The Thesis Committee for James William West
Certifies that this is the approved version of the following thesis:

Characteristics of Undrained Shear Strength in Shallow Soils in Deep Water Gulf of Mexico

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Robert B. Gilbert

____
Jorge G. Zornberg

Characteristics of Undrained Shear Strength in Shallow Soils in Deep Water Gulf of Mexico

by

James William West, B.S.C.E.

Thesis

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Dedication

I dedicate this thesis to my loving family: Susie, Butch, Barb, Rick, Shannon and Nick.

Whose support have been vital to any success it could be said that I’ve had.

And to my partners Wynona and Luna.

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I would like to thank very deeply and sincerely Dr. Robert Gilbert, without whom I would literally be nowhere. Not only has his advice and guidance aided me in my completion of this thesis, but he has helped me get basically every engineering job I’ve ever had. His words of wisdom have always been encouraging, even when what he was really saying is how poorly I had done. I walked out of every meeting I ever had with him feeling not that I had failed but that I could do better, needed to do better. He is unmatched in the field of teaching and deserves every accolade and award that has been bestowed upon him.

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Abstract

Characteristics of Undrained Shear Strength in Shallow Soils in Deep Water Gulf of Mexico

James William West, M.S.E.

The University of Texas at Austin, 2013

Supervisor: Robert B. Gilbert

Shallow foundations are used when designing subsea structures on the seafloor of deep water Gulf of Mexico. In order to design these subsea shallow foundations it is important to understand the behavior of the undrained shear strength of the shallow soils (i.e. upper ten to twenty feet of soil).

The objective of this research is to analyze a database of soil data from deep water Gulf of Mexico originally produced by Cheon (2011) with a focus on shallow soils. The purpose of this analysis is to gain a better understanding of the soil and how it will be usable with regards to shallow foundation design. The methodology of this analysis involves studying raw data collected from different measurements taken to aid in the creation of design profiles of undrained shear strength versus depth.

Within the existing database there are 18 locations with a high resolution of point data from in-situ tests (Halibut Vane) and non in-situ tests (Minivane and Torvane) that provide the clearest picture of undrained shear strength in the shallow region. The data shows that the design profiles originally created for these locations for deep foundations

are generally not representative of the strength in the shallow region. They also show that in-situ test data show more variability than non in-situ data. There are also 25 Cone Penetration Tests in the existing database that show very high resolution data in the shallow region. These Cone Penetration Tests also indicate a crust that appears to be about 1 ft thick and exists along the edge of the continental shelf.

Recommended future activities to build upon this work include re-evaluating the design profiles at these 43 locations at which high resolution studies have been performed in the shallow region, collecting these design profiles as well as any new design profiles and organizing them into a new database focused on shallow soils, generating a new generic profile base on the data within the new database, and creating a model that uses spatial variability analysis to calculate undrained shear strengths at new locations based on the data in the database.

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Chapter 1: Introduction

1.1 Motivation for Research

Extensive research has been done on the Gulf of Mexico, and the deep water region of the Gulf of Mexico in particular. Deep water Gulf of Mexico refers specifically to the region of the Gulf at or just beyond the edge of the continental shelf, where water depths are greater than 3000 ft. The reason for the focus in studies there is that that's where the oil and gas are. More and more offshore platforms are being built in this part of the Gulf, and so lots of data has been collected on the soils there.

Because of the size of these offshore platforms and the softness of the soils at shallower depths in deep water Gulf of Mexico, most platforms are designed with deep foundations that extend dozens of feet into the soil. With most foundations in the region extending so deep, engineers did not see the point in focusing on the shallow soils, which are nowhere near as stiff or strong as deeper soils. So most of the studies from this region focus on deep soils and ignore the soils in the shallow region.

Now, an increasing number of structures built in deep water Gulf of Mexico are using shallow foundations. These are typically subsea structures built directly on the seafloor for the purpose of rerouting oil and gas from active wells. In order to design these shallow foundations it is critical that engineers have data that is focused on the soils in the shallow region.

The goal of this research is to organize and analyze the existing soil shear strength data from deep water Gulf of Mexico with a focus on shallow soils. The ptotential contributions of this research include: (1) to understand the nature of shear strength of the soil in the shallow region of deep water Gulf of Mexico and (2) to make currently available the data useful for future spatial variability analysis of soil strengths in deep water Gulf of Mexico.

1.2 Background

Much of the available soil strength data from the last two decades has been focused on deep foundations that extend tens of feet into the soil below the mudline, which is the boundary between the ocean and the soil. So many studies have been performed on the soil in deep water Gulf of Mexico, but nearly all of it focuses on deep soils.

Quiros et al. (2003) discussed the geotechnical properties of soils in the Gulf of Mexico. They interpreted and compared data from many reports and determined that the type of test performed and the sampling method have a substantial effect on the accuracy of the data.

Francisca et al. (2005) characterized shallow soils in the Gulf of Mexico in detail. They found the shallow soils to be composed of a combination of clay and silt particles and that the characteristics of the soil were predominantly controlled by the presence of illite. Unfortunately, they're study focused on the northern region of the Gulf in shallower waters, but the contribution still stands.

The biggest contributor to the background of this thesis comes from Cheon and Gilbert (2011), which compiled many of the existing reports on deep water Gulf of Mexico soils into a single useable report and catalogued much of the existing data into a database. Cheon and Gilbert (2011) go on to describe the method involved in analyzing the spatial variability of this database and using the database to predict undrained shear strengths at locations where data does not currently exist, as well as an additional factor of safety used to account for the lack of data at that location.

1.3 OBJECTIVES

The goal of this research is to organize data from the existing database of soil shear strengths from deep water Gulf of Mexico and to analyze them with a focus on shallow soils. The specific objectives are:

1 Describe the type of data that will be useful to future users of the database. This data will be focused on shallow soils and will better describe the behavior of the soil in the shallow region. The data used for this description will come from more recent reports which have focused on shallow soils in deep water Gulf of Mexico.

2 Locate the data that will be useful to future users in the existing database based on the previously mentioned description. This data will come from the database established previously by Cheon and Gilbert (2011). It contains data from many different locations in deep water Gulf of Mexico, but only some of the data is useful for the purpose of shallow foundation design.

3 Organize the data from the existing database that will be useful into categories based on the usability of the data. There are degrees to the usability of data for the purpose of shallow soil analysis. This organization will make the data more accessible by categorizing it.

4 Evaluate patterns in the data that may aid in analysis of the shallow reiong of soils in deep water Gulf of Mexico. Usable data with high enough resolution of information will be analyzed to locate the patterns, for example the potential existence of a crust near the mudline in deep water Gulf of Mexico.

5 Provide steps that could be taken in the future to create a database spreadsheet capable of calculating strengths at locations where no data currently exists. This spreadsheet would use spatial variability analysis to calculate new data based on the existing, usable data in the database.

1.4 ORGANIZATION OF REPORT

This thesis is organized into five chapters. In Chapter 2, a description of the database is given including the geographic and geologic setting of the data, a brief summary of the dissertation from which the data was taken, and a description of the types of data in the database and the types of tests used to acquire the data. In Chapter 3, examples are given of the difference between data that focuses on the soil in the shallow region and data that does not. In Chapter 4, the usable data from the database is presented and analyzed to locate patterns between the types of tests used and the level of resolution of the data. In Chapter 5, conclusions are offered and potential next steps are suggested.

Chapter 2: Description of the Database

2.1 Introduction

All of the deep water Gulf of Mexico data used within this thesis comes from the same database, this includes design profiles, raw data from both in-situ and laboratory tests, CPTs and so on. The database was originally produced by Jeong Yeon Cheon as a part of her dissertation entitled "Analysis of Spatial Variability in Geotechnical Data for Offshore Foundations" (2011).

The database was created for the purpose of analysis of undrained shear strengths and axial and lateral capacities of deep water Gulf of Mexico soils, focused specifically on deep foundations. Because the ultimate goal of this thesis is to aid in the creation of a database for use with shallow foundations the existing database is not directly useful. However, the existing database does contain valuable information that can be analyzed to aid in the creation of a new database focused on shallow foundations for deep water Gulf of Mexico.

This chapter will describe the existing database. The first section will discuss the setting of the data, The Gulf of Mexico, specifically its geographic location, geologic setting, and information on deep water design there. The second section will discuss the two types of foundations, shallow and deep, offering clear definitions of both. The third section will discuss Cheon's original dissertation, specifically its conclusions and a description of the shallow soils of deep water Gulf of Mexico in its generic model. The fourth section will describe the database itself, what kinds of data does it contain, where are the data located geographically, what tests are used to produce the data, and when the data was collected.

2.2 The Gulf of Mexico

2.2.1 Geographic Description of the Gulf

The Gulf of Mexico is a large body of water southeast of the United States and east of Mexico (shown in Figure 2.1), and for the last several decades it has been a major source of oil and gas production. On average it is 5000 ft deep, but at its deepest it is 13,000 ft deep. Half of the Gulf of Mexico exists on the continental shelf, where the water is approximately 650 ft deep, but about half of the Gulf consists of the abyssal deep, what is considered the deep water Gulf of Mexico region. This is the region of interest, where the water depth ranges from 3000 ft to 9000 ft and the overall gradient ranges from 3 to 6 degrees.

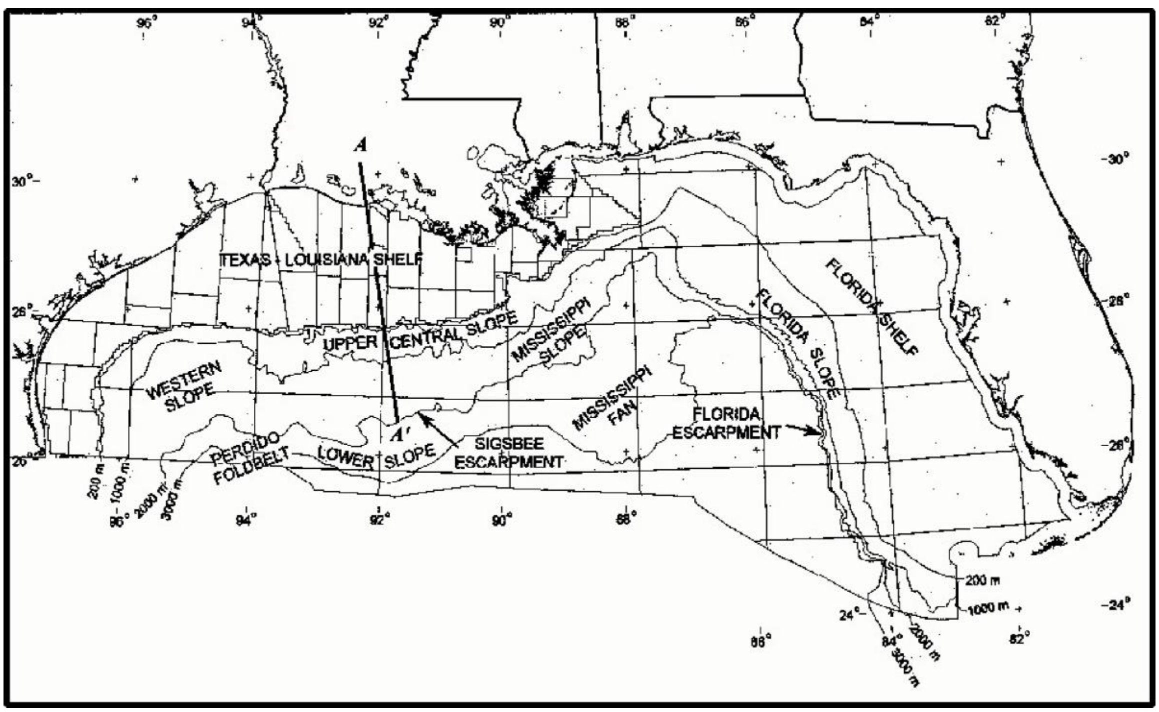


Figure 2.1: The Gulf of Mexico and its Major Physiogeographic Features (MMS, 2000)

2.2.2 Geologic Setting of the Gulf

The Gulf consists primarily of marine clay, which is normal to over consolidated, with some sand seams. The upper 20 ft of soil, the shallow region that will be the focus of this thesis, is Holocene sediments, meaning it is less than 12,000 years old. And below that the soil is Pleistocene sediments, meaning it is more than 12,000 years old. The soil near the top is considered soft clay, and the stiffness increases with depth from stiff to very stiff clay. The most important aspect of the geologic setting with regard to this thesis is that the upper 50 ft of soil consists of hemipelagic sediments; these are sediments deposited during a time of very high sea levels, and as a result the properties vary widely in those upper 50 ft.

2.2.3 Location of Data in the Gulf

Because the data within the database is proprietary, no information can be given about the exact location of the sites where the data was collected. However, generally the sites exist on the continental slope between the inter-continental shelf and the deepest parts of the Gulf. Each location corresponds to a specific study. Studies are gathered into regions, lettered A through Q, based on geographic location and the system of structures for which they were used. And each region is a part of a Group, numbered 1 through 9, based on geographic location.

Table 2.1: Description of the Regions in The Gulf of Mexico

Region	Number of Studies	Group
A	6	Group 1
B	6	Group 1
C	6	Group 1
D	3	Group 1
E	4	Group 2
F	8	Group 3
G	1	Group 4
H	1	Group 4
I	1	Group 5
J	7	Group 6
K	19	Group 6
L	3	Group 7
M	14	Group 7
N	14	Group 8
P	4	Group 2
Q	18	Group 9

The database uses a location system called the Universal Transverse Mercator system, which divides the surface of the Earth into 60 grids. Each grid, or zone, has its own x and y coordinate system so that each zone can be easily plotted on a two-dimensional graph. All of the data within the database exists in either zone 15 or 16. In Figure 2.1, these locations are plotted to show their relative position. All of the locations in zone 16 appear to follow a curve; this is because all of those locations follow along the continental slope.

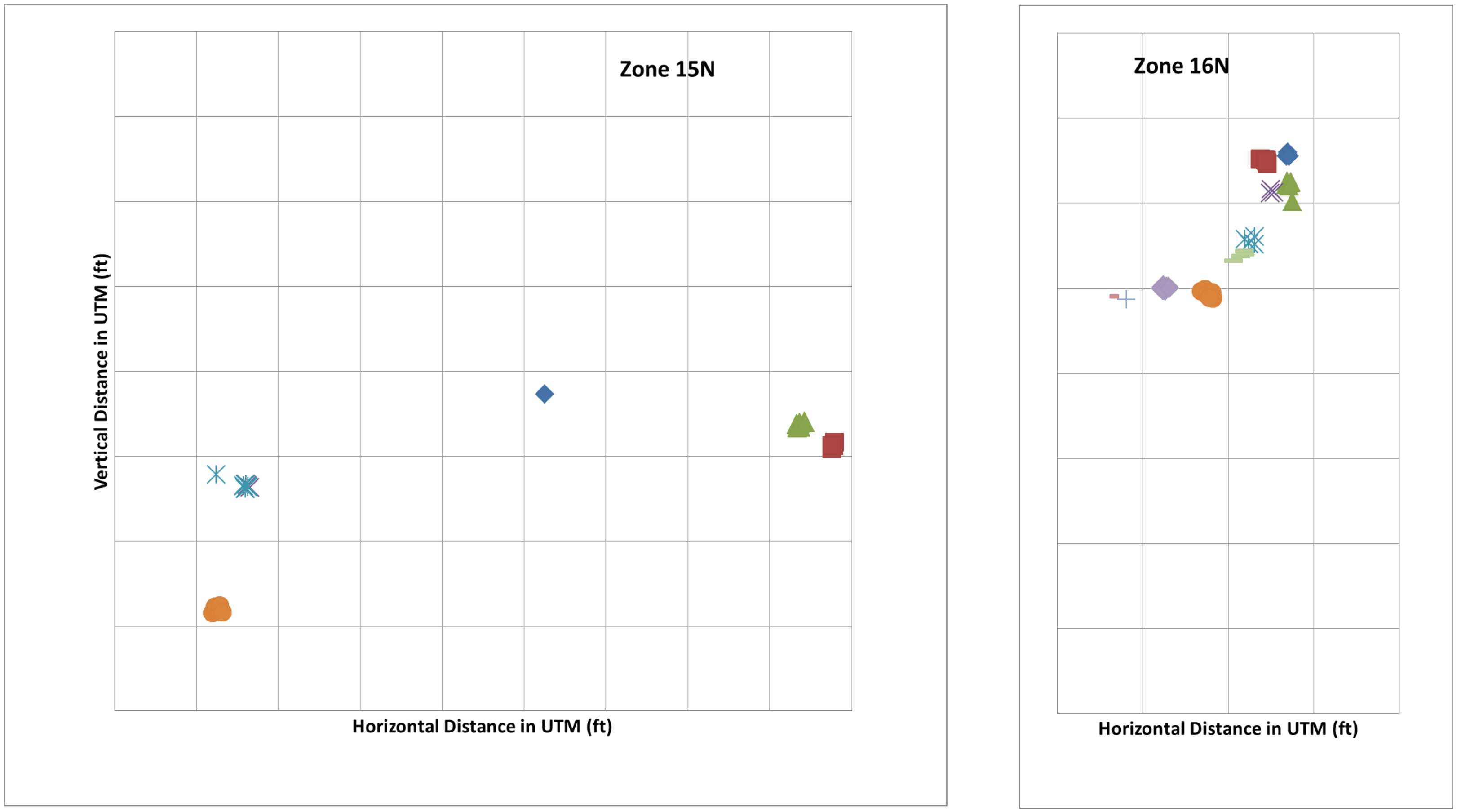


Figure 2.2: Relative Locations of the Data within the Existing Database in Deep Water Gulf of Mexico

2.3 TYPES OF FOUNDATIONS

2.3.1 Types of Foundations

There are many different types of foundations, but there are two major categories: deep foundations and shallow foundations. Quantitatively these two types can be described by their depth into the soil compared to their width. A shallow foundation is a foundation which has a depth less than two and a half times its width. Conversely, a deep foundation is a foundation which extends more than two and a half times its width into the soil. Qualitatively the difference between the two is that shallow foundations rest at or near the soil surface and thus interact with shallower soils whereas deep foundations extend further into the soil and interact with deeper soils.

2.3.2 Deep Foundations in the Gulf

Historically, structures built in the deep water Gulf of Mexico have used deep foundations. This makes intuitive sense as the clay at the seafloor is soft and the structures are rather large. These deep foundations, typically driven piles or suction caissons, are steel pipes that extend more than 50 ft into the soil and are more than a dozen ft in diameter. Because the structures are so heavy and the foundations extend so deep into the soil, minor fluctuations in strength near the mudline, the soil at immediately at the bottom of the water, are of little importance, but they will become vitally important with regards to the other foundation type.

2.3.3 Shallow Foundations in the Gulf

Shallow foundations are becoming more and more prevalent in the modern offshore oil and gas industry. In the past, an offshore facility would be directly connected to a number of wells so that it could draw the oil and gas directly into it. Now, however, many more structures use pipeline end terminations, which collect all of the pipes from all of the wells and connect it to a single pipe, which then connects to the offshore facility to be processed. This is only one example of a type of subsea structure, a structure built directly on the seafloor, which would utilize a shallow foundation as opposed to a deep foundation.

2.4 Discussion of Original Dissertation

2.4.1 Explanation of Original Dissertation

The original dissertation by Cheon was a discussion of the spatial variability of soil in deep water Gulf of Mexico that culminated in a database of soil properties from the Gulf as well as an analysis spreadsheet, which can calculate undrained shear strengths at locations where no data exists based on nearby locations where data does exist. This section will give a brief summary of the topics covered in her report.

She started by describing the database in a format similar to this chapter. She discussed the location and geologic condition of the Gulf of Mexico. She described the data within the database, where it came from and what kind of data it was. She also explained the concept of the design profile for undrained shear strength.

Next she discussed the concepts at the heart of the discussion, undrained shear strength and deep foundation design. These two topics are the end goal of the analysis, the ability to predict the undrained shear strength at new locations for the purpose of designing deep foundations in deep water Gulf of Mexico.

In this section of her dissertation she introduced the concept of axial capacity and lower bound axial capacity. Axial capacity is the maximum load that can be applied to the foundation before it fails; it is calculated using the point undrained shear strength (used to calculate the end bearing capacity of the deep foundation) and another metric called the depth averaged undrained shear strength (used to calculate the side shear capacity of the deep foundation).

The lower bound axial capacity is calculated in a similar way except instead of using the undrained shear strength you use the remolded undrained shear strength. The idea is that by remolding the soil you are destroying any pre-existing soil structure and therefore testing the soil at its weakest level. The axial capacity calculated using the remolded strength would then be, theoretically, the smallest possible axial capacity, or the lower bound axial capacity.

She goes on, in this section, to explain the process of calculating lateral capacity of a suction caisson. This is a complicated process that uses a metric known as the equivalent linear undrained shear strength, which is measured in psf per ft. Finally, she describes calculating capacity under a combined load of axial and lateral capacity.

Next, she explains the concept of analyzing the spatial variability of undrained shear strength. She describes the metrics I have mentioned above and presents samples of them for the reader's consideration. She offers several sources of variability including date of the investigation and test method. She focuses, however, on spatial variability as that is where the largest patterns in variability occur. She gives examples for both design undrained undisturbed shear strength and design undrained remolded shear strength in terms of spatial variability. She also describes the correlation between point undrained shear strength and depth averaged undrained shear strength and the correlation between undisturbed and remolded shear strengths. She explains that spatial variability is more focused on the original method of deposition of the soil (proximity to the mouth of the Mississippi River, distance from the continental shelf) than anything else.

In the next section she described her model of design shear strength. The model is based on a generic model, which is a design profile, based on a likelihood function, that accounts for all the strength data in the database. Using this generic model a spatially conditioned model can be produced based on the coordinates of a new location and depth. This section describes, in detail, the equations involved in the calculation of an average strength and standard deviation of that strength at a new location based on data from the database. Because these calculations are based on the generic model, she discusses how to calibrate the generic model using the likelihood function. The spatial variability model is based on a number of factors including the variables of the generic model and the correlation distance for the point of interest.

In the next section she gives an example of how to calculate the capacity, both axial and lateral, of a suction caisson using the spatial variability model.

The next section discusses reliability and the calculation of the additional factor of safety, which is the factor of safety that must be applied to the capacity to account for the fact that no data exists at the location. Using a reliability based approach, she is able to determine the additional factor of safety based on the available data and the proximity of the data.

2.4.2 Conclusions of Original Dissertation

In her dissertation, Cheon came to sixteen different conclusions. Here are some of the more relevant ones:

She found that the undrained shear strength of the soil varies spatially but does not vary with the date the data was recorded. Looking at all the data within the database she found the average increase in undrained shear strength with depth to be 8.5 psf/ft (pounds per square foot per foot). The standard deviation of the undrained shear strength increases to a depth of 100 ft, after which it no longer increases. The correlation distance (distance from a point beyond which data is too far away to affect spatial variability analysis) for undrained shear strength is 25 ft vertically and 4,400 ft horizontally at the mudline; it increases to 15,500 ft horizontally at a depth of 150 ft.

