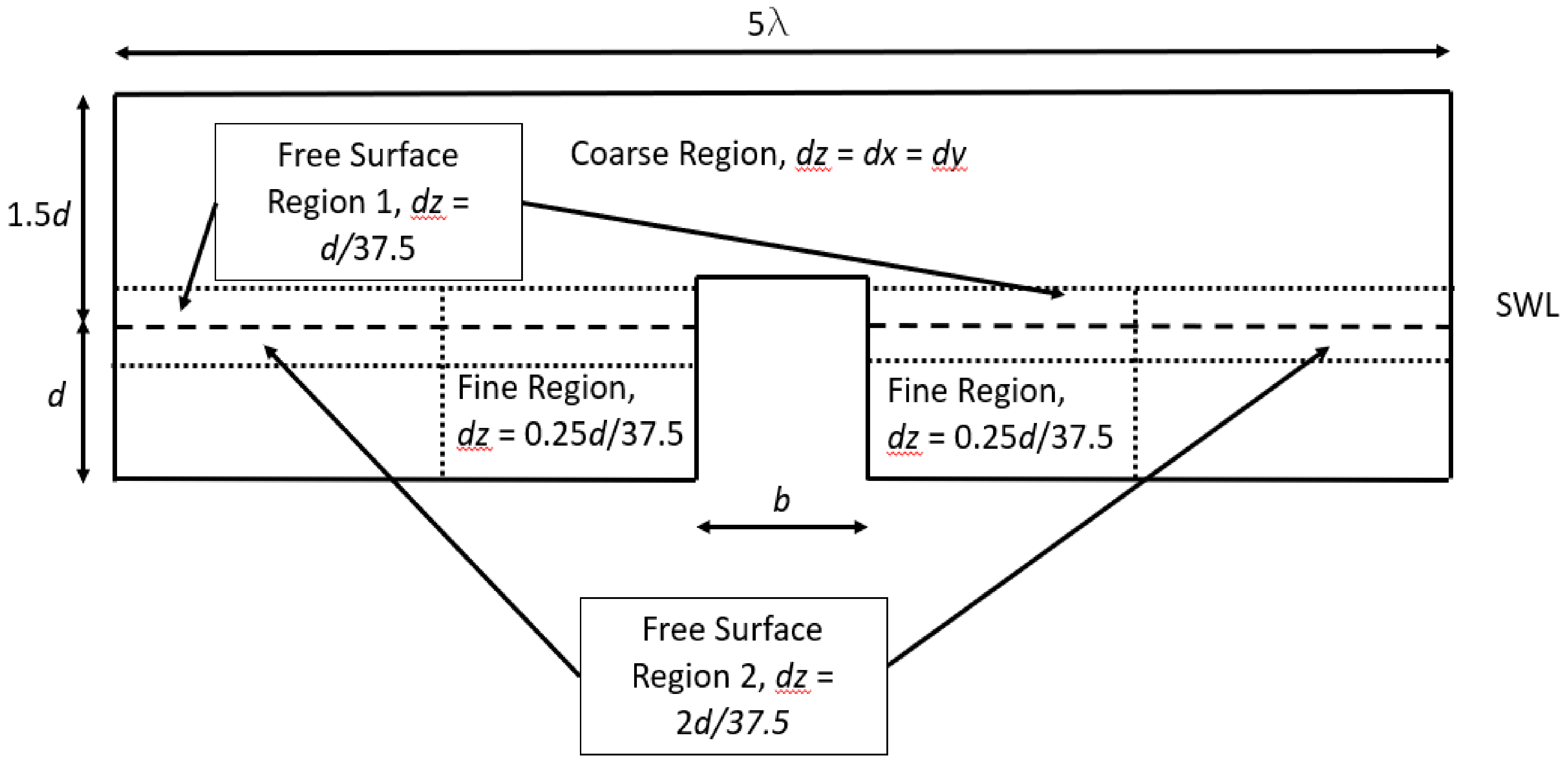
$$\tau_{max} = k_w k_{sp} k_{sh} k_\alpha \left[0.094\rho u^2 \left(\frac{1}{\log_{10} Re} - \frac{1}{10}\right)\right]$$

- τ_{max} = maximum bed stress
- $k_w, k_{sp}, k_{sh}, k_\alpha$ = correction factors for pier width, pile group spacing, pile length, attack angle
- u = mean velocity
- Re = Pile Reynolds Number = $\frac{uD}{\nu}$
  - D = pile diameter
  - ν = kinematic viscosity of water
- <u>Similar equation for wave action does not exist for field-scale structures!</u>

Project Objectives

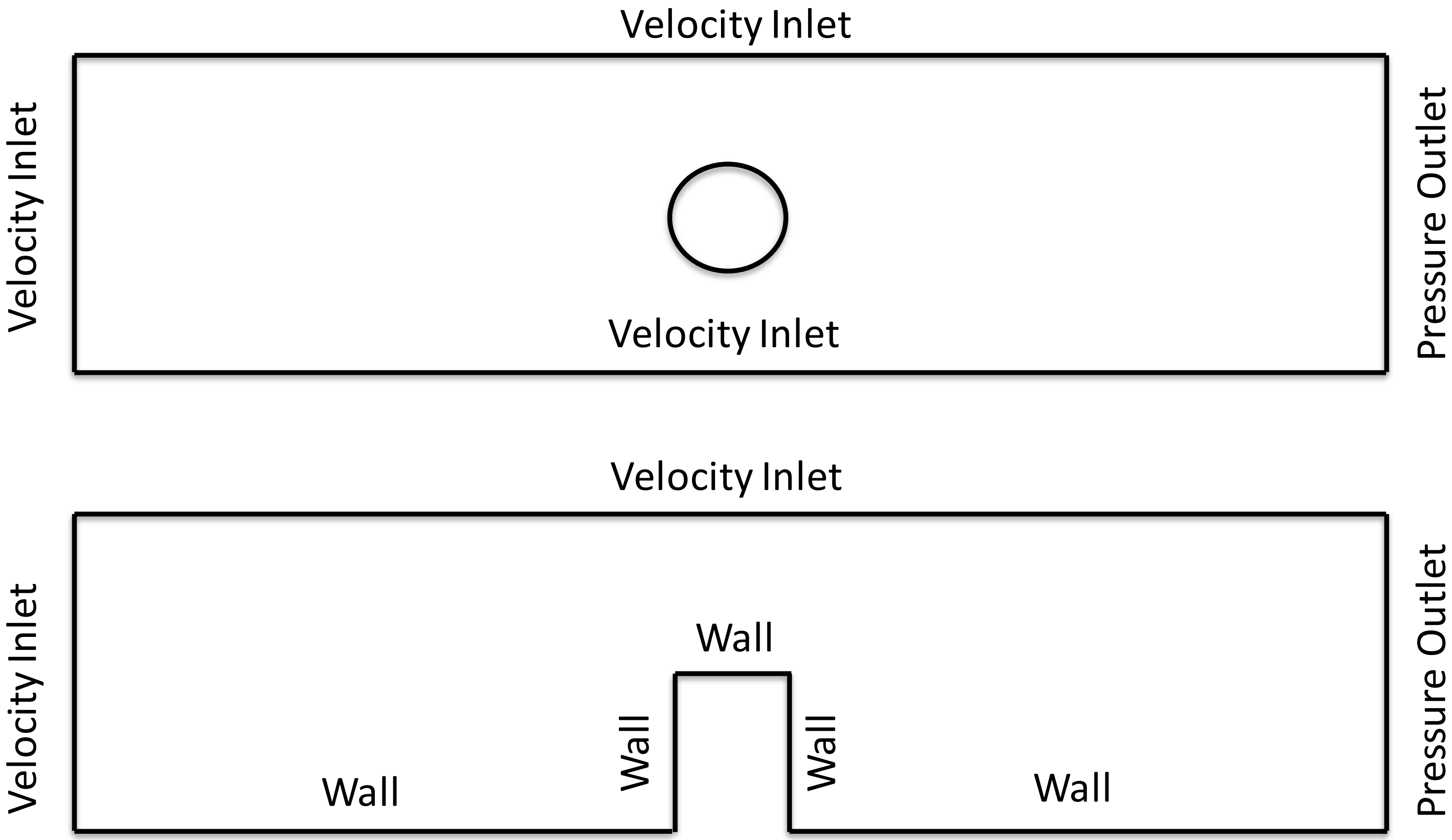
- The goal of this project was to develop a parametric equation for bottom stress around a pile subjected to wave attack

Mesh Parameters



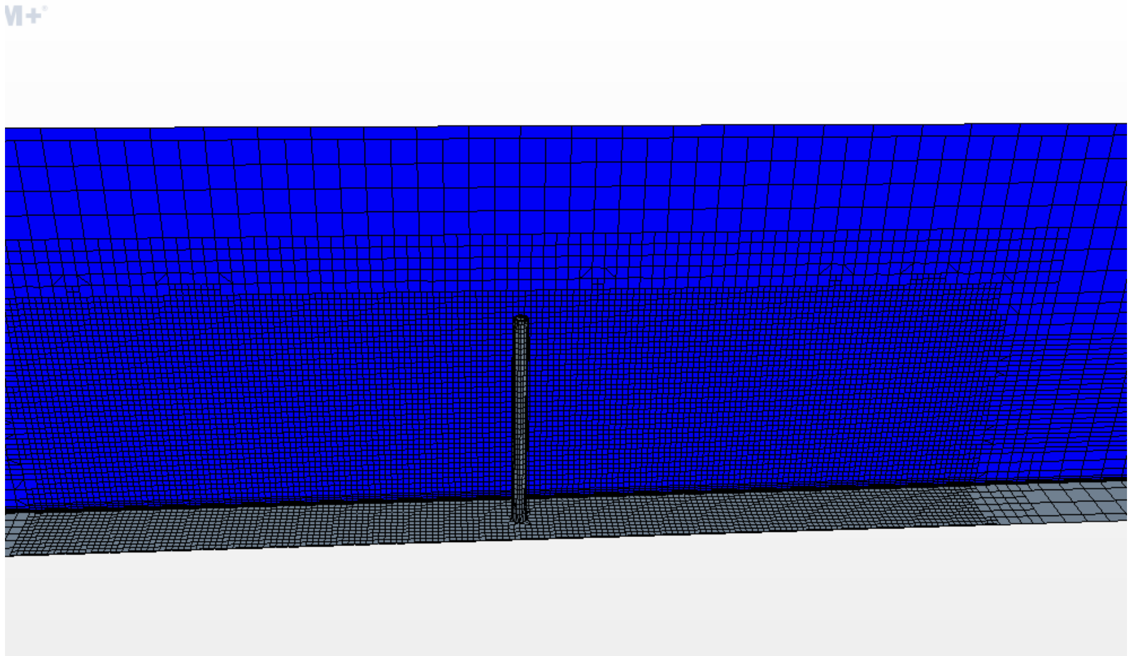
Model Meshing Parameters

Boundary Conditions

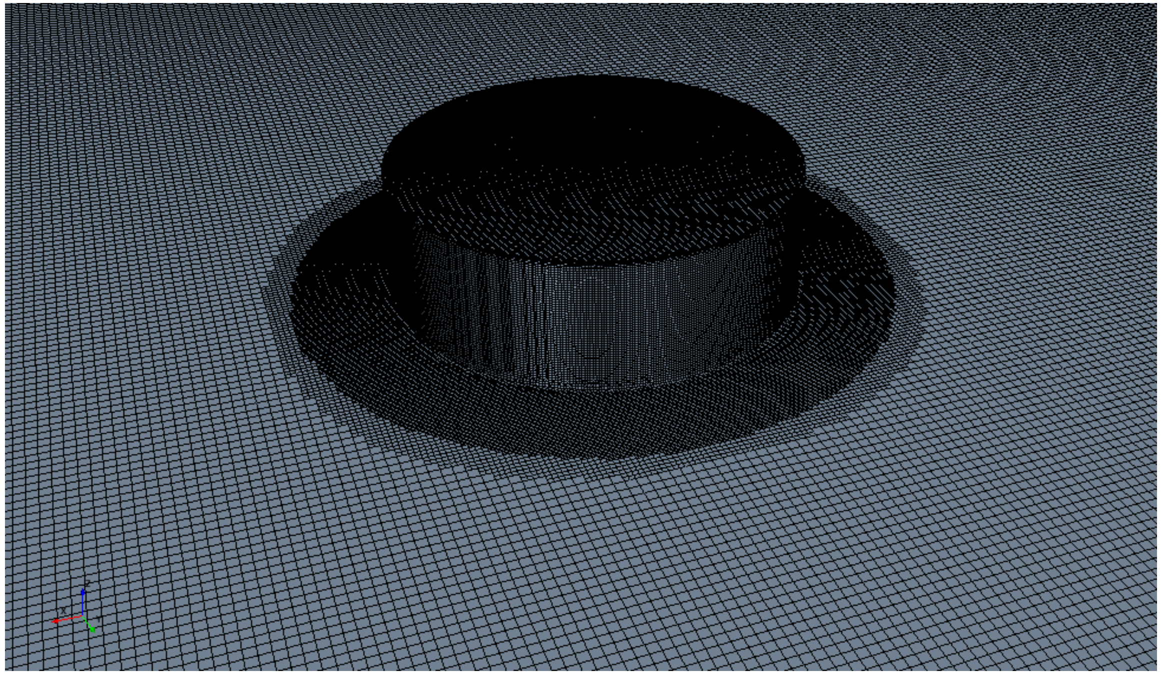


Model boundary conditions showing top-view (top) and side-view (bottom); not to scale

