Implementation of Geo-Statistical Deep Foundation Software

FDOT GRIP - Segment 2 - No. 5 - August 17, 2023

FDOT Project	BDV31 977-143
Project Manager	Rodrigo Herrera, PE
Institution	University of Florida
PI	Michael Davidson, PhD, PE
Co-PI	Michael Rodgers, PhD, PE
Co-PI	Gary Consolazio, PhD

Bridge Software Institute

Outline

- Introduction and background
- Project objective
- Project tasks
- Summary

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- Project tasks
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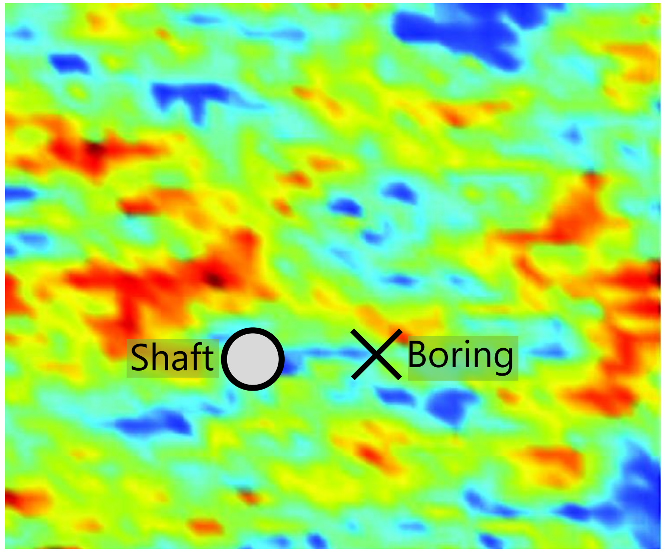
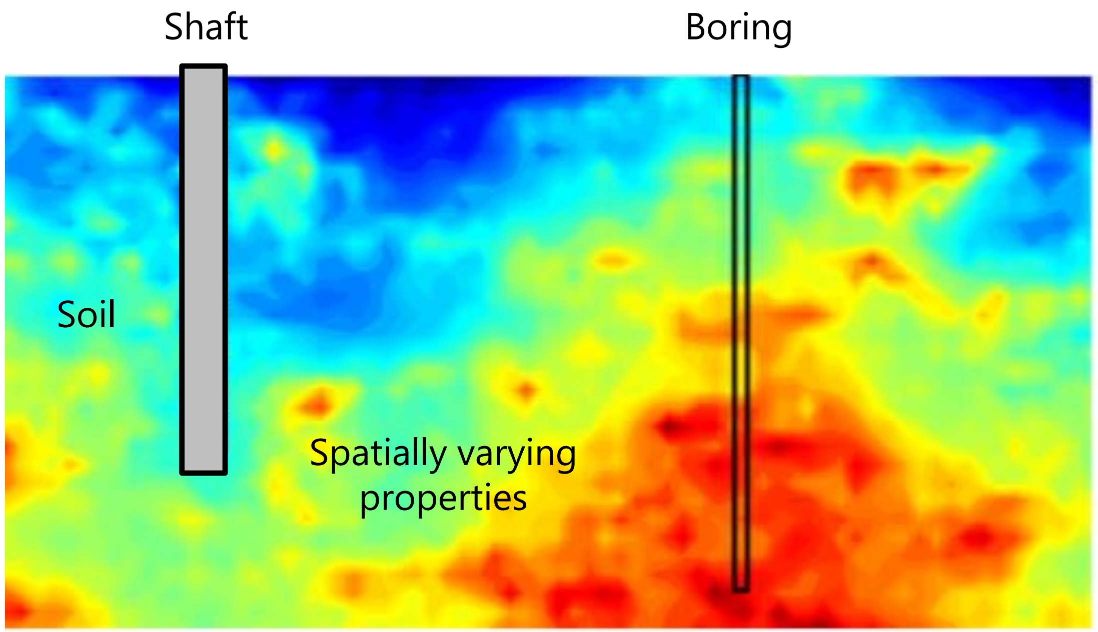
Introduction

- Spatial variability
  - Horizontal
  - Vertical



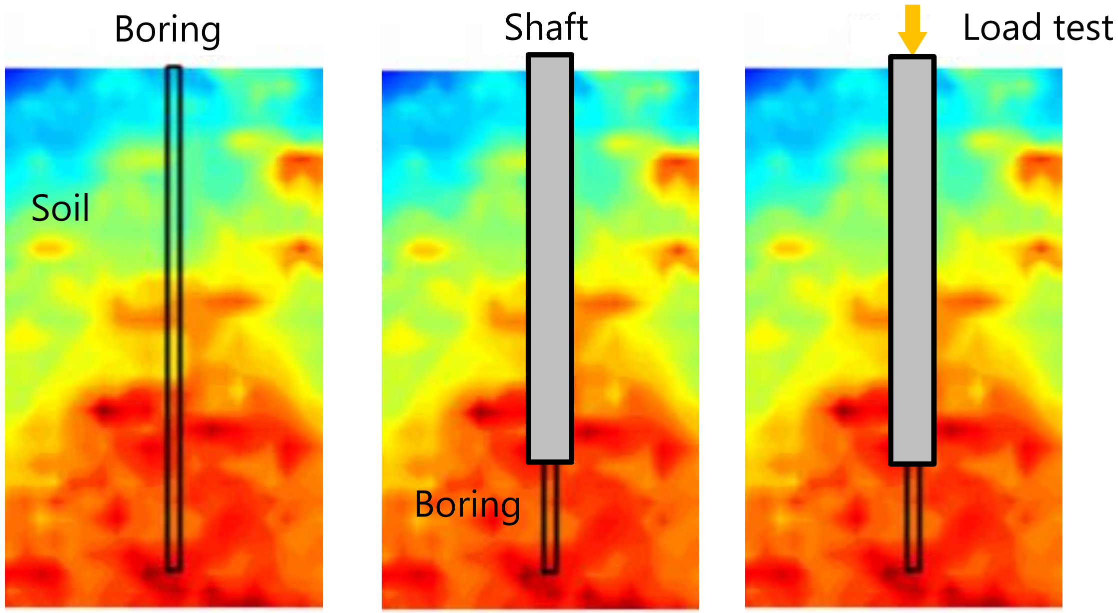
Plan view, illustrative
(contour image from Zhu and Zang 2013)



Elevation view, illustrative
(contour image from McVay et al. 2012)

Introduction

- Method error
  - Due to underlying assumptions in empirical methods
  - Correlation of measurement to unit resistance



Example: boring in footprint of shaft

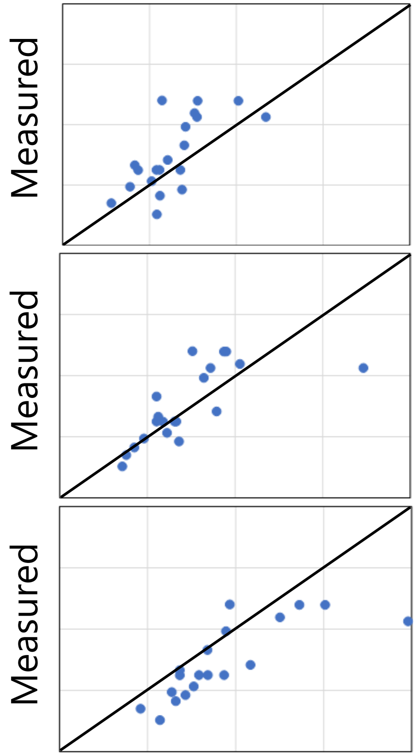
Introduction

- Method error
  - Increases uncertainty in computed capacities

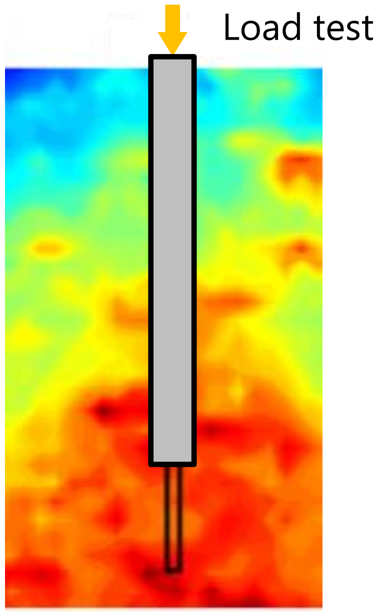
Method A

Method B

Method C



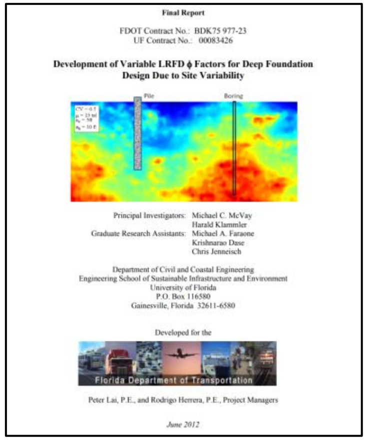
Predicted resistance



Example: boring in footprint of shaft

Background

- FDOT BDK 977-23 and FDOT BDV31 977-108
  - Formulated geostatistical methodologies
  - Compiled method error data
  - Developed prototype and then design tools



Final Report

FDOT Contract No.: BDK75 977-23
UF Contract No.: 00083426

Development of Variable LRFD ϕ Factors for Deep Foundation Design Due to Site Variability

Principal Investigators: Michael C. McVay, Harald Klammler
Graduate Research Assistants: Michael A. Faraone, Krishnarao Dase, Chris Jenneisch