She also found that the analysis she devised would work better using an anisotropic correlation distance model. That is to say the current system as she devised it is isotropic, a point some distance away from a location of interest has exactly the same correlation as a point of equal horizontal distance in any other direction. The system is more accurate though when it is anisotropic, focused on the continental shelf. In this case, correlation distances would be longer along the shelf and shorter transverse to it. This belies the fact that soils along the shelf tend to be similar to each other.

Several of the conclusions involve previously discussed metrics such as depth averaged undrained shear strength and remolded undrained shear strength, which are not directly relevant to this thesis.

2.4.3 Generic Model in the Shallow Region

Because the data within the existing database, including all but four of the undrained shear strength design profiles in the database, are focused on deep foundations the generic model she calculated is going to be focused on deep foundations. In Figure 2.3, the undrained shear strength profile of the generic model, conditioned to be a representation of all the undrained shear strength profiles in the database, is represented to a depth of 30 ft.

The undrained shear strength profile from the generic model makes clear the problem with the database as it exists now. It is a straight line with a strength at the mudline of 0.015 ksf (kilopounds per square foot) and an average slope of 0.0082 ksf/ft (kilopounds per square foot per foot). It shows no real definition of the soil strength in the shallow region, which does not behave like a straight line. Even data within the existing database shows us that the undrained shear strength profiles in the shallow region don't behave like that.

The goal of this thesis is to be the first step in the process that will result in a generic profile and a spatial variability analysis that accurately reflect the behavior of the undrained shear strength of marine soils in deep water Gulf of Mexico.

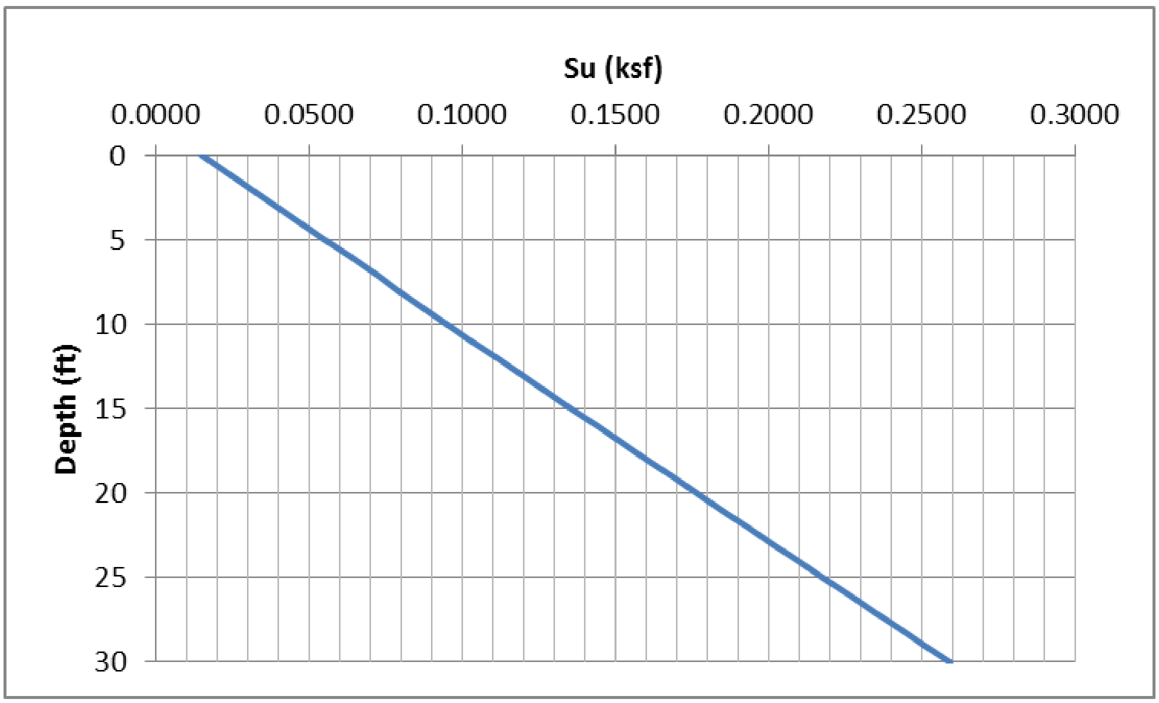


Figure 2.3: Undrained Shear Strength Profile vs. Depth in the Shallow Region from the Generic Model

2.5 Database

2.5.1 Introduction

This section will discuss the existing database itself, going into detail about the types of data contained within it, where the data comes from, and the types of test used to attain the data (specifically the undrained shear strength data).

The data in the database is split into two parts: 1. individual reports that collect the data from the original reports and are organized by region and 2. the input file used in spatial variability analysis. The individual reports contain the undrained shear strength design profile in its original form for each location as well as the raw data used to create that design profile. The input file contains all of the undrained shear strength design profiles from each location but restructured into 10 foot intervals to make them easier with which to work.

The design profiles themselves are descriptions of the undrained shear strength of the soil as it changes with depth. They are based on raw test data collected from in-situ tests and laboratory tests. The design profiles are key in the process of foundation design because they describe the strength of the soil that the engineers will use to design the foundations of the structure.

2.5.2 Types of Data in the Database

The existing database contains several types of data but is focused mainly on undrained shear strength in its various forms. These forms, some of which have been previously discussed, include point undrained shear strength, depth averaged undrained shear strength, remolded point undrained shear strength, remolded depth averaged undrained shear strength, and equivalent linear undrained shear strength. With the exception of the point undrained shear strength and remolded point undrained shear strength, all of these profiles exist exclusively in the input file.

The individual reports contain the raw test data upon which the design profiles are based as well as data on the unit weight of the soil vs. depth and the sensitivity of the soil (the undrained shear strength of the soil divided by the remolded undrained shear strength of the soil). These reports are organized by region and then broken down into individual locations, where each location represents a different exploration.

2.5.2 Sources of Data

The data is collected from 63 engineering reports submitted to the original client by various consulting companies. These reports cover all 16 regions and include discussions of various soil properties that are important for design, including plasticity index, liquid limit, unit weight, undrained shear strength, etc. The reports were created between 1988 and 2009.

The reports describe the different explorations into the soil. These explorations include boreholes and jumbo piston cores (JPCs), which are two different methods for accessing the soil for testing purposes. Both of these exploration methods involve testing at discrete depths, for example you would get data from a depth for two feet then move on and get data from six feet then move on and get data from ten feet. This type of data will be referred to in this thesis as point data. The other type of locations is a cone penetration test, or CPT, which involves driving a cone into the ground at a constant rate and measuring the resistance it feels as you push it. CPTs are useful because unlike boreholes and JPCs they provide a continuous soil profile of very high resolution data. They can be very useful, especially in the shallow region where less testing is done.
Figure 2.4 offers examples of both a point data exploration and a CPT exploration.

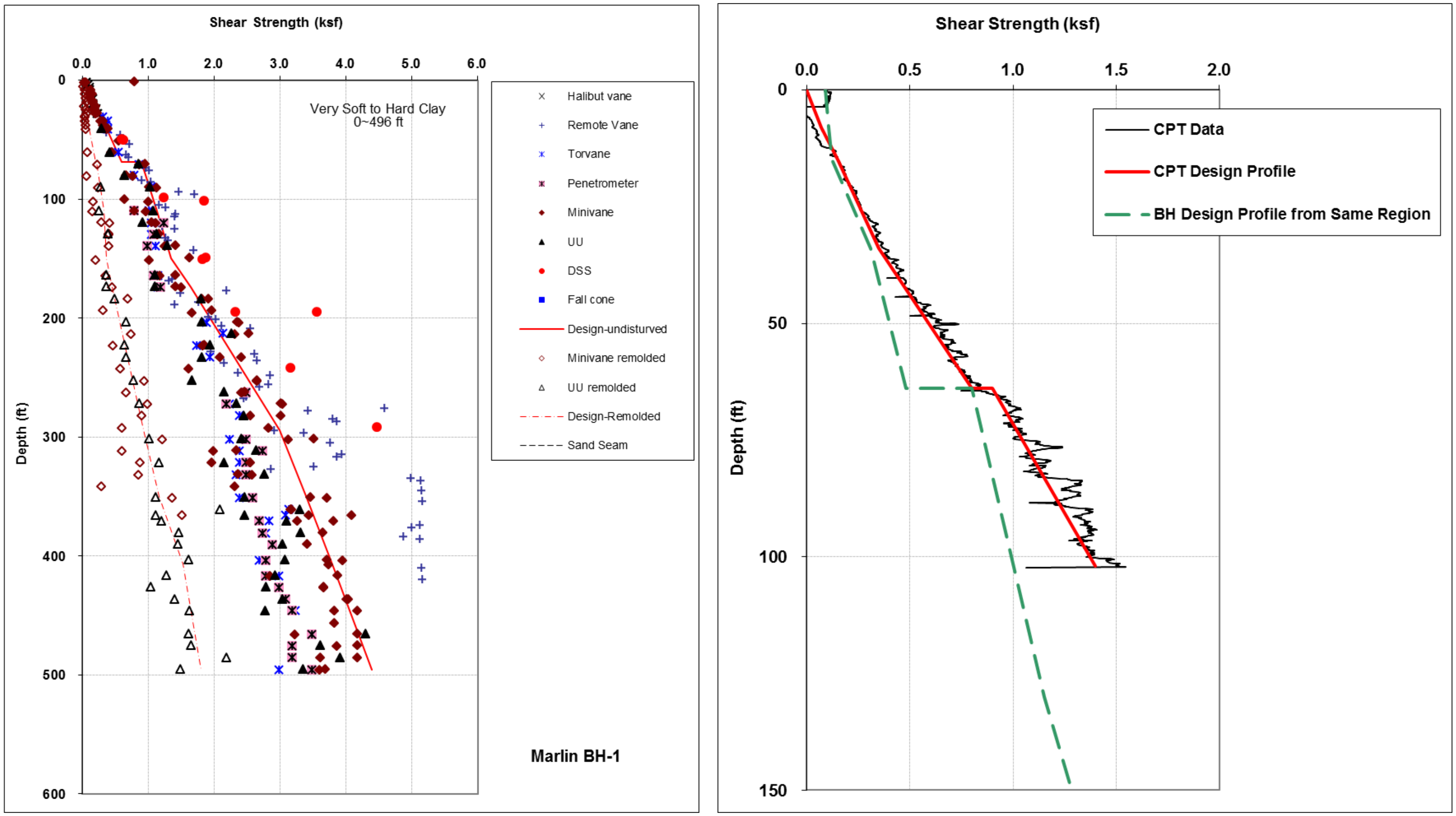


Figure 2.4: Examples of Point Data and CPT Data from an Individual Report within the Existing Database

2.5.3 Test Types

Data collected from boreholes and JPCs are collected through discrete testing methods. This means that during the boring or the coring a test is performed on the soil as it rests in the ground, in-situ testing, or a sample of the soil is removed and brought out of the ground for testing. The value of in-situ testing is that it allows the tester to gain an understanding of the properties of the soil without having to remove the soil from its natural environment, thus providing a more accurate prediction of the soil strength. The value of testing on samples that have been removed from the ground is that it allows direct access to the soil and more control over the test, which increases precision, but it comes at the cost of disturbing the soil sample and decreasing the accuracy of the test.

The in-situ tests that are used in this database include Halibut Vane tests and Remote Vane tests. These tests involve dropping a vane into the boring or coring and inserting it into the soil. The vane is then twisted until the soil moves a certain distance, the force required to twist the vane that distance is recorded and used to calculate the shear strength of the soil. The Halibut Vane test is typically performed in the shallow region and the Remote Vane test is performed on deeper soils; therefore, the Halibut Vane test will be an important focus of this thesis in later chapters.

The tests not performed in-situ include Minivane and Torvane tests, which are very similar to the Halibut and Remote Vane tests in that they involve inserting a vane into the soil and measuring the force required to twist it, the only difference being that Minivane and Torvane tests are performed on soils after they have been removed from the ground. These are not technically laboratory tests as they are both performed on soils that have not been extruded from the tube that was used to extract the soil from the ground. They offer a slightly less accurate picture of the soil strength because they involve disturbing the soil.

There are several other tests used in the existing database including unconsolidated undrained triaxial tests and direct simple shear tests. However, these tests are almost never performed in the shallow region, the reason for this being that they are laboratory tests. The trouble with soils in the shallow region of deep water Gulf of Mexico is that they are very soft and therefore very easy to disturb. It is incredibly difficult to remove a soft soil sample from the ground, extrude it from the sampling tube, ship it to a laboratory, and install it into a testing apparatus without disturbing it heavily and altering the results of any strength testing. Thus lab tests are almost never performed on shallow soils in the Gulf, and that makes them of little value to this report.

2.6 Summary

All of the data within the existing database comes from the deep water (water deeper than 1000 ft) in the Gulf of Mexico, where water depth at the area of interest ranges from 3000 to 9000 ft. The data comes from areas on or near the continental shelf in the Gulf. The soil in the Gulf is a marine clay that is soft in the shallow region and gets stiffer with depth; it is also more variable in the upper 50 ft due to deposition methods.

Two categories of foundations are used in the Gulf. Most structures are built on deep foundations which extend down far into the soil. However, more and more structures are being built on the seafloor and are using shallow foundations that do not extend very deep into the soil.

The database was originally created by Jeong Yeon Cheon in her dissertation entitled “Analysis of Spatial Variability in Geotechnical Data for Offshore Foundations”. She came to several important conclusions including determining the correlation distance for spatial variability in the gulf, the fact that the soils vary anisotropicly along the continental shelf, and that the soil varies most widely in the upper one hundred feet of soil. She also created a generic model of the undrained shear strength vs. depth in the Gulf, which shows that the database is not useful for shallow foundation analysis.

The database contains a combination of raw data from testing performed on the soils in the Gulf and undrained shear strength design profiles created based on that raw data. This data is mainly focused on the undrained shear strength of the soil but contains data on the unit weight of the soil vs. depth as well. The data was collected from 63 different reports and covers 16 different regions within the Gulf. The raw data was collected from boreholes, JPCs, and CPTs. Tests performed on the soils in the shallow region typically include Halibut Vane tests, which are in-situ tests, and Minivane and Torvane tests, which are not in-situ tests.

Chapter 3: The Effect of Shallow Soil Strength Data

3.1 Introduction

Historically, undrained shear strength design profiles in the Gulf of Mexico have payed less attention to the shallow region for reasons which have been previously discussed. The result is that large fluctuations in strength in the shallow region have been overlooked. Specifically, in cases where there has been a high resolution study of the shallow region soils of deep water Gulf of Mexico engineers have found evidence of a crust in the upper few feet of soil with a strength approximately twice that of the soil at the mudline.

The section will demonstrate the value of high resolution studies of the shallow region soils of deep water Gulf of Mexico by offering two regions where design profiles exist and where high resolution studies have occurred and more accurate design profiles have been produced for the shallow region. These are regions E and F.

3.2 Original Data and Design Profiles

The original exploration in region E was performed in 1998. It consists of 4 boreholes. The raw data for each borehole along with the original design profile are given in Figure 3.1 to 3.4. All of the locations include both a Minivane and Halibut Vane tests. As is typical, all of the design profiles from this region are similar in shape and strength. They all have similar strengths at the mudline, which remain constant or near constant to a depth of 7 or 8 ft after which the strength increases sharply with depth. It appears that for several cases the profiles ignore the shape of the raw data and either lean toward the conservative side or attempt to account for the increase in strength near the mudline but retain the same shape as at the other locations.

The original exploration in region F was performed in 2001. It consists of 8 boreholes. The raw data for each borehole along with the resulting design profile are given in figure 3.5 through 3.12. Locations include data from Halibut Vane, Minivane, and Torvane tests, but not necessarily all three at all 8 locations. With the exception of the eighth borehole, all of the design profiles have shapes similar to those described for region E, with little to no increase in strength to a depth of about 7 or 8 ft where the strength increases sharply. The strength at the mudline for all of the profiles is also very similar, excepting the eighth borehole which appears to try to account for the crust at the seafloor by increasing sharply to a depth of 7 or 8 ft.