Sample Meshes

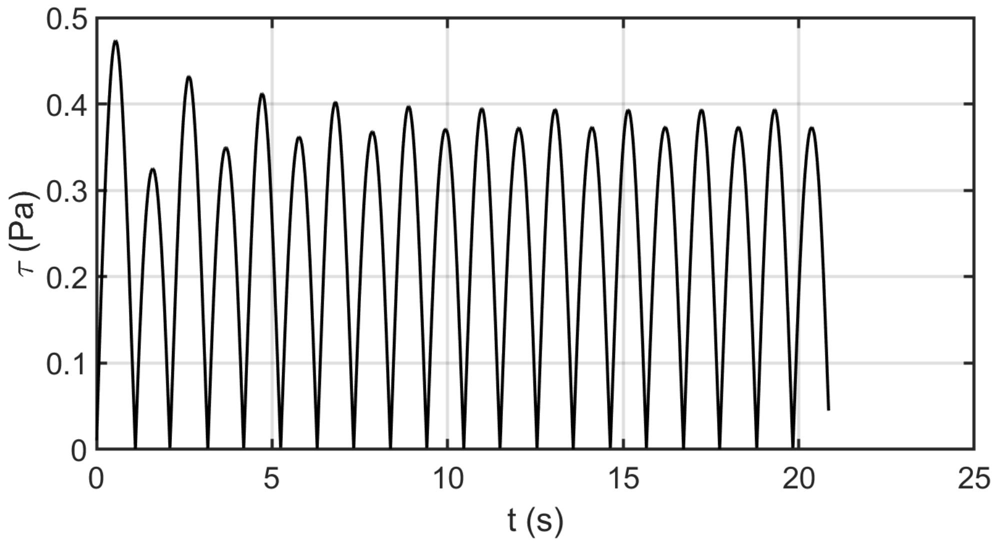


Meshed large-scale pile

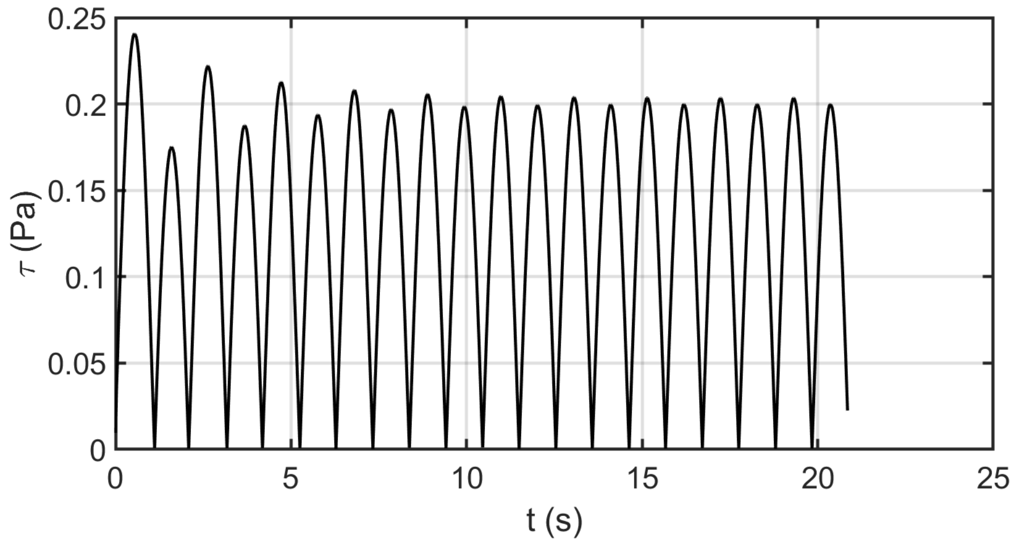


Meshed small-scale pile

Sample Results

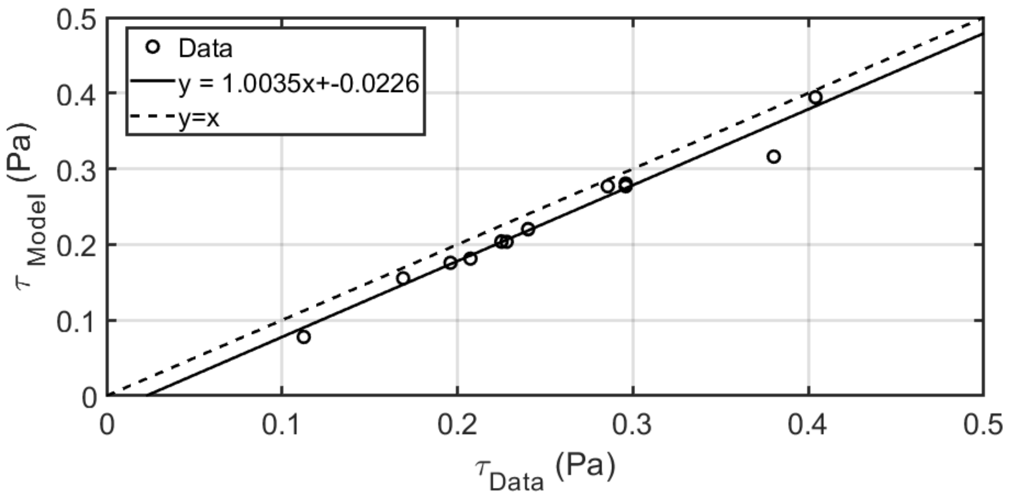


Sample results from SS1

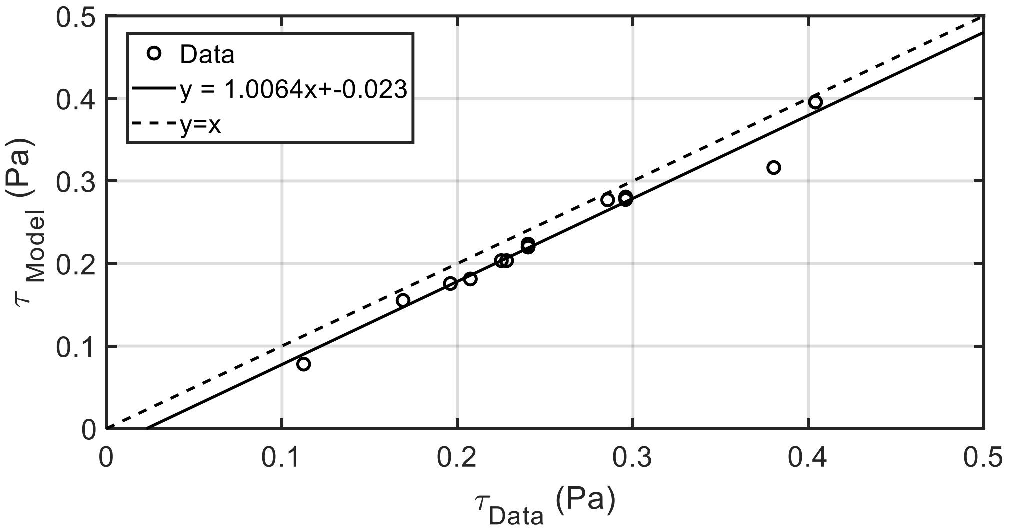


Sample results from SS16

Matching Data

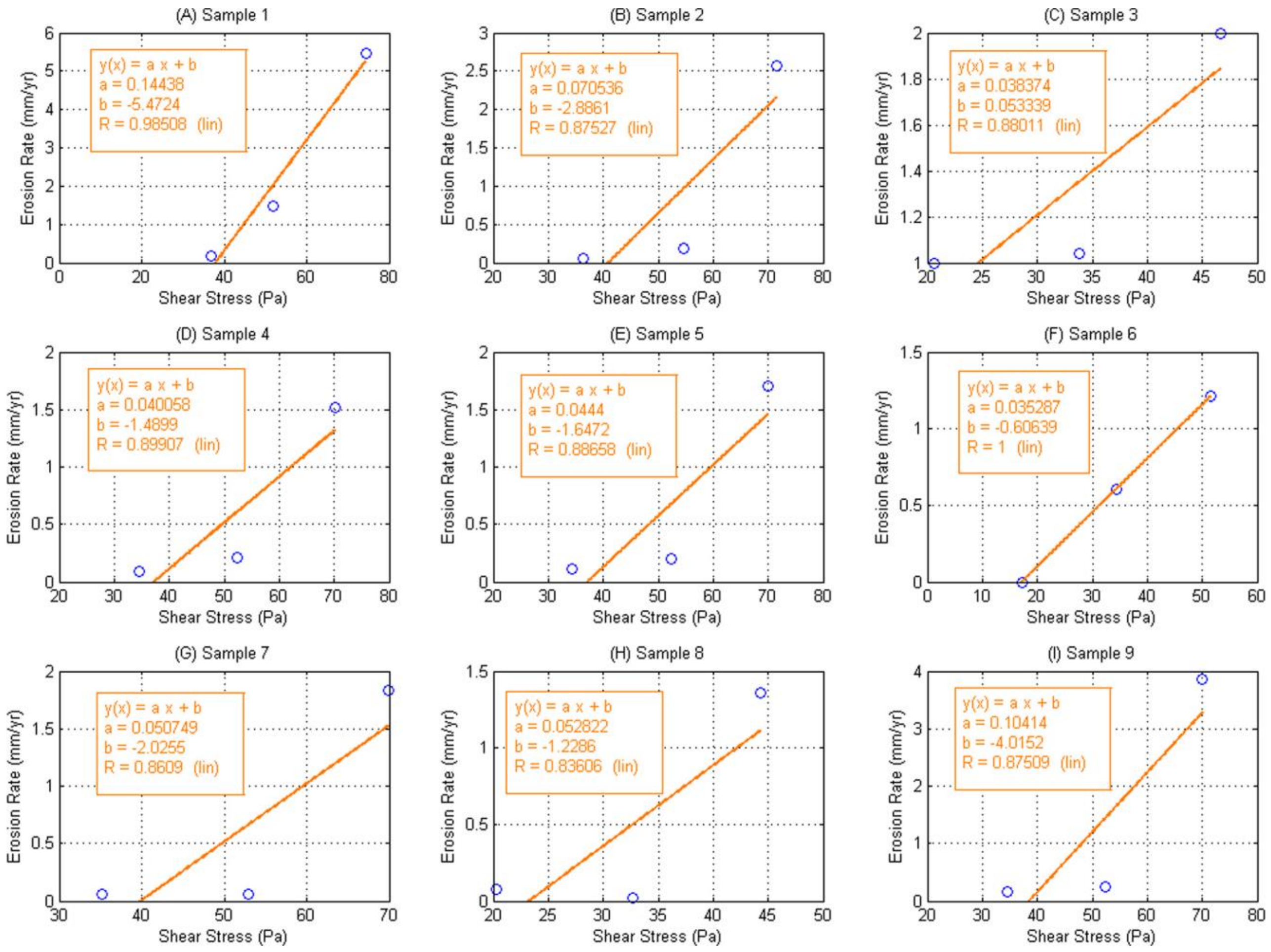


Modeled vs. experimental results using smooth bottom



Modeled vs. experimental results using roughness height of 0.02 inches (0.6 mm)

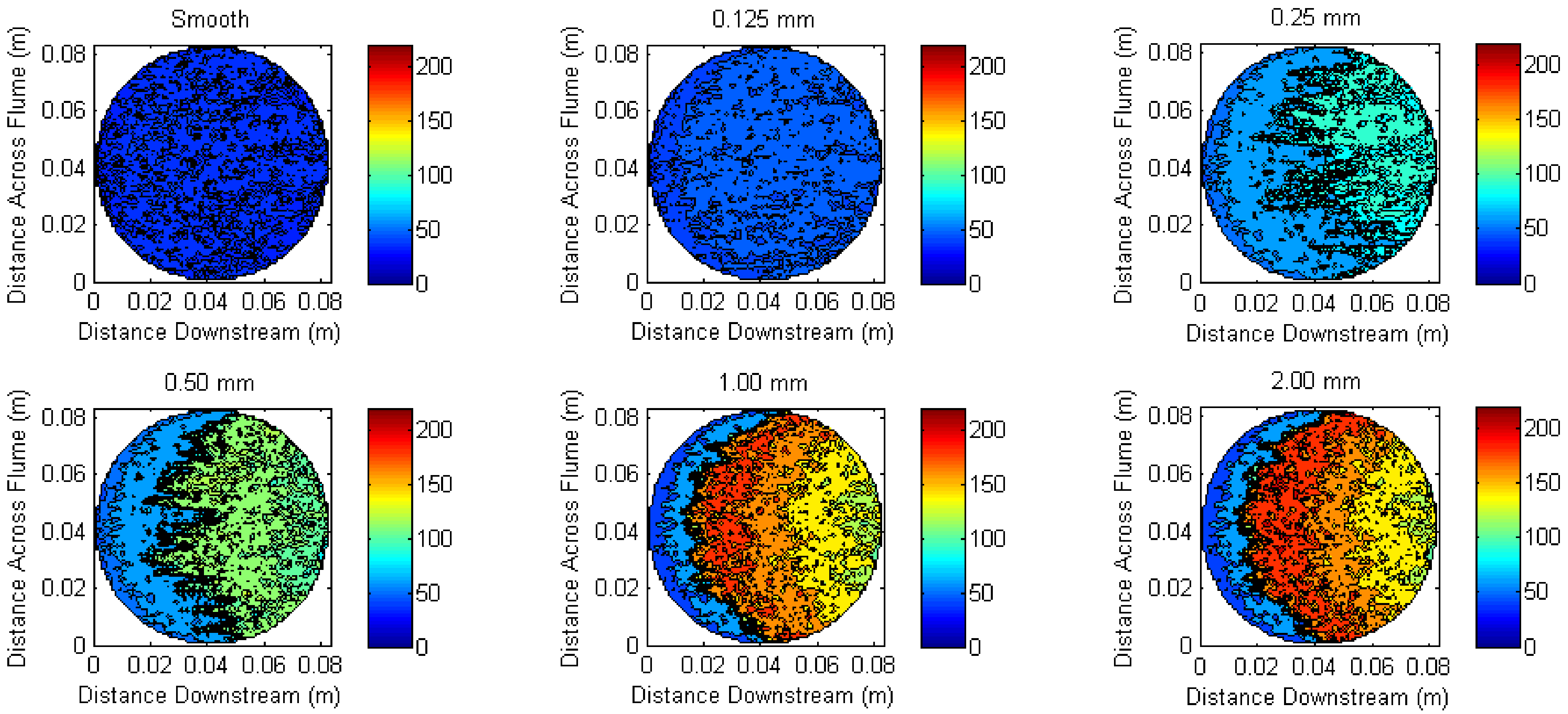
Sensitivity Analysis



Typical RETA erosion functions

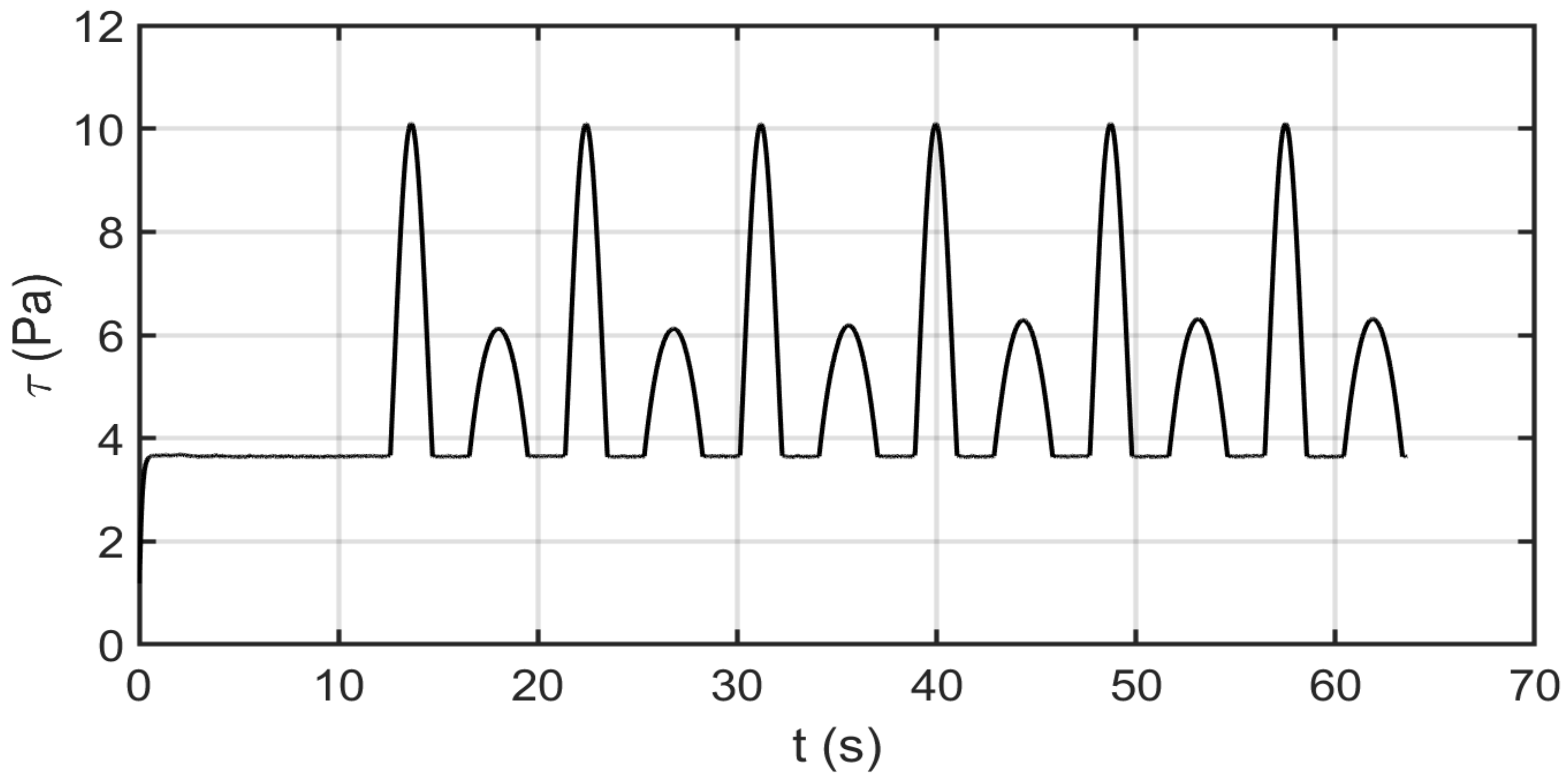
- Erosion rate varies between 0.03 mm/year-Pa and 0.14 mm/year-Pa
- Discrepancy between modeled and experimental data was only 0.02 Pa
- Erosion discrepancy would be expected to be only 0.003 mm/year

