Development of Variable LRFD ϕ factors for Deep Foundation Design due to Site Variability

FDOT Contract No.: BDK-75-977-23

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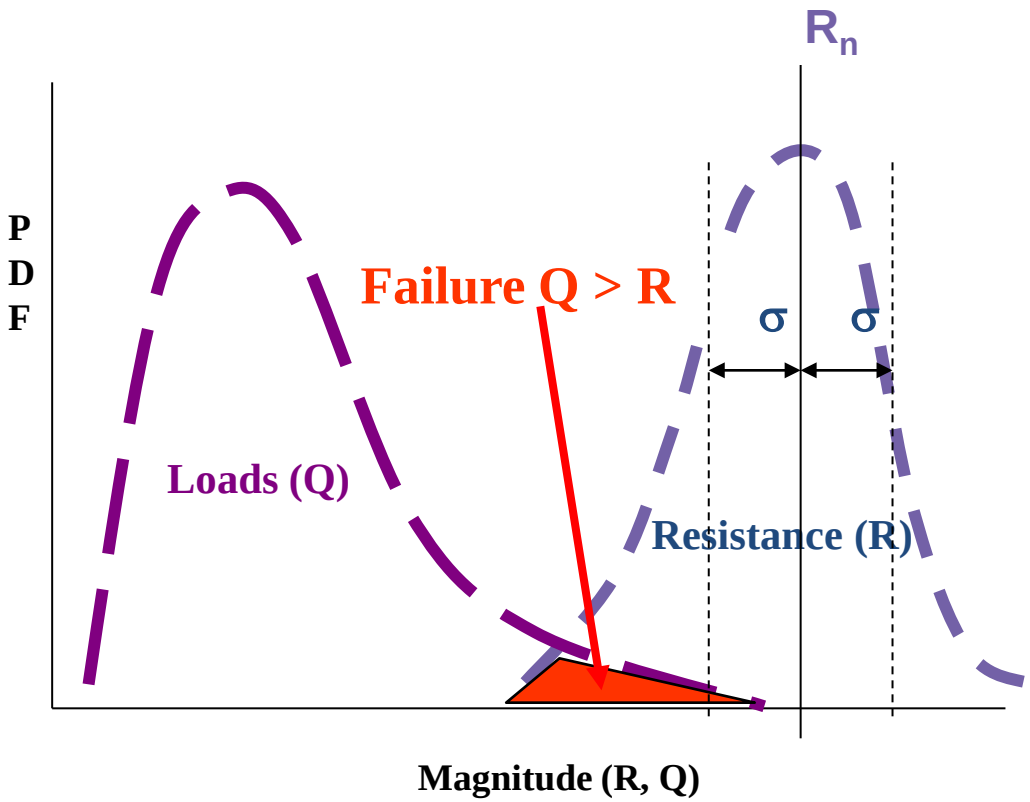
Research Task

1. Collection of Borings and Static Load Test
2. Development of Expected Measure Load Test vs. Predicted Capacity Relationship
3. Development of LRFD ϕ for Combined Side and Tip Resistance
4. Case Studies and Implementation
5. Database Entry and Final Report

Load and Resistance Factored Design (LRFD)



- $\phi R_n \geq \eta \sum \gamma_i Q_i$
- R_n & Q_i represented as **Random Variables**

(Summary Statistics: mean, m_R = R_n and standard deviation, σ; $CV_R = \sigma / R_n$)

η - redundancy

- Risk or Probability of Failure: Mathematically Determined!

LRFD Resistance Factor, ϕ

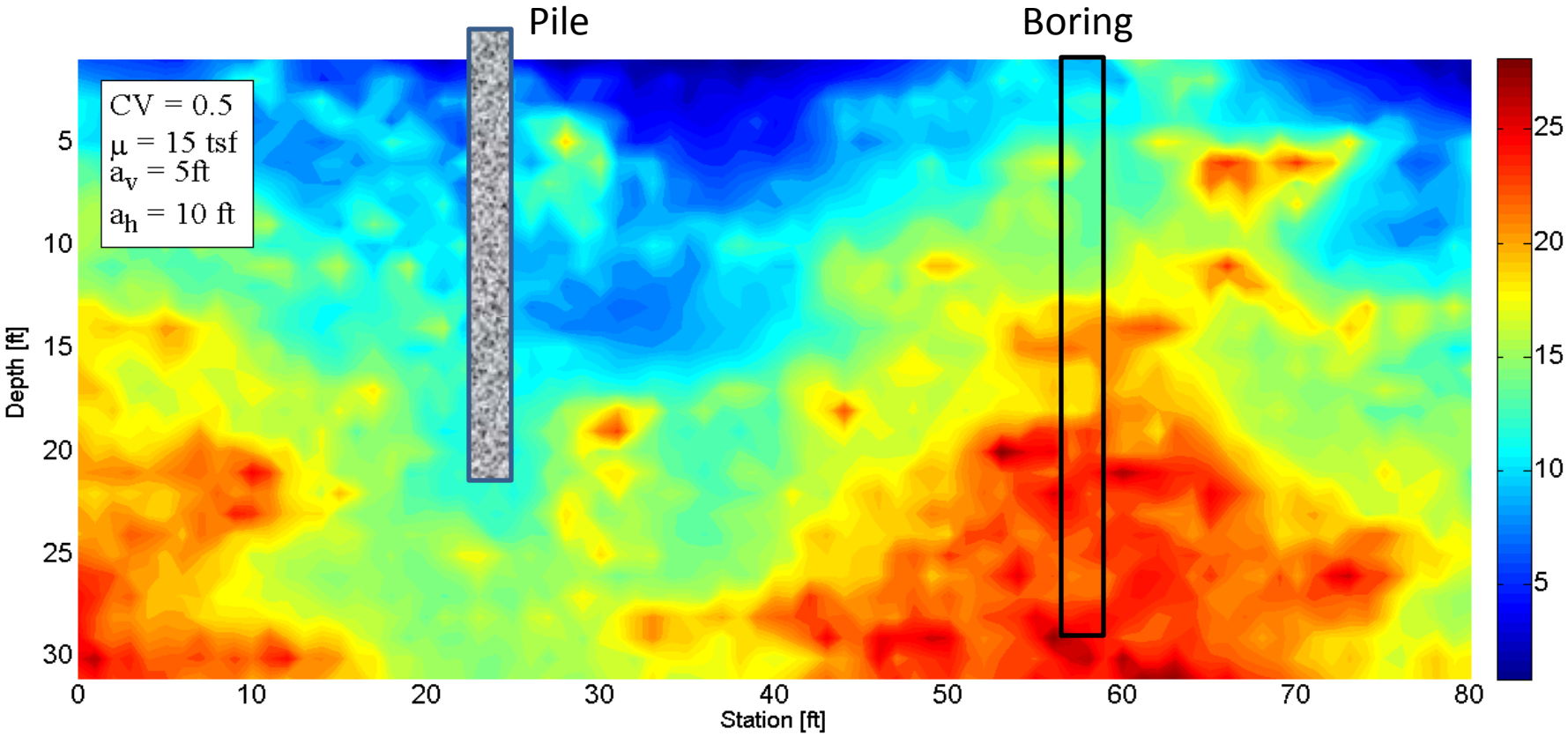
$$\phi = \frac{\lambda_R \left(\gamma_D \frac{Q_D}{Q_L} + \gamma_L\right) \sqrt{\frac{(1 + CV_Q^2)}{(1 + CV_R^2)}}}{\left(\lambda_{QD} \frac{Q_D}{Q_L} + \lambda_{QL}\right) exp\left\{\beta \sqrt{\ln[(1 + CV_R^2)(1 + CV_Q^2)]}\right\}}$$

$$\sigma_R^2 = \sigma_{Spatial}^2 + \sigma_\varepsilon^2 \qquad CV_R = \sigma_R / R_n$$

- CV_R = Pile/Shaft Resistance's Coefficient of Variation
- λ_R = Resistance Bias Factor
- Q_D/Q_L = Dead to Live Load Ratio; Varies from 1.0 to 3.0 (spans, L=57-170ft), Φ is not very sensitive (value of 2.0 used herein)
- $\lambda_{QD}, \lambda_{QL}$ = Dead load and live load bias factors, λ_{QD} = 1.08, λ_{QL} = 1.15 (AASHTO 2000)
- CV_{QD}, CV_{QL} = Dead and Live Load Coefficients of Variation, CV_{QD} = 0.128, CV_{QL} = 0.18 (AASHTO 2000)
- β_T = Target reliability index, AASHTO and FHWA recommend values from 2.0 to 3.0
  3.0 - probability of failure 1 in 1000, 2.0 – probability of failure 1 in 100

Spatial Variability, $\sigma^2_{Spatial}$

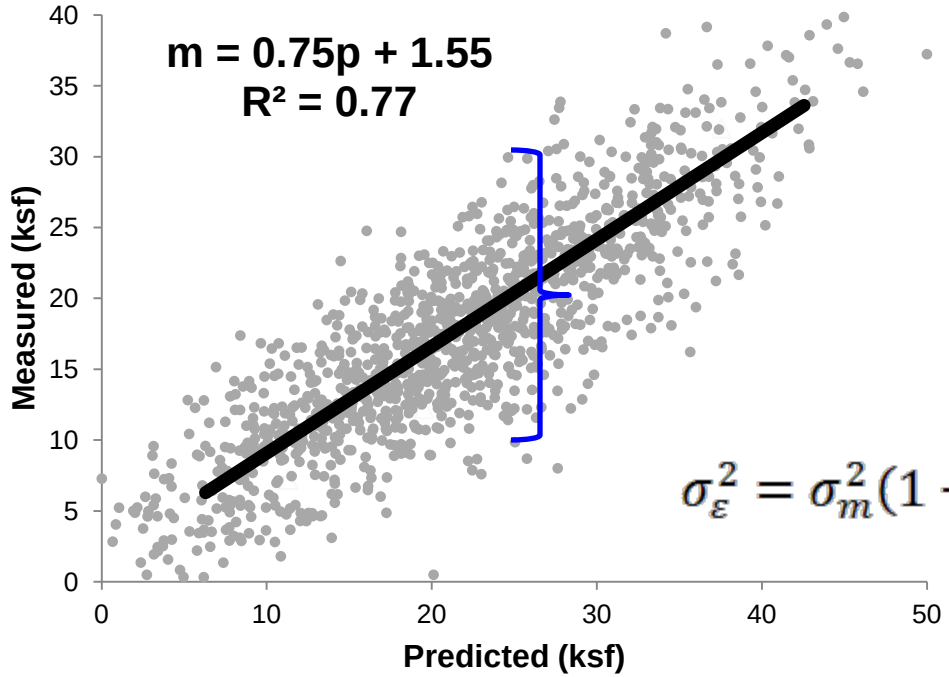
- Spatial Variability of Properties (spatial correlation, variograms)
- Prediction Error (boring location relative to foundation)
- Amount of Data Collected (uncertainty in mean and variance).



Method Error, σ_ε^2

- Accounts for multiple source of variability
  - Calculation Method Error (FB-DEEP-Drilled Shafts, Driven Piles)
  - Insitu Measurement ->Engineering Property (CPT qt -> Cu)
  - Measurement Error (Infield or Lab)
- Use a Regression Analysis of Measured vs Predicted from Load Testing
- Bias (m=b*p+a) accounts for how accurate a method (conservative/unconservative).
- The error (σ_ε^2) accounts for how precise (scatter) a method is.

m-measured (Load Test)
p-predicted (Boring)



$$\sigma_\varepsilon^2 = \sigma_m^2(1 - R^2)$$

Current LRFD Deep Foundation Design
FDOT Structures Design Manual

Table 3.6.3-1 Resistance Factors for Drilled Shafts (Bridge Foundations)

Loading	Design Method	Construction QC Method	Resistance Factor, φ	
			Redundant	Non-redundant[1]
Compression	For soil: FHWA alpha or beta method [2]	Specifications	0.6	0.5
	For rock socket: McVay's method [3] neglecting end bearing	Specifications	0.6	0.5
	For rock socket: McVay's method [3] including 1/3 end bearing	Specifications	0.55	0.45
	For rock socket: McVay's method [3]	Statnamic Load Testing	0.7	0.6
	For rock socket: McVay's method [3]	Static Load Testing	0.75	0.65
Uplift	For clay: FHWA alpha method [2]	Specifications	0.35	0.25
	For sand: FHWA beta method [2]	Specifications	0.45	0.35
	For rock socket: McVay's method [3]	Specifications	0.5	0.4
Lateral [4]	FBPier [5]	Specifications Or Lateral Load Test [6]	1.00	0.9

- Sufficient Borings in Vicinity of Foundation
- No Consideration of Spatial Variability of Soil/Rock properties

Measured Point Variability

Drilled Shaft Projects

Project Name	Financial Project ID	County	q_u		
			Mean (tsf)	CV	n
17 St Bridge	WPI 4110739	Broward	98.19	0.57	99
Jewfish Creek	250445-1	Monroe	40.19	0.77	183
MIC Station	406800-2	Miami-Dade	67.07	0.66	66
MIC People Mover	408320-1	Miami-Dade	65.58	0.74	18