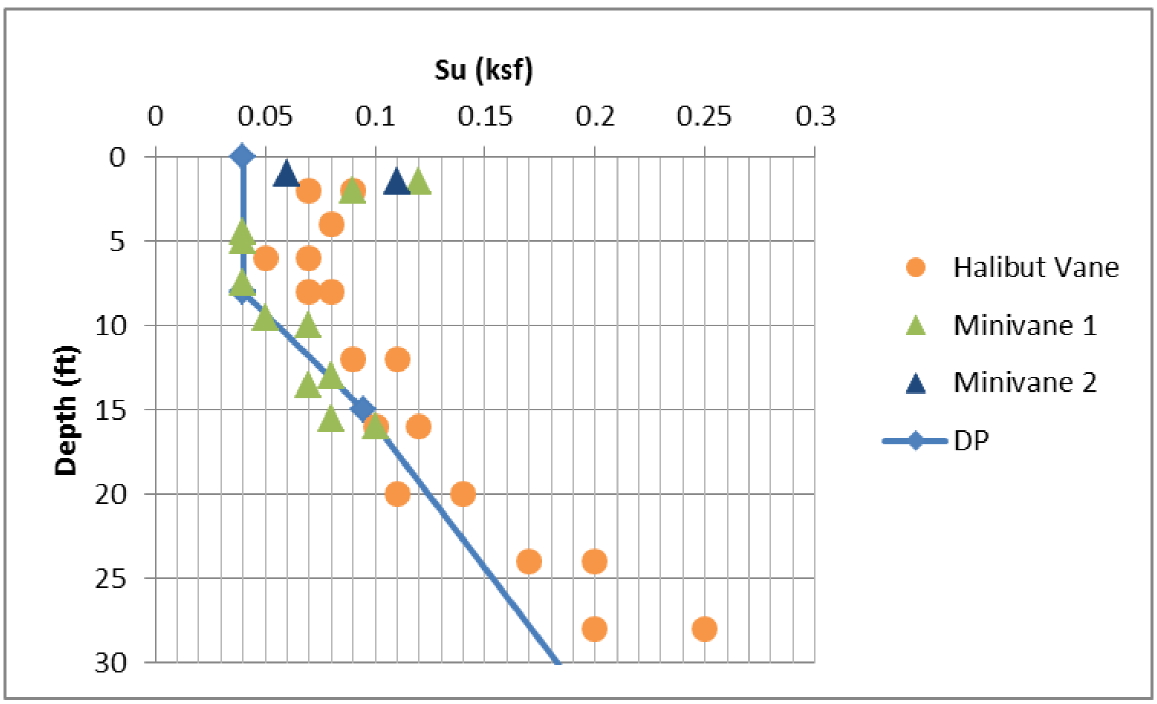


Figure 3.1: Raw Data and Design Profile from First Borehole of Region E

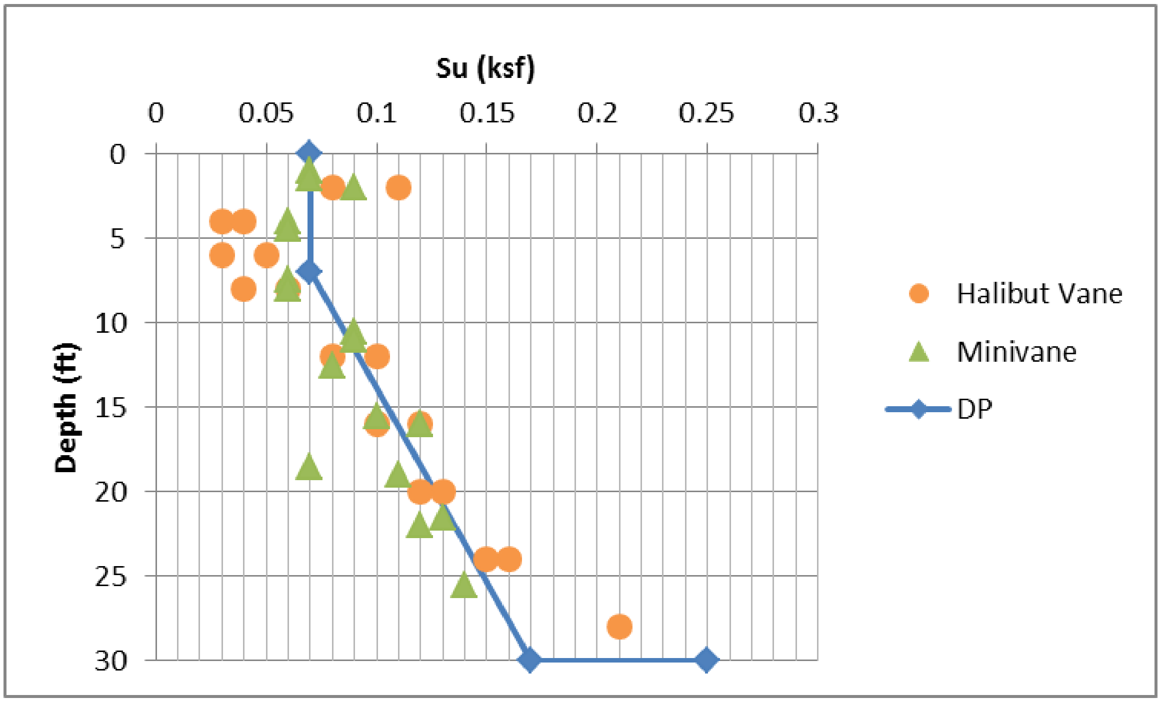


Figure 3.2: Raw Data and Design Profile from Second Borehole of Region E

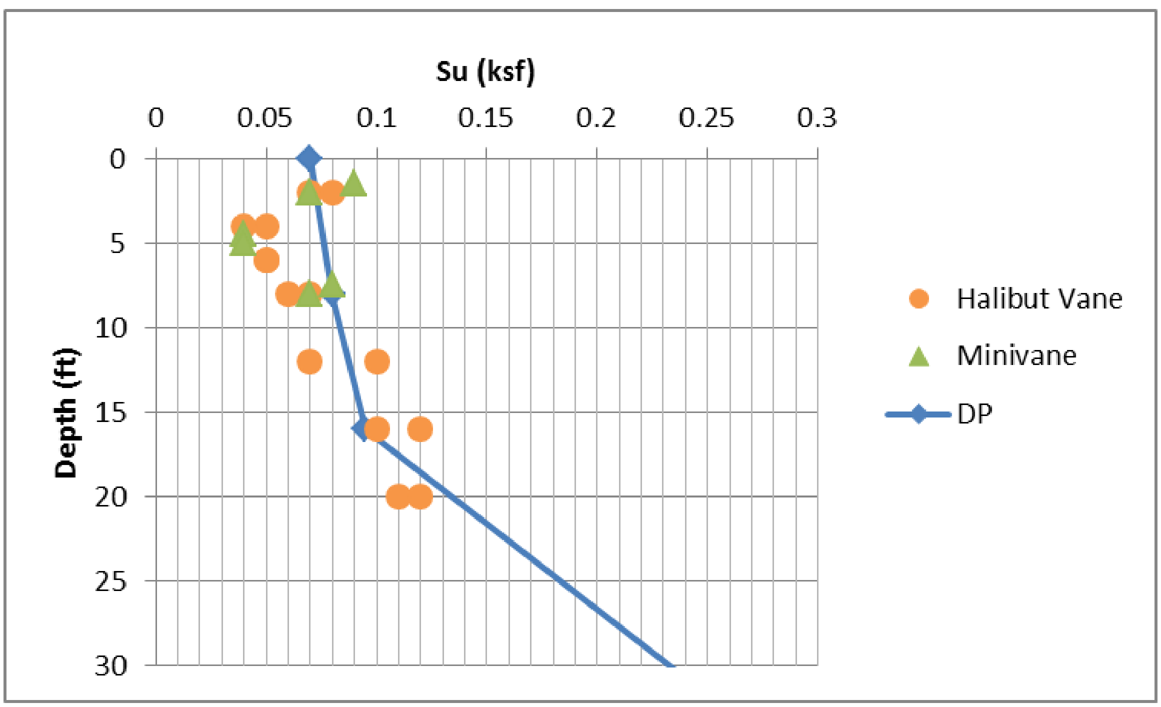


Figure 3.3: Raw Data and Design Profile from Third Borehole of Region E

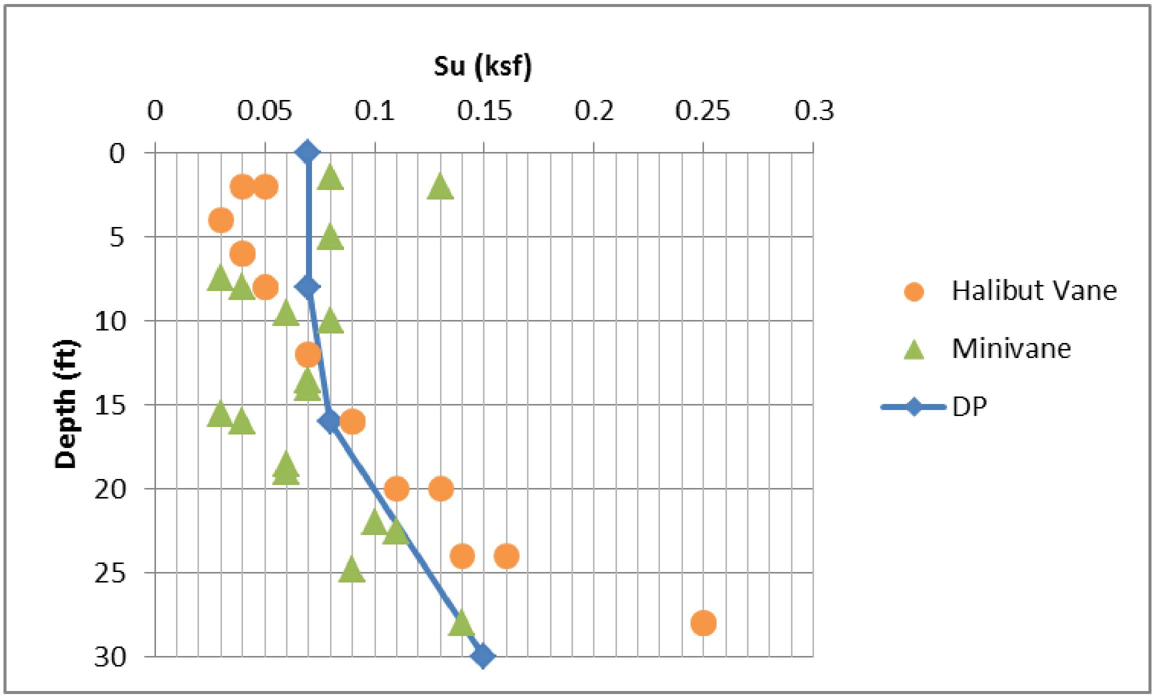


Figure 3.4: Raw Data and Design Profile from Fourth Borehole of Region E

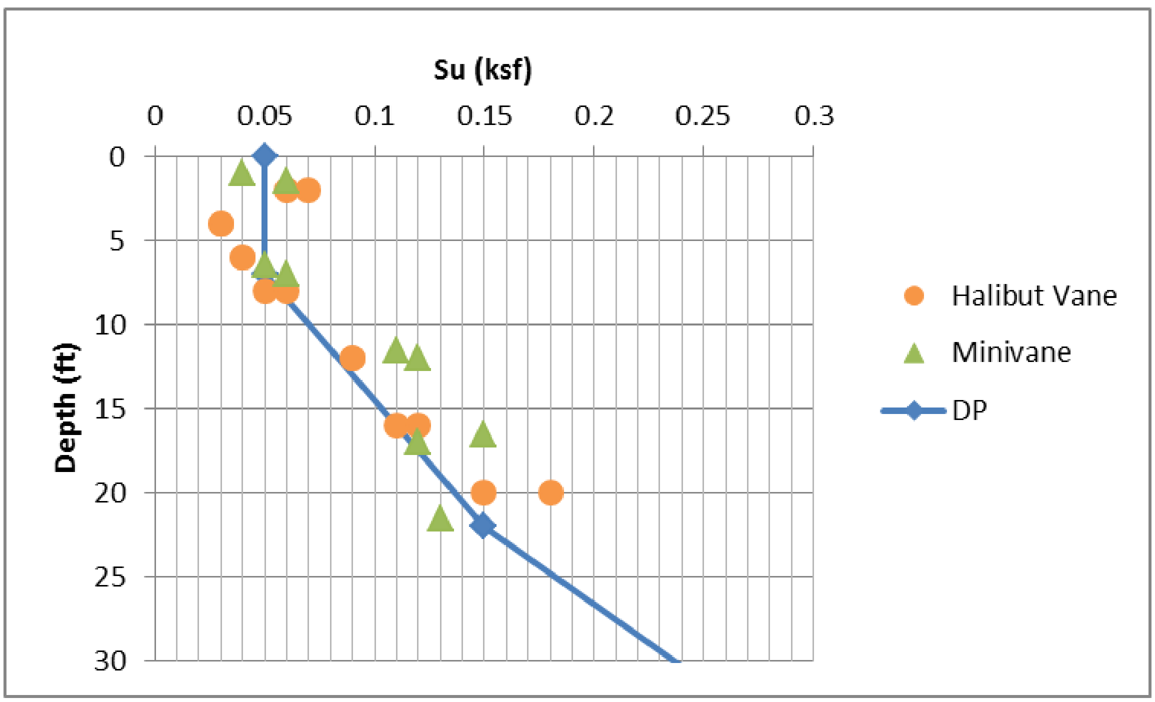


Figure 3.5: Raw Data and Design Profile from First Borehole of Region F

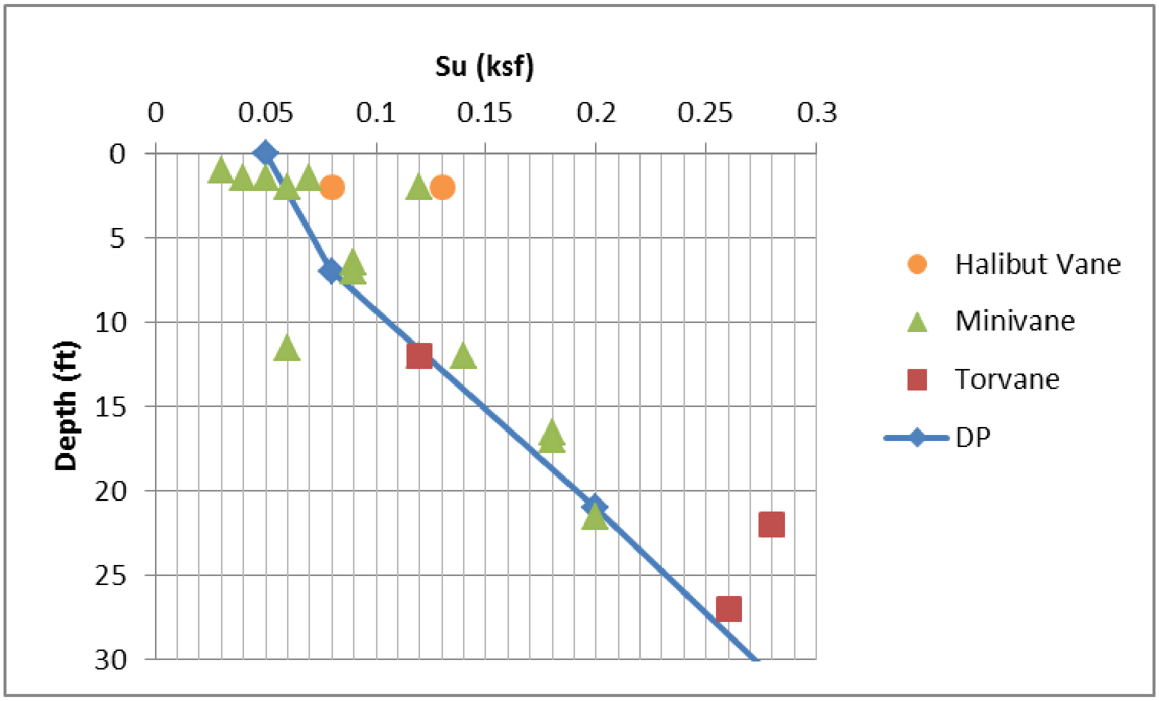


Figure 3.6: Raw Data and Design Profile from Second Borehole of Region F

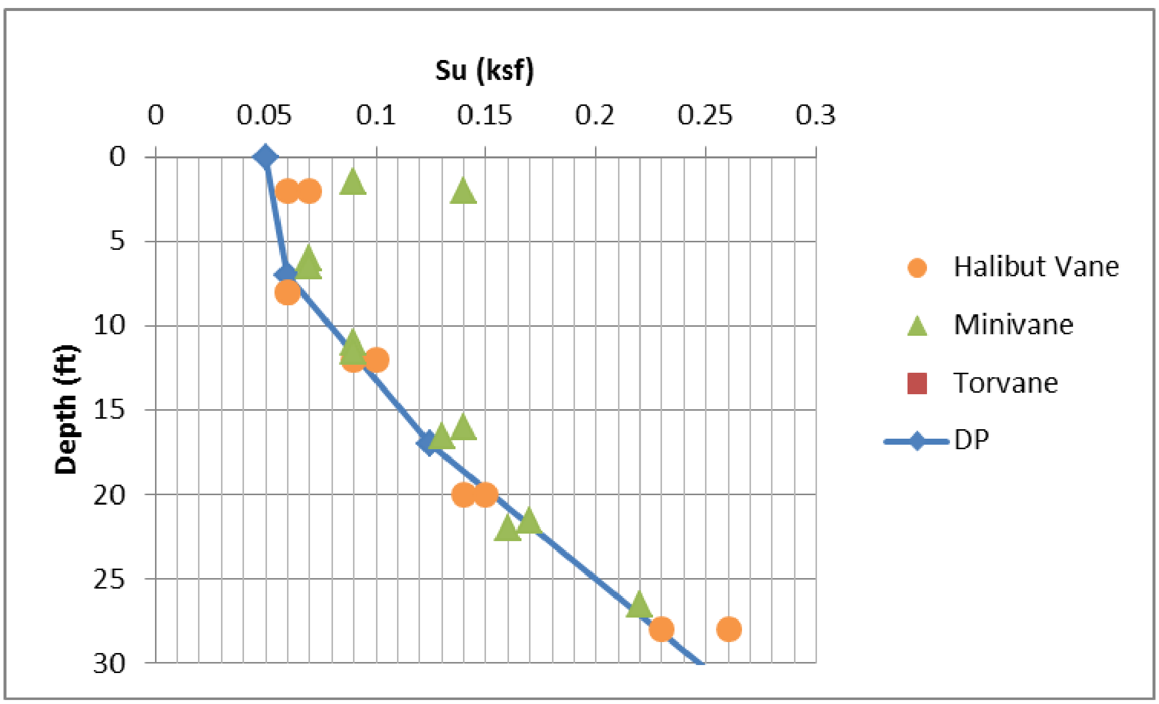


Figure 3.7: Raw Data and Design Profile from Third Borehole of Region F

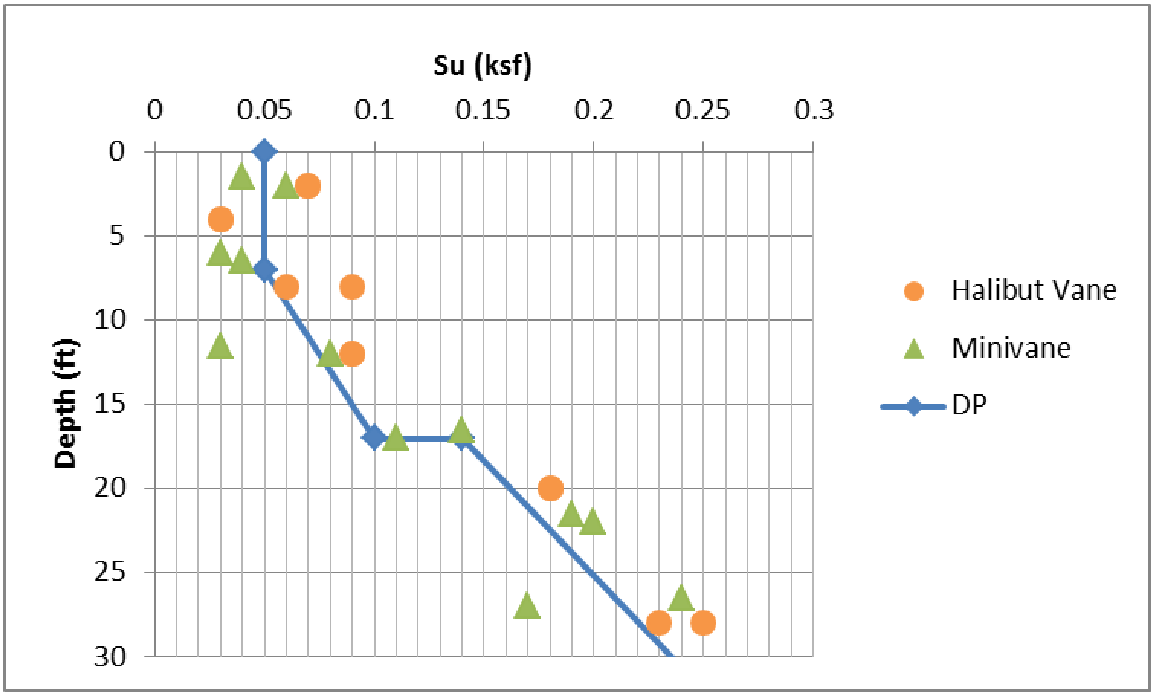


Figure 3.8: Raw Data and Design Profile from Fourth Borehole of Region F

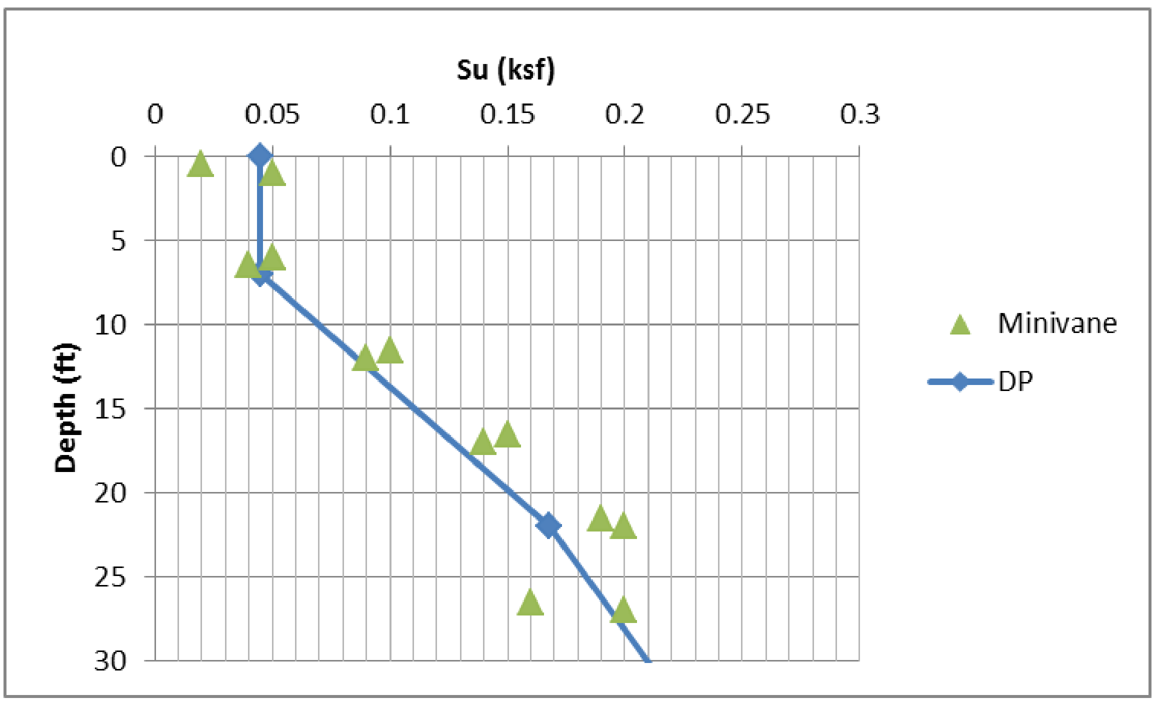


Figure 3.9: Raw Data and Design Profile from Fifth Borehole of Region F

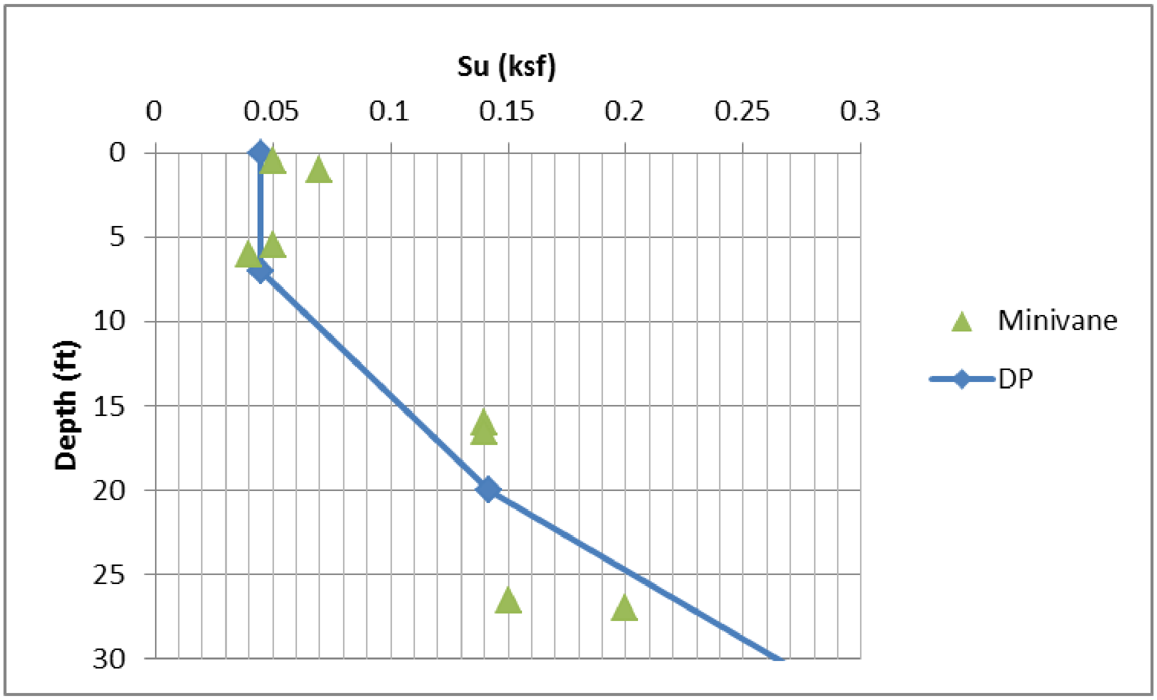


Figure 3.10: Raw Data and Design Profile from Sixth Borehole of Region F

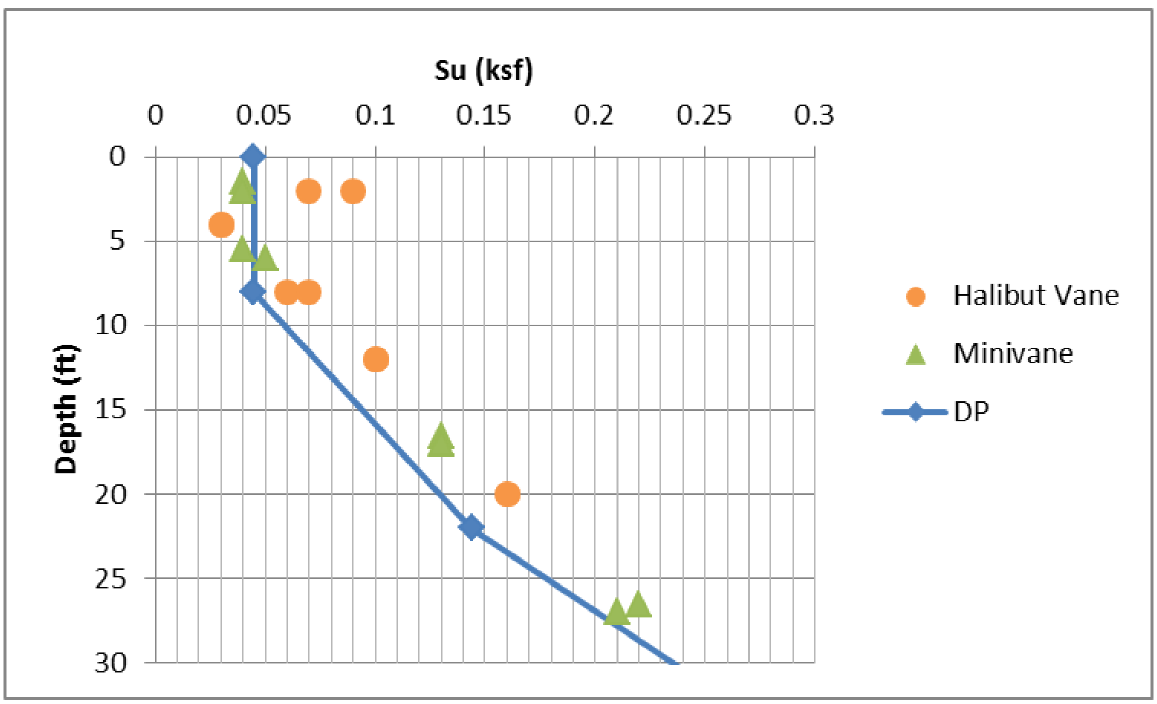


Figure 3.11: Raw Data and Design Profile from Seventh Borehole of Region F

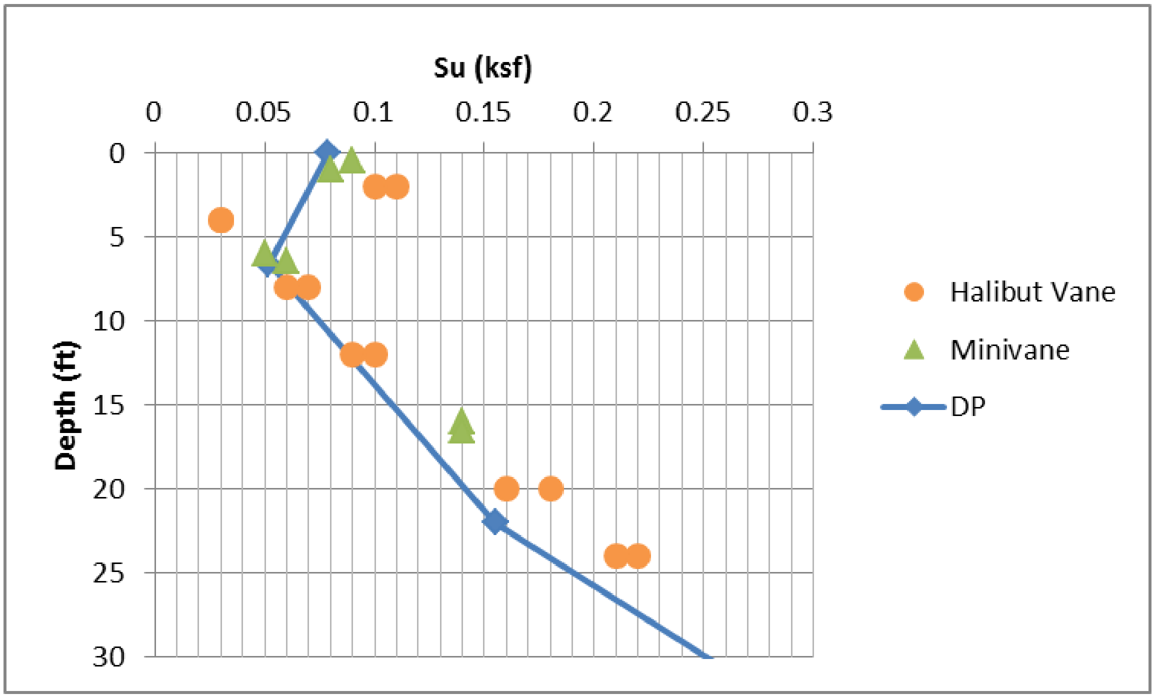


Figure 3.12: Raw Data and Design Profile from Eighth Borehole of Region F

3.3 New Data and Design Profiles

Recently, new studies were performed in regions E and F which focused on creating a higher resolution undrained shear strength design profile in the shallow region of the soil. The goal of these reports, as is the goal of this thesis, was to offer a clearer view of the strength of the soil in the shallow region of deep water Gulf of Mexico for the purpose of shallow foundation design in these regions.