SERF Implementation Implications



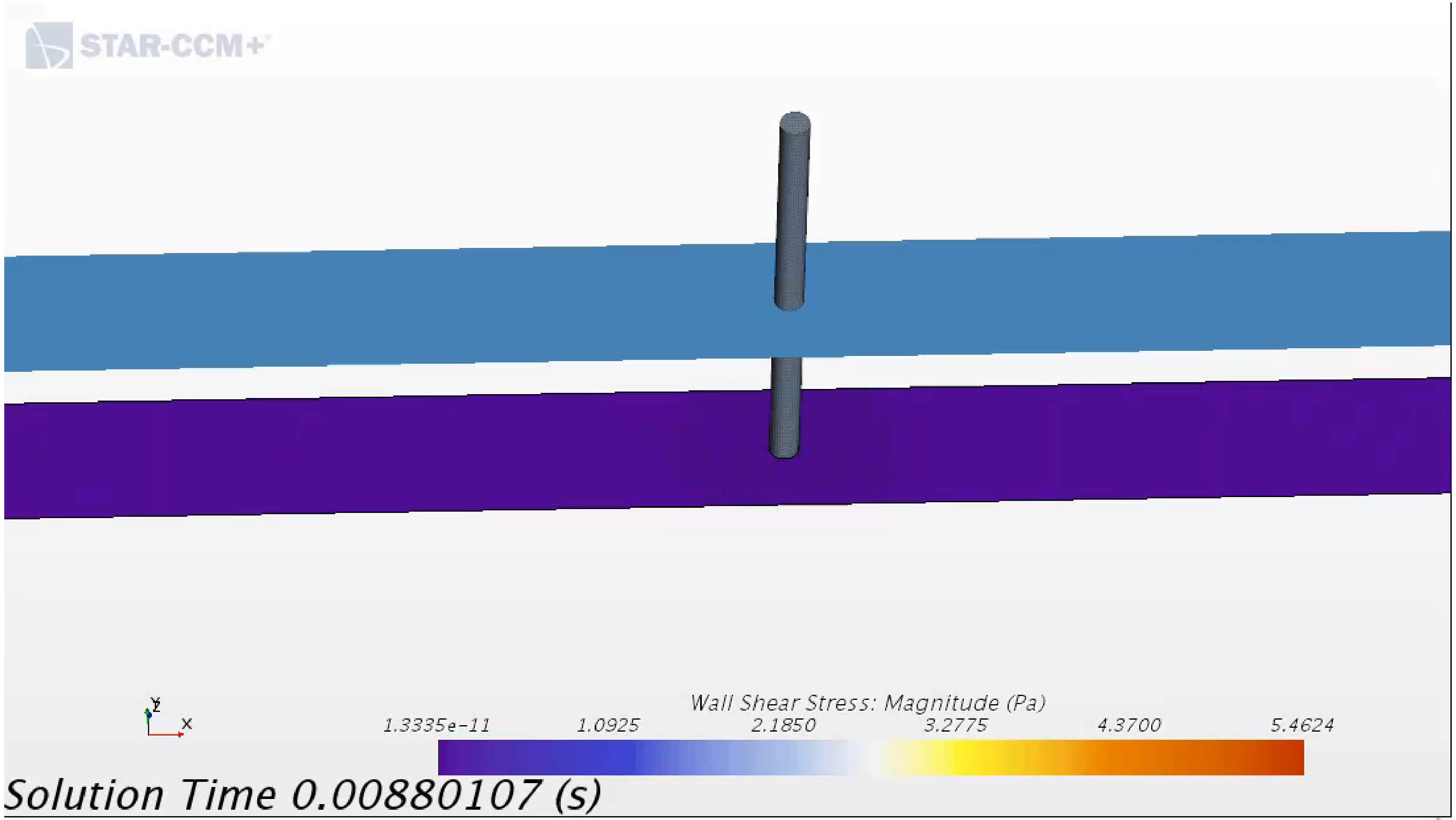
Typical stresses across SERF specimens

Large-Scale Sample Results



Sample Results

Large-Scale Sample Results



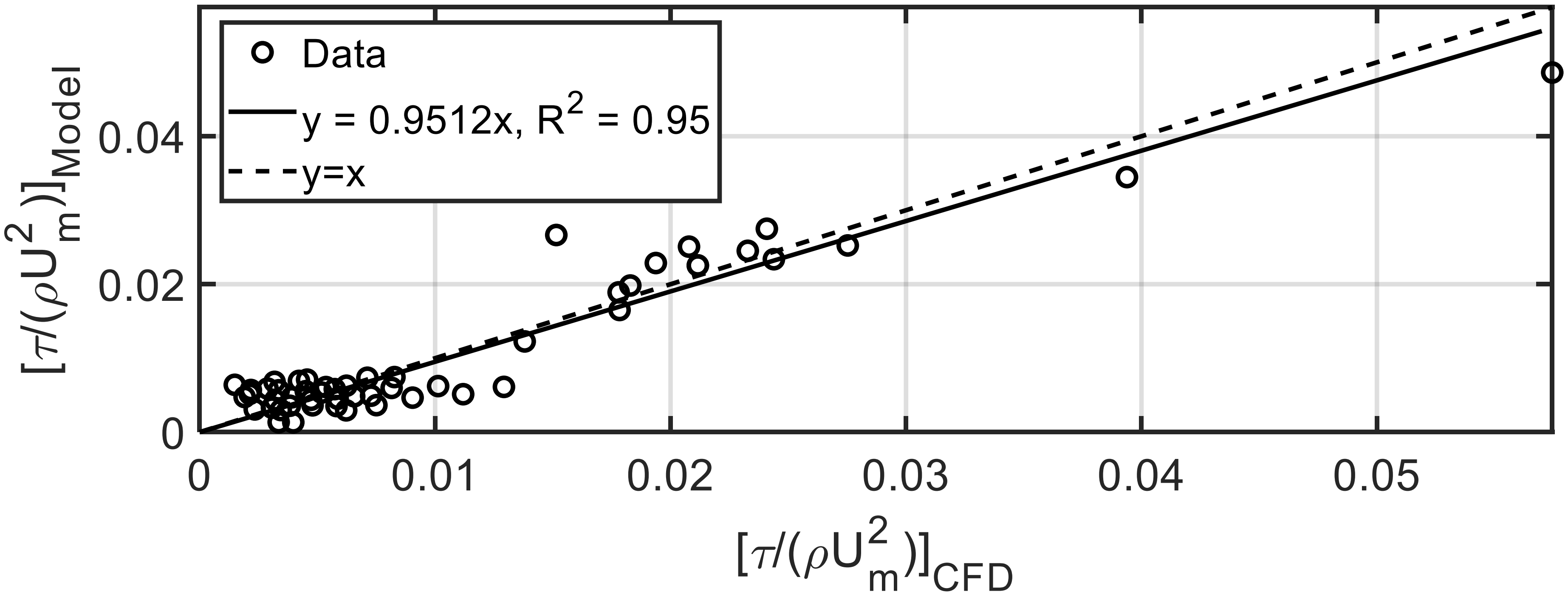
Task 3 – Simple Design Equation

- $\tau_{max} = f\left(KC, Re, \frac{D}{L}\right)$
- Steady Flow: $\tau_{max} = k_w k_{sp} k_{sh} k_\alpha \left[0.094\rho u^2 \left(\frac{1}{\log_{10} Re} - \frac{1}{10}\right)\right]$
- Waves: $\frac{\tau_{max}}{\rho U_m^2} = a_1\left(\frac{D}{L}\right) + a_2\left(\frac{1}{\log_{10} Re} - \frac{1}{10}\right) + a_3\left(\frac{D}{L}\right)\left(\frac{1}{\log_{10} Re} - \frac{1}{10}\right) + a_4 KC^{-1}$
  - $a_1 = -0.4528$
  - $a_2 = 0.1072$
  - $a_3 = 5.1325$
  - $a_4 = 0.00781$