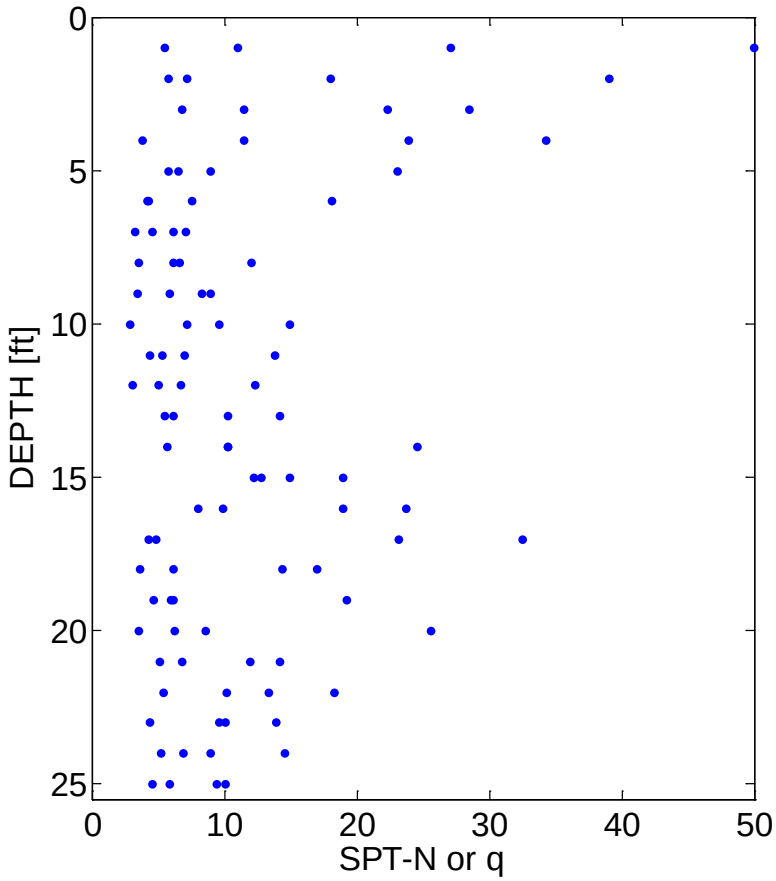
Driven Pile Project

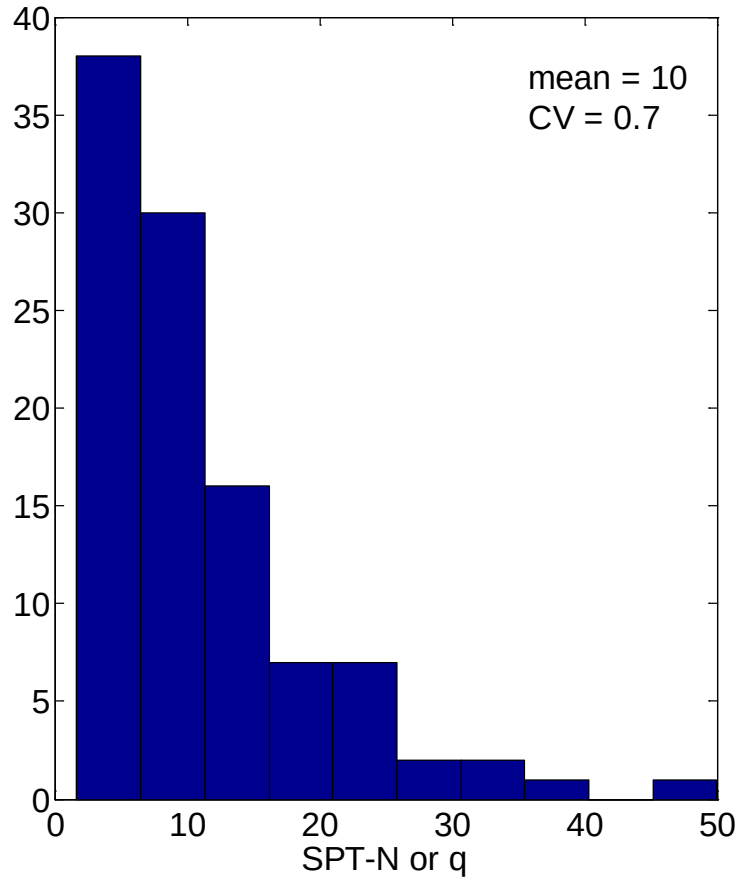
Dixie Highway			
Layer	Mean	CV	n
1	11.35	0.69	183
2	11.49	0.51	154
3	45.42	0.41	317

SPATIAL VARIABILTY

- What does our in situ data look like?
  - Point versus Correlation
- What can measured in situ data tell us?
  - Mean, CV, Variograms
- How can we account for spatial variability?
  - Kriging
  - Simulations

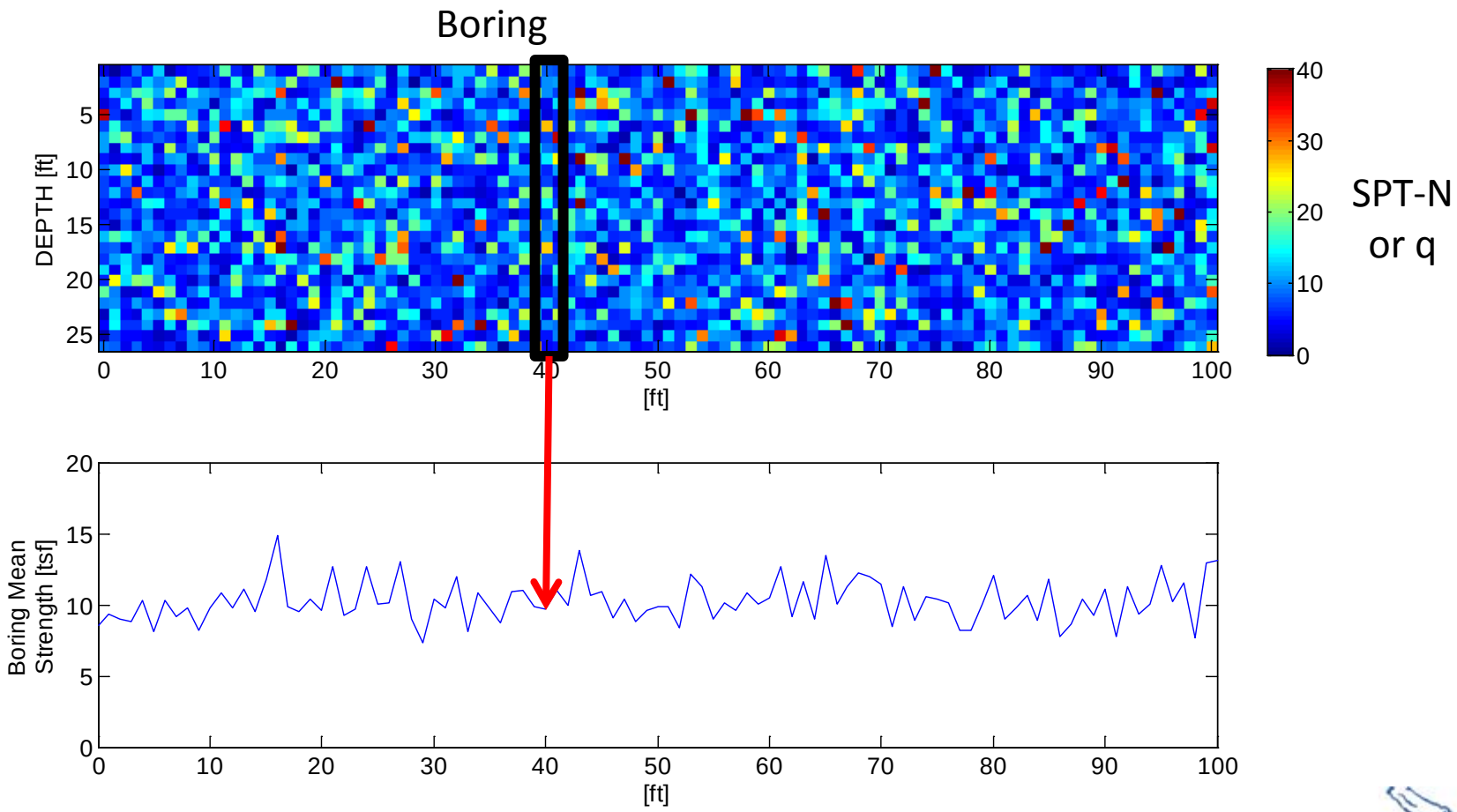
In Situ Measurement Variability





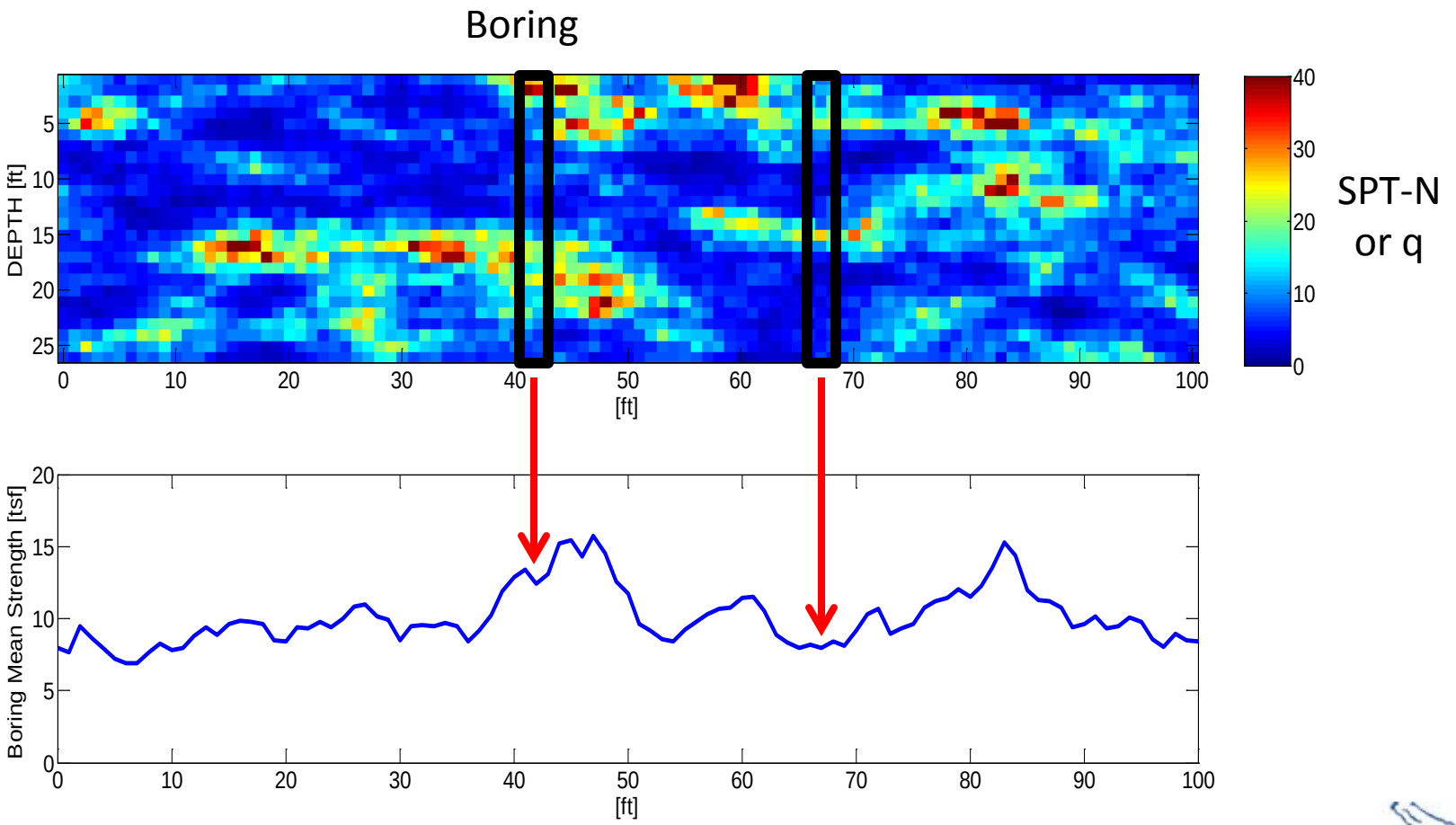
Point Variability
No spatial correlation

Mean = 10
CV = 0.70

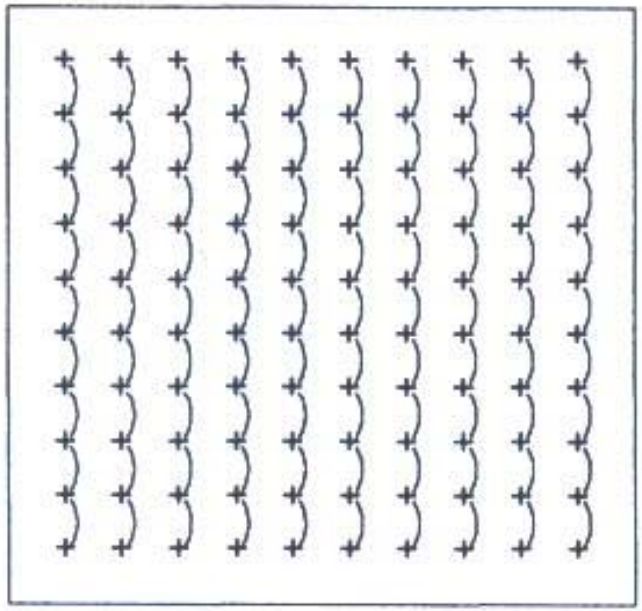


Correlated Spatially

Mean = 10
CV = 0.70
a_h = 12
a_v = 5



Measuring Spatial Correlation

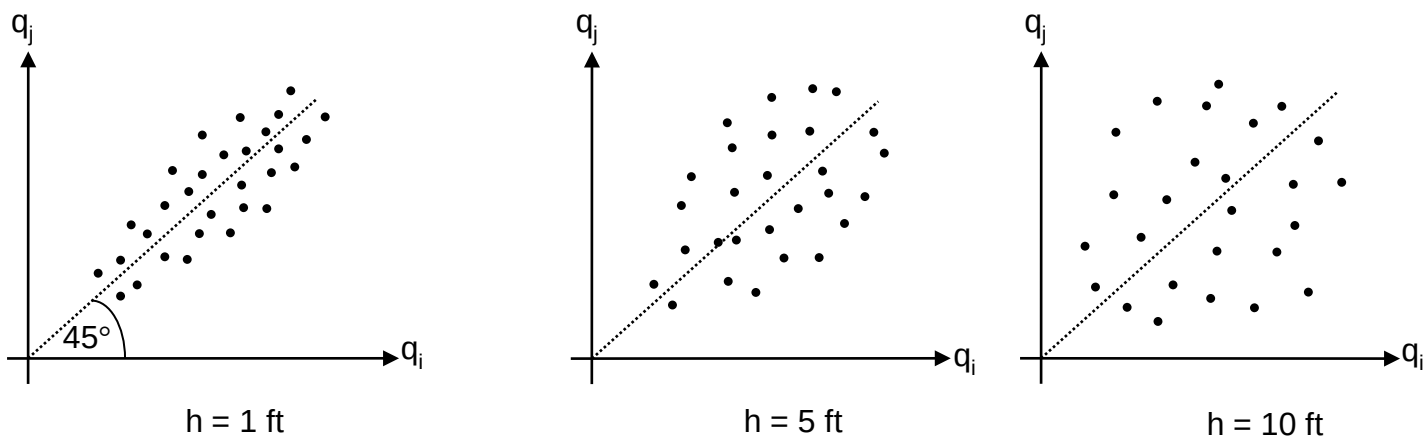


- Variogram γ as a function of h – separation distance

$$\gamma(h) = \frac{1}{2n}\sum(q_i - q_j)^2$$

Scatter Plot

- Spatial Correlation - How similar are properties based on separation distance (h).