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Gainesville, Florida 32611-6580

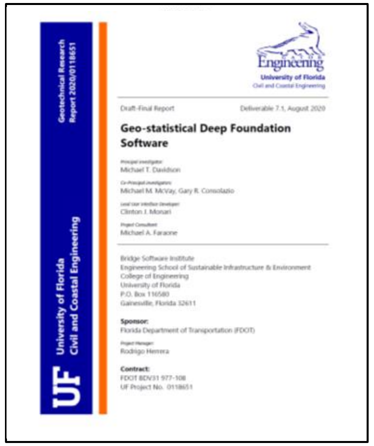
Developed for the

Florida Department of Transportation

Peter Lai, P.E., and Rodrigo Herrera, P.E., Project Managers

June 2012

FDOT BDK75 977-23 final report



Geotechnical Research Report 2020/0118651

UF University of Florida Civil and Coastal Engineering

Engineering University of Florida Civil and Coastal Engineering

Draft-Final Report — Deliverable 7.1, August 2020

Geo-statistical Deep Foundation Software

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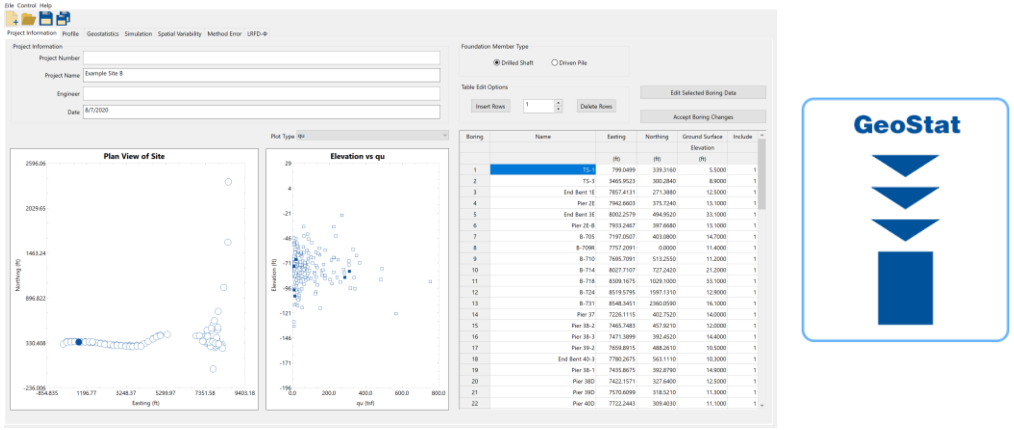
Sponsor:
Florida Department of Transportation (FDOT)

Rodrigo Herrera

Contract:
FDOT BDV31 977-108
UF Project No. 0118651

FDOT BDV31 977-108 final report



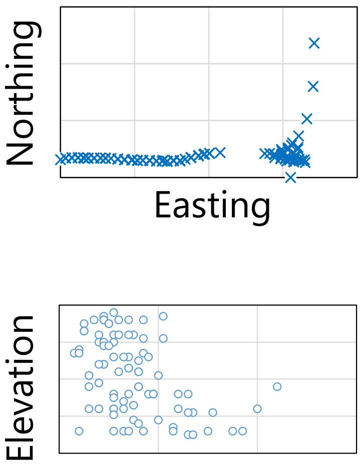
GeoStat design tool

Outline

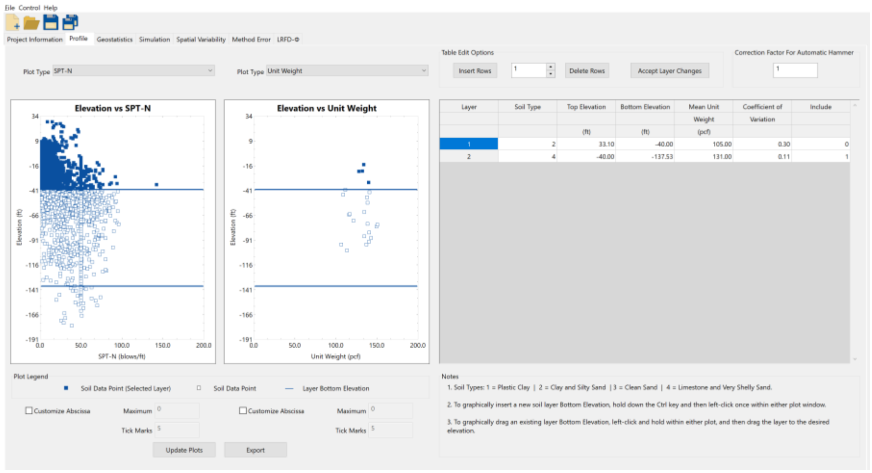
- Introduction and background
- Project objective
- Project tasks
- Summary

Objective

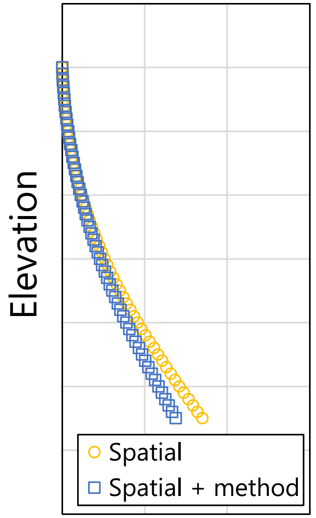
- Implement updates to geostatistical design tool
  - Leverage previous FDOT research
  - Compute axial design capacities of piles and shafts
  - Reflect spatial variability and uncertainty



Site measurements within layer



Illustrative layer definitions in GeoStat



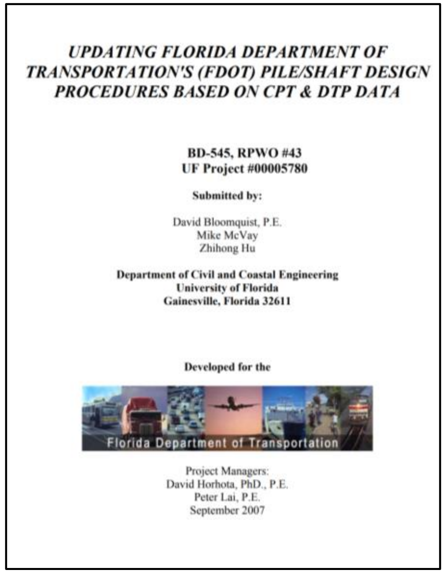
Computed resistance

Outline

- Introduction and background
- Project objective
- Project tasks
- Summary

Project tasks

- Task 1: Incorporate analysis of CPT data
  - Read-write of key variables
  - Generation of variograms
  - Population of analysis files for simulation
  - Identify method error regressions
  - Software manual documentation
  - Deliverable: report



UPDATING FLORIDA DEPARTMENT OF TRANSPORTATION'S (FDOT) PILE/SHAFT DESIGN PROCEDURES BASED ON CPT & DTP DATA

BD-545, RPWO #43
UF Project #00005780

Submitted by:

David Bloomquist, P.E.
Mike McVay
Zhihong Hu

Department of Civil and Coastal Engineering
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Gainesville, Florida 32611

Developed for the

Florida Department of Transportation

Project Managers:
David Horhota, PhD., P.E.
Peter Lai, P.E.
September 2007

FDOT BD-545, RPWO #43 final report

Bridge Software Institute

Project tasks

- Task 1: Incorporate analysis of CPT data
  - Key parameters
    - Tip resistance
    - Sleeve friction
    - Friction ratio
  - UF method, Schmertmann, LCPC
  - Method error
    - FDOT BD-545, RPWO #43 final report, Tables in Ch. 4
    - Approach from Faraone et al. (2021)

UPDATING FLORIDA DEPARTMENT OF TRANSPORTATION'S (FDOT) PILE/SHAFT DESIGN PROCEDURES BASED ON CPT & DTP DATA

BD-545, RPWO #43
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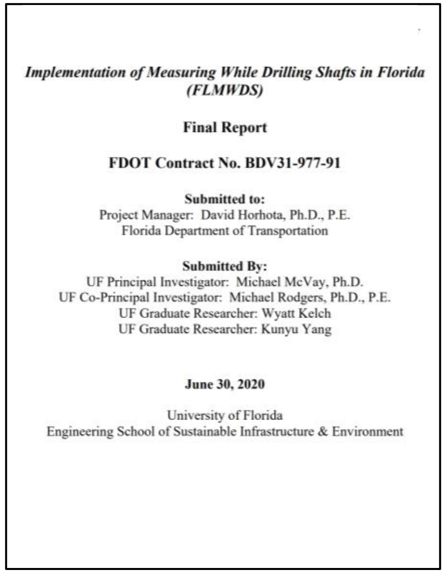
Project Managers:
David Horhota, PhD., P.E.
Peter Lai, P.E.
September 2007

FDOT BD-545, RPWO #43 final report

Project tasks

- Task 2: Incorporate analysis of results from Measuring While Drilling (MWD)
  - Read-write of key variables
  - Generation of variograms
  - Population of analysis files for simulation
  - Identify method error regressions
  - Software manual documentation



Implementation of Measuring While Drilling Shafts in Florida (FLMWDS)

Final Report

FDOT Contract No. BDV31-977-91

Submitted to:
Project Manager: David Horhota, Ph.D., P.E.
Florida Department of Transportation

Submitted By:
UF Principal Investigator: Michael McVay, Ph.D.
UF Co-Principal Investigator: Michael Rodgers, Ph.D., P.E.
UF Graduate Researcher: Wyatt Kelch
UF Graduate Researcher: Kunyu Yang