FDOT

UNF UNIVERSITY of NORTH FLORIDA

Task 3 – Simple Design Equation

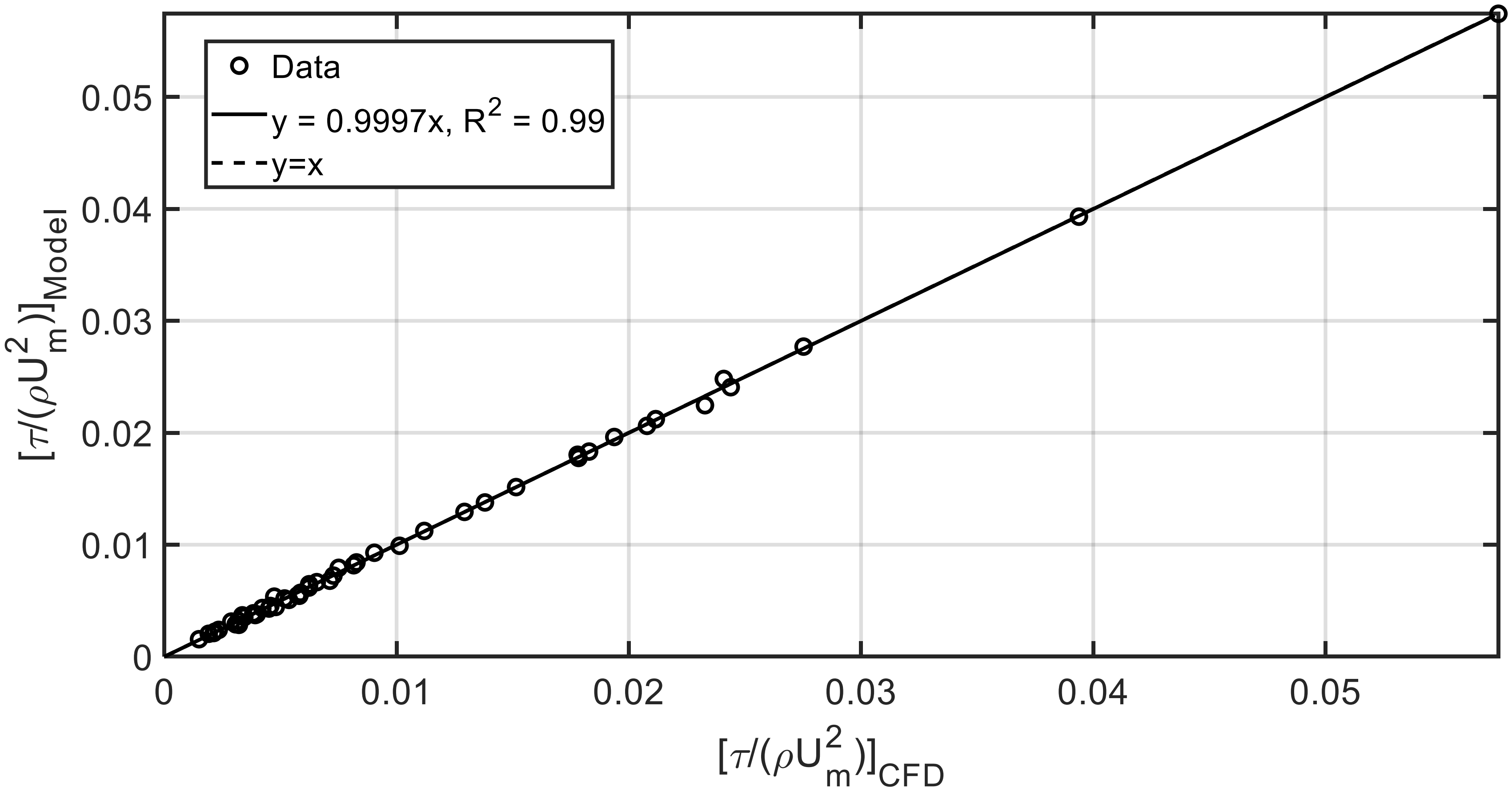


Simple design equation quality of fit

Complicated Design Equation

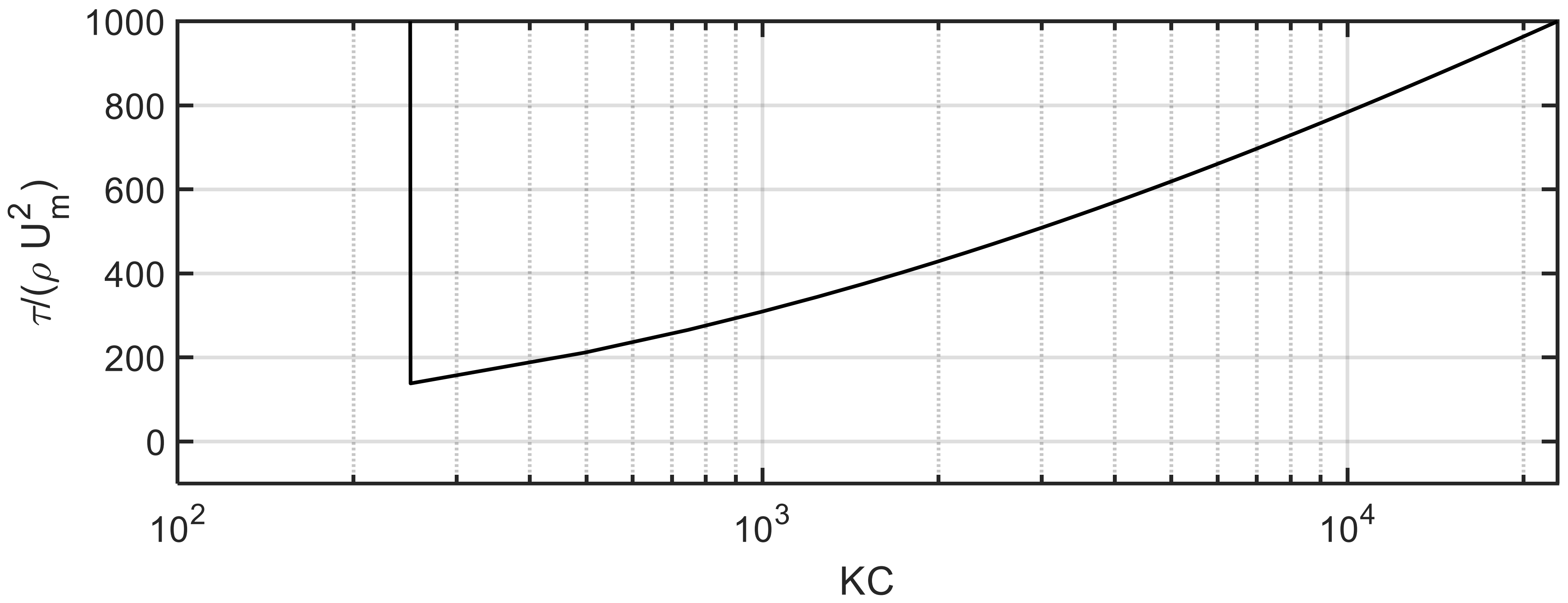
- $\frac{\tau}{\rho U_m^2} = a_0 + a_1 \left(\frac{H}{L}\right)^{1.05} + a_2 \left(\frac{D}{L}\right)^{0.99} + a_3 KC^{-0.65} + a_4 \exp\left(\log_{10} (Re)\right)^3 + a_5 \left(\frac{HD}{L^2}\right)^{1.2} + a_6 \left(\frac{H}{L}\right)^{3.15} KC^{-1.3} + a_7 \left(\frac{H}{L}\right)^{0.95} (\log_{10}(Re))^2 + a_8 \left(\frac{D}{L}\right)^{1.55} KC^{1.05} + a_9 \left(\frac{D}{L}\right)^{1.05} (\log_{10} Re)^{0.72} + a_{10} KC^{\frac{1}{15}} (\log_{10} Re)^{0.125} + a_{11} \left(\frac{H}{L}\right)^{2.1} \left(\frac{D}{L}\right)^{1.05} \ln(KC) + a_{12} \left(\frac{D}{L}\right)^{1.4} KC^{-0.9} (\log_{10} Re)^{-2.6} + a_{13} \left(\ln\left(\frac{H}{L}\right)\right)^5 \left(\frac{D}{L}\right)^{1.05} KC^{0.81} (\log_{10}(Re))^2$
  - $a_0 = -0.045678$
  - $a_1 = 0.08110917$
  - $a_2 = -4.2112$
  - $a_3 = 0.15463676$
  - $a_4 = -12883$
  - $a_5 = 1.2790872$
  - $a_6 = -0.025252$
  - $a_7 = -0.0031414$
  - $a_8 = 0.5468853$
  - $a_9 = 0.87930766$
  - $a_{10} = 0.0367309$
  - $a_{11} = -0.031927$
  - $a_{12} = -11.107$
  - $a_{13} = -0.017212$

Complicated Design Equation



Complicated design equation quality of fit

Task 3 – Complicated Design Equation Limitations



Complicated design equation behavior as a function of KC

Summary and Research Conclusions

- Several CFD simulations used to simulate worst-case stress conditions around piles under wave attack

- Two parametric design equations for predicting worst-case wave stress around pile conditions were developed based upon results

Underwater Noise Level Study during Impact Pile Driving

FDOT Project No. BDV34-985-03, Katasha Cornwell, Office of Environmental Management, Project Manager

University of North Florida
1 UNF Drive, Jacksonville, FL 32224

PI: Raphael Crowley, Ph.D., P.E., Associate Professor, Taylor Engineering Research Institute, r.crowley@unf.edu
Co-PI: Jim Gelsleichter, Ph.D., Associate Professor, Biology, jim.gelsleichter@unf.edu
Co-PI: Brian Kopp, Ph.D., Assistant Professor, Electrical Engineering brian.kopp@unf.edu
Co-PI: Bill Dally, Ph.D., P.E., Associate Professor, Coastal Engineering, w.dally@unf.edu
Research Assistants – Moses Bosco (GRA), Brandon Rivera (GRA), and Amanda Schaaf (GRA)

Motivation

- Pile driving may make enough noise to kill/injure fish and other marine animals

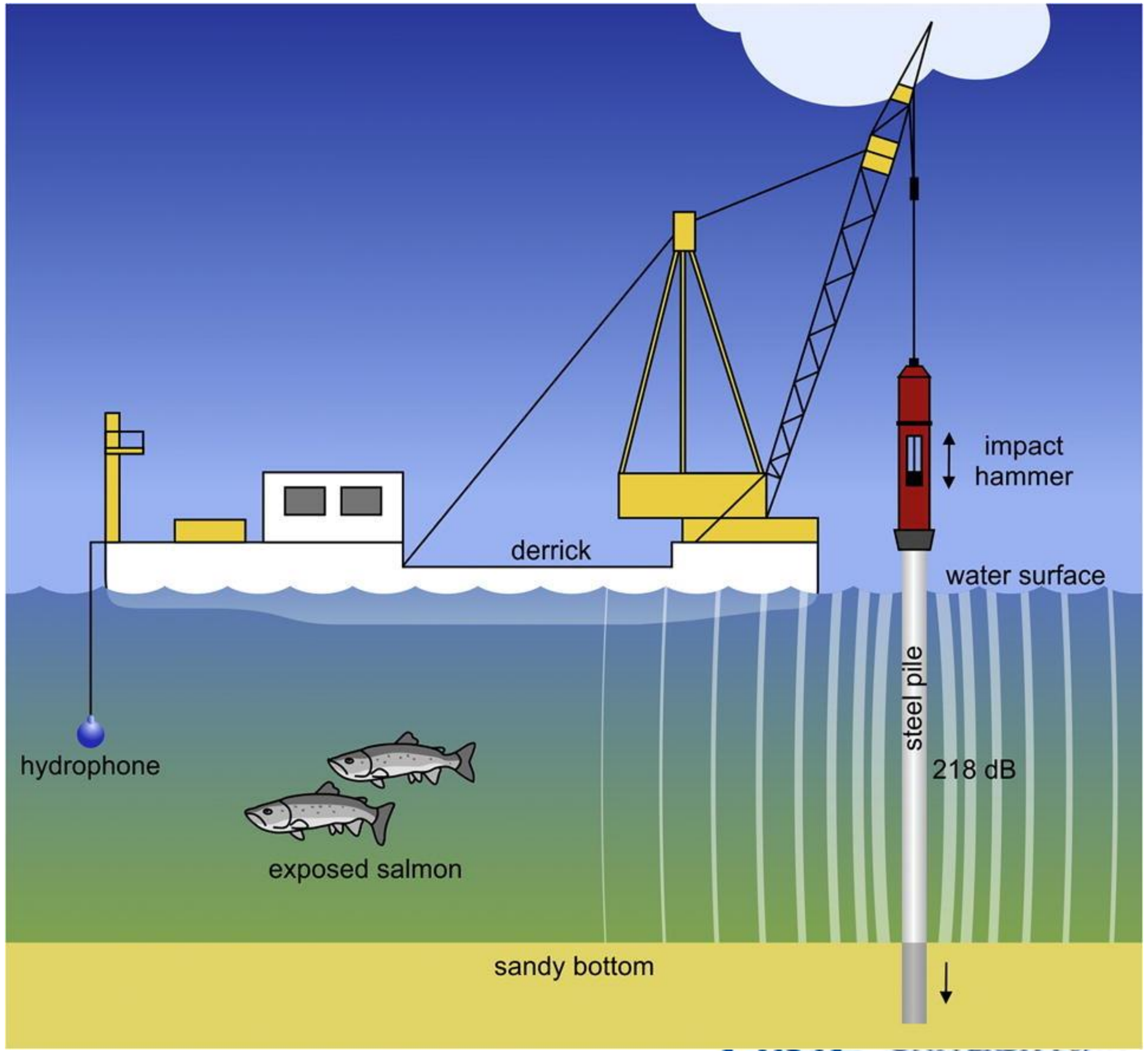
- Florida does not have reliable local guidelines to predict anthropogenic noise during pile driving and it has been using CalTrans' "Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish" (Buehler et al. 2015)

FDOT

UNF UNIVERSITY of NORTH FLORIDA

Underwater Pile Driving Mechanism & Sound Decay

- Geometrical effects
- Absorption at the water surface
- Geotechnical absorption



Project Objectives

- Main Objective – Characterize underwater noise levels during impact pile driving throughout the State of Florida
  - Sample noise data at several bridges throughout the state and use data to develop correlations between noise and other variables
  - Determine transmission loss coefficients and use to data to develop statistics between noise and other variables
  - Develop technical guidance in collaboration with NMFS and USFWS

Specific Variables of Interest

- Decibels
  - $dB = 10\log_{10}\left[\left(\frac{P}{P_{ref}}\right)^2\right]$
  - $P = \text{sound pressure (Pa)}$
  - $P_{ref} = 1\mu\text{Pa}$
- Sound Attenuation Coefficient
  - $TL = F\log_{10}\frac{R}{R_0}$
  - *R* = Range from sound source
  - R_0 = Reference range
  - *F* = Transmission loss coefficient
  - *TL* = Transmission loss (in dB)
- Sound Statistics
  - *Peak* = peak sound-level
  - *RMS* = root-mean-square sound-level
  - *SEL* = sound exposure level

$$SEL = 10\log_{10}\int\left(P/P_{ref}\right)^2 dt$$

FDOT

UNF UNIVERSITY of NORTH FLORIDA

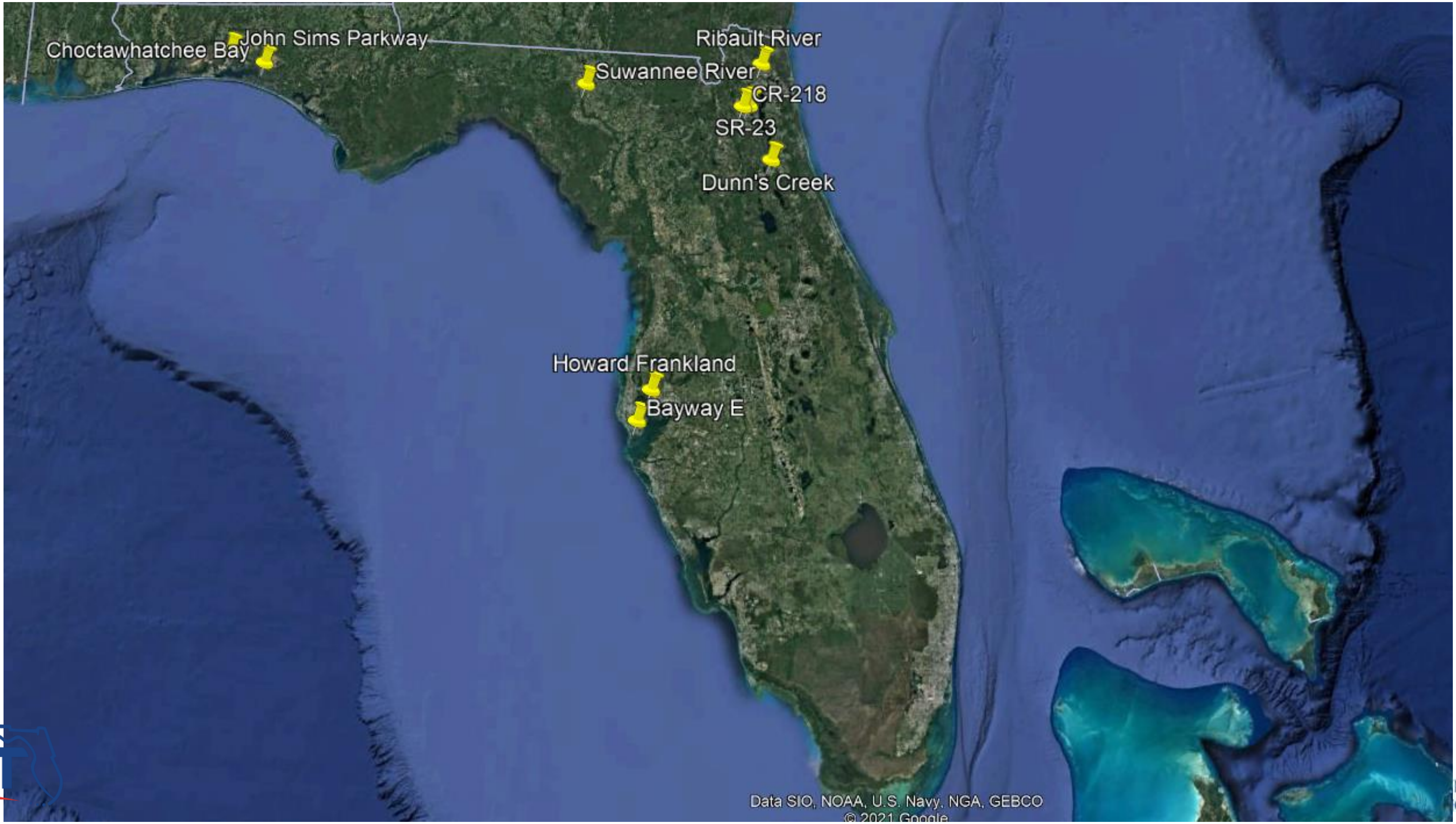
Current Noise Guidelines – Interim Criteria (CalTrans 2015)

Effect	Metric	Fish Mass (g)	Threshold (dB relative to 1 μPa)
Onset of physical injury	Peak Pressure	N/A	206
	Accumulated SEL	$> 2g$	187
		$\leq 2g$	183
Adverse behavior effects	RMS Pressure	N/A	150

New Data for Possibly Updating Guidelines (Popper et al. 2019)

Type of Animal	Mortality and potential mortal injury	Impairment			
		Recoverable injury	Temporary threshold shift (TTS)	Masking	Behavior
Fish: no swim bladder (particle motion detection)	> 219 dB SEL_{cum} or > 213 dB peak	> 216 dB SEL_{cum} > 213 dB Peak	>> 186 dB SEL_{cum}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB SEL_{cum} or > 207 dB peak	203 dB SEL_{cum} or > 207 dB peak	> 186 dB SEL_{cum}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{cum} or > 207 dB peak	203 dB SEL_{cum} or > 207 dB peak	186 dB SEL_{cum}	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea Turtles	210 dB SEL_{cum} or > 207 dB peak	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	> 210 dB SEL_{cum} or > 207 dB peak	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