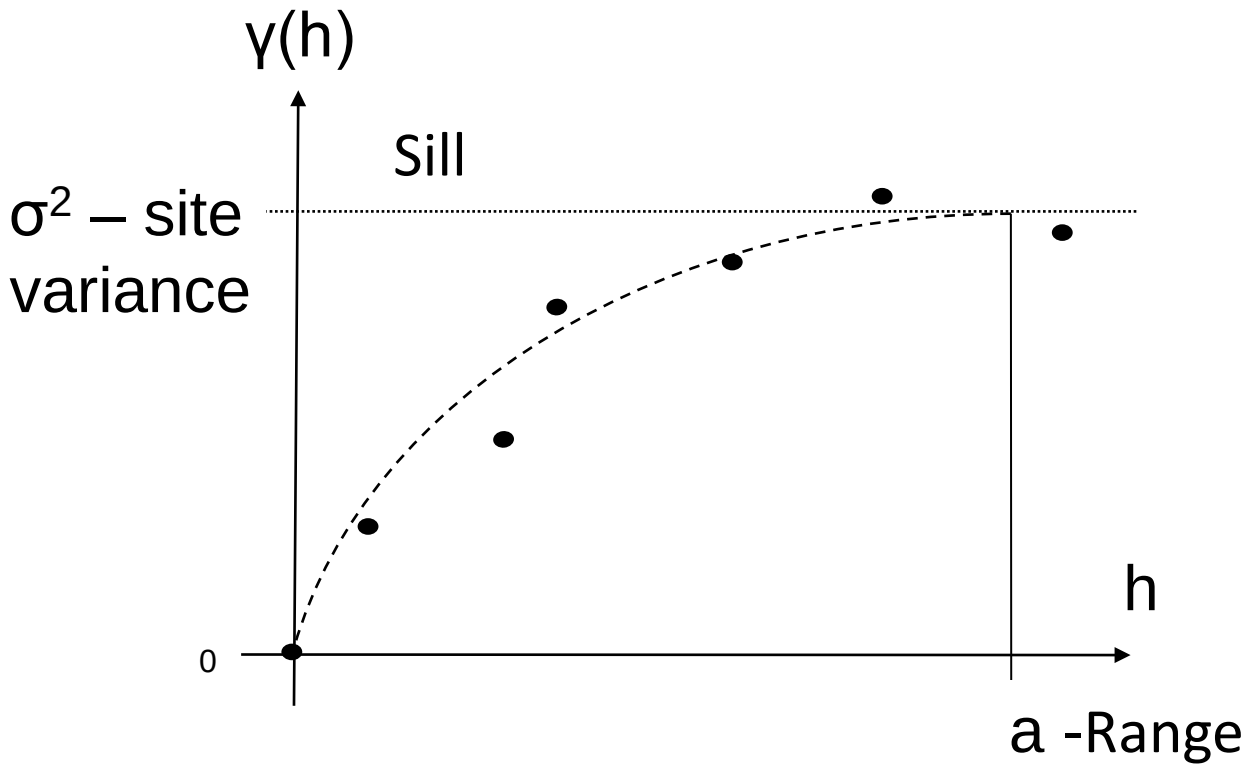


- Variogram γ as a function of h – separation distance

$$\gamma(h) = \frac{1}{2n}\sum(q_i - q_j)^2$$

VARIOGRAM

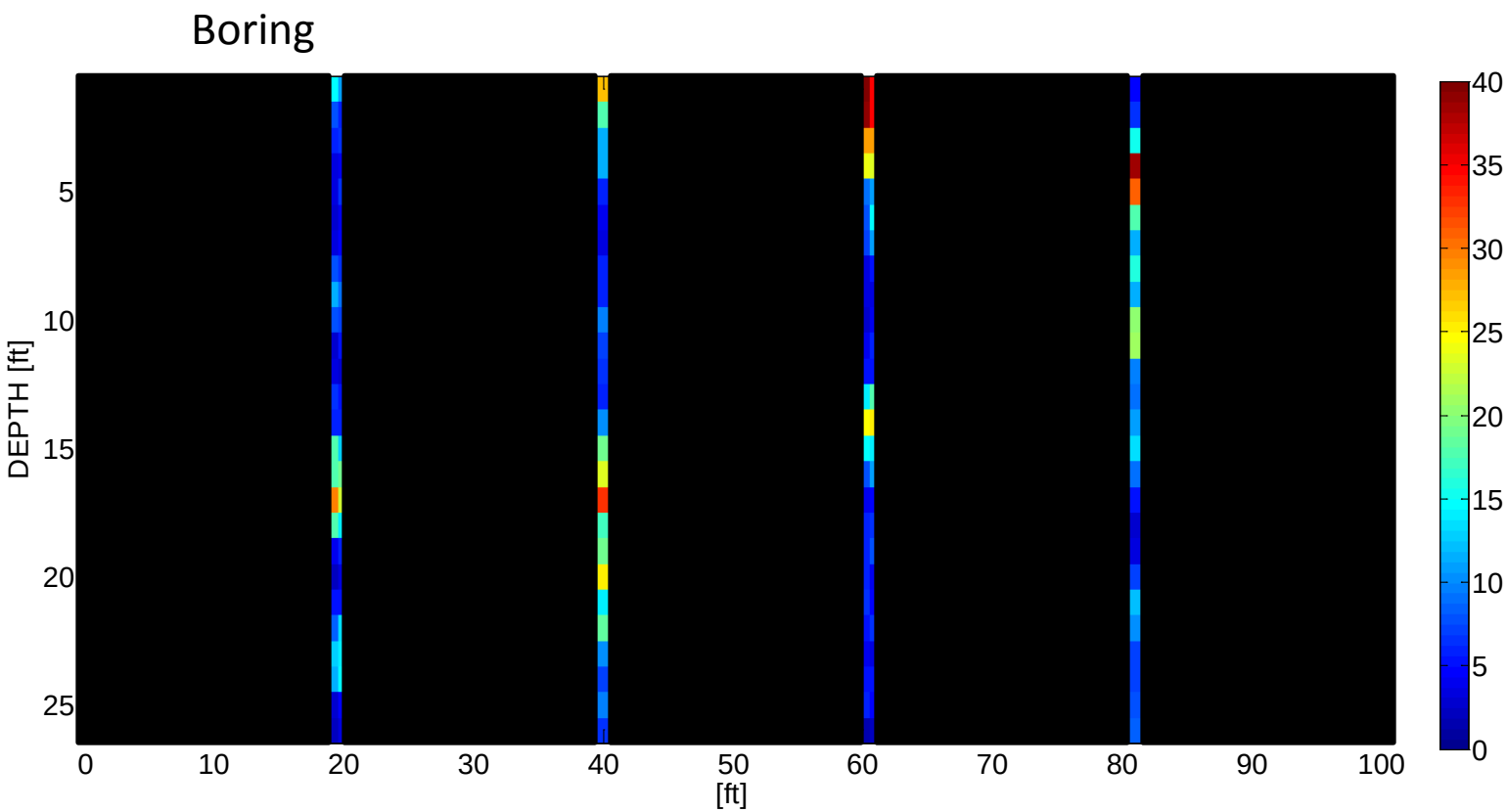
- Measured in Horizontal and Vertical Directions
- Fit with model (exponential, spherical, etc.)



MEASURED VARIOGRAMS

Site	a_v [ft]	a_h [ft]	In situ Property
17th Street Bridge	4.0	12	q_u
Dixie Highway (per layer)	6.0	NA	SPT N
	11.1		
	11.1		
Jewfish Creek	7.3	NA	q_u
MIC/MIA	6.6	NA	q_u
MIC Station	NA	NA	q_u
CR12A	11.8	NA	SPT N
Keystone	8.0	12.0	CPT-qt

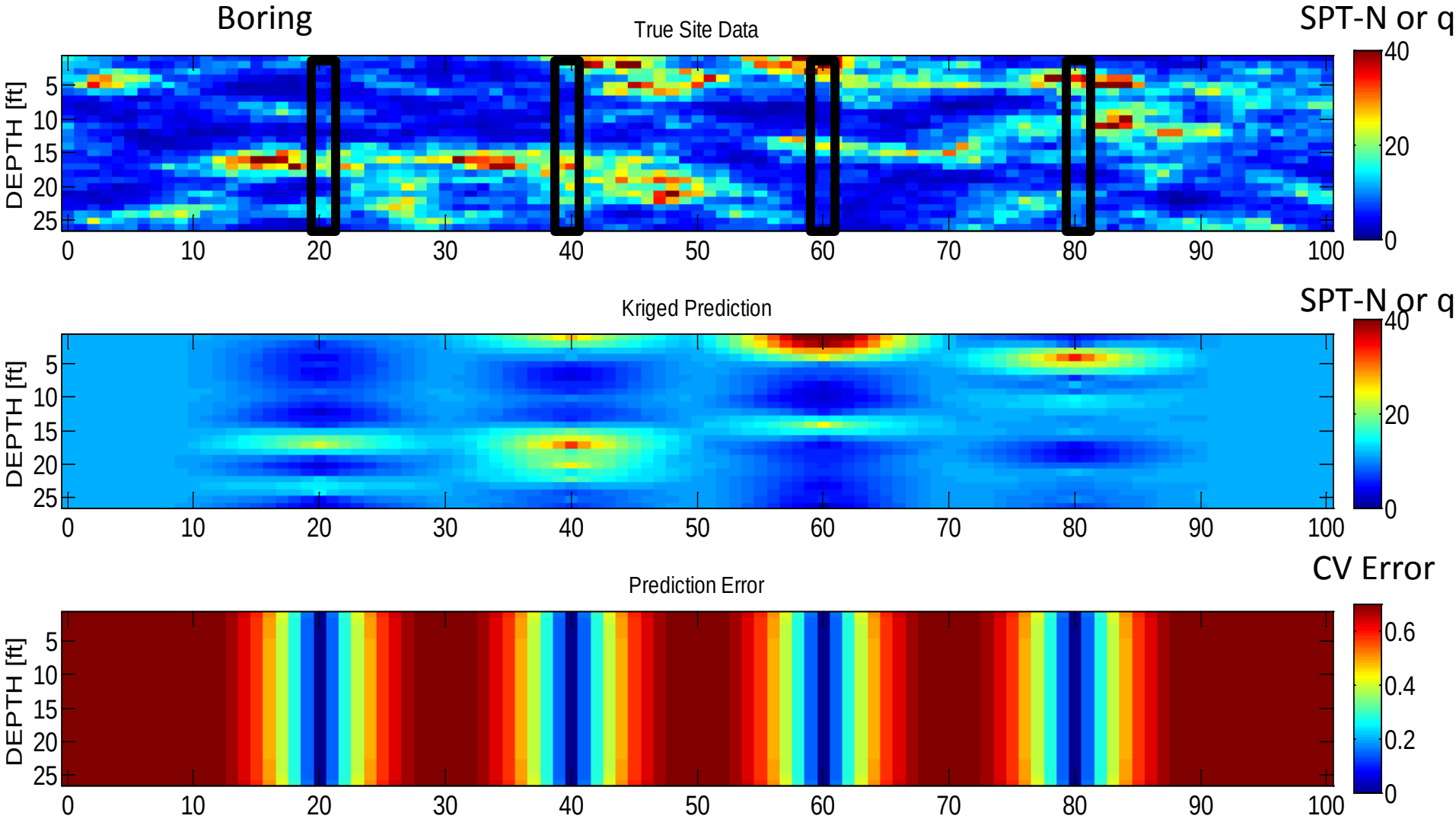
Kriging-Prediction from Borings



Kriging-Estimate from Boring

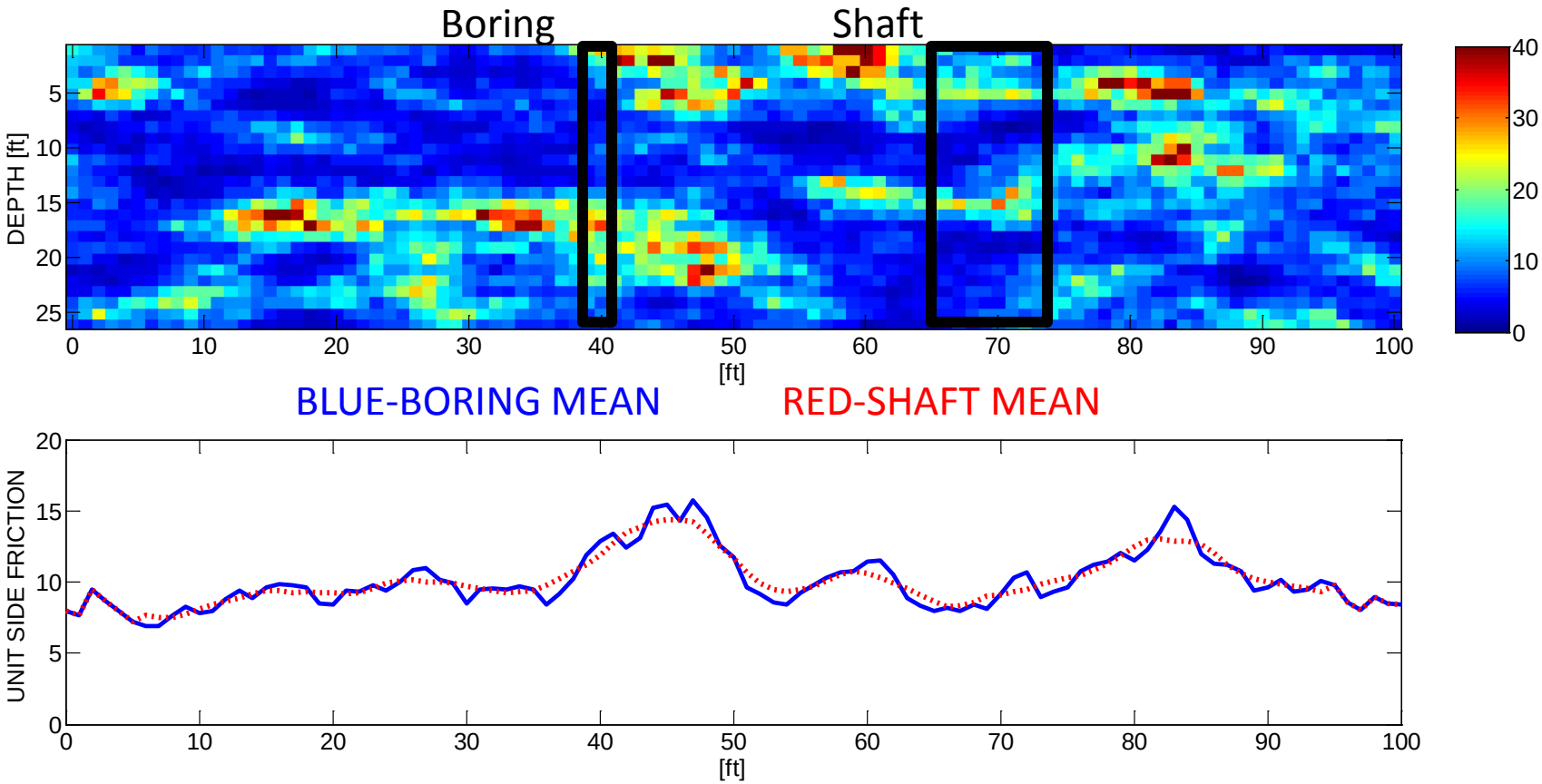
- Prediction of an insitu measurement at an unsampled location.
- Weights prediction based on how close boring samples are (Variogram).
- Has the advantage of also giving the error (accuracy) for a corresponding predicted value.

