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Documenting, Demonstrating and Enhancing an Offshore Geotechnical Database for Reliability-Based Foundation Design

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Documenting, Demonstrating and Enhancing an Offshore Geotechnical Database for Reliability-Based Foundation Design

by

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Thesis

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Abstract

Documenting, Demonstrating and Enhancing an Offshore Geotechnical Database for Reliability-Based Foundation Design

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There is a large amount of geotechnical data. By putting it into a database, it can be applied to design reliable offshore foundations. The goal of this research is to improve the efficiency and transparency of the implementation of the previously developed reliability-based framework to streamline the process for analyzing and developing an offshore site in the Gulf of Mexico by looking at spatial variations among data sets.

This thesis documents how to store soil behavior information in the database and how to use that information for offshore foundation design. The process is illustrated through observing the steps with figures provided directly from the database so the user can more readily use the database to produce results. This makes the database more transparent for the user to follow the flow of information from input to analysis and to follow the calculation process as well. Enhancements were also made to the database to provide a more readily accessible interface. There is now an allowance of data to streamline the data input process. There is also a set amount of fifty data points to be used in each spatially conditioned analysis.

These detailed explanations and consistencies in data collection help the user to understand the models. This database provides a synthetic image of the site using both physical and statistical parameters where there might not be exact data at a desired foundation location. By providing the industry with a database that uses reliability-based design from actual data and spatial variation analysis, this project will continue to provide a more efficient design process.

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Chapter 1: Introduction

1.1 BACKGROUND INFORMATION

Subsurface explorations present a unique challenge to the practitioner. The practitioner has to work with a small sampling of the subsurface to observe potential soil behaviors over the larger site area. A geotechnical investigation, involving both field and lab observations, is performed to get as much perspective as possible. This investigation is especially difficult when sampling and designing hundreds to thousands of feet below the ocean.

Offshore, these investigations are used to design foundations in deep water. Offshore foundations are generally supported by various arrangements of suction caissons extending into the subsurface, Figure 1-1. Suction caissons, Figure 1-2, are essentially hollow piles that are suctioned into the seafloor through the negative pressure from pumping water out.

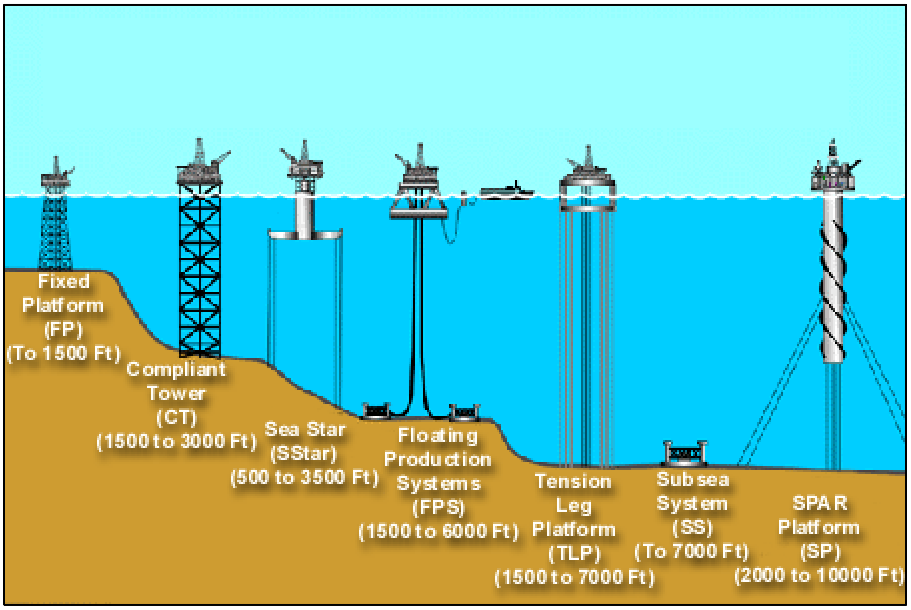


Figure 1-1: Various Offshore Foundation Types (www.naturalgas.org)

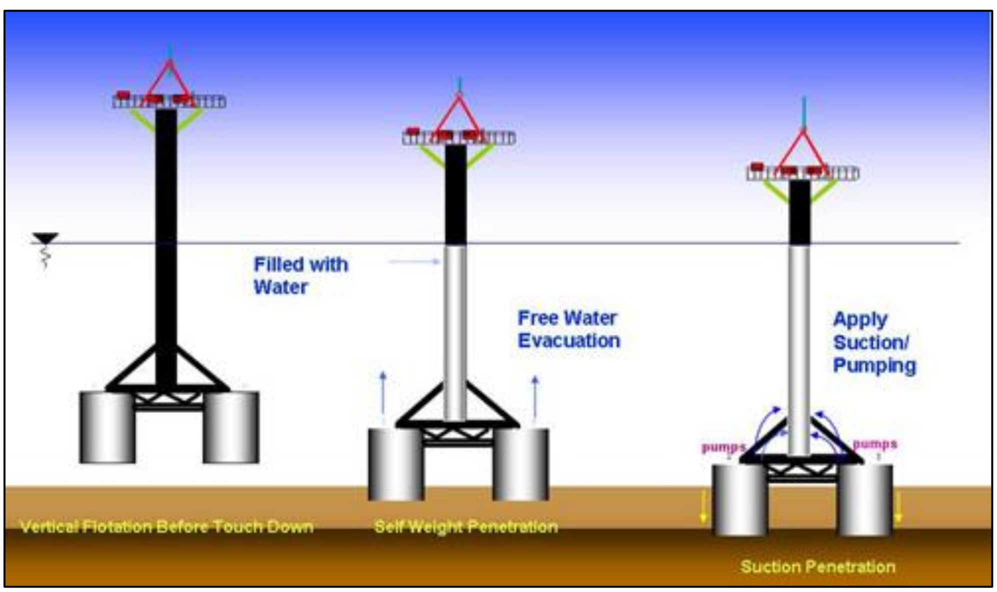


Figure 1-2: Suction Caisson Installation (www.power-technology.com)

As new offshore facilities are developed, new geotechnical data are also being collected. Previous research developed a database to store and use data for foundation design (Cheon 2011). The database is currently designed for deep offshore foundation analysis specifically for the geologic setting of the Gulf of Mexico, which primarily consists of normally to slightly overconsolidated marine clay. The data are analyzed through a reliability-based framework which generates results using both nearby data and overall site generic data for offshore foundation design. The reliability in the design is reflected through inputs based on a target reliability level and outputs an additional factor of safety that accounts for the uncertainty in soil behavior between data points.

The geostatistical methods applied by Cheon are useful to model the spatial variations in soil behavior between data points. The model helps to maximize the value of information from the site investigation. This allows the practitioner to see more of the subsurface behavior while keeping the cost of the investigation within reason.

1.2 MOTIVATION FOR RESEARCH

The database presented has only been used by researchers so far. The reliability-based design implementation developed, as with any research database, becomes more efficient through user demands. The motivation for this thesis is to revise the database to be more easily used by practitioners and to make it more transparent to provide a more efficient design process and to optimize design.

1.3 OBJECTIVES

The goal of this research is to improve the efficiency and transparency of the implementation of the reliability-based framework to streamline the process for analyzing and developing a site. The goal is achieved through the following objectives:

1. Document the practical implementation of a reliability-based framework that has been previously developed to account for spatial variations in soil properties to develop designs for offshore foundations.
2. Demonstrate the implementation of the reliability-based framework, including the steps to input new data, to compile results from new and existing data, to perform the calculations used to develop foundation designs, and to present the results.
3. Conduct a sensitivity analysis to study the effect of the reliability-based framework input parameters on the resulting foundation design.
4. Devise improvements for the implementation of the reliability-based framework to increase the size of the available database and to make the process more user-friendly.

1.4 THESIS ORGANIZATION

This report is organized into six chapters. Chapter 2 documents the framework of the database created by Cheon (2011). A case study in Chapter 3 demonstrates how to use the database from receiving and inputting data to producing an ultimate safety factor for application in foundation design. Chapter 4 provides a sensitivity analysis showing the effects of three statistical parameters on the additional factor of safety and the design axial capacity. In Chapter 5, the improvements to the implementation of the framework are outlined. Finally, Chapter 6 recommends future work and draws conclusions on the research performed. Appendix A provides the theoretical backgrounds for the models discussed and Appendix B provides the Visual Basic code used in various workbooks.

Chapter 2: Framework Documentation

This chapter will provide the user with information on how to use the workbooks, the workbooks' individual worksheets, and where to find the results of those worksheets' analyses. The workbooks are broken into two categories: workbooks that store data and workbooks that use data for foundation design purposes. The workbooks that are used specifically to store information input by the user are:

Table 2-1: Workbooks to Store Information

Workbook Name	Worksheets	Function(s)
Boring Information Location.xlsx	Borings	Store information about boring location and boring sampling
Input.xlsx	Home, Definitions, Borings, Design Su, Design Su_r, Input-Su and Su_avg, Input-Sur and Sur_avg, Input-Su1	Store boring locations, design undrained shear strength data, remolded undrained shear strength data, and equivalent linear undrained shear strength data

The workbooks that are used for foundation design purposes are:

Table 2-2: Workbooks to Analyze Information

Workbook Name	Worksheets	Function(s)
Depth-Averaged and Point Undrained Shear Strength.xlsm	Home, Definitions, Borings, Input, Generic and Conditioned, Correlated Data	Returns the depth-averaged and point undrained shear strengths using the generic and conditional models for user-input location and depth of penetration; returns ranges of correlation coefficients; utilizes a macro for analysis
Generic and Conditional Axial Capacity.xlsm	Home, Definitions, Borings, Input, 1 Existing Data Point, Multiple Existing Data Points, Correlated Data	Returns the axial capacity and additional partial factor of safety using the generic and conditioned models for user-input location and caisson dimensions; returns the ranges of correlation coefficients; utilizes a macro for analysis
Generic and Conditional Lower Bound Axial Capacity.xlsm	Home, Definitions, Borings, Input, 1 Existing Data Point, Multiple Existing Data Points, Correlated Data	Returns the lower bound axial capacity and additional partial factor of safety using the generic and conditioned models for user-input location and caisson dimensions; returns the ranges of correlation coefficients; utilizes a macro for analysis
Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm	Home, Definitions, Borings, Input, Generic and Conditioned, Correlated Data	Returns the equivalent linear undrained shear strength gradient using the generic and conditioned models for user-input location and depth of penetration; returns the ranges of correlation coefficients; utilizes a macro for analysis
Modified Additional Factor of Safety for Lateral Capacity.xlsm	Home, Analysis	Returns the lateral capacity using the model developed by Aubeny et al (2003) for user-input caisson design properties and the equivalent linear undrained shear strength gradient (as found with Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm) and the additional partial spatial factor of safety; utilizes Solver for analysis
UT Caisson Capacities.xlsm	Home, Definitions, Background, Analysis, W' Caisson, 2-tip	Returns the axial and lateral capacity for user-input caisson dimensions and linear or nonlinear point undrained shear strength design profile; utilizes Solver for analysis
FALL16Rev3Mar2008-N	TitlePage, UserGuide, Nomenclature, InputForm, MasterPage	Returns suctions caisson capacities for user-input caisson properties, load characteristics, and soil properties; utilizes Solver for analysis

Within both the input workbooks and the analysis workbooks, the worksheets are set up to highlight where the user will input new information, yellow highlighted cells, and where the user will see results generated from analysis, blue highlighted cells. The workbooks are all organized into a framework. Information located within certain worksheets in "Input.xlsx" is used among the various analysis worksheets as follows.

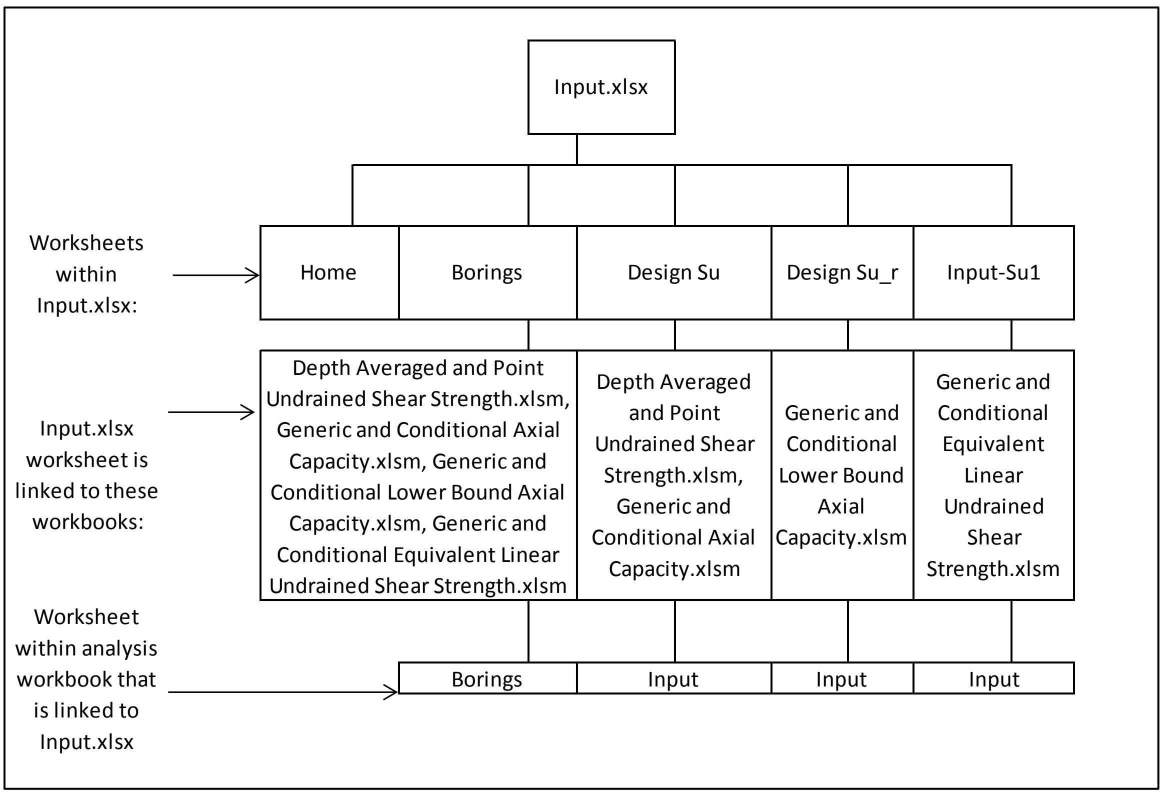


Figure 2-1: Flow of Information from Input.xlsx to Analysis Workbooks

Section 2.1 documents using the input workbooks and Section 2.2 documents using the analysis workbooks.

2.1 INPUT WORKBOOKS

The input workbooks are used to hold all the data to be used in the various analyses. The user will manually input information into these workbooks and copy adjacent formulas for an accurate analysis. Some information within the input workbooks was used for research purposes only and is hidden for this documentation as it is not relevant; the gaps can be recognized as inconsistencies in the alphabetic labeling of columns. Also, some information will be grayed out as it is confidential and cannot be shown. One last thing to note is that the information or data for a sample may be received with different information depending on sampling conditions and what information was recorded by the data provider. So when viewing the sampling information, some samples might have empty fields where other samples have a full set of information. These data gaps do not affect the analysis; they are simply how the information was received.

2.1.1 Boring Location Information

"Boring Location Information.xlsx" provides a comprehensive list of all lab and field information. The boring is identified first by a unique identifier and name. The unique identifier, UT ID, is an integer that identifies that unique boring and the data points on the design shear strength profile from that boring. The "New Name" is a combination of the name of the site and the boring number. For example, if the site was named Field 1 and the boring was named BH-1, the "New Name" would be Field 1 BH-1. The location information is stored next in easting and northing, in feet and meters, with the UTM zone, and then longitude and latitude. The location information is provided as UTM location using the NAD 1927 projection datum and an online converter was used to find the longitude and latitude with that given location information.

.

	A	B	C	D	E	F	G	H	I	J
1										
2	UT ID	New Name	Easting (ft)	Northing (ft) = y	UTM Zone	x (ft)	Easting (m)	Northing (m)	longitude (deg)	latitude (deg)
3	1									
4	2									

Figure 2-2: Name and Location Information in Columns A-J of Borings Worksheet within "Boring Location Information.xlsx"

The next set of information for the boring provides location information relative to the nearest river inlet to the Gulf of Mexico.

	K	L	M	N	P	Q	R	S	T	U	V	W
1												
2	r_M (ft)	θ_M (deg)	x_M (ft)	y_M (ft)	distance (ft)	from mouth of	Mississippi	Calcasieu	Sabine	Trinity	Brazos	Colorado
3												
4												

Figure 2-3: Location Information in Columns K-W of Borings worksheet within "Boring Location Information.xlsx"

The r-θ coordinates are relative to the mouth of the nearest river. In columns R-W, the distance to the rivers is displayed and the nearest distance is highlighted in orange.

The next set of information has to do with the sampling of the specimens from type of sampling and the sampling tube. "DB" is the client that the site investigation is done for. Maximum penetration is the total depth of sampling below the mudline.

	X	Y	AA	AC	AD	AE	AF	AG	AH	AI
1										
2	Type of Sampling	Max Depth	ProjDatum	DB	Water Depth (ft)	Max Penetration	Sampling Method: Pushed (0) / Driven (1)	Sampling Tube, Primary	Boring Date	Report Date
3	Boring	496	NAD1927		3221		0	3" Shelby		
4	Boring	297	NAD1927		3438		0	3" Shelby		

Figure 2-4: Sampling Information in Columns X-AI of Borings worksheet within "Boring Location Information.xlsx"

The final set of information fields has to do with the sample's proximity to the nearest coast and where that nearest coast location is.

	AK	AL	AM	AN	AO	AP	AQ	AR	AS
1					Nearest Coast				Distance off coast (ft)
2		x-distance to mouth of river	distance from mouth		Easting (ft)	Northing=y (ft)	UTM Zone	x (ft)	d
3								2864508	416282.0179
4								2864508	420012.0669

Figure 2-5: Columns AK-AS of Borings

2.1.2 Input

"Input.xlsx" contains all of the data used in generating results. The "Home" worksheet reminds the user to change data in this workbook only as this information is linked to certain analysis worksheets. The information stored in "Borings," "Design Su," and "Design Su_r" is directly received from the client. The "Input-…" worksheets are where the user translates the provided design profiles to data points that are used in analysis. There is a text box in each of the worksheets in "Input.xlsx" to remind the user to check that data have carried from the appropriate fields in analysis worksheets, so that all data are included in the model.

The "Borings" worksheet is set to deal with 200 unique borings. The information provided in the "Borings" worksheet is the same information stored in "Boring Location Information.xlsx."

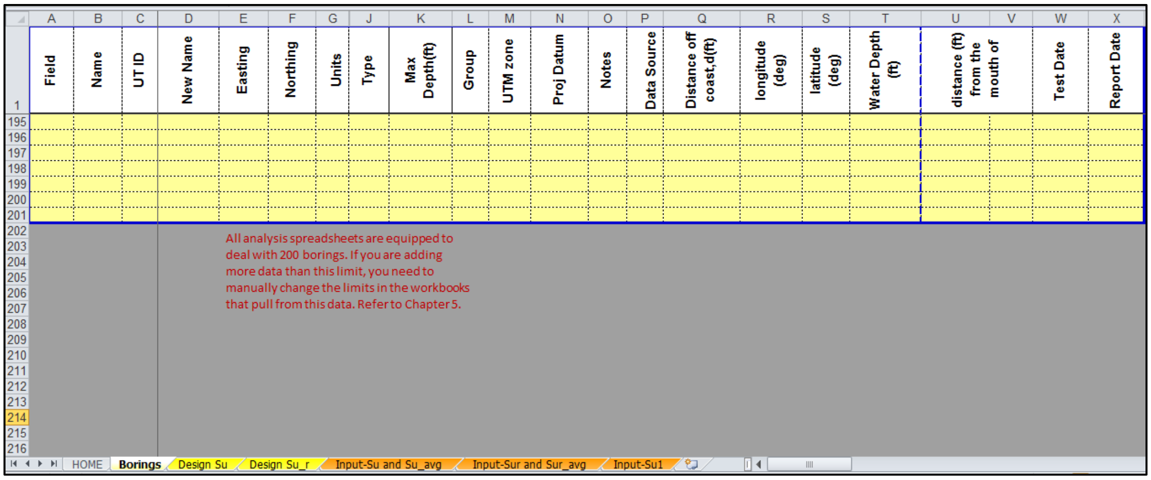
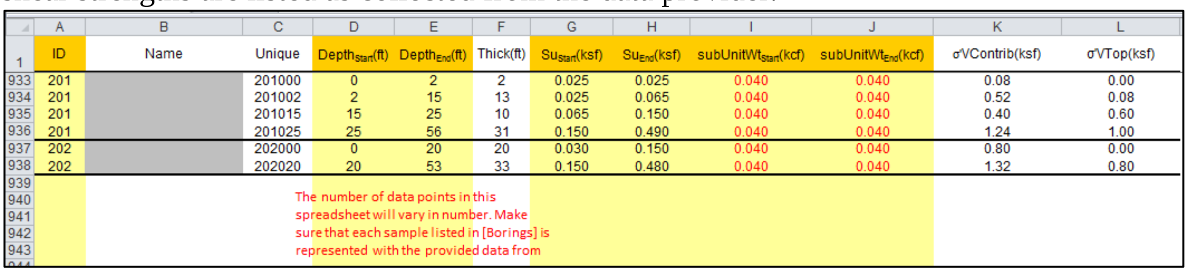


Figure 2-6: “Borings” Worksheet of “Input.xlsx”

The next worksheet, “Design Su,” in “Input.xlsx” is where the design undrained shear strengths are listed as collected from the data provider.



	ID	Name	Unique	$Depth_{Start}$(ft)	$Depth_{End}$(ft)	Thick(ft)	Su_{Start}(ksf)	Su_{End}(ksf)	$subUnitWt_{Start}$(kcf)	$subUnitWt_{End}$(kcf)	σ'VContrib(ksf)	σ'VTop(ksf)
933	201		201000	0	2	2	0.025	0.025	0.040	0.040	0.08	0.00
934	201		201002	2	15	13	0.025	0.065	0.040	0.040	0.52	0.08
935	201		201015	15	25	10	0.065	0.150	0.040	0.040	0.40	0.60
936	201		201025	25	56	31	0.150	0.490	0.040	0.040	1.24	1.00
937	202		202000	0	20	20	0.030	0.150	0.040	0.040	0.80	0.00
938	202		202020	20	53	33	0.150	0.480	0.040	0.040	1.32	0.80

Figure 2-7: “Design Su” worksheet of “Input.xlsx”

The ID and name are the same as in “Boring Location Information.xlsx.” The unique number is calculated as multiplying the ID by one thousand and adding the start depth of the sample. This was chosen based on the potential amount of data so that each individual data point has its own unique identifier. The depths of sampling are provided from the data provider with the design undrained shear strength and unit weight. The effective strength is calculated as follows:

$$\sigma' v_{Contrib} = (subUnitWt_{Start} + subUnitWt_{end}) \times Thickness/2 \qquad (2.1)$$

$$\sigma' v_{Top,i} = \sigma' v_{Top,i-1} + \sigma' v_{Contrib,i} \qquad (2.2)$$

where: $\sigma' v_{Contrib}$= vertical effective stress at depth of top of sample

$\sigma' v_{Top,i}$= vertical effective stress at depth of bottom of sample

$\sigma' v_{Top,i-1}$= vertical effective stress at top of sample

The remolded design shear strength data input, “Design Su_r” worksheet, is set up similar to “Design Su,” but with the remolded design undrained shear strength profile.

	A	B	C	D	E	F	G	H	I	J	K	L
1	ID	Name	Unique	$Depth_{Start}$ (ft)	$Depth_{End}$ (ft)	Thick (ft)	Su_{Start} (ksf)	Su_{End} (ksf)	$subUnitWt_{Start}$ (kcf)	$subUnitWt_{End}$ (kcf)	σ'VContrib (ksf)	σ'VTop (ksf)
819	185		185012	12	30	18	0.030	0.100	0.022	0.035	0.51	0.26
820	185		185030	30	50	20	0.100	0.180	0.035	0.040	0.75	0.77
821	185		185050	50	65	15	0.180	0.240	0.040	0.043	0.62	1.52
822	185		185065	65	110	45	0.240	0.500	0.043	0.047	2.03	2.14
823	185		185110	110	145	35	0.500	0.650	0.047	0.048	1.66	4.16
824	185		185145	145	172	27	0.650	0.650	0.045	0.054	1.34	5.82
825	185		185172	172	187	15	0.650	0.650	0.054	0.054	0.81	7.16
925												
926			Data in this spreadsheet will vary in									
927			number. Make sure that each sample									
928			listed in [Borings] is represented with the									
929			provided data from lab/field tests.									
930												

Figure 2-8: “Design Su_r” Worksheet of “Input.xlsx”

The next worksheet in Input.xlsx is called “Input-Su and Su_avg.” This worksheet contains the point undrained shear strength, column G, read from the design profile in “Design Su,” and the depth-averaged undrained shear strength, which is calculated from the point undrained shear strength as documented in Appendix A from Cheon (2011).

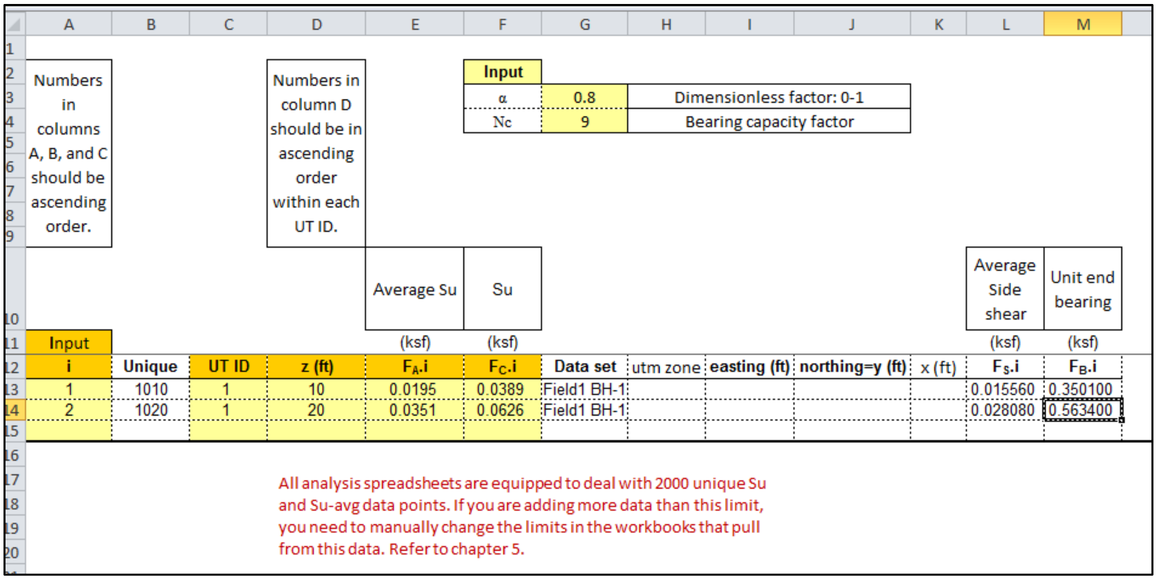


Figure 2-9: “Input-Su and Su_avg” worksheet of “Input.xlsx”

Column A is a unique identifier for each data point determined by numbering the individual data points in ascending order. This “i” value is the value that corresponds to the “2000 unique Su and Su-avg data points” mentioned in the text box. The worksheet is set to deal with a maximum of 2000 unique data points.