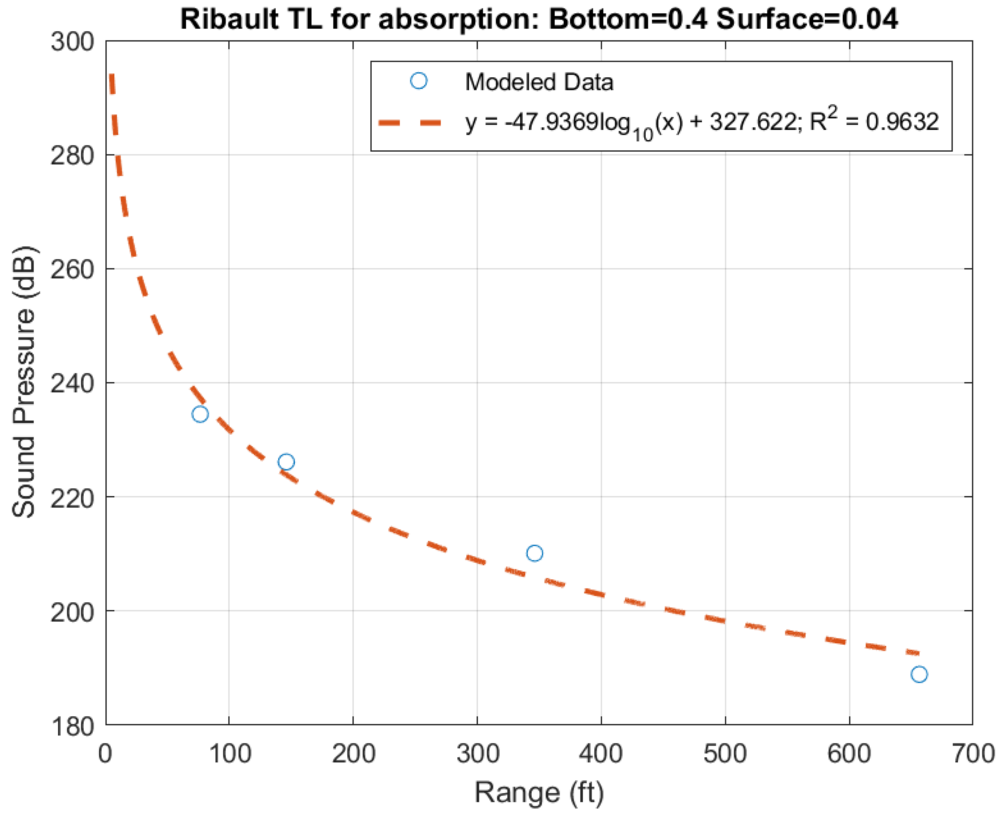
Site Locations



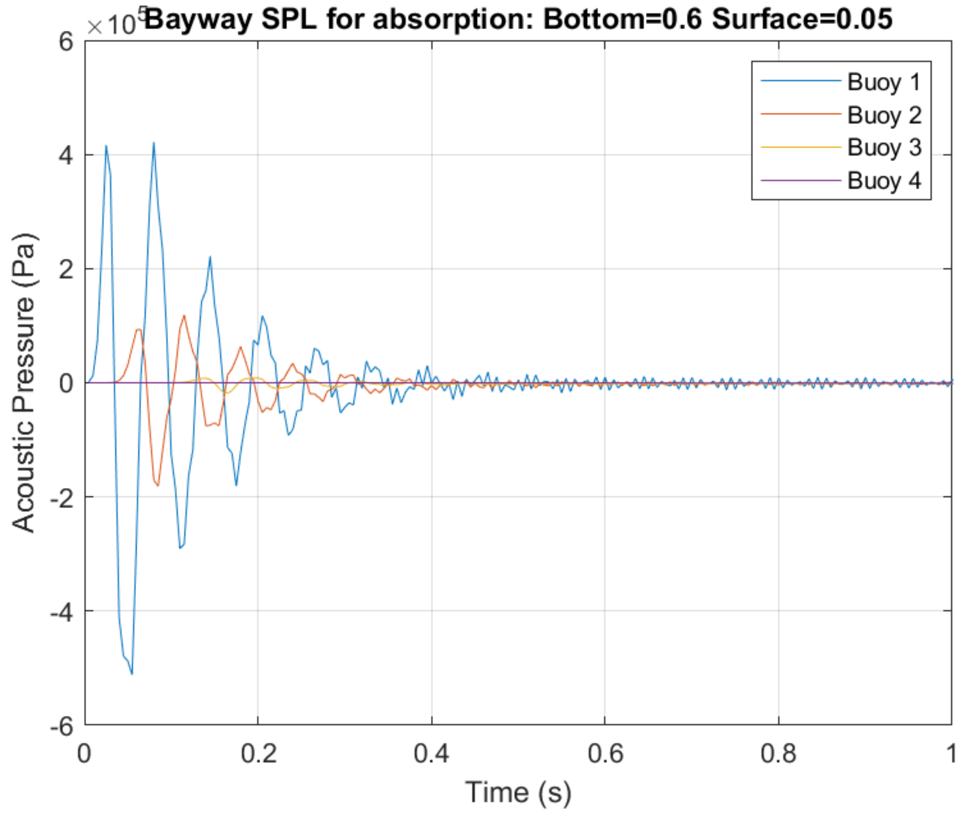
FDOT

UNIVERSITY of NORTH FLORIDA

Computer Modeling – Sample Results

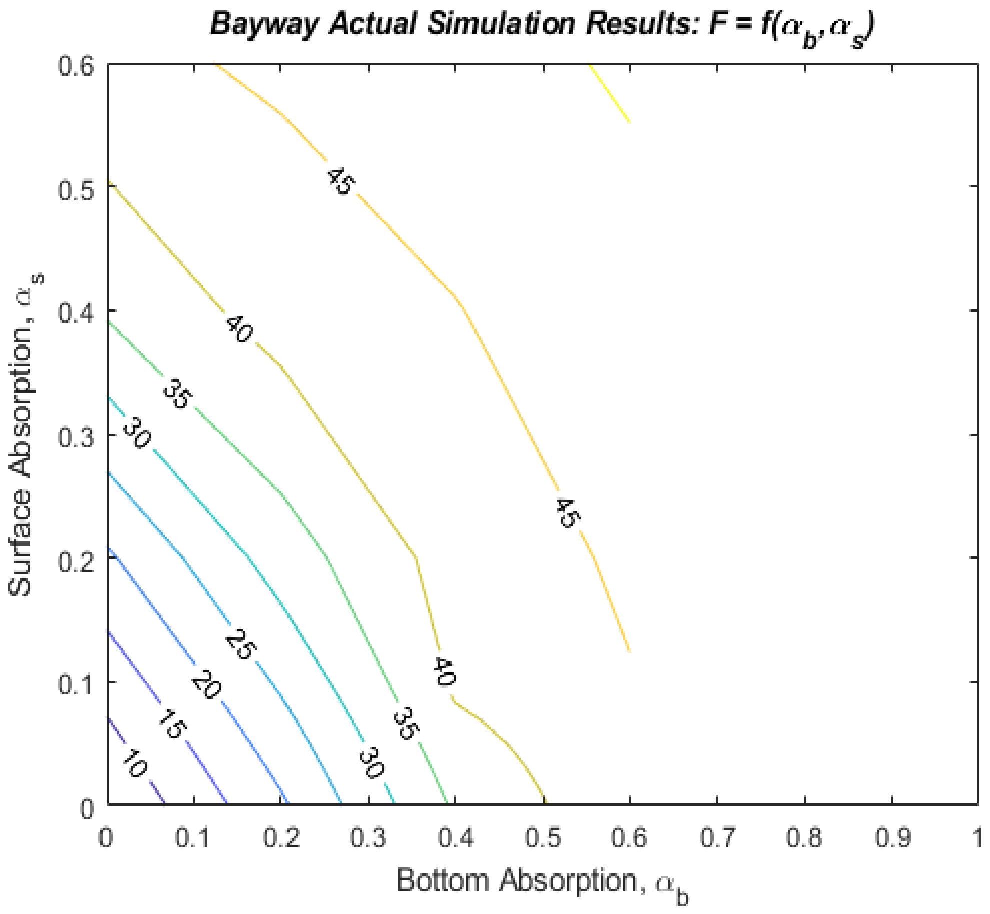


Sample Results from Ribault

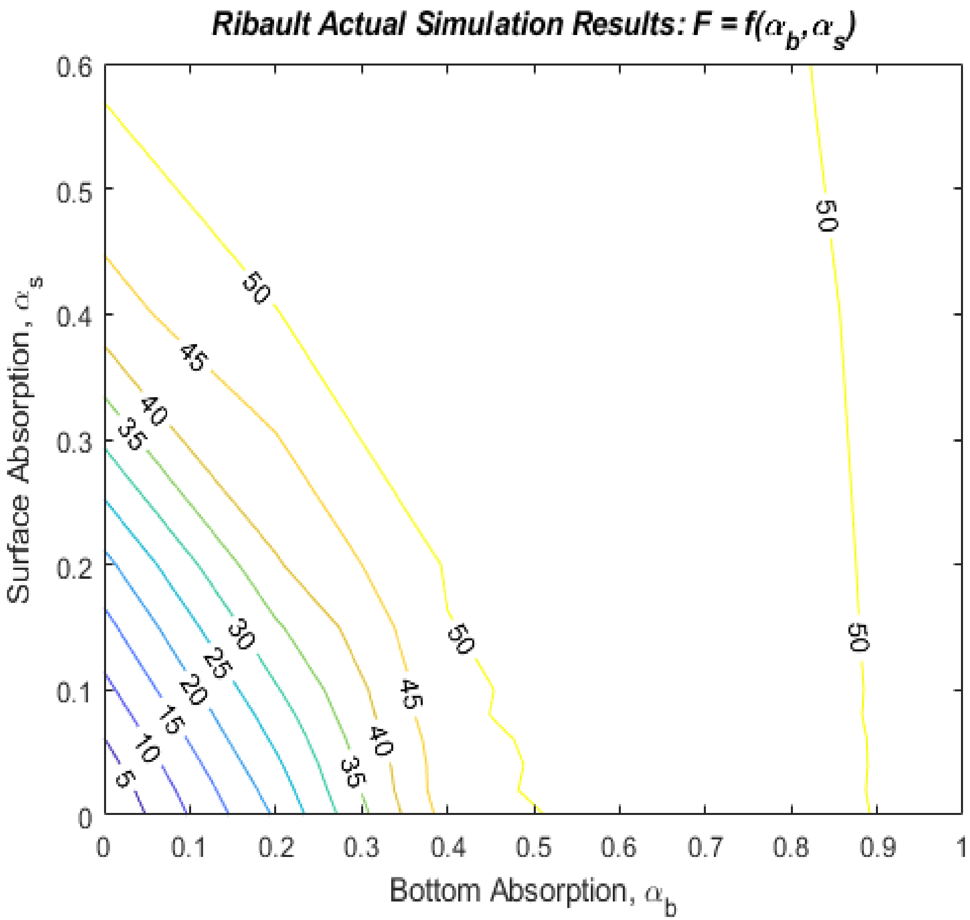


Sample Results from Bayway

Computer Modeling – Results Contours



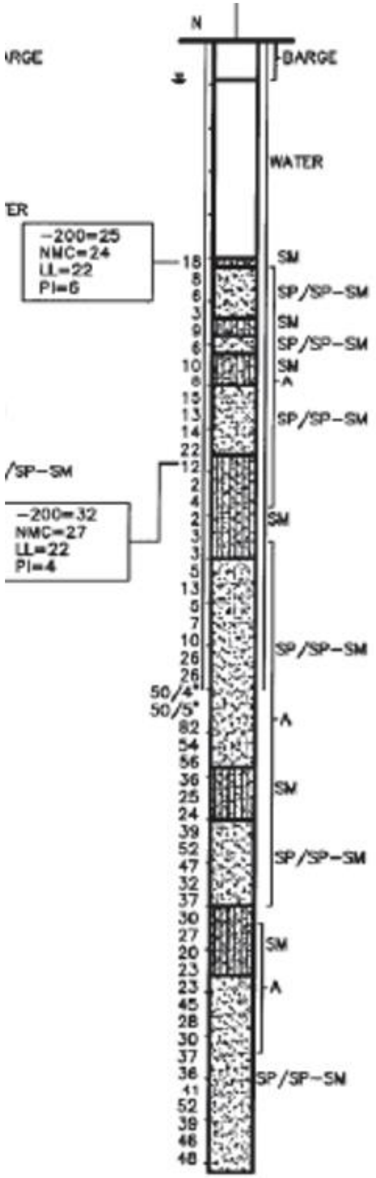
Contour Results from Bayway
(actual TL coefficient = 18)

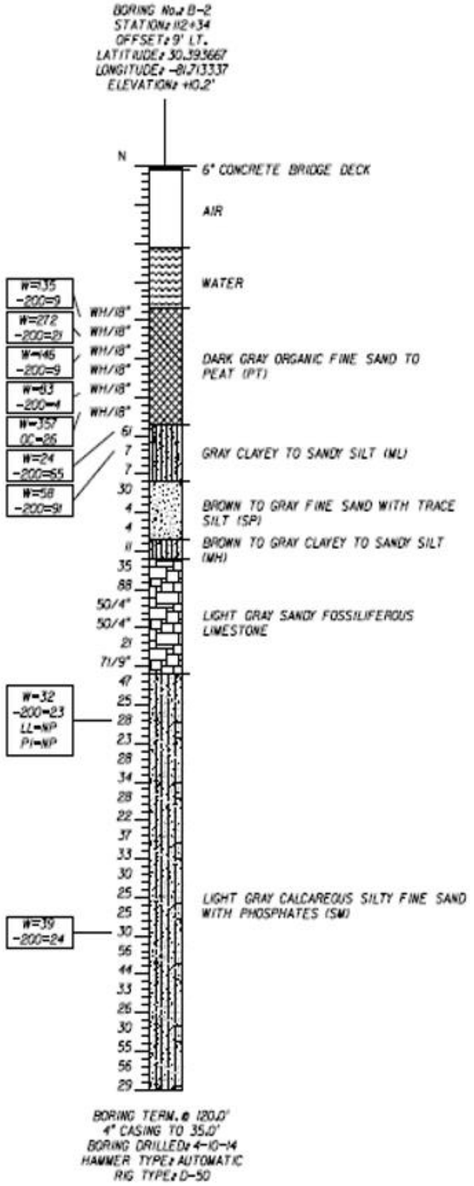


Contour Results from Ribault
(actual TL coefficient = 44)