KRIGING


Boring
True Site Data
SPT-N or q
DEPTH [ft]
5
10
15
20
25
0
10
20
30
40
50
60
70
80
90
100
40
20
0
Kriged Prediction
SPT-N or q
Prediction Error
CV Error
0.6
0.4
0.2

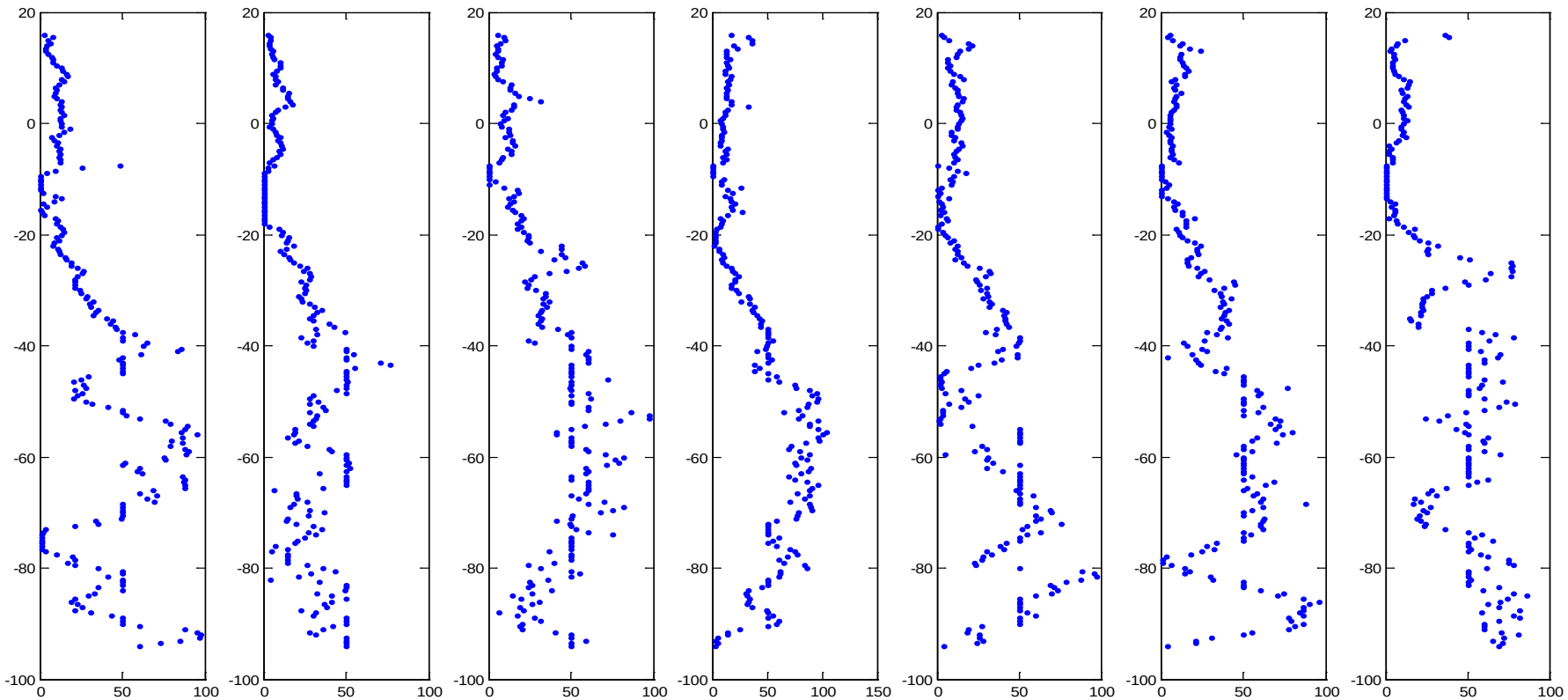
Point Variability to Shaft/Pile Variability

- Shaft scale >> Point scale
- Area Averaging => reduced spatial variability



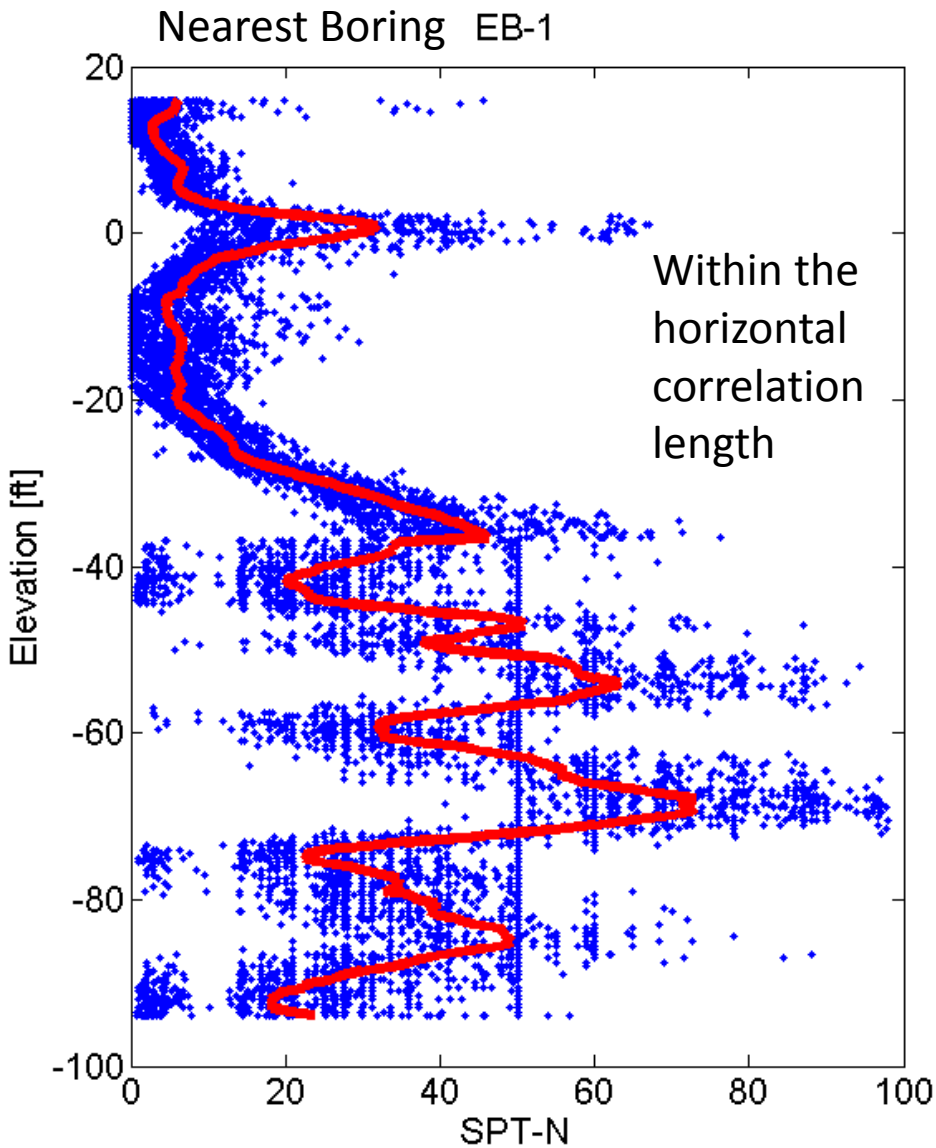
Simulation Process

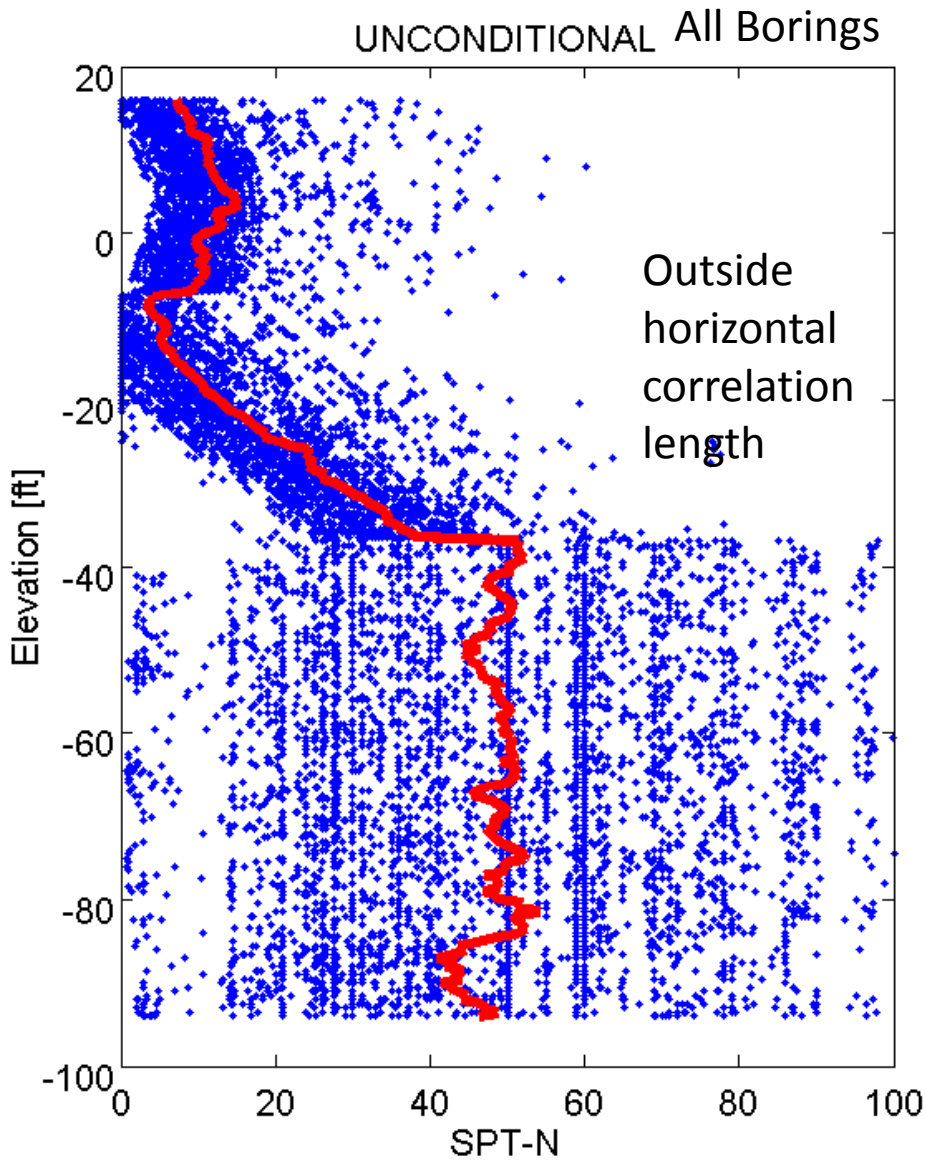
- Can account for more complex models-non linear.
- Using kriging process and incorporate prediction error to generate borings.
- Replicates measured data
  - Distribution – mean and variance
  - Spatial Correlation-Vertical and Horizontal Variograms
  - Observed Trends



