Pile/Shaft Design Using Artificial Neural Networks (i.e. Genetic Programming) with Spatial Variability Considerations

FDOT Contract No.:	BDK-75-977-68
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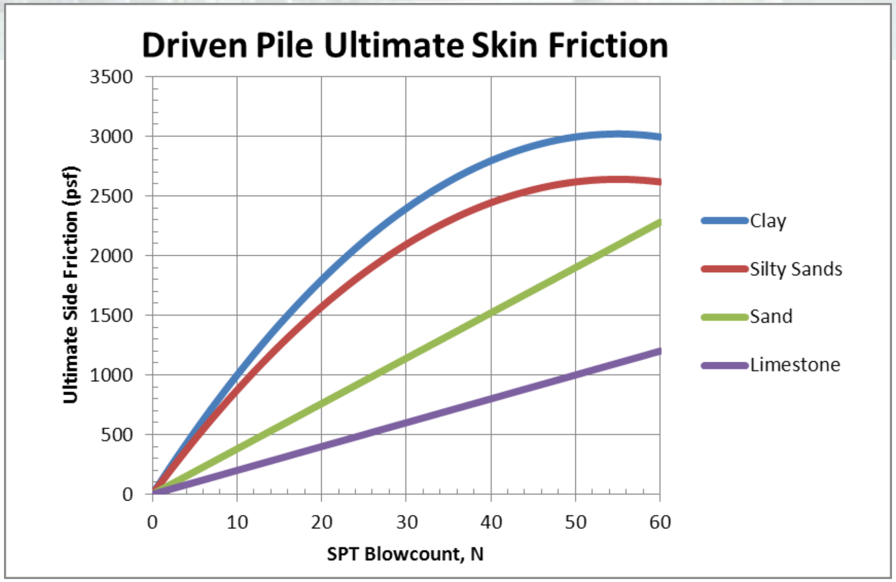
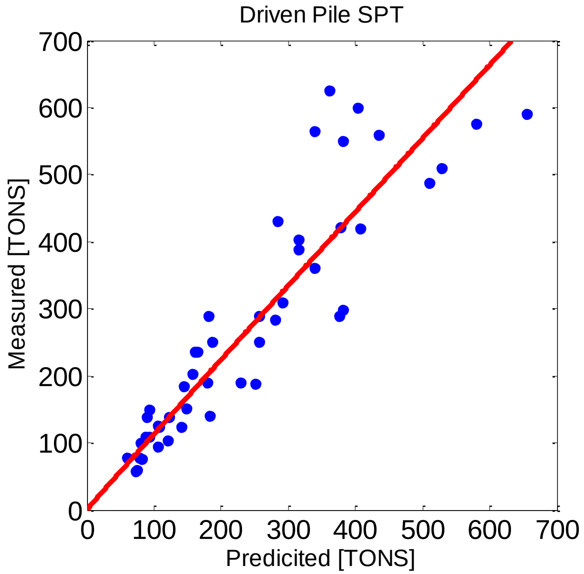
Scope

- Improvement of prediction equations (side and tip resistance) used by FB-DEEP for both prestressed concrete piles and drilled shafts.
- Optimizing prediction equations by use of a Genetic Program (GP) from site insitu and load test data.
- Reduce both the bias and error.





Research Tasks

1. Data Collection
2. Development of Genetic Code to improve Pile/Shaft predictions
3. Inclusion of Spatial Variability in assessment of Pile/Shaft Capacity Equations
4. Development and Evaluation of Pile Capacity Equations from Insitu Data
5. Final Report and Database Upload

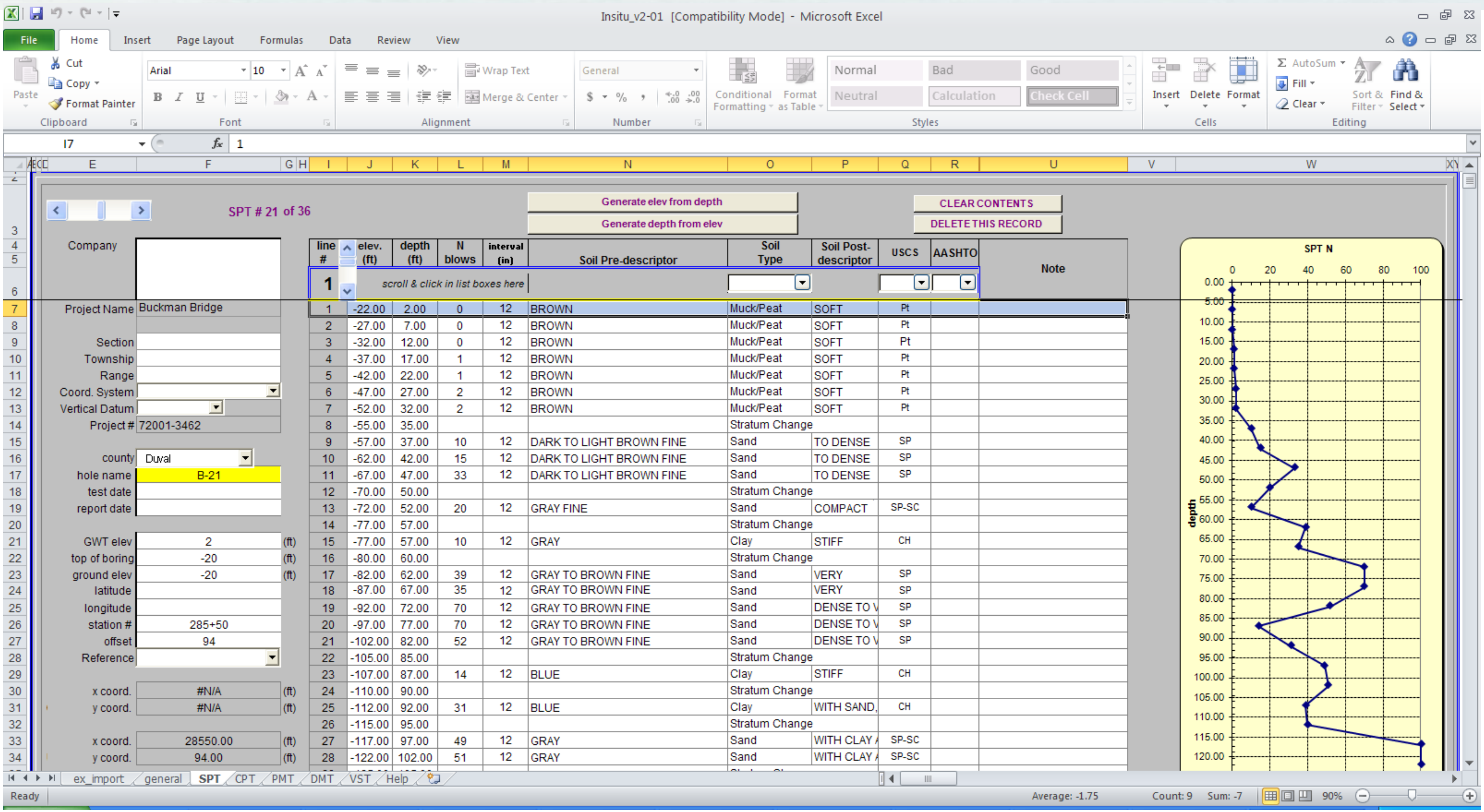
Data Collection

- Geotechnical Reports
  - SPT Boring Logs
  - Lab Test for Rock
    - q_u - unconfined compressive strength
    - qt - split tensile
    - E - Modulus
    - REC/RQD – Recovery
- Load Test Reports
  - Drilled Shafts and Driven Piles
  - Static
  - Osterberg
  - Statnamic

FDOT Database

- Uploading to online database
- Standardize format
- Organize site data based on hierarchy structure
  - Project
    - Bridge
      - Pier
        - Pile/Shaft
          - Load Test
    - Subsurface
      - Borings
      - Lab Data
- fdot.ce.ufl.edu

Formatting Insitu Data



Insitu_v2-01 [Compatibility Mode] - Microsoft Excel

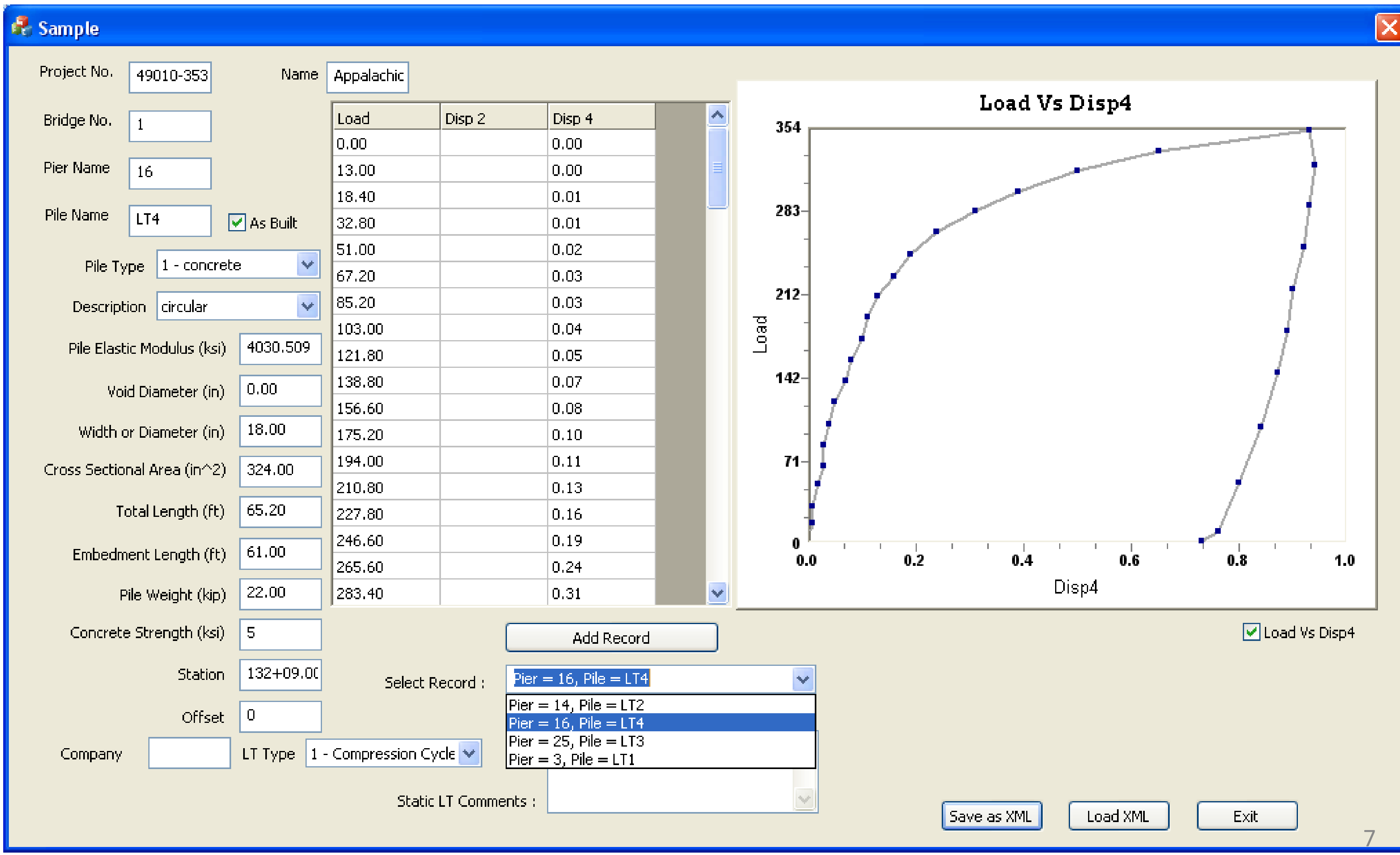
SPT # 21 of 36

Generate elev from depth | Generate depth from elev | CLEAR CONTENTS | DELETE THIS RECORD

Company		
Project Name	Buckman Bridge	
Section		
Township		
Range		
Coord. System		
Vertical Datum		
Project #	72001-3462	
county	Duval	
hole name	B-21	
test date		
report date		
GWT elev	2	(ft)
top of boring	-20	(ft)
ground elev	-20	(ft)
latitude		
longitude		
station #	285+50	
offset	94	
Reference		
x coord.	#N/A	(ft)
y coord.	#N/A	(ft)
x coord.	28550.00	(ft)
y coord.	94.00	(ft)

line #	elev. (ft)	depth (ft)	N blows	interval (in)	Soil Pre-descriptor	Soil Type	Soil Post-descriptor	USCS	AASHTO	Note
1	-22.00	2.00	0	12	BROWN	Muck/Peat	SOFT	Pt		
2	-27.00	7.00	0	12	BROWN	Muck/Peat	SOFT	Pt		
3	-32.00	12.00	0	12	BROWN	Muck/Peat	SOFT	Pt		
4	-37.00	17.00	1	12	BROWN	Muck/Peat	SOFT	Pt		
5	-42.00	22.00	1	12	BROWN	Muck/Peat	SOFT	Pt		
6	-47.00	27.00	2	12	BROWN	Muck/Peat	SOFT	Pt		
7	-52.00	32.00	2	12	BROWN	Muck/Peat	SOFT	Pt		
8	-55.00	35.00				Stratum Change				
9	-57.00	37.00	10	12	DARK TO LIGHT BROWN FINE	Sand	TO DENSE	SP		
10	-62.00	42.00	15	12	DARK TO LIGHT BROWN FINE	Sand	TO DENSE	SP		
11	-67.00	47.00	33	12	DARK TO LIGHT BROWN FINE	Sand	TO DENSE	SP		
12	-70.00	50.00				Stratum Change				
13	-72.00	52.00	20	12	GRAY FINE	Sand	COMPACT	SP-SC		
14	-77.00	57.00				Stratum Change				
15	-77.00	57.00	10	12	GRAY	Clay	STIFF	CH		
16	-80.00	60.00				Stratum Change				
17	-82.00	62.00	39	12	GRAY TO BROWN FINE	Sand	VERY	SP		
18	-87.00	67.00	35	12	GRAY TO BROWN FINE	Sand	VERY	SP		
19	-92.00	72.00	70	12	GRAY TO BROWN FINE	Sand	DENSE TO V	SP		
20	-97.00	77.00	70	12	GRAY TO BROWN FINE	Sand	DENSE TO V	SP		
21	-102.00	82.00	52	12	GRAY TO BROWN FINE	Sand	DENSE TO V	SP		
22	-105.00	85.00				Stratum Change				
23	-107.00	87.00	14	12	BLUE	Clay	STIFF	CH		
24	-110.00	90.00				Stratum Change				
25	-112.00	92.00	31	12	BLUE	Clay	WITH SAND,	CH		
26	-115.00	95.00				Stratum Change				
27	-117.00	97.00	49	12	GRAY	Sand	WITH CLAY /	SP-SC		
28	-122.00	102.00	51	12	GRAY	Sand	WITH CLAY /	SP-SC		

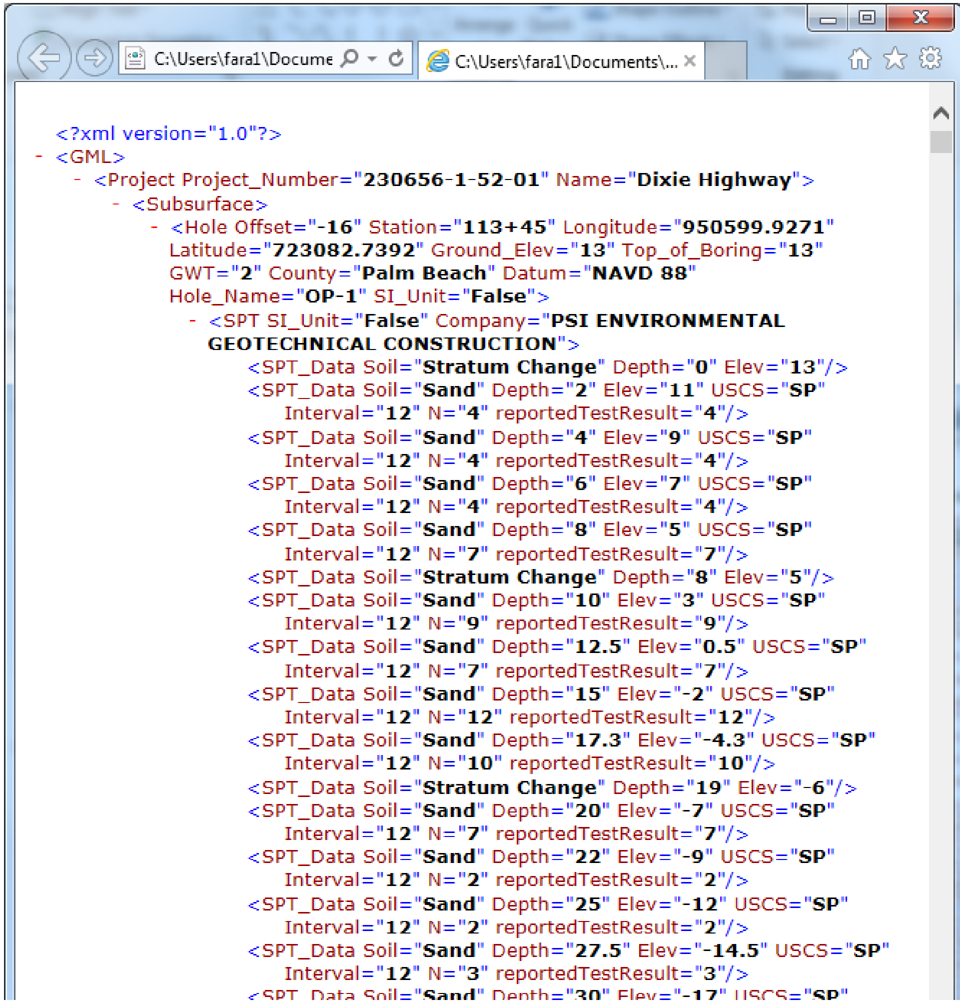
Formatting Load Test Data



Load	Disp 2	Disp 4
0.00		0.00
13.00		0.00
18.40		0.01
32.80		0.01
51.00		0.02
67.20		0.03
85.20		0.03
103.00		0.04
121.80		0.05
138.80		0.07
156.60		0.08
175.20		0.10
194.00		0.11
210.80		0.13
227.80		0.16
246.60		0.19
265.60		0.24
283.40		0.31

Database Format

- XML file
  - Hierarchical Structure
  - Format to upload or download from database
  - Viewable in internet browser

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        GWT="2" County="Palm Beach" Datum="NAVD 88"
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Driven Pile Projects

Project Site	Project Number	Borings (Firm)	Load Test (Firm)	No. Borings	No. Load Tests
Acosta Bridge	72160-3506	Law Engineers	Schmertmann & Crapps	53	3
Apalachicola Bay	49010-3536	FDOT	Schmertmann & Crapps	28	5
Apalachicola River	49010-3533	FDOT	Schmertmann & Crapps	33	4
Blackwater Bridge (I-10)	58002-3449	Williams Earth Sciences	William Earth Sciences	4	2
Buckman Bridge	72001-3462	Ardaman & Associates	Schmertmann & Crapps	40	4
Caminida Bay	061-01-0040	Applied Foundations	LADOT	4	2
Choctawhatchee	60040-3527	FDOT	Schmertmann & Crapps	35	9

Driven Pile Projects Cont.