Soil Conditions – Computer Modeled Sites

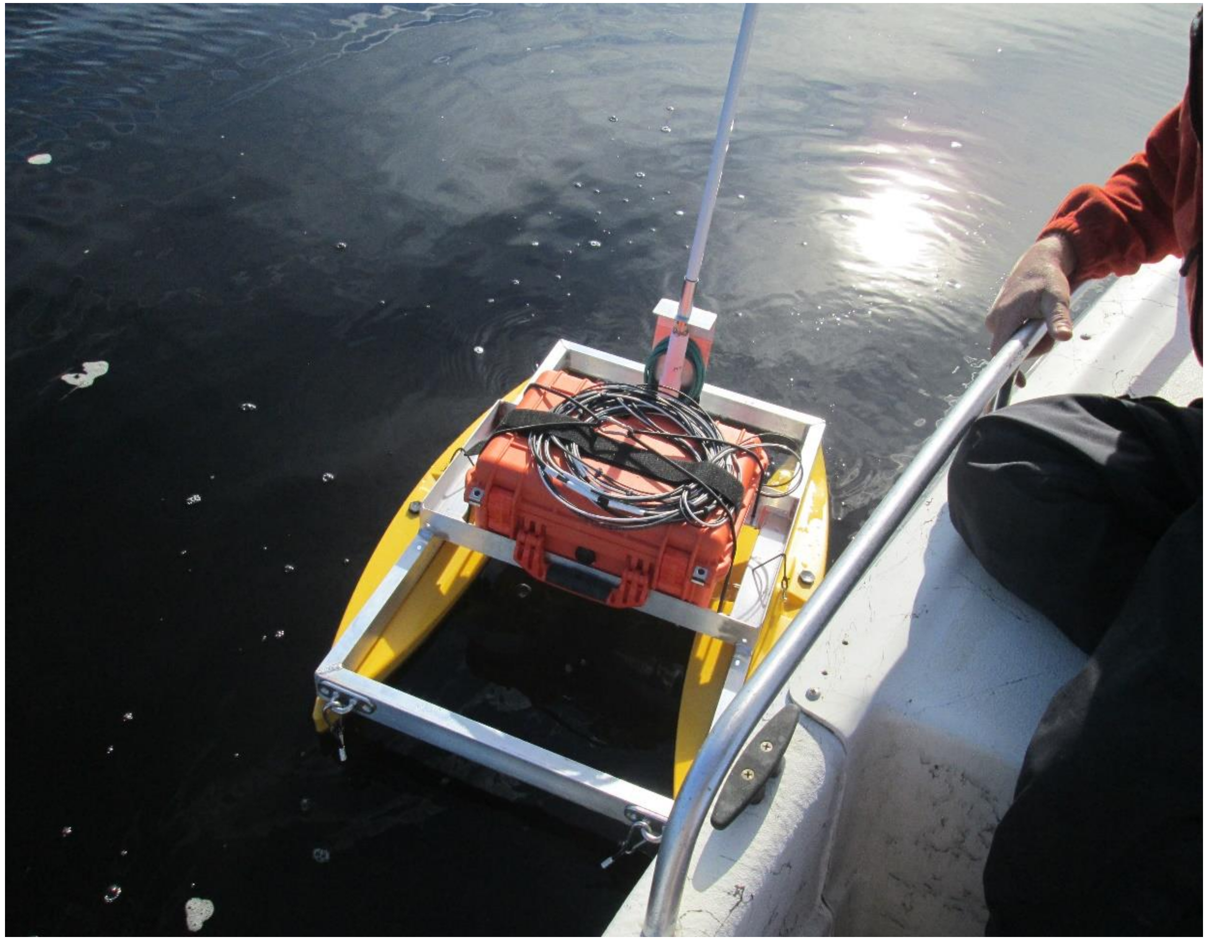
- Bayway E (left) – SM surface layer followed by varying SP/SP-SM and SM layers
- Ribault River (right) – PT surface layer followed by clay
- Preliminarily – results indicate that geotech conditions play a significant role in sound attenuation





UNF UNIVERSITY of NORTH FLORIDA

Data Collection – Buoy System



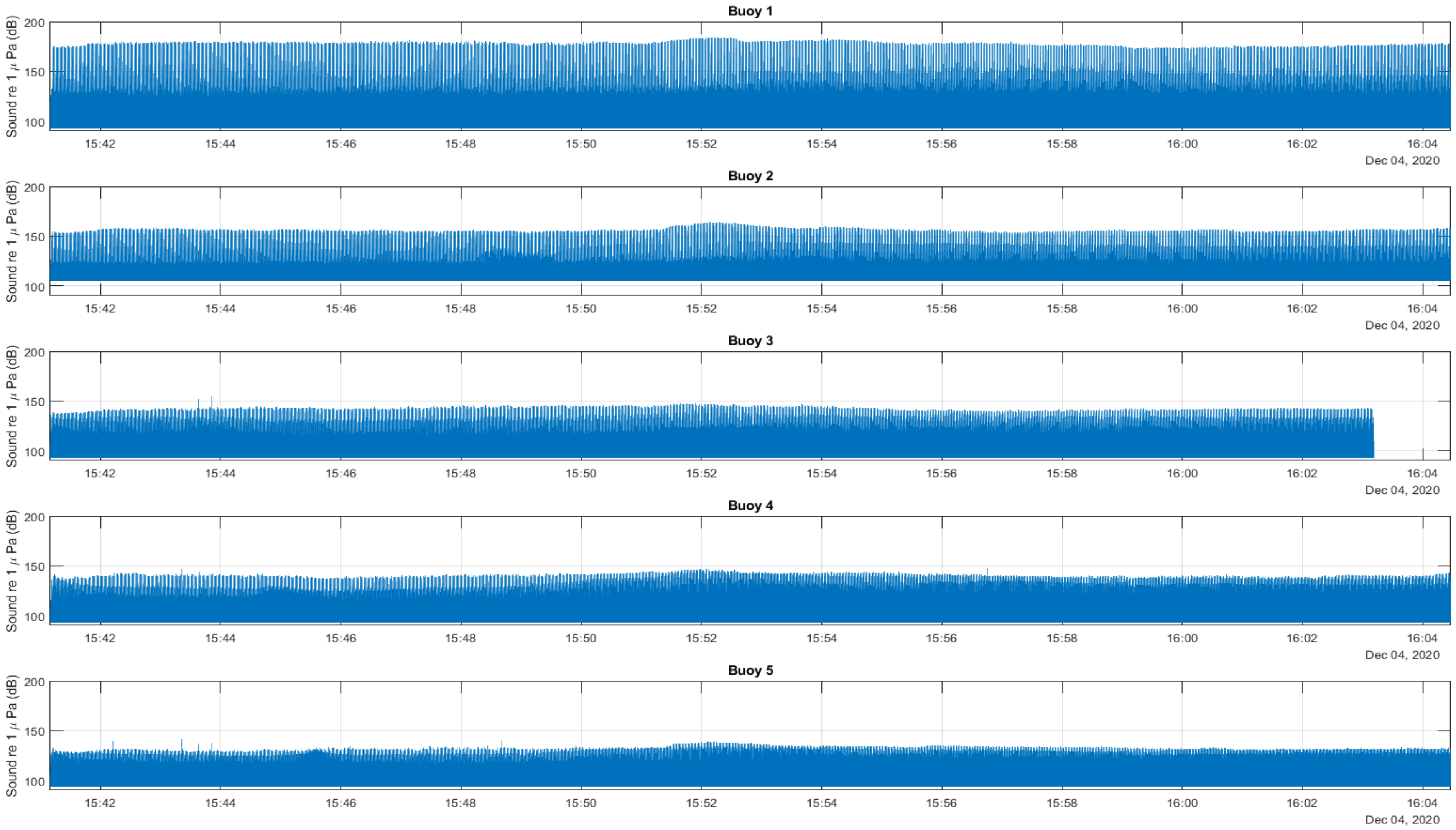
Data Collection Buoy

Deploying the Data Collection System

FDOT

UNF UNIVERSITY of NORTH FLORIDA

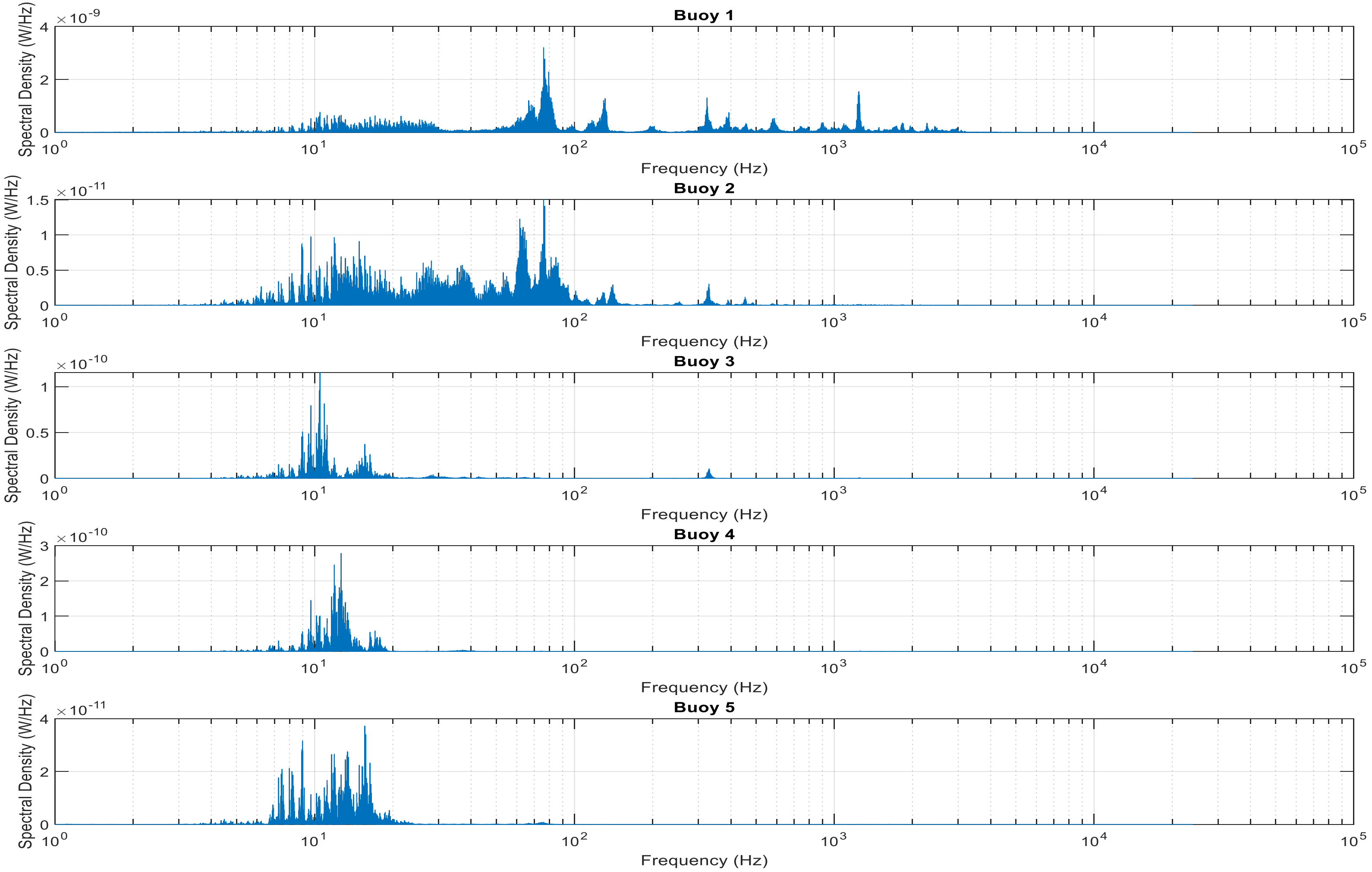
Sample Time-Series Data – CR 218



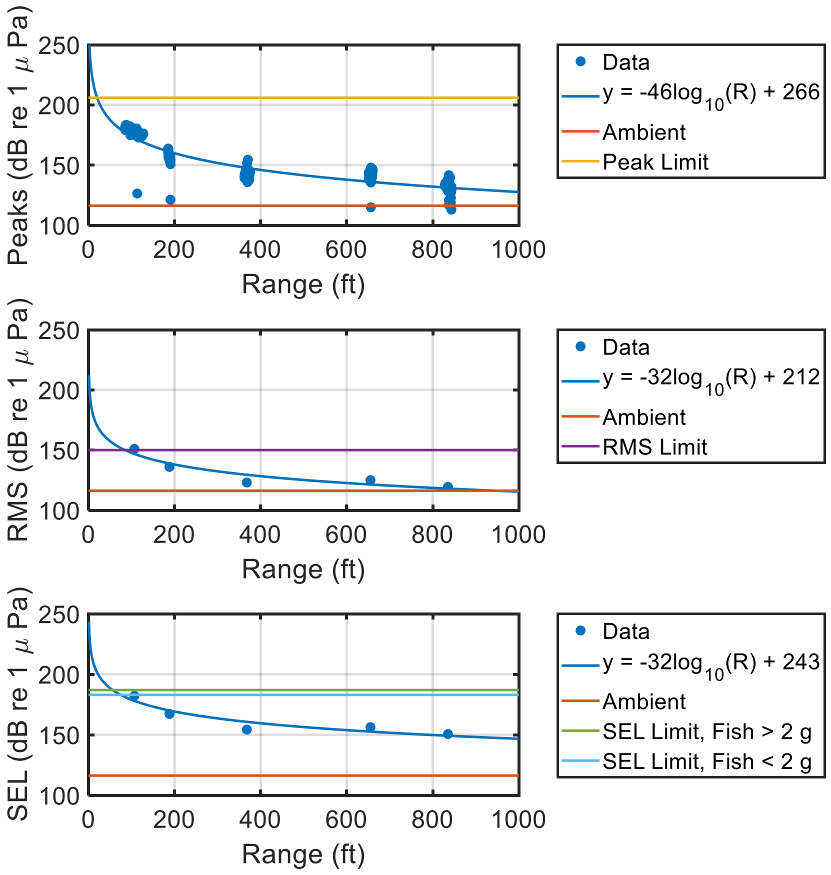
FDOT

UNF UNIVERSITY of NORTH FLORIDA

Sample Frequency Data – CR 218



Sample Transmission Loss Data – CR 218



- $TL = L_s - L_r = F\log_{10}\left(\frac{R}{R_0}\right)$
- $L_r = L_s - F\log_{10}\left(\frac{R}{R_0}\right)$
  - L_r = sound-level at R
  - L_s = sound-level at source

Transmission Loss Data Summary Table

Site Number	Site Name	No. Drives	Drive Type/Hammer	Avg. Peak TL Coeff
1	Suwannee River	3	24-inch diameter steel piles/Del-Mag D-46	25
2	Ribault River	4	24-inch square PCP/APE D36-42 impact driver	46
3	Bayway E	2	36-inch steel piles/200T vibratory driver	13
4	Dunn's Creek	4	PZ-27 steel sheet pile/200T vibratory driver	16
5	John Sims Parkway	2	18-inch square PCP/CX85-u impact driver	23
6	CR-218	3	24-inch square PCP/APE D62-22 impact driver	35
7	SR-23	9	24-inch square PCP/APE D62 impact driver with D70 ram	17
8	Choctawatchee Bay	2	36-inch steel sheet pile/200T vibratory driver	48
9	Howard Frankland (West)	10	24-inch square PCP/APE D62 impact driver	36 to 58