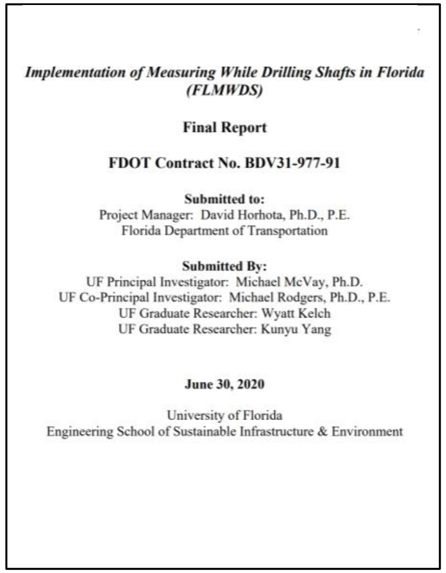
June 30, 2020

University of Florida
Engineering School of Sustainable Infrastructure & Environment

FDOT BDV31-977-31 final report

Project tasks

- Task 2: Incorporate analysis of MWD data
  - Drilled shafts in limestone
  - Key parameters
    - Specific energy, e
    - MWD estimates for rock properties such as q_u
      - McVay and Rodgers (2020)
      - Rodgers et al. (2018)
  - Method error
    - Strong correlation to side shear (McVay and Rodgers 2020)
    - Site-specific



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June 30, 2020

University of Florida
Engineering School of Sustainable Infrastructure & Environment

FDOT BDV31-977-31 final report

Recent progress: geostatistical analysis (MWD)

Preparatory steps for stochastic simulation using MWD data

Given: profiles and location data of specific energy; candidate drilled shaft properties; range of shaft embedment lengths; presence of limestone layer(s)

Select empirical calculation method

MWD (Rodgers et al. 2018)

Define soil/rock layers

Inspect profiles of MWD Parameters

Measured values of specific energy and MWD estimates of rock parameters

Assign layer properties

Decide upon number of layers
For each layer:
- Assign top and bottom elevations
- Assign layer type

End of loop on layers

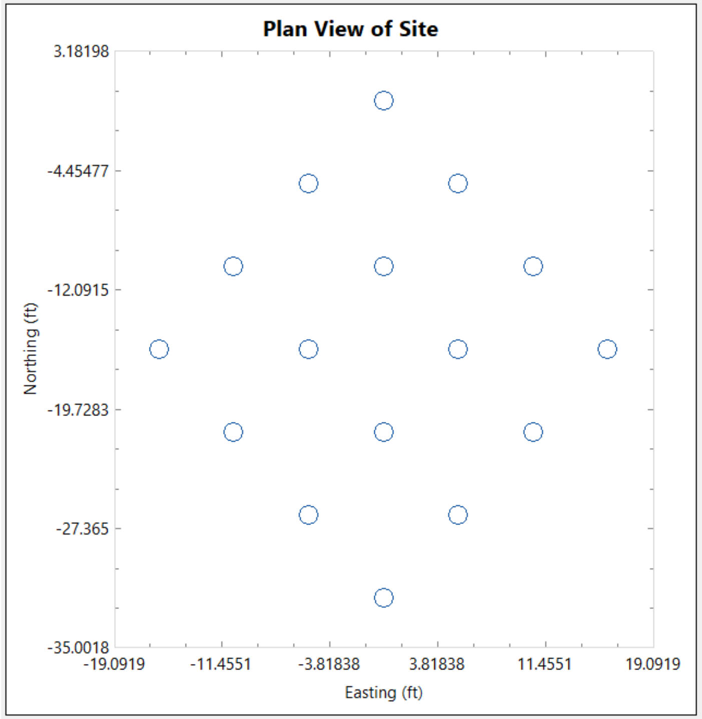
Generate variograms

For each limestone layer:
- Use guidance in Chs. 2, 4, and 5 of the GeoStat Technical Manual to form variograms based on available pairs of (calculated) unconfined compressive strength

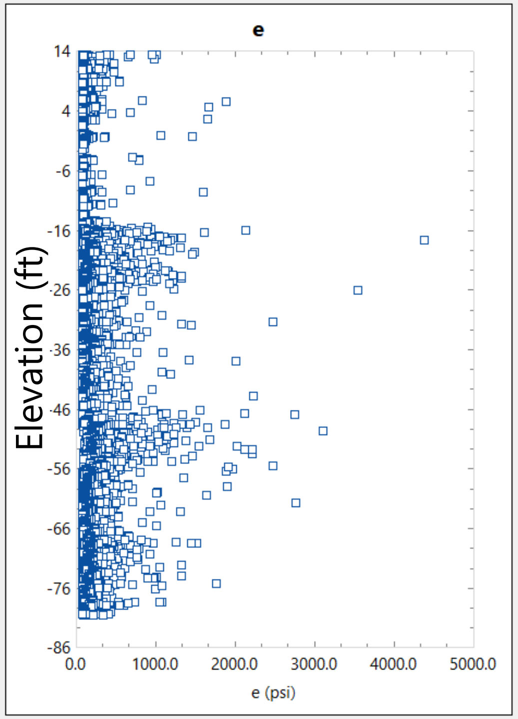
End of loop on layers

Formation of layer variograms using MWD site data

Illustrative model file of MWD site data:

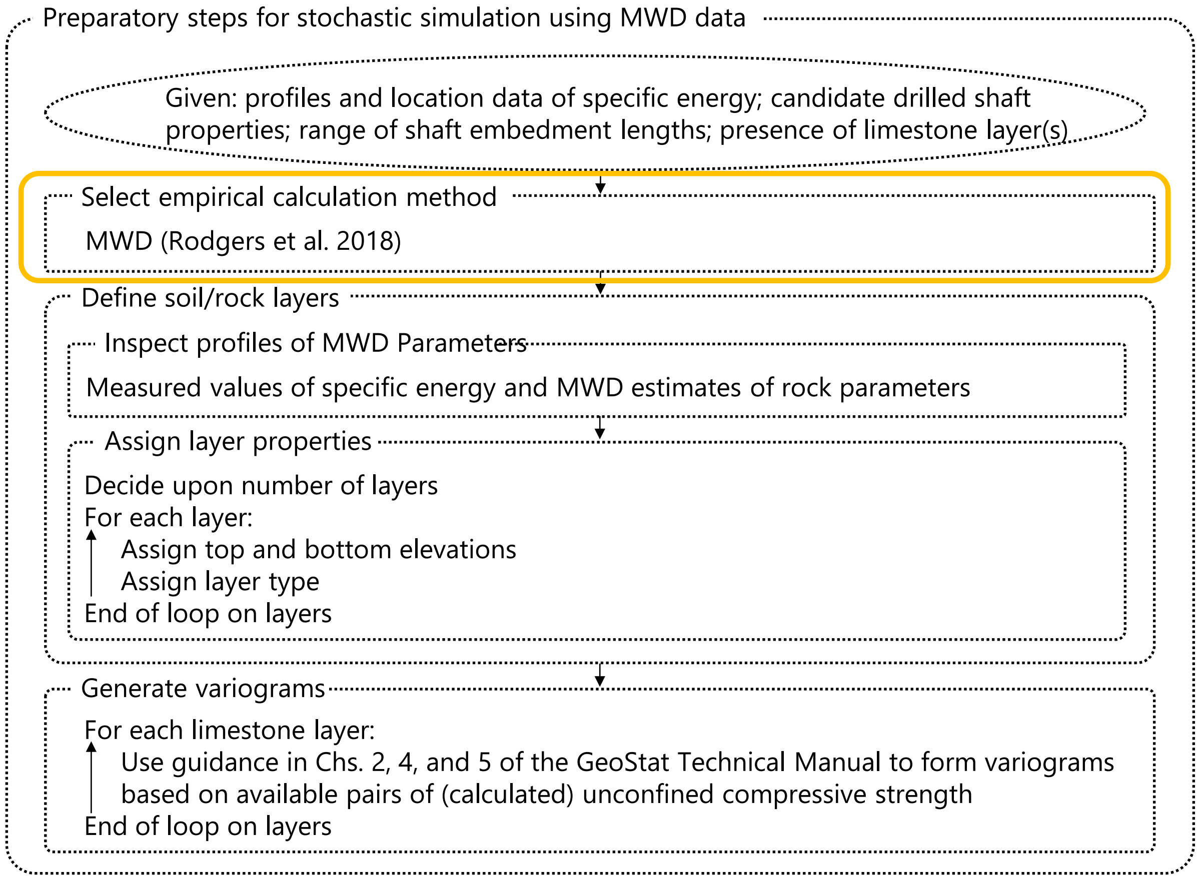


Plan view of MWD borings



Specific energy, e (psi)

Task 2: geostatistical analysis (MWD)



Formation of layer variograms using MWD site data

- For Florida limestone (Rodgers et al. 2018):

$$e = 0.0066 \cdot {q_u}^2 + 13.68 \cdot q_u$$

- Invert to produce MWD estimate, q_{u_MWD}:

$$q_{u\_MWD} = \frac{-13.7 + \sqrt{13.7^2 - 4 \cdot 0.0066 \cdot (-e)}}{2 \cdot 0.0066}$$

- MWD estimate, q_{t_MWD}, (McVay and Rodgers 2020):

$$q_{t\_MWD} = 0.436 \cdot {q_{u\_MWD}}^{0.825}$$

Note: all units in psi

Task 2: geostatistical analysis (MWD)