Project Site	Project Number	Borings (Firm)	Load Test (Firm)	No. Borings	No. Load Tests
Dixie Highway	230656-1-52-01	PSI	Applied Foundations	22	3
Dodge Island	87000-3675	Law Engineers	Law Engineers	6	1
Escambia River	48140-3509/58080-3516	FDOT	Schmertmann & Crapps	53	2
Howard Frankland	15190-3479	Williams and Associates	HDR	49	4
Port Orange	79180-3514	Franco/Williams & Dawson	Schmertmann & Crapps	11	2
Roosevelt Bridge	89010-3541	Law Engineers	Law Engineers	41	2
Sunshine Skyway	15170-3421	Williams and Associates	Schmertmann & Crapps	22	7

Driven Pile Projects Cont.

Project Site	Project Number	Borings (Firm)	Load Test (Firm)	No. Borings	No. Load Tests
West Bay Bridge	217911-5-52-01	FDOT	Dames & Moore	19	3
White City Bridge	51020-3514	FDOT	Applied Foundations	16	2
5th St. Bascule Bridge	412808-1-52-01	Mactec	Applied Foundations	7	4
Bayou Chico	48050-3536	FDOT	Williams Earth Sciences	7	3
Matanzas River (SR 312)	78002-3509	FDOT	Williams Earth Sciences	8	2
			Totals:	**458**	**64**

Drilled Shaft Projects

Project Site	Project Number	Borings (Firm)	Load Tests (Firm)	No. Borings	Osterberg Tests	Statnamic	Static
17th St. Causeway	86180-1522	Williams and Associates	LOADTEST / Applied Foundation	165	4	6	0
Acosta Bridge	72160-3528	Law Engineers	Schmertmann & Crapps	53	4	0	2
Appalachicola River (S.R.20)	47010-3519/ 56010-3520	Ardaman and Associates	Schmertmann & Crapps	64	6	0	0
Fuller Warren	72020-1485	Law Engineering	Williams and Associates	26	4	0	0
Gandy Bridge	10130-1544	Beiswenger, Hoch & Assoc.	Williams and Associates	98	3	3	0
Hillsborough Ave.	10150-3543/ 10150-3546	Williams and Associates	Williams and Associates	34	1	2	0

Drilled Shaft Projects Cont.

Project Site	Project Number	Borings (Firm)	Load Tests (Firm)	No. Borings	Osterberg Tests	Statnamic	Static
Howard Frankland	15190-3479	HDR	Williams and Associates	49	0	0	5
I-4 Widening	418760-2-52-01	Ardaman and Associates	LOADTEST	14	1	0	0
I-595 Fort Lauderdale	86095-3406	Schmertmann & Crapps	Schmertmann & Crapps	2	0	0	2
Jewfish_Creek	250445-1-52-01	MACTEC	MACTEC	98	0	2	0
Macarthur Causeway	87060-1549	Law Engineering	Law Engineering	44	0	0	1
Miami Intermodal Center	406800-2-32-01	MACTEC	MACTEC	17	0	1	0
MIC/MIA Elevated People Mover	408320-1-52-01	PSI	LOADTEST	24	1	0	0
Port Orange Bridge	79180-3502	Schmertmann & Crapps	Schmertmann & Crapps	2	2	0	1

Drilled Shaft Projects Cont.

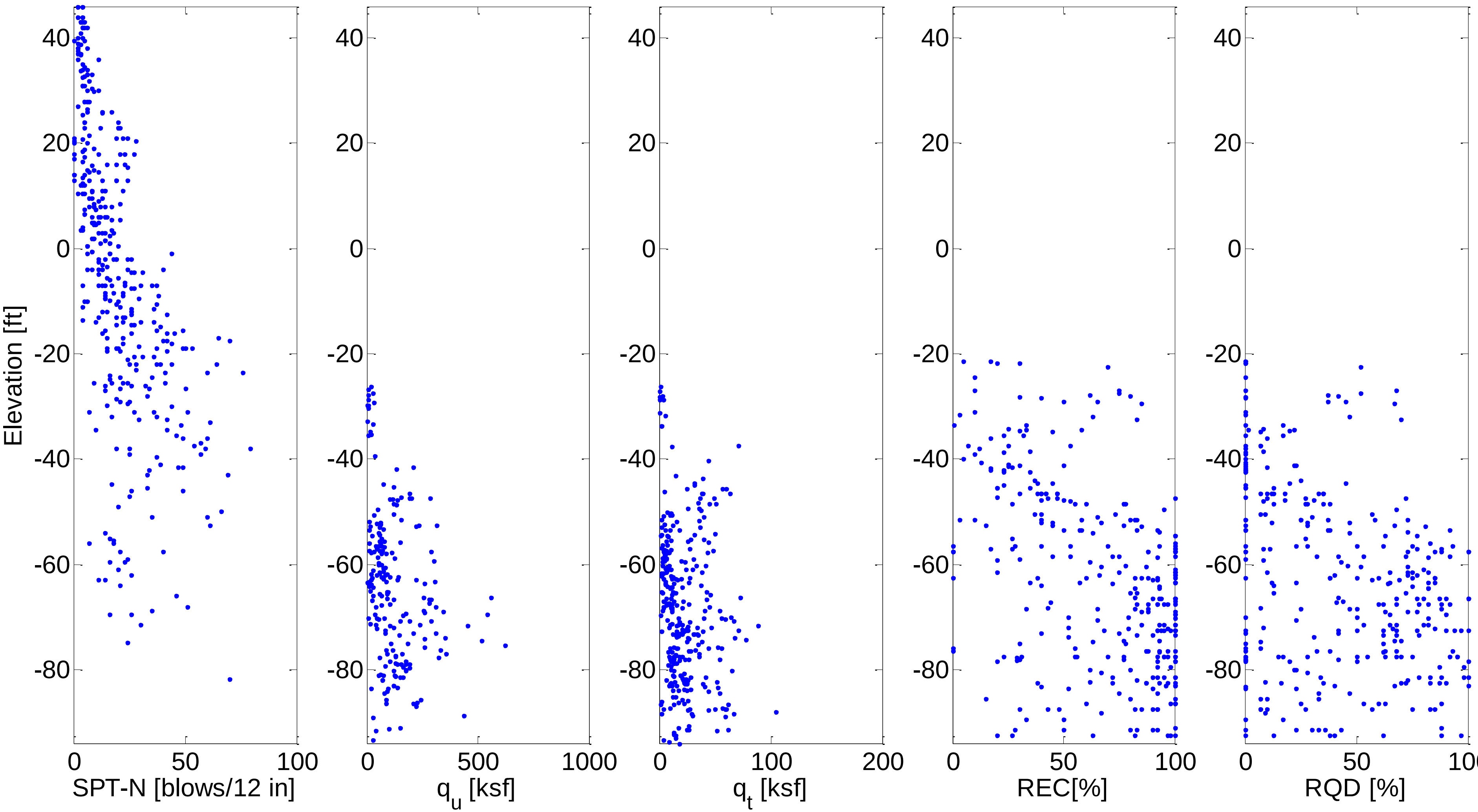
Project Site	Project Number	Borings (Firm)	Load Tests (Firm)	No. Borings	Osterberg Tests	Statnamic	Static
SR 686	256994-1-52-01	Ardaman and Associates	Ardaman and Associates	58	2	0	0
Sunshine Skyway	15170-3421	Williams and Associates	Schmertmann & Crapps	22	0	0	4
Venetian Causeway	87000-1601	Dames & Moore	Florida Testing & Engineering, Inc	17	0	0	0
Victory Bridge	53020-3540	Schmertmann & Crapps	Schmertmann & Crapps	28	5	1	0

Totals	815	33	15	15

FDOT Database Summary

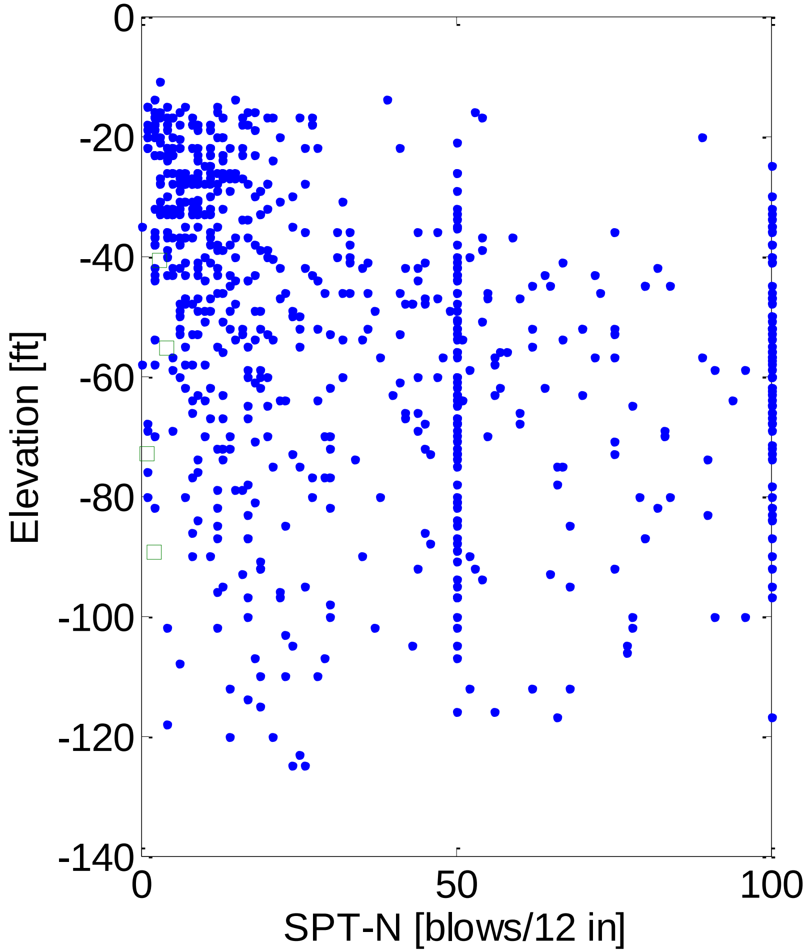
- 19 Driven Pile Projects
  - 64 Static Load Test – Concrete Piles
    - 48 Reached Davisson Capacity
    - 28 reported separation of skin and tip resistance
  - 458 SPT borings
  - Use GP to develop better models for prediction of Davisson Capacity
- 18 Drilled Shaft Projects
  - 33 Osterberg
  - 15 Static
  - 15 Statnamic
  - 815 SPT Borings and available lab test.