The next columns are where the user inputs data in ten-foot increments as prescribed by the model (Cheon 2011), starting with z=10 feet and continuing in ten-foot increments until the bottom of sampling for that boring. For example, if a boring is sampled from 2 to 75 feet, there will be seven unique data points from z=10 ft to z=70 ft. The point design undrained shear strength, Su, column F, is found as the point on the design shear strength profile, provided in “Design Su.” The depth-averaged design undrained shear strength is found as the area under the point-undrained shear strength profile curve. The depth-averaged design undrained shear strength is calculated as follows:

$$S_{u,avg}(L) = \frac{1}{L}\int_0^L S_u(z)dz \tag{2.3}$$

where: L=depth of penetration in feet

Using the data provided in figure 2-6 with equation 2.3, the depth-averaged undrained shear strength at 10 feet is calculated as follows:

$$S_{u,avg}(20) = \frac{1}{20}\left[\frac{0 + 0.0389}{2} \times 10 + \frac{0.0389 + 0.0626}{2} \times 10\right] = 0.0351\ ksf$$

Columns L and M are the average side shear and end bearing, which are the factored depth-averaged undrained shear strength and point undrained shear strength, respectively.

$$F_{s\cdot i} = F_{A\cdot i} \times \alpha \tag{2.4}$$

$$F_{B\cdot i} = F_{C\cdot i} \times N_c \tag{2.5}$$

where: $F_{s\cdot i}$= factored average side shear at depth

$F_{A\cdot i}$= depth-averaged shear strength

α= friction factor for side shear

$F_{B\cdot i}$= unit end bearing at depth

$F_{C\cdot i}$= point undrained shear strength

N_c= bearing capacity factor

The next worksheet in “Input.xlsx” is for use in lower bound axial capacity analyses, “Input-Sur and Sur_avg”. The calculations are the exact same as the undisturbed strengths except for the data being used. The data used are from the remolded samples, where the design remolded undrained shear strength profiles are located in “Design Su_r.”

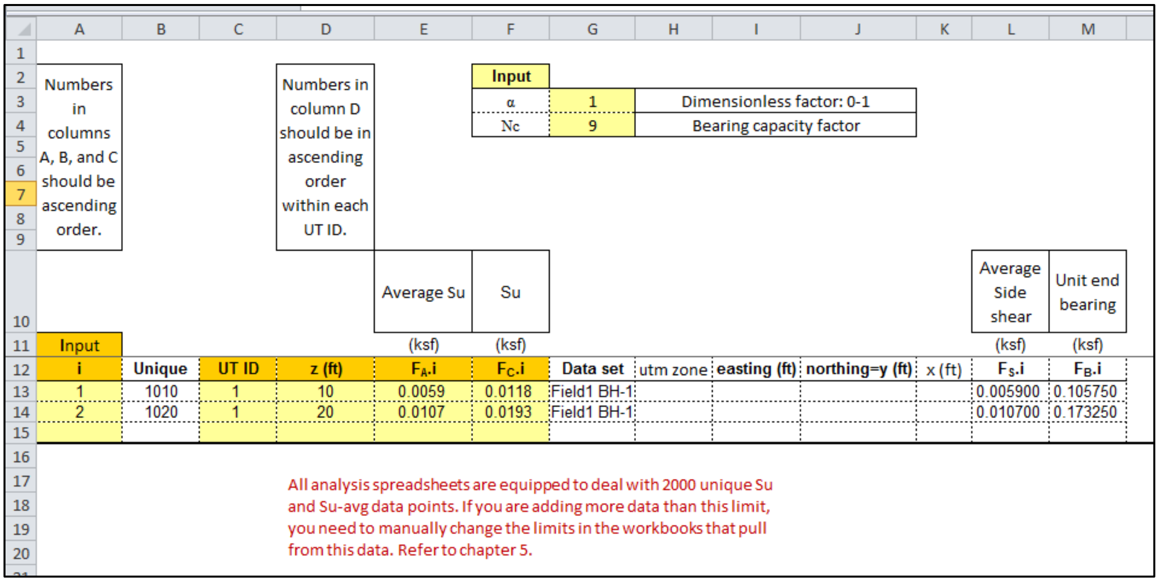


Figure 2-10: “Input-Sur and Sur_avg” Worksheet of “Input.xlsx”

The identifying numbers, “i,” are reused with the data used in different analyses. The data sets share the same names as well. The equations to find the averaged side shear and unit end bearing here are the same as for “Input Su”, but use an alpha of 1 to account for remolded strengths being used in this lower-bound analysis.

The final worksheet of “Input.xlsx” is stores the equivalent linear undrained shear strength profile, Su1. This gradient is calculated using the nonlinear design undrained shear strength profile. The lateral capacity is found for the design profile using “UT Caisson Capacities.xlsm.” Then, the user uses “Fall16Rev3Mar2008-N.xlsm” and calculates the lateral capacity while guessing on the shear strength gradient until the lateral capacity matches that calculated in “UT Caisson Capacities.xlsm.”

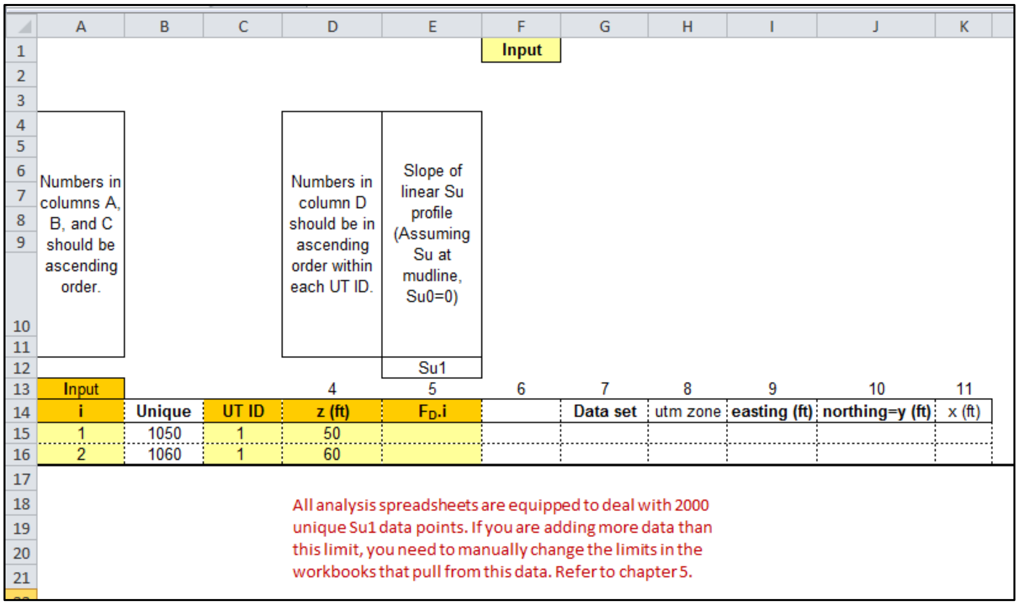


Figure 2-11: "Input-Su1" Worksheet of "Input.xlsx"

2.2 ANALYSIS IMPLEMENTATION

The analysis workbooks are grouped according to their respective results. The workbooks used for axial capacity analysis are set up very similarly while the workbooks used for lateral capacity analysis are set up similarly as well. The models referenced from Cheon (2011) in this section are presented in Appendix A.

The "Home" worksheets within the workbooks have been enhanced to make the database more transparent and more user-friendly. The "Home" worksheets now contain notes on how to use the workbook from inputting information to finding the calculated results and seeing the ranges in the correlated data that were used in the calculations. The "Borings" worksheets in the analysis workbooks is similar to the "Borings" worksheet in "Input.xlsx" and the number of borings should be the same between the "Borings" worksheets.

There are visual similarities between the worksheets within the analysis workbooks in the organization of the data and model calculations. The orange, gray, or white cells are either linked to other worksheets within that workbook or are linked to worksheets within “Input.xlsx” and the blue cells are the results of the calculations. Figures are provided to follow the process of inputting new data, which cells are activated during analysis, and where to find the generated results. The information in the “Borings” and “Input” worksheets must be linked to “Input.xlsx” through the following path within Excel: Data → Connections → Edit Links and then either Update Values if the source is already linked or Change Source if the proper Input workbook is not linked.

2.2.1 Unfactored Undrained Shear Strength Analysis

“Depth-Averaged and Point Undrained Shear Strength.xlsm” calculates the mean, standard deviation, and coefficient of variation of the unfactored depth-averaged undrained shear strength and the unfactored point undrained shear strength of both the generic and the conditional models.

CHEON, JEONG YEON-UT2009 luv.doogie@gmail.com
Revisions by:
Zadrozny, Katherine - UT 2013 zadroke@gmail.com

◆NOTE
-Do not move, delete or hide worksheets.
-Fill or change values only in the yellow highlighted cells.
-This workbook has been updated so that the macros work with the present version of Microsoft Excel 2010.
-As more data is received, make sure to carry down the formulas within the [Input] sheet and update the n-value, G4, to match the number of data points

To change or update values in the [Borings] sheet, open c:\BP-database\C-Analysis Workbooks\INPUT.xls.x

Input worksheet

Borings	Contains UT ID, data set name, location information, Utm zone
Input	Contains Su and Su_avg with depth and correlation calculations

To change or update values in the [Input] sheet, copy the formulas throughout all the columns , A-AH, to include all data from c:\BP-database\C-Analysis Workbooks\INPUT.xls.x

Calculation worksheet

generic and conditioned	Reports generic Su and Su_avg and spatially conditioned, unfactored, Su and Su_avg calculated from muliple existing data points
Correlated Data	Reports ranges of correlation coefficients with maximum and minimum corresponding data point
cmatrix	Covariance matrix calculations

◆how to use:
1. Check all input data in the "INPUT.xls" workbook (C:\BP-database\C-Analysis Workbooks\)
2. Fill the model parameters in the "[nput] worksheet for depth averaged and point shear strength, respectively: cells B3-10 and D3-D10.
3.Go to the [generic and conditioned] sheet and fill in location information it UTM format.
4. Fill in specified caisson diameter.
5. To generate a profile, generate results at a regular depth interval (i.e. 10 foot intervals to a depth of 100 ft).
6. With steps 3,4, and 5, the results for generically calculated values will be shown with each interval.
7. Click the macro button to calculated spatially conditioned shear strengths
8. If there is an error in the data being "out of range," increase the m1 and m2 values, G2 and G3, in [Input].
9. If the results return no correlated points for the spatially conditioned profile, try increasing the m1 and m2 values, G2 and G3, in [Input].

◆results of [generic and conditioned]:
1. The mean spatially conditioned depth averaged shear strength is given in cell I4.
2. The spatially conditioned point shear strength is given in cell I9.
3. In columns L-T, are the data sets that were used in the spatially conditioned calculations for depth averaged shear strength.
4. In columns V-AD, are the data sets that were used in the spatially conditioned calculations for point shear strength.

Figure 2-12: “Home” Worksheet Information of “Depth-Averaged and Point Undrained Shear Strength.xlsm”

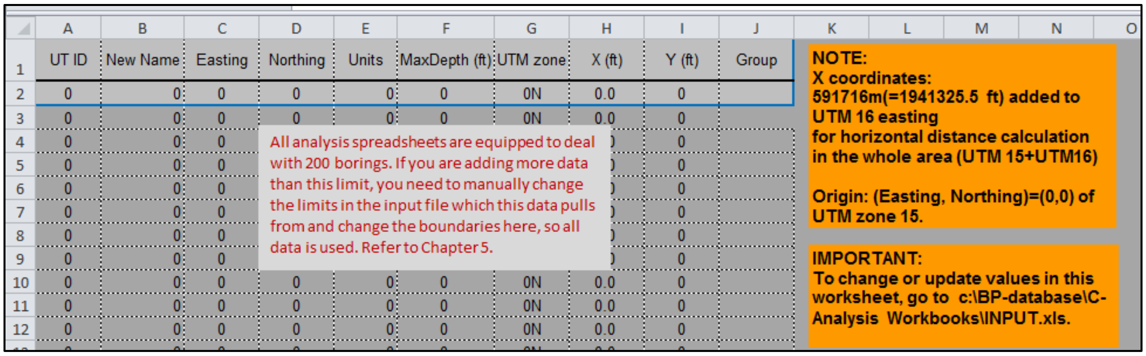


Figure 2-13: “Borings” Worksheet of “Depth-Averaged and Point Undrained Shear Strength.xlsm”

The “Input” worksheet of this workbook contains the design shear strength data from “Input-Su and Su_avg” of “Input.xlsx” and the calculations that correlate those points to the user-input foundation location for analysis.

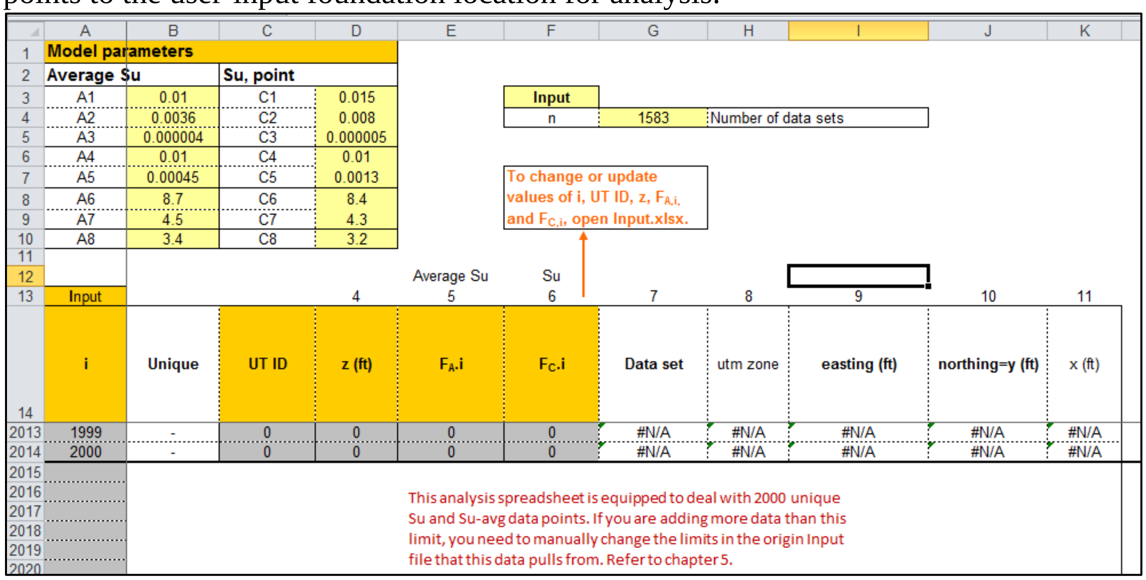


Figure 2-14: “Input” Worksheet of “Depth-Averaged and Point Undrained Shear Strength.xlsm”

The model parameters listed in the top right corner of the worksheet are used to calculate depth-averaged undrained shear strength and point undrained shear strength for each data point, i.e. each “i.” The number of data points, cell G4, uses the built-in Excel Count() function to count how many data points are currently available for analysis.

Columns A, C, D, E, and F are all linked to “Input-Su and Su_avg” of “Input.xlsx.” Columns B and G-K are as explained in 2.1.3. Columns G-K are linked to the “Borings” worksheet within this analysis workbook using the built-in Excel function Vlookup(). The Vlookup() function finds the UT ID in Column C in “Borings” and then returns the respective value, such as x, y, or data set.

Scrolling right within “Input” shows where the calculations are performed for analysis. The reliability-based model is provided in Appendix A with the calculations used to populate the cells.

	P	Q	R	S	T	U	V	W	X	Y	Z	AA
13	16	17	18	19	20	21	22	23	24	25	26	27
14	μFs	δFs	σFs	Fs-μFs	$\theta_{H,s}$	$\theta_{V,s}$	μF_B	δF_B	σF_B	F_B-μF_B	$\theta_{H,B}$	$\theta_{V,B}$
15	0.046	0.313	0.015	0.041192	6903	30	0.096	0.241	0.023	0.015333	5184	25
16	0.084	0.227	0.019	0.034738	7803	30	0.177	0.203	0.036	0.018000	5921	25

	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1–7			This value checks with the reported maximum correlation coefficient for side shear	This value checks with the reported maximum correlation coefficient for end bearing					
8			0.000112084	6.21973E-06					
13	28	29	30	31	32	33			
14	τ_h	τ_v	ρ_s	ρ_B	$C_{AB\ for\ s}$	$C_{AB\ for\ B}$	i	Rank of Correlation Coefficient for Side Shear (Column 30)	Rank of Correlation Coefficient for End Bearing (Column 31)
15	########	10	1.06912E-61	4.58676E-81	3.4463E-73	1.5251E-95	1	796	796
16	########	0	1.49267E-61	6.895E-81	5.3885E-65	8.9359E-84	2	785	787

Figure 2-15: “Input” Worksheet Calculations of “Depth Averaged and Point Undrained Shear Strength.xlsm”

These fields are located in columns P-AJ of the “Input” worksheet. They are numbered to help reference the columns in the VBA code provided in Appendix B which is used to generate results. Columns 16-33 are as calculated in Appendix A and use the same parameters that Cheon (2011) devised for the model. The “i” value is provided to the right for ease of referencing so that the user doesn’t have to scroll from side to side of the worksheet. The ranks of columns 30 and 31 are an enhancement to the database and are used to select the highest 50 correlated values to be used in the covariance matrix calculations, provided in Appendix A.

The next worksheet of this workbook is where the macro button is to return the calculated results for the generic and conditioned models relating a new foundation location to the existing data.

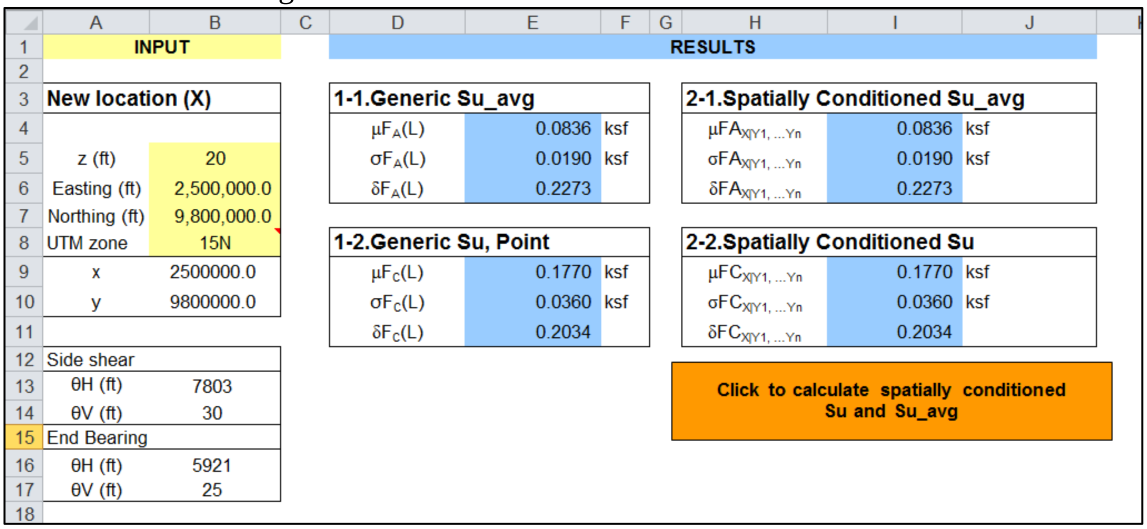


Figure 2-16: "Generic and Condtioned" Worksheet of "Depth-Averaged and Point Undrained Shear Strength.xlsm"

The generic model will be the same at depth regardless of location. The spatially conditioned results are calculated by clicking on the orange button which runs the macro and populates the blue cells.

Upon putting in a new location, certain columns of the "Input" worksheet change to relate the new location to each data point. Columns A-K will stay the same regardless of what new location is put in and columns P-AJ will be populated using the model developed by Cheon (2011). Then a rank for correlation coefficient values of depth-averaged undrained shear strength and point undrained shear strength between existing datum and the new location is produced. The top fifty correlation coefficients correspond to the data points that are used in the covariance matrix analysis to generate the spatially conditioned results.

Also within this analysis worksheet are those 50 correlated data points used in the calculations.

	L	M	N	O	P	Q	R	S	T	U
1	Number of correlated data points									
2	50		Average Su							
3	i	ρ_{XY}	$F_{A,i}$(ksf)	z (ft)	Easting (ft)	Northing (ft)	UTM zone	UT ID	Data set	

	V	W	X	Y	Z	AA	AB	AC	AD
1	Number of correlated data points								
2	50		Su						
3	i	ρ_{XY}	F_C.i	z (ft)	Easting (ft)	Northing (ft)	UTM zone	UT ID	Data set

Figure 2-17: Correlated Data Points Used in Calculations from "Generic and Conditioned" Worksheet of "Depth-Averaged and Point Undrained Shear Strength.xlsm"

The "Correlated Data" worksheet has been added to check and make sure the model is working correctly and that the model is using fifty individual correlated data points. Columns M and W of "Generic and Conditioned" are further analyzed in the next worksheet to show the ranges of the correlation coefficients.

	A	B	C	D	E	F	G	H
1		Depth-Averaged:				Point:		
2		Correlated Data Summary				Correlated Data Summary		
3		Max and Min ρ		Data set		Max and Min ρ		Data set
4		highest value	--	--		highest value	--	--
5		lowest value	--	--		lowest value	--	--
6		ρ limits	Number of Correlated Points			ρ limits	Number of Correlated Points	
7		>0.5	0			>0.5	0	
8		0.4-0.5	0			0.4-0.5	0	
9		0.3-0.4	0			0.3-0.4	0	
10		0.2-0.3	0			0.2-0.3	0	
11		0.1-0.2	0			0.1-0.2	0	
12		0-0.1	50			0-0.1	50	
13		sum to check:	50 Correlated Points			sum to check:	50 Correlated Points	
14								

Figure 2-18: "Correlated Data" Worksheet of "Depth-Averaged and Point Undrained Shear Strength.xlsm"

These tables in "Correlated Data" read information from the two tables in "Generic and Conditioned" and return the highest and lowest correlation coefficients used in analysis with their corresponding data set "i," which is column A in the "Input" worksheet of this analysis workbook. The correlation coefficient limits are set to provide an overview of the correlated data used. The current display is showing 50 points with correlation coefficients of 0 to 0.1 because there was no analysis run. The sum to check should always be 50, all coefficients will be accounted for when "sum to check:" reads "50 Correlated Points."

2.2.2 Average and Lower Bound Axial Capacity Analyses

Generic and Conditional Axial Capacity

"Generic and Conditional Axial Capacity.xlsm" calculates the mean, standard deviation, and coefficient of variation of the axial side shear capacity, the axial end bearing capacity, and the total axial capacity of a new location using just one location or using the fifty locations with the highest correlation coefficients. The analysis returns a generic and conditional additional partial spatial factor of safety using a target reliability index to reflect the uncertainty in the model from not having exact site specific data.

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♦**NOTE**

-Do not move, delete or hide worksheets.

-Fill or change values only in the yellow highlighted cells.

-This workbook has been updated so that the macros work with Microsoft Excel 2010.

-As more data is received, make sure to carry down the formulas within the [Input] sheet and update the n-value, G4, to match the available number of data points.

To change or update values in the [Borings] sheet, open c:\BP-database\C-Analysis Workbooks\INPUT.xls.x

Input worksheet

Borings	Contains UT ID, data set name, location information, Utm zone
Input	Contains Su and Su_avg with depth and correlation calculations

To change or update values in the [Input] sheet, copy the formulas throughout all the columns , A-AH, to include all data from c:\BP-database\C-Analysis Workbooks\INPUT.xlsx.

Calculation worksheet

1 existing data point	Reports axial capacity conditioned generically and exactly as reported from one existing data point
multiple existing data points	Reports generic capacty and axial capacity conditioned generically and spatially from muliple existing data points
Correlated Data	Reports ranges of correlation coefficients with maximum and minimum corresponding data point
cmatrix	Covariance matrix calculations

♦**how to use:**

1. Check all input data in the "INPUT.xls" workbook (C:\BP-database\C-Analysis Workbooks\)
2. Fill the model parameters in the [Input] worksheet for side shear and end bearing, respectively: cells B3-B10 and D3-D10.
3. Go to the [multiple existing data points] sheet and fill in location information in UTM format.
4. Fill in specified caisson diameter and length and check that the correlation coefficient is 0.5.
5. Fill in the statistical parameters for the reliability-based design.
6. With steps 3, 4, and 5, the results for the generically calculated values will be shown.
7. Click the macro button to calculate spatially conditioned capacities.
8. If there is an error in the data being "out of range," increase the m1 and m2 values, G2 and G3, in [Input].
9. If the results return no correlated points for the spatially conditioned profile, try increasing the m1 and m2 values, G2 and G3, in [Input].

♦results of [multiple existing data points]:

1. The mean spatially conditioned total axial capacity is given in cell I20.
2. The partial spatial factor of safety and the partial resistance factor are given in cells I38 and I39, respectively.
3. In columns L-T, are the data sets that were used in the spatially conditioned calculations for side shear.
4. In columns V-AD, are the data sets that were used in the spatially conditioned calculations for end bearing.

Figure 2-19: “Home” Worksheet of “Generic and Conditional Axial Capacity.xlsm”

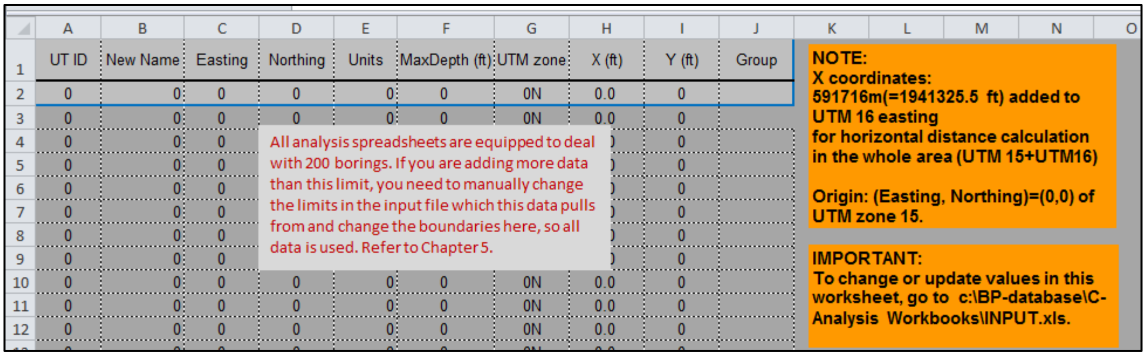


Figure 2-20: “Borings” Worksheet of “Generic and Conditional Axial Capacity.xlsm”

The “Input” worksheet of this workbook contains the shear strength data from “Input-Su and Su_avg” of “Input.xlsx” and the calculations that correlate those data points to the user-input foundation location for analysis. It is similar to the depth-averaged and point undrained shear strength data with factors, α and N_c, to convert the shear strengths to axial capacities.