Preparatory steps for stochastic simulation using MWD data

Given: profiles and location data of specific energy; candidate drilled shaft properties; range of shaft embedment lengths; presence of limestone layer(s)

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End of loop on layers

Formation of layer variograms using MWD site data

Simulate REC_{MWD} values

Prepare length intervals

Given an elevation profile of measured values of e
From top to bottom, divide profile into n_{int} intervals
- Assign 5-ft lengths to intervals 1…n_{int}-1
- Assign remaining length (≤5 ft) to interval n_{int}

Estimate REC_{MWD} value within each interval

For i = 1, n_{int}
- Determine n_e: number of e values within interval
- Initialize n_{accept} to zero
- For j = 1, n_e
  - If $e_j \geq e_{threshold}$
    - $n_{accept} = n_{accept} + 1$
- End of loop on j
- $REC_{MWD} = n_{accept}/n_e$

End of loop on i

MWD estimate of REC_{MWD}

Task 2: geostatistical analysis (MWD)

Preparatory steps for stochastic simulation using MWD data

Given: profiles and location data of specific energy; candidate drilled shaft properties; range of shaft embedment lengths; presence of limestone layer(s)

Select empirical calculation method

MWD (Rodgers et al. 2018)

Define soil/rock layers

Inspect profiles of MWD Parameters

Measured values of specific energy and MWD estimates of rock parameters

Assign layer properties

Decide upon number of layers
For each layer:
 Assign top and bottom elevations
 Assign layer type
End of loop on layers

Generate variograms

For each limestone layer:
 Use guidance in Chs. 2, 4, and 5 of the GeoStat Technical Manual to form variograms based on available pairs of (calculated) unconfined compressive strength
End of loop on layers

Formation of layer variograms using MWD site data

Simulate RQD_{MWD} values

Prepare length intervals

Given an elevation profile of measured values of e
From top to bottom, divide profile into n_{int} intervals
 Assign 5-ft lengths to intervals 1…n_{int}-1
 Assign remaining length (≤5 ft) to interval n_{int}

Estimate RQD_{MWD} value within each interval

For i = 1, n_{int}
 Determine n_e: number of e values within interval
 Initialize L_{int} to length of i^{th} interval
 Initialize L_{sub} and L_{RQD_MWD} to zero
 For j = 1, n_e
  If $e_j \geq e_{threshold}$
   Mark j^{th} entry as above threshold
 End of loop on j
 For j = 2, n_e
  If entry j was marked as above threshold
   $L_{sub} = L_{sub} + z_j - z_{j-1}$
  Else
   If $L_{sub} \geq L_{threshold}$
    $L_{RQD\_MWD} = L_{RQD\_MWD} + L_{sub}$
   L_{sub} = 0 ft
 End of loop on j
 $RQD_{MWD} = L_{RQD\_MWD}/L_{int}$
End of loop on i

MWD estimate of RQD_{MWD}

Task 2: geostatistical analysis (MWD)

Preparatory steps for stochastic simulation using MWD data

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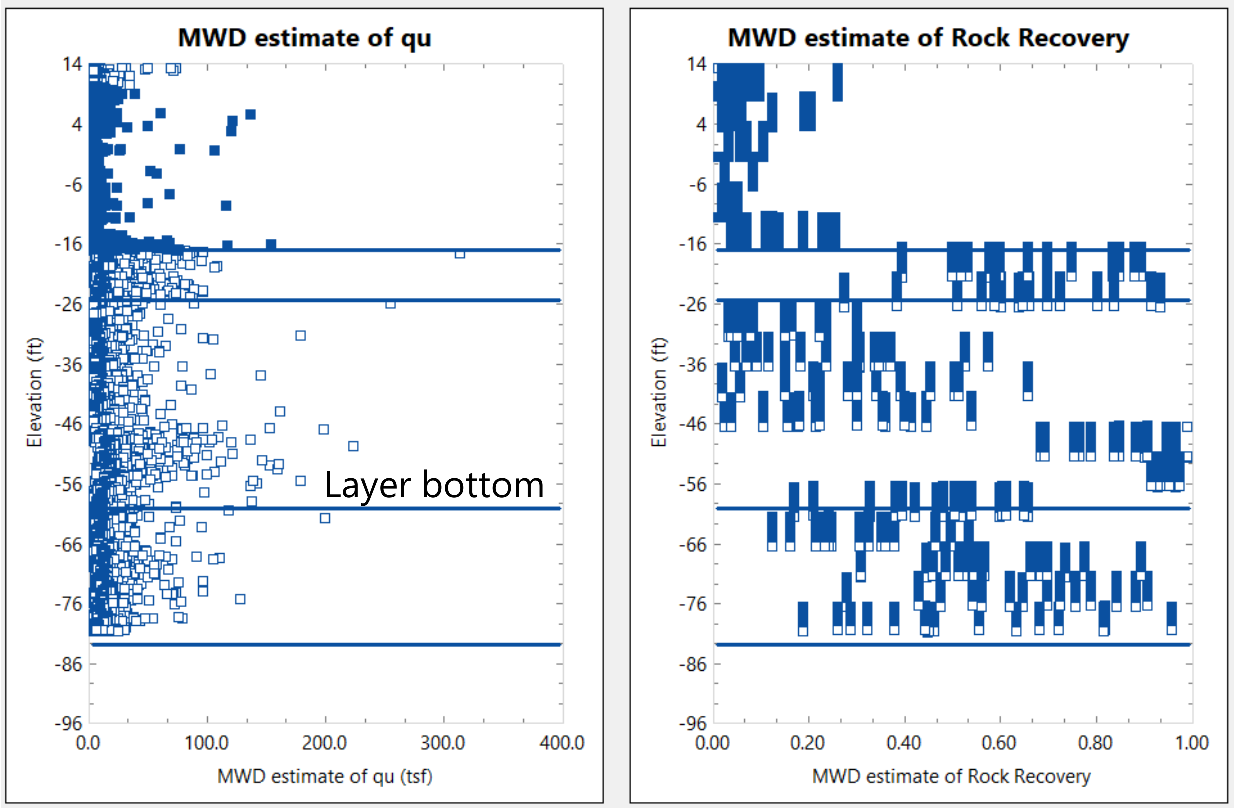
Formation of layer variograms using MWD site data



Illustrative layer definitions

Task 2: geostatistical analysis (MWD)

Preparatory steps for stochastic simulation using MWD data

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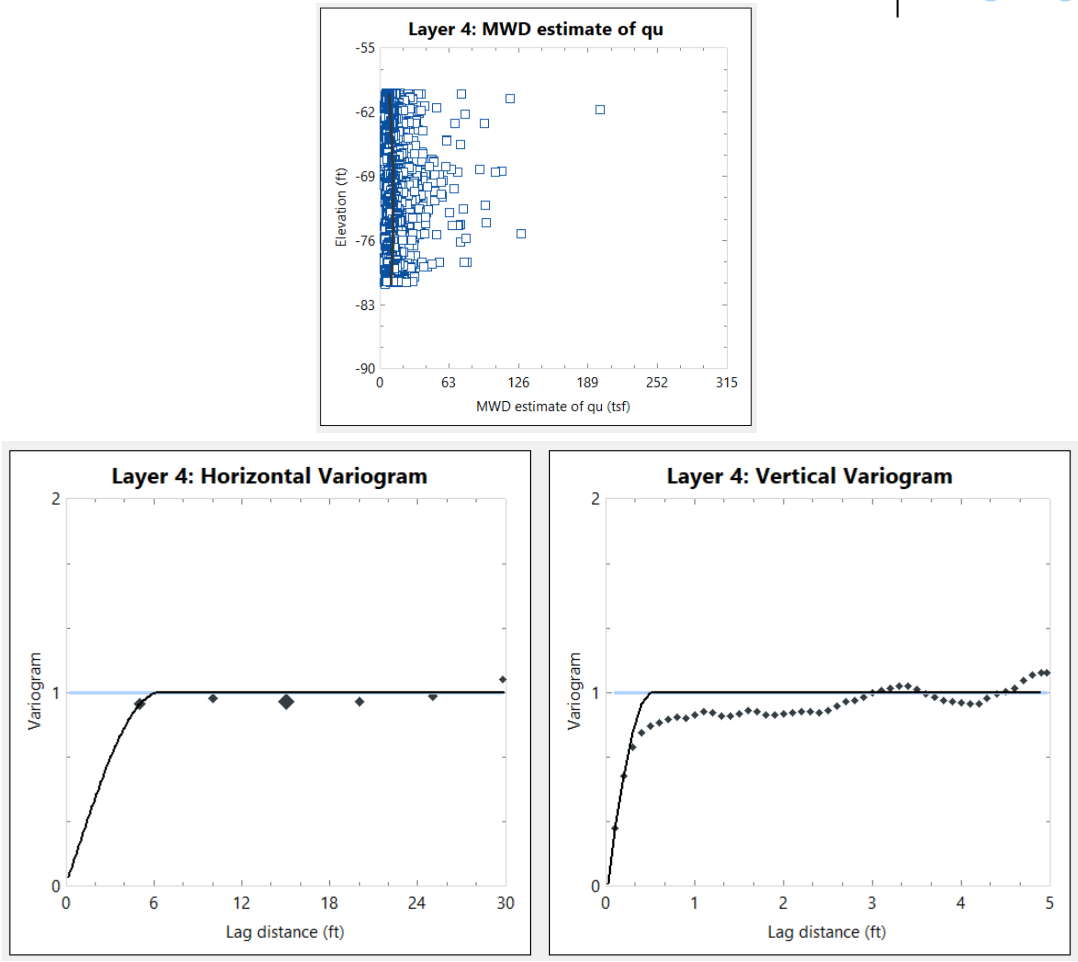
Formation of layer variograms using MWD site data