SR 20 Channel Data

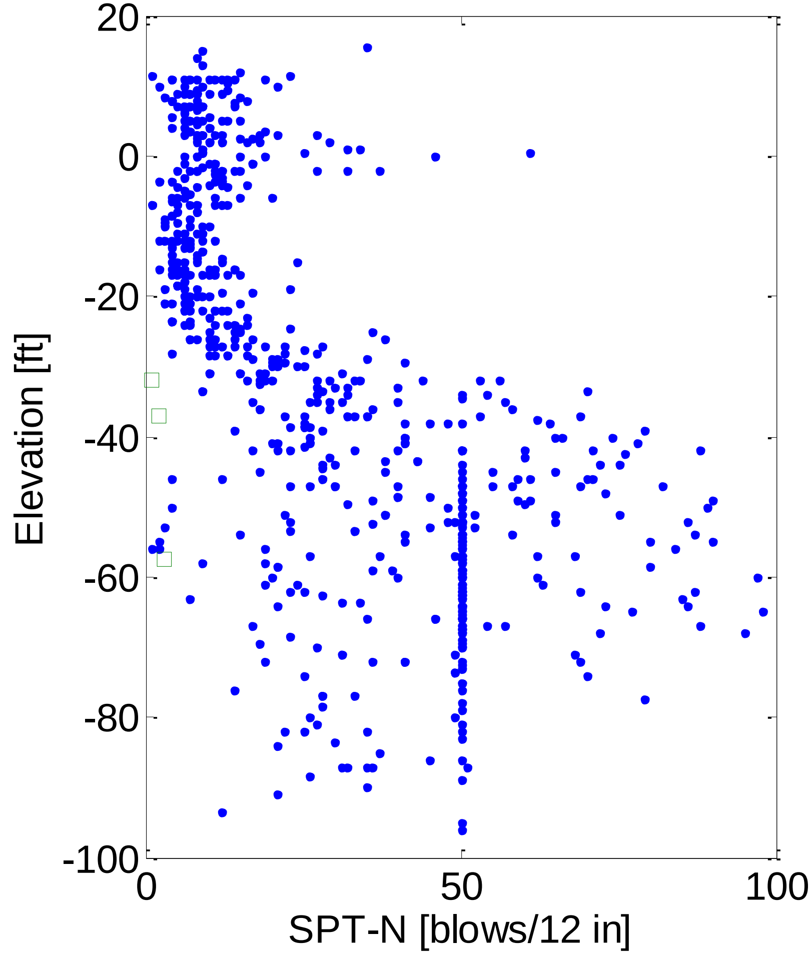


Driven Pile Projects

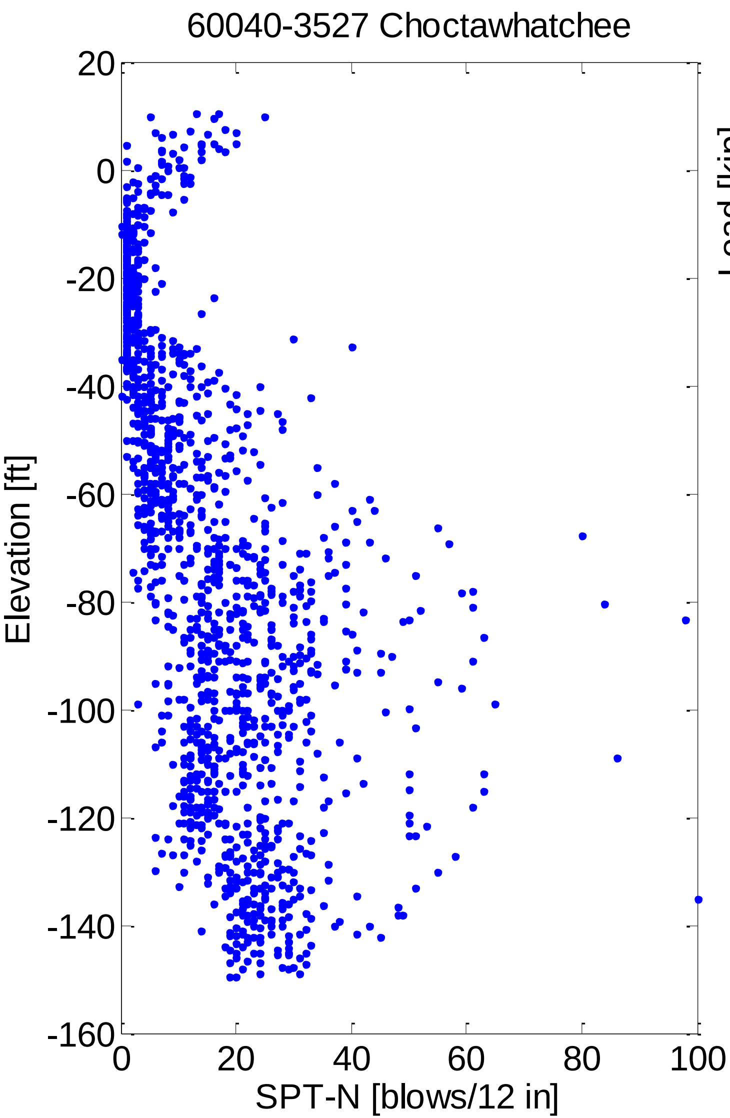
Howard Frankland

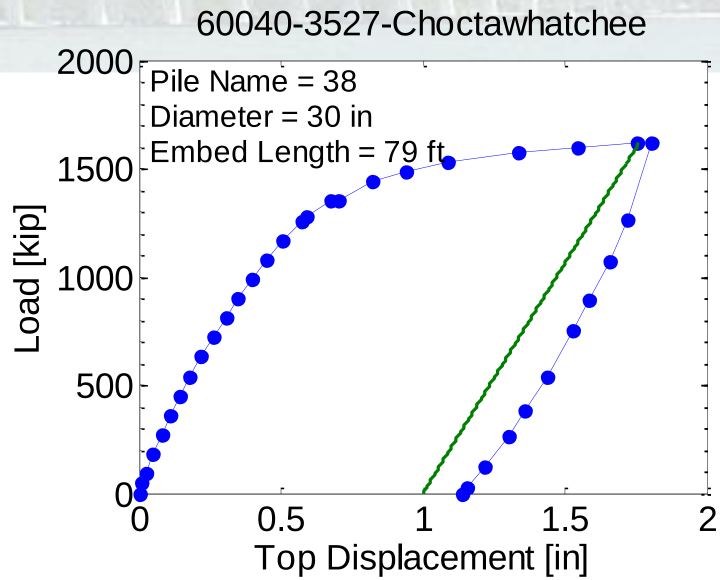


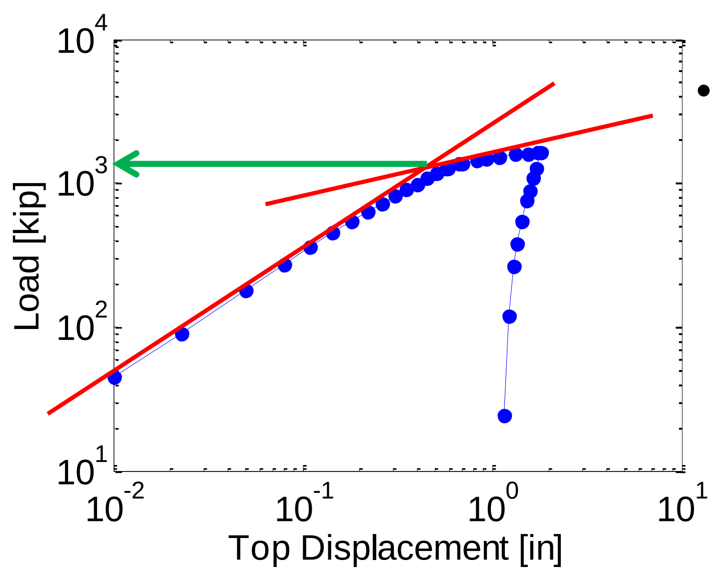
Dixie Highway



Data for Genetic Program



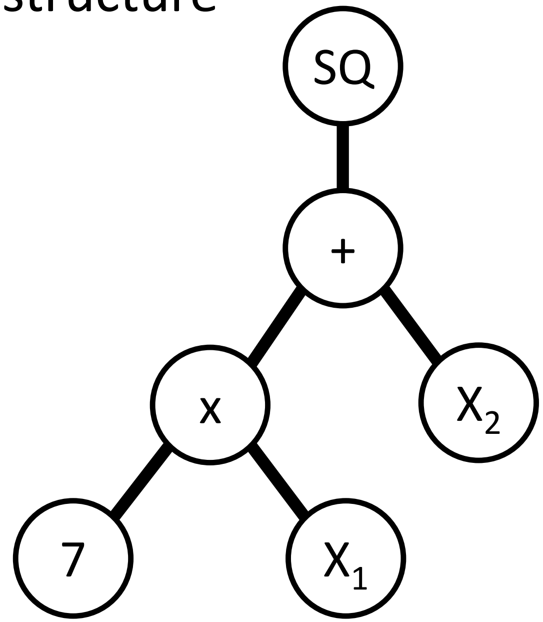




- Side = 1050 kips
- Davisson Tip = 445 kips
- Collected from instrumented reading in report. (strain gages or telltale data)

Genetic Program (GP)

- Optimization tool based on natural selection and genetic operators.
- Optimizes a prediction model based on a set of inputs (insitu data) and corresponding outputs (load test).
- Previous work done for driven pile models using CPT-q_t, and shallow foundation settlement from SPT-N.
- Begins with generation of random population of models
- Model represented by tree structure



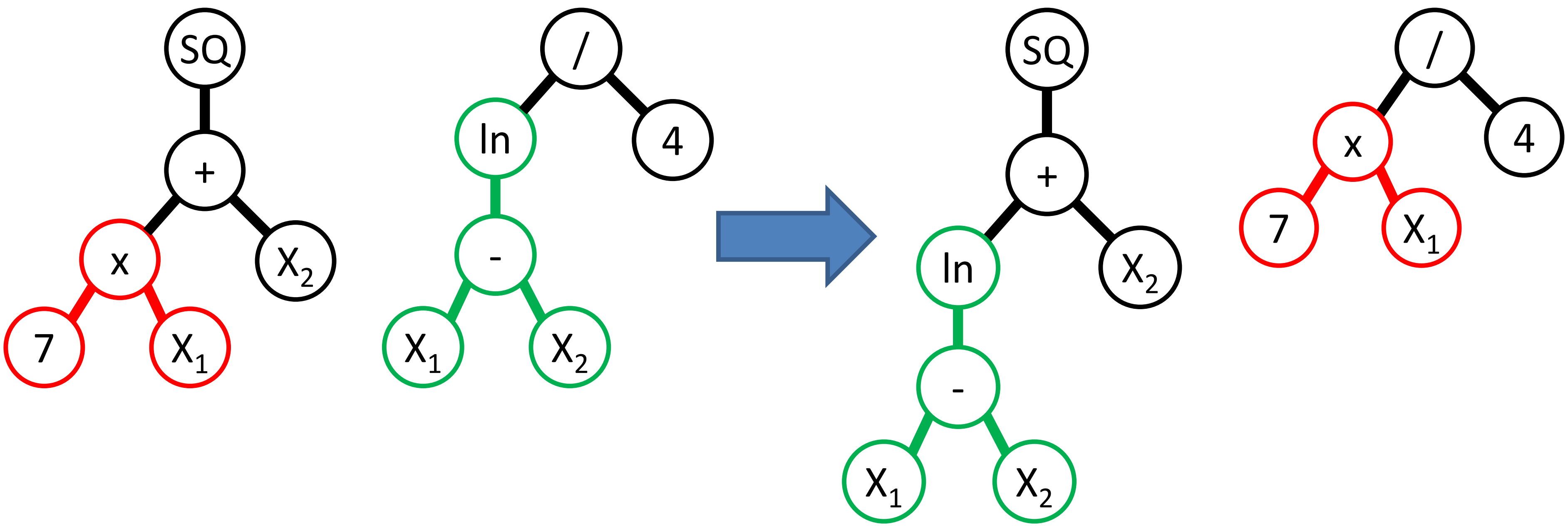
$$[7X_1 + X_2]^2$$

Genetic Operators

- Goal of improving models that are initially generated
- Mimics the evolutionary process
  - Crossover
  - Mutation
  - Reproduction
- Uses old models to help produce a population of new ones.

Crossover

Selection of two models from the population | Resulting new models for next generation

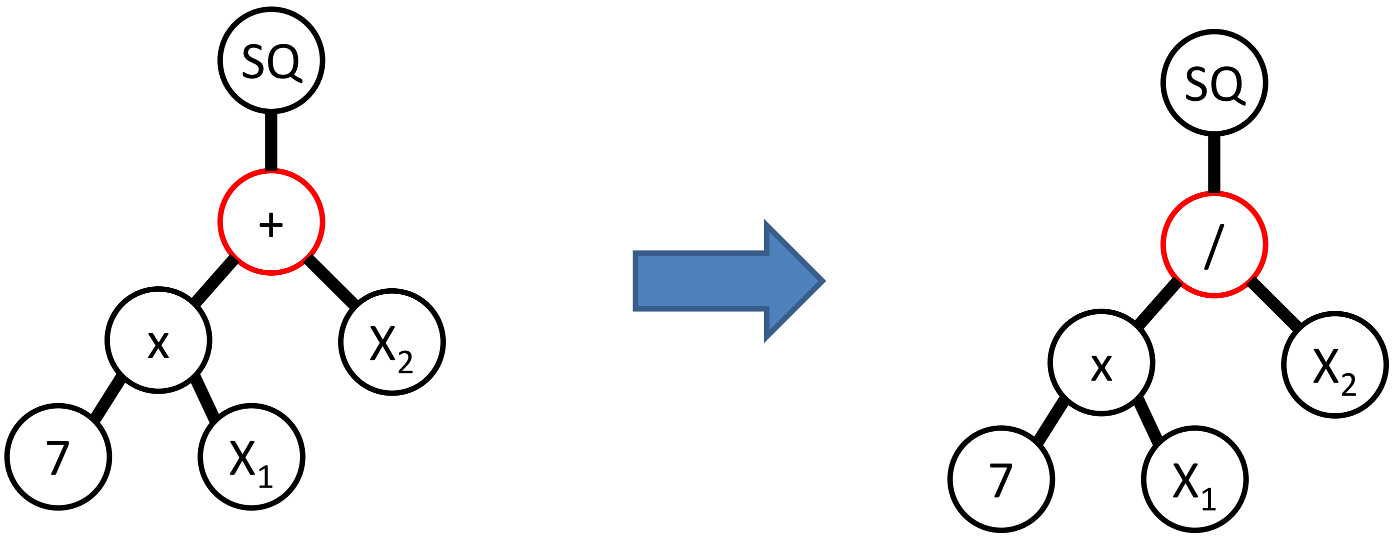


$$[7X_1 + X_2]^2 \qquad \frac{\ln(X_1 - X_2)}{4} \qquad [\ln(X_1 - X_2) + X_2]^2 \qquad \frac{7X_1}{4}$$

Mutation

Selection of one model from the population

Resulting new model for next generation

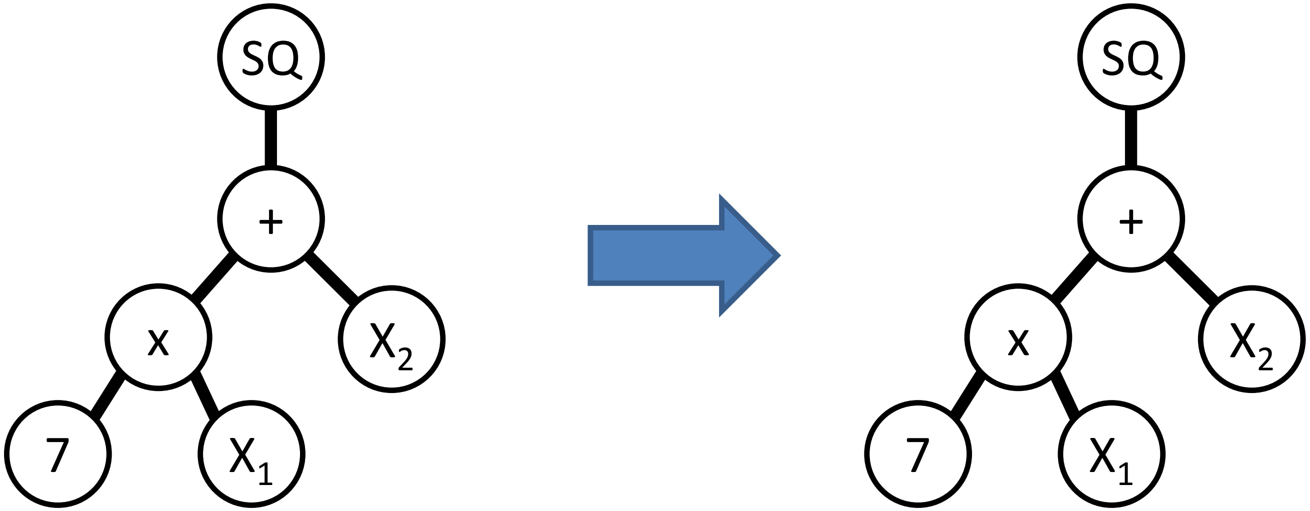


$$[7X_1 + X_2]^2$$

$$\left[\frac{7X_1}{X_2}\right]^2$$

Reproduction

- One model is selected from the population and copied over to the next generation.



$$[7X_1 + X_2]^2$$

$$[7X_1 + X_2]^2$$

Selection Criteria/Fitness

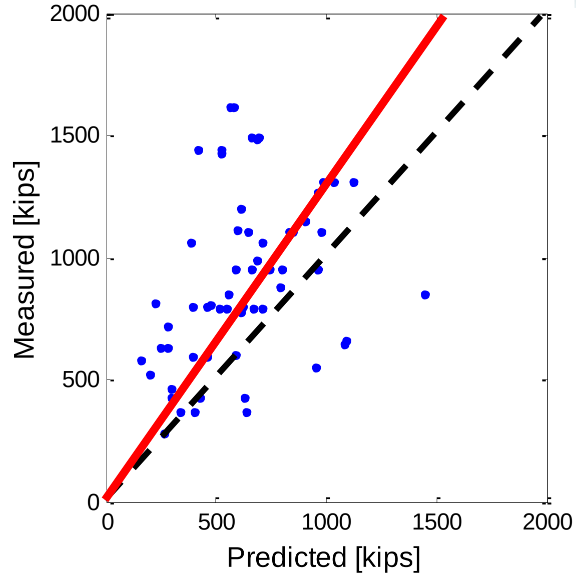
- Need a basis for which models are selected for use in genetic operators.
- For symbolic regression can use R^2, mean squared error (MSE), etc. to quantify how well the predicted model fits the measured data.
- Assign a probability of selection for model based on fitness score relative to the entire population.
  - i.e. Better fitting models have a higher chance of being selected.
- Repeat this process for multiple generations until optimal solution is determined.