Because of the proprietary nature of the data, no specific information can be given about the locations of the new data or the exact values of the design profiles. Nor is the raw data given; however, it is likely that the raw data at the new locations mirrors the raw data at the old locations.

The report from region E includes three new design profiles from locations shown in Figure 3.13. These locations will be referred to as Locations 1, 2 and 3 to protect proprietary information. The profiles, shown in Figure 3.14, all have very similar shapes showing a large spike in undrained shear strength at a depth of approximately 2 ft. The strength then drops back down at a depth of 3 ft, and the slope changes dramatically. This spike in strength is a clear indicator of the presence of a crust at this location.

The report from region F includes a single new design profile and does not indicate a particular location, suggesting that the new design profile may be applicable to shallow soils everywhere within the region. The profile, shown in figure 3.15, shows a sharp increase in strength from the mudline to a depth slightly greater than 1 ft, where it remains constant for a short time before dropping back down at around 3 ft deep and changing in slope. The spike in strength here is slightly different in shape of the spike at the locations in region E, but it still indicates the presence of a crust.

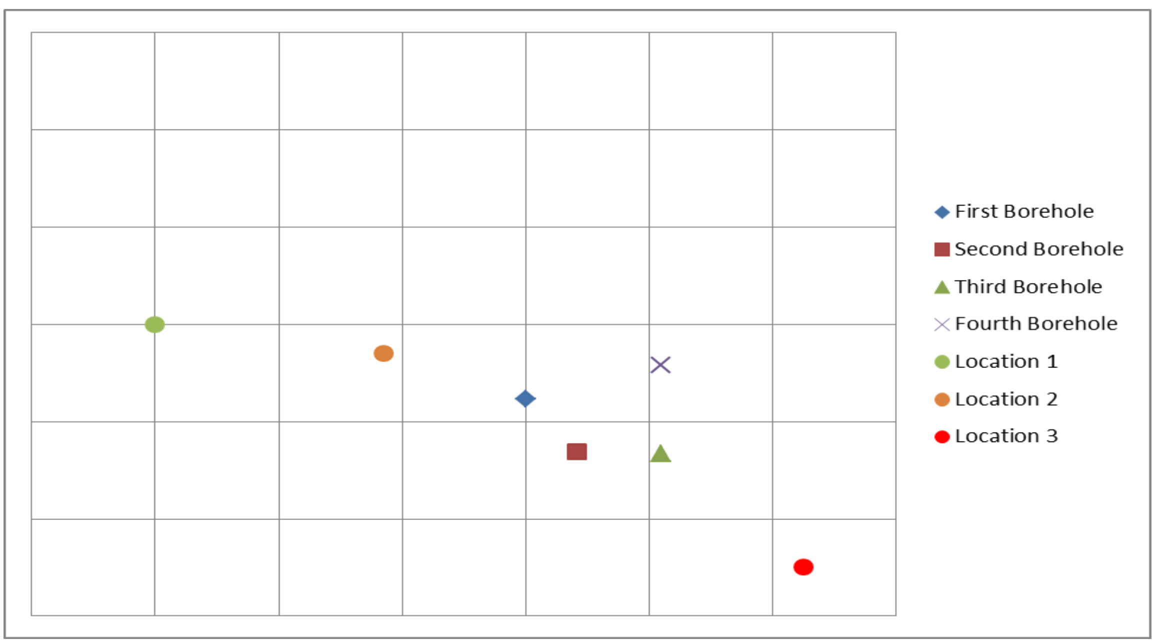


Figure 3.13: Relative Location of the New and Original Design Profiles in Region E

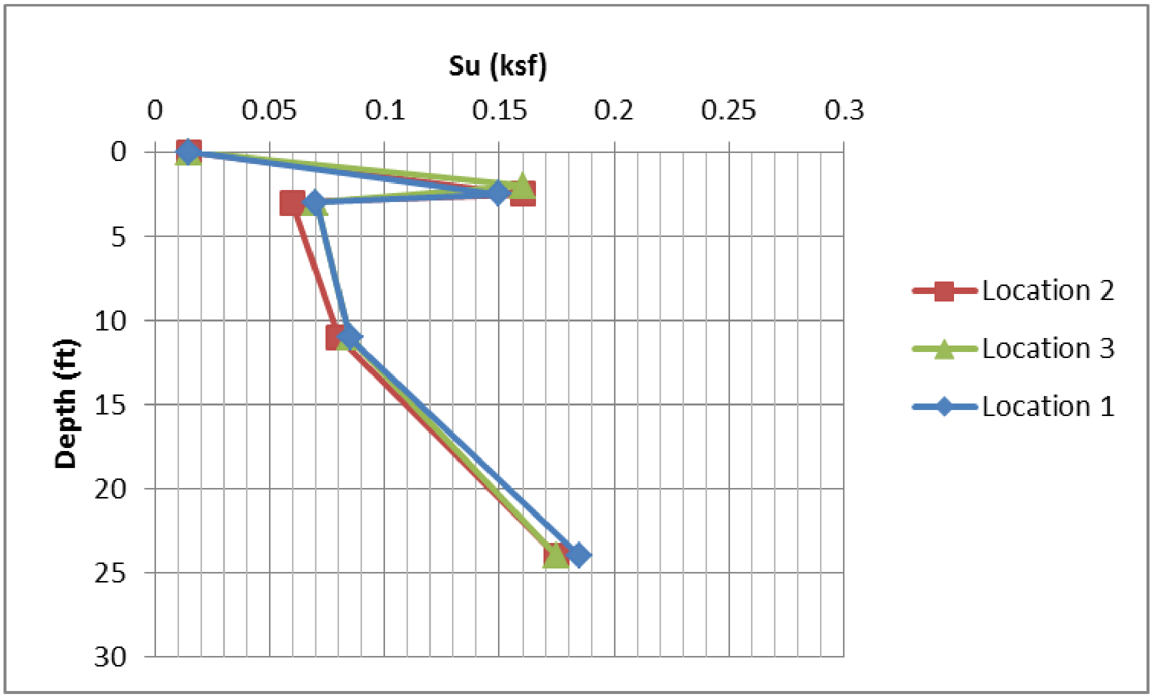


Figure 3.14: New Design Profiles from Region E using High Resolution Data

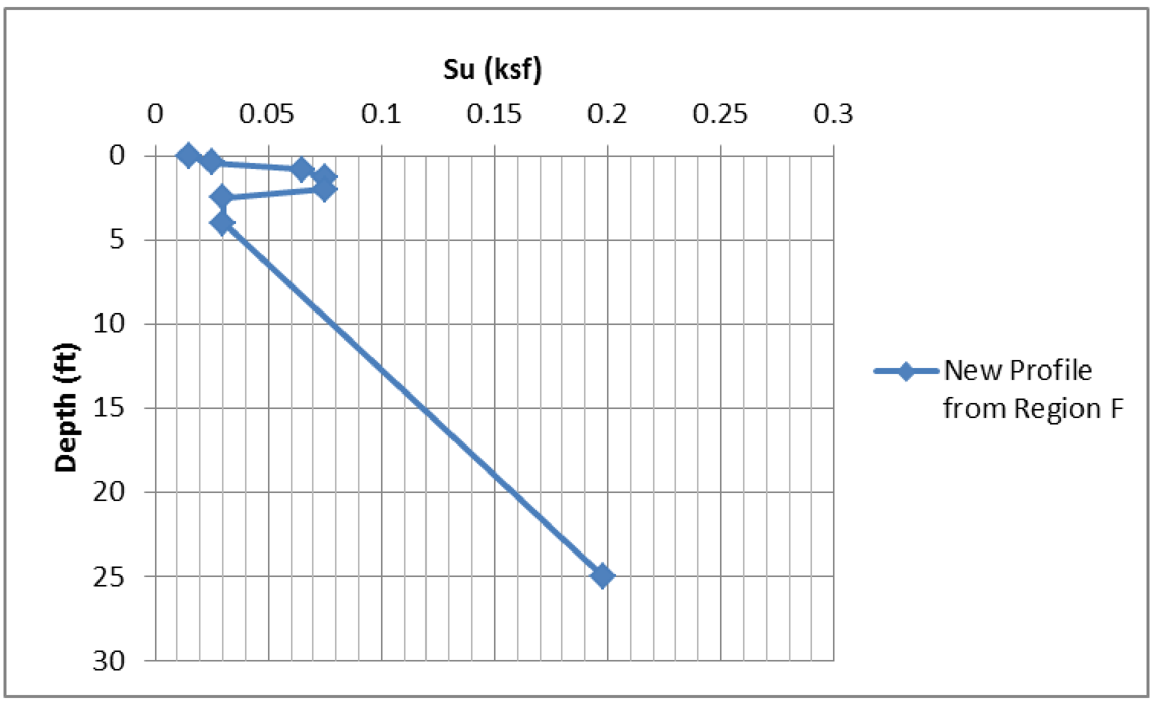


Figure 3.15: New Design Profiles from Region F using High Resolution Data

3.4 Comparison of Original and New Design Profiles

The new data suggests a radical change in shape of the undrained shear strength profile at these locations, but how do the new design profiles compare in terms of scale to the original design profiles. Figure 3.16 and 3.17 offer a comparison of the original design profiles with the new design profiles from regions E and F respectively.

In region E, the new design profile shows a considerably smaller undrained shear strength at the mudline compared to the original design profiles. This is likely because the engineers who designed the original design profiles were trying to account for the spike in strength that occurs in the raw data near the mudline by boosting the strength of the design profile at the mudline. The spike that occurs in the new design profiles is enormous compared to the original design profiles, more than twice the strength of the original design profiles at that depth. Once the new design profiles get below the crust though the new design profiles fall more in line with the original design profiles, which would suggest that the original design profiles are accurate at depths greater than 5 or 10 ft.

In region F, similar patterns occur. The new design profile is about half as weak at the mudline compared to the original design profiles, but at 1 to 2 ft it increases considerably and is much larger than the original design profiles at the same depth. The new design profile then dips back down at a depth of about 3 ft to a strength closer to its strength at the mudline increasing with a slope similar to the original design profiles. The one major outlier here is the eighth borehole, which was likely an attempt by the engineers who designed the original profile to account for the presence of a crust by using a much larger strength at the mudline. It looks as if the eighth borehole extrapolates the strength of the new design profile at a depth of about 7 ft and a depth of about 2 ft to find a strength at the mudline.

One final important point this figure makes is that deeper in the soil the strengths are much higher than they are at the mudline; therefore, spikes in strength at the mudline that may even double the strength become insignificant compared to strengths at greater depths. The presence of a crust is an important factor that needs to be considered for shallow foundations, but it is unimportant when dealing with deep foundations.

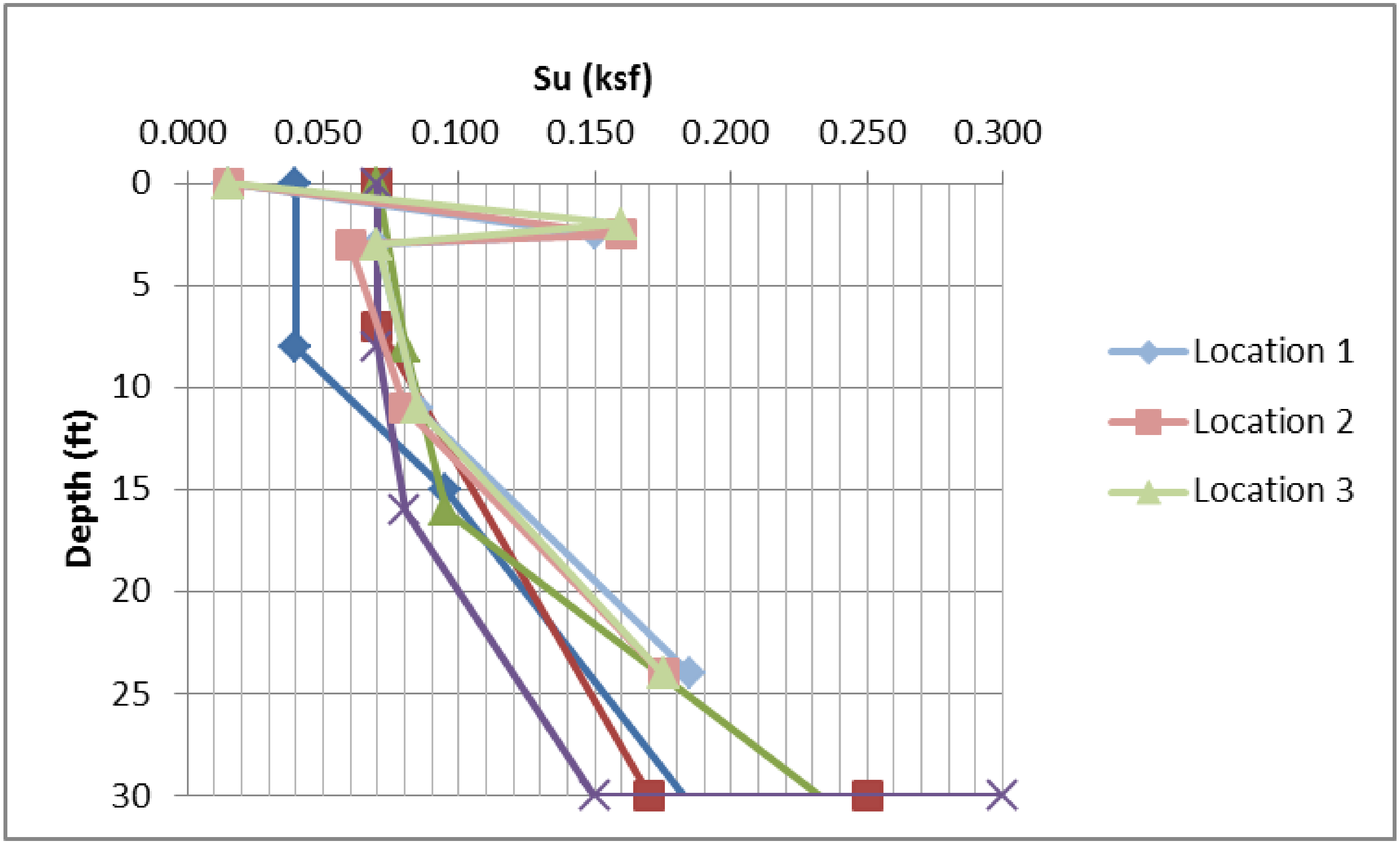


Figure 3.16: Comparison of Original and New Design Profiles from Region E

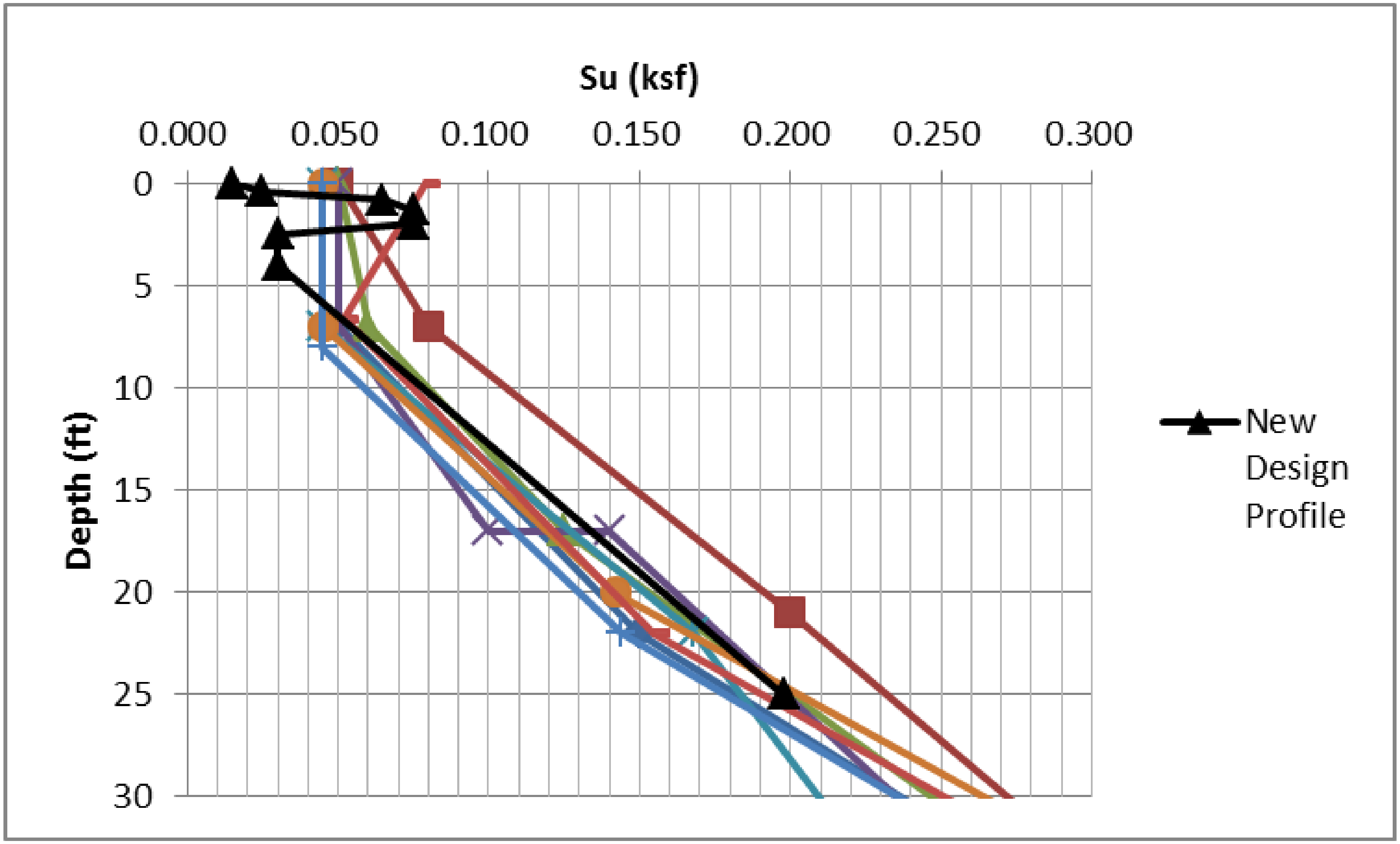


Figure 3.17: Comparison of Original Design Profiles and the New Design Profile from Region F

3.5 Conclusions

The value of this kind of high resolution study of shallow soils in deep water Gulf of Mexico should be obvious with regards to shallow foundations. These design profiles are only a few examples, but they show that in-depth study of the shallow region provides an understanding of the strength that goes far beyond what most of the existing design profiles will offer. The presence of a crust and the corresponding spike in undrained shear strength would have a massive effect on any future shallow foundations designs in these regions.

This new data also shows how the original data is not as descriptive in terms of shallow soils. The strengths of the original design profiles at around 2 ft deep are small compared to the strengths of the new design profiles. Any attempt to calculate capacity based on the original data would likely result in an over-design of the foundation. Therefore, the majority of the design profiles within the database, as they currently exist, are useless for the purpose of shallow foundation design.

3.6 Summary

In the past engineers have ignored shallow soils in deep water Gulf of Mexico because they were unimportant to deep foundations, but more recently engineers have started focusing on the shallow soils for the purpose of shallow foundation design. Two locations in particular illustrate the value of performing new research into shallow soils by offering a comparison between the original, deep foundation focused data and the new, shallow foundation focused data.

In region E there are four locations consisting of boreholes where Halibut Vane and Minivane tests were performed. In region F there are eight locations consisting of boreholes where Halibut Vane, Minivane, and Torvane tests were performed. There is a corresponding design profile for each borehole and all the profiles have very similar shapes with very little change in the shear strength of the soil to a depth of 7 or 8 ft.

The new data in region E consists of 3 new design profiles which start with relatively small strengths at the mudline but sharply increase in strength to a depth of 2 ft before decreasing at a depth of 3 ft. The new data in region F consists of a single design profile, which was not given a specific location, and which shows a bump in shear strength from the relatively small strength at the mudline to a peak at a depth of between 1 and 2 ft before dropping back down around a depth of 3 ft. In both regions, the design profiles show the presence of a crust.

Comparing the original design profiles with the new design profiles it's easy to see that the original design profiles do not accurately represent the changes in strength in the shallow region, but that the soils are actually much stronger than originally predicted around a depth of 2 ft. In the case of region E the soil is more than twice as strong as suggested by the original design profiles. The new design profile in region F also showed a marked increase in undrained shear strength at a depth of about 2 ft compared to the original design profiles at that depth. All design profiles appeared to converge below a depth of between 5 and 10 ft, so at greater depths the original design profiles are still accurate. The graphs also show that the strengths at deeper depths dwarf the strengths at the crust, so the presence of a crust is unimportant for deep foundation design.