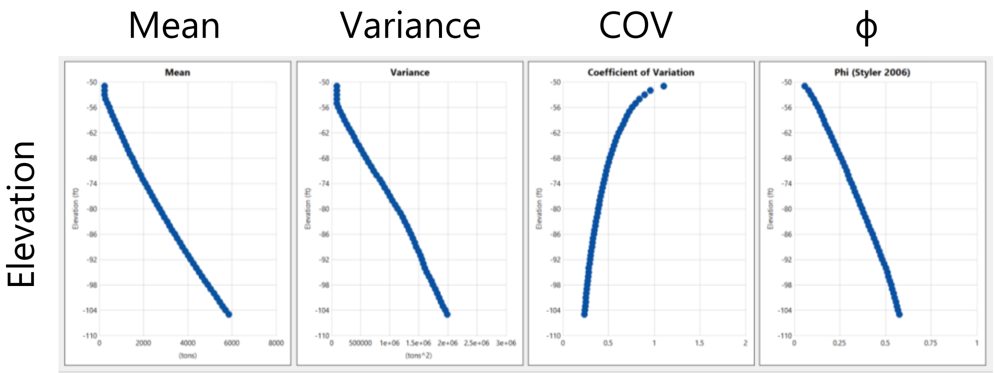
Illustrative variograms formed using q_{u_MWD}

Task 2: geostatistical analysis (MWD)

- Stochastic simulation using MWD site data
  - Leverage geostatistical approaches for drilled shafts in limestone
    - FDOT BDK 977-23
    - FDOT BDV31 977-108
  - Simulate numerous profiles of limestone parameters, including:
    - q_u
    - q_t
    - *recovery*

Task 2: geostatistical analysis (MWD)

- Stochastic simulation using MWD site data (cont'd):
  - Calculate unit side friction (f_s) using McVay et al. (1992)
    - $f_s = 0.5 \cdot \sqrt{q_u \cdot q_t} \cdot recovery$
  - Integrate over candidate lengths of embedment for each profile
    - Produces collection of axial resistance profiles
  - Calculate resistance and variability
    - Mean
    - Variance
    - COV
    - Resistance factor (ϕ)
      - First-order second-moment (FOSM), Styler (2006)
      - First order reliability method (FORM), NCHRP 507

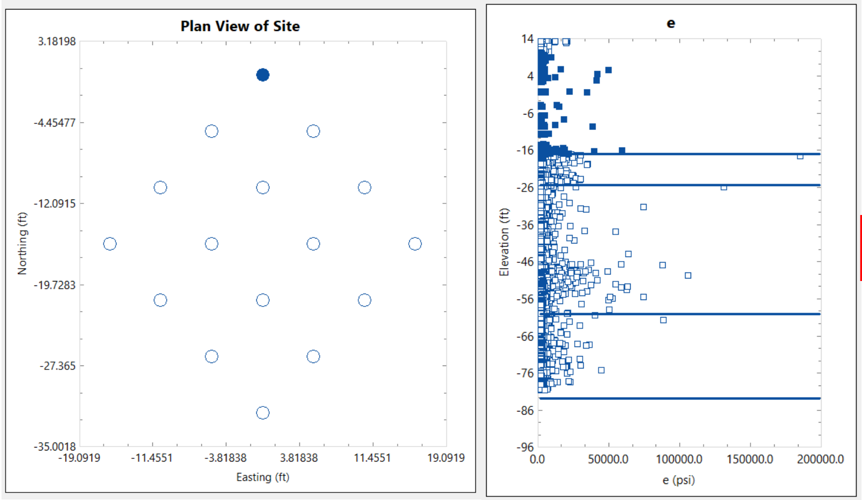


Profiles of axial resistance data

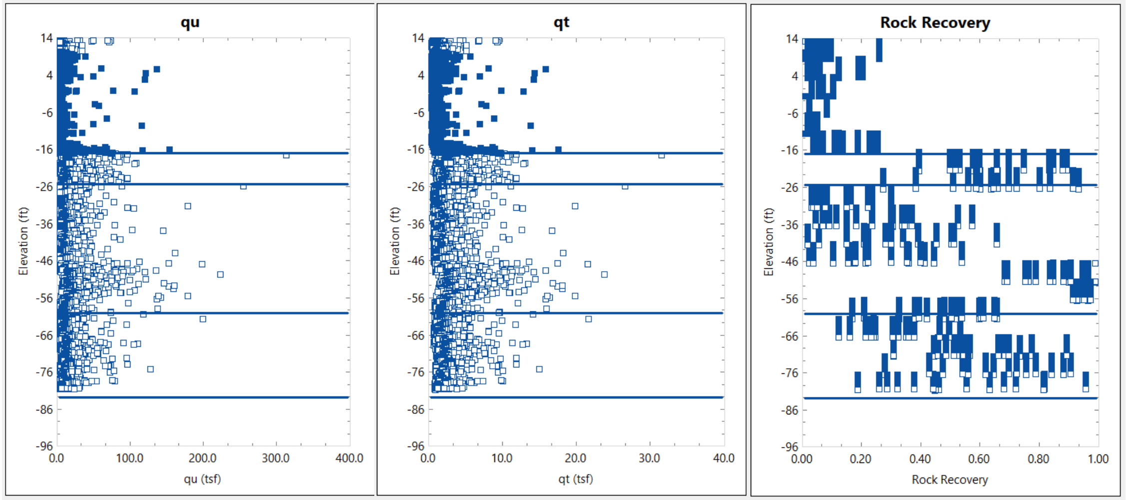
Project tasks

- Task 3: Conduct quality assurance (QA) testing
  - Develop test input sets
    - CPT
    - MWD
  - Add data validation checks
  - Ensure integrity of data writes to simulation files
  - Deliverables
    - Report
    - Beta version of software with CPT and MWD capabilities