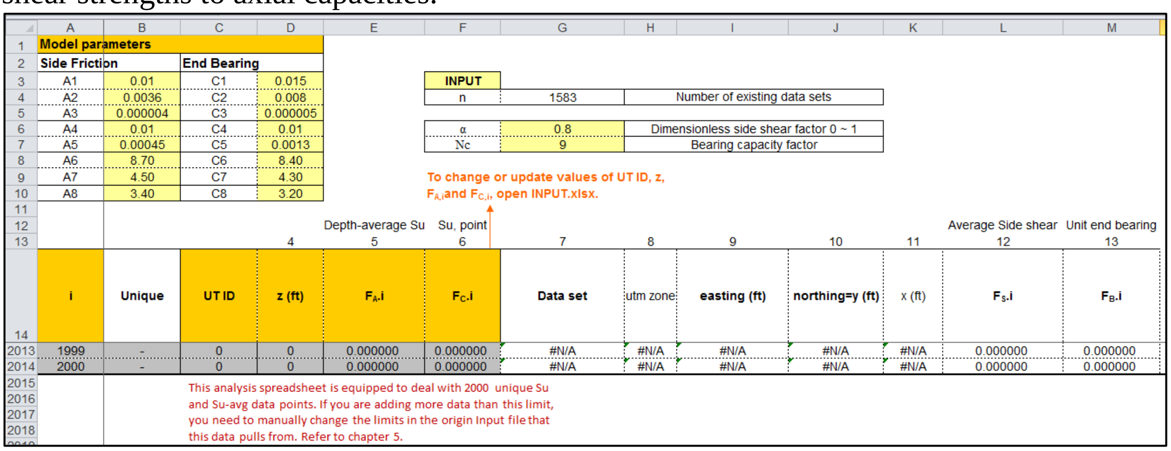
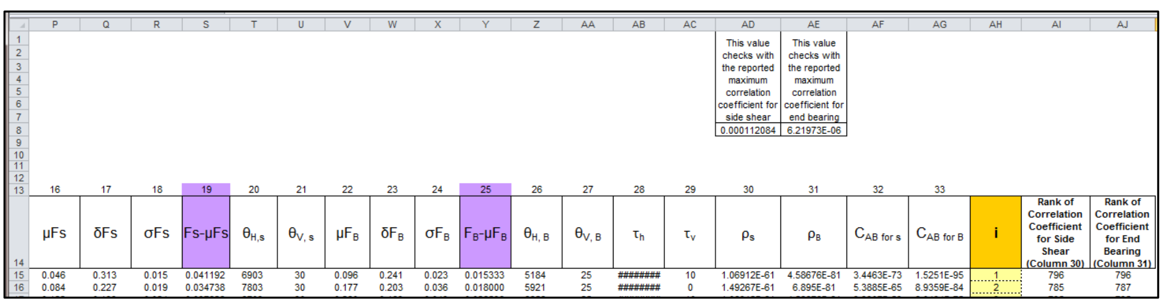


Figure 2-21: “Input” Worksheet of “Generic and Conditional Axial Capacity.xlsm”

The model parameters listed in the top right corner of the worksheet are used to calculate depth-averaged undrained shear strength and point undrained shear strength for each data point, i.e. each “i.” The average side shear and unit end bearing capacity calculations use these parameters and then factor the strengths accordingly to produce side shear and end bearing capacities. The number of data pointts, cell G4, uses the built-in Excel Count() function to count how many data points are currently available for analysis.

Columns A, C, D, E, and F are all linked to “Design-Su and Su_avg” of “Input.xlsx.” Columns B and G-K are as explained in 2.1.3. Columns G-K are linked to the “Borings” worksheet within this analysis workbook using the built-in Excel function Vlookup(). The Vlookup() function finds the UT ID in Column C in “Borings” and then returns the respective value, such as x, y, or data set.

Scrolling right within “Input” shows where the calculations are performed for analysis. The reliability-based model is provided in Appendix A with the calculations used to populate the cells.

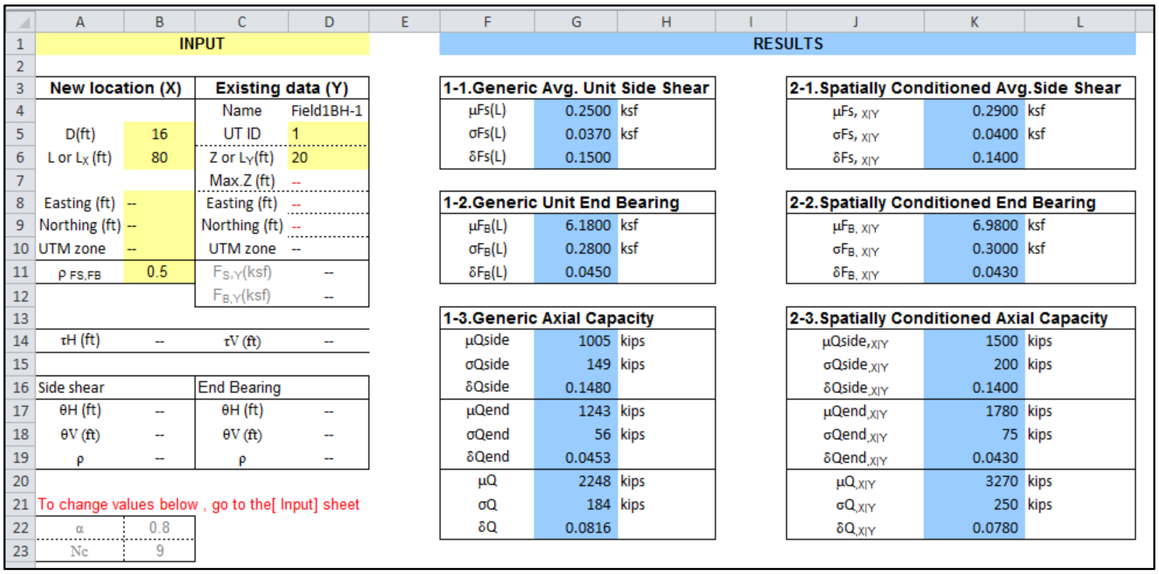


	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1–7															This value checks with the reported maximum correlation coefficient for side shear	This value checks with the reported maximum correlation coefficient for end bearing					
8															0.000112084	6.21973E-06					
13	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33			
14	μFs	δFs	σFs	Fs-μFs	$\theta_{H,s}$	$\theta_{V,s}$	μF_B	δF_B	σF_B	F_B-μF_B	$\theta_{H,B}$	$\theta_{V,B}$	τ_h	τ_v	ρ_s	ρ_B	$C_{AB\ for\ s}$	$C_{AB\ for\ B}$	i	Rank of Correlation Coefficient for Side Shear (Column 30)	Rank of Correlation Coefficient for End Bearing (Column 31)
15	0.046	0.313	0.015	0.041192	6903	30	0.096	0.241	0.023	0.015333	5184	25	########	10	1.06912E-61	4.58676E-81	3.4463E-73	1.5251E-95	1	796	796
16	0.084	0.227	0.019	0.034738	7803	30	0.177	0.203	0.036	0.018000	5921	25	########	0	1.49267E-61	6.895E-81	5.3885E-65	8.9359E-84	2	785	787

Figure 2-22: “Input” Worksheet Calculations of “Generic and Conditional Axial Capacity.xlsm”

These fields are located in columns P-AJ of the “Input” worksheet. They are numbered to help reference the columns in the VBA code. Columns 16-33 are as calculated in Appendix A and use the same parameters that Cheon (2011) devised for the model. The “i” value is provided to the right for ease of referencing so that the user doesn’t have to scroll from side to side of the worksheet. Columns 30 and 31 are an enhancement to the existing database and are used to select the highest 50 correlated values to be used in the c-matrix calculation to generate the results.

The next worksheet of this workbook is where the results for the generic and conditioned models relating a new foundation location to one existing data point are located.



	A	B	C	D
1	INPUT			
2				
3	New location (X)		Existing data (Y)	
4			Name	Field1BH-1
5	D(ft)	16	UT ID	1
6	L or L_X (ft)	80	Z or L_Y(ft)	20
7			Max.Z (ft)	--
8	Easting (ft)	--	Easting (ft)	--
9	Northing (ft)	--	Northing (ft)	--
10	UTM zone	--	UTM zone	--
11	$\rho_{FS,FB}$	0.5	$F_{S,Y}$(ksf)	--
12			$F_{B,Y}$(ksf)	--
13				
14	τH (ft)	--	τV (ft)	--
15				
16	Side shear		End Bearing	
17	θH (ft)	--	θH (ft)	--
18	θV (ft)	--	θV (ft)	--
19	ρ	--	ρ	--
20				
21	To change values below , go to the[Input] sheet			
22	α	0.8		
23	Nc	9		

RESULTS

1-1.Generic Avg. Unit Side Shear		
μFs(L)	0.2500	ksf
σFs(L)	0.0370	ksf
δFs(L)	0.1500	

2-1.Spatially Conditioned Avg.Side Shear		
μFs, X|Y	0.2900	ksf
σFs, X|Y	0.0400	ksf
δFs, X|Y	0.1400	

1-2.Generic Unit End Bearing		
μF_B(L)	6.1800	ksf
σF_B(L)	0.2800	ksf
δF_B(L)	0.0450	

2-2.Spatially Conditioned End Bearing		
$\mu F_{B,X\|Y}$	6.9800	ksf
$\sigma F_{B,X\|Y}$	0.3000	ksf
$\delta F_{B,X\|Y}$	0.0430	

1-3.Generic Axial Capacity		
μQside	1005	kips
σQside	149	kips
δQside	0.1480	
μQend	1243	kips
σQend	56	kips
δQend	0.0453	
μQ	2248	kips
σQ	184	kips
δQ	0.0816	

2-3.Spatially Conditioned Axial Capacity		
μQside,X|Y	1500	kips
σQside,X|Y	200	kips
δQside,X|Y	0.1400	
μQend,X|Y	1780	kips
σQend,X|Y	75	kips
δQend,X|Y	0.0430	
μQ,X|Y	3270	kips
σQ,X|Y	250	kips
δQ,X|Y	0.0780	

Figure 2-23: "1 Existing Data Point" Worksheet of "Generic and Conditional Axial Capacity.xlsm"

This implementation of the model is useful to see how the results change with respect to singular points. The information presented for the generic model is still the same over the whole site regardless of where the new location is and which of the existing data points are being used. The spatially conditioned model will be different than when using the fifty highest correlated data points because the model is correlating between different data.

INPUT

New location (X)	
D(ft)	16
L or L_X (ft)	60
Easting (ft)	2,500,000.0
Northing (ft)	9,800,000.0
UTM zone	15N
x	2500000.0
y	9800000.0
$\rho_{FS,FB}$	0.5

Side shear	
θH (ft)	11404
θV (ft)	30
End Bearing	
θH (ft)	8869
θV (ft)	25

To change values below , go to the[Input] sheet

α	0.8
Nc	9

RESULTS

1-1.Generic Unit Avg.Side Shear			2-1.Spatially Conditioned Avg.Side Shear		
μFs(L)	0.1923	ksf	$\mu Fs,_{X\mid Y1,\ldots,Yn}$	0.1923	ksf
σFs(L)	0.0296	ksf	$\sigma Fs,_{X\mid Y1,\ldots,Yn}$	0.0296	ksf
δFs(L)	0.1539		$\delta Fs,_{X\mid Y1,\ldots,Yn}$	0.1540	

1-2.Generic Unit End Bearing			2-2.Spatially Conditioned End Bearing		
$\mu F_B(L)$	4.61700	ksf	$\mu F_{B,\ X\mid Y1,\ldots,Yn}$	4.6165	ksf
$\sigma F_B(L)$	0.7920	ksf	$\sigma F_{B,\ X\mid Y1,\ldots,Yn}$	0.7920	ksf
$\delta F_B(L)$	0.1715		$\delta F_{B,\ X\mid Y1,\ldots,Yn}$	0.1716	
Soil contribution Only			Soil contribution Only		

1-3.Generic Axial Capacity			2-3.Spatially Conditioned Axial Capacity		
μQside	580	kips	$\mu Qside,_{X\mid Y1,\ldots,Yn}$	580	kips
σQside	89	kips	$\sigma Qside,_{X\mid Y1,\ldots,Yn}$	89	kips
δQside	0.1539		$\delta Qside,_{X\mid Y1,\ldots,Yn}$	0.1540	
μQend	928	kips	$\mu Qend,_{X\mid Y1,\ldots,Yn}$	928	kips
σQend	159	kips	$\sigma Qend,_{X\mid Y1,\ldots,Yn}$	159	kips
δQend	0.1715		$\delta Qend,_{X\mid Y1,\ldots,Yn}$	0.1716	
μQ	1508	kips	$\mu Q,_{X\mid Y1,\ldots,Yn}$	1508	kips
σQ	218	kips	$\sigma Q,_{X\mid Y1,\ldots,Yn}$	218	kips
δQ	0.1446		$\delta Q,_{X\mid Y1,\ldots,Yn}$	0.1446	

Click to **calculate spatially conditioned capacity**

Reliability-based design		Reliability-based design	
β	4.5	β	4.5
W'	0.0	W'	0.0
ρ	0.5	ρ	0.5
Ω_R	0.3	Ω_R	0.3
Ω_S	0.1	Ω_S	0.1
$\Omega_{R'}$	0.3000	$\Omega_{R'}$	0.3000
μR	1508	μR	1508
σR	218	σR	218
δR	0.1446	δR	0.1446
$Fs_{\delta R}$	1.1522	$Fs_{\delta R}$	1.1522
$\Phi_{\delta R}$	0.8679	$\Phi_{\delta R}$	0.8679

Figure 2-24: “Multiple Existing Data Points” Worksheet of “Generic and Conditional Axial Capacity.xlsm”

The generic model will be the same at a given caisson length and diameter regardless of location. The example provided was chosen arbitrarily to display the unconditional results. The spatially conditioned results are calculated by clicking on the orange button, which runs the macro. The code for the macro is provided in Appendix B.

The reliability-based design is shown in the lower part of the worksheet and provides an additional partial spatial factor of safety, $Fs_{\delta R}$, and an additional partial resistance factor, $\phi_{\delta R}$.

Upon putting in a new location, certain columns of the "Input" worksheet change to relate the new location to each data point. Columns A-K will stay the same regardless of what new location is put in and columns P-AJ will be populated using the model developed by Cheon (2011). Then a rank for correlation coefficient values of depth-averaged undrained shear strength and point undrained shear strength between existing datum and the new location is produced. The top fifty correlation coefficients correspond to the data points that are used in the covariance matrix analysis to generate the spatially conditioned results.

Also within this analysis worksheet are those 50 correlated data points used in the calculations.

	L	M	N	O	P	Q	R	S	T	U	V	Formula Bar	X	Y	Z	AA	AB	AC	AD
1	Number of correlated data points										Number of correlated data points								
2	50		Side Shear								50		End Bearing						
3	i	ρ_{AB}	Fs.i(ksf)	z (ft)	Easting (ft)	Northing (ft)	UTM zone	UT ID	Data set		i	ρ_{AB}	F_B.i	z (ft)	Easting (ft)	Northing (ft)	UTM zone	UT ID	Data set

Figure 2-25: Correlated Data Points Used in Calculations from "Multiple Existing Data Points" Worksheet of "Generic and Conditional Axial Capacity.xlsm"

The "Correlated Data" worksheet has been added to check and make sure the model is working correctly and is using fifty individual correlated data points for analysis. Columns M and W of "Multiple Existing Data Points" are further analyzed in the next worksheet to show the ranges of the correlation coefficients.

	A	B	C	D	E	F	G	H
1		Side Shear:				End Bearing:		
2		Correlated Data Summary				Correlated Data Summary		
3		Max and Min ρ		Data set		Max and Min ρ		Data set
4		highest value	--	--		highest value	--	--
5		lowest value	--	--		lowest value	--	--
6		ρ limits	Number of Correlated Points			ρ limits	Number of Correlated Points	
7		>0.5	0			>0.5	0	
8		0.4-0.5	0			0.4-0.5	0	
9		0.3-0.4	0			0.3-0.4	0	
10		0.2-0.3	0			0.2-0.3	0	
11		0.1-0.2	0			0.1-0.2	0	
12		0-0.1	50			0-0.1	50	
13		sum to check:	50 Correlated Points			sum to check:	50 Correlated Points	

Figure 2-26: "Correlated Data" Worksheet of "Generic and Conditional Axial Capacity.xlsm"

These tables read information from the lists of correlated data points in "Multiple Existing Data Points" and return the highest and lowest correlation coefficients used in calculations with their corresponding data set "i," which is column A in the "Input" worksheet of this analysis workbook. The correlation coefficient limits are set to provide an overview of the correlated data used. The current display is showing 50 points with correlation coefficients of 0 to 0.1 because there was no analysis run. The sum to check should always read "50 Correlated Points", showing that all correlation coefficients are accounted for.

Generic and Conditional Lower Bound Axial Capacity with Additional Factor of Safety

"Generic and Conditional Lower Bound Axial Capacity.xlsm" calculates the mean, standard deviation, and coefficient of variation of the lower bound axial side shear capacity, the lower bound axial end bearing capacity, and the lower bound total axial capacity of a new location using just one location or using the fifty locations with the highest correlation coefficients. Also, using the fifty locations with the highest correlation coefficients, the analysis returns a generic and conditional additional partial spatial factor of safety using a target reliability index to reflect the uncertainty in the model from not having exact site specific data. The organization is the exact same as “Generic and Conditional Axial Capacity.xlsm” but using the remolded undrained shear strength data and is linked to “Input-Sur and Sur_avg” of “Input.xlsx.”

2.2.3 Lateral Capacity Analyses

Generic and Conditional Equivalent Linear Undrained Shear Strength for Lateral Capacity

“Generic and Conditional Equivalent Linear Undrained Shear Strength for Lateral Capacity.xlsm” calculates the mean, standard deviation, and coefficient of variation of a linear shear strength profile. This information is used along and in another workbook, documented in the next subsection, when calculating lateral capacity. Also, using the fifty locations with the highest correlation coefficients, the analysis returns a generic and a conditional equivalent linear undrained shear strength at depth.

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♦**NOTE**

-Do not move, delete or hide worksheets.

-Fill or change values only in the yellow highlighted cells.

-This workbook has been updated so that the macros work with the present version of Microsoft Excel 2010.

-As more data is received, make sure to carry down the formulas within the [Input] sheet and update the n-value, G4, to match the available number of data points.

To change or update values in the [Borings] sheet, open c:\BP-database\C-Analysis Workbooks\INPUT.xls.x

Input worksheet

Borings	Contains UT ID, data set name, location information, Utm zone
Input	Contains Su1 with depth and correlation calculations

To change or update values in the [Input] sheet, copy the formulas throughout all the columns , A-AH, to include all data from c:\BP-database\C-Analysis Workbooks\INPUT.xlsx.

Calculation worksheet

generic and conditioned	Reports generic and spatially conditioned Su1 from multiple existing data points
Correlated Data	Reports ranges of correlation coefficients with maximum and minimum corresponding data point
cmatrix	Covariance matrix calculations

♦**how to use:**

1. Check all input data in the "INPUT.xls" workbook (C:\BP-database\C-Analysis Workbooks\)
2. Fill the model parameters in the [Input] worksheet for equivalent linear shear strength: cells B3-B8.
3. Go to the [generic and conditioned] sheet and fill in location information in UTM format.
4. Fill in the depth at which is desired for lateral capacity calculations, which is generally the caisson length.
5. With steps 3 and 4, the results for the generically calculated values will be shown.
6. Click the macro button to calculate spatially condtioned equivalent linear shear strength.

8. If there is an error in the data being "out of range," increase the m value, G2, in [Input].

9. If the results return no correlated points for the spatially conditioned profile, try increasing the m value, G2, in [Input].

♦results of [generic and conditioned]:

1. The mean spatially conditioned total axial capacity is given in cell I4.
2. In columns L-T, are the data sets that were used in the spatially conditioned calculations for equivalent linear shear strength.

Figure 2-27: "Home" Worksheet of "Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm"

	A	B	C	D	E	F	G	H	I	J
1	UT ID	New Name	Easting	Northing	Units	MaxDepth (ft)	UTM zone	X (ft)	Y (ft)	Group
2	0	0	0	0	0	0	0N	0.0	0	
3	0	0	0	0	0	0	0N	0.0	0	
4	0	0	0						0	
5	0	0	0						0	
6	0	0	0						0	
7	0	0	0						0	
8	0	0	0						0	
9	0	0	0						0	
10	0	0	0	0	0	0	0N	0.0	0	
11	0	0	0	0	0	0	0N	0.0	0	
12	0	0	0	0	0	0	0N	0.0	0	

All analysis spreadsheets are equipped to deal with 200 borings. If you are adding more data than this limit, you need to manually change the limits in the input file which this data pulls from and change the boundaries here, so all data is used. Refer to Chapter 5.

NOTE:
X coordinates:
591716m(=1941325.5 ft) added to UTM 16 easting for horizontal distance calculation in the whole area (UTM 15+UTM16)

Origin: (Easting, Northing)=(0,0) of UTM zone 15.

IMPORTANT:
To change or update values in this worksheet, go to c:\BP-database\C-Analysis Workbooks\INPUT.xls.

Figure 2-28: “Borings” Worksheet of “Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm”

The “Input” worksheet of this workbook contains the shear strength data from the “Input-Su1” worksheet of “Input.xlsx” and the calculations that correlate those points to the requested data location for analysis.

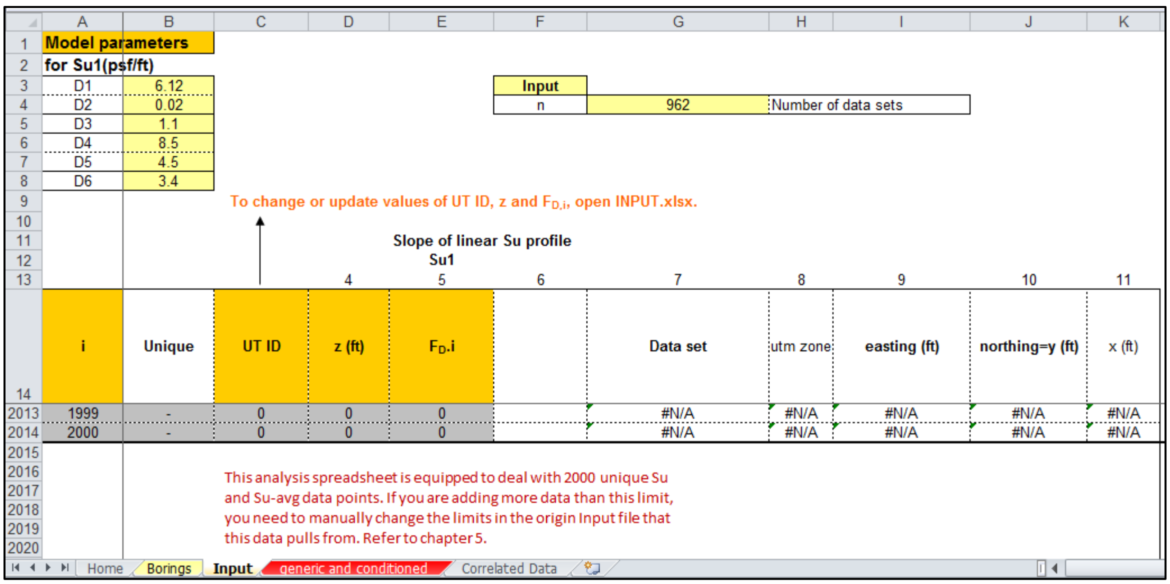
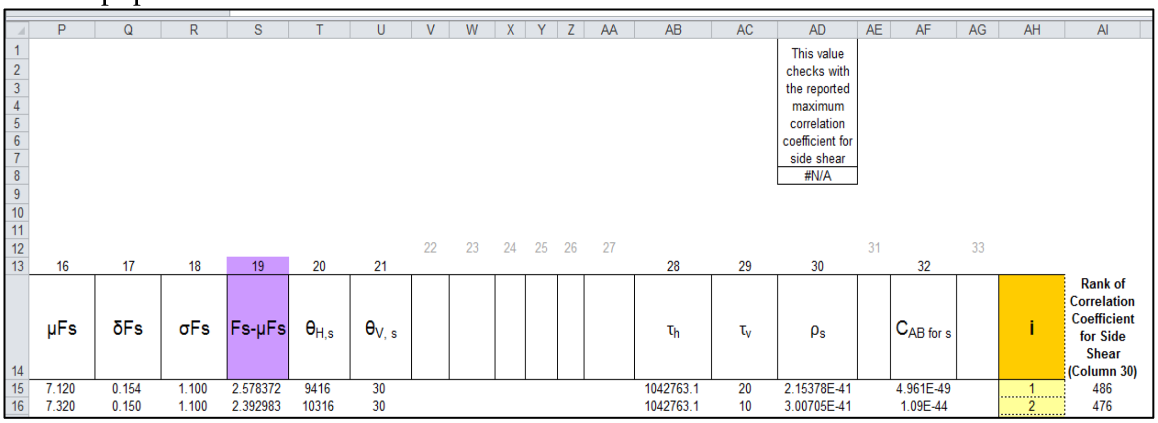


Figure 2-29: “Input” Worksheet of “Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm”

The model parameters listed in the top right corner are used to calculate statistical parameters as outlined in Appendix A for the slope of the linear shear strength profile, S_{u1}, for each data point, i.e. each “i.” The number of data points, cell G4, uses the built-in Excel Count() function to count how many data points are currently available for analysis.

Columns A, C, D, E, and F are all linked to “Input-Su1” of “Input.xlsx.” Columns G-K are linked to the “Borings” worksheet within this analysis workbook using the built-in Excel function Vlookup(). The Vlookup() function finds the UT ID in Column C in "Borings" and then returns the respective value, such as x, y, or data set.

Scrolling right within "Input" shows where the calculations are performed for analysis. The reliability-based model is provided in Appendix A with the calculations used to populate the cells.



This value checks with the reported maximum correlation coefficient for side shear: #N/A

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI
12							22	23	24	25	26	27				31		33		
13	16	17	18	19	20	21							28	29	30		32			
14	μFs	δFs	σFs	Fs-μFs	$\theta_{H,s}$	$\theta_{V,s}$							τ_h	τ_v	ρ_s		$C_{AB\ for\ s}$		i	Rank of Correlation Coefficient for Side Shear (Column 30)
15	7.120	0.154	1.100	2.578372	9416	30							1042763.1	20	2.15378E-41		4.961E-49		1	486
16	7.320	0.150	1.100	2.392983	10316	30							1042763.1	10	3.00705E-41		1.09E-44		2	476

Figure 2-30: "Input" Worksheet Calculations of "Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm"

These fields are located in columns P-AJ of "Input. They are numbered to help reference the columns in the VBA code. Columns 16-21, 28-30, and 32 are as calculated in Appendix A and use the same parameters that Cheon (2011) devised for the model. The "i" value is provided to the right for ease of referencing so that the user doesn't have to scroll from side to side of the worksheet. The ranking of correlation coefficients of column 30 is an enhancement to the database and is used to select the highest 50 correlation coefficient values to be used in the c-matrix calculation to generate the results.

The next worksheet of this workbook is where the macro button is to return the calculated results for the generic and conditioned models relating a new site to the existing data.