These new design profiles show the value of performing high resolution studies of undrained shear strength in deep water Gulf of Mexico. They also show how inadequate the original design profiles that make up the bulk of the existing database are with regards to shallow foundation design.

Chapter 4: Shallow Soil Strength Data within the Database

4.1 INTRODUCTION

As has been previously stated, most of the undrained shear strength design profiles within the database are inadequate with regards to shallow foundation analysis. Very few of the design profiles within the database offer a clear description of the undrained shear strength of the shallow soil. However, the studies within the database, and the data they contain, can be useful if they are of a high enough resolution (i.e. large quantity of data in the shallow region and wide variety of tests used to acquire the data). The goal of this chapter is to discuss the levels of resolution of shallow soil studies within the database and the characteristics of the high resolution studies.

First, this chapter will better define the concept of high resolution shallow soil strength data and discuss the high resolution data that exists within the current database. This chapter will also discuss the low resolution data. Then this chapter will compare the value of in-situ testing versus non in-situ testing as well as compare cone penetration tests of very high resolution to other tests of lower resolution.

4.2 HIGH RESOLUTION STUDIES OF SHALLOW SOILS

High resolution studies of shallow soils, in very general terms, are studies of the shallow region of soils in deep water Gulf of Mexico that contain a large enough amount of data to give a clear picture of the behavior of the soil in the area of focus of the study. To put it simply, a high resolution study contains lots of data in the shallow region, but its more than that as it must also include a variety of testing types used in the acquisition of the data. The purpose of this is to provide the most complete picture of the soil strength behavior that is possible. Defining what exactly a high resolution study is can be nebulous prospect, but for the purposes of this thesis a high resolution study will be defined as any location containing more than 10 points of strength data in the shallow region (the upper ten feet of soil) and at least two different test types, where one of the test types is an in-situ test.

Within the database there are a total of 115 exploratory locations spread over 16 different regions, and of these 115 locations only 18 of them qualify as high resolution studies under the previous description. The raw data and design profiles from these locations are shown in Figures 4.2 through 4.19 to a depth of 30 ft. These locations are all boreholes of varying total depth. Of the locations, 15 are located in zone 16 with the remaining 3 located in zone 15. The locations of high resolution studies relative to low resolution studies are given in Figure 4.1 The tests used to obtain the data at these locations are Halibut Vane tests and Minivane tests at all 18 locations, and additionally Torvane tests at 3 of the locations.

The number of locations that show potential evidence of a crust is 14, with 3 of the 4 remaining locations being the locations in zone 15. This potential is characterized by an increase in the measured undrained shear strength near the mudline. Typically this increase is shown more clearly by the data from a Halibut Vane (in-situ) test. It is also worth noting that of the 4 locations at which no evidence of a crust exists 3 of those locations are in zone 15. The locations that do show evidence of a crust are relatively close together in zone 16 and appear to follow along the continental shelf, which would suggest that the crust may exist specifically at the continental shelf. It is also important to note that of these 14 locations that show evidence of a crust at the seafloor, none of the undrained shear strength design profiles for these locations reflect this presence of a crust.

When looking at the design profiles that correspond to the high resolution studies there are a few patterns to note. Of the 18 locations, only one actually shows the presence of a crust, the last borehole in Region F, but it does this by increasing the strength at the mudline and not by actually mimicking the shape of the raw data. For the rest of the design profiles, they account for the raw data in a few ways. Some design profiles ignore the Halibut Vane data, which shows higher strengths near the mudline, in favor of following the Minivane or Torvane Data because it offers a straight line through the shallow region. Other design profiles attempt to account for the higher strength in-situ data by sitting in between the in-situ data and the non in-situ data, glossing over the subtleties of the soil behavior that the data actually reveals. Most, however, take the conservative route by following the weakest soil data in the shallow region.

The raw data and the design profiles from the 18 locations with high resolution studies are plotted in Figures 4.2 through 4.19. In addition to the data and the design profiles (DP), the figures include the average of all the high resolution data from the same region. This average was determined by taking the average of all test data surrounding the point at that depth within in a range of 1 ft above or below the point. The figures also include an upper and lower standard deviation boundary that is plotted by adding or subtracting the standard deviation of the data to the average of the data. These plots offer insight into the general trends of the raw data itself and how those trends compare to the design profile that exists there. Figure 4.20 shows the average design profiles from all of the regions with high resolution studies. Figure 4.21 shows the standard deviation of the design profiles from all of the regions with high resolution studies.

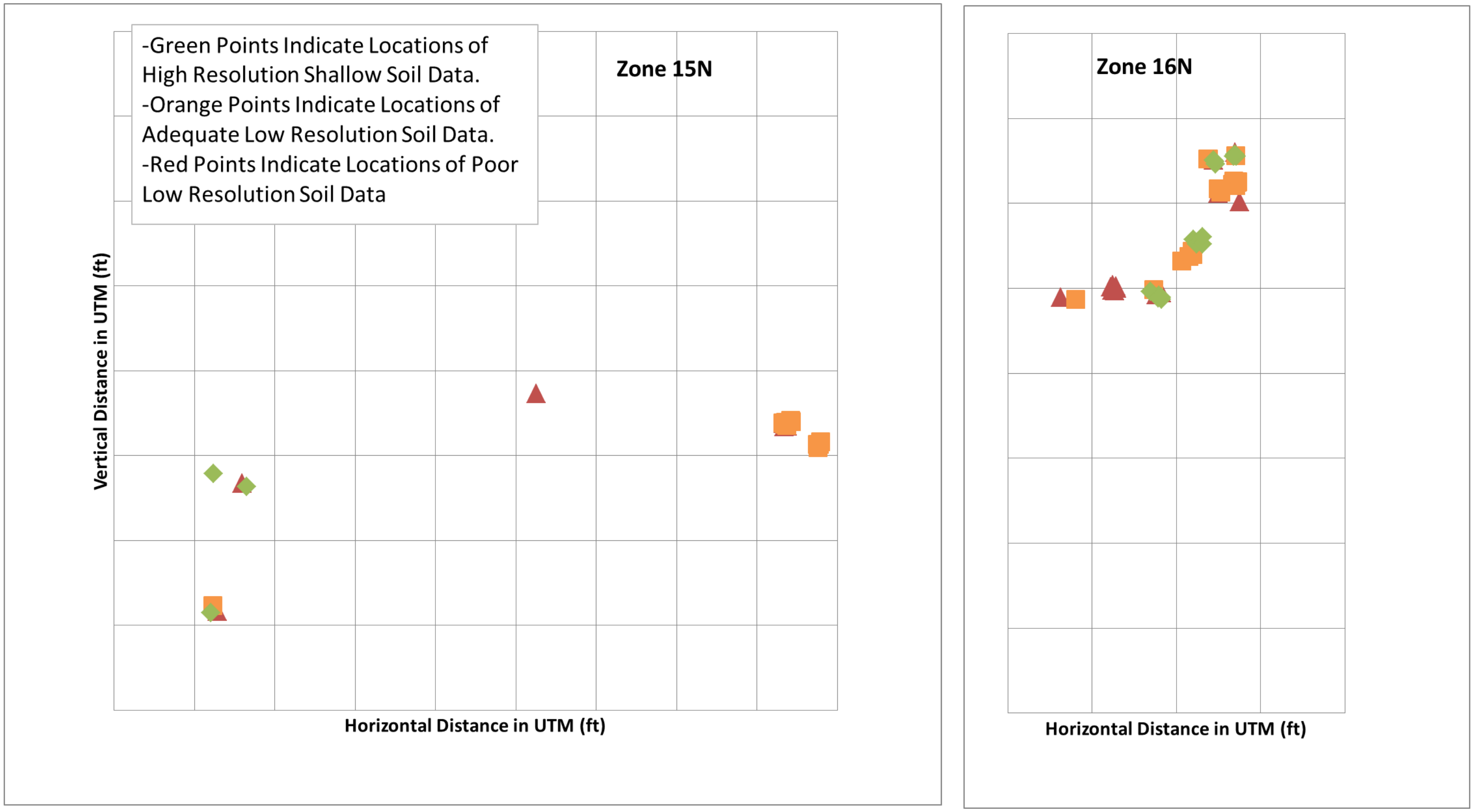


Figure 4.1: Relative Locations of High Resolution Studies and Low Resolution Studies

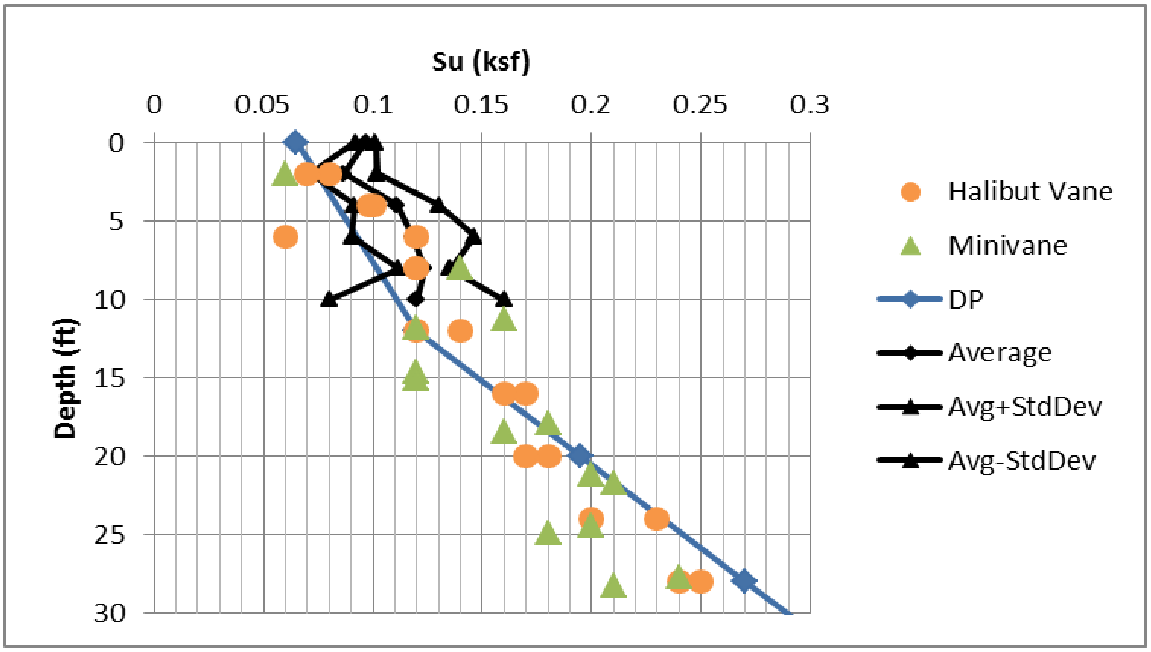


Figure 4.2: Raw Data and Design Profile from a High Resolution Borehole in Region A

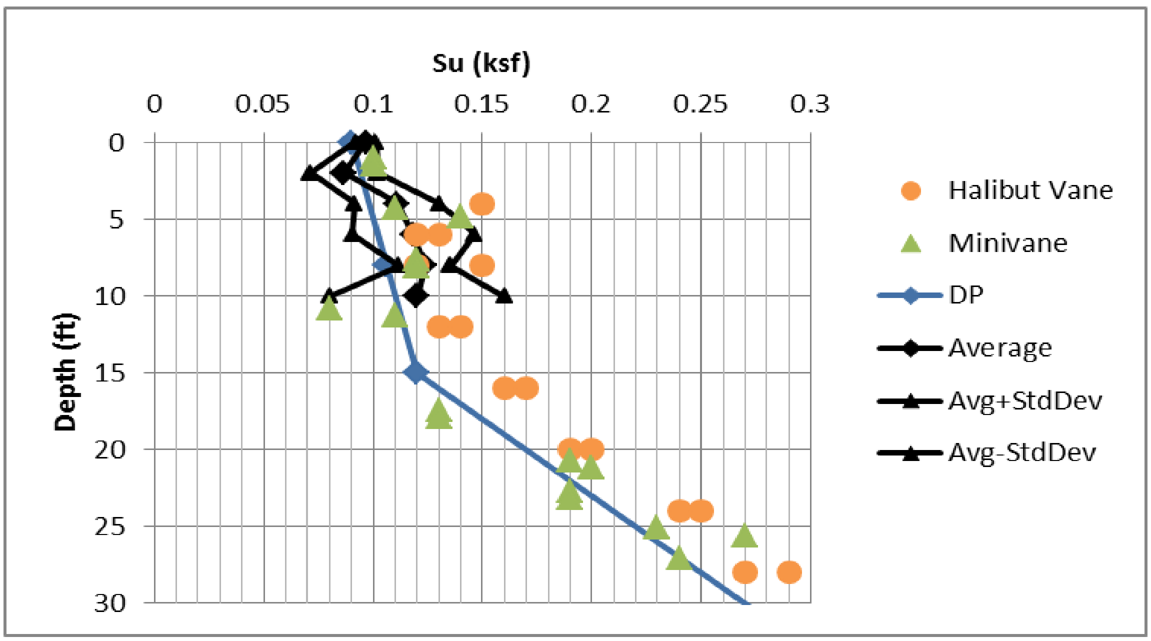


Figure 4.3: Raw Data and Design Profile from a High Resolution Borehole in Region A

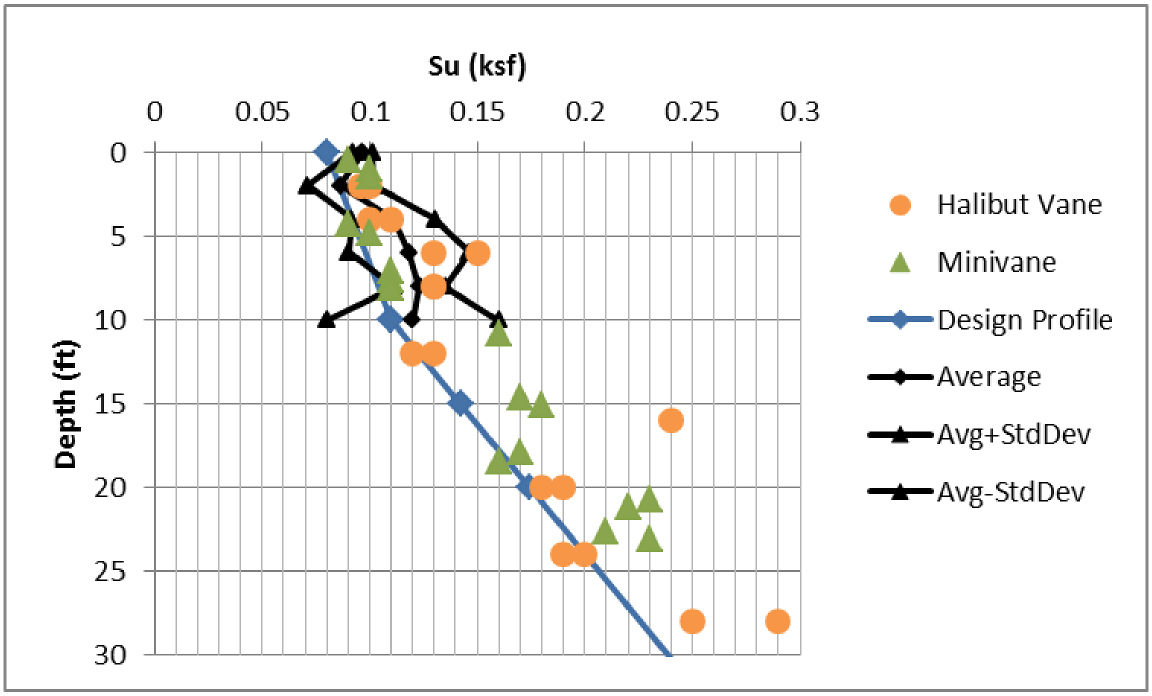


Figure 4.4: Raw Data and Design Profile from a High Resolution Borehole in Region A

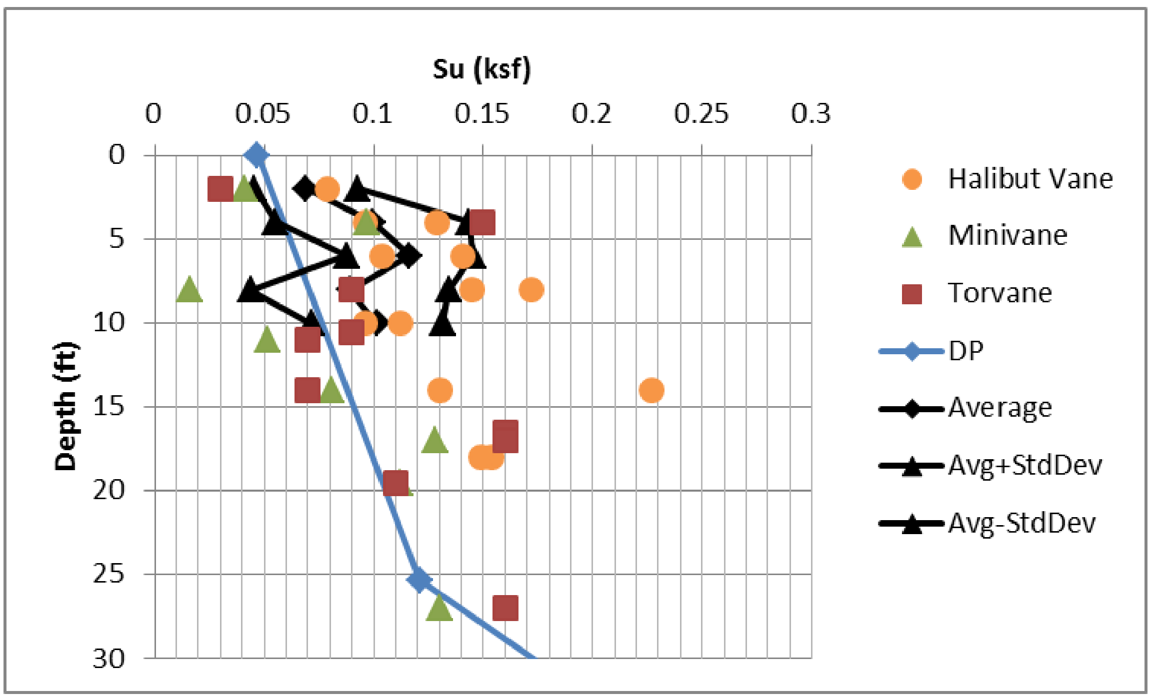


Figure 4.5: Raw Data and Design Profile from a High Resolution Borehole in Region B

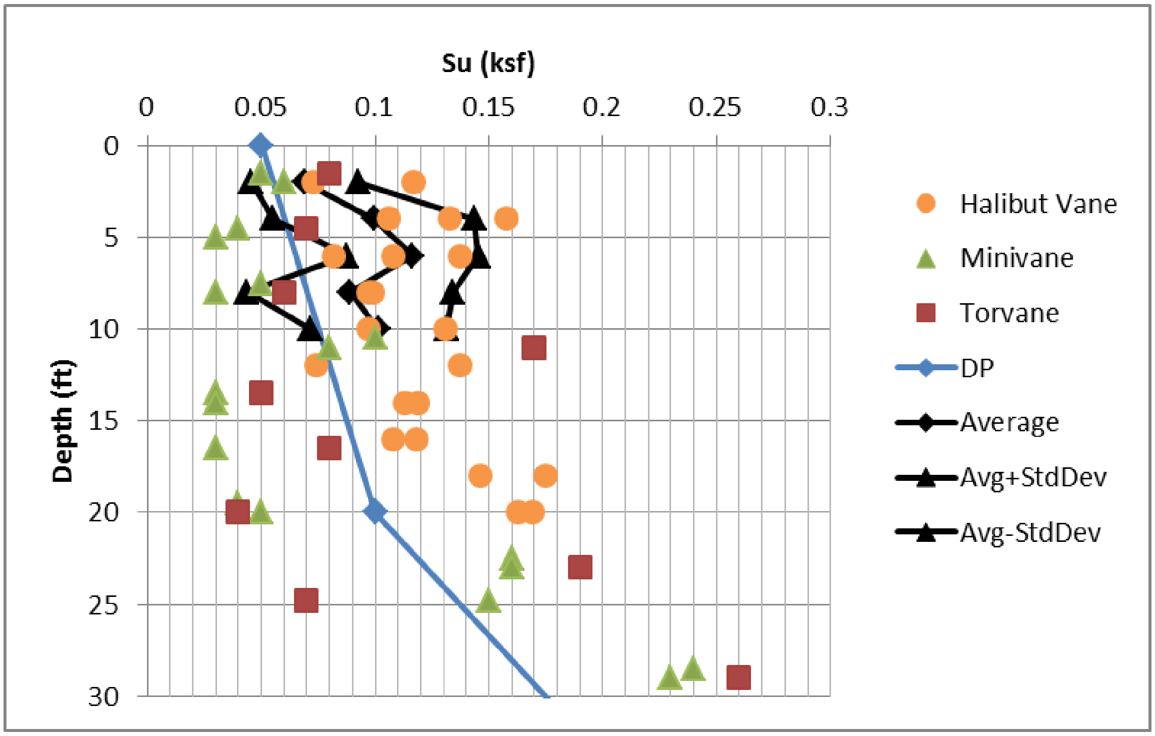


Figure 4.6: Raw Data and Design Profile from a High Resolution Borehole in Region B

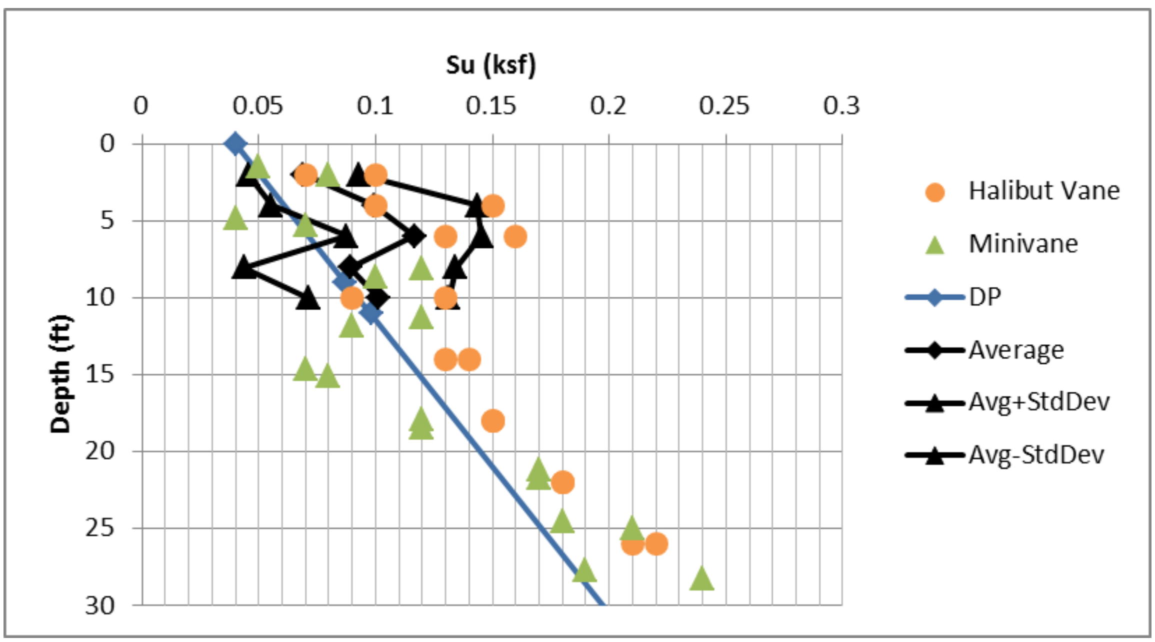


Figure 4.7: Raw Data and Design Profile from a High Resolution Borehole in Region B