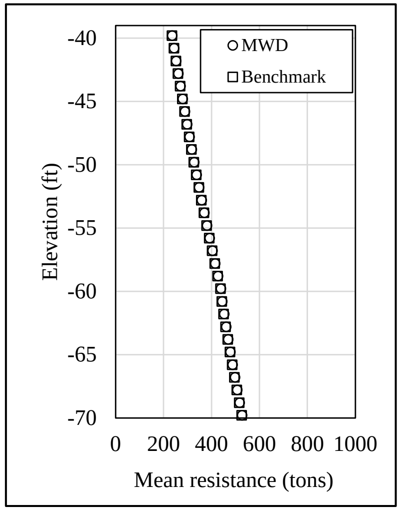
Task 3: Quality Assurance Testing



44,250 specific energy (e) data points from 16 piles



Specific energy transformed into qu, qt, and REC data points



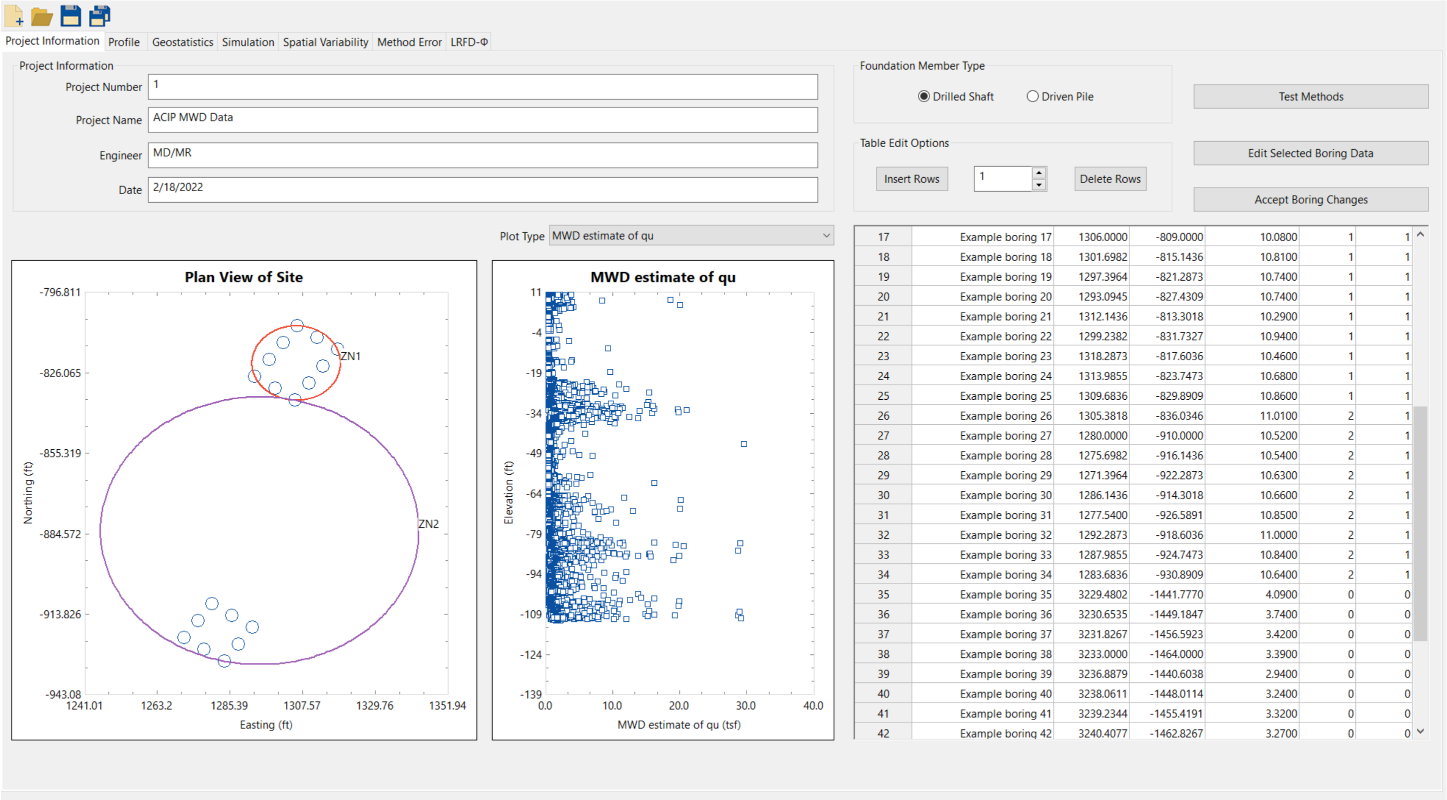
f_s from "e" vs. benchmark f_s

Project tasks

- Task 4: Investigate methodology for effective radius
  - Assess GeoStat capabilities to aid engineers in producing estimates of zonal radii
    - Focus on effective radius of test shaft data
    - Applicability of LRFD resistance factors
  - If identified as feasible:
    - Obtain site data from Project Manager
    - Build up illustration case
    - Add feature to visualize radius on plan-view plot within program
  - Document if not feasible

Project Tasks

- Task 4: Zonal radii
  - Visualization



Visualization of geological zones (shown for illustration only)

Tasking 4: Zonal Radii – Excel Input File

ACIP MWD - 50 Production Piles - Specific Energy for Ge... • Last Modified: 7/28/2022

	A	B	C	D	E
1	This tab must be populated with data prior to loading GS-Deep.				
2					
3	Program Data	Input Options	Units	Value	
4	Version			0.01	
5	Time			1:12pm	
6	Date			7/28/2022	
7	Random Seed			1	
8					
9	Project Item	Input Options	Units	Value	
10	Project Number			1	
11	Project Name			ACIP MWD Data	
12	Engineer			MD/MR	
13	Unit System	[English | SI]	ft | m	English	
14	Foundation Type	[Drilled | Driven]		Drilled	
15					
16	Boring Name	Easting	Northing	Ground Surface Elevation	Include
17					[1 | 0]
18		ft | m	ft | m	ft | m	
19	B7W-3-1	0.00	0.00	13.40	1
20	B7W-3-2	-5.30	-5.30	13.40	1
21	B7W-3-3	-10.61	-10.61	13.46	1
22	B7W-3-4	-15.91	-15.91	13.42	1
23	B7W-3-5	5.30	-5.30	13.51	1
24	B7W-3-6	0.00	-10.61	13.52	1
25	B7W-3-7	-5.30	-15.91	13.54	1
26	B7W-3-8	-10.61	-21.21	13.58	1
27	B7W-3-9	10.61	-10.61	13.52	1
28	B7W-3-10	5.30	-15.91	13.50	1
29	B7W-3-11	0.00	-21.21	13.58	1
30	B7W-3-12	-5.30	-26.52	13.51	1
31	B7W-3-13	15.91	-15.91	13.55	1
32	B7W-3-14	10.61	-21.21	13.55	1
33	B7W-3-15	5.30	-26.52	13.53	1
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38	B4-11-4	1,293.09	-827.43	10.74	1
39	B4-11-5	1,312.14	-813.30	10.29	1
40	B4-11-6	1,299.24	-831.73	10.94	1
41	B4-11-7	1,318.29	-817.60	10.46	1
42	B4-11-8	1,313.99	-823.75	10.68	1
43	B4-11-9	1,309.68	-829.89	10.86	1

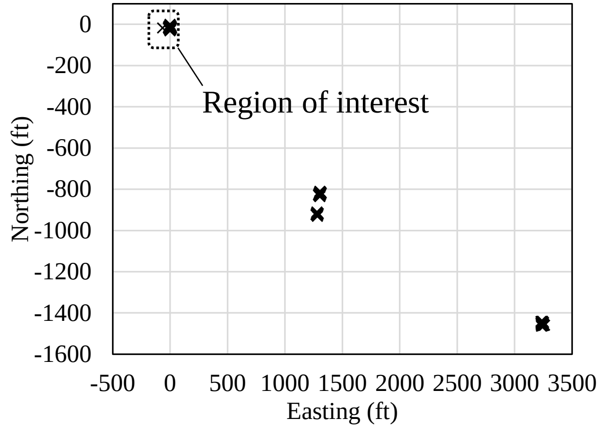
1. Project Information | 2. Profile | 3. Geostatistics | 4. Simulation | 5. Spatial Variability | 6. Method Error | 7. LRFD-phi

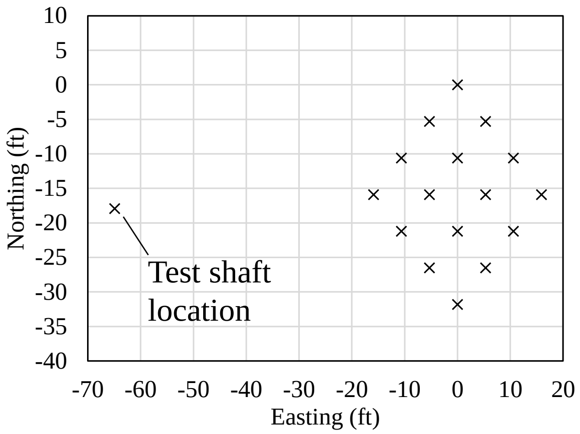
ACIP MWD - 50 Production Piles - Specific Energy for Ge... • Last Modified: 7/28/2022

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	This tab must be populated with data prior to loading GS-Deep.														
2															
3	Depth	Soil Type	N. Blows	qt (CPT)	fs (CPT)	Unit Weight	Cu	e	qu	qt	qb	Em	RQD	Socket Roughness	Rock Recovery
4		[1 | 2 | 3 | 4 | 5]											[0.0 to 1.0]	[0 | 1]	[0.0 to 1.0]
5	ft | m		blows/ft | blows/300mm	tsf | MPa	tsf | kPa	pcf | kN/m^3	tsf | kPa	psi | kPa	tsf | kPa	tsf | kPa	tsf | kPa	ksi | MPa			
6	0.032808	4				92.05284683		2567.343856							
7	0.065617	4				92.05284683		2567.343856							
8	0.098425	4				92.05284683		2567.343856							
9	0.131233	4				87.22345118		1785.129116							
10	0.164042	4				87.22345118		1785.129116							
11	0.19685	4				86.88126996		1738.895452							
12	0.229658	4				86.39176285		1674.621647							
13	0.262467	4				86.39176285		1674.621647							
14	0.295275	4				82.94267039		1278.619286							
15	0.328083	4				80.61109993		1060.320259							
16	0.360892	4				80.62141931		1061.209036							
17	0.3937	4				80.62141931		1061.209036							
18	0.426508	4				80.90763517		1086.122317							
19	0.459317	4				80.90763517		1086.122317							
20	0.492125	4				80.54807118		1054.905964							
21	0.524933	4				81.08755994		1102.045571							
22	0.557742	4				81.08755994		1102.045571							
23	0.59055	4				81.60802774		1149.26958							
24	0.623358	4				80.53524414		1053.807076							
25	0.656167	4				81.22880856		1114.689545							
26	0.688975	4				81.22880856		1114.689545							
27	0.721783	4				81.09603084		1102.800277							
28	0.754592	4				81.8567586		1172.460744							
29	0.7874	4				81.8567586		1172.460744							
30	0.820208	4				81.58971381		1147.578119							
31	0.853017	4				81.52982169		1142.061835							
32	0.885825	4				81.52982169		1142.061835							
33	0.918633	4				81.90704527		1177.199189							
34	0.951442	4				84.22403689		1414.75845							
35	0.98425	4				87.02468704		1758.140766							
36	1.017058	4				87.02468704		1758.140766							
37	1.049867	4				87.02468704		1758.140766							
38	1.082675	4				87.02468704		1758.140766							
39	1.115483	4				87.02468704		1758.140766							
40	1.148292	4				82.19826877		1204.974501							
41	1.1811	4				82.19826877		1204.974501							
42	1.213908	4				82.19826877		1204.974501							
43	1.246717	4				79.96635907		1006.070251							

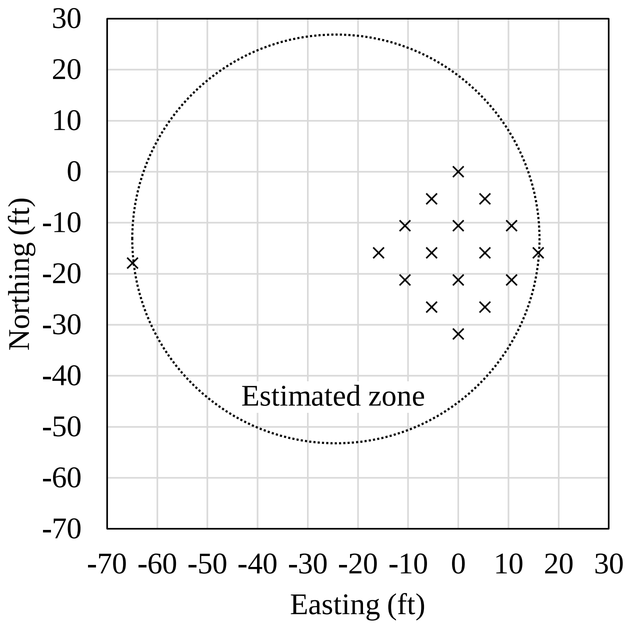
1. Project Information | 2. Profile | 3. Geostatistics | 4. Simulation | 5. Spatial Variability | 6. Method Error | 7. LRFD-phi | B7W-3-1 | B7W-3-2 | B7W-3-3 | B7W-3-4 | B7W-3-5 | B7W-3-6 | B7W-3-7 | B7V ...