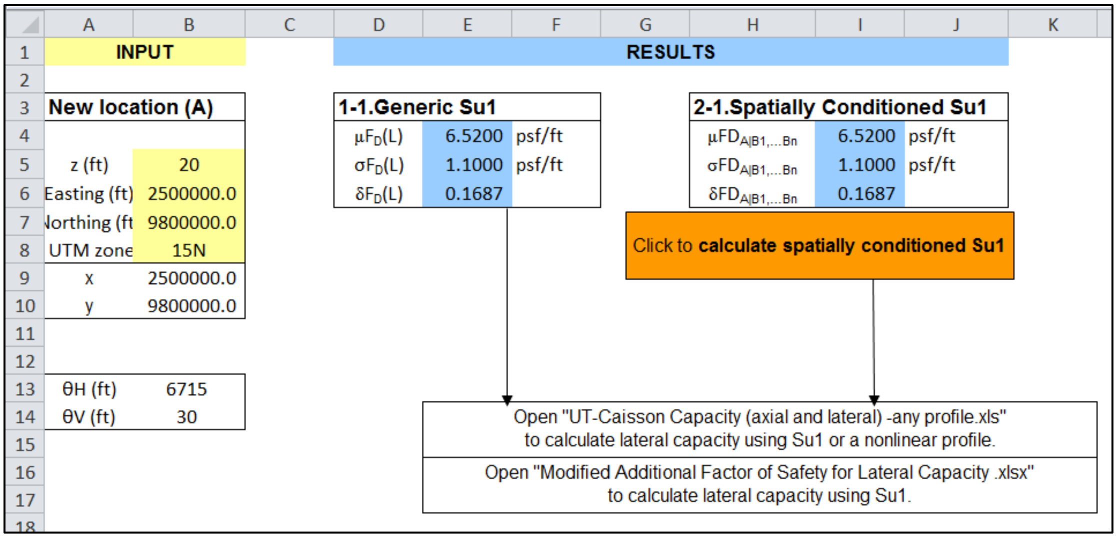


Figure 2-31: "Generic and Conditioned Worksheet" of "Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm"

The generic model will be the same at a given caisson length and diameter regardless of location. The spatially conditioned results are calculated by clicking on the orange button, which runs the macro. The code for the macro is provided in Appendix B.

Upon putting in a new foundation location, certain columns of the "Input" worksheet change to correlate the new location to each existing data point. Columns A-K stay the same as they are specific for each data point. Columns P-AI change with a new foundation location as those are the cells that are populated using the model developed by Cheon (2011) to generate the rank of correlation coefficient values of the equivalent shear strength profile between existing data and the new location. The top fifty correlation coefficients correspond to the data points that are used in the c-matrix analysis, as provided in Appendix A, to generate the spatially conditioned results.

Also within this analysis worksheet are the correlated data points used in the calculations.

	L	M	N	O	P	Q	R	S	T
1	Number of correlated data points								
2	50		Su1						
3	i	ρ_{AB}	$F_{D,i}$(psf/ft)	z (ft)	Easting (ft)	Northing (ft)	UTM zone	UT ID	Data set

Figure 2-32: Correlated Data Points Used in Calculations of "Generic and Conditioned" Worksheet of "Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm"

The "Correlated Data" worksheet has been added to check and make sure the model is working correctly and that the model is using fifty individual correlated data points. Column M "Generic and Conditioned" is further analyzed in the next worksheet to show the ranges of the correlation coefficients.

	A	B	C	D
1		Su1:		
2		Correlated Data Summary		
3		Max and Min ρ		Data set
4		highest value	--	--
5		lowest value	--	--
6		ρ limits	Number of Correlated Points	
7		>0.5	0	
8		0.4-0.5	0	
9		0.3-0.4	0	
10		0.2-0.3	0	
11		0.1-0.2	0	
12		0-0.1	50	
13		sum to check:	50 Correlated Points	

Figure 2-33: "Correlated Data" Worksheet of

This table reads information from "Generic and Conditioned" and returns the highest and lowest correlation coefficients used in calculations with their corresponding data point "i," which is column A in the "Input" worksheet of this analysis workbook. The correlation coefficient limits are set to provide an overview of the correlated data used. The current display is showing 50 points with correlation coefficients of 0 to 0.1 because there was no analysis run. The sum to check should always read “50 Correlated Points”, showing that all coefficients are accounted for.

Modified Additional Factor of Safety for Lateral Capacity

“Modified Additional Factor of Safety for Lateral Capacity.xlsx” was created by Ching Hsiang Chen (2012). This implement uses results from “Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm” to produce a lateral capacity at a location using the equivalent linear shear strength gradient and corresponding depth of suction caisson penetration. There are only two worksheets within this workbook, a “Home” worksheet that provides notes and instructions to use the workbook and an “Analysis” worksheet that reports generically or spatially conditioned lateral capacity with an additional partial spatial factor of safety to apply in lateral capacity design. The analysis will report a generic capacity if the generic equivalent linear profile is input and will report a spatially conditioned capacity if the spatially conditioned equivalent linear profile is input.

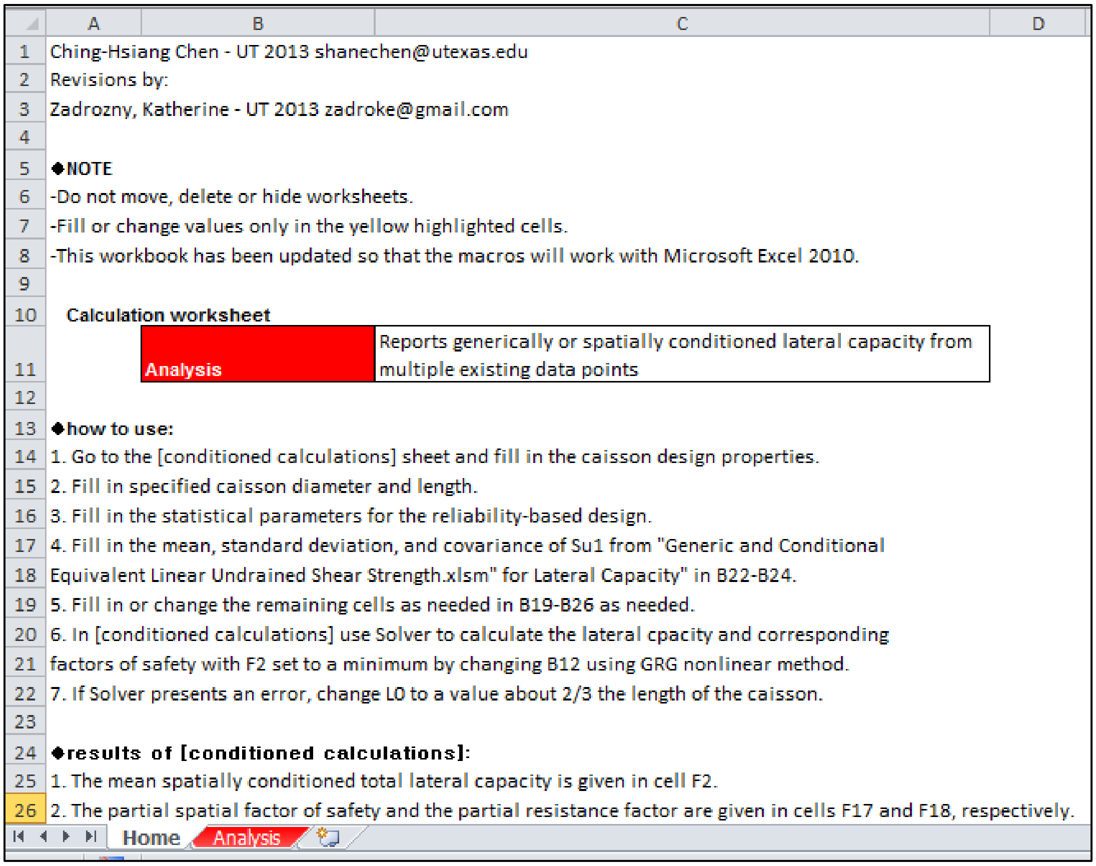


Figure 2-34: "Home" Worksheet of "Modified Additional Factor of Safety for Lateral Capacity.xlsm"

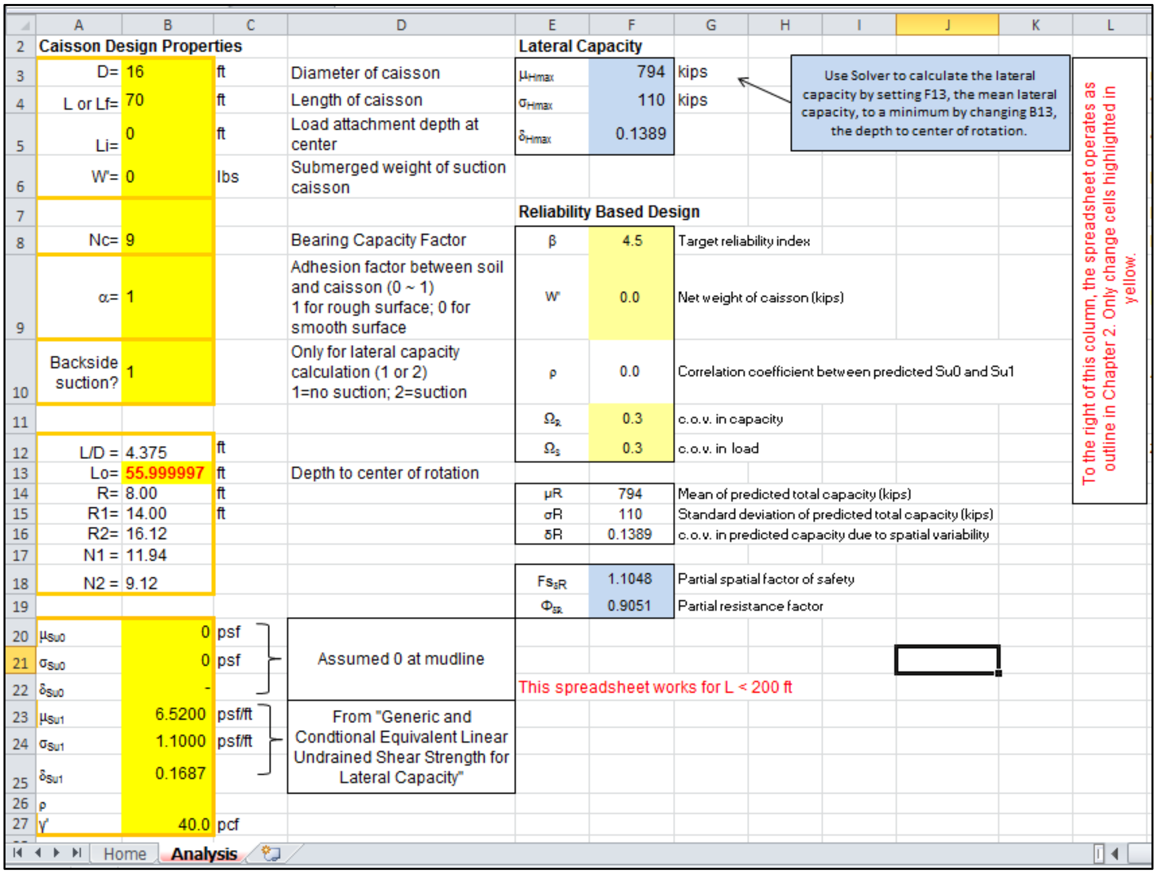


Figure 2-35: “Analysis” Worksheet of “Modified Lateral Capacity with Additional Factor of Safety.xlsm”

The user will input information to calculate the lateral capacity and use Solver to produce the mean, standard deviation, and coefficient of variation of the lateral capacity with the provided information. The depth to center of rotation is highlighted with red text to emphasize that the user needs to put in an estimate for Solver to work correctly. Solver works with the worksheet, which is calculating lateral capacity as described in Appendix A and is iterating through calculations to find a minimum capacity by changing the depth to center of rotation which is the limiting factor.

Note that the worksheet is applicable to a depth of penetration less than two hundred feet. Also, the text in column L tells the user to not change anything to the right of that column as those are the model calculations.

Once the user has input specifications for design, open the Solver function box, within the Data menu in Excel. Solver will then step through the model as implemented by Ching-Hsiang Chen (2012) to produce a minimum lateral capacity by changing the depth to the center of rotation. The reliability based design operates as stated in the model developed by Cheon (2011) to yield an additional partial spatial factor of safety to account for the uncertainty in spatial variations in soil properties.

2.2.4 UT Caisson Capacities via Linear or Nonlinear Profile

"UT Caisson Capacities.xlsm" calculates axial and lateral capacities for a given caisson dimension via a linear or nonlinear design undrained shear strength profile. At present use, this workbook should only be used to calculate lateral capacity. The calculations use the linear equivalent shear strength profile, Su1, or the nonlinear design undrained shear strength profile.

The "Home" worksheet provides notes for the user on what results the workbook provides the user, short descriptions of what each worksheet does within the workbook, how to use each of the worksheets, and references for the calculations. The "Background" worksheet provides compiled text from the listed references to give the user an idea of how the calculations are performed. This background information is further supported with Appendix A.

The "W'caisson" worksheet calculates the approximate submerged unit weight of the caisson.

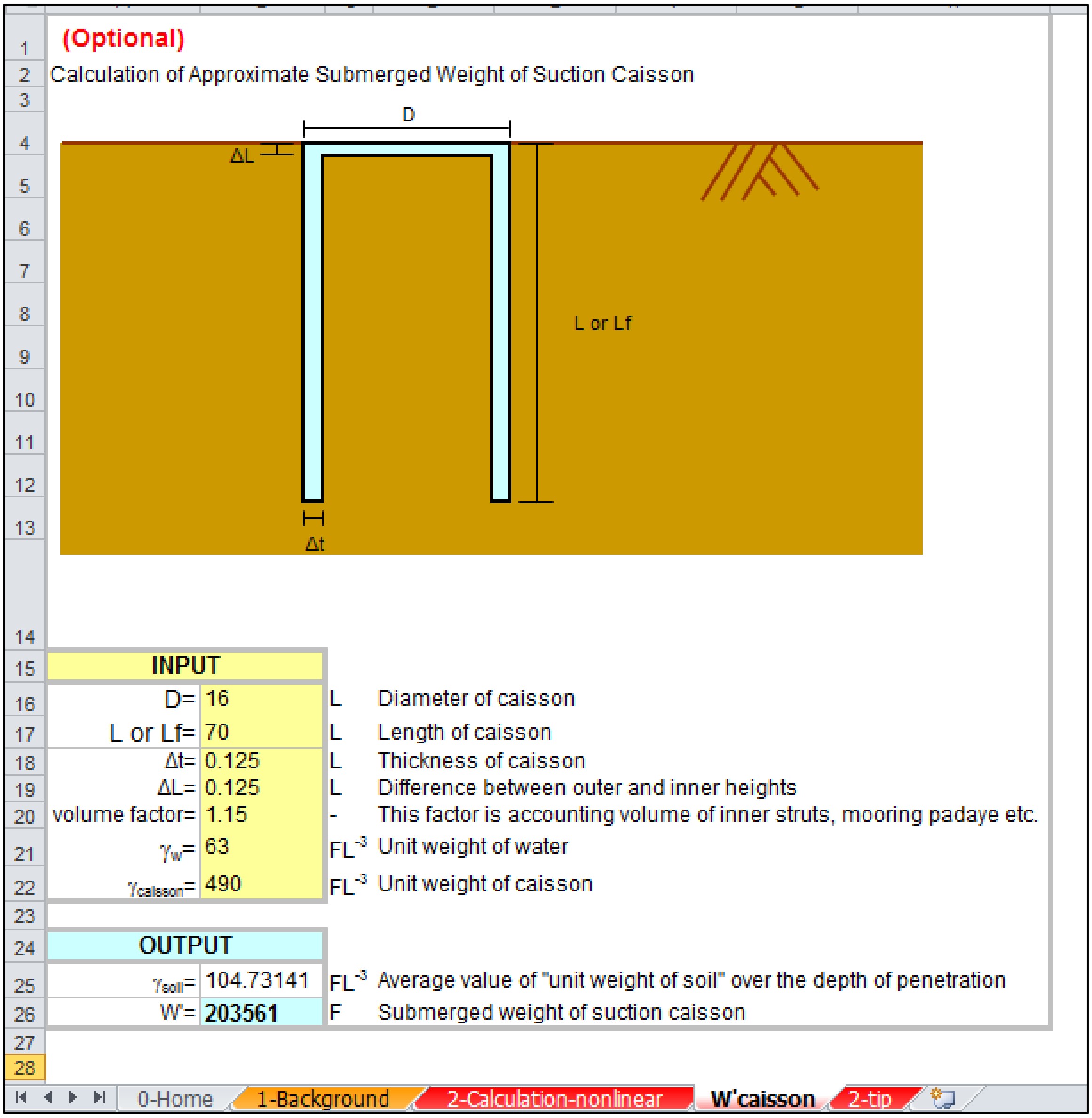
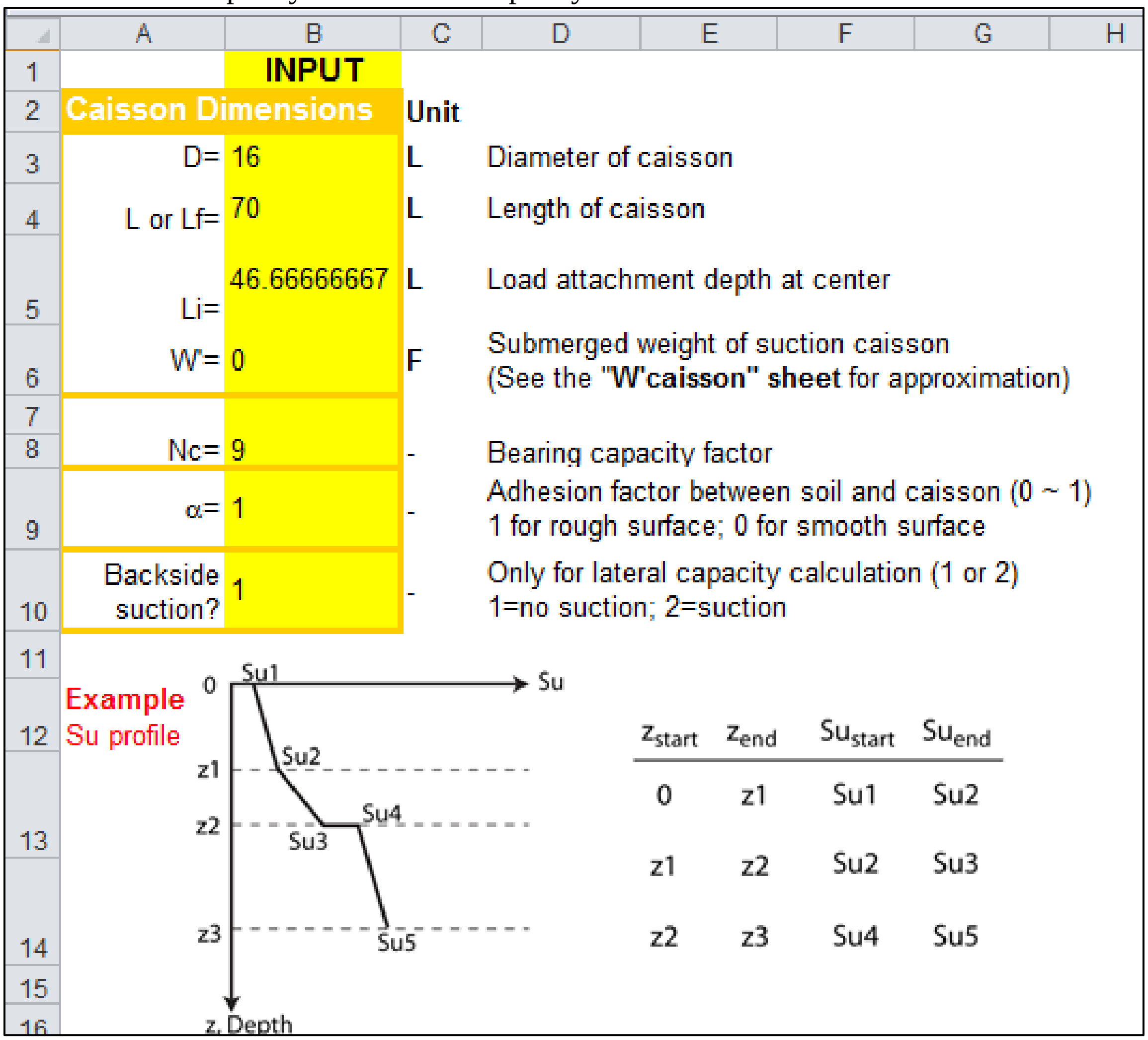


Figure 2-36: “W’caisson” Worksheet of “UT Caisson Capacities.xlsm”

The image in the figure above shows a cross section of the cylindrical caisson used in analysis. Each of the variables is defined here, with the calculations explained in “Background.” The final worksheet listed is “2-tip” which steps through the calculations for lateral capacity as explained in Appendix A and that follow the model provided in Aubeny et al (2001 and 2003).

"Calculation-nonlinear" is where the user will put in his caisson dimensions, undrained shear strength profile, and submerged unit weight profile of the soil to get either the axial capacity or the lateral capacity.



	A	B	C	D
1		INPUT		
2	Caisson Dimensions		Unit	
3	D=	16	L	Diameter of caisson
4	L or Lf=	70	L	Length of caisson
5	Li=	46.66666667	L	Load attachment depth at center
6	W'=	0	F	Submerged weight of suction caisson (See the "**W'caisson" sheet** for approximation)
7				
8	Nc=	9	-	Bearing capacity factor
9	α=	1	-	Adhesion factor between soil and caisson (0 ~ 1) 1 for rough surface; 0 for smooth surface
10	Backside suction?	1	-	Only for lateral capacity calculation (1 or 2) 1=no suction; 2=suction

z_{start}	z_{end}	Su_{start}	Su_{end}
0	z1	Su1	Su2
z1	z2	Su2	Su3
z2	z3	Su4	Su5

Figure 2-37: Caisson Parameter Inputs with Example Su Profile of "Calculation-nonlinear" Worksheet of "UT Caisson Capacities.xlsm"

The example Su profile is provided to show the user how to input values into the design shear strength profile table. The point undrained shear strength is listed with its corresponding depth to provide the nonlinear profile for analysis. If analyzing a linear profile, the user will simply input the shear strength at the mudline, either calculated using previous analysis implements or using data from Input.xlsx, to find the equivalent linear profile for data, which is explained in the case study, and then the equivalent linear shear strength value at depth.

17	Design Profiles-Non-Linear							
18		Depth (L)		Thickness (L)	Su Profile (FL^{-2})		γ' profile(FL^{-3})	
19	Unique	z_{Start}	z_{End}		Su_{Start}	Su_{End}	γ'_{Start}	γ'_{end}
20	1000.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0
21	-		0.0	0.0		0.0		0.0
22	-		0.0	0.0		0.0		0.0
23	-		0.0	0.0		0.0		0.0
24	-		0.0	0.0		0.0		0.0
25	-		0.0	0.0		0.0		0.0
26	-		0.0	0.0		0.0		0.0
27	-		0.0	0.0		0.0		0.0
28	-		0.0	0.0		0.0		0.0
29	-		0.0	0.0		0.0		0.0
30	-		0.0	0.0		0.0		0.0
31	-		0.0	0.0		0.0		0.0
32	-		0.0	0.0		0.0		0.0
33	-		0.0	0.0		0.0		0.0
34	-		0.0	0.0		0.0		0.0
35	-		0.0	0.0		0.0		0.0
36								

L/D =	4.375	-
Lo=	-1E-11	-
R=	8.00	L
R1=	70.00	L
R2=	70.46	L
N1 =	11.94	-
N2 =	9.12	-

Tip: try -0.00000000001 and Lf value for the initial guess

Figure 2-38: Shear Strength and Submerged Unit Weight Profile Inputs of "Calculation-nonlinear" Worksheet of "UT Caisson Capacities.xlsm"

The R- and N- values in the yellow outlined table are from the model developed by Aubeny et al (2001 and 2003). The Lo value, the depth to the center of rotation in lateral capacity analysis, is initially guessed by the user to begin the calculation iterations.

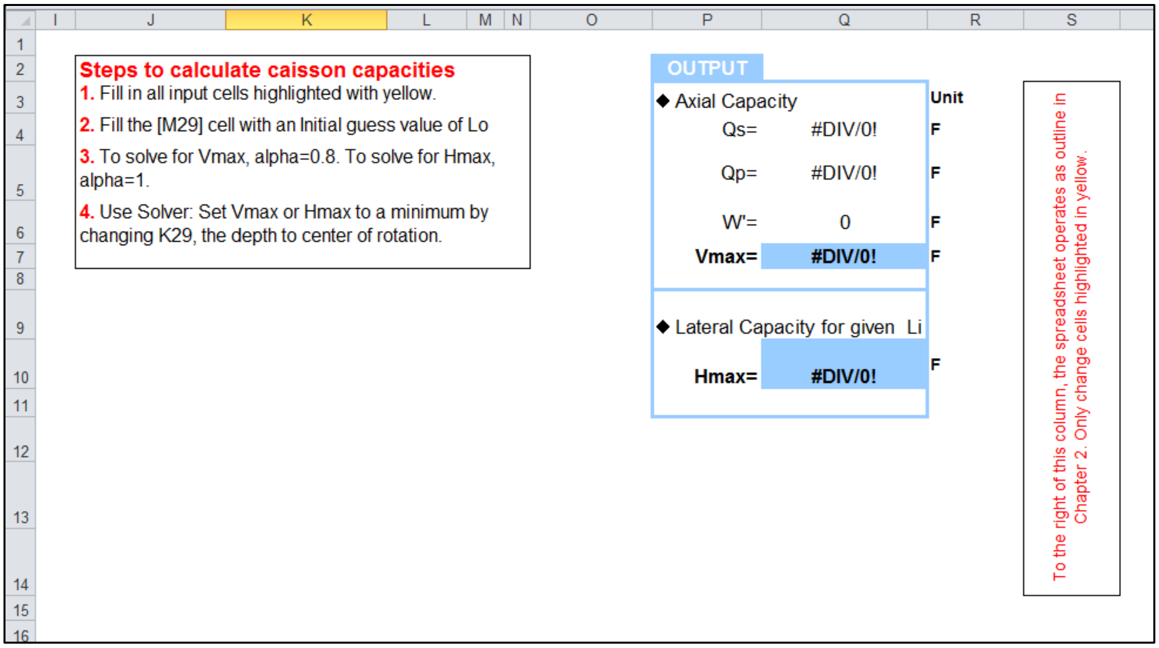


Figure 2-39: Instructions and Results of Analysis in "Calculation-nonlinear" Worksheet of "UT Caisson Capacities.xlsm"

The text box gives instructions on how to use Solver to generate results. Note that axial capacity and lateral capacity cannot be solved simultaneously due to the fact that alpha is different for each analysis as it has been applied for this research. Also, note that the lateral capacity is dependent on the user-input load attachment point. The text box to the right of the figure reminds the user to not change columns to the right as that information is the model implementation.

2.3 SUMMARY OF FRAMEWORK DOCUMENTATION

This chapter provided the user with the necessary steps and accompanying figures to operate the database. The Input files were documented to show the user how to store boring information from the data provider and where to input that data to specific worksheets from which the data are used in analysis. The user also has a quick guide on how to operate each analysis workbook with the revised "Home" worksheets.

Chapter 3: Framework Demonstration

This chapter demonstrates the process of receiving and inputting data, producing results from that existing data, and showing which results are ultimately emphasized to be applied in foundation design. Section 3.1 outlines receiving and inputting data. Section 3.2 outlines generating results, which is independent of section 3.1

3.1 INPUTTING NEW DATA

The data are given as undrained shear strength at a point at sampling intervals. The boring data are provided with location in UTM format. The data are initially input as provided from field and lab test results, at the sampling depth within the boring with the thickness of the sample between testing depths, design shear strength, and unit weight.

The data needs to be listed by data points at ten foot intervals for analysis, and then the necessary calculations are performed to report design undrained shear strengths at a point, averaged over depth, and equivalent linear gradient.

Table 3-1: Raw Data for Boring A

z (ft)	Design Shear Strength (psf)
0	25
2	25
15	65
25	150
56	490

This profile is translated to ten-foot intervals by reading the data at that depth on the curve to create a design undrained shear strength profile to the depth of exploration within the geologic setting, i.e. disregarding heavily consolidated materials from an ancient debris flow.