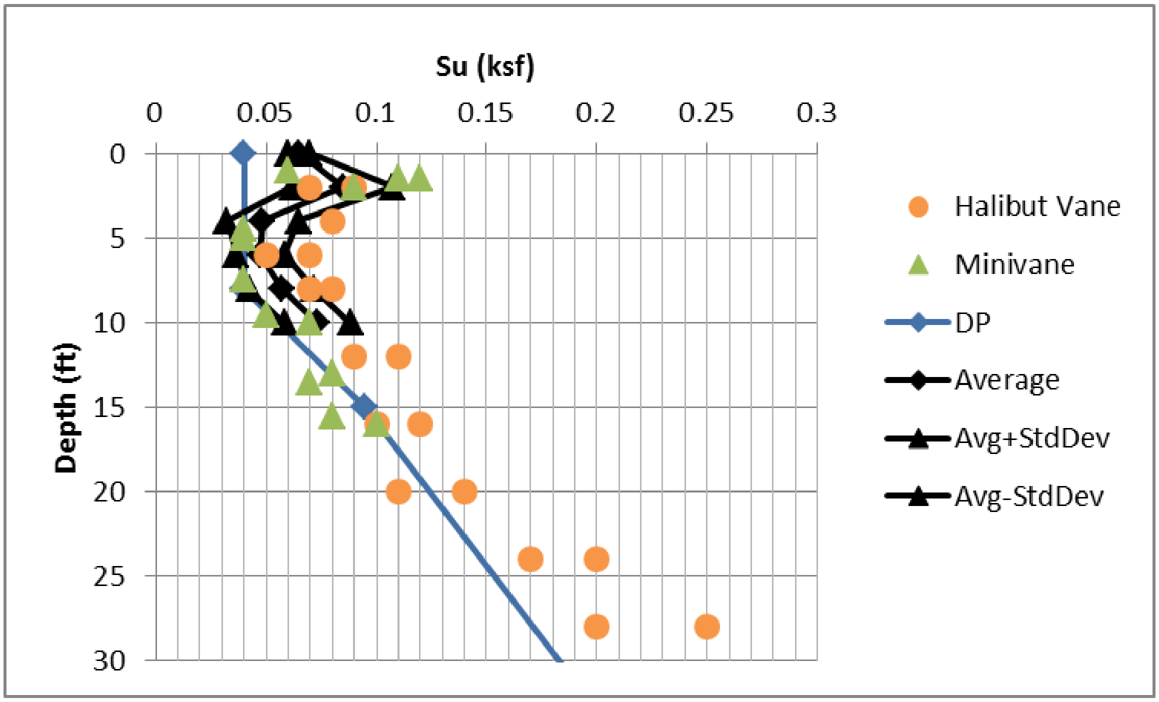


Figure 4.8: Raw Data and Design Profile from a High Resolution Borehole in Region E

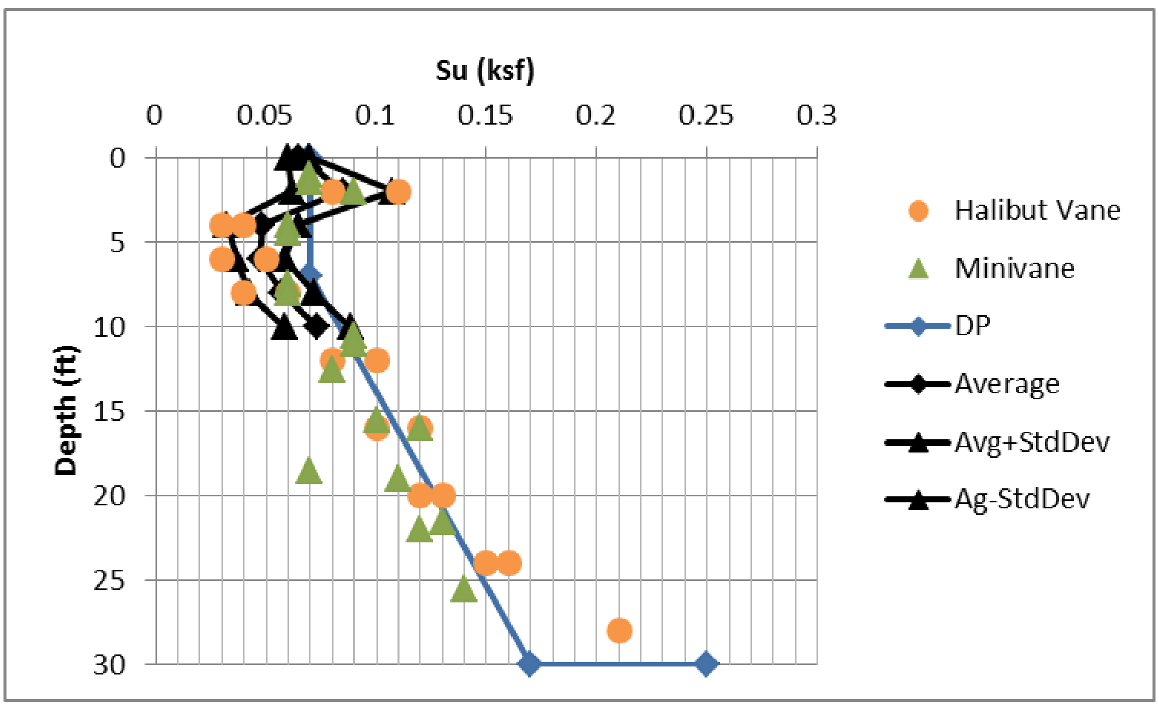


Figure 4.9: Raw Data and Design Profile from a High Resolution Borehole in Region E

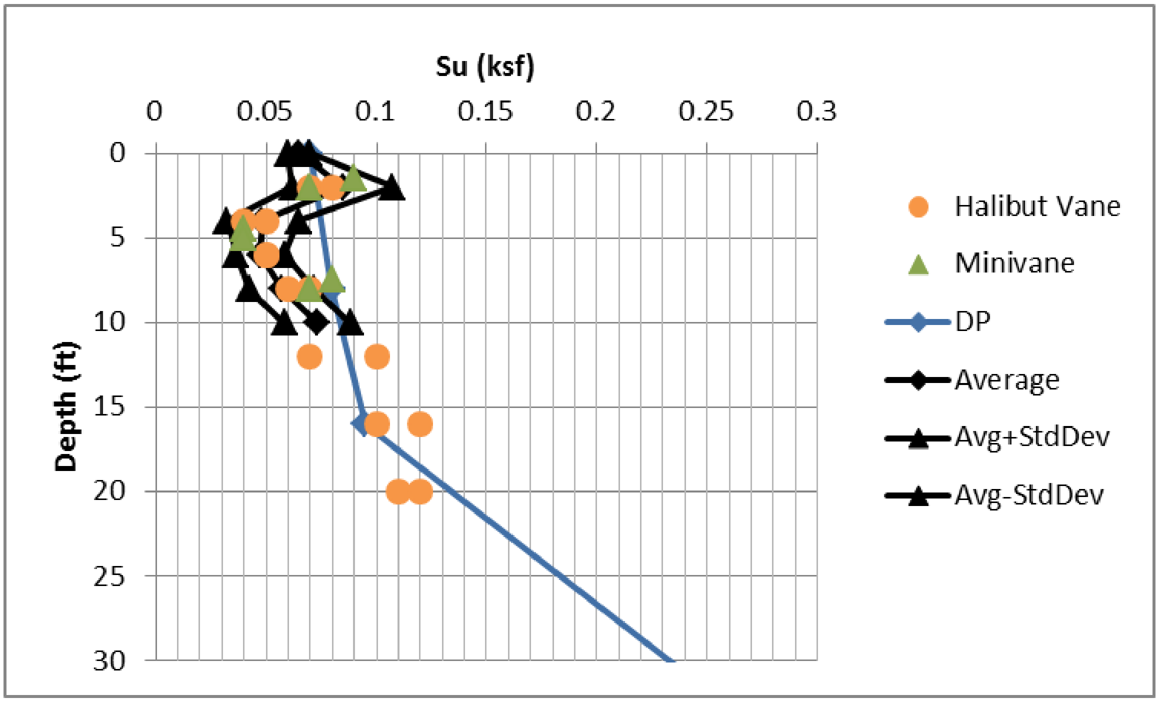


Figure 4.10: Raw Data and Design Profile from a High Resolution Borehole in Region E

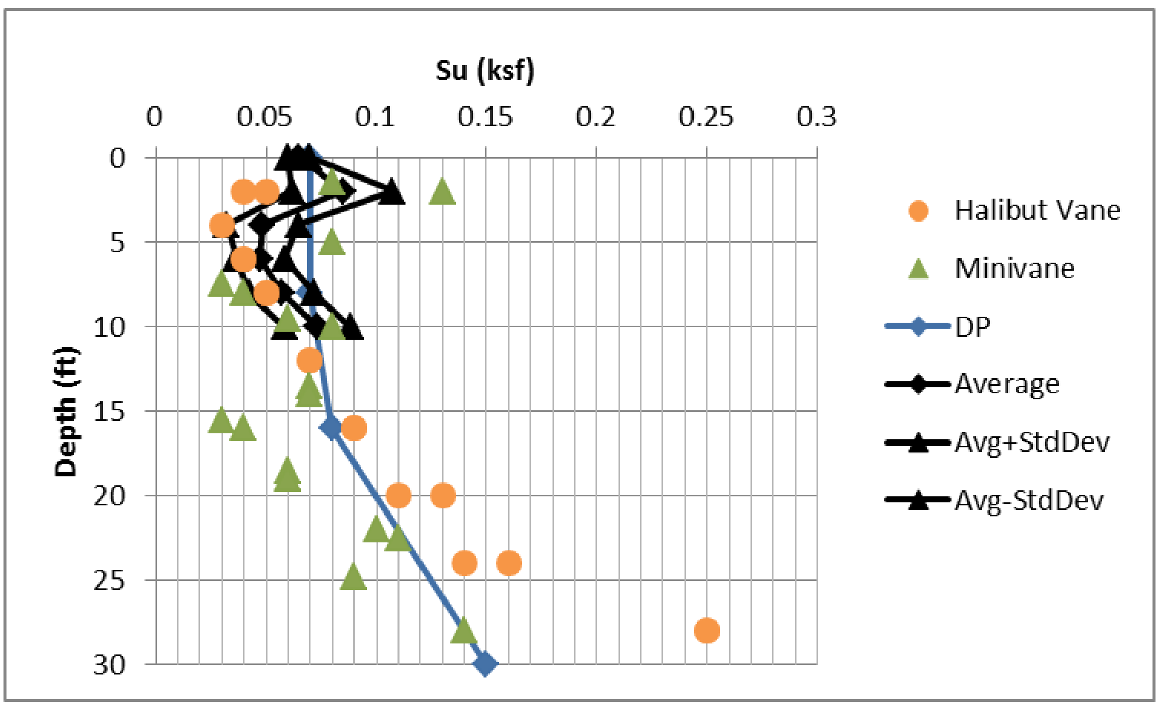


Figure 4.11: Raw Data and Design Profile from a High Resolution Borehole in Region E

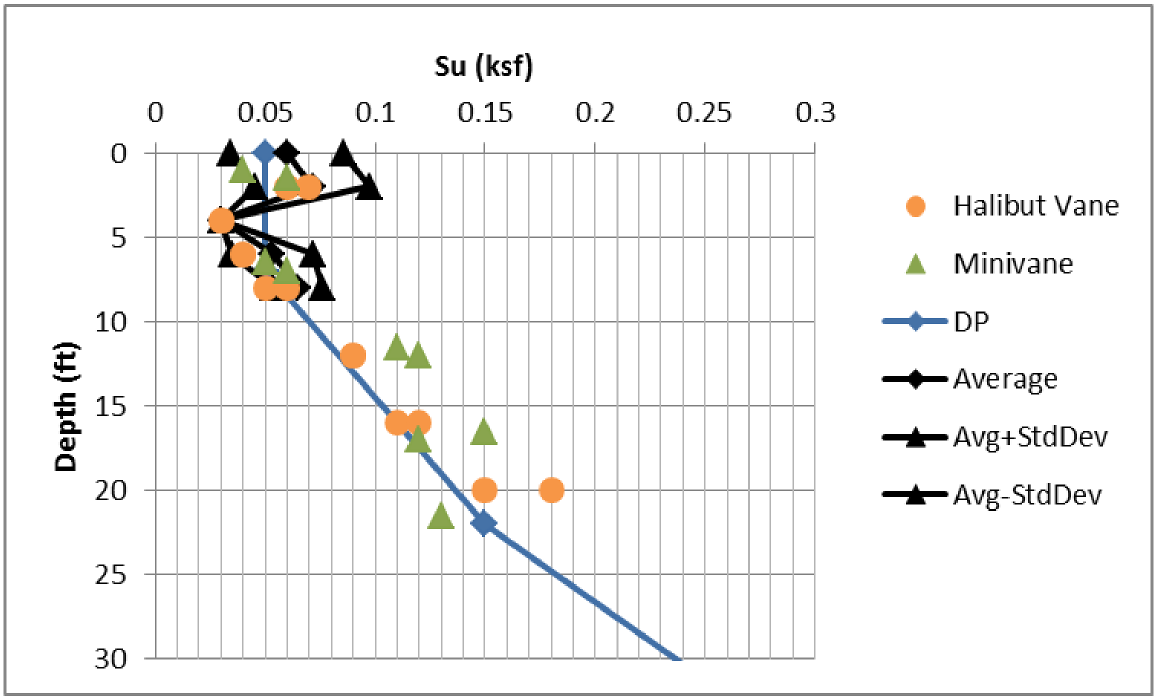


Figure 4.12: Raw Data and Design Profile from a High Resolution Borehole in Region F

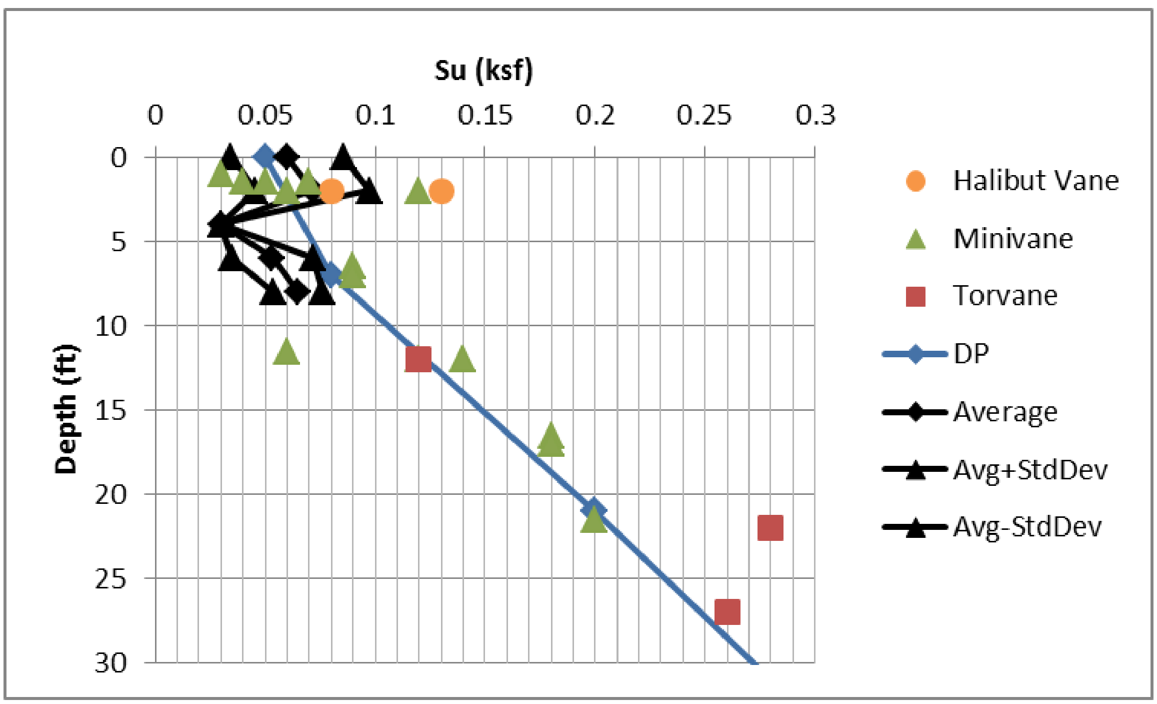


Figure 4.13: Raw Data and Design Profile from a High Resolution Borehole in Region F

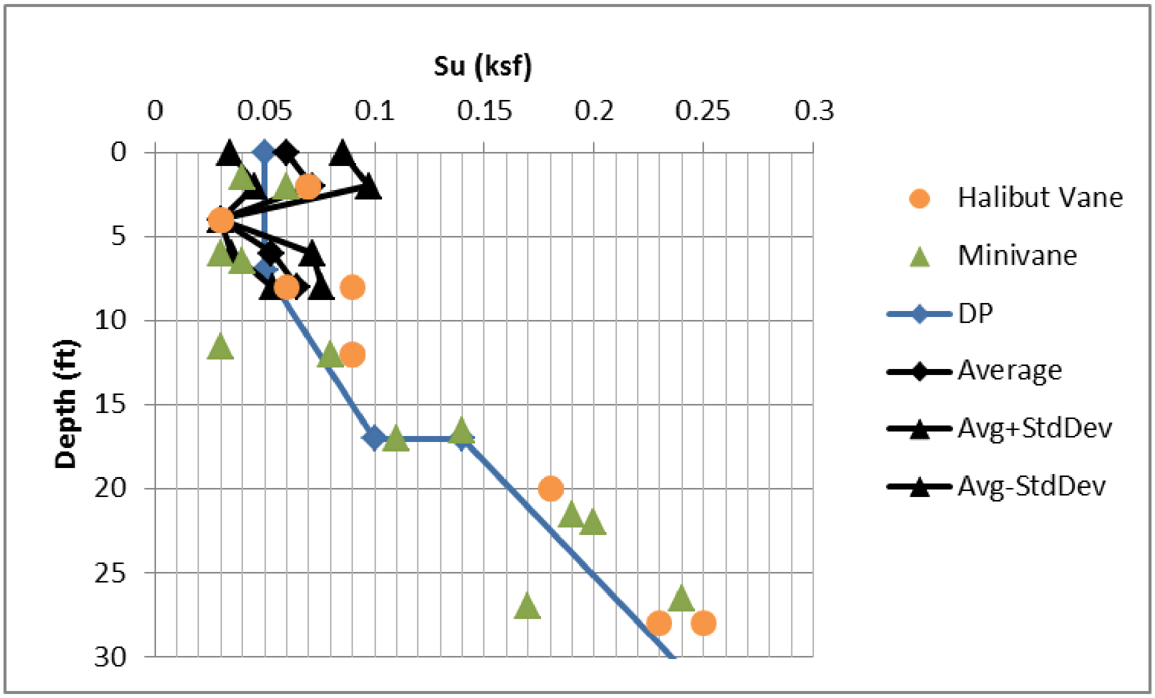


Figure 4.14: Raw Data and Design Profile from a High Resolution Borehole in Region F

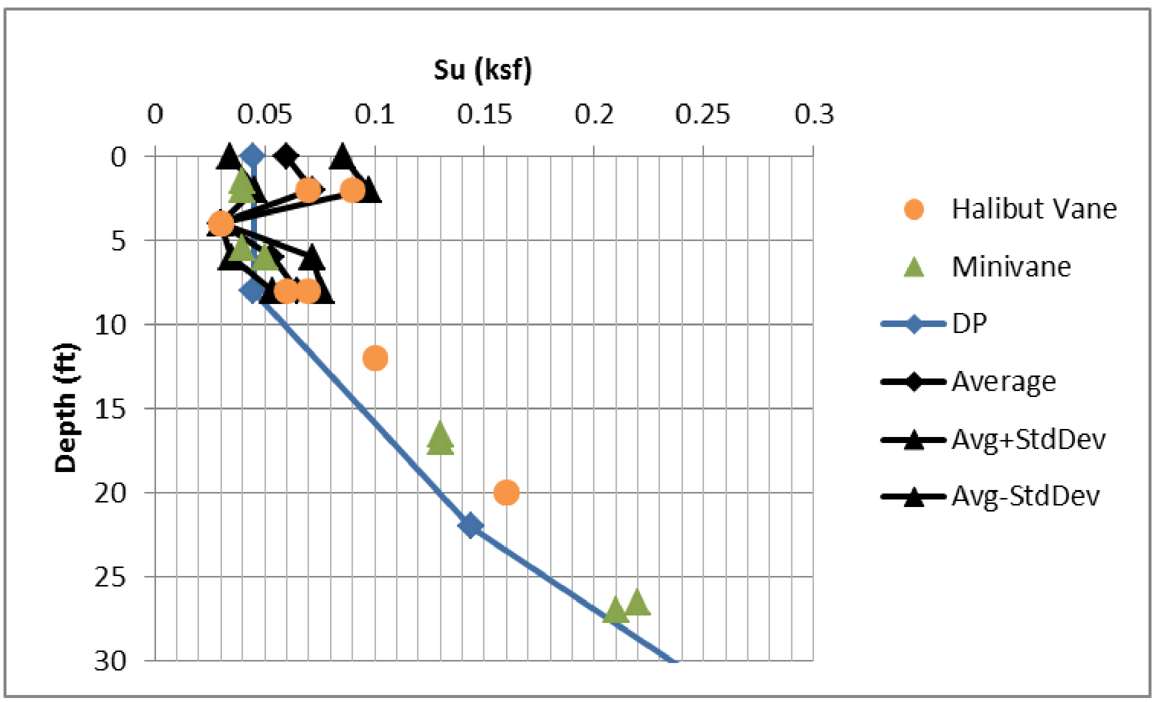


Figure 4.15: Raw Data and Design Profile from a High Resolution Borehole in Region F