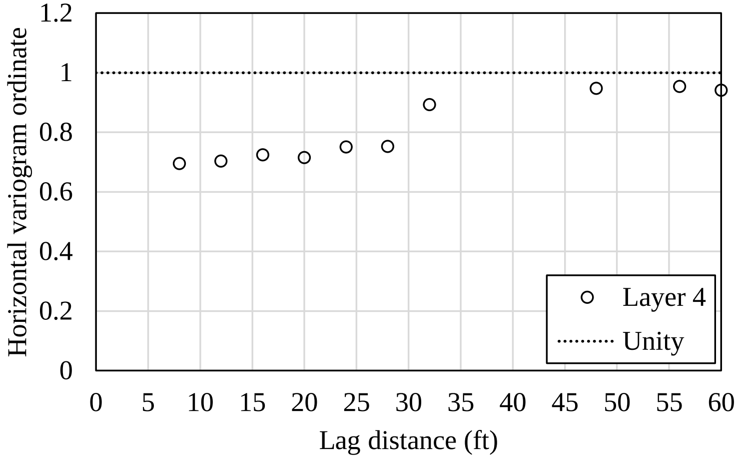
Task 4: Zonal Radii – 17 Boring Locations

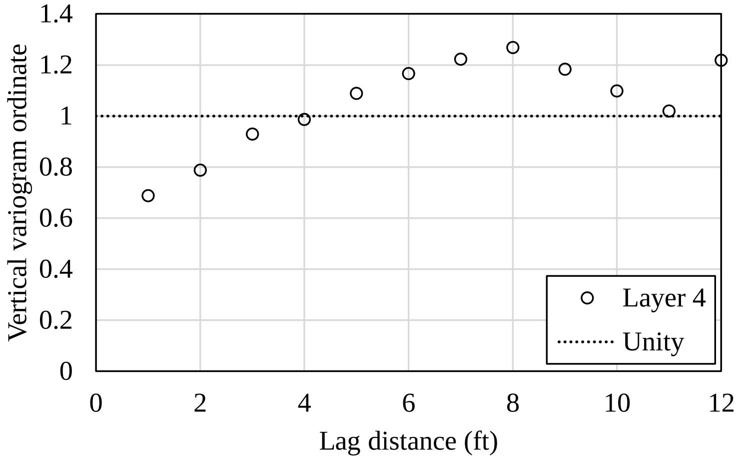




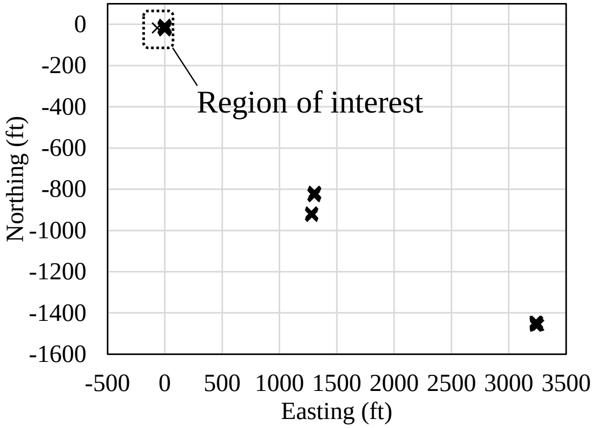
- Lag distance & number of lags is iterative
- For each iteration of lag:
- Horizontal
  - Tolerance = ½ lag distance
  - Bandwidth = 2 ft
- Vertical
  - Tolerance = ½ lag distance
  - Bandwidth = 0 ft

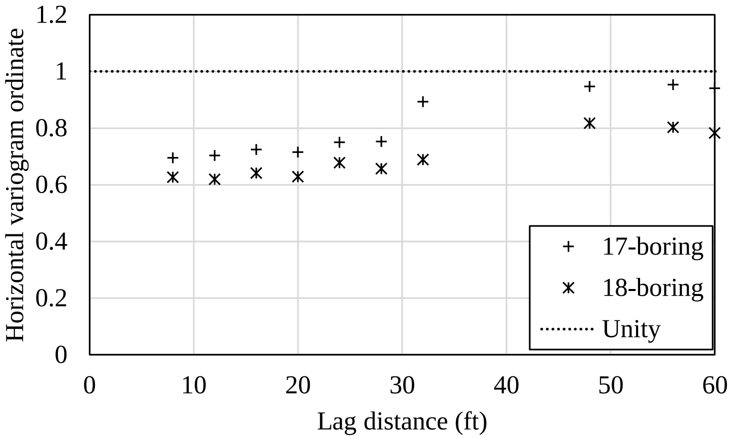


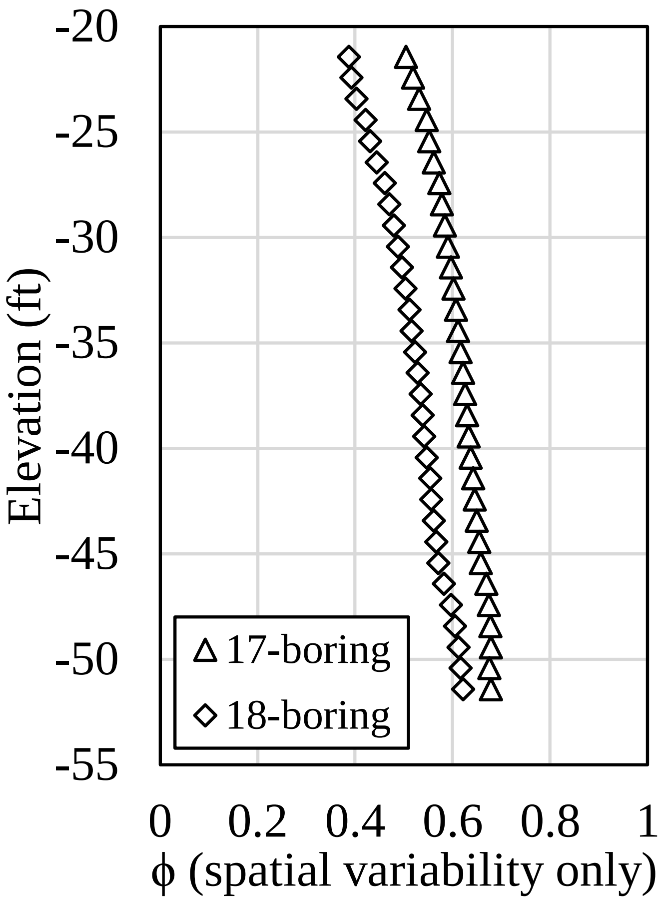


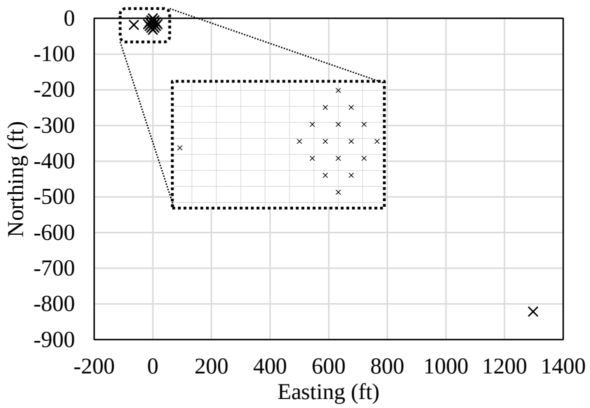


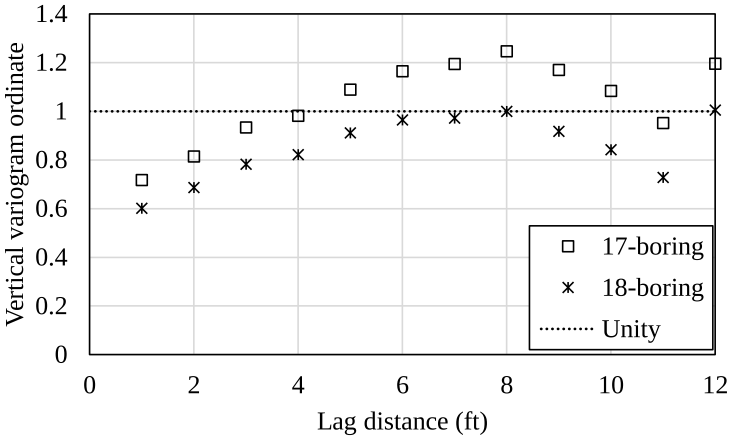
Task 4: Zonal Radii – 18 Boring Locations











***10-20% increase in Variance**

Project tasks

- Task 5: Technology transfer
  - Leverage sample projects in FDOT BDV31-97-108
  - Web-based
  - Delivered to FDOT district engineers
  - Two sessions
    - Theoretical basis and driven pile sample project (2 hrs)
    - Drilled shaft sample project and Q&A (2 hrs)