The depth-averaged shear strength is found by calculating the area under the point undrained shear strength curve with the provided design shear strength profile. Note that data at the mudline is not part of the used data. An example of the steps is given here for Boring A:

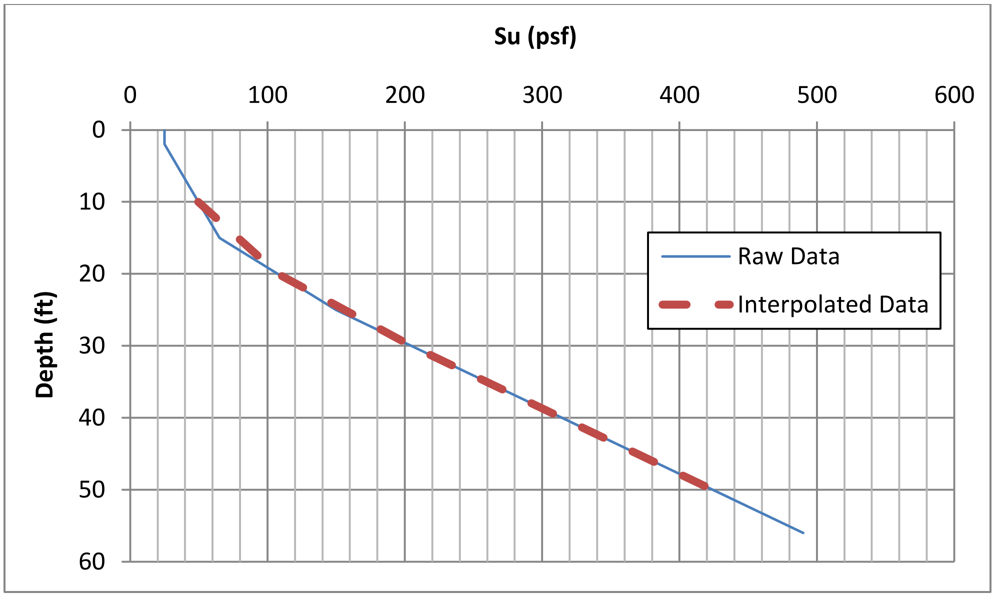


Figure 3-1: Design Undrained Shear Strength for Boring A

The depth-averaged undrained shear strength and equivalent linear undrained shear strength were then calculated as follows from the interpolated data:

$$S_{u,avg}(L) = \frac{1}{L}\int_0^L S_u(z)dz \qquad 3.2$$

$$S_{u,avg}(20) = \frac{\frac{.025+.0496}{2}\times 10 + \frac{.0496+.1075}{2}\times 10}{20} = 0.0579\ ksf\ at\ z = 20\ ft$$

$$S_{u1}(L) = S_{u0} + S_{u1}L \qquad 3.3$$

The equivalent linear shear strength was recorded at depths greater than fifty feet for the database. The slope of the equivalent linear profile is found using the nonlinear design shear strength profile from the "Design Su" Worksheet of "Input.xlsx." Specifically, the nonlinear profile is used as the input profile in "UT Caisson

Capacities.xlsm." The lateral capacity is then found. To find the equivalent gradient, use "Fall16Rev3Mar2008-N.xlsx" and estimate the gradient, cell D24 in the "InputForm" worksheet. By implementing a guess-and-check process, guess the gradient until the lateral capacities are practically equal.

Table 3-2: Input Design Shear Strengths for Boring A

z (ft)	Su (psf)	z (ft)	S_u (ksf)	$S_{u,avg}$ (ksf)	Su1 (psf/ft)
0	25	10	.0496	.0373	-
2	25	20	.1075	.0579	-
15	65	30	.2048	.0907	-
25	150	40	.3145	.1329	-
56	490	50	.4242	.1802	7.1889

3.2 SHOWING RESULTS

The results produced were a combination of the data, spatial variations between data points, and statistical reliabilities using the models as defined in Appendix A. Provided in this section are results for a sample location and then figures showing comparisons of all results.

Pipeline end termination (PLET) 1 is located in an area with 12 existing data points that were used to calculate design capacities at that site. These existing data points are correlated to PLET 1 as described in Appendix A.

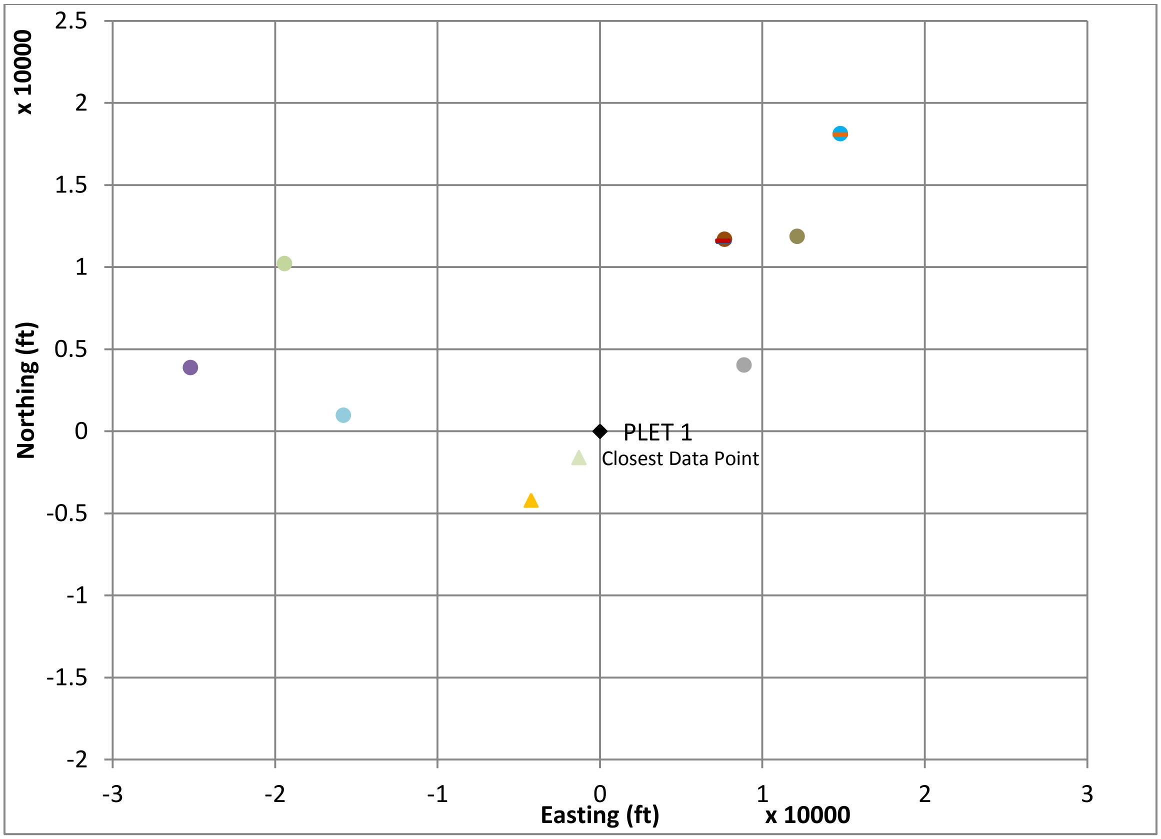


Figure 3-2: Location of PLET 1 with 12 Nearest Data Borings

The generic profiles were first reported as those are the same regardless of where the new foundation locations are. Those values for depth-averaged and point undrained shear strength are found by putting the location and depth information in “Depth-Averaged and Point Undrained Shear Strength.xlsm.” This screenshot shows the results at a penetration of ten feet.

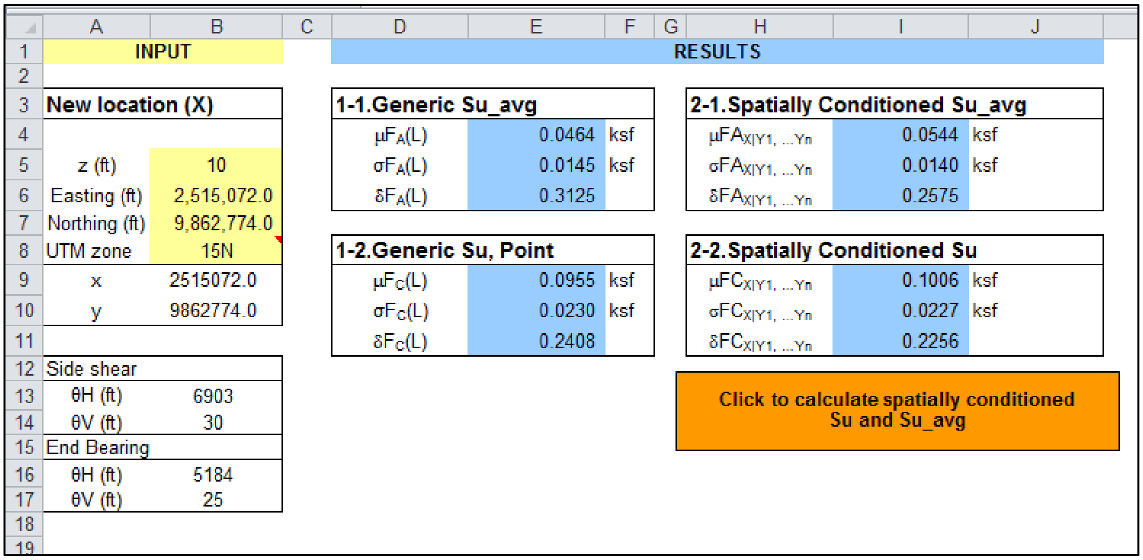


Figure 3-3: Results Generated Using "Depth-Averaged and Point Undrained Shear Strength.xlsm"

Table 3-3: Generic Undrained Shear Strength Profiles

	Depth-Averaged Undrained Shear Strength					Undrained Shear Strength at a Point				
z (ft)	μSu (ksf)	σ	μ+σ	μ-σ	δ	μSu (ksf)	σ	μ+σ	μ-σ	δ
0	0.0100	0.0100	0.0200	0.0000	1.0000	0.0150	0.0100	0.0250	0.0050	0.6667
10	0.0464	0.0145	0.0609	0.0319	0.3125	0.0955	0.0230	0.1185	0.0725	0.2408
20	0.0836	0.0190	0.1026	0.0646	0.2273	0.1770	0.0360	0.2130	0.1410	0.2034
30	0.1216	0.0235	0.1451	0.0981	0.1933	0.2595	0.0490	0.3085	0.2105	0.1888
40	0.1604	0.0280	0.1884	0.1324	0.1746	0.3430	0.0620	0.4050	0.2810	0.1808
50	0.2000	0.0325	0.2325	0.1675	0.1625	0.4275	0.0750	0.5025	0.3525	0.1754
60	0.2404	0.0370	0.2774	0.2034	0.1539	0.5130	0.0880	0.6010	0.4250	0.1715
70	0.2816	0.0415	0.3231	0.2401	0.1474	0.5995	0.1010	0.7005	0.4985	0.1685
80	0.3236	0.0460	0.3696	0.2776	0.1422	0.6870	0.1140	0.8010	0.5730	0.1659
90	0.3664	0.0505	0.4169	0.3159	0.1378	0.7755	0.1270	0.9025	0.6485	0.1638
100	0.4100	0.0550	0.4650	0.3550	0.1341	0.8650	0.1400	1.0050	0.7250	0.1618

The mean, standard deviation, and coefficient of variation for the spatially conditioned model were recorded next.

Table 3-4: PLET 1 Spatially Conditioned Undrained Shear Strength Results

	Depth-Averaged Undrained Shear Strength					Undrained Shear Strength at a Point				
z (ft)	μSu (ksf)	σ	μ+σ	μ-σ	δ	μSu (ksf)	σ	μ+σ	μ-σ	δ
0	0.0100	0.0100	0.0200	0.0000	1.0000	0.0150	0.0100	0.0250	0.0050	0.6667
10	0.0544	0.0140	0.0684	0.0404	0.2575	0.1006	0.0227	0.1233	0.0779	0.2256
20	0.0847	0.0184	0.1031	0.0663	0.2167	0.1745	0.0356	0.2101	0.1389	0.2042
30	0.1217	0.0224	0.1441	0.0993	0.1840	0.2537	0.0482	0.3019	0.2055	0.1899
40	0.1589	0.0263	0.1852	0.1326	0.1654	0.3320	0.0604	0.3924	0.2716	0.1818
50	0.1963	0.0300	0.2263	0.1663	0.1529	0.4086	0.0723	0.4809	0.3363	0.1768
60	0.2343	0.0336	0.2679	0.2007	0.1434	0.4858	0.0838	0.5696	0.4020	0.1725
70	0.2749	0.0378	0.3127	0.2371	0.1375	0.5691	0.0965	0.6656	0.4726	0.1696
80	0.3173	0.0421	0.3594	0.2752	0.1328	0.6621	0.1091	0.7712	0.5530	0.1648
90	0.3603	0.0461	0.4064	0.3142	0.1281	0.7609	0.1212	0.8821	0.6397	0.1592
100	0.4043	0.0499	0.4542	0.3544	0.1235	0.8538	0.1325	0.9863	0.7213	0.1552

With this data, the mean (expected value if there was data at that location) profiles are plotted showing the data within one standard deviation of the mean, the standard deviations are plotted with depth. The standard deviations represent the uncertainty due to the fact that there is no data at PLET 1 and exist due to the spatial variability in the geologic setting. The design profiles are plotted showing the depth-averaged undrained shear strength and the undrained shear strength at a point with the correlated surrounding data. The significance of each data point on the conditioned mean is essentially weighted by its correlation coefficient, which is reported in the worksheet output with the results, also shown in Appendix A.

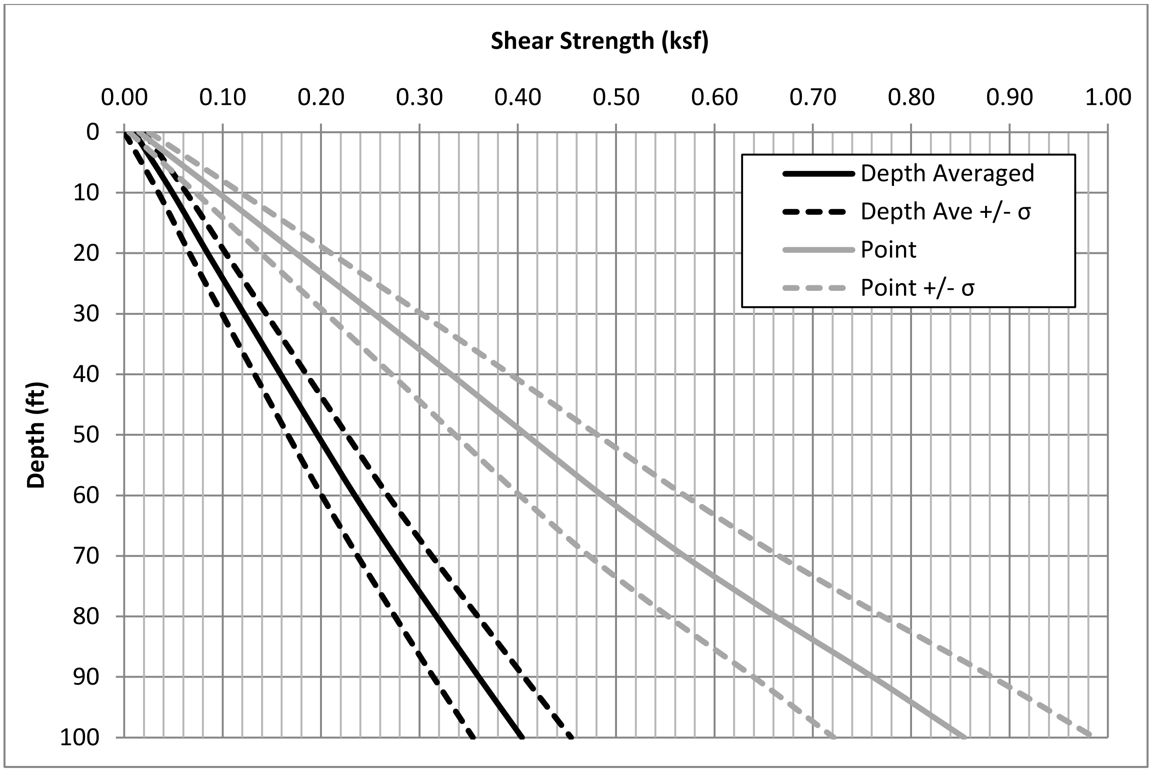


Figure 3-4: PLET 1 Undrained Shear Strength Profiles for Axial Capacity Analysis

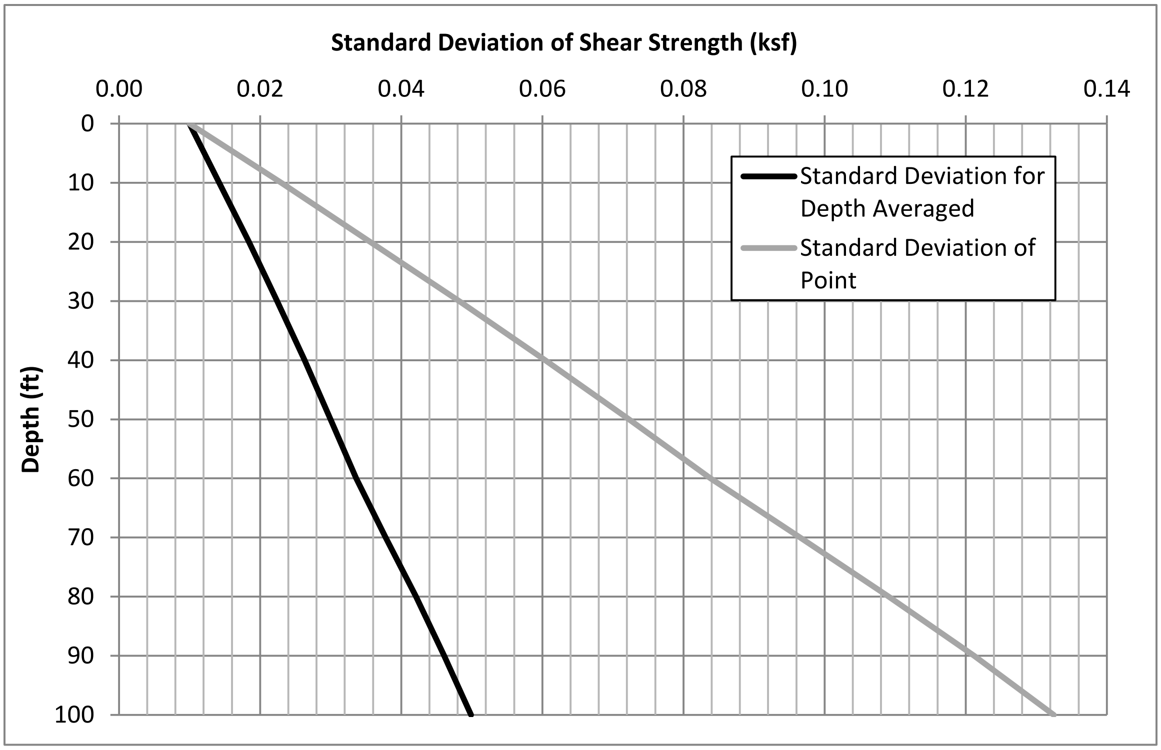


Figure 3-5: PLET 1 Standard Deviation of Undrained Shear Strength Profiles for Axial Capacity Analysis

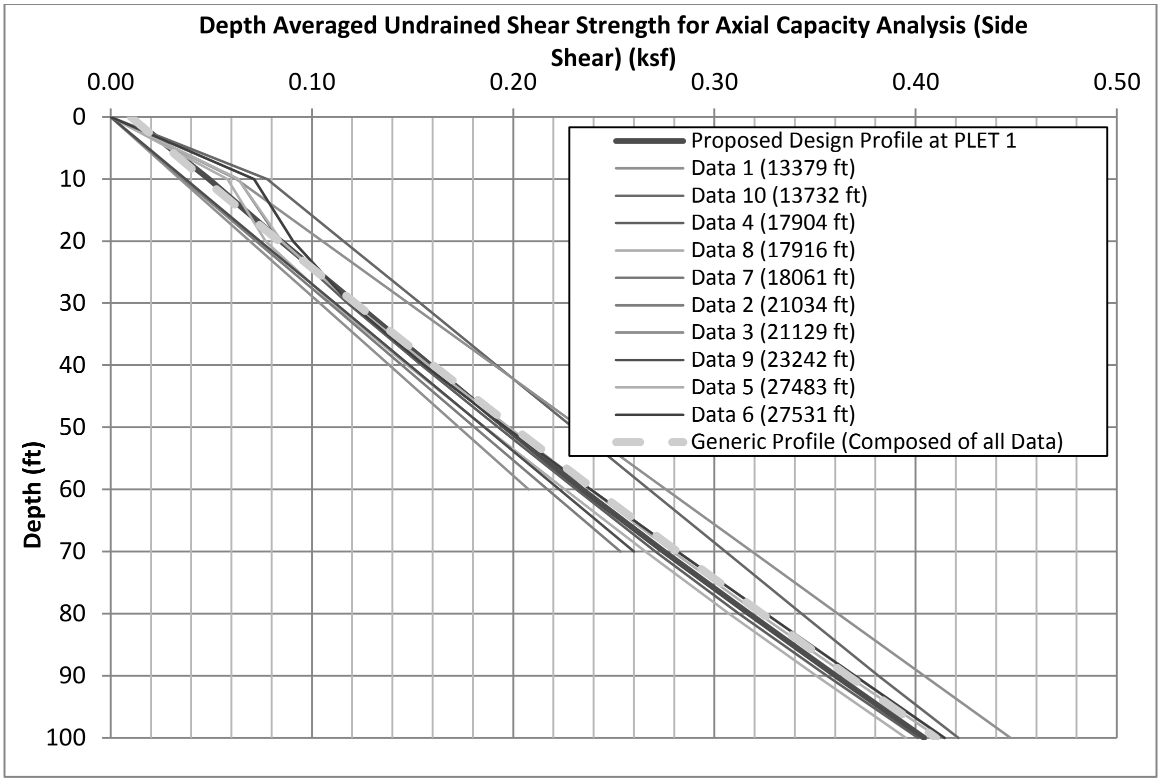


Figure 3-6: PLET 1 Depth-Averaged Undrained Shear Strength Profile for Axial Capacity Analysis in Side Shear

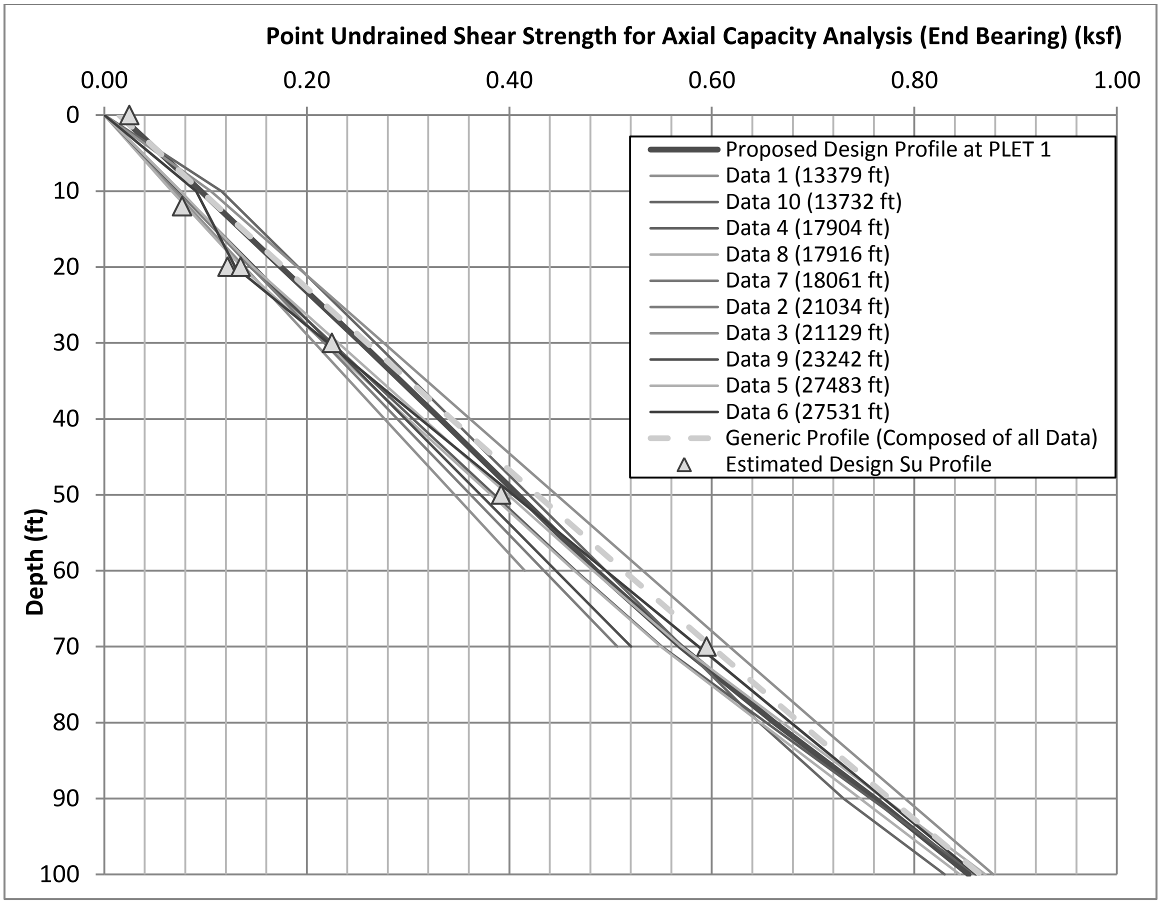


Figure 3-7: PLET 1 Undrained Shear Strength at a Point Profile for Axial Capacity Analysis in End Bearing

The surrounding data points listed are the sets that were used to formulate the profile for PLET 1. The mean profile of the depth-averaged undrained shear strength versus depth is used to estimate the axial side shear capacity of a suction caisson. For a given depth of penetration, the depth-averaged side shear is multiplied by the circumference and length of the caisson and the side shear friction coefficient to calculate the side shear. The mean profile of the point undrained shear strength versus depth is used to estimate the axial end bearing capacity of a suction caisson. For a given depth of penetration, the point undrained shear strength is calculated at the tip of the caisson and multiplied by the cross-sectional area of the tip and the bearing capacity factor to calculate the end bearing.

The next values reported are the spatially conditioned, unfactored, axial capacity and the partial spatial factor of safety for axial capacity for a caisson length of sixty feet and a caisson diameter of sixteen feet. These results are calculated in “Generic and Conditional Axial Capacity.xlsm.”