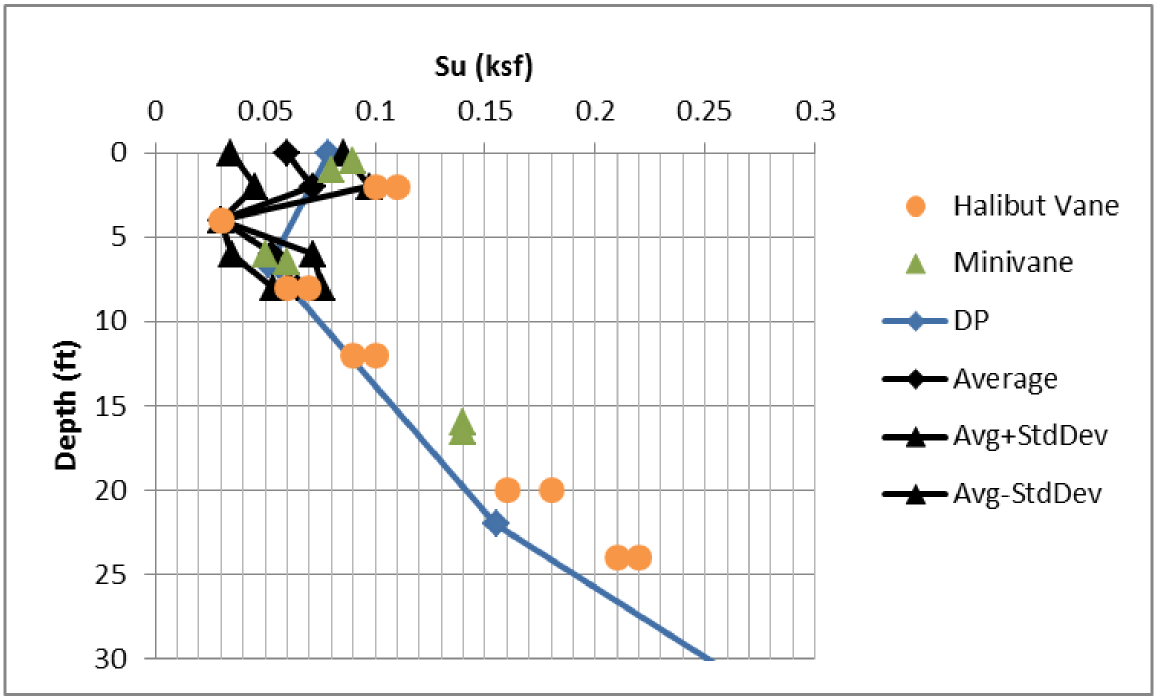


Figure 4.16: Raw Data and Design Profile from a High Resolution Borehole in Region F

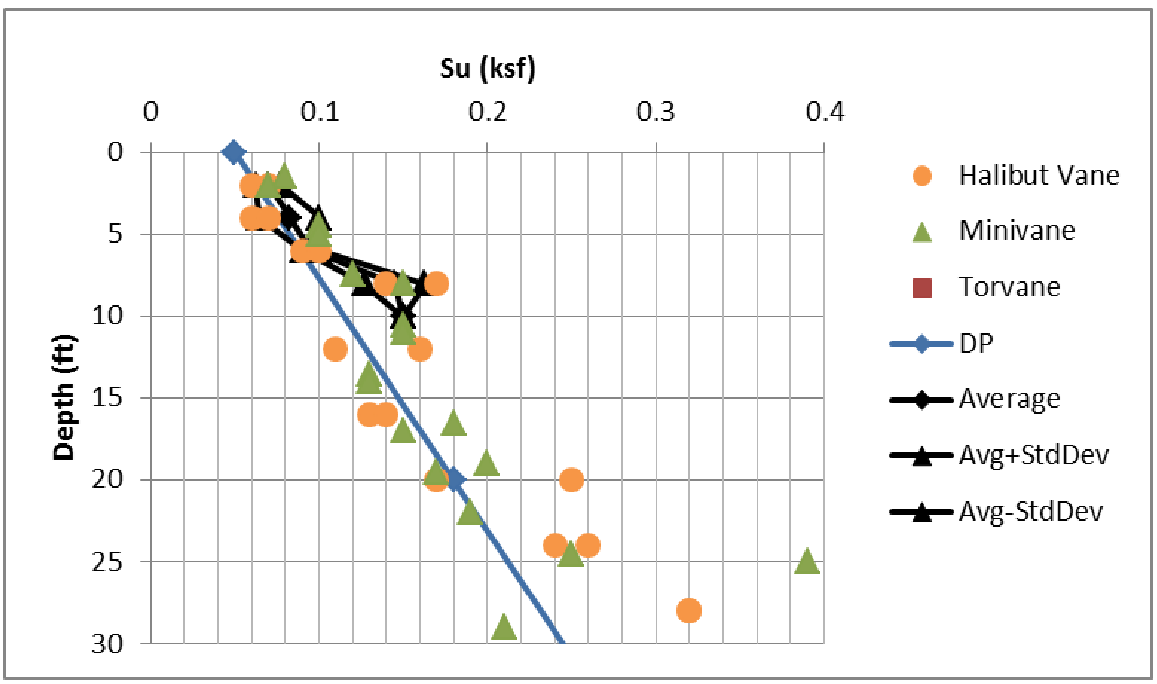


Figure 4.17: Raw Data and Design Profile from a High Resolution Borehole in Region L

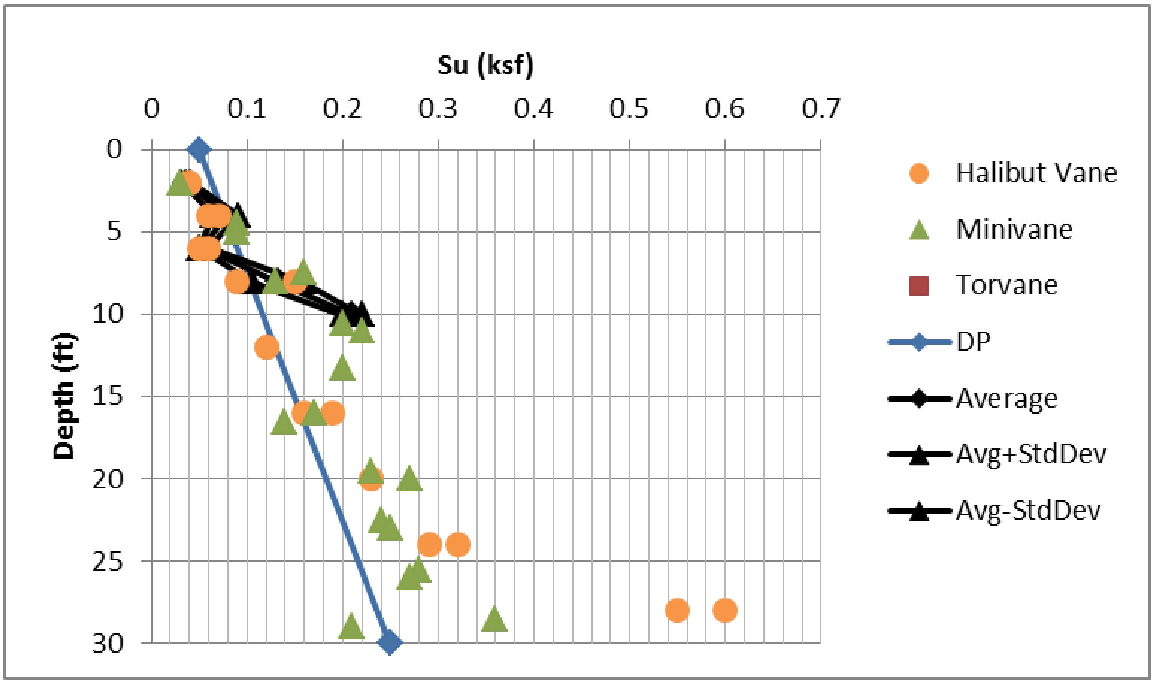


Figure 4.18: Raw Data and Design Profile from a High Resolution Borehole in Region M

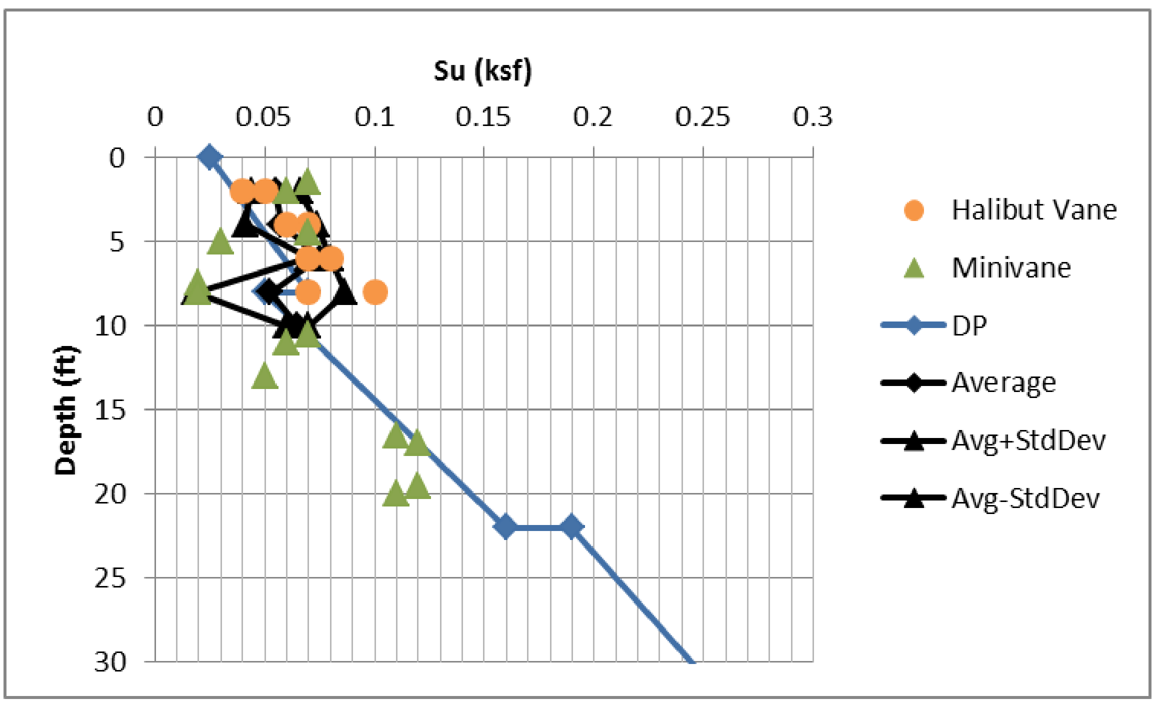


Figure 4.19: Raw Data and Design Profile from a High Resolution Borehole in Region N

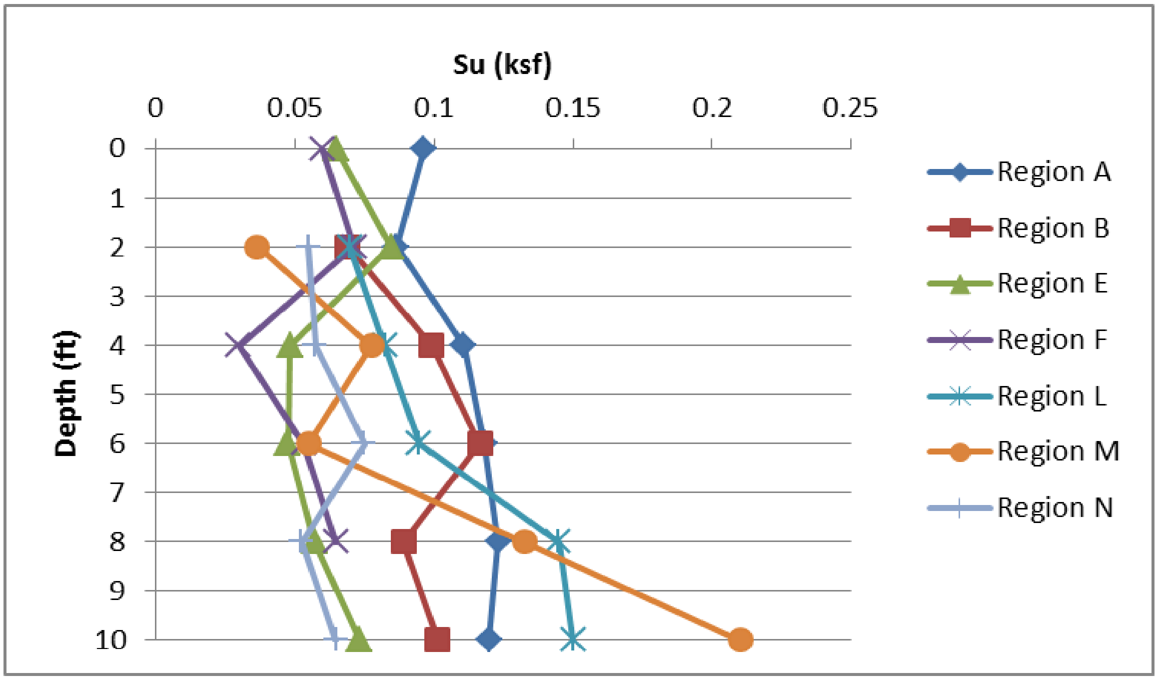


Figure 4.20: Average Design Profiles of High Resolution Studies from Each Region

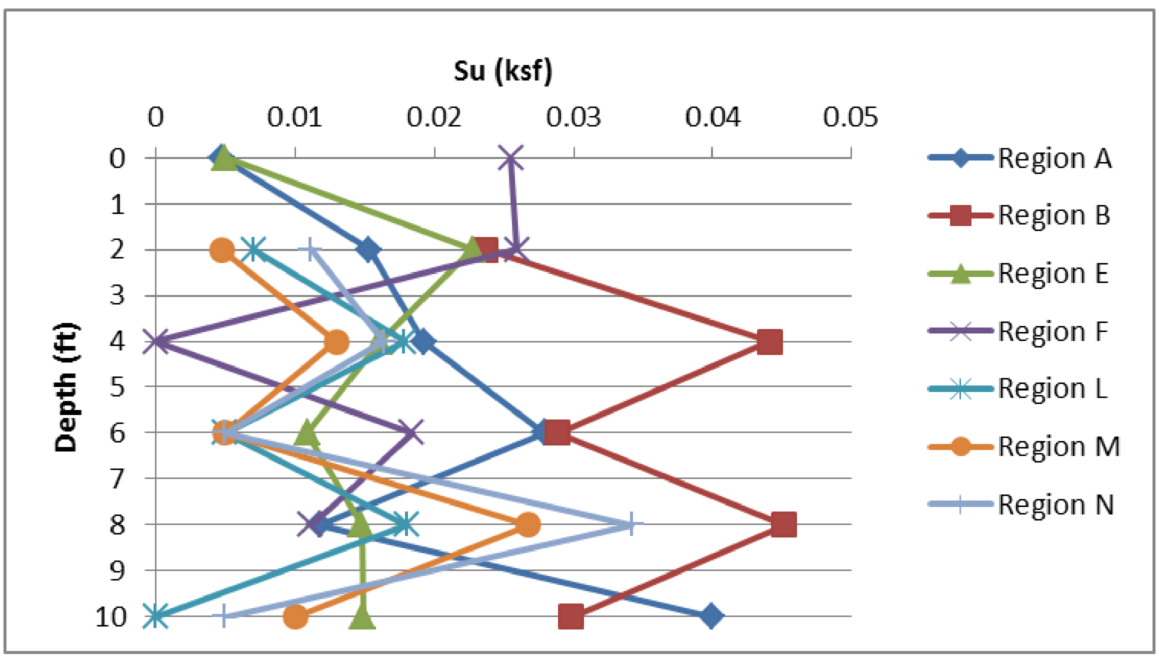


Figure 4.21: Standard Deviation of Design Profiles of High Resolution Studies from Each Region

4.3 Low Resolution Studies

Low resolution studies include everything that does not meet the standards of a high resolution study (i.e. less than 10 points of data in the shallow region and/or fewer than 2 tests used to acquire the data). They have so little data in the shallow region that it becomes difficult to characterize the behavior of the soil strength in the shallow region. Of the total exploratory locations, 48 are low resolution studies.

The low resolution studies are also subdivided into two more categories, adequate resolution studies and poor resolution studies. Qualitatively, the difference between these two is that adequate resolution studies have just enough data to give a general idea of the behavior of the soil in the shallow region without being detailed enough to really predict the behavior fully where as poor resolution studies contain so little data as to be functionally inadequate. Quantitatively this translates to a boundary of 5 points, more than 5 points in the shallow region and it is of adequate resolution but less than 5 points in the shallow region and it is of poor resolution.

Examples of both an adequate resolution study and a poor resolution study are provided in Figures 4.22 and 4.23 respectively.

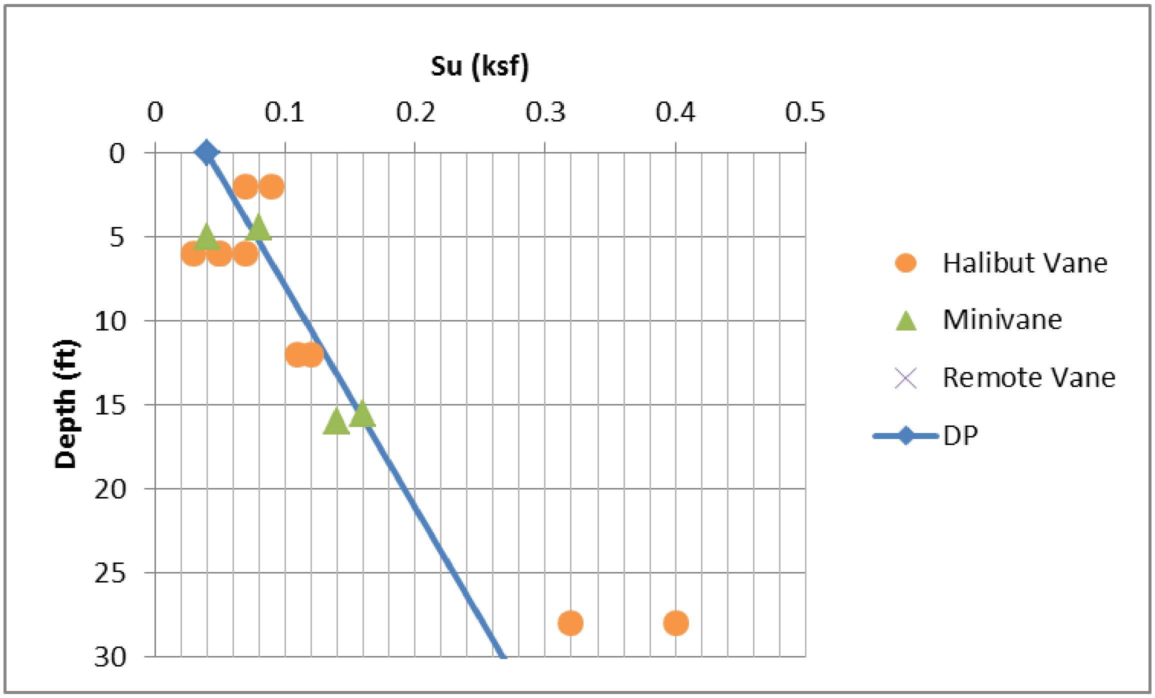


Figure 4.22: Example of an Adequate Low Resolution Study from a Borehole in Region J

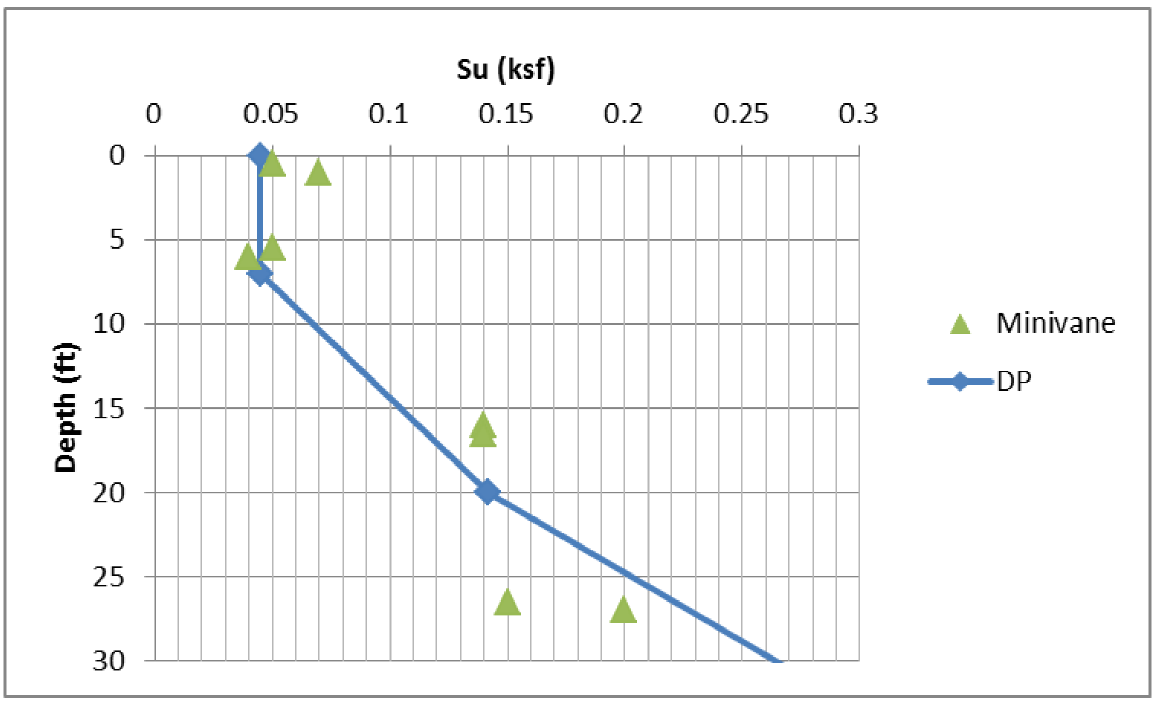


Figure 4.23: Example of a Poor Low Resolution Study from a Borehole in Region F

4.4 Comparison of In-Situ Data to Non In-Situ Data

The differences between in-situ and non in-situ data have been discussed previously, but to reiterate, in-situ data offers a more accurate picture of the soil strength because it is gathered from undisturbed soil samples. Non in-situ data is less accurate because it is performed on soil that has been removed from the ground and disturbed from its natural state. The tests this section will focus on are Halibut Vane tests (in-situ) and Minivane and Torvane tests (non in-situ) because they are the most common types of tests run in the shallow region.

When comparing the two types of tests there are three possible outcomes: 1. the two test types will offer similar results, 2. the two test types will offer differing results, or 3. there will not be enough data from a particular test to be able to say. Of the high resolution studies, 6 of the studies show the two test types in agreement, 10 show the two in disagreement, and 2 do not contain enough data from one type of test to be able to say. Examples of the three outcomes are shown in Figures 4.24, 4.25, and 4.26 respectively.