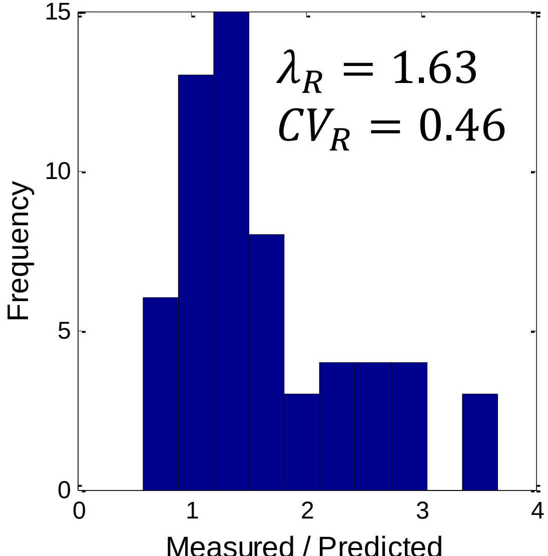
$$MSE = \frac{1}{N}\sum(M - P)^2$$

M– measured value
P– corresponding model prediction
N– number of data points

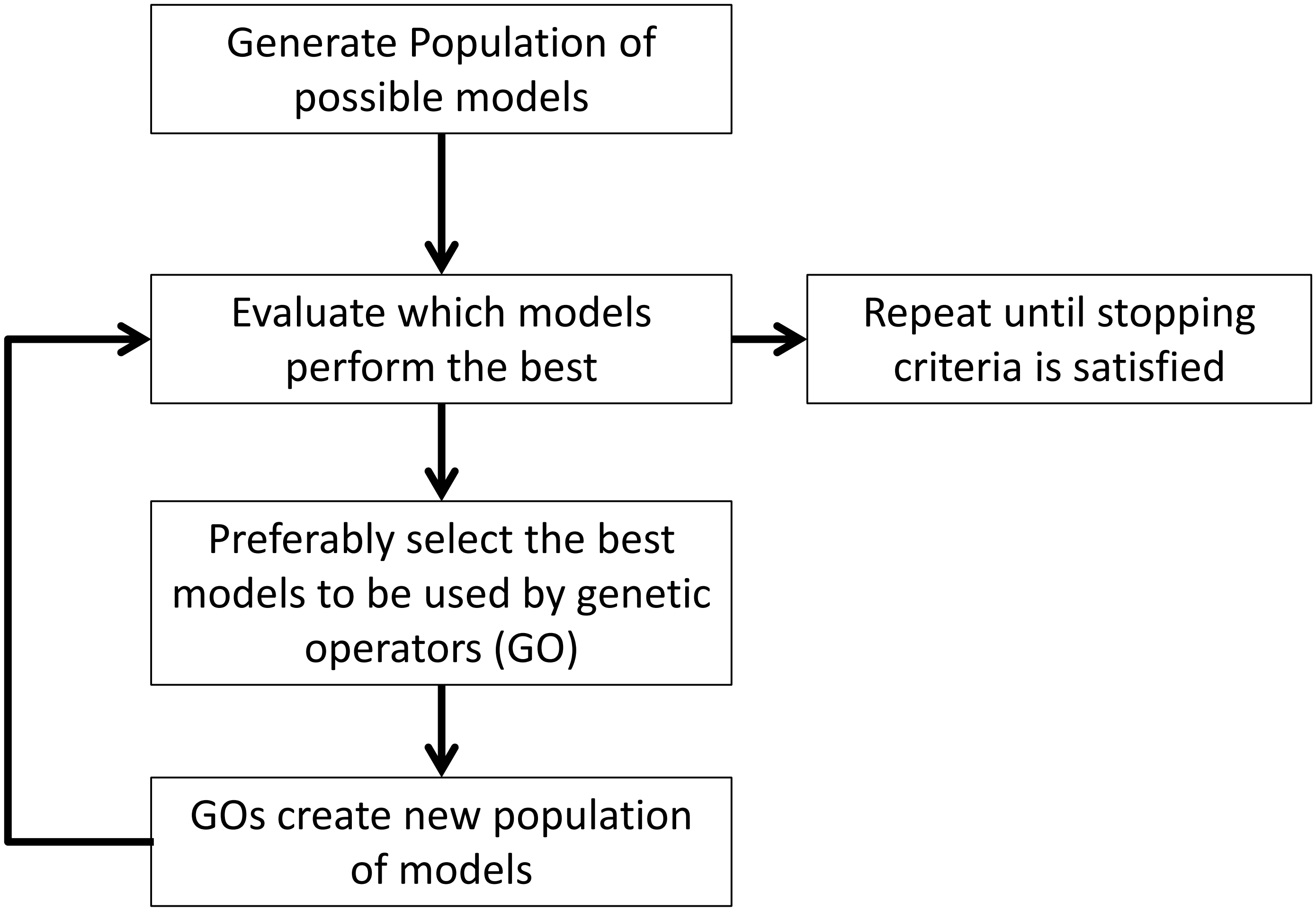
Method Error

- Method Error
  - Method used (FB-DEEP, Schmertmann etc.)
  - Measurement errors (in situ or lab)
  - Construction Method
- LRFD resistance factor
  - Calibration based distribution of measured over predicted.
  - Bias λ_R
    - Mean of Measured/Predicted
    - Over or under predict
  - Error CV_R
    - Standard deviation /mean
    - Precision of the method, spread about bias
- GP
  - Uses MSE
  - As MSE => 0, λ_R=>1
  - CV_R is reduced



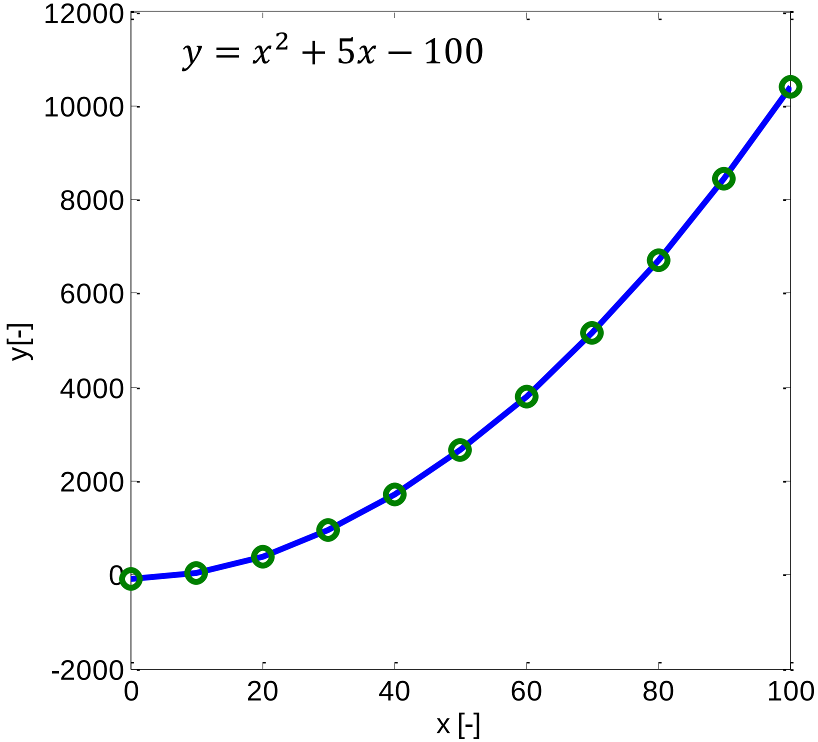


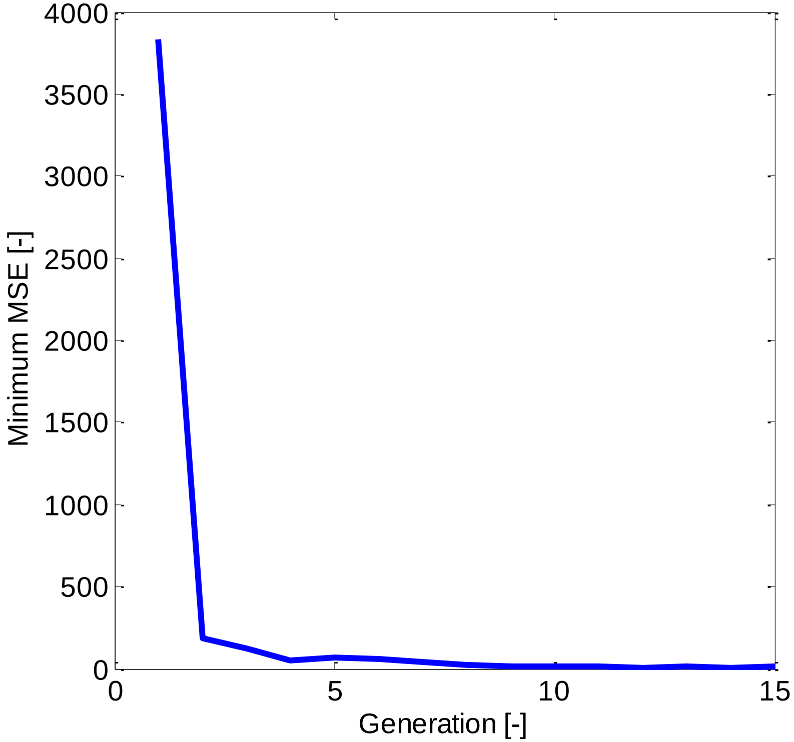
GP Overview


Generate Population of possible models
Evaluate which models perform the best
Repeat until stopping criteria is satisfied
Preferably select the best models to be used by genetic operators (GO)
GOs create new population of models

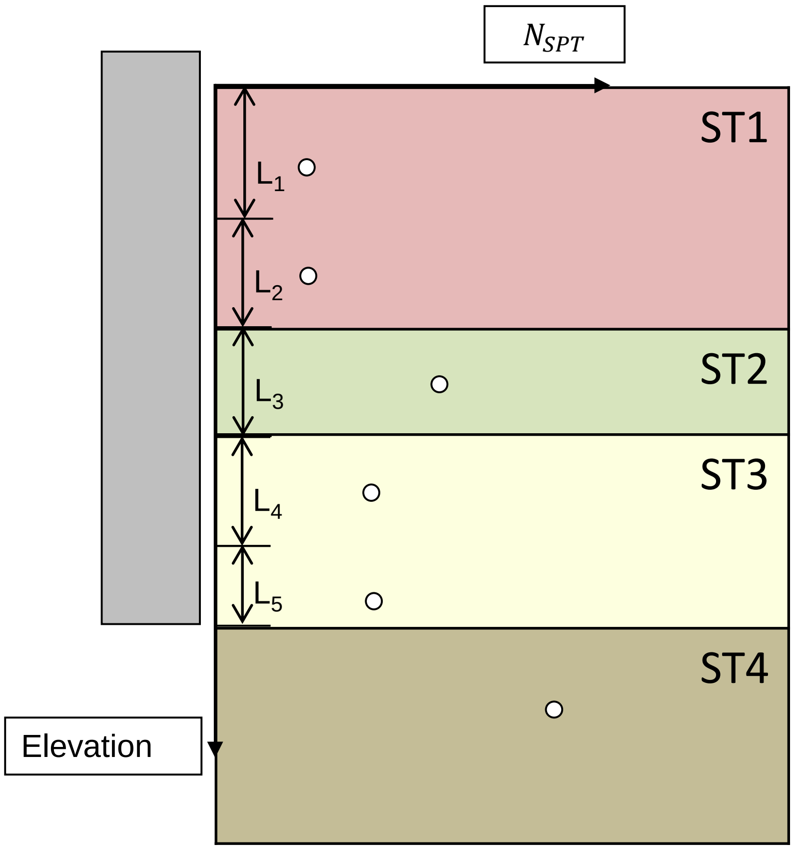
Implementation and Validation

- Coded in MATLAB using data downloaded from the FDOT database.
- Validation for solving 1 equation.





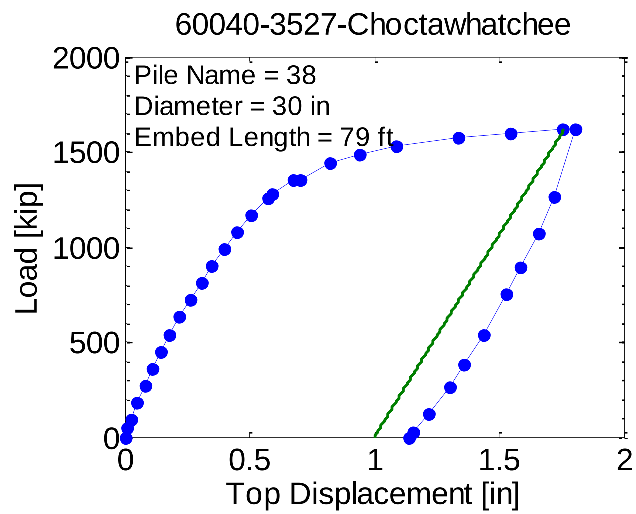
FB-DEEP

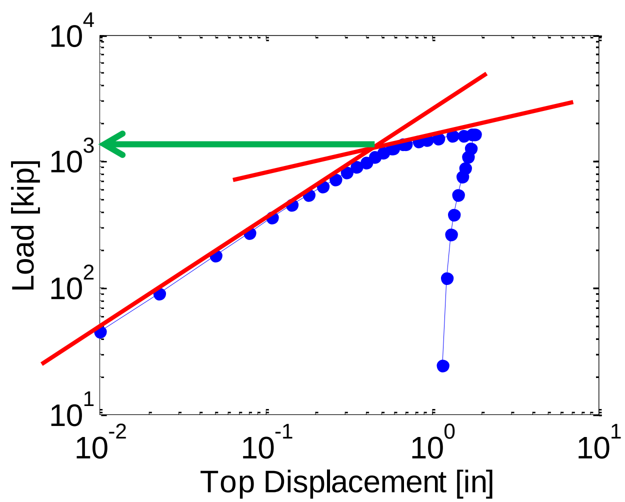


- Calculates pile capacity based on
  - Pile Type
  - SPT-N
  - Soil Type
- Uses 4 soil types
  - 1. Plastic Clay
  - 2. Clay and Silty Sand
  - 3. Clean Sand
  - 4. Limestone, Very Shelly Sand

Data Limitations

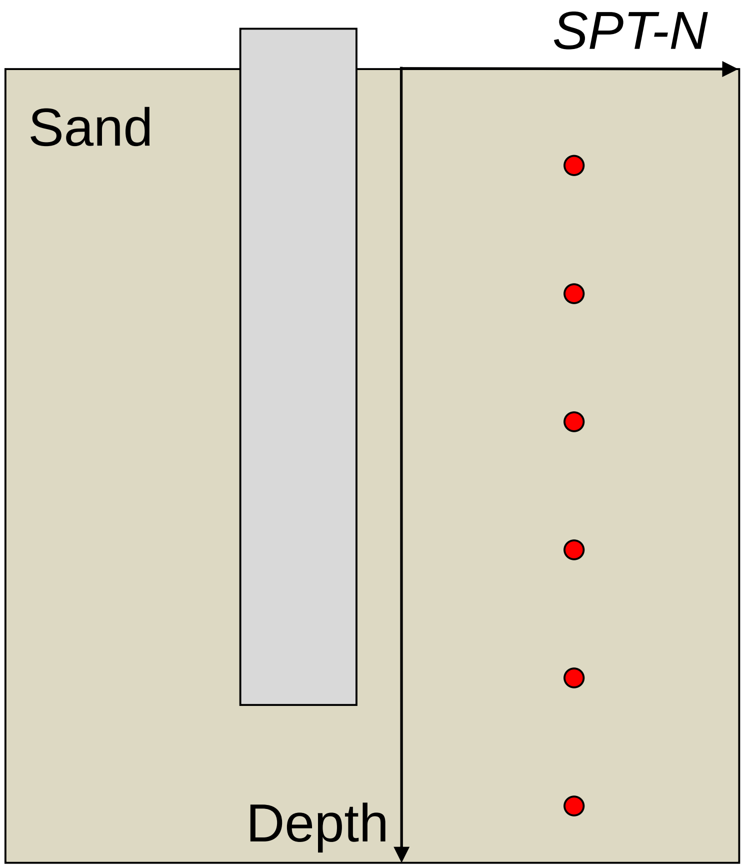
- Majority of collected data for driven piles can only be separated into total side and tip resistance
- Unable to determine side resistance for different layers or soil types from the load tests.
- GP will have to fit multiple models based on comparison to total side resistance.





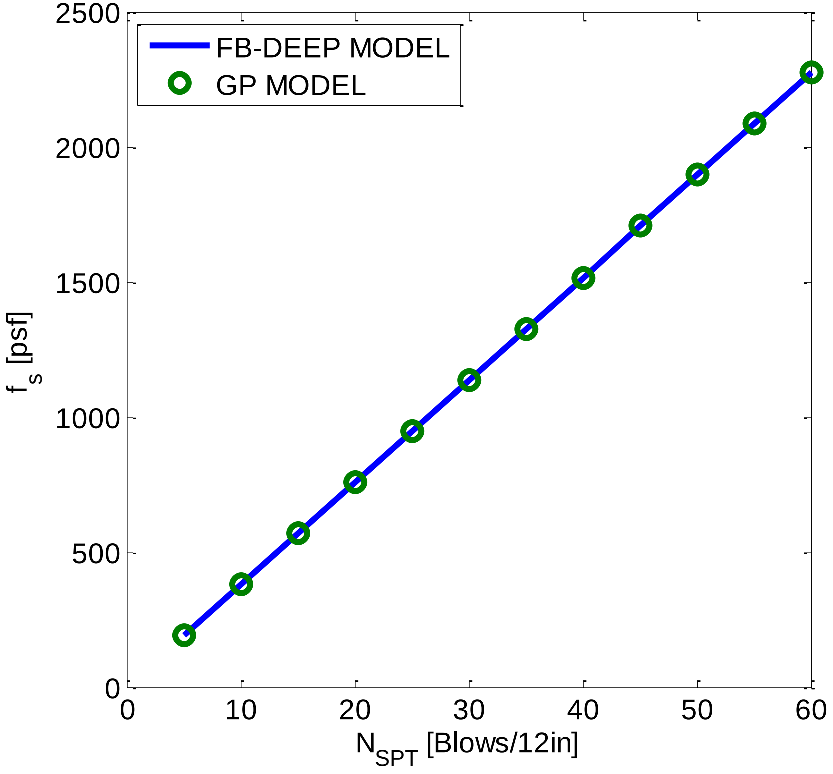
Validation cont.