INPUT

New location (X)	
D(ft)	16
L or L_X (ft)	60
Easting (ft)	2,515,072.0
Northing (ft)	9,862,774.0
UTM zone	15N
x	2515072.0
y	9862774.0
$\rho_{FS,FB}$	0.5
Side shear	
θH (ft)	11404
θV (ft)	30
End Bearing	
θH (ft)	8869
θV (ft)	25

To change values below , go to the[Input] sheet

α	0.8
Nc	9

70	235
75	250
80	270
85	285
90	300
95	315
100	330

RESULTS

0.7129

1-1.Generic Unit Avg.Side Shear			2-1.Spatially Conditioned Avg.Side Shear		
$\mu Fs(L)$	0.1923	ksf	$\mu Fs,_{X\mid Y1,\ldots,Yn}$	0.1995	ksf
$\sigma Fs(L)$	0.0296	ksf	$\sigma Fs,_{X\mid Y1,\ldots,Yn}$	0.0211	ksf
$\delta Fs(L)$	0.1539		$\delta Fs,_{X\mid Y1,\ldots,Yn}$	0.1058	

1-2.Generic Unit End Bearing			2-2.Spatially Conditioned End Bearing		
$\mu F_B(L)$	4.61700	ksf	$\mu F_{B,\ X\mid Y1,\ldots,Yn}$	4.6254	ksf
$\sigma F_B(L)$	0.7920	ksf	$\sigma F_{B,\ X\mid Y1,\ldots,Yn}$	0.6301	ksf
$\delta F_B(L)$	0.1715		$\delta F_{B,\ X\mid Y1,\ldots,Yn}$	0.1362	

Soil contribution Only

1-3.Generic Axial Capacity			2-3.Spatially Conditioned Axial Capacity		
$\mu Qside$	580	kips	$\mu Qside,_{X\mid Y1,\ldots,Yn}$	602	kips
$\sigma Qside$	89	kips	$\sigma Qside,_{X\mid Y1,\ldots,Yn}$	64	kips
$\delta Qside$	0.1539		$\delta Qside,_{X\mid Y1,\ldots,Yn}$	0.1058	
$\mu Qend$	928	kips	$\mu Qend,_{X\mid Y1,\ldots,Yn}$	930	kips
$\sigma Qend$	159	kips	$\sigma Qend,_{X\mid Y1,\ldots,Yn}$	127	kips
$\delta Qend$	0.1715		$\delta Qend,_{X\mid Y1,\ldots,Yn}$	0.1362	
μQ	1508	kips	$\mu Q,_{X\mid Y1,\ldots,Yn}$	1532	kips
σQ	218	kips	$\sigma Q,_{X\mid Y1,\ldots,Yn}$	168	kips
δQ	0.1446		$\delta Q,_{X\mid Y1,\ldots,Yn}$	0.1096	

Click to **calculate spatially conditioned capacity**

Reliability-based design

Generic		Spatially conditioned		
β	4.5	β	4.5	Target reliability index
W'	0.0	W'	0.0	Net weight of caisson (kips)
ρ	0.5	ρ	0.5	Correlation coefficient between predicted side and tip c
Ω_R	0.3	Ω_R	0.3	c.o.v. in capacity
Ω_S	0.1	Ω_S	0.1	c.o.v. in load
$\Omega_{R'}$	0.3000	$\Omega_{R'}$	0.3000	Reduced c.o.v. in capacity
μR	1508	μR	1532	Mean of predicted total capacity (kips)
σR	218	σR	168	Standard deviation of predicted total capacity (kips)
δR	0.1446	δR	0.1096	c.o.v. in predicted capacity due to spatial variability
$Fs_{\delta R}$	1.1522	$Fs_{\delta R}$	1.0865	Partial spatial factor of safety
$\Phi_{\delta R}$	0.8679	$\Phi_{\delta R}$	0.9204	Partial resistance factor

Figure 3-8: Generic and Conditional Axial Capacity for PLET 1 with Additional Partial Spatial Factors of Safety

3.3 TRANSLATING RESULTS TO DESIGN USE

The results for a foundation are reported in the same order as in section 3.2. The methodology is also provided to help the user document where the user got the individual results from. While the results are important to show the practitioner the site conditions, the reliability in design is a main point of concern, which is reflected in the additional partial spatial factors of safety. The factors found for the individual sites are compared to the provided design and an overall factor for the site is provided to the practitioner to be applied in addition to standard design factors of safety.

Table 3-5: Ultimate Additional Factor of Safety

	Framework Analysis							
D = 16 ft L = 60 ft	Axial Capacity (kips)	Lateral Capacity (kips)	$FS_{\delta r}$-Axial	$FS_{\delta r}$-Lateral	Ratio of Axial Capacities	Ratio of Lateral Capacities	$FS_{\delta r}$-Axial Using Estimated Su Profile	$FS\delta r$-Lateral Using Estimated Su Profile
PLET 1	1454	645	1.14	1.04	1.0117	1.0496	1.1533	1.0916
PLET 2	1461	653	1.13	1.04	1.0068	1.0368	1.1377	1.0782
PLET 3	1476	678	1.13	1.04	0.9966	0.9985	1.1262	1.0385
PLET 4	1456	651	1.13	1.04	1.0103	1.0399	1.1416	1.0815
Estimated Su Profile	1471	677			(3.4)	(3.4)	(3.5)	(3.5)

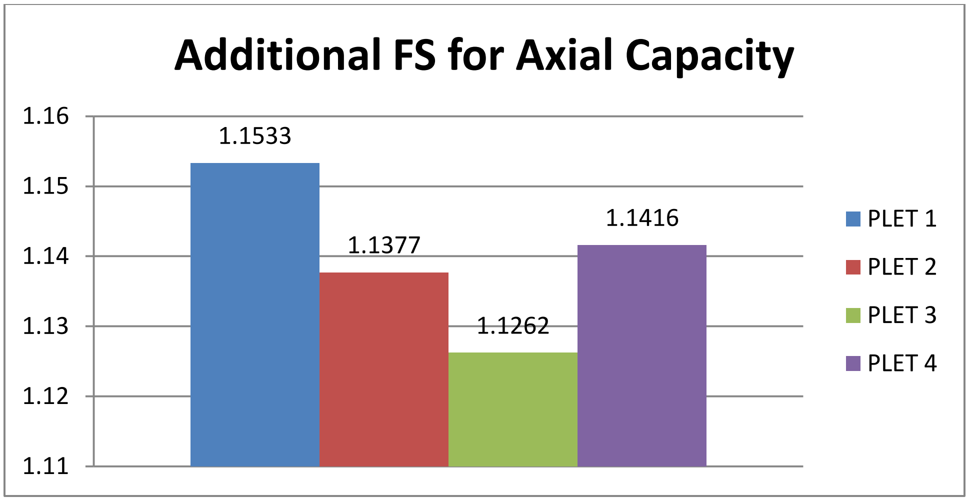


Figure 3-9: Additional Partial Spatial Factor of Safety to be Applied for Axial Capacity

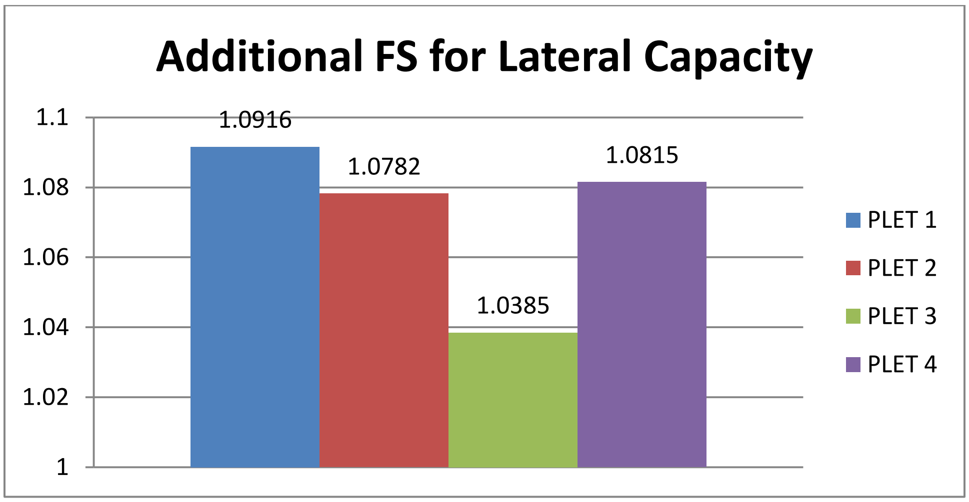


Figure 3-10: Additional Partial Spatial Factor of Safety to be Applied for Lateral Capacity

$$Ratio\ of\ Capacities = \frac{Capacity_{Estimated\ Su\ Profile}}{Capacity_{Framework\ Analysis}} \tag{3.4}$$

$$FS_{\delta R} using\ Estimated\ Su\ Profile = FS_{\delta R} \cdot Ratio\ of\ Capacities \tag{3.5}$$

These results show that the overall factor of safety to be applied, if the designer wishes to do so, is 1.15 for axial capacity foundation design and 1.09 for lateral capacity foundation design. These additional factors of safety account for the spatial variations in data and the consequent uncertainty in design for not having data exactly at the foundation location.

3.4 SUMMARY OF FRAMEWORK DEMONSTRATION

This demonstration provided the user with the steps to translate sampling information from the data provider to appropriate intervals so that data can be used in analysis. Examples of shear strength design profiles and capacities were also given to show how to effectively communicate results for design purposes. The comparisons of additional partial spatial factors of safety are an output of the database used to tell the designer the reliability of the model given no specific data at the foundation location; the maximum of these factors is the limiting factor for design.

Chapter 4: Sensitivity Analysis

In the statistical analyses performed to get the additional partial spatial factor of safety, there are three main variables that the framework uses in calculations: the target reliability index, the coefficient of variation in load, and the coefficient of variation in capacity. See Appendix A for statistical variable interactions with the reliability-based model.

A caisson weight of 0 kips has thus far been assumed, the target reliability index was 4.5, the coefficient of variation in capacity was 0.3, and the coefficient of variation in load is 0.1. Using 0.3 for the c.o.v. in capacity was determined based on pile load tests and using 0.1 for the c.o.v. in load was determined based on the fact that a manifold's capacity is generally governed by the weight of the manifold and the manifold's capacity relatively deterministic.

The following sections provide sensitivity analyses on axial capacity by varying these three variables to better understand model inputs. The values previously mentioned are used as the standard for comparison. The analysis was performed over the whole site using the unconditioned model for PLET 1 which was used in the case study with caisson length-to-diameter aspect ratio of 4 to 1.

4.1 Sensitivity to Target Reliability Index

The relationship between target reliability index, design reliability, and probability of failure are given in Table 4-1.

Table 4-1: Relationship between Reliability and Probability of Failure

β	Reliability	Probability of failure
1.5	0.933193	0.06681
2.0	0.977250	0.02275
2.5	0.993790	0.00621
3.0	0.998650	0.00135
3.5	0.999767	0.00023
4.0	0.999968	0.00003
4.5	0.999997	3.4E-06
5	1	2.87E-07

The target reliability index was varied from 3.5 to 4.0 to 4.5 keeping the coefficient of variation in capacity at 0.3 and the coefficient of variation in load at 0.1. A plot of the generic capacity and additional factor of safety are given below.

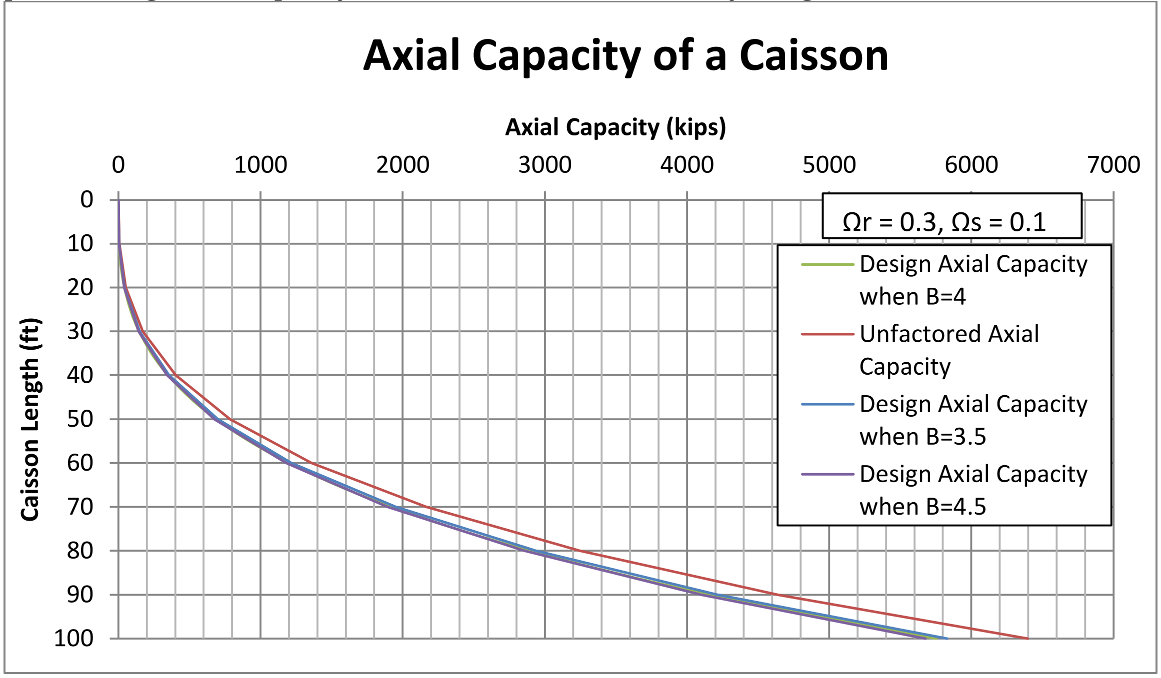


Figure 4-1: Axial Capacity Sensitivity to Target Reliability Index

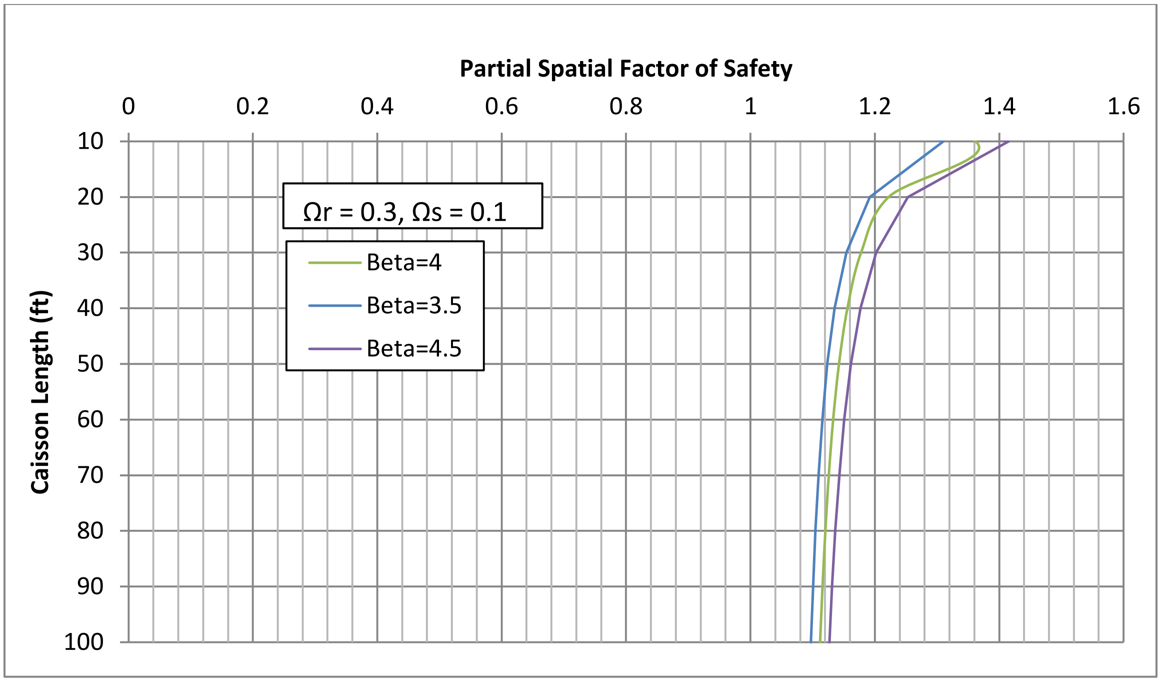


Figure 4-2: Effect of Target Reliability Index on Additional Partial Spatial Factor of Safety for Axial Capacity Analysis

As the target reliability increases, and the probability of failure decreases, the additional factor of safety increases to reflect the higher degree of structural reliability in that the foundation was designed with a higher degree of confidence in not failing. This is also reflected in the capacity as caisson penetration increases and the design capacity slightly decreases due to the increased confidence and less conservative factor.

4.2 SENSITIVITY TO COEFFICIENT OF VARIATION IN CAPACITY

The coefficient of variation in capacity is the ratio of the standard deviation to the expected value and accounts for the uncertainty in the caisson's capacity. This value is found through lab tests and these lab tests gave the standard value used in offshore design as 0.3.

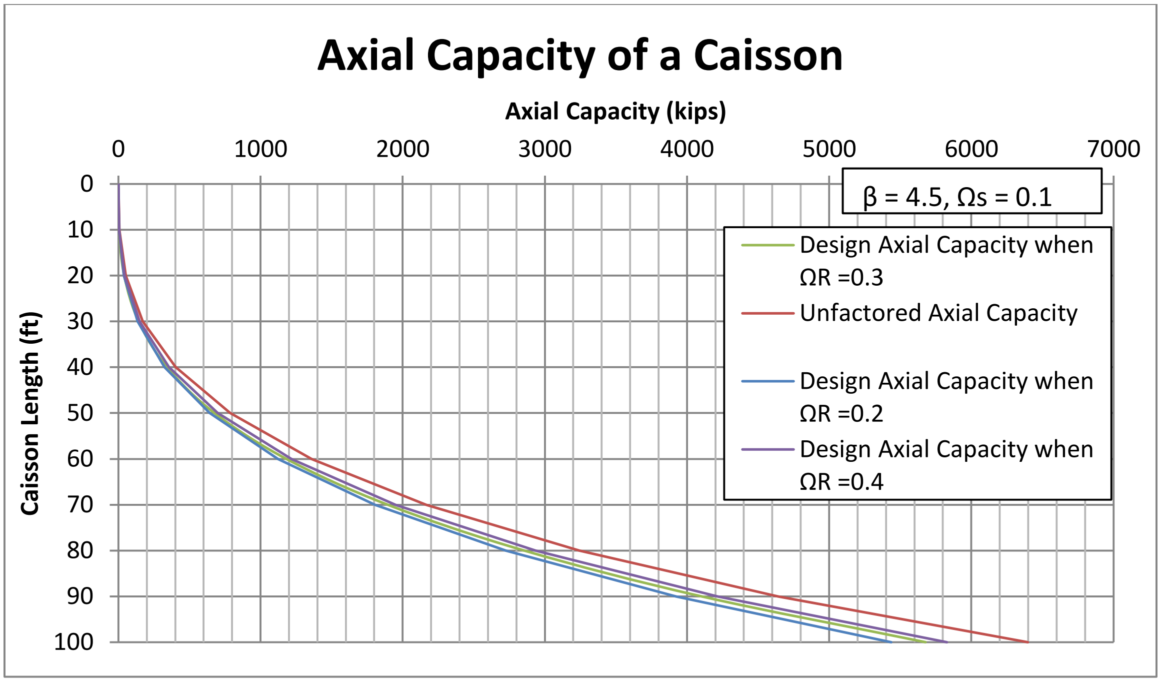


Figure 4-3: Axial Capacity Sensitivity to c.o.v. in Capacity

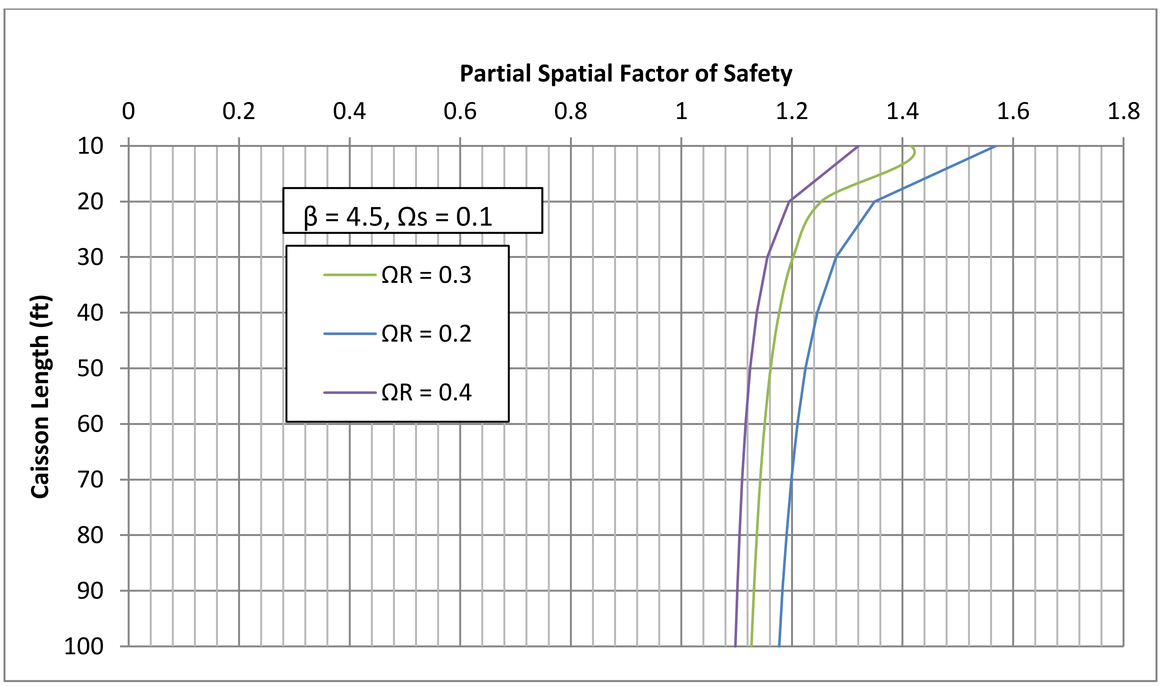


Figure 4-4: Effects of c.o.v. in Capacity on Additional Partial Spatial Factor of Safety for Axial Capacity Analysis

Increasing Ω_R shows a greater confidence in the capacity of the caisson, i.e. the axial capacity increased with depth as the c.o.v. in capacity increased, which consequently decreased the factor of safety. As the factor of safety decreased, the axial capacity increased and the design capacity became less conservative.

4.3 SENSITIVITY TO COEFFICIENT OF VARIATION IN LOAD

The coefficient of variation in load is the ratio of the standard deviation to the expected value and accounts for the uncertainty in the applied load to the caisson. This value is found through lab tests and field experience, which together yielded the standard value used in offshore design as 0.1.

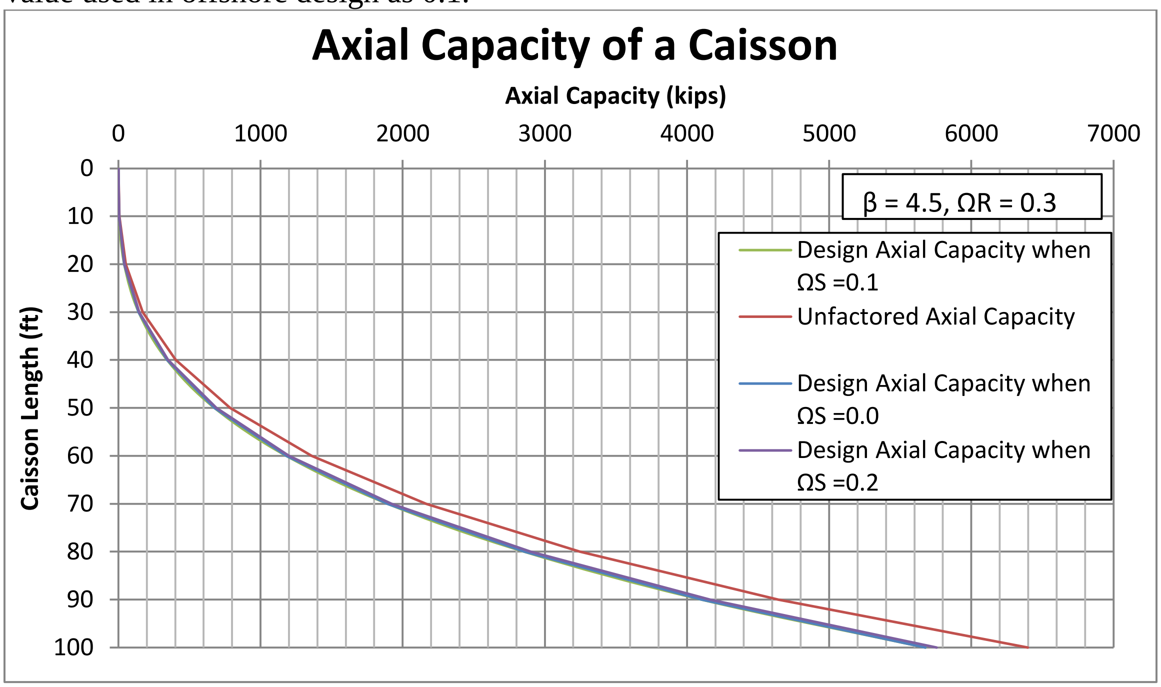


Figure 4-5: Axial Capacity Sensitivity to c.o.v. in Load

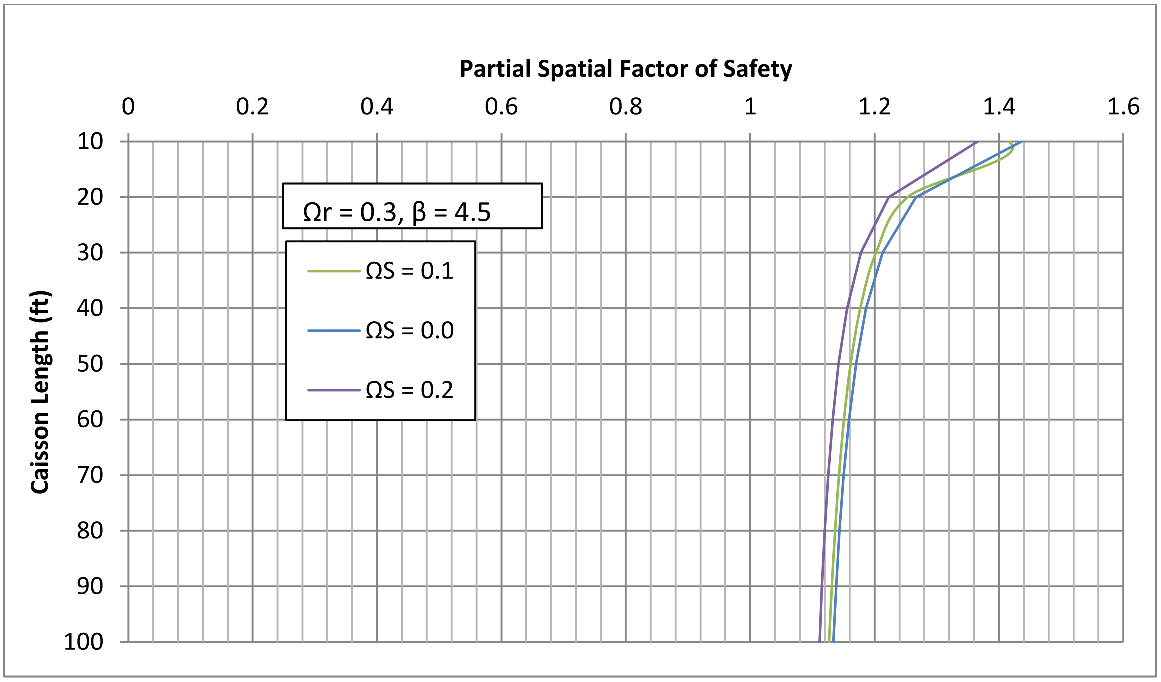


Figure 4-6: Effects of c.o.v. in Load on Additional Partial Spatial Factor of Safety for Axial Capacity Analysis

Increasing Ω_S shows a greater confidence in the load which the caisson can withstand which consequently decreased the factor of safety. As the factor of safety decreased, the axial capacity increased and the design capacity became less conservative.

4.4 CONCLUSIONS

When looking at the capacities, conclusions were drawn at caisson lengths greater than 50 feet for practical purposes; suction caissons generally penetrate at least that deep into the seafloor.