Simulated Borings for Dixie Highway

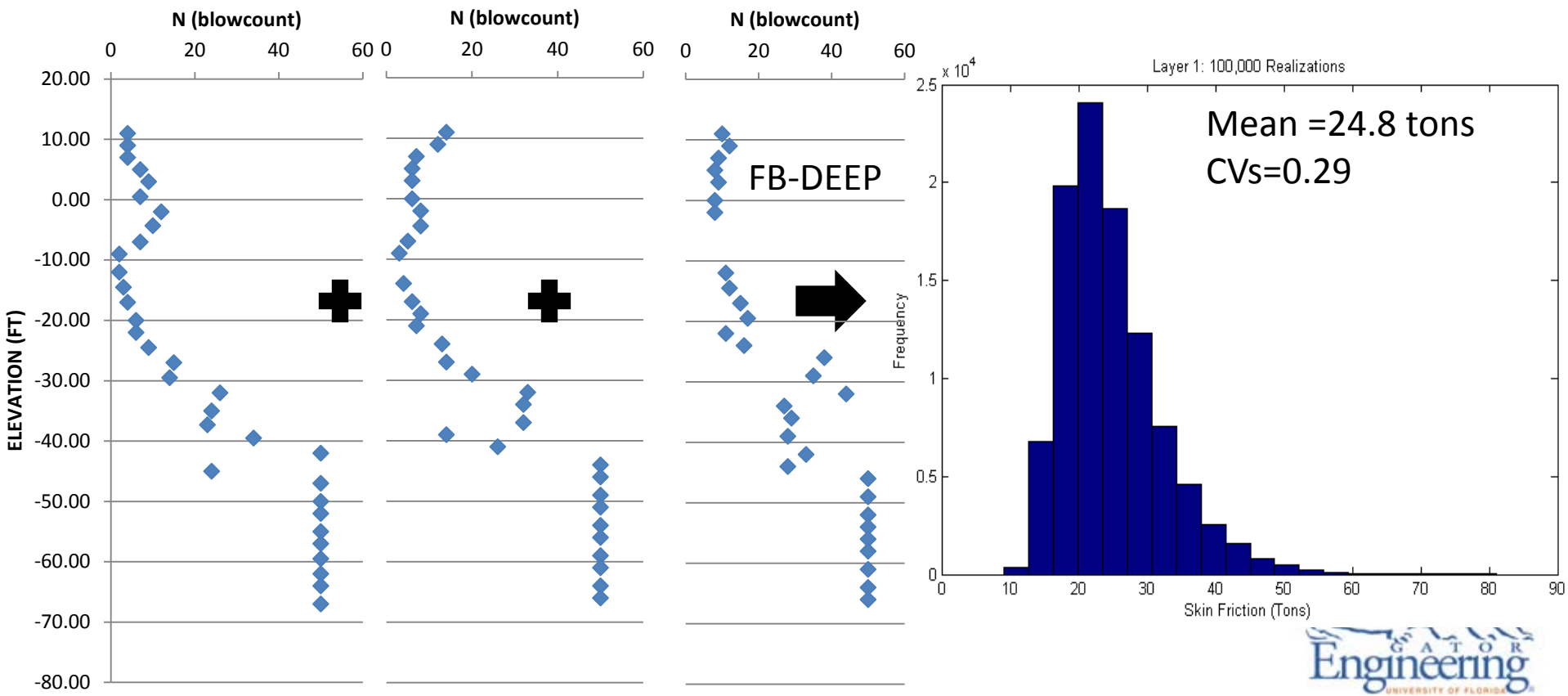
Dixie Highway Kriging





Simulation Process

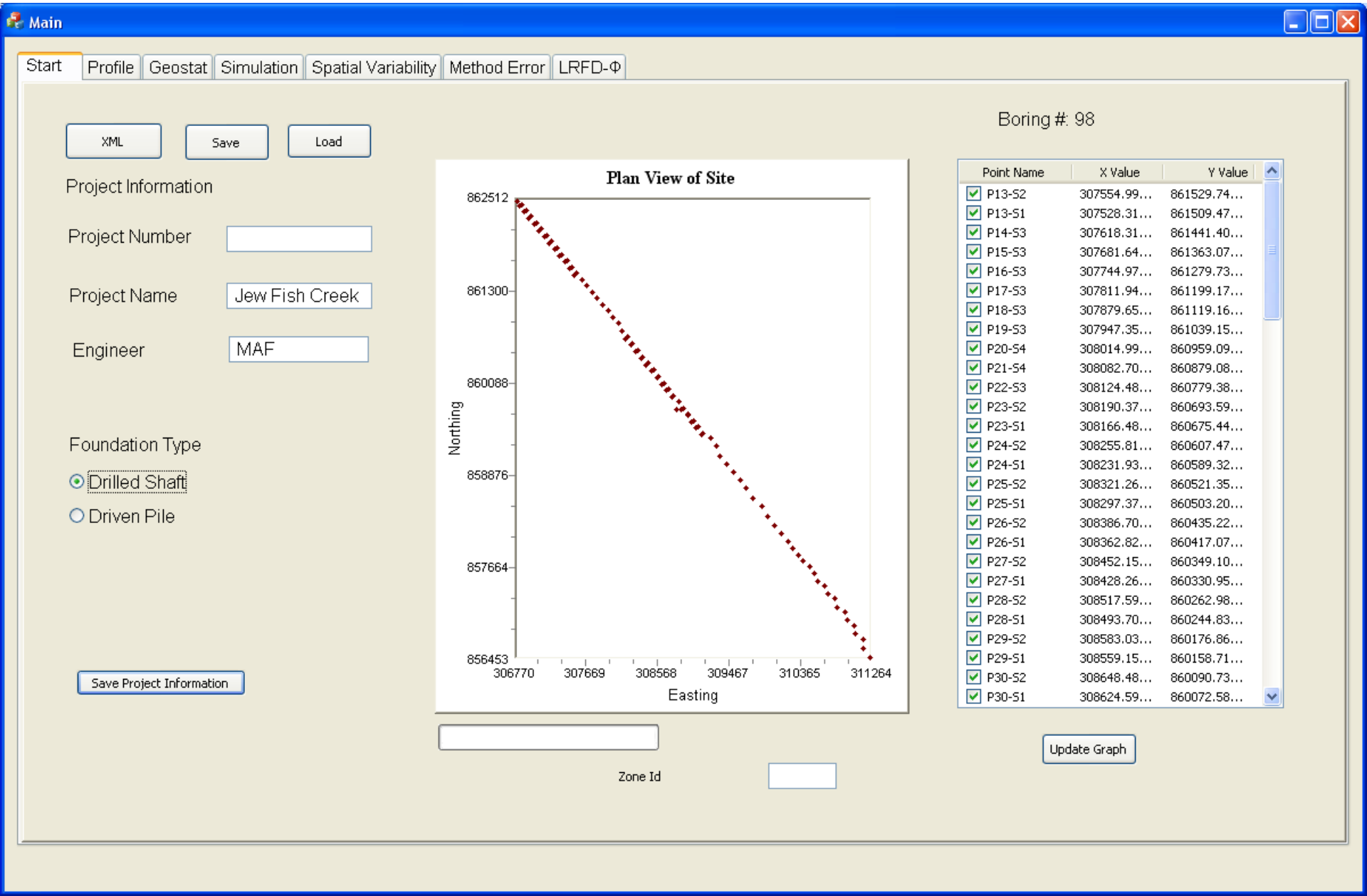
- Each generated boring is run through FB-DEEP
- Hundreds of realizations result in a distribution of resistance(Total, Skin & Tip).



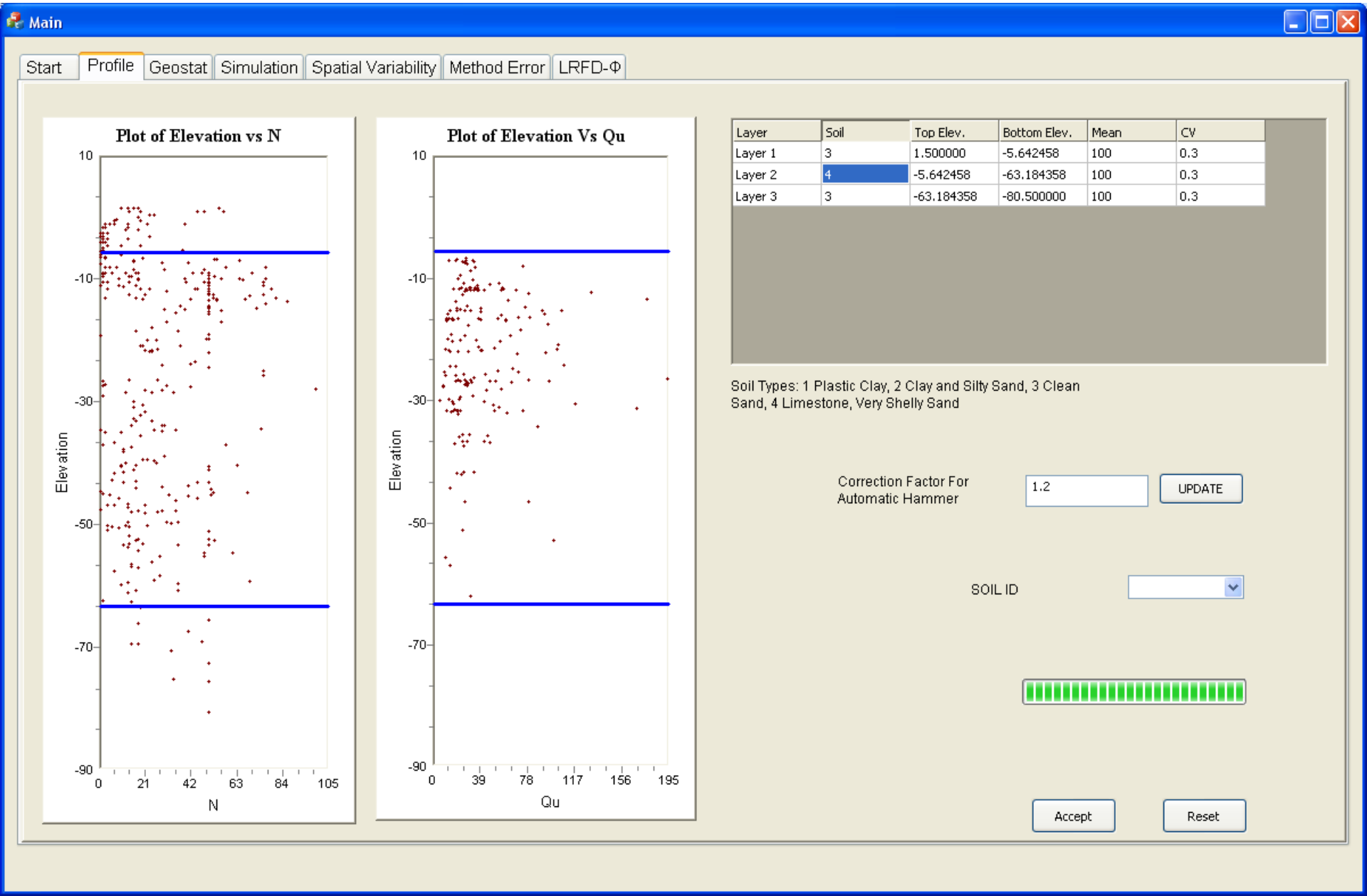
Graphical User Interface

- Allows engineer to incorporate all collected in the design process.
- Faster analysis of data.
- Tools Available
  - FDOT Database
  - Geostatistics
  - FB-DEEP