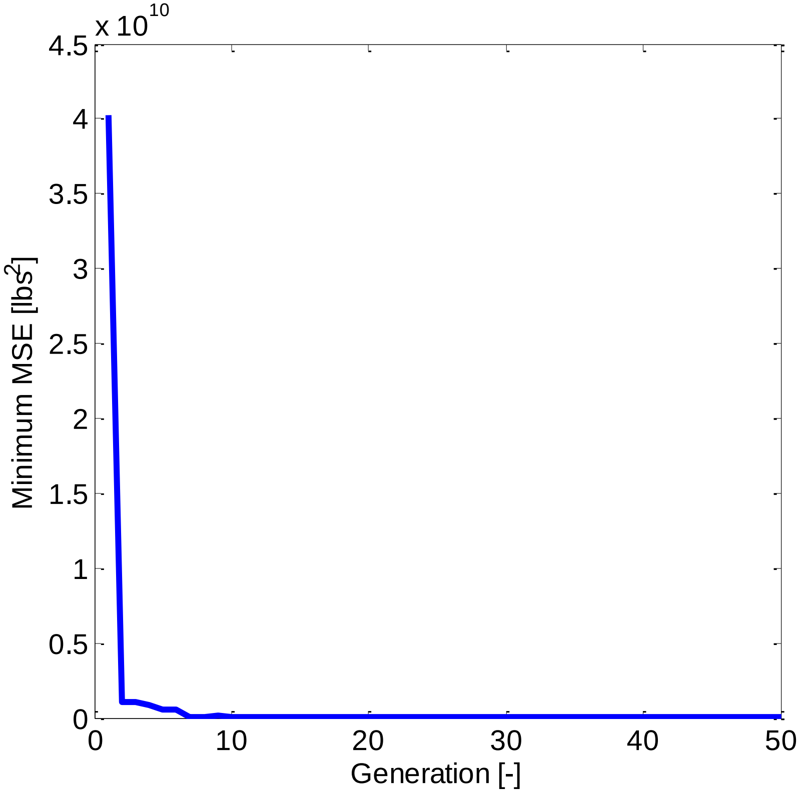
- Start with GP predicting FB-DEEP models.
- Create borings logs of uniform SPT-N blow count and soil type.
- Generate multiple profiles with different SPT-N.
- Use FB-DEEP calculation to be synthetic load test.
- GP used generated borings to estimate unit side and tip resistance as function of blowcount.



Validation cont.

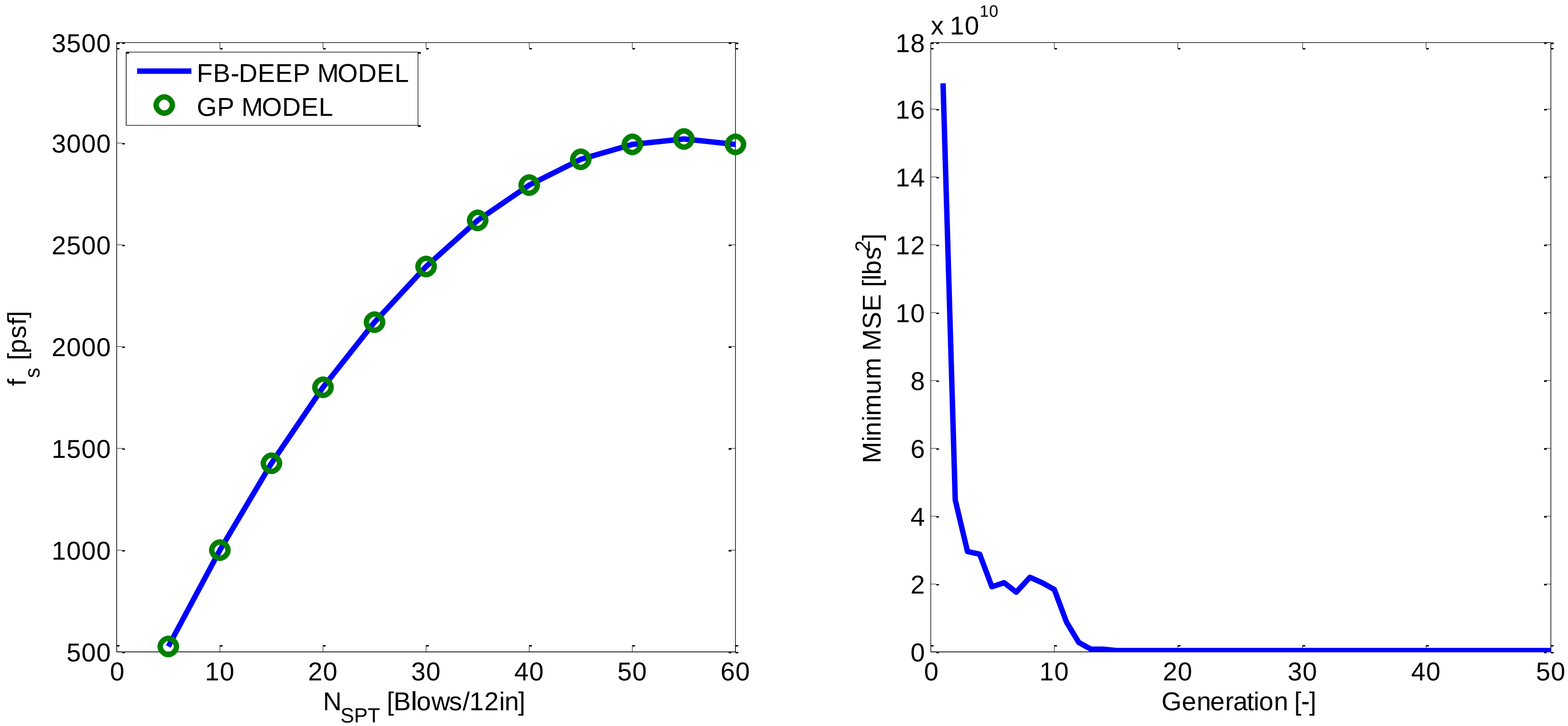
FB-DEEP SOIL TYPE 3 (Sand) Fitting





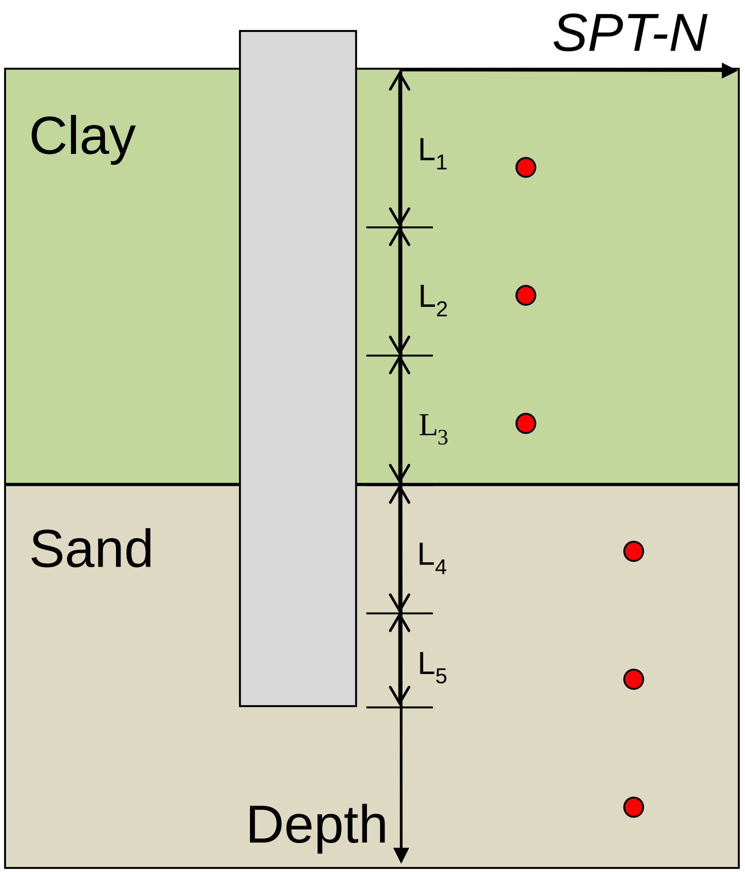
Validation cont.

FB-DEEP SOIL TYPE 1 (Clay) Fitting



Validation cont.

- See how well GP predicts 2 layered models at the same time.
- Create borings logs with 2 uniform layers of SPT-N blow count and soil type.
- Generate multiple profiles with different layering and SPT-N.
- Generated borings are run through FB-DEEP to act as synthetic load test.
- Determine Li, to evaluate SPT-N's contribution to side resistance.



GP Capacity Prediction

- GP needs to account for different layering sizes as well as sample spacing.
- Li provides means to determine a weighted average.
- Driven Pile data set only provides total side resistance.
- GP uses total side resistance to optimize individual soil type models.

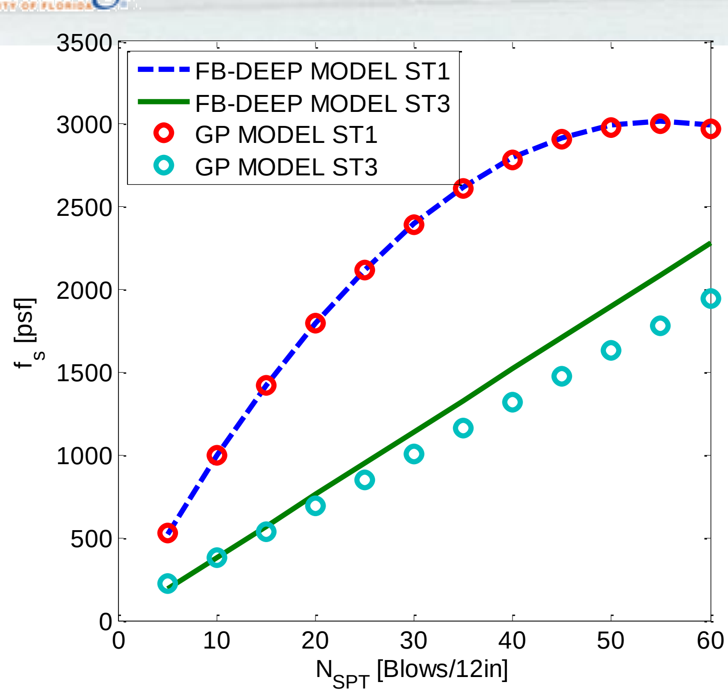
GP Side Friction Calculation

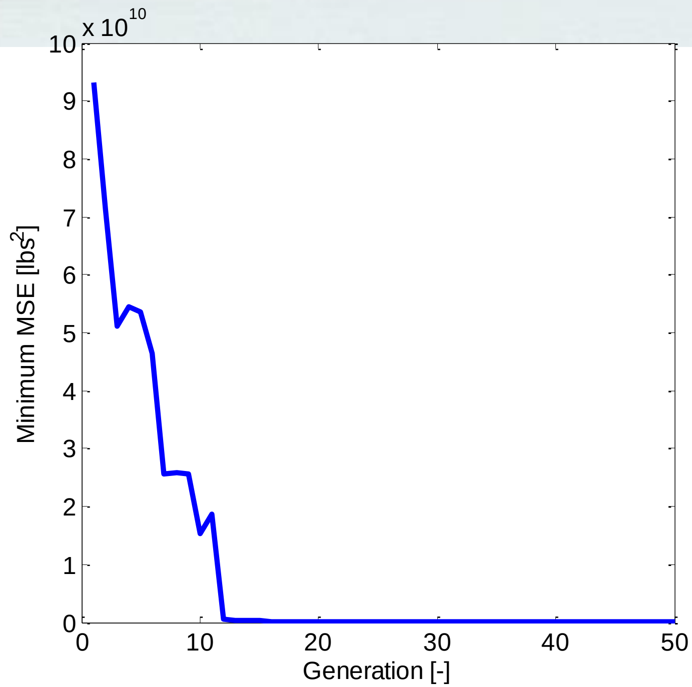
$$\bar{f_s} = \frac{1}{\sum L_i} \sum f_{s_i} L_i$$ Layer

$$USF = P \sum \bar{f_s} \sum L_i$$ Total Pile

$\bar{f_s}$ – mean unit side friction of soil type
f_{s_i} – unit side friction, function of soil type and SPT-N
L_i – samples attributed length
USF – Ultimate Side Friction of Pile
P – Pile's perimeter

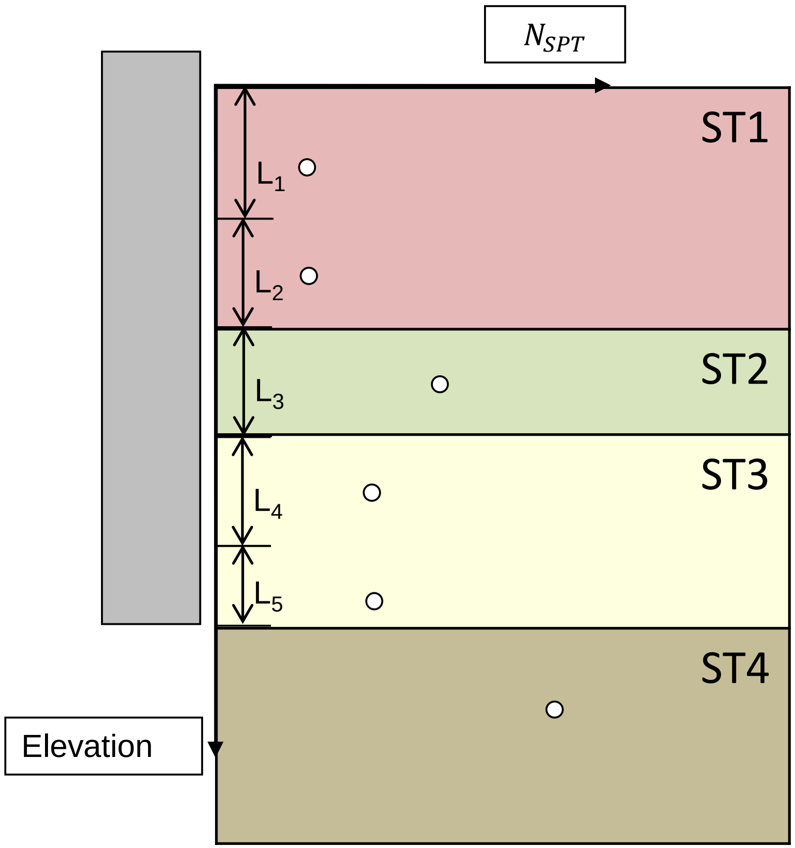
Validation cont.





GP Run	ST 1 Model $f_s = 109.8N_{SPT} - N_{SPT}^2 \ (psf)$	ST 3 Model $f_s = 38N_{SPT}(psf)$	MSE (lbs^2)
1	$109.8N_{SPT} - N_{SPT}^2 + 5.28$	$31.3N_{SPT} - \sin(N_{SPT} + 65.5) + 65.1$	1.14e+08
2	$65.9N_{SPT}$	$38.1N_{SPT} - 3.6/\ln(N_{SPT}) + 26.6$	2.07e+10
3	$109.6N_{SPT} - \sin(\sin(14.3 - N_{SPT})) - N_{SPT}^2$	$33.2N_{SPT}$	1.25e+08

GP Pile Model

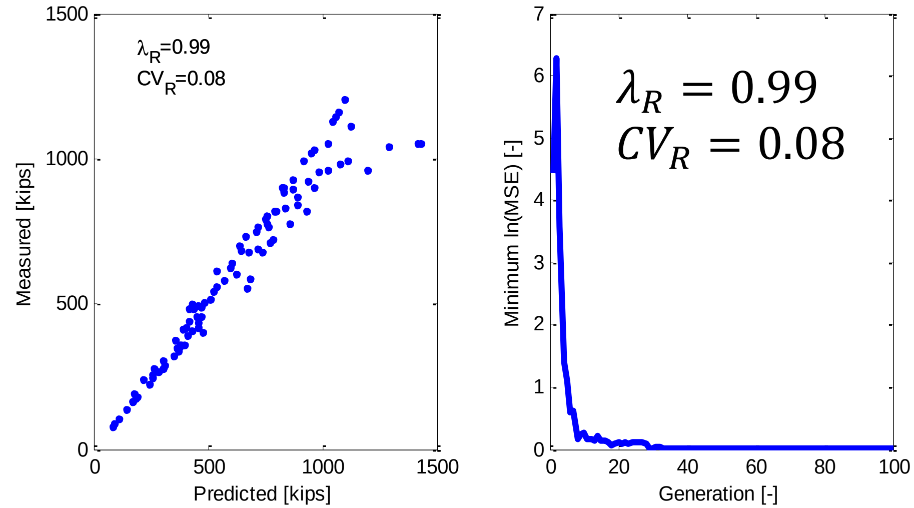


- End Bearing
  - $q_{tip} = \frac{1}{2}\left[\frac{1}{n_{below}}\sum_{tip}^{tip+3.5B} q_{t_i} + \frac{1}{n_{above}}\sum_{tip-8B}^{tip} q_{t_i}\right]$
  - $\bar{q}_T = \left(\sum W_i\, q_{T_i}^{k}\right)^{\frac{1}{k}}$
  - $W_i = \frac{L_i}{L}$
  - $Q_{TIP} = A_{Tip}\, \bar{q}_T$
- Test GP using this synthetic data to see if reproduces FB-DEEP curves.
  - Input – Random Borings
  - Measured – FB-DEEP result (synthetic load test)
  - Predicts side and tip resistance separately
  - Optimizes all four soil type models simultaneously