FDOT

UNF UNIVERSITY of NORTH FLORIDA

More with Transmission Loss

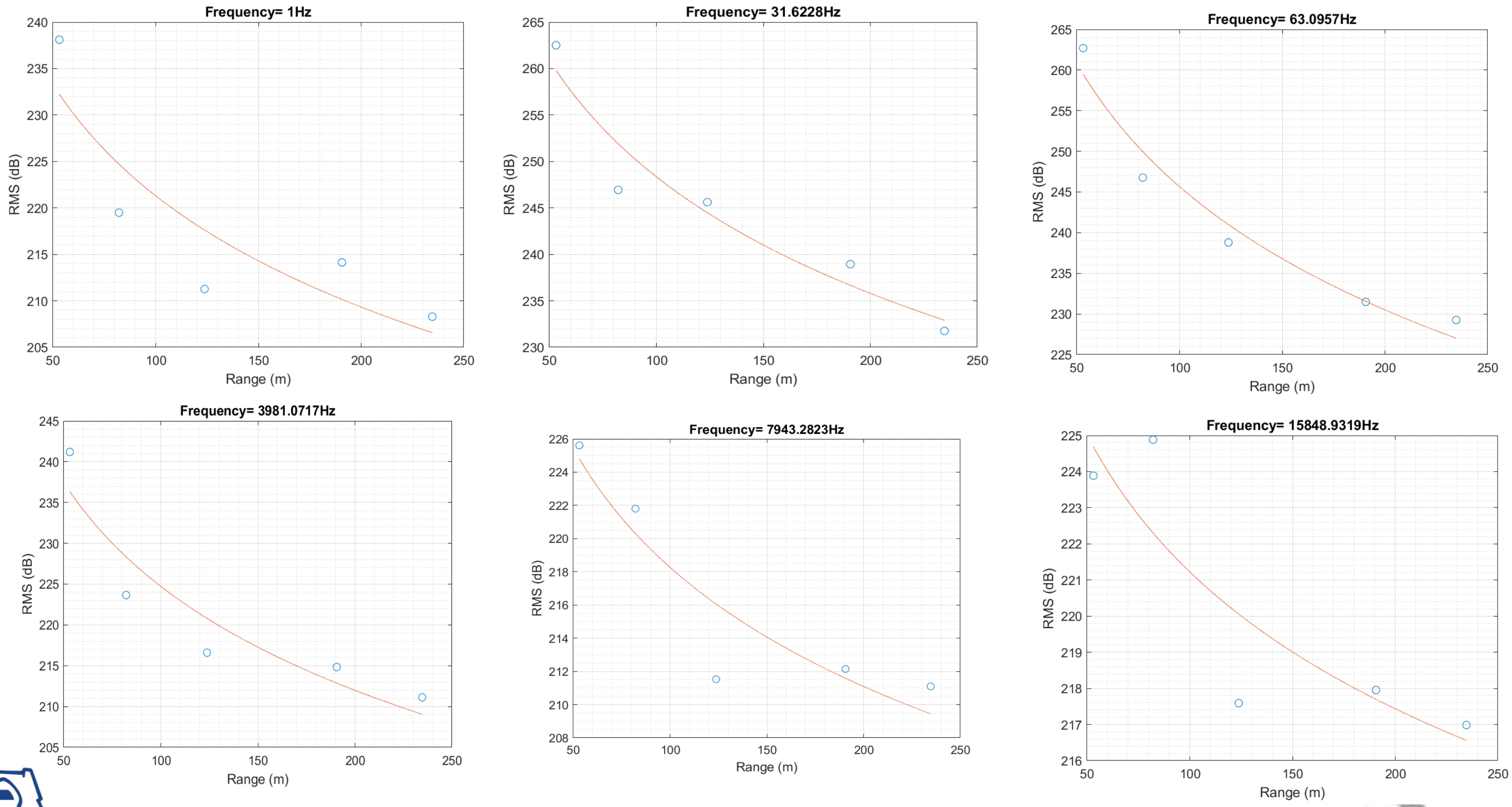
Ainslie et al. (2014)

- $TL = L_s - L_r = A \log_{10}\left(\frac{R}{R_0}\right) + B$
- $L_r = (L_s - B) - A \log_{10}\left(\frac{R}{R_0}\right)$

Simple Spreading Loss Model

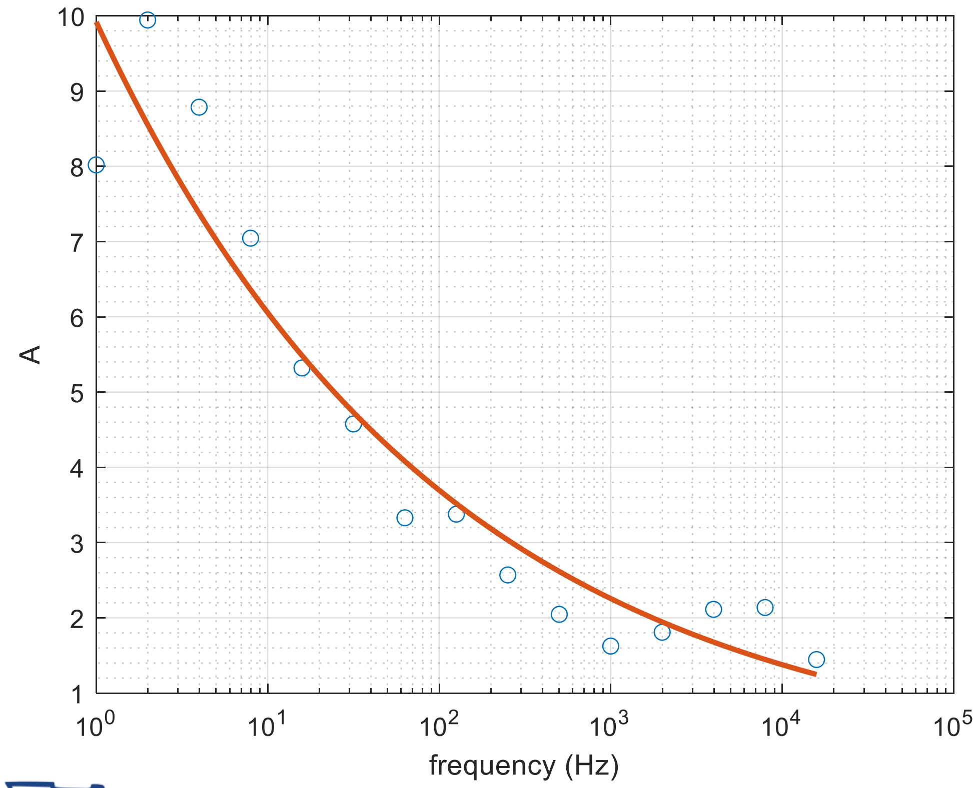
- $TL = L_s - L_r = F \log_{10}\left(\frac{R}{R_0}\right)$
- $L_r = L_s - F \log_{10}\left(\frac{R}{R_0}\right)$

Octave Decay (RMS Data Shown)

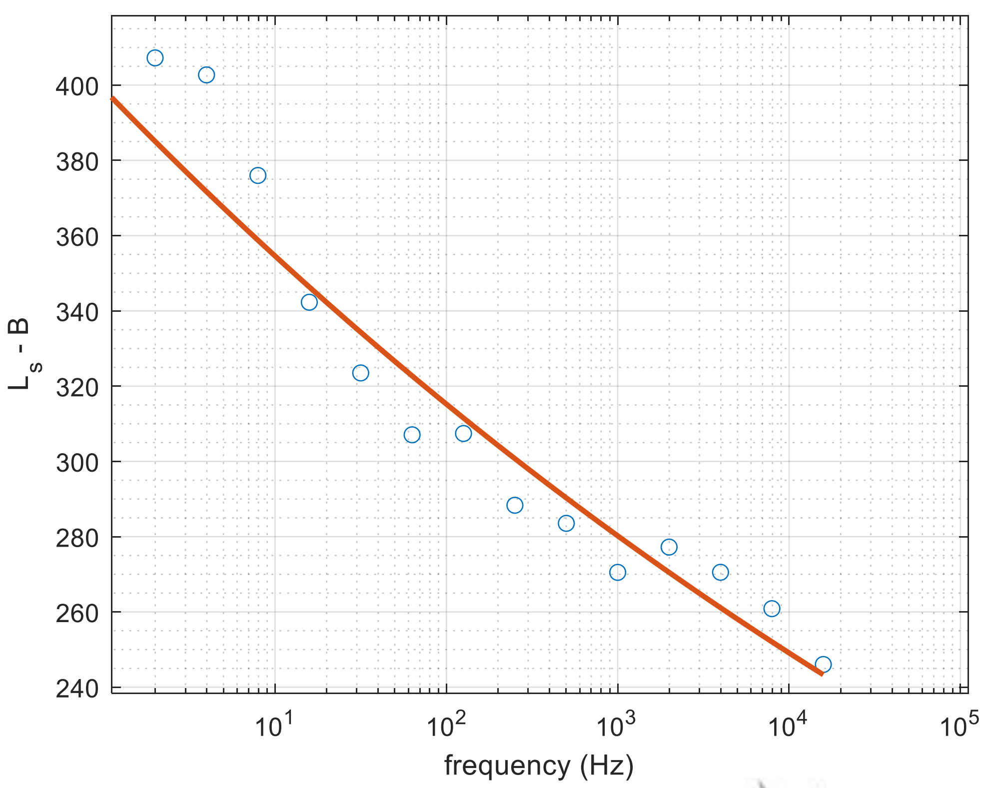


Relationship Between *A* and *B*

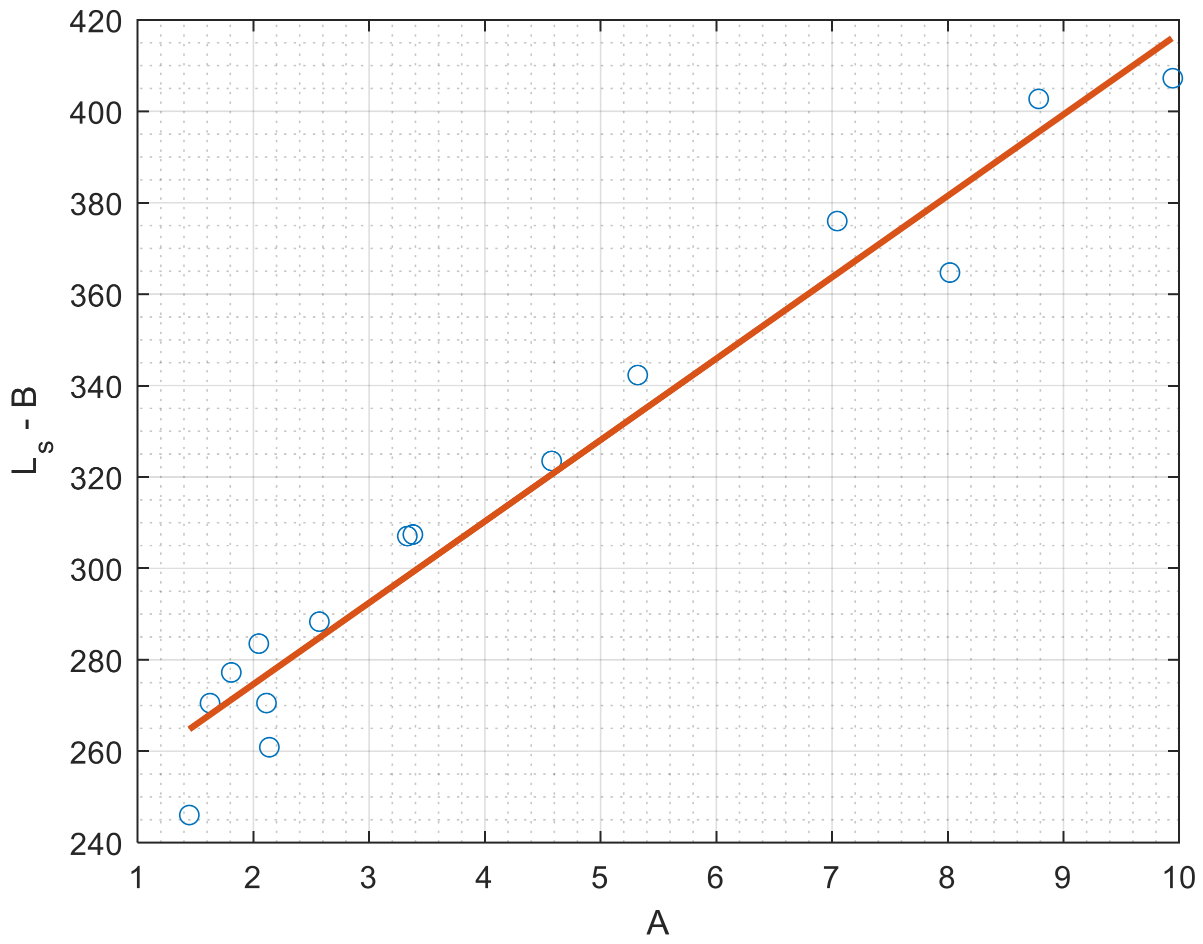
A as a Function of Frequency (CR-218)



$L_s - B$ as a Function of Frequency



Correlation Between *A* and *B*



Relationship between $(L_s - B)$ and A

The Rogers (1981) Model & Cutoff Frequency

- $TL = 15\log_{10}\left(\frac{R}{R_0}\right) + 5\log_{10}(H\beta) + \beta\left(\frac{R}{R_0}\right)\theta_L^2 + \alpha_w R - 7.18$
- $\beta = 12.282 N_0 \left[\frac{\sqrt{1+\frac{N_0 K_s}{18.19(1-N_0^2)}}-1}{(1-N_0^2)\left(1+\left\{\frac{N_0 K_s}{18.19(1-N_0^2)}\right\}^2\right)}\right]$
- $N_0 = \frac{c_w}{c_s}$
- $M_0 = \frac{\rho_s}{\rho_w}$
- $\theta_c = \frac{c_w}{2fH}$
- $\theta_{g\,max} = \sqrt{\frac{2g}{c_w}}$
- $\theta_L = \max(\theta_{g\,max}, \theta_c)$
- $\alpha_w = 0.001936\left[\frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2}\right]$

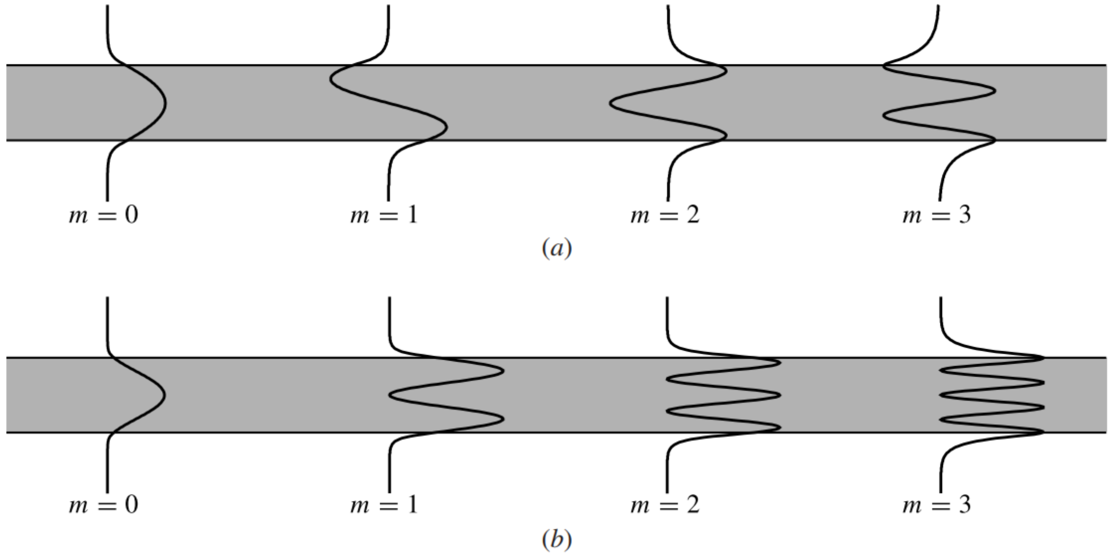
- c_w, c_s = speed of sound in water, soil
- ρ_s, ρ_w = density of water, soil
- α_w = water absorption coefficient but calibrated at 39 degrees at a depth of 3,000 ft
- θ_c = cutoff frequency angle
- K_s = soil attenuation coefficient proportional to frequency and related to porosity