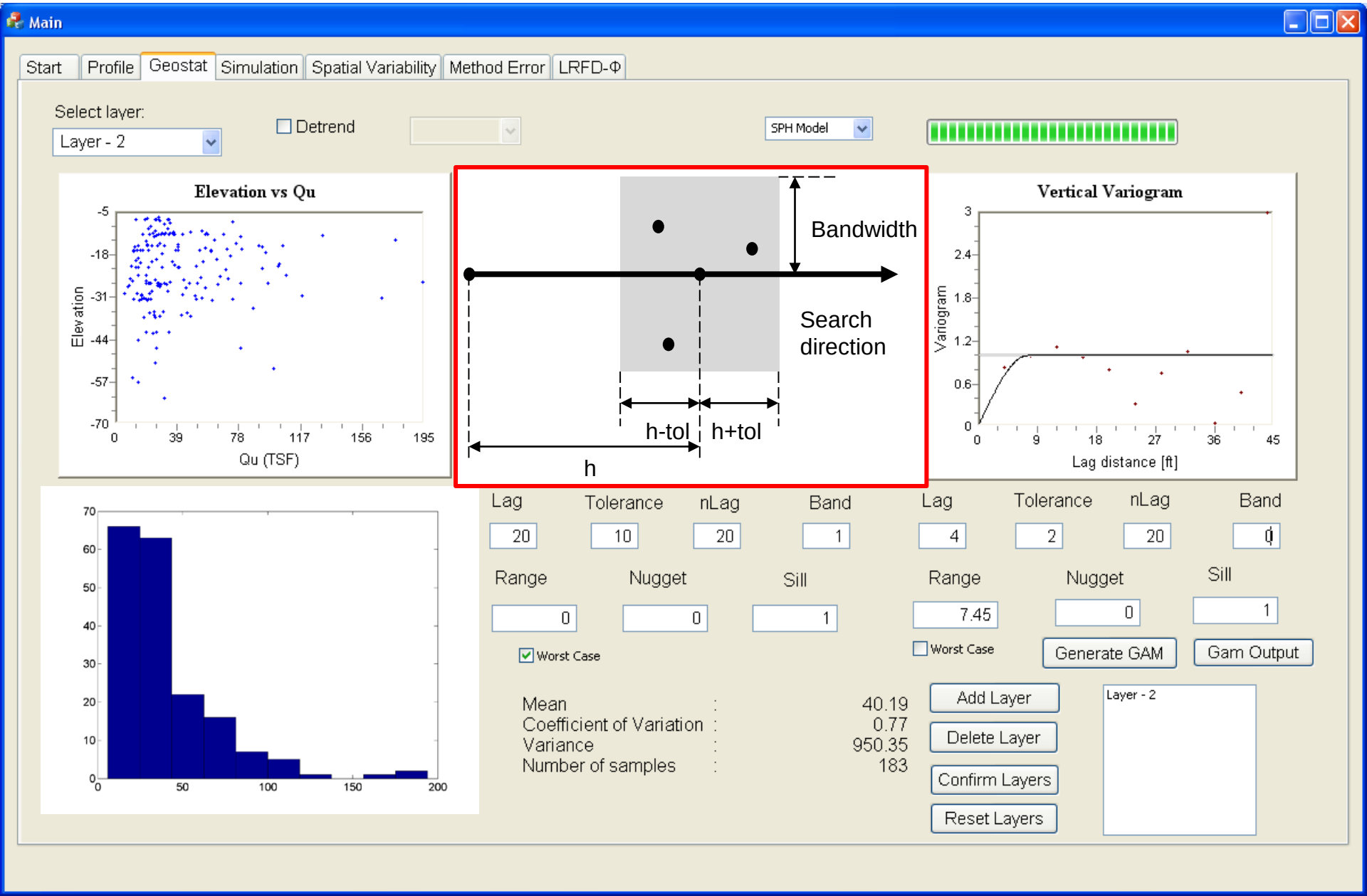
Drilled Shaft: Jewfish Creek



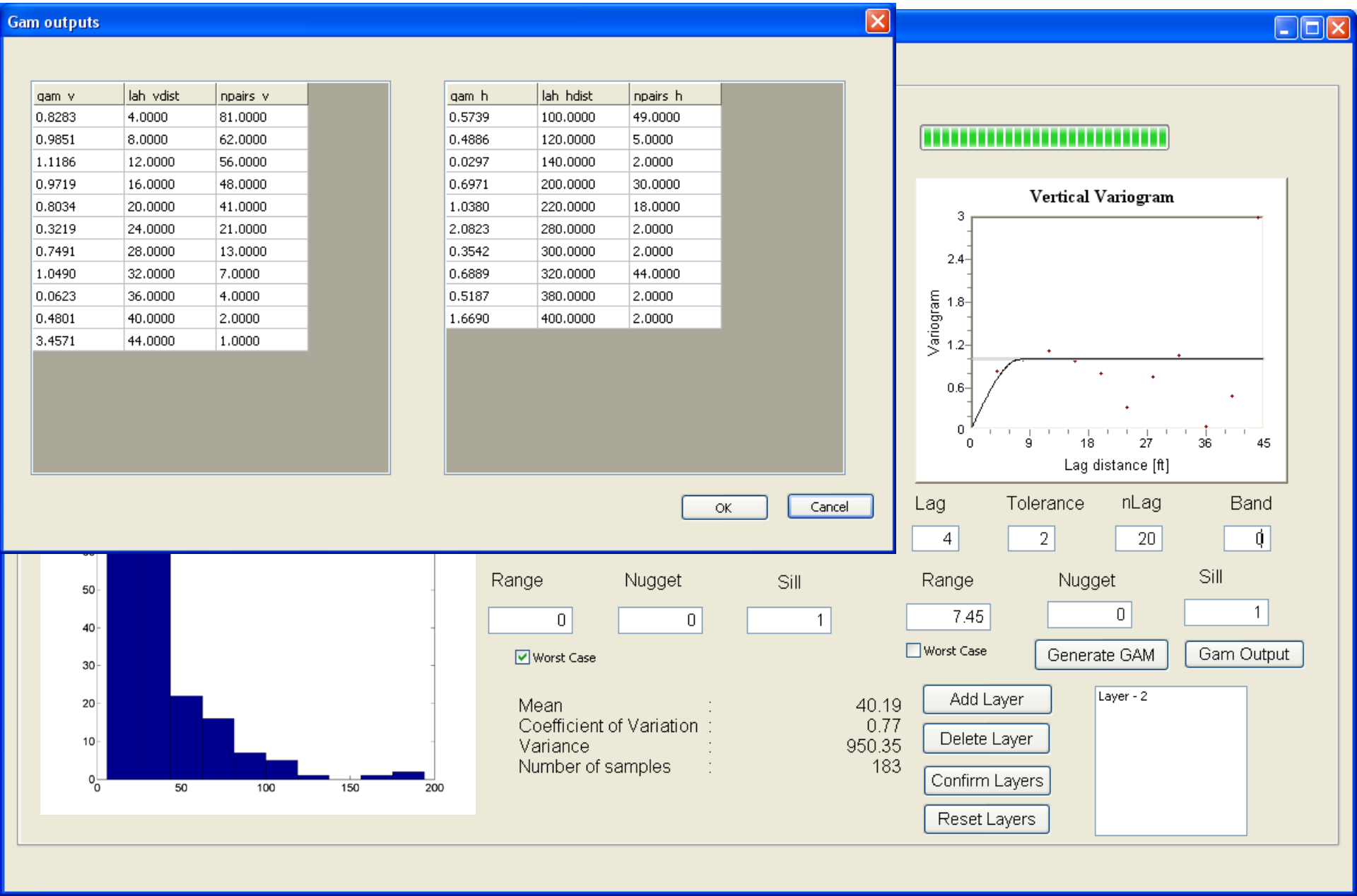
Profile of SPT-N and Rock Strength q_u



Performing Geostatistics



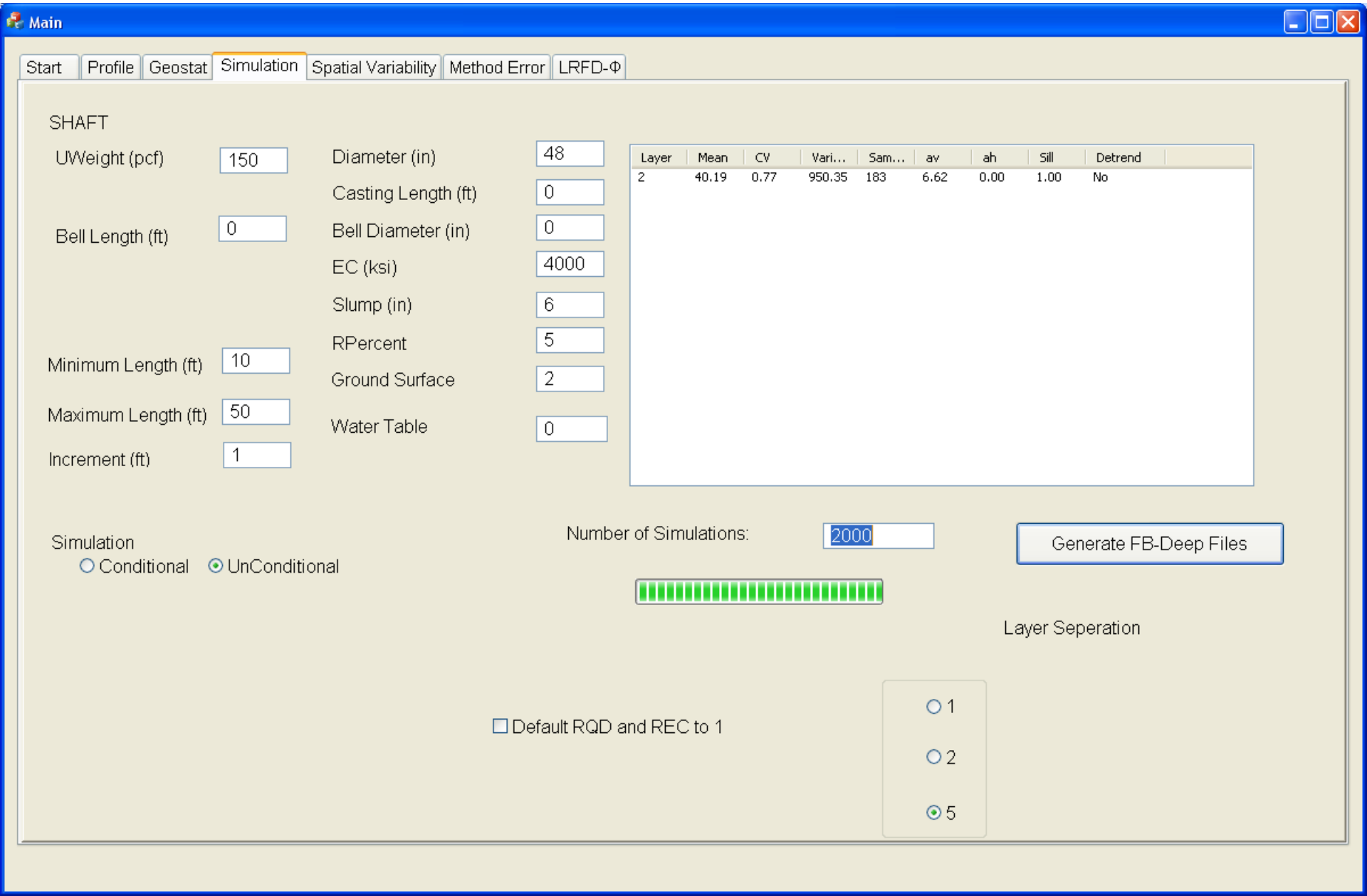
Performing Geostatistics



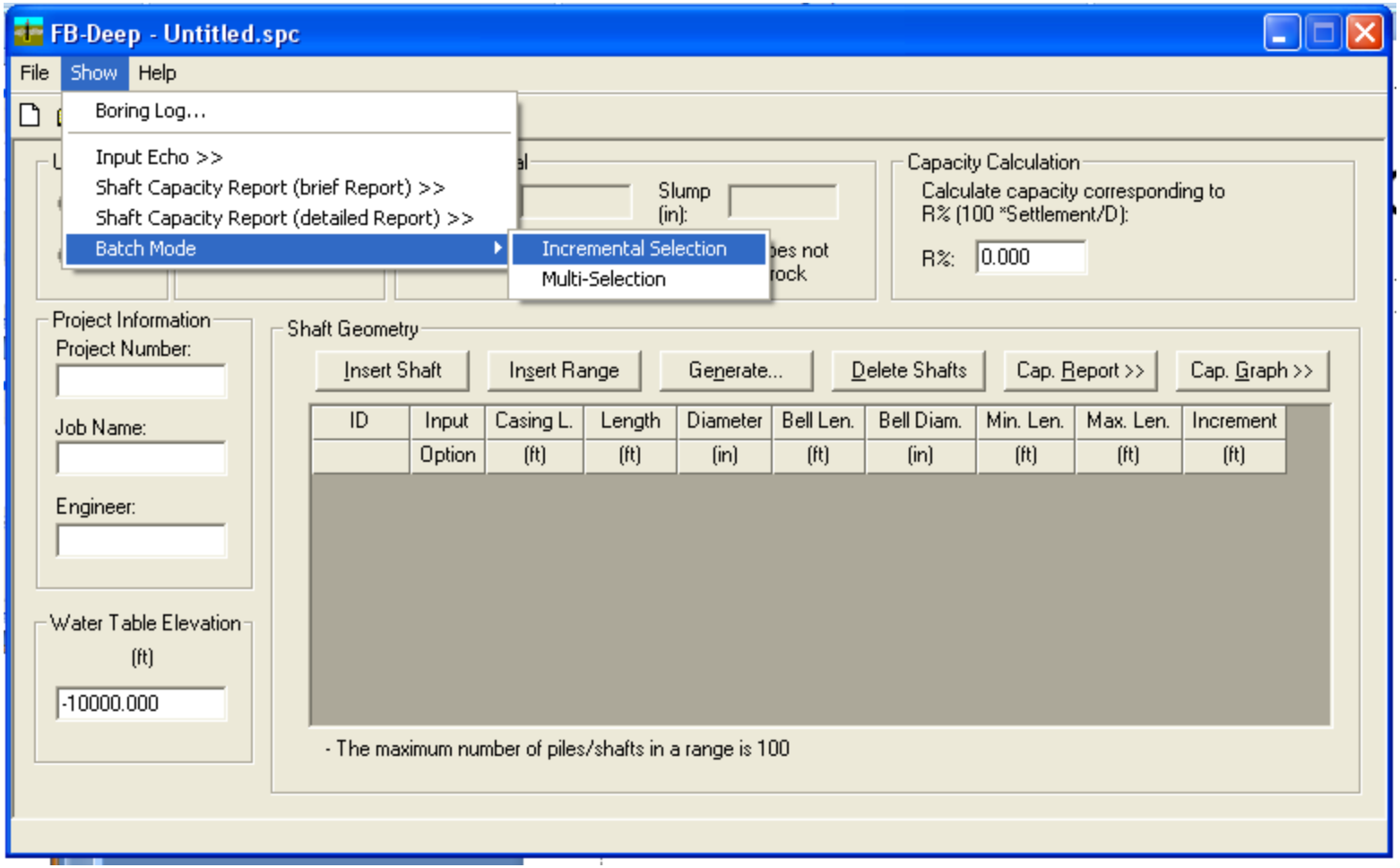
qam_v	lah_vdist	npairs_v
0.8283	4.0000	81.0000
0.9851	8.0000	62.0000
1.1186	12.0000	56.0000
0.9719	16.0000	48.0000
0.8034	20.0000	41.0000
0.3219	24.0000	21.0000
0.7491	28.0000	13.0000
1.0490	32.0000	7.0000
0.0623	36.0000	4.0000
0.4801	40.0000	2.0000
3.4571	44.0000	1.0000

qam_h	lah_hdist	npairs_h
0.5739	100.0000	49.0000
0.4886	120.0000	5.0000
0.0297	140.0000	2.0000
0.6971	200.0000	30.0000
1.0380	220.0000	18.0000
2.0823	280.0000	2.0000
0.3542	300.0000	2.0000
0.6889	320.0000	44.0000
0.5187	380.0000	2.0000
1.6690	400.0000	2.0000