Increasing the target reliability index decreased the design axial capacity by about three percent. Likewise, the additional partial spatial factor of safety decreased by approximately three percent. Increasing the target reliability index, within the range demonstrated, improves the reliability, but likely not to the point where the design can be made more economical.

Changing the coefficient of variation in capacity increased the design axial capacity an average of about eight percent. The additional partial spatial factor of safety decreased by about seven percent with the change in the c.o.v. in capacity. With greater certainty in the capacity, the additional partial spatial factor of safety decreased and the design axial capacity increased.

The coefficient of variation in load follows a similar trend but shows less of an effect than the coefficient of variation in capacity. The design axial capacity decreased by approximately one and one-half percent with more certainty in the load and the additional partial spatial factor of safety decreased by approximately two percent with increased certainty in load.

Chapter 5:Improvements for Framework Implementation

The improvements made to the analysis process involved making changes to the structure of how existing data were used and increasing the amount of data used to produce more reliable results. The worksheets are also set up to allow for a finite amount of data, which optimizes the input process.

5.1 ALLOWANCE FOR FINITE AMOUNT OF DATA

Once data are put into the database, through a Microsoft Excel® workbook (Input.xlsx), each of the analysis workbooks then calls the corresponding data through a worksheet named "Input" which is in each of the applied workbooks. The data from the borings are also in each of the workbooks located in "Borings."

These two worksheets, "Input.xlsx" and "Boring Location Information.xlsx", are now set to allow for a finite amount of data to save the user time in updating the analysis implements. As of publication, the database contains 120 individual borings and is set to a capacity of 200 individual borings.

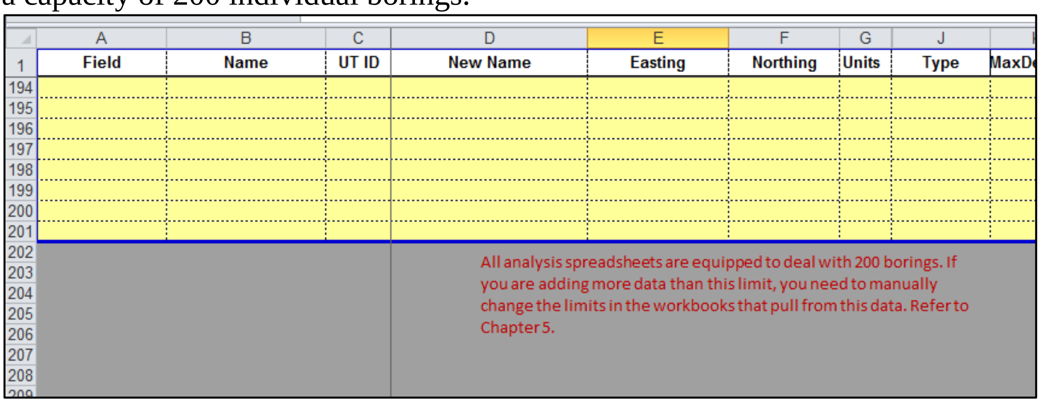


Figure 5-1: Borings Data Limitation

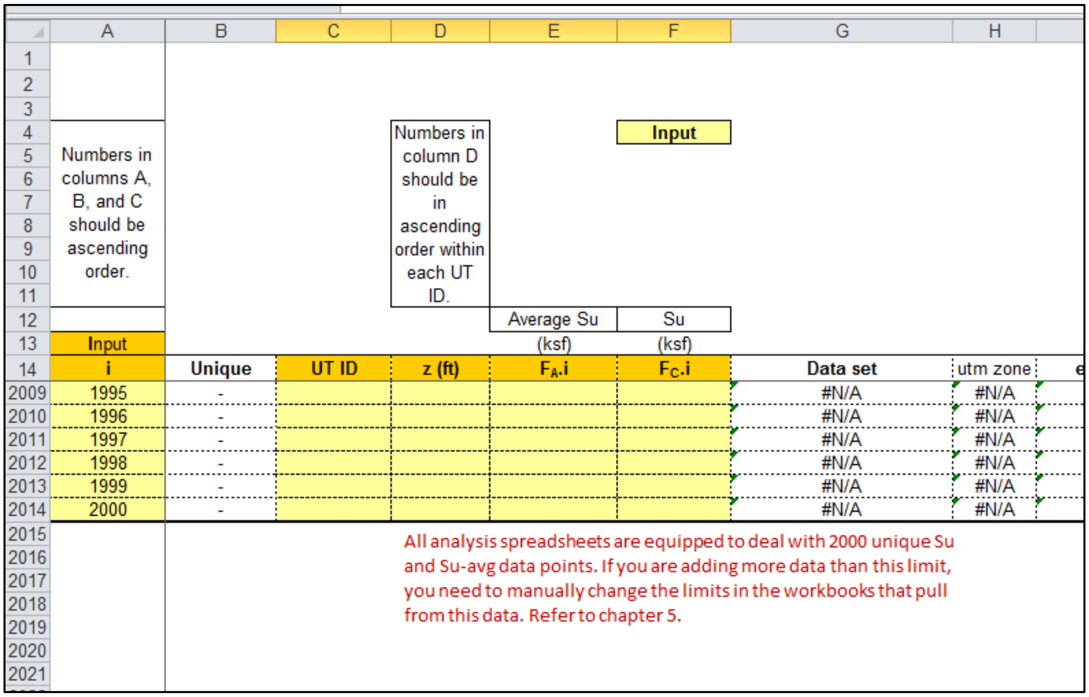


Figure 5-2: Input Data Limitation

Also as of publication, the database is set to a capacity of 2000 individual data points. The individual data point is the previously mentioned data translate from sampling intervals to ten feet intervals.

Follow these steps when dealing with the database:

1) Make sure that the data in the analysis worksheets are always linked to the most up-to-date Input file.
2) Do not change numbers in the “Borings” or “Input” worksheets in analysis workbooks. Any changes should be done in the “Input.xlsx” and, when properly linked, will update automatically in the appropriate cells in the “Borings” and “Input” worksheets.

3) In the “Input” worksheet, the model parameters are formatted to be changed as needed. The calculation worksheets, which are highlighted red, however, are where the user should focus when generating results.
4) The input worksheets and calculation worksheets are set to deal with the unique geologic setting of the Gulf of Mexico, normally to overconsolidated marine clays.

As data continue to be put into the database, the limits on linked data between the “Input.xlsx” and the analysis workbooks will be reached. In order to increase the capacity of “Borings”:

1) Copy all of row 201within the “Borings” worksheet and drag that information and the formulas located in those cells down through more rows to allow for as many borings as needed.
2) Expand the formatted area by dragging the thick blue line at the bottom of row 201 to the bottom of the rows with information from step 1.
3) Ensure this has worked correctly by checking that columns A-X are highlighted yellow with dashed cell borders. Also row 1 and columns A-C should still be frozen panes within Excel® to more easily view the boring data.

Once the borings are updated, the “Design Su” and “Design Su_r” worksheets need to be updated with the corresponding lab and field data. Columns B and C within those worksheets are linked to “Borings.” The last row needs to be highlighted and copied in columns B and C to reflect the new borings. These data points are then processed by the user to put into the “Input-Su and Su_avg,” “Input-Sur and Sur_avg,” and “Input Su1” worksheets.

The three “Input-…” worksheets within “Input.xlsx” are set to a capacity of 2000 unique data poits. In order to increase the data point capacity of these worksheets:

1) Highlight row 2014, within the worksheet and drag the information and the respective formulas down to allow for as many data sets as needed.
2) Make note of the new capacity so that other users will understand the data limits.
3) Ensure this has worked correctly by checking that columns A and B-M are highlighted yellow with dashed cell borders, that column B has no fill color, and rows 1-14 and column A are still frozen panes.

Once “Input.xlsx” is correctly filled with the given data, the analysis workbooks must be updated to reflect the changes so that the analysis will take into account all available data. Each of the following analysis workbooks is organized similarly, as demonstrated in Chapter 2, so the process of updating the new input data will be the same: “Generic and Conditional Axial Capacity.xlsm,” “Generic and Conditional Lower Bound Axial Capacity.xlsm,” “Depth-Averaged and Point Undrained Shear Strength-Unfactored.xlsm,” and “Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm.” To update these analysis workbooks:

1) Make sure that the data are linked to the most up-to-date “Input.xlsx” by checking cell B2 in “Borings” and cell A15 in “Input.” The cells should read: “='C:\...” which is the path to the user’s Input file. When used correctly, these cells will automatically update, which is why it is necessary to verify that the information is linked.
2) In “Borings,” drag the thick blue line at the bottom of row 201 to allow for the appropriate amount of data.
3) Highlight A201:J201 and drag the formulas down to the thick blue line. The newly input data should populate the cells now and will consequently be available for analysis.

4) In “Input” select row 2014 and drag the formulas and formatting down to allow for the correct amount of data that there is. Make sure to highlight A2014:AJ2014 to check that all of the necessary calculations for analysis are copied. Cell G4, the value n, should update to reflect the new number of data sets.

Do this for each of the worksheets and check that the data are being used correctly by entering a new point close to the newly input data into the analysis worksheets and check that the correlated data show the new data in the analysis.

5.2 Definite Amount of Existing Data Used in Analysis

The structure through which the calculations used correlated data were initially limited by matrix size limitations within Excel and a user-defined minimum correlation coefficient between existing data points and the location being analyzed. This method would produce a Visual Basic® run error if the minimum correlation coefficient returned more than fifty correlated data points. To prevent this problem, and to streamline the analysis process, the analysis is now structured so that the correlated data used are the fifty correlated data points with the highest correlation coefficients between themselves and the new location. These changes were made by ranking correlation coefficients within the Input worksheet of the analysis workbooks and then calling those fifty highest ranked data sets through Visual Basic to use in matrix calculations and calculate final values.

Once the analysis is implemented, the fifty correlated data points are summarized in a recently-added worksheet called “Correlated Data.” The worksheet will report the highest and lowest correlation coefficients as well as the corresponding data set names. Then the numbers of correlation coefficients within one-tenth incremental ranges are reported between 0 and 0.5, reporting all values above 0.5 as one number. Below is an example of the information.

Table 5-1: Summary of Correlated Data Using "Correlation Summation"

Correlated Data Summary		
Max and Min ρ		Data set
highest value	0.59	1583
lowest value	0.10	612
ρ limits	Number of Correlated Points	
>0.5	1	
0.4-0.5	3	
0.3-0.4	4	
0.2-0.3	15	
0.1-0.2	27	
0-0.1	0	
sum to check:	50 Correlated Points	

5.3 SUMMARY OF IMPROVEMENTS FOR FRAMEWORK IMPLEMENTATION

The database was revised as documented to create a more user-friendly interface for foundation design. Enhancements were made to allow the user to readily add additional data and streamline the data input process.

The correlation coefficient ranking system now shows the user which data points are being used in analysis and the “Correlated Data” worksheets show what those respective correlation coefficients are.

Chapter 6: Conclusions and Recommendations for Future Work

6.1 Conclusions

There is a large amount of geotechnical data. By putting it into a database, it can be applied to reliable offshore foundation designs. The database has been enhanced to be more transparent and more user-friendly. Instructions with complimentary figures have been provided to show the user how to operate both the input and analysis workbooks of the database. The revised "Home" worksheets are a quick reference to use the analysis workbooks.

An example of data points, like would be given by the data provider, has been provided to show the user how to translate that design profile, at sampling depths, to a design profile at ten-foot intervals to be used in foundation analysis for a new foundation location. A case study for a pipeline end termination foundation showed how results are presented to the practitioner with overall comparisons of the additional partial spatial factors of safety, which are used to account for not having site specific data and are to be applied in addition to design factors of safety.

A sensitivity analysis looked at the effects of reliability-based design parameters on caisson lengths between fifty and one hundred feet. Increasing the target reliability index, decreased the design axial capacity and increased the additional partial spatial factor of safety both by about three percent. Increasing the certainty in the foundation's capacity had a similar effect with an increase by about eight percent in the design axial capacity and a decrease by about seven percent in the additional partial spatial factor of safety. Likewise, increasing the certainty in the load induced on the foundation, the design axial capacity increased by approximately one and one-half percent while the additional partial spatial factor of safety decreased by about two percent.

The revisions to the database were documented to provide a more user-friendly interface for foundation design. Enhancements to the data input process allow the user to readily add additional data. The model is also now set to use fifty correlated data points in analysis. A ranking system has been created and shows the user which data points are being used in analysis with the additional "Correlated Data" worksheets that show what those respective correlation coefficients are.

In initiating work with a database, basic steps like detailed explanations and consistency in data collection methods can help the user to understand the models. This database gives as full of a picture of real conditions as possible with physical and statistical parameters reporting reliable strengths where there is in fact no data. With increased experience in the lab and field, and consequently increased data and results, the model is continually being updated to decrease uncertainty and increase reliability.

By providing the industry with a database that uses reliability-based design from actual data and spatial variation analysis, this project will continue to provide a more efficient design process. Reliability-based design can create a more optimized offshore foundation design with increasing reliability through process efficiency.

6.2 FUTURE RECOMMENDATIONS

Through user needs and process optimization, there will continue to be room for improvements. Some of those ideas are highlighted here:

- Implement a lower bound analysis for lateral capacity
- Develop a model where the data points are correlated to points along the continental shelf.
- Recognize other geologic settings within the Gulf of Mexico

- Show the information in three dimensions to help spot areas of weakness in strength or weakness in data, i.e. locations with a greater degree of uncertainty due to lack of data
- Develop a model to account for foundation capacities in sands alone, clays alone, and a combination of the two soils
- Develop a model to account for designing shallow foundations

Appendix A: Reliability-Based Equations (Cheon, 2011)

DATABASE MODEL

The database created by Cheon (2011) uses reliability-based methods to calculate both factored and unfactored design strengths at a site. Design strengths are calculated using nearby data and horizontal and vertical spatial variation correlations among existing data points and between existing data points and the location in question. Refer to Cheon for further background on theory and model calibration.

The reliability-based calculations provided in this section are the backbone of this framework. Understanding how the implementation uses existing data to produce results at a new location is key to further optimizing the framework. The next section of this chapter provides subsequent steps in foundation analysis.

Generic Model

There is a generic model that is not spatially conditioned and represents the field as a whole. The probability distribution that describes design property variations for a particular location, i, is described by a cumulative distribution function, F_{xi} (x_i), which is characterized by the mean, standard deviation, and coefficient of variation (Ang and Tang 1975). The mean is the expected soil property value at a site if there was an actual investigation performed there. The standard deviation represents the uncertainty in that predicted value. (Cheon 2011)

Spatially Conditioned Model

The spatially conditioned model takes existing data into account that is within the area of the requested location. The spatially conditioned forms for the mean and standard deviation, the first and second moments, respectively, for a new location j, using existing data location i are (Ang and Tang 1975):

$$\mu_{Xj|Xi} = \mu_{Xj} + \rho_{Xi,Xj}\left(\frac{\sigma_{Xj}}{\sigma_{Xi}}\right)(x_i - \mu_{Xi}) \qquad \text{(A.1)}$$

$$\sigma_{Xj|Xi} = \left[\sigma_{Xj}\left(1 - \rho_{Xi,Xj}\right)^2\right]^{1/2} \qquad \text{(A.2)}$$

where $\mu_{Xj|Xi}$= mean value at j given value at i

μ_{Xj}, μ_{Xi}= mean values from generic model

$\sigma_{Xj|Xi}$= standard deviation at j given i

σ_{Xj}, σ_{Xi}= standard devition values from generic model

x_i= known value at location i

$\rho_{Xi,Xj}$= correlation coefficient between values at i and j

These equations show how the spatial conditioning can affect the design values. Looking at equation 2.1, as the correlation coefficient increase, i.e. as the new location gets closer to existing data, the conditional mean is more affected by the existing location. As the correlation coefficient decreases, the mean value at j given the mean at i approaches the mean value at j. Likewise, looking at equation 2.2, as the correlation coefficient decreases, i.e. as the new location gets further from the existing location, the uncertainty becomes larger and approaches the generic value. (Cheon 2011)

The probability distribution for the conditional variable is assumed to be the same as that for the unconditional variable. It is also assumed to be fully characterized by its first two moments, the mean and standard deviation. With these assumptions, the cumulative distribution function is as follows (Journel and Huijbregts 1978):

$$F_{Xj|Xi}\left(x_j|x_i\right) = g_f(x_i, location\ i, location\ j, \mu_{Xj|Xi}, \sigma_{Xj|Xi}, \overrightarrow{\Phi_F}) \qquad \text{(A.3)}$$

where $F_{Xj|Xi}\left(x_j|x_i\right)$ = cumulative distribution function for value at j given i

g_f (…) = model for the cumulative distribution function

$\overrightarrow{\Phi_F}$= vector of model parameters that describe g_f()

With one or more nearby data points, the conditional model is as follows:

$$\mu_{Xj|Xi} = \mu_{Xj} + C_{ij}C_{ii}^{-1}(\overrightarrow{x_i} - \overrightarrow{\mu_{Xi}}) \tag{A.4}$$

$$\sigma_{Xj|Xi} = \sqrt{\sigma_{Xj}^{2} - C_{ij}C_{ii}^{-1}C_{ij}^{T}} \tag{A.5}$$

where $\overrightarrow{x_i}$= vector containing the known values at location i

$\overrightarrow{\mu_{Xi}}$= vector containing the mean values from the generic model

$$C_{ii} = \begin{bmatrix} \rho_{i1,i1}\sigma_{i1}\sigma_{i1} & \cdots & \rho_{i1,in}\sigma_{i1}\sigma_{in} \\ \vdots & \ddots & \vdots \\ \rho_{in,i1}\sigma_{in}\sigma_{i1} & \cdots & \rho_{in,in}\sigma_{in}\sigma_{in} \end{bmatrix}$$

$$C_{ij} = \{\rho_{j,i1}\sigma_j\sigma_{i1} \cdots \rho_{j,in}\sigma_j\sigma_{in}\}$$

where square brackets denote matrices and curved brackets denote vectors.

The correlation coefficient changes depending on the distance between the two locations being used, whether among existing data or considering a new location's proximity to existing data. It is expressed as:

$$\rho_{Xi,Xj} = g_R(x_i, x_j, location\ i, location\ j, \overrightarrow{\Phi_R}) \tag{A.6}$$

where g_R (…) = model for the correlation coefficient

$\overrightarrow{\Phi_R}$= vector of model parameters that describe g_R()

The model parameter calibration is documented in detail in Cheon 2011. The maximum likelihood method was used to calibrate the models. This calibration was used to estimate the model parameters, $\overrightarrow{\Phi}$, which are given with the appropriate equations in the next section.

MODELS FOR DESIGN UNDRAINED SHEAR STRENGTH

Using the basic form of the model described in 2.1, the mean and standard deviation of the generic model, the mean, standard deviation, and horizontal and vertical correlations of the conditioned model are used to describe the design shear strength models.

Design Undrained Shear Strength at a Point, S_u(L)

The design undrained shear strength at a point is predicted in terms of the mean and the standard deviation as follows:

$$\mu_{Su(L)} = \phi_{C1} + \phi_{C2}L + \phi_{C3}L^2 \quad \text{(A.7)}$$

$$\sigma_{Su(L)} = \phi_{C4} + \phi_{C5}L \quad \text{(A.8)}$$

where $\mu_{Su(L)}$= mean [ksf]

$\sigma_{Su(L)}$= standard deviation [ksf]

L= depth of penetration [ft]

For a new location X that is conditioned of existing data points Y_1, Y_2,…Y_n, the conditional forms of the mean and standard deviation are as follows:

$$\mu_{X|Y\ for\ Su(L)} = \mu_{Su(X)} + C_{XY}{C_{YY}}^{-1}(\overrightarrow{S_{u,Y}} - \overrightarrow{\mu_{Su(Y)}}) \quad \text{(A.9)}$$

$$\sigma_{X|Y\ for\ Su(L)} = \sqrt{{\sigma_{Su(X)}}^2 - C_{XY}{C_{YY}}^{-1}C_{XY}^T} \quad \text{(A.10)}$$

The correlation coefficient between two locations is:

$$\rho = \left(e^{-|\tau|/\theta}\right) \quad \text{(A.11)}$$

where τ=distance separating j and i

θ= correlation distance

The correlation coefficient in undrained shear strength between locations is modeled as:

$$\rho = \left(e^{-|\tau_H|/\theta_H}\right)\left(e^{-|\tau_V|/\theta_V}\right) \quad \text{(A.12)}$$

where τ_H= horizontal distance between points

τ_V= vertical distance between points

θ_H= horizontal correlation distance [ft]

θ_V= vertical correlation distance [ft]

The correlation distance is the distance to where the correlation coefficient becomes comparatively small. The data points within the correlation distance tend to be relatively close in value. For example, if the location in question is within the correlation distance of design shear strengths higher than the generic value, that shear strength at that location will likely be higher than the generic value as well (Cheon 2011).

The correlation distances are modeled as:

$$\theta_{H\ for\ Su(L)} = e^{\phi_{C6}} + Le^{\phi_{C7}} \tag{A.13}$$

$$\theta_{V\ for\ Su(L)} = e^{\phi_{C8}} \tag{A.14}$$

Note that the horizontal correlation distance is modeled as a function of penetration due to the fact that within the study area, the correlation in design shear strength at a point tends to increase with depth.

The model parameters that describe the design shear strength are presented in table A-1.

Table A-6-1: Model Parameters for Su(L)

μ			σ		θ_H		θ_V
ϕ_{C1}	ϕ_{C2}	ϕ_{C3}	ϕ_{C4}	ϕ_{C5}	ϕ_{C6}	ϕ_{C7}	ϕ_{C8}
0.015	0.008	0.000005	0.01	0.0013	8.4	4.3	3.2
[ksf]	[ksf/ft]	[ksf/ft^2]	[ksf]	[ksf/ft]	[ln(ft)]		[ln(ft)]

Depth-Averaged Design Undrained Shear Strength ($S_{u,avg}$)

The depth-averaged design undrained shear strength is predicted in terms of the mean and the standard deviation as follows:

$$\mu_{Su,avg(L)} = \phi_{A1} + \phi_{A2}L + \phi_{A3}L^2 \tag{A.15}$$

$$\sigma_{Su,avg(L)} = \phi_{A4} + \phi_{A5}L \tag{A.16}$$

where $\mu_{Su,avg(L)}$= mean [ksf]

$\sigma_{Su,avg(L)}$= standard deviation [ksf]

L= depth of penetration [ft]

For a new location X that is conditioned of existing data points Y_1, Y_2,…Y_n, the conditional forms of the mean and standard deviation are as follows:

$$\mu_{X|Y\ for\ Su,avg(L)} = \mu_{Su,avg(X)} + C_{XY}{C_{YY}}^{-1}(\overrightarrow{S_{u,avg,Y}} - \overrightarrow{\mu_{Su,avg(Y)}}) \quad (A.17)$$

$$\sigma_{X|Y\ for\ Su,avg(L)} = \sqrt{{\sigma_{Su,avg(X)}}^2 - C_{XY}{C_{YY}}^{-1}C_{XY}^T} \quad (A.18)$$

The correlation coefficient in depth-averaged undrained shear strength between locations is modeled the same as undrained shear strength at a point:

$$\rho = \left(e^{-|\tau_H|/\theta_H}\right)\left(e^{-|\tau_V|/\theta_V}\right) \quad (A.19)$$

The correlation distances for the predicted depth-averaged undrained shear strength are:

$$\theta_{H\ for\ Su,avg(L)} = e^{\phi_{A6}} + Le^{\phi_{A7}} \quad (A.20)$$

$$\theta_{V\ for\ Su,avg(L)} = e^{\phi_{A8}} \quad (A.21)$$

The model parameters that describe the depth-averaged undrained shear strength are presented in table 2-2.

Table A-6-2: Model Parameters for $S_{u,avg}(L)$

μ			σ		θ_H		θ_V
ϕ_{A1}	ϕ_{A2}	ϕ_{A3}	ϕ_{A4}	ϕ_{A5}	ϕ_{A6}	ϕ_{A7}	ϕ_{A8}
0.01	0.0036	0.000004	0.01	0.00045	8.7	4.5	3.4
[ksf]	[ksf/ft]	[ksf/ft^2]	[ksf]	[ksf/ft]	[ln(ft)]		[ln(ft)]

Equivalent Linear Profile of Design Shear Strength ($S_{u,1}$)

To predict the equivalent linear shear strength profile, the model of deign undrained shear strength at a point is used. The equivalent linear profile is predicted in terms of the mean and the standard deviation as follows:

$$\mu_{Su1(L)} = \phi_{D1} + \phi_{D2}L \quad (A.22)$$

$$\sigma_{Su1(L)} = \phi_{D3} \quad (A.23)$$

where $\mu_{Su1(L)}$= mean [ksf]

$\sigma_{Su1(L)}$= standard deviation [ksf]

L= depth of penetration [ft]

The correlation coefficient for the predicted slope of the equivalent linear shear strength profile between locations is modeled the same as undrained shear strength at a point:

$$\rho = \left(e^{-|\tau_H|/\theta_H}\right)\left(e^{-|\tau_V|/\theta_V}\right) \quad (A.24)$$

The correlation distances for the predicted slope of equivalent linear undrained shear strength are:

$$\theta_{H\ for\ Su1(L)} = e^{\phi_{D4}} + Le^{\phi_{D5}} \quad (A.25)$$

$$\theta_{V\ for\ Su1(L)} = e^{\phi_{D6}} \quad (A.26)$$

The model parameters that describe the equivalent linear undrained shear strength are presented in table 2-3.

Table A-6-3: Model Parameters for $S_{u1}(L)$

μ		σ	θ		
ϕ_{D1}	ϕ_{D2}	ϕ_{D3}	ϕ_{D4}	ϕ_{D5}	ϕ_{D6}
6.12	0.02	1.10	8.5	4.5	3.4
[psf/ft]	[psf/ft^2]	[psf/ft]	[ln(psf/ft)]		[ln(psf/ft)]

Design Remolded Shear Strength at a Point (S_{uR})

The design undrained remolded shear strength is predicted in terms of the mean and the standard deviation as follows:

$$\mu_{SuR(L)} = \phi_{E1} + \phi_{E2}L \quad (A.27)$$

$$\sigma_{SuR(L)} = \phi_{E3} + \phi_{E4}L \quad (A.28)$$

where $\mu_{SuR(L)}$= mean [ksf]

$\sigma_{SuR(L)}$= standard deviation [ksf]

L= depth of penetration [ft]

For a new location X that is conditioned of existing data points Y_1, Y_2,…Y_n, the conditional forms of the mean and standard deviation are as follows:

$$\mu_{X|Y\ for\ SuR(L)} = \mu_{SuR(X)} + C_{XY}{C_{YY}}^{-1}(\overrightarrow{S_{uR,Y}} - \overrightarrow{\mu_{SuR(Y)}}) \quad (A.29)$$

$$\sigma_{X|Y\ for\ SuR(L)} = \sqrt{{\sigma_{SuR(X)}}^2 - C_{XY}{C_{YY}}^{-1}C_{XY}^T} \quad (A.30)$$

The correlation coefficient for design remolded undrained shear strength between locations is modeled as:

$$\rho = \left(e^{-|\tau_H|/\theta_H}\right)\left(e^{-|\tau_V|/\theta_V}\right) \quad (A.31)$$

The correlation distances for the predicted design remolded undrained shear strength are:

$$\theta_{H\ for\ SuR(L)} = e^{\phi_{E5}} \quad (A.32)$$

$$\theta_{V\ for\ SuR(L)} = e^{\phi_{E6}} \quad (A.33)$$

The model parameters that describe the design remolded undrained shear strength are presented in table 2-4.