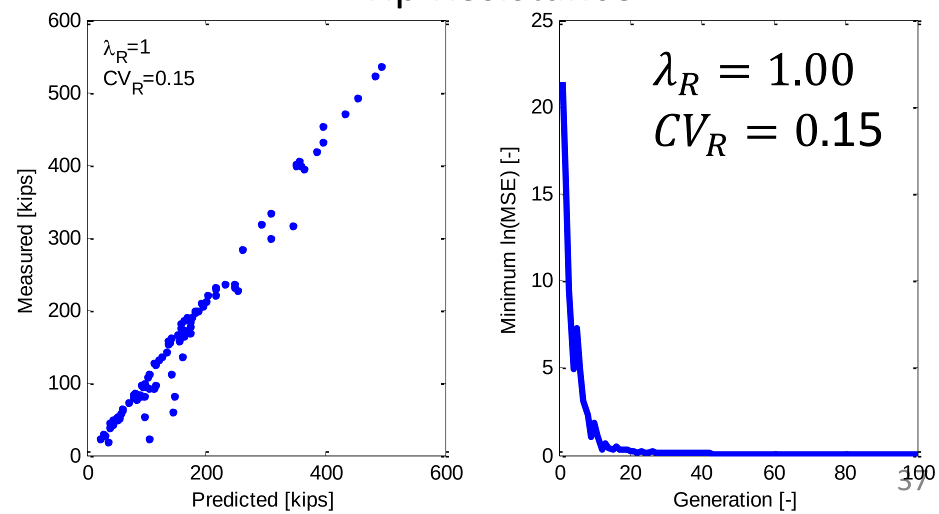
GP Validation

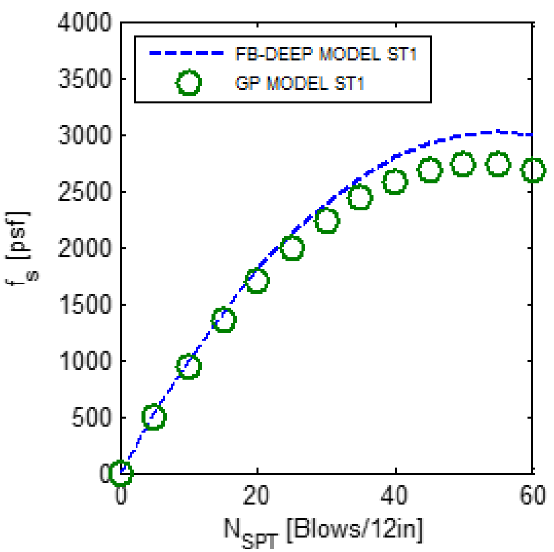
- Use of 100 Random Borings
- GP predicted FB-DEEP's Side and Tip models reasonably well.
- Deviation from FB-DEEP partly due to embedment depth correction is not used by GP

Side Resistance



Tip Resistance





GP Model Prediction

- Predicts side and tip resistance separately
- Optimizes all four soil type models simultaneously
- Separate analysis using borings within 100 ft, 500 ft, and 1000 ft. Based on stationing.
  - Investigate degree of spatial variability
- GP Analysis, considers
  - 200 Population (models)
  - 100 Generations (iterations)

Assignment of Soil Type

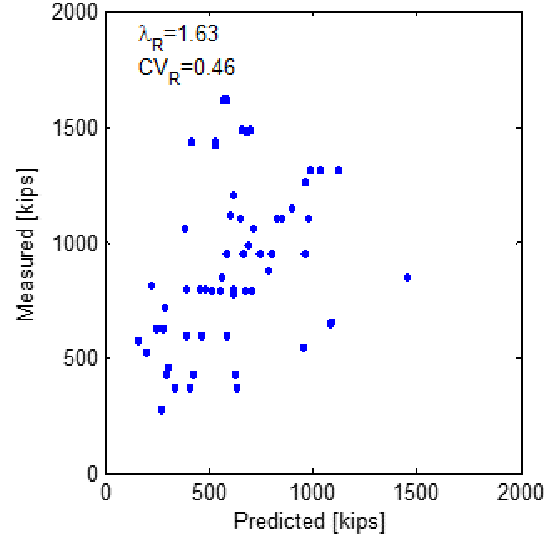
- Binning based on USCS classification if given or boring log soil. description otherwise.
- Automatically sorted using the database.
- (~ 500 borings).

Soil Type 1	Soil Type 2	Soil Type 3	Soil Type 4
CL	SM	SW	GW
ML	SC	SP	GP
CL-ML	SW-SC		GM
CH	SP-SC		GC
MH	SM-SC		GC-GM
OL	SW-SM		GW-GM
OH	SP-SM		GW-GC
			GP-GM
			GP-GC

SPT-N Limits

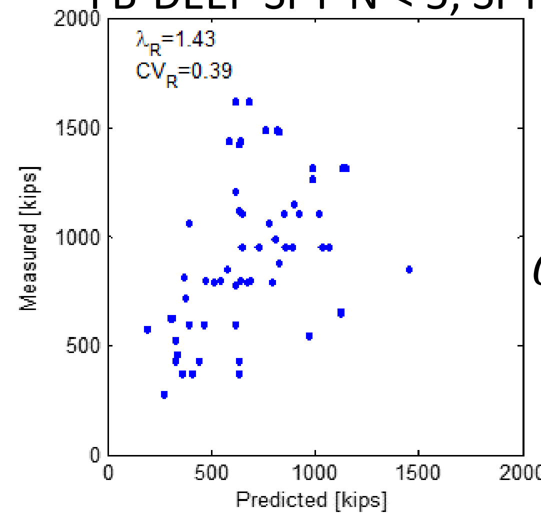
- FB-DEEP
  - SPT-N < 5, SPT-N = 0
  - SPT-N > 60, SPT-N = 60
- Investigated different truncation.
  - SPT-N < 5, SPT-N = 5
- GP analysis - Refusals and SPT-N greater than 60 set equal to 60.
- Results shown are for FB-DEEP curves used in GP algorithm.

FB-DEEP SPT-N < 5, SPT-N = 0



$$\lambda_R = 1.63$$
$$CV_R = 0.46$$

FB-DEEP SPT-N < 5, SPT-N = 5



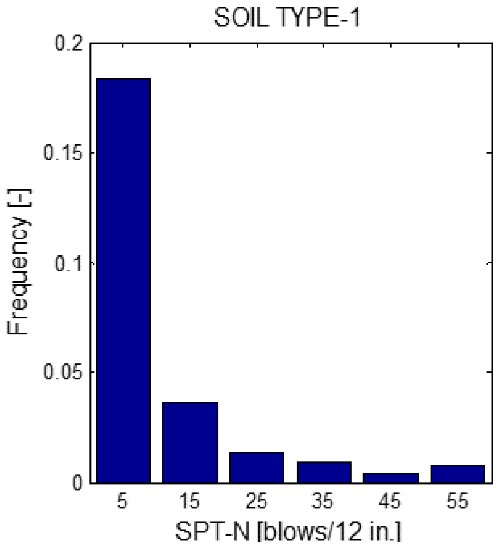
$$\lambda_R = 1.43$$
$$CV_R = 0.39$$

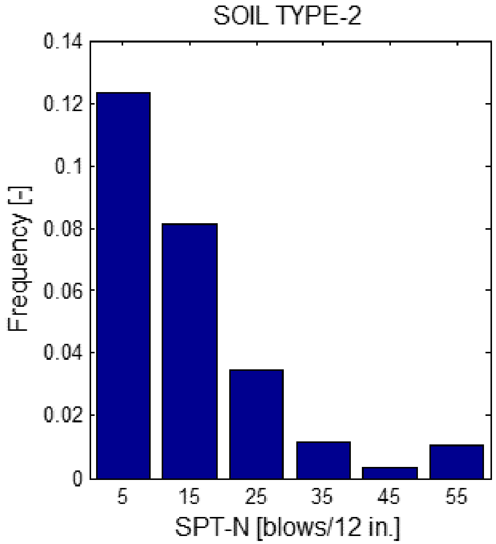
Distribution of Data for GP Analysis

- Check to see how much data for each soil type is available for side and tip resistance calculation.
- Is there enough data??
  - For each soil type
  - Sufficient range of SPT-N values
  - i.e., confidence in GP models

Data for Side Resistance

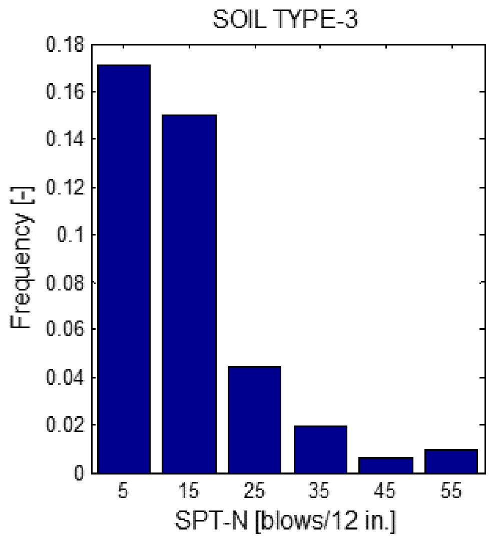
- Collect borings within 100ft
- Sort by soil type located along side pile length.
- Evaluate SPT-N distribution to asses impact on developed GP models
  - Frequency – percentage of entire data set.
- Soil Type 1 and Soil Type 2
  - Lot of low range values.
  - GP models may be unreliable for SPT-N > 45

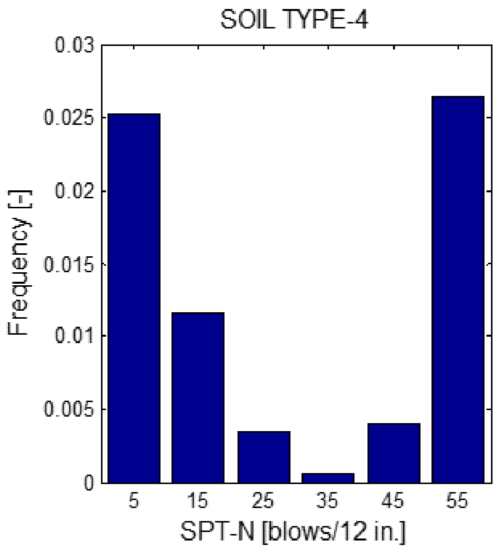




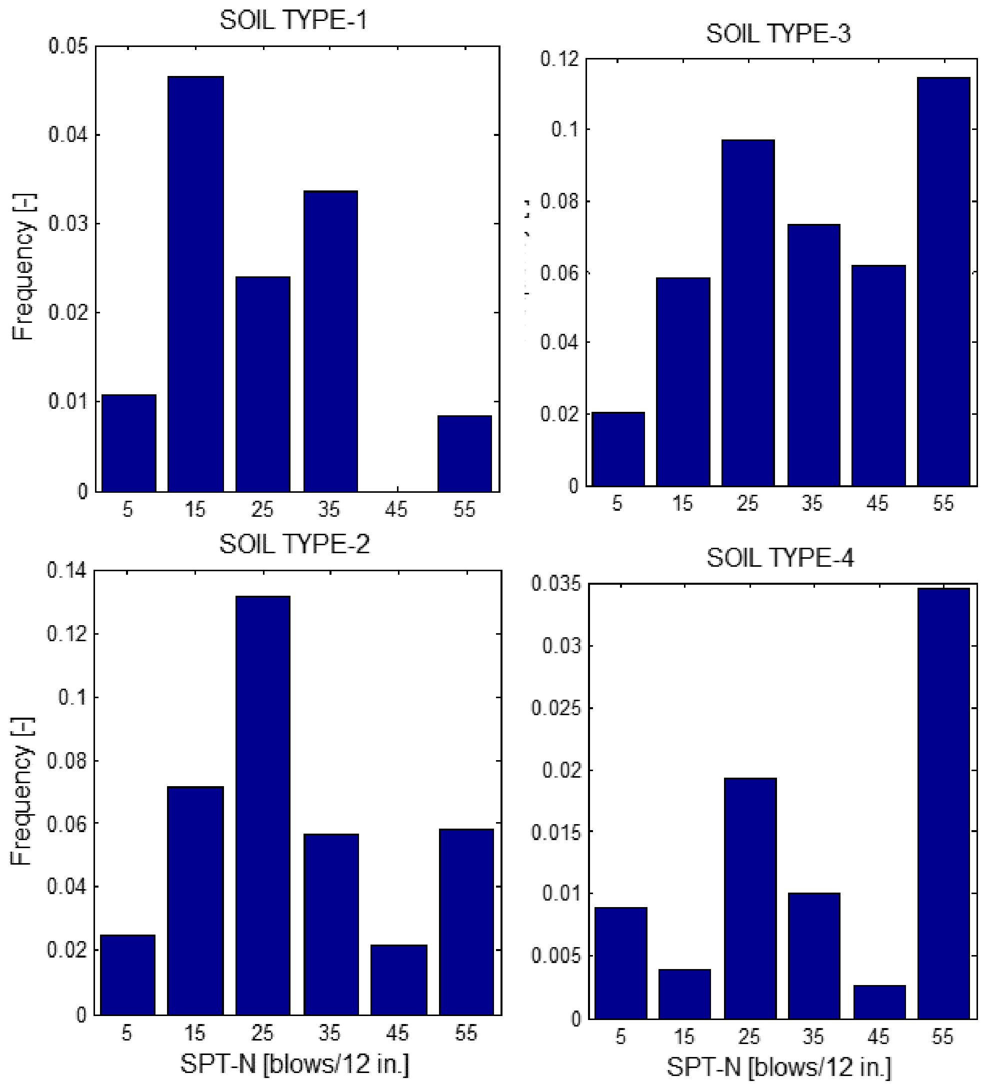
Data for Side Resistance Cont.

- Soil Type 3
  - Good distribution for lower range values
- Soil Type 4
  - Not a lot of data compared to other soil types
  - GP model may not be reliable

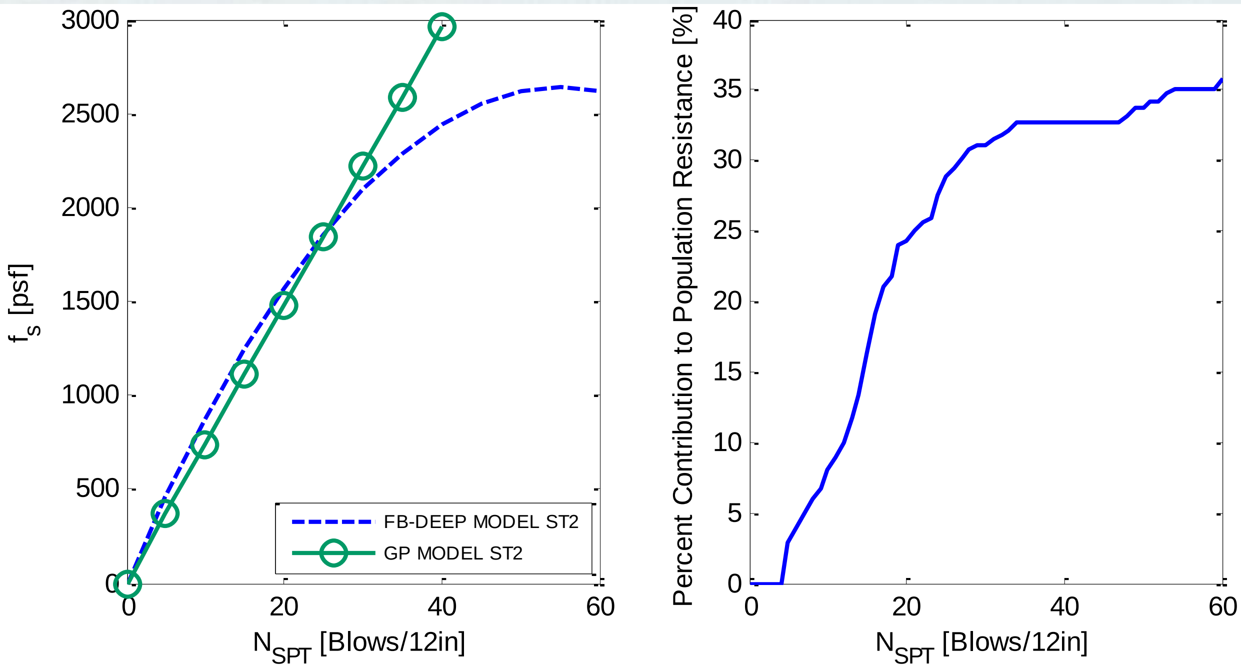




Data for Tip Resistance (ex. 3.5B below pile tip only)



GP Side Resistance Results



- Example of result for Soil Type 2
  - Lots of data available for range of N_{SPT} 0-40.
  - Recommended cutoff at N_{SPT}= 40 limiting to 2750 psf
- GP converged on linear models for all soil types.
- Soil Type 4 difficult to converge, small amount of data relative to population
  - Used linear model for further analysis.