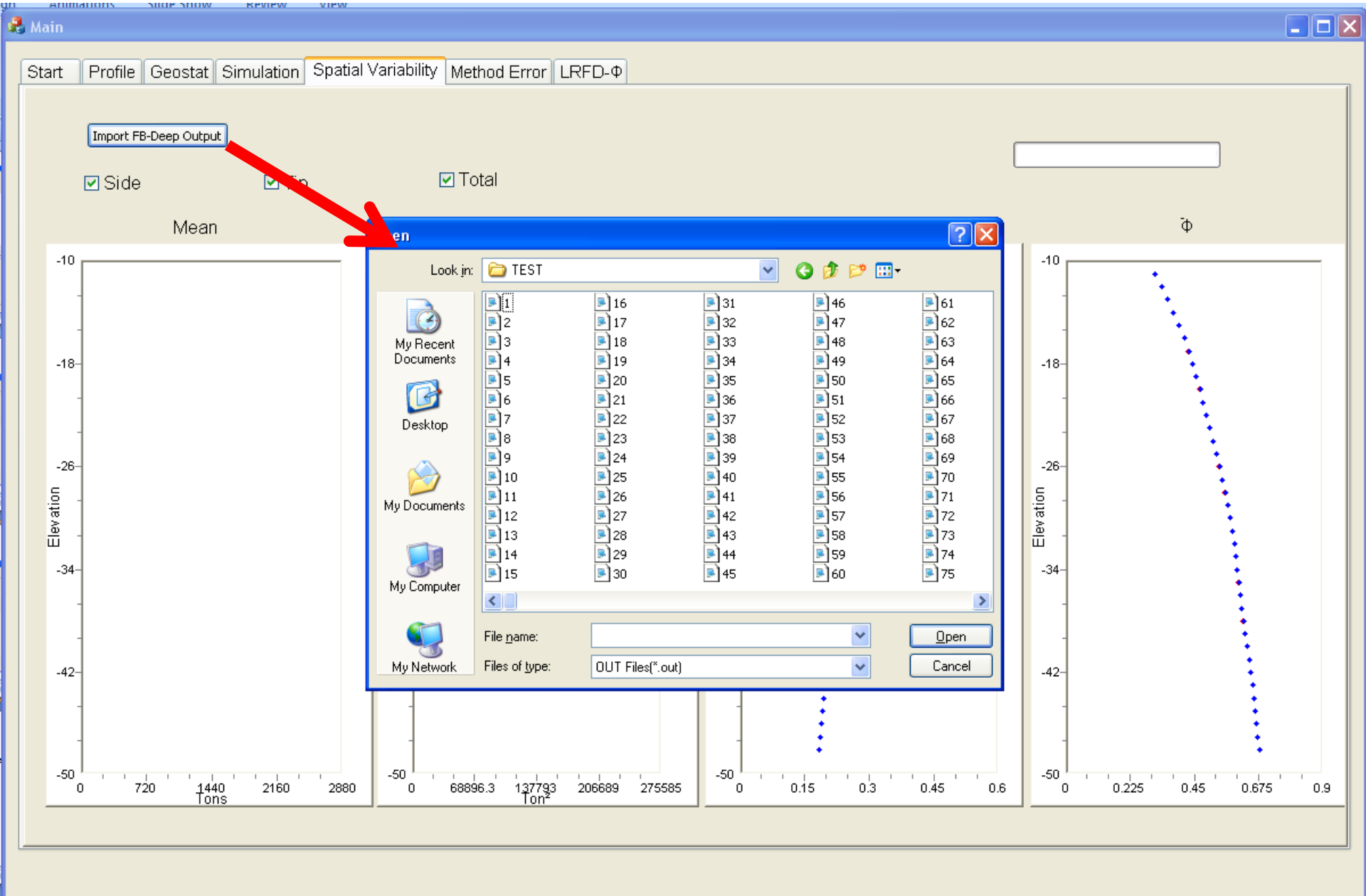
Drilled Shaft Parameters



FB-DEEP Batch Mode



Import of FB-DEEP Output

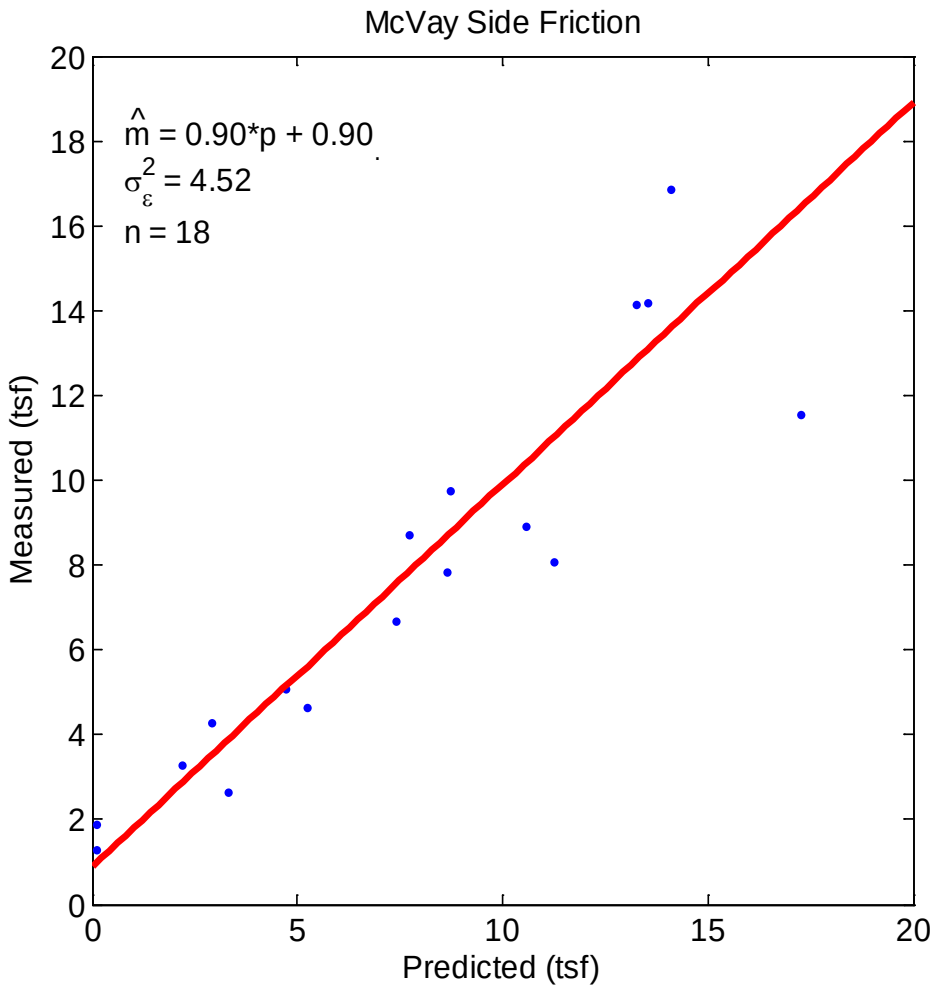


Method Error σ_ε^2

- Spatial variability, $\sigma^2_{spatial}$, has been quantified
- Need to quantify total uncertainty σ^2_R, of pile/shaft predictedresistance.
- σ_ε^2 determined from regression Analysis of Measured (Load Test) versus Prediction (FB-DEEP).

$$\sigma_R^2 = \sigma_{Spatial}^2 + \sigma_\varepsilon^2$$

FB-DEEP McVay Side Friction, Limestone



$$b = \rho \frac{\sigma_m}{\sigma_p}$$

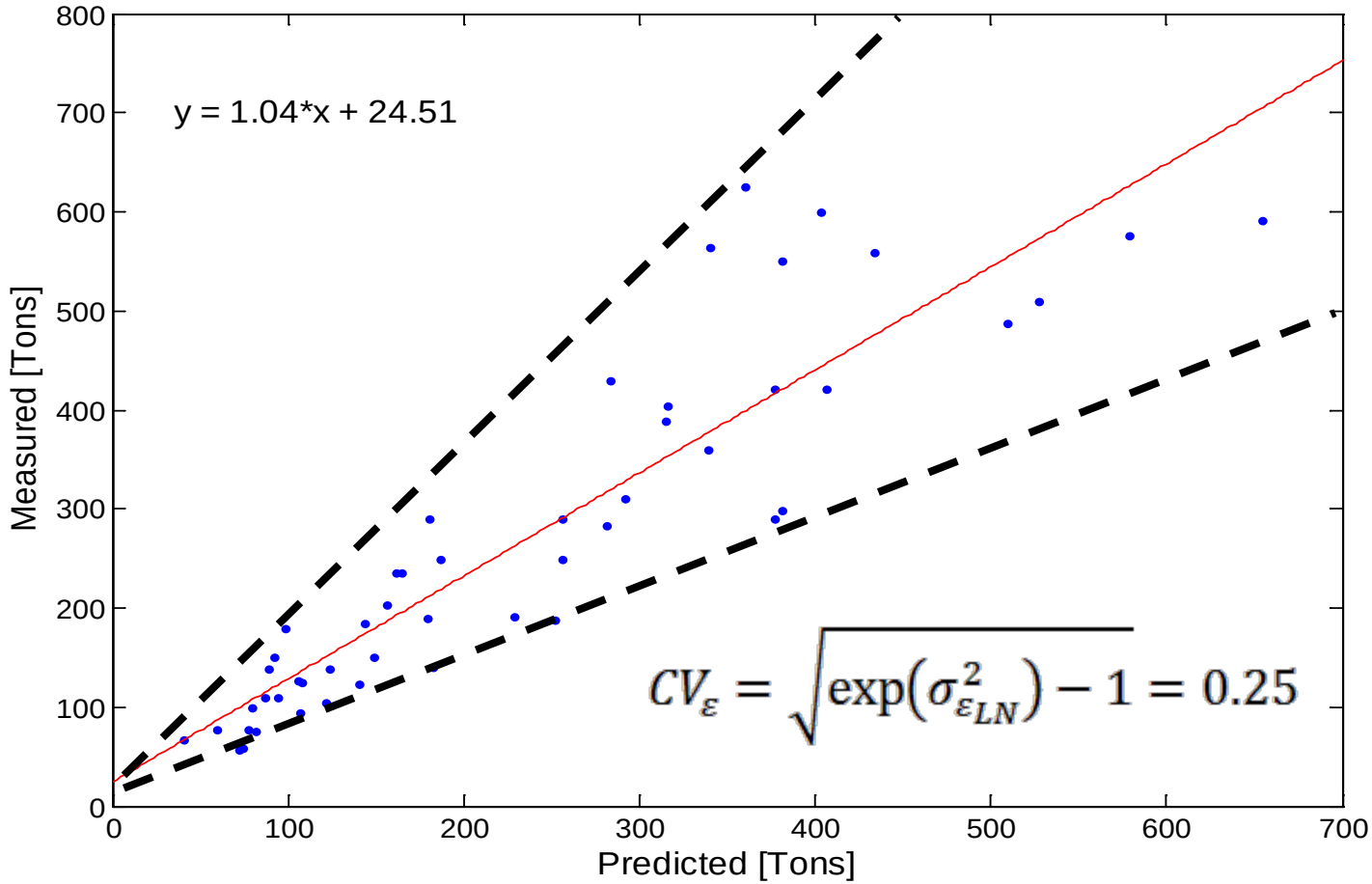
$$a = \bar{m} - b\bar{p}$$

$$\sigma_\varepsilon^2 = \sigma_m^2(1 - R^2)$$

σ_ε^2 is fixed.

FB-DEEP Concrete Driven Pile, FL Soils Total Uncertainty

$$CV_R = \frac{\sqrt{b^2\sigma_\rho^2 + (CV_\varepsilon p)^2}}{a + bp}$$



σ_ε^2 is proportional to mean prediction $\sigma_\varepsilon^2 = (CV_\varepsilon p)^2$

a- intercept
b-slope
σ_p- spatial variability

Inclusion of Method Error

Main

Start | Profile | Geostat | Simulation | Spatial Variability | Method Error | LRFD-Φ

Limestone [TSF]

	a	b	σ_ε^2
Mcvay	0.47	0.77	7.45
O'Neil			

Default

Load Test

For methods with constant error

Drilled Shaft Soil [TONS]

	a	b	CV_ε
Clay			
Sand			

Default

Load test

For methods with proportional error

Parameters from load testing can be determined using excel.

Default values determine load test data from previous FDOT reports.

Continue

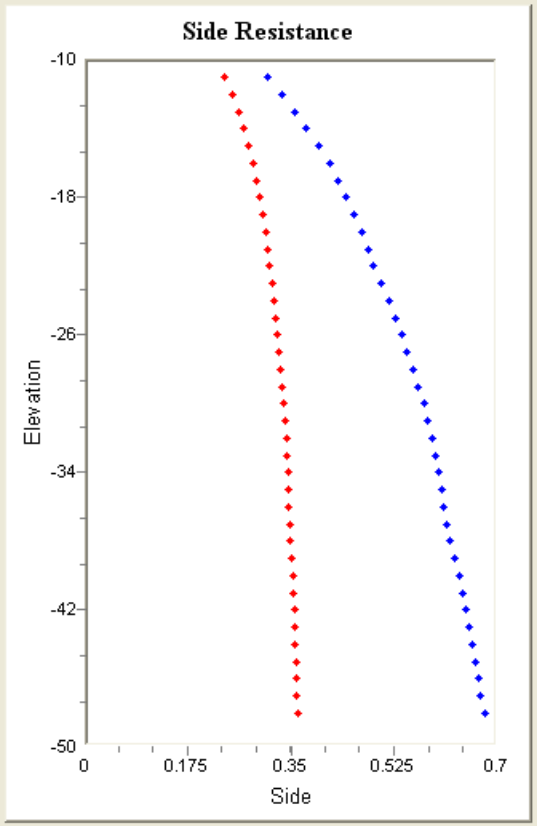
LRFD PHI assessment for drilled shaft

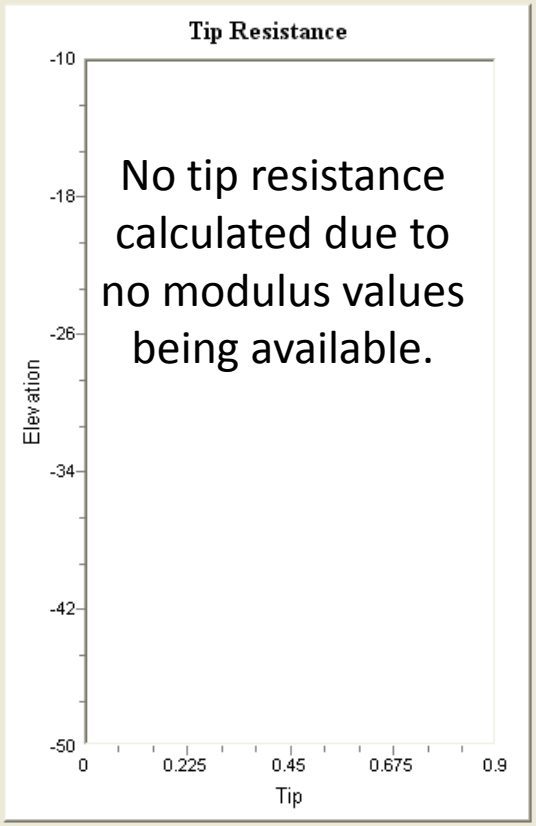
Main

Start | Profile | Geostat | Simulation | Spatial Variability | Method Error | LRFD-Φ

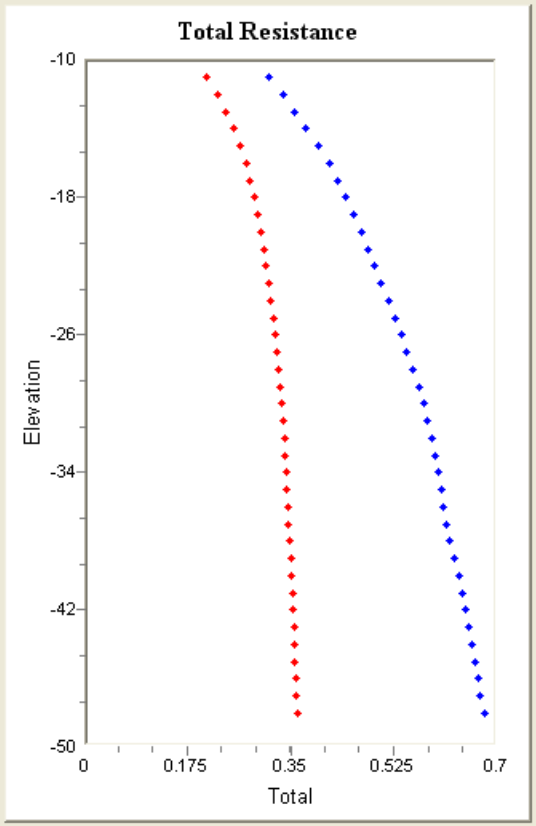
Fixed sigma epsilon for phi calc.