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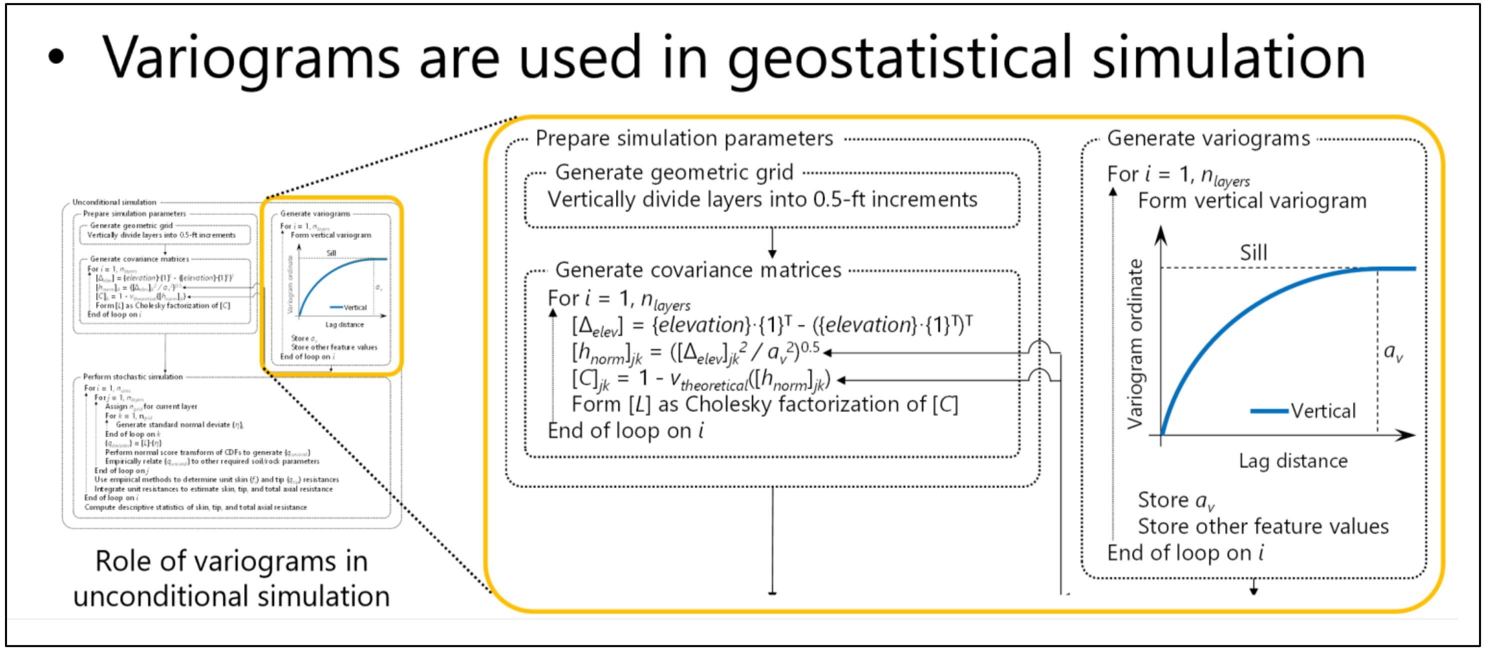
Project tasks

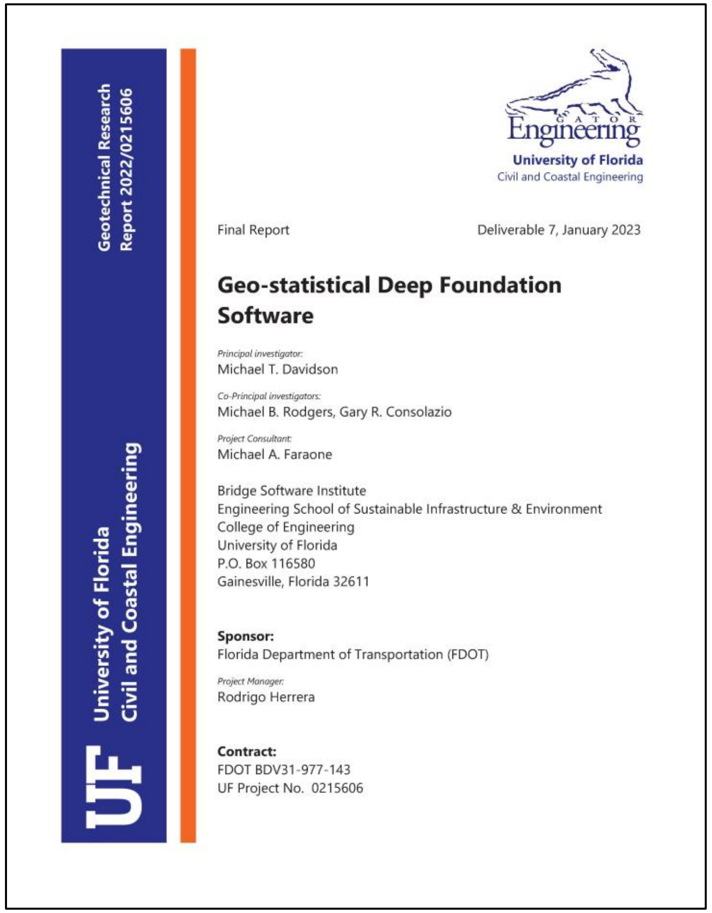
- Deliverable 5: Technology transfer materials
  - Zip-file package
    - Slides
    - Models



Illustrative technology transfer content for variogram generation

Project tasks

- Task 6: Draft final and closeout teleconference
  - Deliverable 6.1: draft final report
  - Deliverable 6.2: Closeout teleconference
- Task 7: Final report
  - Deliverable 7: Submission of final report



Geotechnical Research Report 2022/0215606

University of Florida Civil and Coastal Engineering

UF

Gator Engineering
University of Florida
Civil and Coastal Engineering

Final Report
Deliverable 7, January 2023

Geo-statistical Deep Foundation Software

Principal investigator:
Michael T. Davidson

Co-Principal investigators:
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Sponsor:
Florida Department of Transportation (FDOT)

Project Manager:
Rodrigo Herrera

Contract:
FDOT BDV31-977-143
UF Project No. 0215606

Outline

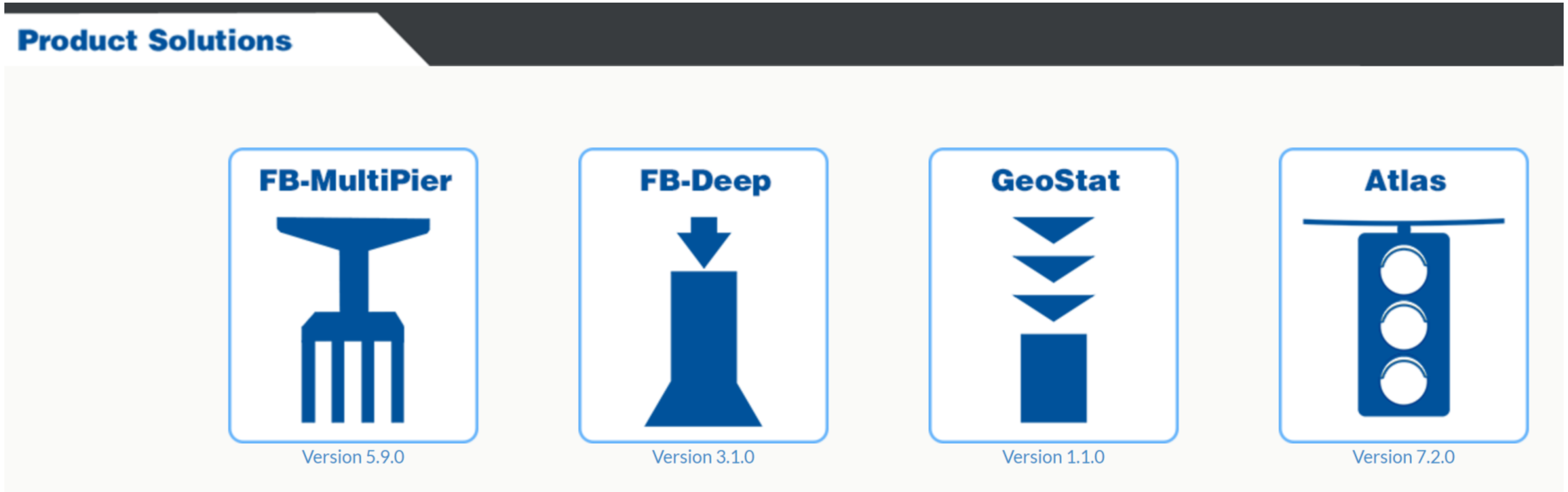
- Introduction and background
- Project objective
- Project tasks
- Summary

Summary of research conclusions

- For predicting axial capacities of deep foundation members, geostatistical approaches offer benefits over deterministic approaches
- GeoStat software contains features encompassing numerous types of site investigation methods and is capable of predicting axial capacities of deep foundation members in various soil/rock media
- Site-specific (or zone-specific) resistance factors (ϕ), when Owner-approved, can contribute to more uniform levels of conservatism

Implementation items

- Updated version of GeoStat available to practicing engineers at bsi.ce.ufl.edu
- Maintained by BSI



Implementation items

Recommendations

- Use of GeoStat in design applications
- Expansion of MWD-based analysis
  - Sand and clay soils
  - Custom correlations to geotechnical parameters
- Automation of several procedures
  - Layer-specific unit weight input parameters
  - Layer detection
  - Detection of zones

Thank you

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FDOT

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Engineering School of Sustainable Infrastructure & Environment