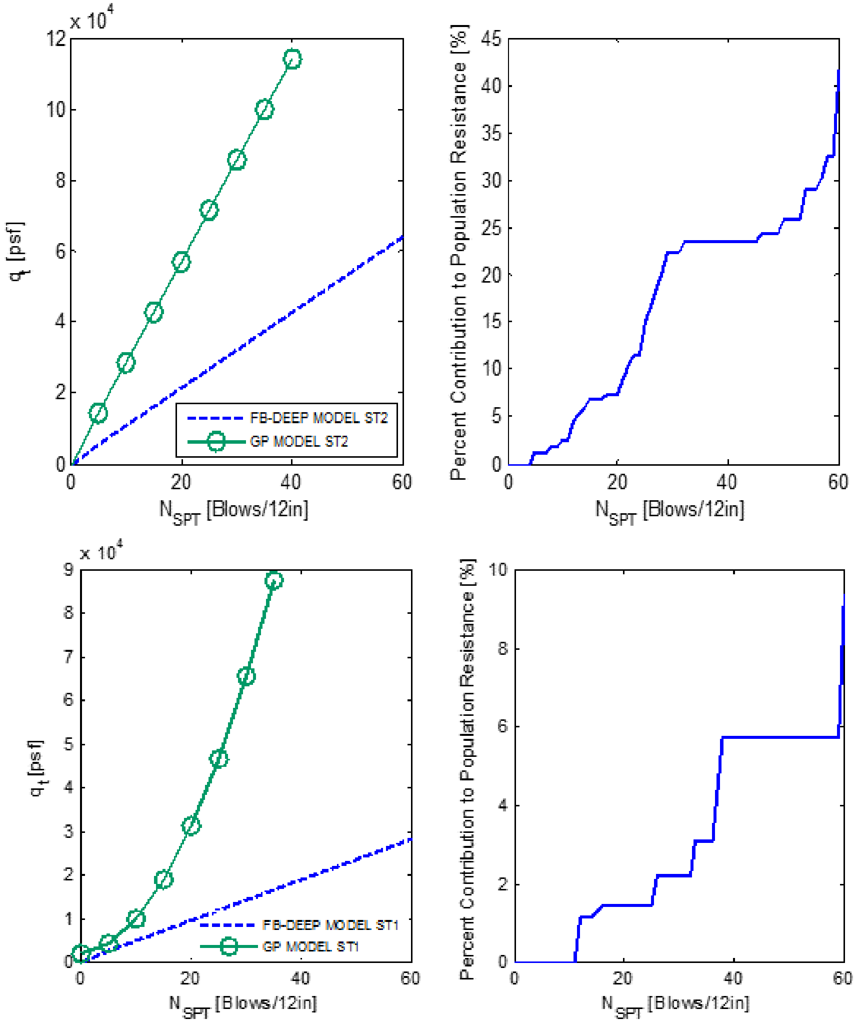
GP End Bearing Results

- Analyzed different averaging domains and averaging types.
- 4B Below Arithmetic was selected.
- Other methods with lower CV_R had unreasonable models.
  - large intercepts
- Averaging above pile tip increases the bias of the estimated resistance.

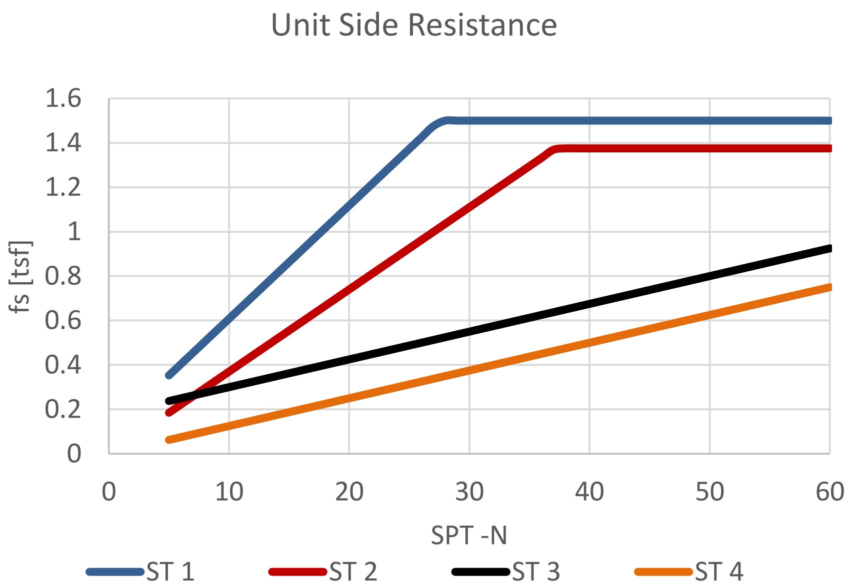
Averaging Domain	Averaging Type	CV_R	λ_R
4B Below	Arithmetic	0.668	1.110
4B Below	Harmonic	0.690	1.384
4B Above and 4B Below	Arithmetic	0.614	1.568
4B Above and 4B Below	Harmonic	0.608	1.023
2B Below	Arithmetic	0.568	1.094
2B Below	Harmonic	0.586	1.287
8B Above and 3.5B Below	Arithmetic	0.614	1.569
8B Above and 3.5B Below	Harmonic	0.602	1.209

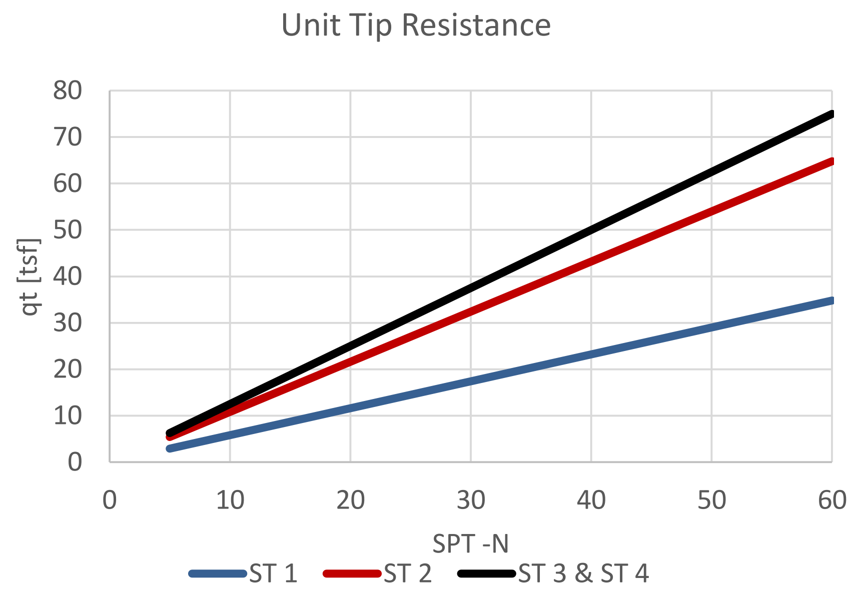
GP End Bearing Results

- GP suggests that FB-DEEP is conservative for soil models 1 and 2.
- Soil Type 2
  - Linear
  - Lots of data
- Soil Type 1
  - Quadratic
  - Unreasonably high q_t for higher N_{SPT}.
  - Minimal amount of data.
  - Used linear model with reduced slope
- Soil Type 3 & 4
  - Similar linear models between GP FB-DEEP



Recommended Curves from GP analysis



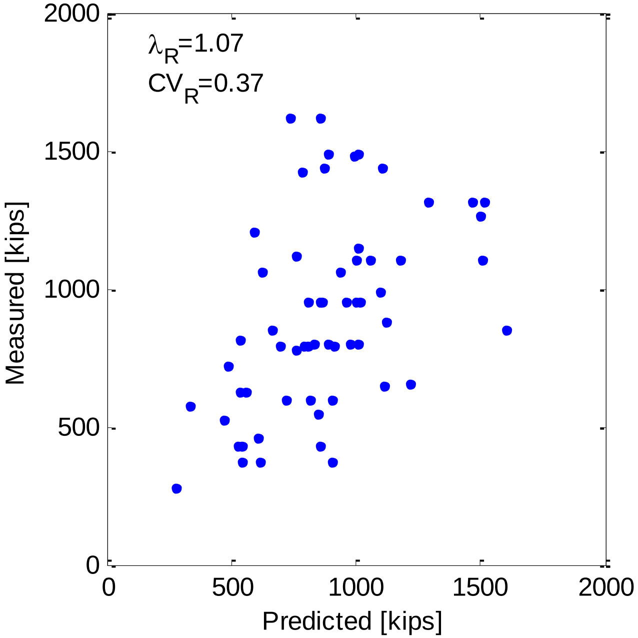


- Pile Side Resistance
  - ST 1 $f_s(tsf) = 0.051N + 0.098 < 1.5tsf$
  - ST 2 $f_s(tsf) = 0.037N \quad < 1.375tsf$
  - ST 3 $f_s(tsf) = 0.0125N + 0.175$
  - ST 4 $f_s(tsf) = 0.0125N$

- Pile Tip Resistance
  - Average 4D below
  - ST1 $q_T(tsf) = 0.58\ N$
  - ST 2 $q_T(tsf) = 1.08\ N$
  - ST 3 & 4 $q_T(tsf) = 1.25\ N$

Measured vs Predicted Davisson Capacity

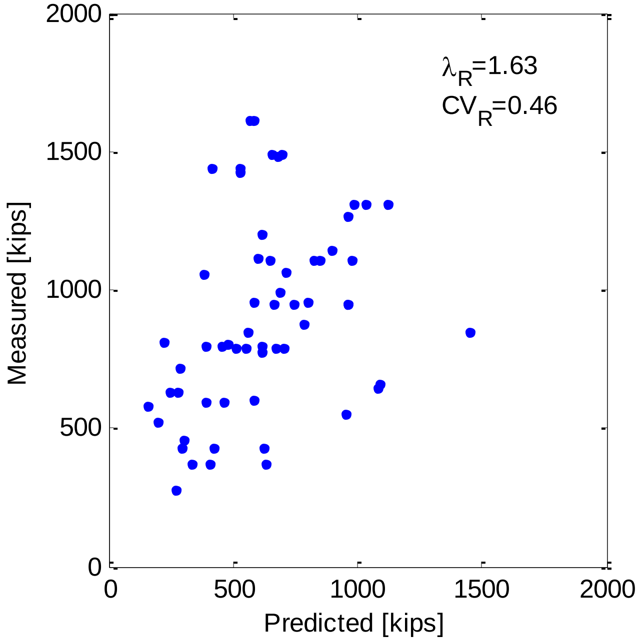
For borings within 100 ft of load test.



GP Predicted Pile Capacities

$\lambda_R = 1.07$

$CV_R = 0.37$

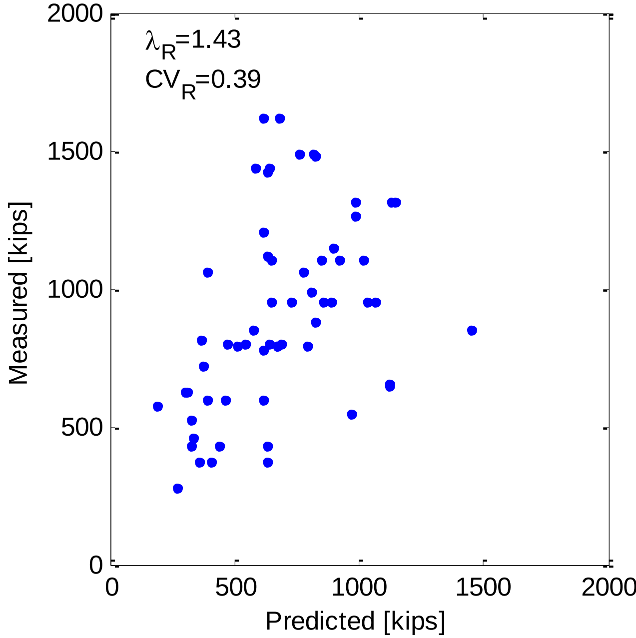


FB-DEEP Curves

(N ≤ 5, N =0)

$\lambda_R = 1.63$

$CV_R = 0.46$



FB-DEEP Curves

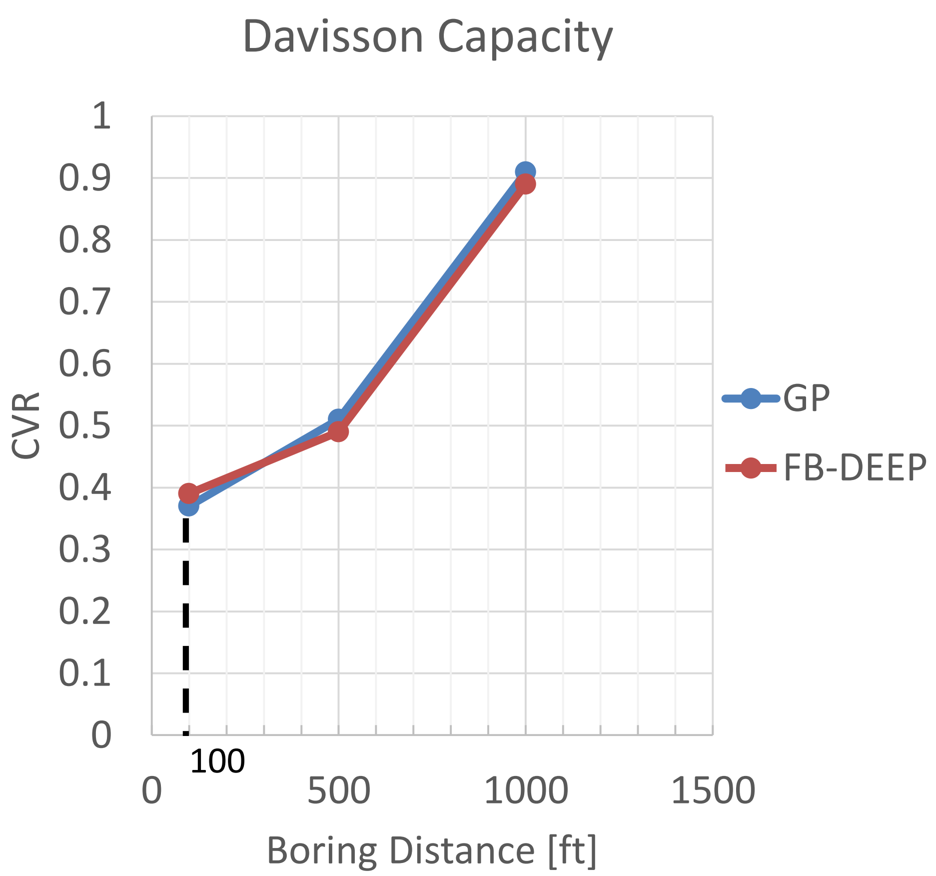
(N ≤ 5, N =5)

$\lambda_R = 1.43$

$CV_R = 0.39$

Accounting for Spatial Variability

- Borings typically not within foot print of load test.
- $CV_R = \sqrt{(CV_S)^2 + (CV_M)^2}$
  - CV_R - Total Uncertainty
  - CV_S - Spatial Variability
  - CV_M - Method Error
- CV_R increases with boring distance from pile.