BLUE-Spatial Only
RED-Total Uncertainty

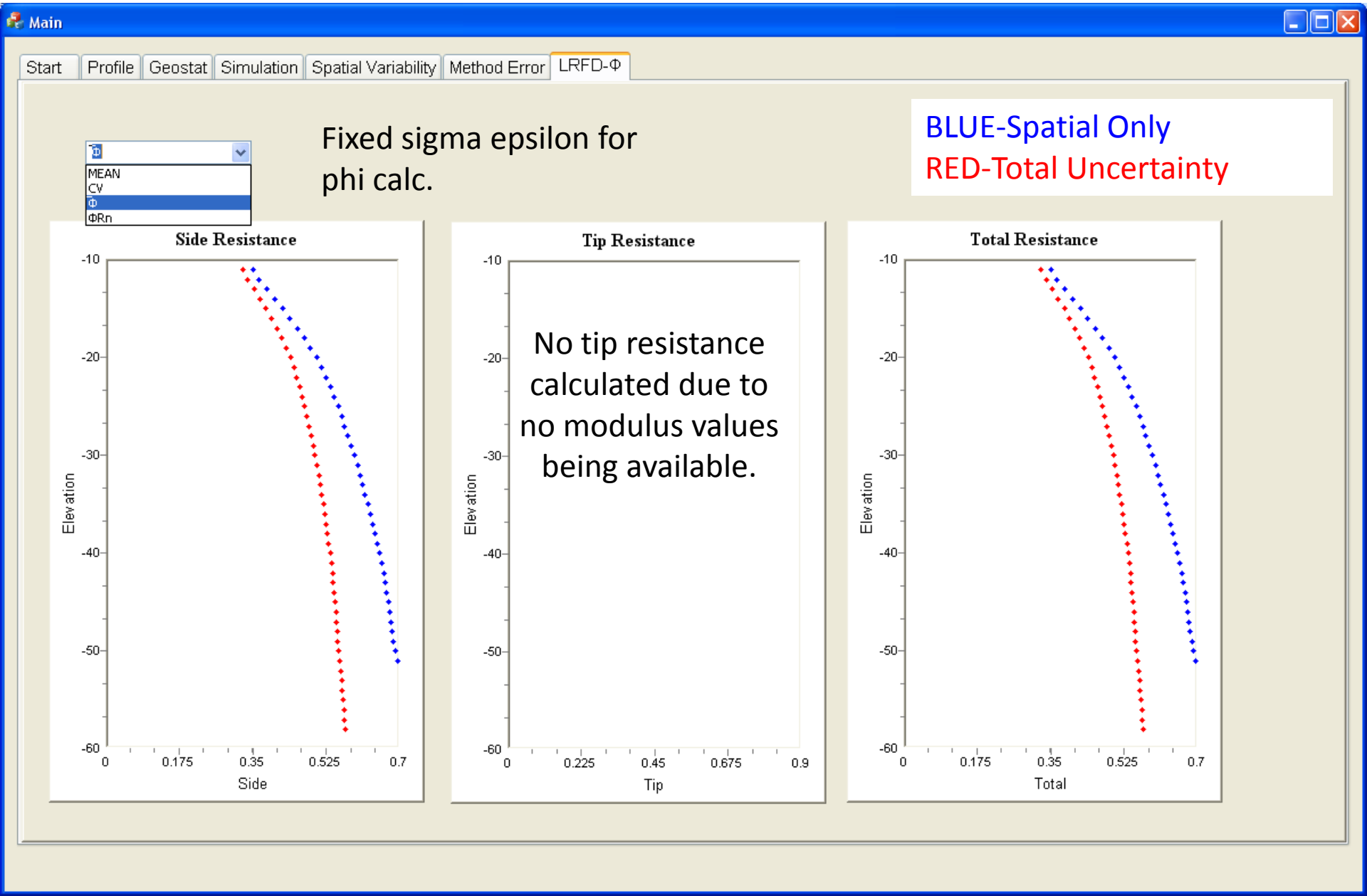




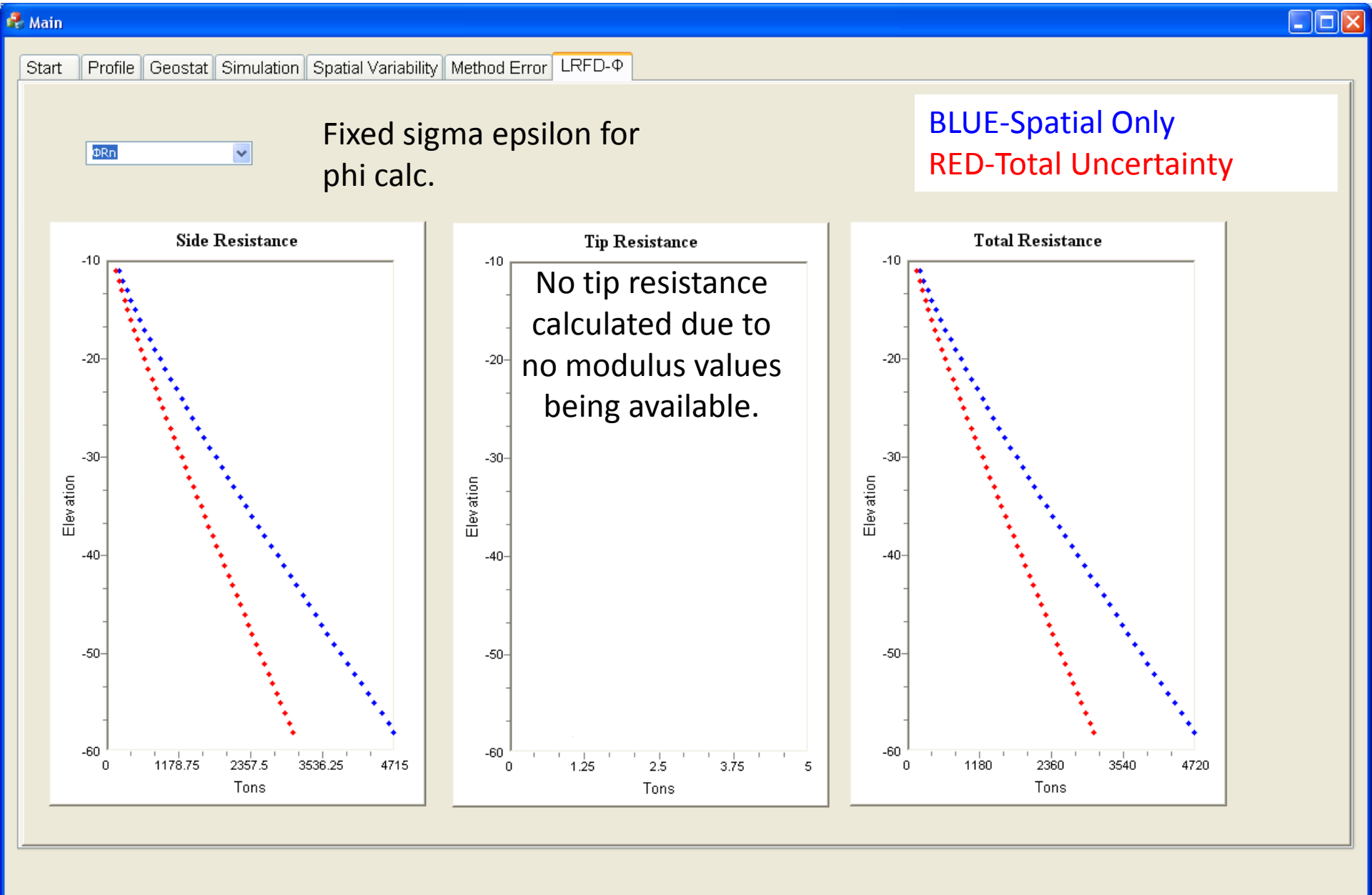
No tip resistance calculated due to no modulus values being available.

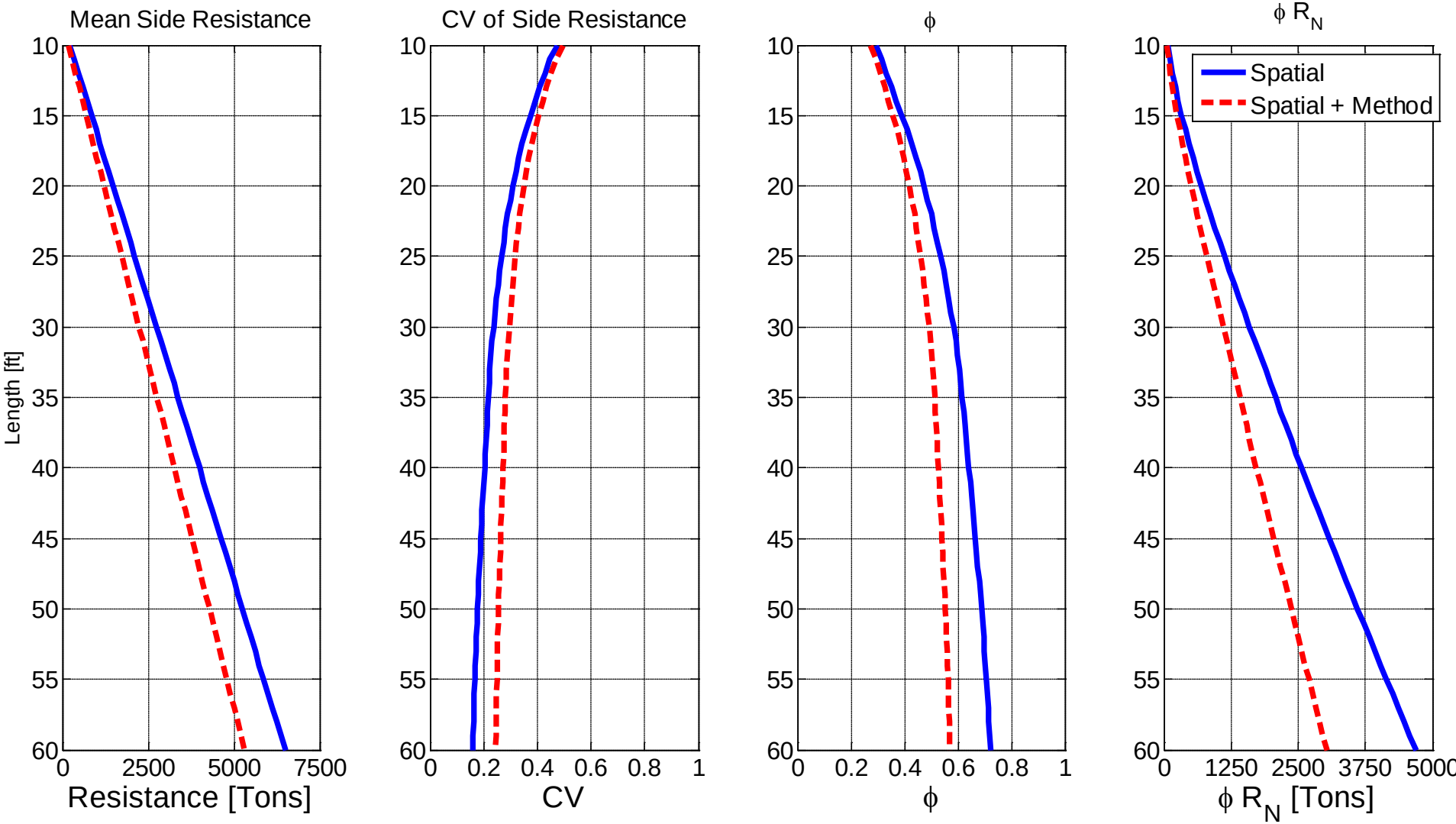


LRFD PHI assessment for drilled shaft



LRFD PHI assessment for drilled shaft




Mean Side Resistance
CV of Side Resistance
ϕ
ϕ R_N
Length [ft]
10
15
20
25
30
35
40
45
50
55
60
0
2500
5000
7500
Resistance [Tons]
0
0.2
0.4
0.6
0.8
1
CV
ϕ
1250
3750
ϕ R_N [Tons]
Spatial
Spatial + Method

Reported LRFD ϕ

Current FDOT ϕ

Design Method	Quality Control Method	ϕ		λ_R	ϕ/λ_R	
		Redundant	Non-redundant		Redundant	Non-redundant
For soil: FHWA alpha or beta method	Specs.	0.6	0.5	1.03	0.58	0.49
For rock socket: McVay's method, neglecting end bearing	Specs.	0.6	0.5	1.06	0.57	0.47
For rock socket: McVay's method, including 1/3 end bearing	Specs.	0.55	0.45	NA	NA	NA
For rock socket: McVay's method	Statnamic	0.7	0.6	1.06	0.66	0.57
For rock socket: McVay's method	Static	0.75	0.65	1.06	0.71	0.61

ϕ from previous FDOT research

Design Method	CV_R	λ_R	ϕ for listed β			ϕ/λ_R for listed β			Report
			2.0	2.5	3.0	2.0	2.5	3.0	
Rock: Side friction	0.280	1.060	0.81	0.69	0.59	0.76	0.65	0.56	BC354-08, Table 8.5
Rock: O'Neill's end bearing (nearest boring approach)	0.290	1.400	0.86	0.71	0.60	0.61	0.51	0.43	BC354-08, Table 11.21
Rock: O'Neill's end bearing (random selection - Monte Carlo)	0.460	1.210	0.56	0.43	0.33	0.46	0.36	0.27	BC354-08, Table 11.22
Driven piles: SPT 94	0.246	1.172	0.81	0.69	0.59	0.69	0.59	0.50	510772, Tables 3.2 and 3.3

GUI's LRFD $\bar{\phi}$

Site	Method	Sim Type	Case	Length [ft]	$\bar{\phi}$
17th Street Bridge	McVay	UC	a_v & a_h known	(8– 28)	0.51 – 0.64
		CON(B4)			0.56 – 0.62
		CON(B6)			0.54 – 0.68
Dixie Highway	FB-DEEP Driven Pile	UC	a_h unknown	20 – 75	0.36 – 0.58
		CON(EB1)			0.44 – 0.61
Jewfish Creek	McVay	UC	a_h unknown historical data	(12 – 52)	0.41– 0.55
		CON(P10-S2)			0.43 – 0.52
		CON(P56-S3)			0.46 – 0.58
		UC	a_h unknown load test data		0.42– 0.57
		CON(P10-S2)			0.45 – 0.55
		CON(P56-S3)			0.47 – 0.61
MIC/MIA	McVay	UC	a_h unknown	(5 – 14.5)	0.43 – 0.54
		CON(WB9)	a_h unknown		0.44 – 0.56
		UC	a_v & a_h unknown		0.38 – 0.39
MIC Station	McVay	UC	a_v & a_h unknown	(10 – 29)	0.45 – 0.46
			a_v & a_h unknown & uncertainty in mean		0.37 – 0.38
CR12A	FB-DEEP Driven Pile	UC	a_h unknown	35– 70	0.36 – 0.58

UC – Unconditional simulation.
CON(Boring#) – Conditional simulation
(## – ##) – Embedment length in limestone layer.

Design Process

- Use of all borings in the design.
  - FDOT Geotech Database
    - Excel sheets to format insitu and lab data.
  - Identify Layering and zones
  - Geostatistical Analysis
- Predicting Boring Variability at Foundation
  - Predicting Resistance from Nearby Boring
  - Mean Site Parameters-Foundation Location Unknown
- For LRFD ϕ need to assess total uncertainty
  - Site Variability-FB-DEEP batch mode
  - Method Error with Bias Correction
- For given design load the nominal resistance ϕR_n is a function of depth and length.

Recommendations

- Obtain adequate number of samples to accurately quantify statistical parameters (mean and CV) for the layers significantly contributing to foundation capacity.
- Collect enough samples at intervals of 2 to 5 ft to provide enough data pairs to accurately infer the experimental vertical variogram.
- If spatial uncertainty still results in low , make improvements by either splitting the site into zones (presence of high CVs and zonal anisotropy in variograms) or using more layers for separate geospatial analysis.

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Recommendations

- In the case of sites with non-redundant foundations, soil/rock with high-point variability, large vertical correlation structure, and no planned load testing, use more borings spaced closer to identify horizontal correlation (e.g., identification of mean at pier, etc.)
- With spatial uncertainty minimized, make improvements to the method error through load testing at the site of interest; however, enough measured versus predicted data points must be collected for regression analysis.
- Consider load tests on sites where low rock strengths are recorded, since the developed method error was for the case of high- and low-strength rock.

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QUESTIONS?

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