Table A-6-4: Model Parameters for S_{uR}(L)

μ		σ		θ_H	θ_v
ϕ_{E1}	ϕ_{E2}	ϕ_{E3}	ϕ_{E4}	ϕ_{E5}	ϕ_{E6}
0.005	0.0031	0.004	0.00085	8.7	3.55
[ksf]	[ksf/ft]	[ksf]	[ksf/ft]	[ln(ft)]	[ln(ft)]

Depth-Averaged Remolded Shear Strength ($S_{uR,avg}$)

The depth-averaged design undrained remolded shear strength is predicted in terms of the mean and the standard deviation as follows:

$$\mu_{SuR,avg(L)} = \phi_{F1} + \phi_{F2}L \quad (A.27)$$

$$\sigma_{SuR,avg(L)} = \phi_{F3} + \phi_{F4}L \quad (A.28)$$

where $\mu_{SuR,avg(L)}$= mean [ksf]

$\sigma_{SuR,avg(L)}$= standard deviation [ksf]

L= depth of penetration [ft]

For a new location X that is conditioned of existing data points Y_1, Y_2,…Y_n, the conditional forms of the mean and standard deviation are as follows:

$$\mu_{X|Y\ for\ SuR,avg(L)} = \mu_{SuR,avg(X)} + C_{XY}C_{YY}{}^{-1}(\overrightarrow{S_{uR,avg,Y}} - \overrightarrow{\mu_{SuR,avg(Y)}}) \quad \text{(A.29)}$$

$$\sigma_{X|Y\ for\ SuR(L)} = \sqrt{\sigma_{SuR(X)}{}^2 - C_{XY}C_{YY}{}^{-1}C_{XY}^T} \quad \text{(A.30)}$$

The correlation coefficient for design remolded undrained shear strength between locations is modeled as:

$$\rho = \left(e^{-|\tau_H|/\theta_H}\right)\left(e^{-|\tau_V|/\theta_V}\right) \quad \text{(A.31)}$$

The correlation distances for the predicted design remolded undrained shear strength are:

$$\theta_{H\ for\ SuR,avg(L)} = e^{\phi_{F5}} \quad \text{(A.32)}$$

$$\theta_{V\ for\ SuR,avg(L)} = e^{\phi_{F6}} \quad \text{(A.33)}$$

The model parameters that describe the design remolded undrained shear strength are presented in table 2-4.

Table A-6-5: Model Parameters for $S_{uR,avg}$(L)

μ		σ		θ_H	θ_V
ϕ_{F1}	ϕ_{F2}	ϕ_{F3}	ϕ_{F4}	ϕ_{F5}	ϕ_{F6}
0.004	0.0015	0.004	0.00034	8.9	3.6
[ksf]	[ksf/ft]	[ksf]	[ksf/ft]	[ln(ft)]	[ln(ft)]

FRAMEWORK SUMMARY

The comprehensive approach between the lab and the field allows for a more reliable design by seeing how the parameters correspond to each other through different testing methods. The main goal of the site investigation is to gain as clear a picture as possible with representative data to design with.

The geostatistical models developed and calibrated by Cheon use spatial variations to represent a large site with a small amount of data. The uncertainty in this reliability-based design is represented by the standard deviation and further reflected in an additional factor of safety for design. This step uses statistical parameters to produce a reliability factor to account for load and capacity variations with a target reliability index. Using reliability-based design helps to maximize the value of information obtained from the geotechnical site investigation.

With this framework, the predicted values of design shear strength at a point are used for design axial end bearing capacity, the predicted values of depth-averaged design shear strength are used for design axial side shear capacity, and the predicted values of the equivalent linear design shear strength are used for design lateral capacity.

Design Axial Capacity of a Suction Caisson

The axial capacity of a suction caisson in clay is a combination of side shear, Q_s, and reverse end bearing, Q_p, capacities estimated using the API (2003) design guide. The framework yields a design axial capacity that analyzes spatial variation due to soils only and no considering the submerged unit weight of the caisson (Cheon 2011):

$$Q_{axial} = Q_s + Q_p \tag{A.34}$$

The axial side shear capacity is calculated using the depth-averaged undrained shear strength over the length of the caisson as follows below. Note that the alpha value used is a dimensionless friction coefficient that is assumed to be 0.8 throughout the side shear calculations. The value of 0.8 is a typical value used in offshore foundation designs founded in normally consolidated clays in the Gulf of Mexico (Cheon 2011):

$$Q_s = A_s F_s \tag{A.35}$$

$$F_s = \frac{1}{L}\int_0^L f_s(z)dz = \frac{1}{L}\int_0^L \alpha(z)s_u(z)dz = \alpha_{avg}S_{u,avg}(L)$$

$$Q_s = A_s\alpha_{avg}S_{u,avg}(L) \tag{A.36}$$

where A_s=side surface area (πDL)

F_s=average unit side shear

z = depth of penetration

$f_s(z)$=unit side shear as a function of depth of penetration

α_{avg}= friction coefficient

D = diameter of caisson

L = length of caisson

The end bearing develops at the tip of the caisson under undrained loading conditions using the undrained shear strength at a point and is calculated below. Note that the bearing capacity factor is assumed to be 9 throughout the database as recommended in accordance with API (2003):

$$Q_p = A_p q_b \tag{A.37}$$

$$qb = N_c S_u$$

$$Q_p = A_p N_c S_u \tag{A.38}$$

where A_p= cross sectional area of the caisson ($\pi D^2/4$)

q_b= unit reverse end bearing

N_c= bearing capacity factor

Design Lateral Capacity of a Suction Caisson

Aubeny et al. (2003) proposed a simplified plasticity model to calculate the lateral capacity of a suction caisson. This model uses energy equations to translate work applied by the plastic failure of the soil to a lateral capacity through the work that is dissipated over a local zone. The lateral capacity, H_{max}, of a suction caisson is calculated as follows:

$$H_{max} = Q_{lateral} = \frac{(D_s+D_e)/v_0}{\left|1-\frac{L_i}{L_o}\right|} \tag{A.39}$$

where D_s= energy dissipated due to side resistance

D_e= energy dissipated due to the spherical soil end cap

v_0= velocity at the mudline

L_i= depth of load attachment on the caisson

L_o= depth of the center of rotation

The database minimizes the lateral capacity, with a known load attachment point, with respect to the center of rotation through a solver iteration.

Partial Spatial Factor of Safety ($FS_{\delta R}$)

The partial spatial factor of safety is a way to quantify the reliability based on the target reliability index, β, and the coefficients of variation in load, Ω_s, and capacity, Ω_R. Assuming that the available load and ultimate load are lognormally distributed, the partial spatial factor of safety is found as the probability that the load imposed on the caisson is less than the ultimate load the caisson can support.

Design reliability for a suction caisson is calculated based on R, the capacity, and S, the load, which are both modeled as random variables with a normal distribution. The capacity and load are also assumed statistically independent. The reliability is calculated as:

$$Reliability = P(R > S) = 1 - P_f \tag{4.1}$$

$$P_f = P(R < S) = \Phi(-\beta) \tag{4.2}$$

where P_f= probability of failure

$\Phi(-\beta)$= standard normal function of β

The target reliability index is normally distributed as:

$$\Phi(\beta) = \Phi\left(\frac{\ln(FS_m \cdot FS_{\delta R})}{\sqrt{\Omega_R^2 + \delta_R^2 + \Omega_S^2}}\right) \tag{A.40}$$

where FS_m= median factor of safety

δ_R= coefficient of variation in spatial variability in resistance

Then to find the partial spatial factor of safety, the target reliability is set to equal the same value with and without spatial variability. Through equation simplification, the partial spatial factor of safety, for both axial and lateral capacity is:

$$FS_{\delta R} = \frac{\exp\left(\beta\sqrt{\Omega_R{}^2+\delta_R{}^2+\Omega_S{}^2}\right)}{exp\left(\beta\sqrt{\Omega_R{}^2+\Omega_S{}^2}\right)} \qquad \text{(A.41)}$$

Appendix B: Visual Basic Code

Depth Averaged and Point Undrained Shear Strength.xlsm:

```
Public x(2000), y(2000), z(2000), sFs(2000), sFB(2000)
Public Rhos(2000), RhoB(2000), k1(50), k2(50), C1(50, 50), C2(50, 50)
```

```
Sub DepthAvgPointShearStrengths()

'Initiates model parameters
Dim A1, A2, A3, A4, A5, A6, A7, A8, m1, m2 As Single
Dim B1, B2, B3, B4, B5, B6, B7, B8 As Single



Sheets("input").Select
A1 = Range("B3").Value
A2 = Range("B4").Value
A3 = Range("B5").Value
A4 = Range("B6").Value
A5 = Range("B7").Value
A6 = Range("B8").Value
A7 = Range("B9").Value
A8 = Range("B10").Value
```

```
B1 = Range("D3").Value
B2 = Range("D4").Value
B3 = Range("D5").Value
B4 = Range("D6").Value
B5 = Range("D7").Value
B6 = Range("D8").Value
B7 = Range("D9").Value
B8 = Range("D10").Value

'Uses updated n-value to represent number of data sets
n = Range("g4").Value



'============
'Initates stepping through the existing data
ns = 0
nb = 0
For j = 1 To n

Sheets("input").Select
   z(j) = Range(Cells(j + 14, 4), Cells(j + 14, 4)).Value
   x(j) = Range(Cells(j + 14, 11), Cells(j + 14, 11)).Value
   y(j) = Range(Cells(j + 14, 10), Cells(j + 14, 10)).Value
```

```
sFs(j) = Range(Cells(j + 14, 18), Cells(j + 14, 18)).Value

sFB(j) = Range(Cells(j + 14, 24), Cells(j + 14, 24)).Value


'Rho values for both side shear (s) and end bearing (B)
Rhos(j) = Range(Cells(j + 14, 30), Cells(j + 14, 30)).Value
RhoB(j) = Range(Cells(j + 14, 31), Cells(j + 14, 31)).Value

'Ranks of correlation coefficients from columns 35 and 36
Ranksj = Range(Cells(j + 14, 35), Cells(j + 14, 35)).Value
RankBj = Range(Cells(j + 14, 36), Cells(j + 14, 36)).Value

'If loop that takes ranks 1-50 for depth-averaged correlation
If Ranksj <= 50 Then
    ns = ns + 1
    k1(ns) = j
End If

'If loop that takes ranks 1-50 for point correlation
If RankBj <= 50 Then
    nb = nb + 1
    k2(nb) = j
End If
```

```
Next j
    nks = ns
    nkb = nb

'==========depth-averaged strength c matrix=c1
For ii1 = 1 To nks
      For jj1 = 1 To ii1
            'Calculation to populate c-matrix
            C1(ii1, jj1) = Exp(-Sqr((x(k1(ii1)) - x(k1(jj1))) ^ 2 + (y(k1(ii1)) - y(k1(jj1))) ^ 2) / (Exp(A6) + Exp(A7) * z(k1(ii1)))) * Exp(-Abs(z(k1(ii1)) - z(k1(jj1))) / Exp(A8)) * sFs(k1(ii1)) * sFs(k1(jj1))
            'Code to populate c-matrix
            If ii1 <> jj1 Then
            C1(jj1, ii1) = C1(ii1, jj1)
            End If
     Next jj1
Next ii1

'==========point strength c matrix=c2
For ii2 = 1 To nkb
     For jj2 = 1 To ii2
            'Calculation to populate c-matrix
            C2(ii2, jj2) = Exp(-Sqr((x(k2(ii2)) - x(k2(jj2))) ^ 2 + (y(k2(ii2)) - y(k2(jj2))) ^ 2) / (Exp(B6) + Exp(B7) * z(k2(ii2)))) * Exp(-Abs(z(k2(ii2)) - z(k2(jj2))) / Exp(B8)) * sFB(k2(ii2)) * sFB(k2(jj2))
```

```
    'Code to populate c-matrix
    If ii2 <> jj2 Then
    C2(jj2, ii2) = C2(ii2, jj2)
    End If
    Next jj2
Next ii2

'Fills columns L and V to show existing data used=====
Sheets("generic and conditioned").Select
Range("l4:l300,v4:v300").Select
Range("l4").Activate
Selection.ClearContents

'Fills cells with number of correlation points, 50 points
'for code at present use
Range("l2").Value = nks
Range("v2").Value = nkb
   With Application
      .Calculation = xlMabnual
      .MaxChange = 0.001
   End With
   ActiveWorkbook.PrecisionAsDisplayed = False
   Range("J20").Select
For j = 1 To nks
   'generic and conditioned sheet correlated data
```

```
    'points for Su_avg
    Range("L4").Offset(j - 1, 0).Value = k1(j)
Next j
For j = 1 To nkb
    'generic and conditioned sheet correlated data
    'points for Su_point
    Range("v4").Offset(j - 1, 0).Value = k2(j)
Next j
'Shows c-matrix
Sheets("cmatrix").Visible = True
Sheets("cmatrix").Select
'Fills c-matrices
    Range("E3:bb52,E60:bb109").Select
    Range("E3").Activate
    Selection.ClearContents
'==========depth-averaged c matrix=c1
For ii1 = 1 To nks
      For jj1 = 1 To nks
           Range(Cells(ii1 + 2, jj1 + 4), Cells(ii1 + 2, jj1 + 4)).Value = C1(ii1, jj1)
      Next jj1
Next ii1
'==========point c matrix=c2
For ii2 = 1 To nkb
      For jj2 = 1 To nkb
           Range(Cells(ii2 + 59, jj2 + 4), Cells(ii2 + 59, jj2 + 4)).Value = C2(ii2, jj2)
```

```
    Next jj2
Next ii2
'Symmetric matrix
For p1 = nks + 1 To 50
Range(Cells(p1 + 2, p1 + 4), Cells(p1 + 2, p1 + 4)).Value = 1
Next p1

For p2 = nkb + 1 To 50
Range(Cells(p2 + 59, p2 + 4), Cells(p2 + 59, p2 + 4)).Value = 1
Next p2

'Select c-matrixes
  Range("e3:bb52,e60:bb109").Select

  Calculate
  With Application
    .Calculation = xlAutomatic
    .MaxChange = 0.001
  End With
  ActiveWorkbook.PrecisionAsDisplayed = False

'Names values from c-matrix sheet then selects generic and conditioned
' to fill conditional values
muFs = Range("A2").Value
siFs = Range("A4").Value
```

```
muFB = Range("A59").Value
siFB = Range("A61").Value

'select "generic and conditioned" sheet
Sheets("generic and conditioned").Select
Range("i4").Value = muFs
Range("i5").Value = siFs
Range("i9").Value = muFB
Range("i10").Value = siFB

'CMATRIX
    Sheets("cmatrix").Select
    ActiveWindow.SelectedSheets.Visible = False

 Range("a1").Select
 'Formats correlated existing data in multiple existing data points
    Range("L4:T4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Sort Key1:=Range("M4"), Order1:=xlDescending, Key2:=Range("L4") _
        , Order2:=xlAscending, Header:=xlNo, OrderCustom:=1, MatchCase:= _
        False, Orientation:=xlTopToBottom, DataOption1:=xlSortNormal, DataOption2 _
         :=xlSortNormal
    Range("V4:AD4").Select
   Range(Selection, Selection.End(xlDown)).Select
    Selection.Sort Key1:=Range("W4"), Order1:=xlDescending, Key2:=Range("V4") _
```

```
, Order2:=xlAscending, Header:=xlNo, OrderCustom:=1, MatchCase:= _
False, Orientation:=xlTopToBottom, DataOption1:=xlSortNormal, DataOption2 _
:=xlSortNormal

End Sub
```

Generic and Conditional Axial Capacity.xlsm:

```
Public x(2000), y(2000), z(2000), sFs(2000), sFB(2000)
Public Rhos(2000), RhoB(2000), k1(50), k2(50), C1(50, 50), C2(50, 50)
Sub ConditionalAxCapFS()

'Initiates model parameters
Dim A1, A2, A3, A4, A5, A6, A7, A8, m1, m2 As Single
Dim B1, B2, B3, B4, B5, B6, B7, B8 As Single

Sheets("input").Select
A1 = Range("B3").Value
A2 = Range("B4").Value
A3 = Range("B5").Value
A4 = Range("B6").Value
A5 = Range("B7").Value
A6 = Range("B8").Value
A7 = Range("B9").Value
A8 = Range("B10").Value

B1 = Range("D3").Value
B2 = Range("D4").Value
B3 = Range("D5").Value
B4 = Range("D6").Value
B5 = Range("D7").Value
```

```
B6 = Range("D8").Value
B7 = Range("D9").Value
B8 = Range("D10").Value

'Uses updated n-value to represent number of data sets
n = Range("g4").Value

'===========
'Initates stepping through the data
ns = 0
nb = 0
For j = 1 To n
Sheets("input").Select
    z(j) = Range(Cells(j + 14, 4), Cells(j + 14, 4)).Value
    x(j) = Range(Cells(j + 14, 11), Cells(j + 14, 11)).Value
    y(j) = Range(Cells(j + 14, 10), Cells(j + 14, 10)).Value
    sFs(j) = Range(Cells(j + 14, 18), Cells(j + 14, 18)).Value
sFB(j) = Range(Cells(j + 14, 24), Cells(j + 14, 24)).Value

   'Rho values for both side shear (s) and end bearing (B)
   Rhos(j) = Range(Cells(j + 14, 30), Cells(j + 14, 30)).Value
   RhoB(j) = Range(Cells(j + 14, 31), Cells(j + 14, 31)).Value

   'Ranks of correlation coefficients from columns 35 and 36
   Ranksj = Range(Cells(j + 14, 35), Cells(j + 14, 35)).Value
```

```
   RankBj = Range(Cells(j + 14, 36), Cells(j + 14, 36)).Value
   'If loop that takes ranks 1-50 for side shear correlation
   If Ranksj <= 50 Then
       ns = ns + 1
       k1(ns) = j
   End If
   'If loop that takes ranks 1-50 for end bearing correlation
   If RankBj <= 50 Then
       nb = nb + 1
       k2(nb) = j
   End If
Next j
    nks = ns
    nkb = nb

'==========side shear c matrix=c1
For ii1 = 1 To nks
For jj1 = 1 To ii1
'Calculation to populate c-matrix
            C1(ii1, jj1) = Exp(-Sqr((x(k1(ii1)) - x(k1(jj1))) ^ 2 + (y(k1(ii1)) - y(k1(jj1))) ^ 2) / (Exp(A6) + Exp(A7) * z(k1(ii1)))) * Exp(-Abs(z(k1(ii1)) - z(k1(jj1))) / Exp(A8)) * sFs(k1(ii1)) * sFs(k1(jj1))
           'Code to populate c-matrix
            If ii1 <> jj1 Then
            C1(jj1, ii1) = C1(ii1, jj1)
```

```
        End If
Next jj1
Next ii1

'==========end bearing c matrix=c2
For ii2 = 1 To nkb
    For jj2 = 1 To ii2
'Calculation to populate c-matrix
        C2(ii2, jj2) = Exp(-Sqr((x(k2(ii2)) - x(k2(jj2))) ^ 2 + (y(k2(ii2)) - y(k2(jj2))) ^ 2) /
(Exp(B6) + Exp(B7) * z(k2(ii2)))) * Exp(-Abs(z(k2(ii2)) - z(k2(jj2))) / Exp(B8)) *
sFB(k2(ii2)) * sFB(k2(jj2))
'Code to populate c-matrix
     If ii2 <> jj2 Then
     C2(jj2, ii2) = C2(ii2, jj2)
     End If
Next jj2
Next ii2

'Fills columns L and V to show existing data used=====
Sheets("multiple existing data points").Select

Range("l4:l300,v4:v300").Select
Range("l4").Activate
Selection.ClearContents
```

```
'Fills cells with number of correlation points, 50 for code at present use
Range("l2").Value = nks
Range("v2").Value = nkb

    With Application
        .Calculation = xlManual
        .MaxChange = 0.001
    End With
    ActiveWorkbook.PrecisionAsDisplayed = False
    Range("J20").Select

For j = 1 To nks
    'multiple existing borings sheet correlated data points for side shear
    Range("l4").Offset(j - 1, 0).Value = k1(j)
Next j
For j = 1 To nkb
    'multiple existing borings sheet correlated data points for end bearing
    Range("v4").Offset(j - 1, 0).Value = k2(j)
Next j

'Shows c-matrix
Sheets("cmatrix").Visible = True
Sheets("cmatrix").Select
'Fills c-matrices
    Range("E3:bb52,E60:bb109").Select
```

```
    Range("E3").Activate
    Selection.ClearContents
'==========side shear c matrix=c1
For ii1 = 1 To nks
      For jj1 = 1 To nks
Range(Cells(ii1 + 2, jj1 + 4), Cells(ii1 + 2, jj1 + 4)).Value = C1(ii1, jj1)
    Next jj1
Next ii1
'==========end bearing c matrix=c2
For ii2 = 1 To nkb
      For jj2 = 1 To nkb
           Range(Cells(ii2 + 59, jj2 + 4), Cells(ii2 + 59, jj2 + 4)).Value = C2(ii2, jj2)
      Next jj2
Next ii2

'Symmetric matrix
For p1 = nks + 1 To 50
Range(Cells(p1 + 2, p1 + 4), Cells(p1 + 2, p1 + 4)).Value = 1
Next p1

For p2 = nkb + 1 To 50
Range(Cells(p2 + 59, p2 + 4), Cells(p2 + 59, p2 + 4)).Value = 1
Next p2

'Select c-matrices
```

```
    Range("e3:bb52,e60:bb109").Select

    Calculate
    With Application
        .Calculation = xlAutomatic
        .MaxChange = 0.001
    End With
    ActiveWorkbook.PrecisionAsDisplayed = False
    'Names values from c-matrix sheet then selects multiple existing data
'points to fill conditional values
muFs = Range("A2").Value
siFs = Range("A4").Value
muFB = Range("A59").Value
siFB = Range("A61").Value
Sheets("multiple existing data points").Select
Range("i4").Value = muFs
Range("i5").Value = siFs
Range("i9").Value = muFB
Range("i10").Value = siFB

'CMATRIX
   Sheets("cmatrix").Select
   ActiveWindow.SelectedSheets.Visible = False
Range("a1").Select
'Formats correlated existing data in multiple existing data points
```

```
 Range("L4:T4").Select
Range(Selection, Selection.End(xlDown)).Select
 Selection.Sort Key1:=Range("M4"), Order1:=xlDescending, Key2:=Range("L4") _
     , Order2:=xlAscending, Header:=xlNo, OrderCustom:=1, MatchCase:= _
     False, Orientation:=xlTopToBottom, DataOption1:=xlSortNormal, DataOption2 _
     :=xlSortNormal
 Range("V4:AD4").Select
 Range(Selection, Selection.End(xlDown)).Select
 Selection.Sort Key1:=Range("W4"), Order1:=xlDescending, Key2:=Range("V4") _
     , Order2:=xlAscending, Header:=xlNo, OrderCustom:=1, MatchCase:= _
     False, Orientation:=xlTopToBottom, DataOption1:=xlSortNormal, DataOption2 _
     :=xlSortNormal

End Sub
```

Generic and Conditional Equivalent Linear Undrained Shear Strength.xlsm:

```
Public x(2000), y(2000), z(2000), sFs(2000)
Public Rhos(2000), k1(50), C1(50, 50)
Sub EquivLinearProfLatCap()

Dim D1, D2, D3, D4, D5, D6, m As Single
'Initiates model parameters
Sheets("input").Select
D1 = Range("B3").Value
D2 = Range("B4").Value
D3 = Range("B5").Value
D4 = Range("B6").Value
D5 = Range("B7").Value
D6 = Range("B8").Value
'Uses updated n-value to represent number of data sets
n = Range("g4").Value
'============
'Initates stepping through the data
ns = 0
For j = 1 To n
Sheets("input").Select
   z(j) = Range(Cells(j + 14, 4), Cells(j + 14, 4)).Value
   x(j) = Range(Cells(j + 14, 11), Cells(j + 14, 11)).Value
```

```
    y(j) = Range(Cells(j + 14, 10), Cells(j + 14, 10)).Value

    sFs(j) = Range(Cells(j + 14, 18), Cells(j + 14, 18)).Value

  'Rho value for Su1
   Rhos(j) = Range(Cells(j + 14, 30), Cells(j + 14, 30)).Value
   'Ranks of correlation coefficient from column 35
   Ranksj = Range(Cells(j + 14, 35), Cells(j + 14, 35)).Value
 'If loop that takes ranks 1-50 for side shear correlation
   If Ranksj <= 50 Then
        ns = ns + 1
        k1(ns) = j
   End If

Next j
    nks = ns
'==========Su1 c matrix=c1
For ii1 = 1 To nks
For jj1 = 1 To ii1
   'Calculation to populate c-matrix
            C1(ii1, jj1) = Exp(-Sqr((x(k1(ii1)) - x(k1(jj1))) ^ 2 + (y(k1(ii1)) - y(k1(jj1))) ^ 2) /
(Exp(D4) + Exp(D5) * z(k1(ii1)))) * Exp(-Abs(z(k1(ii1)) - z(k1(jj1))) / Exp(D6)) *
sFs(k1(ii1)) * sFs(k1(jj1))
          'Code to populate c-matrix
            If ii1 <> jj1 Then
```

```
            C1(jj1, ii1) = C1(ii1, jj1)
            End If
      Next jj1
 Next ii1
'==========================================
'Fills column L to show existing data used=====
Sheets("generic and conditioned").Select
Range("l4:l300").Select
Range("l4").Activate
Selection.ClearContents
'Fills cells with number of correlation points, 50 for code at present use
Range("l2").Value = nks

With Application
        .Calculation = xlManual
        .MaxChange = 0.001
    End With
    ActiveWorkbook.PrecisionAsDisplayed = False
    Range("J20").Select
For j = 1 To nks
    'multiple existing borings sheet correlated data points
    Range("l4").Offset(j - 1, 0).Value = k1(j)
Next j
'Shows c-matrix
Sheets("cmatrix").Visible = True
```

```
Sheets("cmatrix").Select
'Fills c-matrix
    Range("E3:iv254").Select
    Range("E3").Activate
    Selection.ClearContents
'==========Su1 c matrix=c1
For ii1 = 1 To nks
For jj1 = 1 To nks
Range(Cells(ii1 + 2, jj1 + 4), Cells(ii1 + 2, jj1 + 4)).Value = C1(ii1, jj1)
      Next jj1
     Next ii1
'Symmetric matrix
For p1 = nks + 1 To 50
Range(Cells(p1 + 2, p1 + 4), Cells(p1 + 2, p1 + 4)).Value = 1
Next p1
'Select c-matrix
    Range("e3:bb52").Select

    Calculate
    With Application
        .Calculation = xlAutomatic
        .MaxChange = 0.001
    End With
    ActiveWorkbook.PrecisionAsDisplayed = False
'Names values from c-matrix sheet then selects multiple existing data
```

```
'points to fill conditional values
muFs = Range("A2").Value
siFs = Range("A4").Value

Sheets("generic and conditioned").Select
Range("i4").Value = muFs
Range("i5").Value = siFs
'CMATRIX
    Sheets("cmatrix").Select
    ActiveWindow.SelectedSheets.Visible = False

 'Formats correlated existing data
    Range("L4:T4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Sort Key1:=Range("M4"), Order1:=xlDescending, Key2:=Range("L4") _
        , Order2:=xlAscending, Header:=xlGuess, OrderCustom:=1, MatchCase:= _
        False, Orientation:=xlTopToBottom, DataOption1:=xlSortNormal, DataOption2 _
        :=xlSortNormal
End Sub
```

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