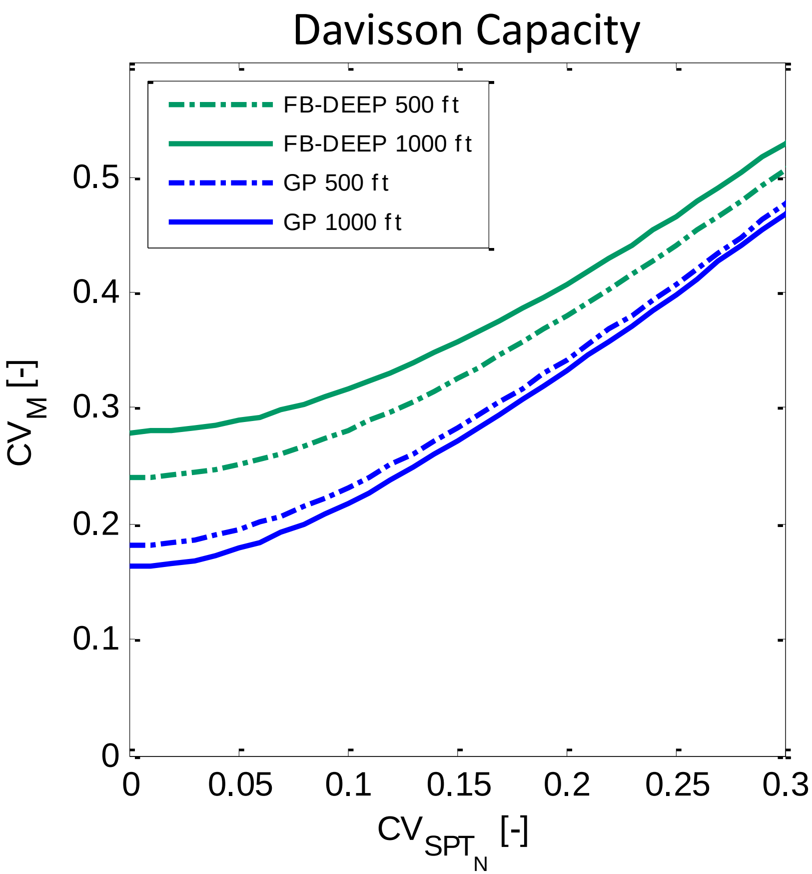
LRFD Resistance Factors

Method	LRFD Φ	Φ/λ
GP/Recommended		
Side – 100ft	0.66	0.62
Side -500ft	0.35	0.30
Davisson -100ft	0.49	0.52
Davisson -500ft	0.34	0.36
FB-DEEP(N<5,N=0)		
Side – 100ft	0.60	0.40
Side -500ft	--	---
Davisson -100ft	0.63	0.39
Davisson -500ft	0.25	0.15
FB-DEEP(N<5,N=5)		
Side – 100ft	0.65	0.54
Side -500ft	0.39	0.28
Davisson -100ft	0.61	0.43
Davisson -500ft	0.42	0.35

Φ/λ - % of available load test

Evaluating Degree of Method Error for Davisson Capacity

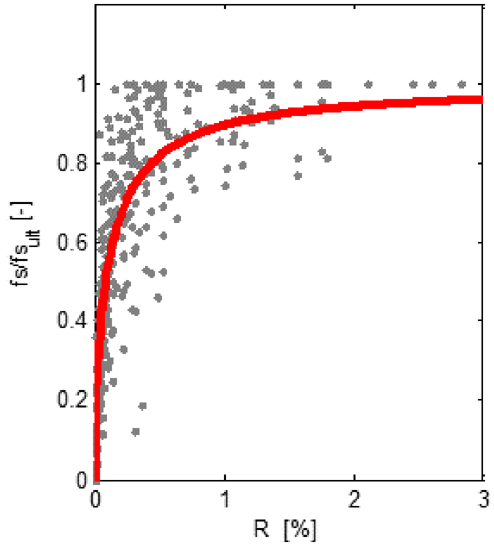
- $CV_M^2 = CV_R^2 - CV_S^2 + CV_{SPT}^2$
  - CV_R - Total Uncertainty
  - CV_S - Spatial Variability
  - CV_M - Method Error
  - CV_{SPT} - SPT Measurement Error
- CV_{SPT}^2 is in both CV_S^2 and CV_M^2
  - Added back in.
- CV_S^2 determined from sites boring variability
- Investigate range of CV_{SPT}^2 values
  - Function of rig type and calibration
- Importance of rig calibration to reduce CV_{SPT}^2

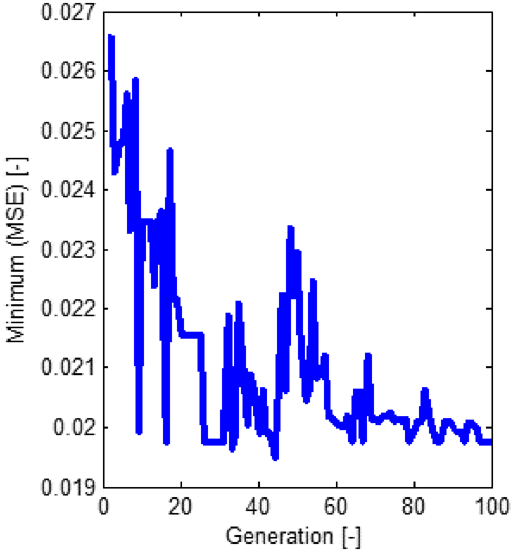


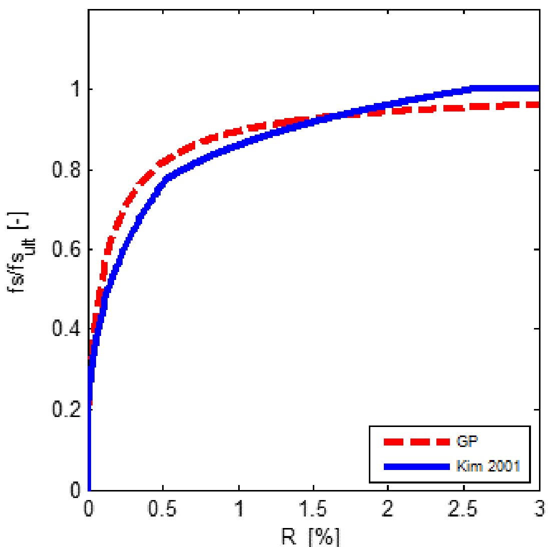
FB-DEEP N<5, N=5

Drilled Shafts Load Transfer

- GP optimization of t-z models.
- Data set
  - 33 normalized t-z curves Florida Limestone
- $\frac{f_s}{f_{s,ult}} = \left[\frac{4*R}{4*R+1}\right]^{0.5}$
  - R – displacement/diameter
  - f_s – side resistance

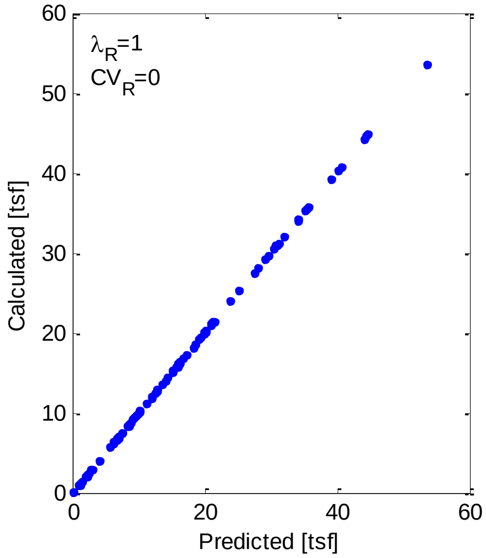


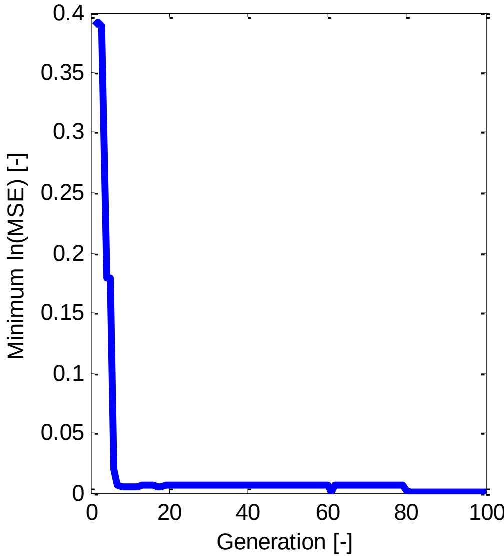




GP Validation

- GP analysis validated for solving 3 inputs.
- $f_{s,ult} = REC\frac{1}{2}\sqrt{q_u}\sqrt{q_t}$
- Used FDOT equation with random inputs for q_u q_t and REC.
  - (synthetic load test)
- $f_{s,ult} = 0.498\sqrt{q_u}\sqrt{q_t}\,REC$

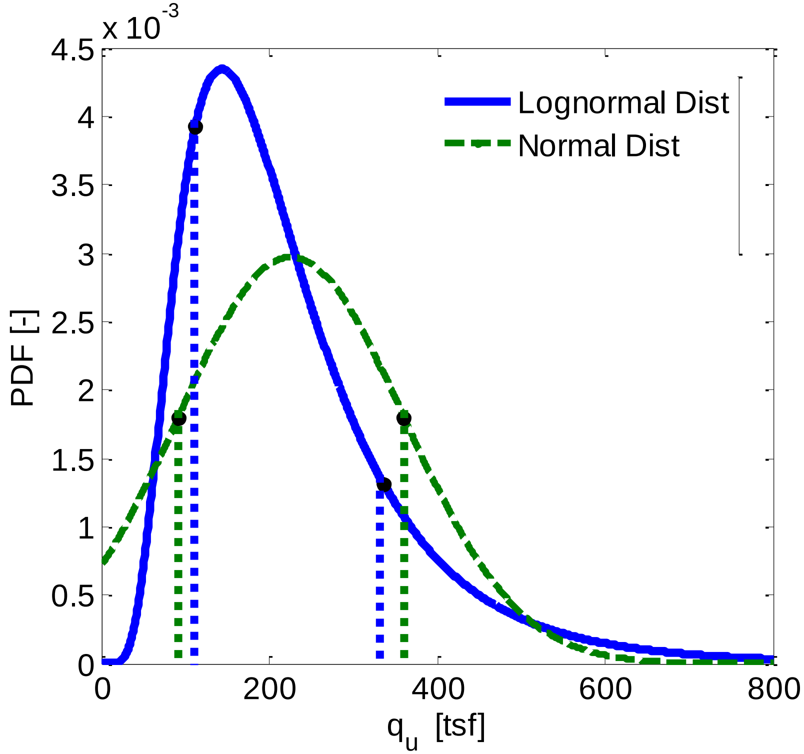




$$\lambda_R = 1$$
$$CV_R = 0$$

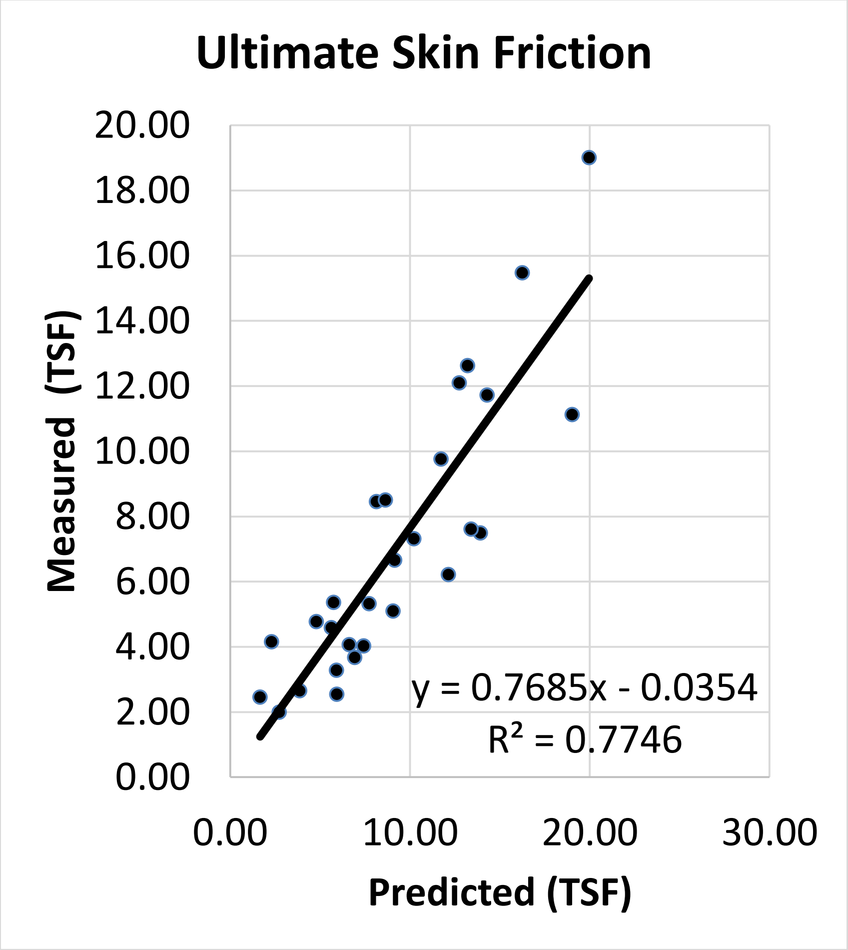
Ultimate Side Resistance

- $f_{s,ult} = Recovery\frac{1}{2}\sqrt{q_u}\sqrt{q_t}$
- Soils and Foundation Hand Book
  - Modify data set limits
  - Assumes normal distribution
  - Selection of q_u and q_t within ± standard deviation
- Rock strength data (q_u and q_t) is generally lognormal.
  - Log (qu and qt) ± standard deviation.



Using Log Normal Distribution for limits

- Upper limit for
  - $q_u > 120$ tsf , $q_u = 120$ tsf
  - $q_t > 20$ tsf, $q_t = 20$ tsf.
  - Highest observed side resistance from database.
- Compared lower limit, mean, and upper limit of laboratory estimated f_s to measured f_s.
- $f_{s,ult} = 0.8\left(\frac{1}{2}\sqrt{q_u}\sqrt{q_t}\ x\ REC\right)$

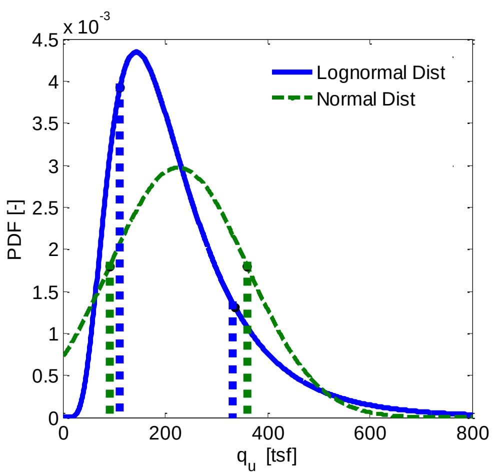


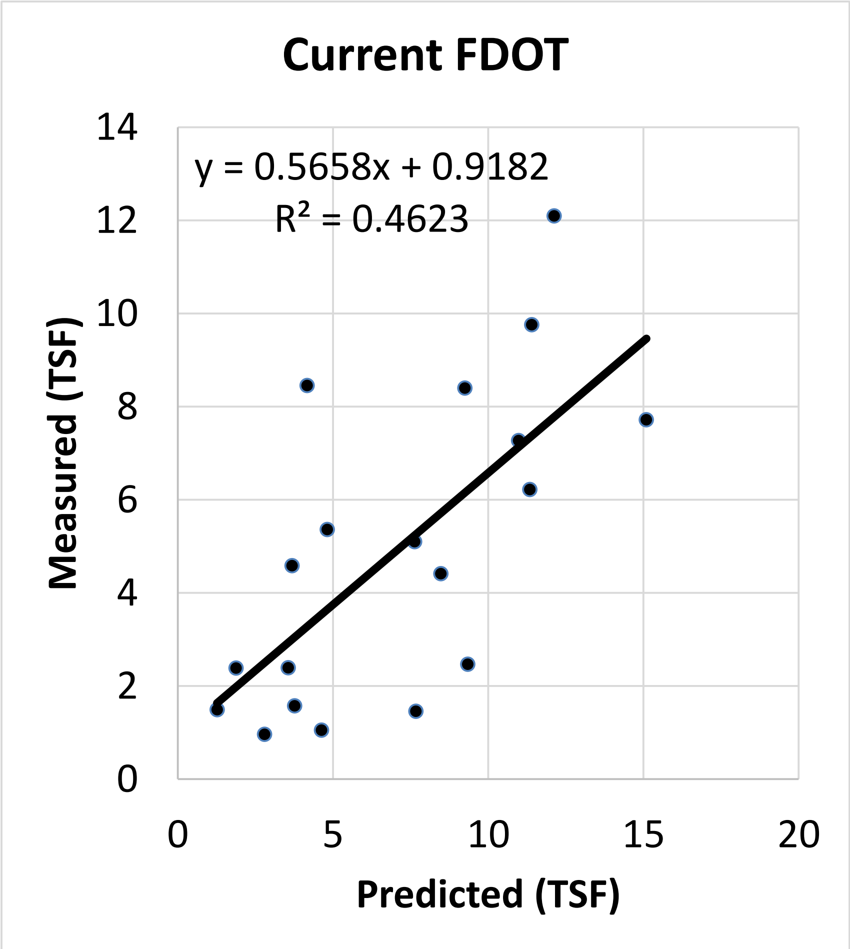
$\lambda_R = 0.80$

$CV_R = 0.37$

Using FDOT Criteria

- Selection of q_u and q_t within ± 1 standard deviation
- Compare lower bound and mean f_s prediction to measured lower bound and mean f_s values.





$\lambda_R = 0.77$

$CV_R = 0.58$

Summary and Conclusions

- GP powerful optimization tool if adequate data is available.
- Database provides means to efficiently access project data.
- Pile Prediction greatly affected by SPT-N truncation (N<5,N=0)
- GP side results similar to FB-DEEP
- Tip is conservative for soil type models 1 and 2.
- Averaging above pile tip results in more conservative estimate.
- Sampling near pile/pier important (< 100 ft)
  - Reduce spatial variability
- Rig Calibration has large influence on method error.

Summary and Conclusion Cont.

- Concrete Pile Side Resistance (Davisson)
  - Soil Type 1 $f_s(tsf) = 0.051 * N + 0.098 \quad < 1.5tsf$
  - Soil Type 2 $f_s(tsf) = 0.037 * N \quad < 1.375tsf$
  - Soil Type 3 $f_s(tsf) = 0.0125 * N + 0.175$
  - Soil Type 4 $f_s(tsf) = 0.0125 * N$
- Concrete Pile Tip Resistance (Davisson)
  - Average 4D below
  - Soil Type 1 $q_T(tsf) = 0.58 * N$
  - Soil Type 2 $q_T(tsf) = 1.08 * N$
  - Soil Type 3 & 4 $q_T(tsf) = 1.25 * N$
- Drilled Shaft Limestone
  - $\frac{f_s}{f_{s,ult}} = \left[\frac{4*R}{4*R+1}\right]^{0.5}$
  - $f_{s,ult} = 0.8\left(\frac{1}{2}\sqrt{q_u}\sqrt{q_t}\ x\ REC\right)$
  - Sort q_u and q_t data in log space.

Questions?