FDOT

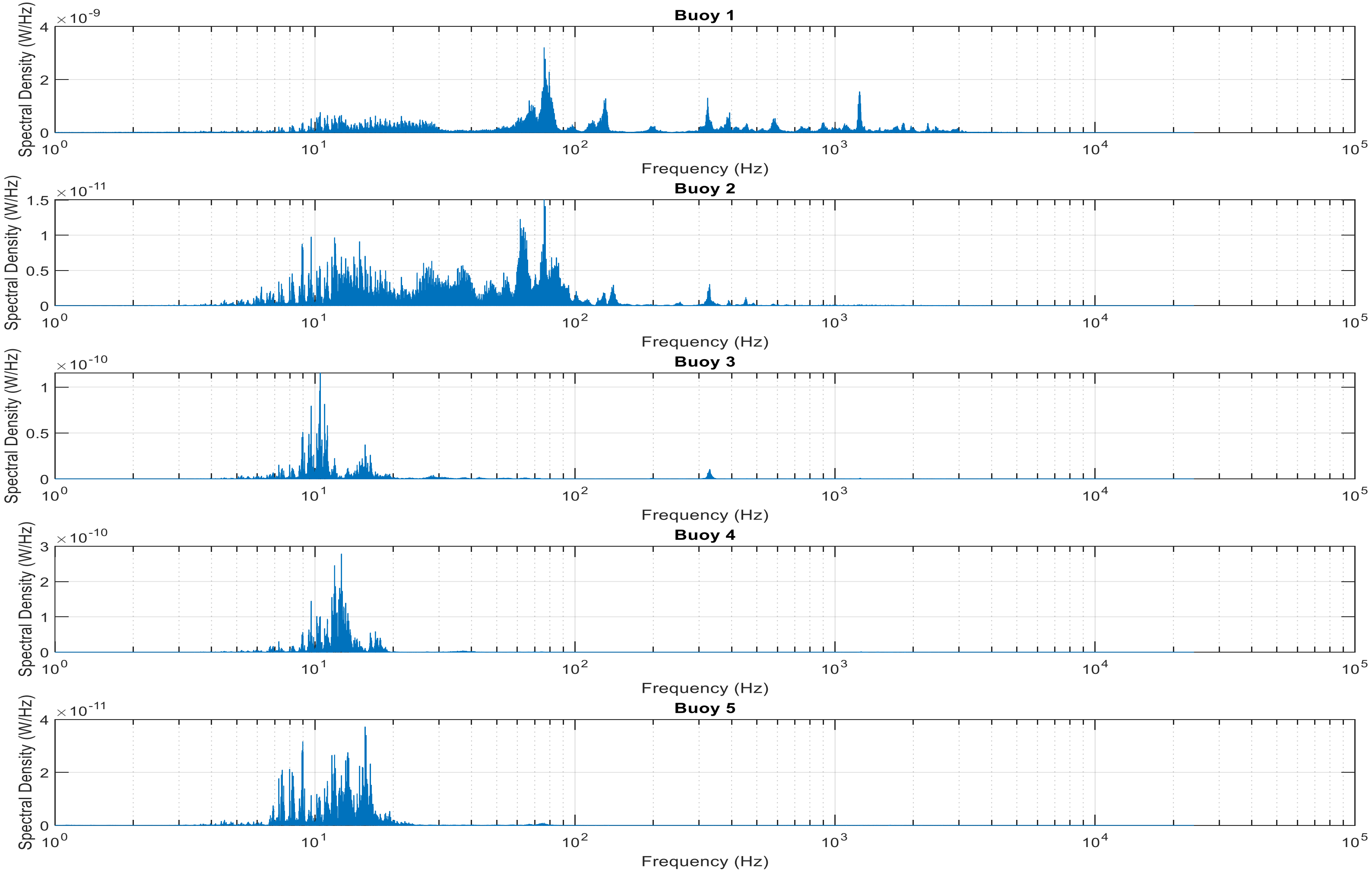
UNF UNIVERSITY of NORTH FLORIDA

Cutoff Frequency

- $f_{min} = \frac{\pi - \frac{\rho_s}{\rho_w}}{2\pi \sin(\psi_c)} \frac{c_w}{H}$
- $\psi_c = \cos^{-1}\left(\frac{c_w}{c_s}\right)$
- For $H \sim 10\ ft$, $f_{min} \sim 100\ Hz$
- $\lambda_{max} = \frac{c}{f_{min}}$
- $\lambda_{max} \sim 15\ m$

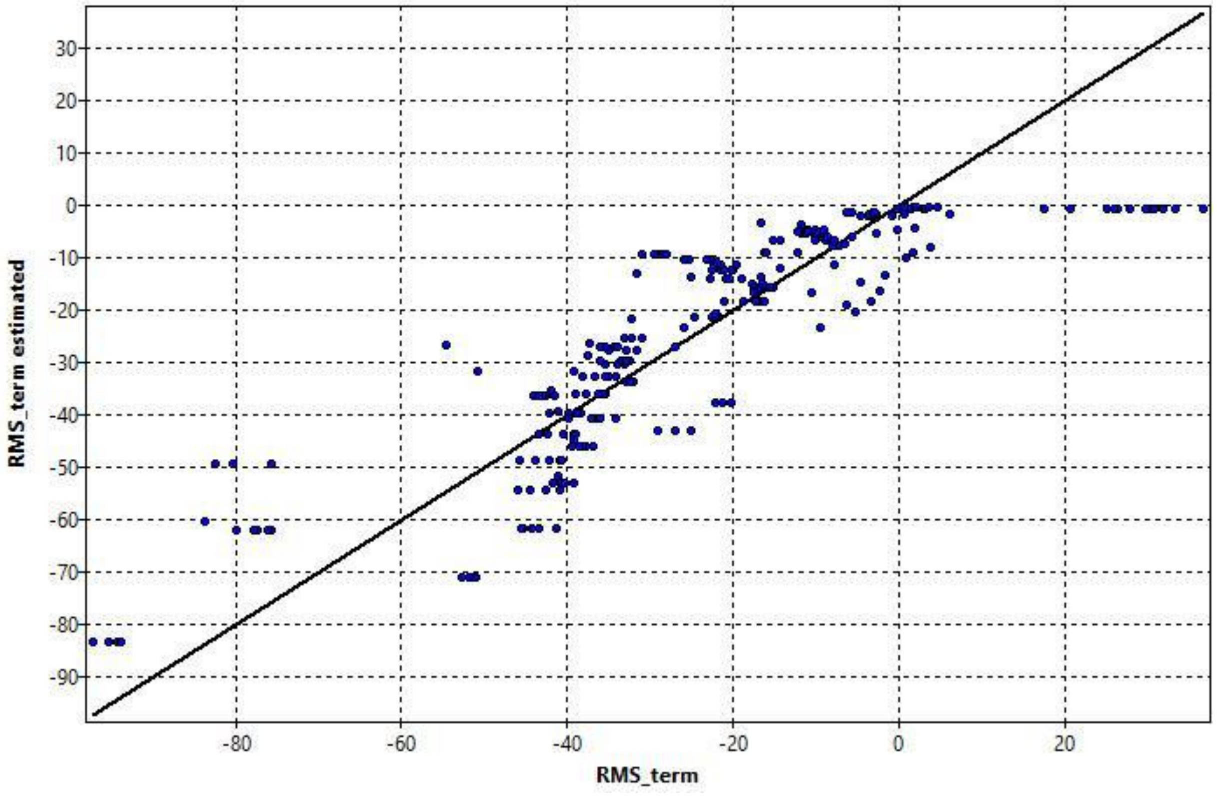


“Forcing” the Rogers Model

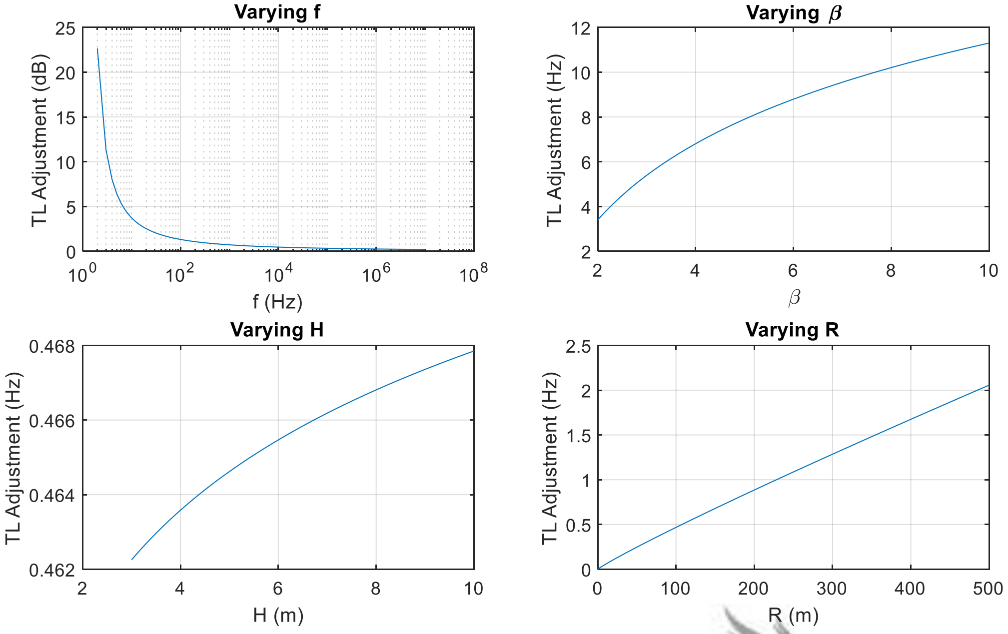


Reminder of typical frequency decay (CR-218 Data Shown)

Rogers Model Adjustment

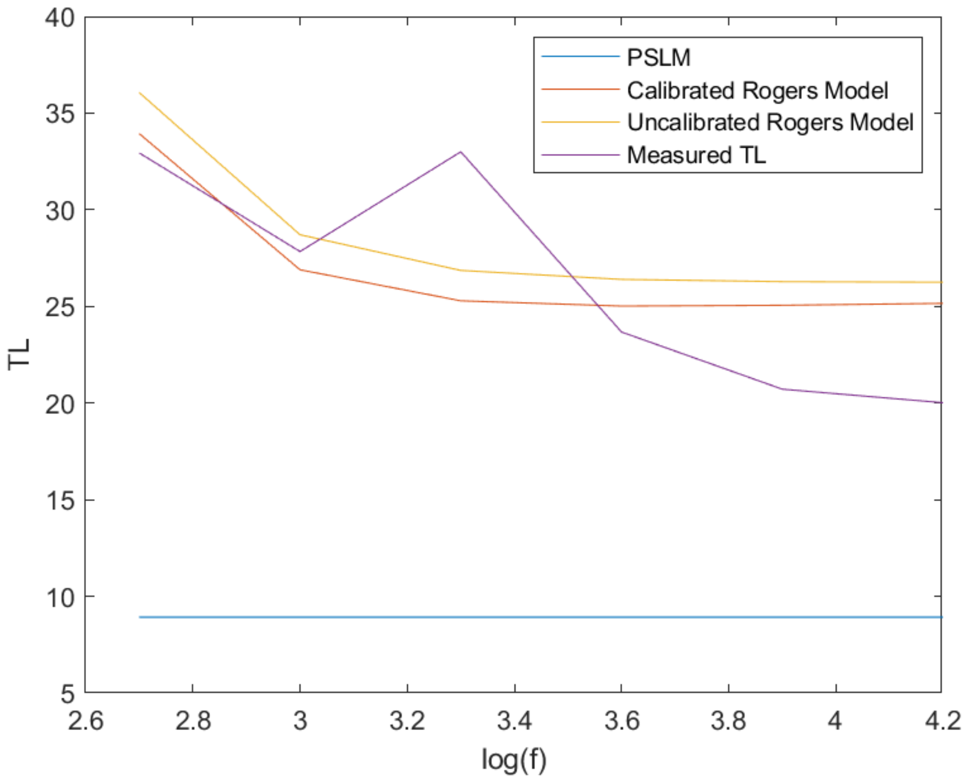


- $TL = 15\log_{10}\left(\frac{R}{R_0}\right) + 5\log_{10}(H\beta) + \beta\left(\frac{R}{R_0}\right)\theta_L^2 + \alpha_w R - 7.18 + E$
- E = adjustment term
- $E = a_1[\log_{10}(f)]^{-1.5} R^{0.92} \ln(\beta) H^{0.01}$; $a_1 = 0.55447$

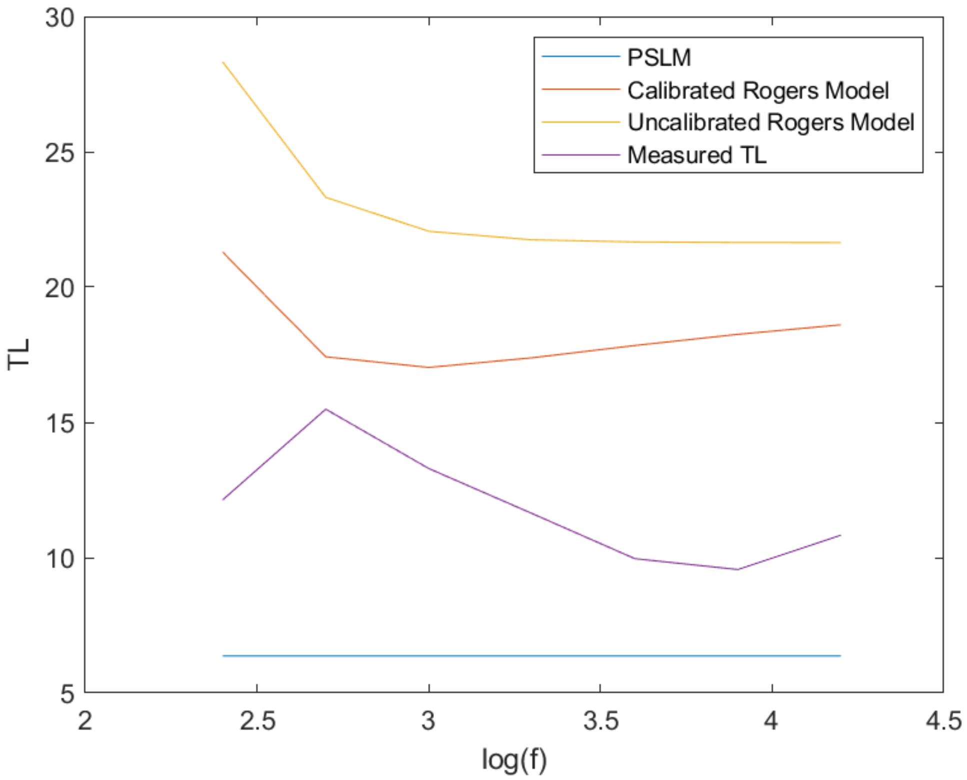


Model Performance Comparison

Ribault River, Range = 50 m



Suwannee River, Range = 15 m



Model Weaknesses

- Semi-site specific
- Assumes no dispersion
- Performance varies but almost always as good or better than PSLM

Ongoing Work

- SEL/RMS analysis ongoing for three sites
- Examining potential dispersive effects
- Examining two-function approach above and below cutoff frequency
- Physical explanation for A and $(L_s - B)$

- Upcoming Site Visits
  - C Street Cedar Key Channel (D2)
  - Manatee River Bridge (D1)
  - Howard Frankland (ongoing; D7)
  - Simpson Creek (D2)
  - Simpson River (D3)
  - North Causeway Bridge (D4)
  - Broward River Bridge (D4)
  - Drayton Island Ferry Landing (D2)
  - Jupiter Inlet (D4)

Questions?