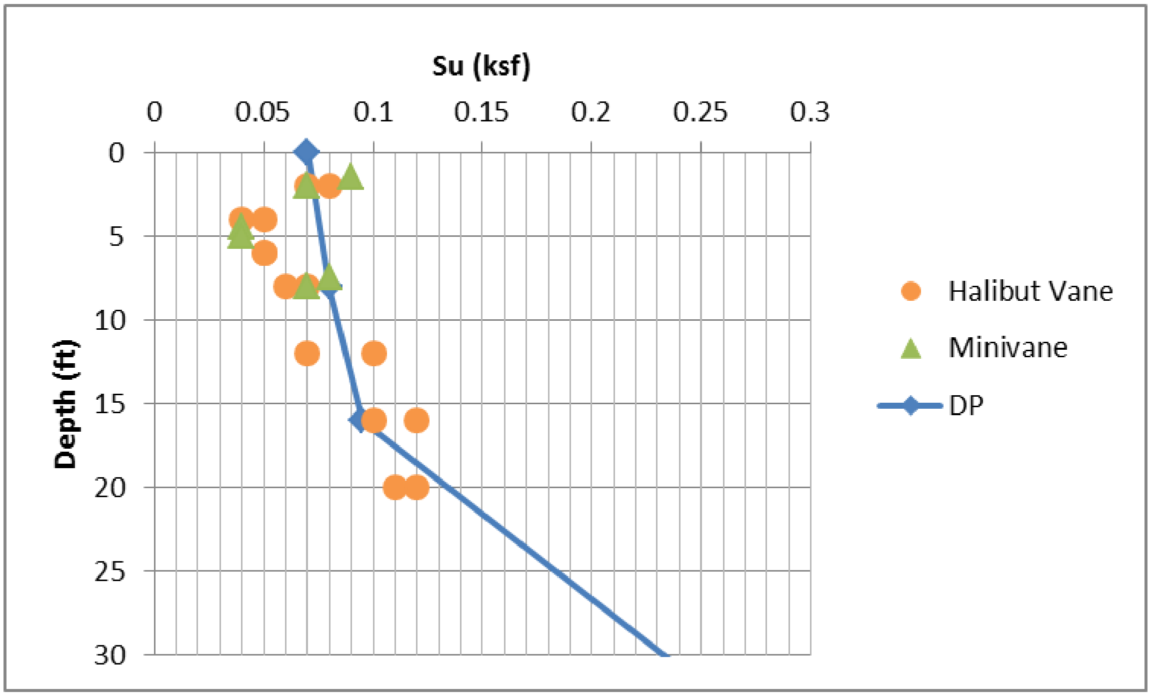


Figure 4.24: Example of Case where the Test Types Agreed at a Borehole in Region E

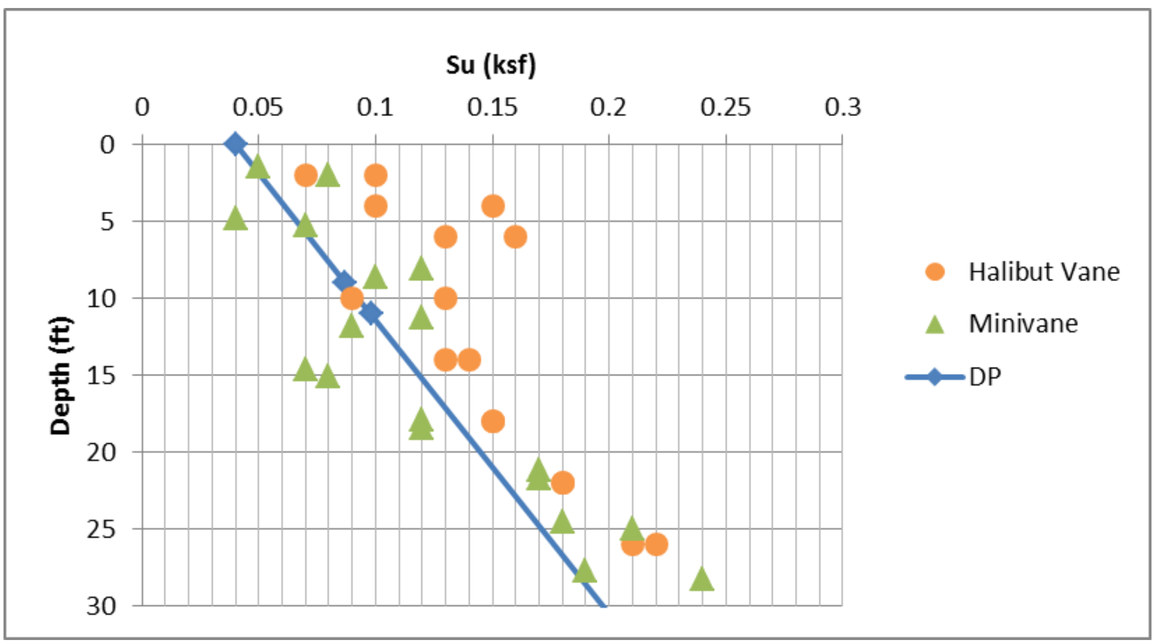


Figure 4.25: Example of Case where the Test Types Disagree at a Borehole in Region B

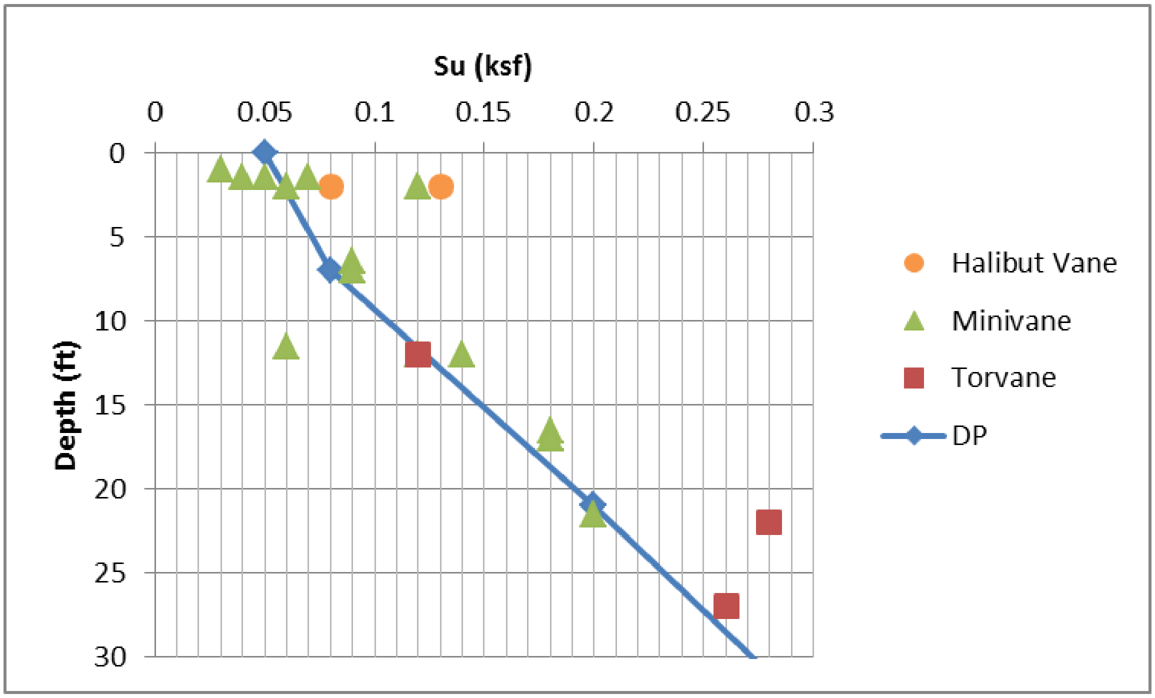


Figure 4.26: Example of a Case where there is Too Little Data To Tell if the Test Types Agree at a Borehole in Region F

The conclusion that can be drawn from this is that more often than not the two test types disagree on the behavior of the soil in the shallow region. Typically this difference is that the in-situ data is higher in strength than the non in-situ data, which would suggest that somewhere between the soil being in the ground and the soil being above the ground the strength of the soil is altered. This is not hard to believe as the soil in the shallow region is relatively soft clay, which makes it very difficult to remove soil samples from the ground in an undisturbed state.

Engineers tend to base design profiles on non in-situ test data in the shallow region, as is shown in Figure 4.27. This is likely because the non in-situ test data is less variable, which makes it easier to locate patterns in the change in strength with depth. In-situ test data tends to be more variable, which is exemplified in Figure 4.28. Of course the other factor in this neglect of data is that until recently the behavior of the soil in the shallow region has been a non-issue.

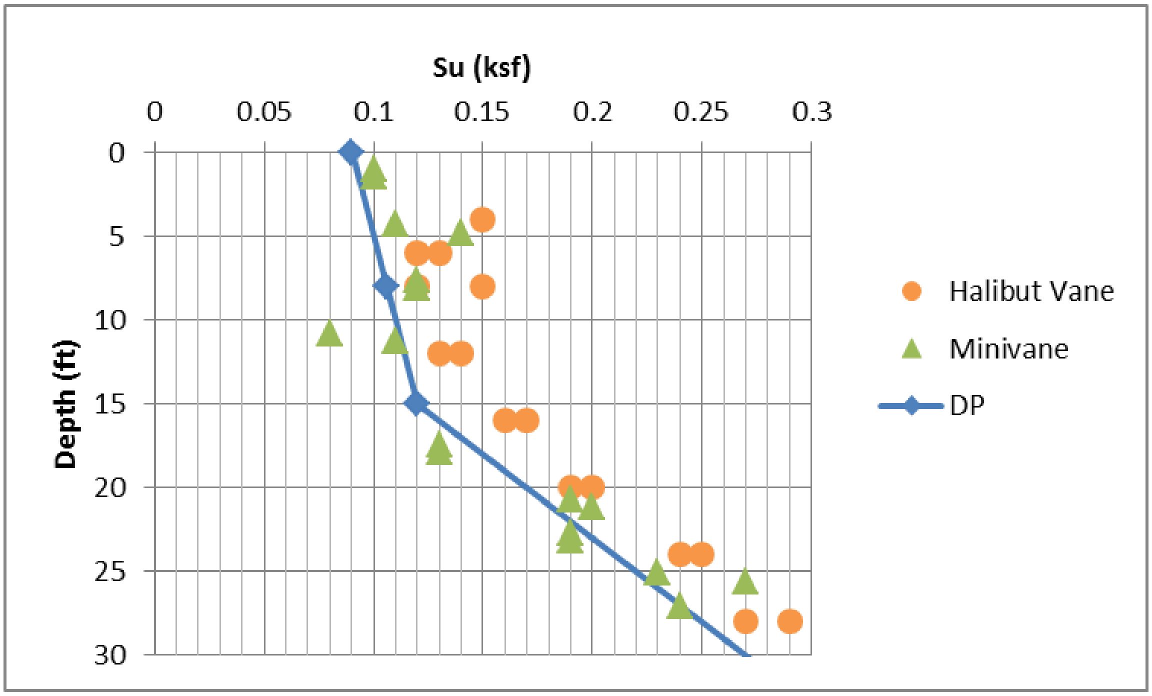


Figure 4.27: Example of Design Profile Focusing on Non In-Situ Testing from a Borehole in Region A

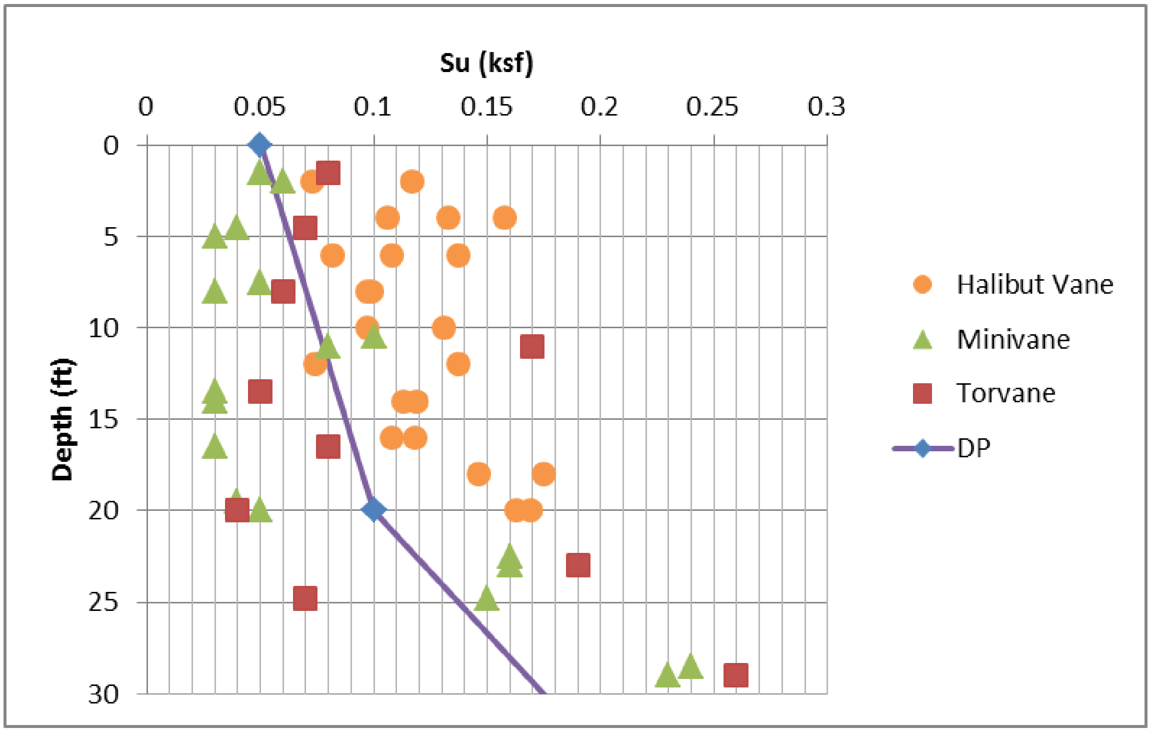


Figure 4.28: Example of the Large Amount of Scatter in In-Situ Test Data from a Borehole in Region B

4.5 Comparison of CPT Data to Point Test Data

A third category of study type is the CPT. It Is unique from both high and low resolution studies because it offers a continuous profile of the soil strength. The CPTs are the highest resolution studies available and thus offer, in most cases, the most detailed understanding of the behavior of the soil in the shallow region.

The reason that all CPT data is not useful for shallow soil analysis is twofold. For one, not all CPTs contain data in the shallow region. Several of the CPTs from the existing database do not contain any data in the shallow region, either because the testing did not start until the cone passed this region or because the engineers who recorded the test data felt that the data from recorded in the shallow region was not an accurate representation of the soil's behavior. The other reason CPT data might not be useful is because it does not make sense. Sometimes the recorded strengths from a CPT had to be recorded in error because it is the only explanation for the resulting CPT Profile, which may include ridiculous strengths at the mudline or even negative strength values. In either case, these CPT results are useless for the purpose of shallow soil analysis, and so any CPT exhibiting these properties should be eliminated from any future shallow soil strength database. Unfortunately, nearly half of the CPTs (20 of a total of 44 CPT profiles) in the existing database fall into this category.

The remainder of the CPTs (25) shows very high resolution descriptions of the soil behavior at that CPT's respective location. These remaining locations are spread over three regions, K, N, and Q and are shown in Figure 4.29. Each CPT has an N_{kt} value, which is the factor by which the original resistance data from the CPT must be divided in order to convert it to undrained shear strength data. The N_{kt} used in to convert from the cone resistance recordings to the shear strength of the soil varies from location to location based on the report the data was pulled from and has a range between 16 and 19 with an average of 17.4. The N_{kt} is determined by comparing the CPT resistance data to results from point shear strength data and applying the factor until the two types of data match. Often times engineers will focus on matching the CPT to deeper data points, neglecting the shallow soil strengths.

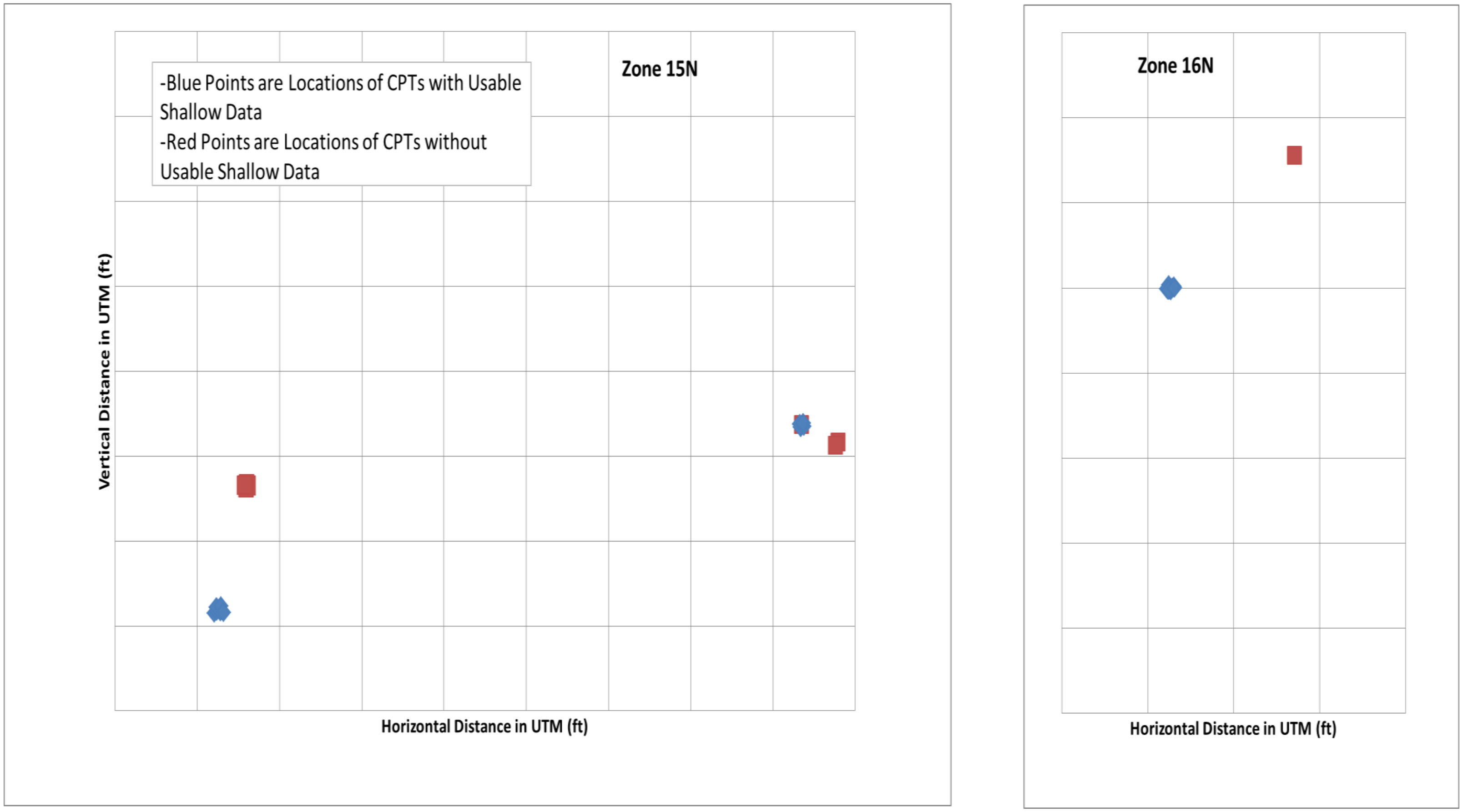


Figure 4.29: Relative Locations of CPTs with Usable Shallow Data and without Usable Shallow Data

In order to understand the nature of the CPT profiles, they will be compared to the all of the point data from the same region. The goal is to locate any major patterns that exist or correlations that can be identified between the CPT profiles and the point data. In discussing these profiles and to better clarify their relationship to the point data, references will be made to the upper and lower bound of the point data; these bounds are merely the visual boundary created by the outermost point data.

In Region K, there is wide scatter in the CPT profiles (Figure 4.30), with the sixth CPT exhibiting the largest amount of noise in the profile, but all of the profiles have similar shapes with differing strength values. The first CPT (Figure 4.31) follows the point data in the upper 5 ft of soil, but it deviates with a spike at a depth of 10 ft and deviates considerably from the point data at greater depths. It has an N_{kt} value of 17. The second CPT (Figure 4.32) sits toward the upper boundary of the data consistently throughout its depth. It has an N_{kt} value of 17. The third CPT (Figure 4.33) is consistently lower than the point data until a depth of 20 ft, where it converges with the point data. It has an N_{kt} value of 17. The fourth CPT (Figure 4.34) follows the point data the most closely of all the CPTs from this region; it sits near the average of the scatter, but it doesn't mimic the shape of the point data in the shallow region. It has an N_{kt} value of 17. The fifth CPT (Figure 4.35) sits at the upper bound of the point data but doesn't go much farther beyond it; it appears to follow the Halibut Vane data, but there isn't much Halibut Vane data in the shallow region. It has an N_{kt} value of 17. The sixth CPT (Figure 4.36) sits in the middle of the point data but closer to the upper bound. It has an N_{kt} value of 17. The seventh (Figure 4.37) has the largest amount of noise of all the CPT profiles in this region, and it sits above the upper bound of the data until a depth of 20 ft, where it drastically increases compared to the point data. It has an N_{kt} value of 17.

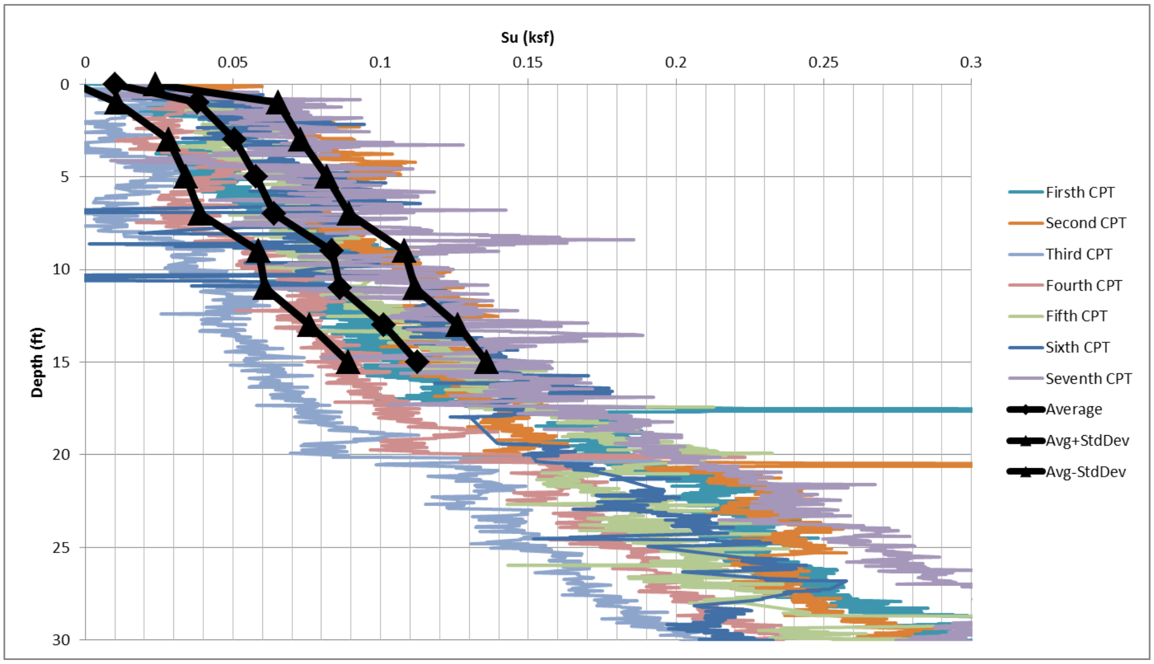


Figure 4.30: All CPT Profiles from Region K

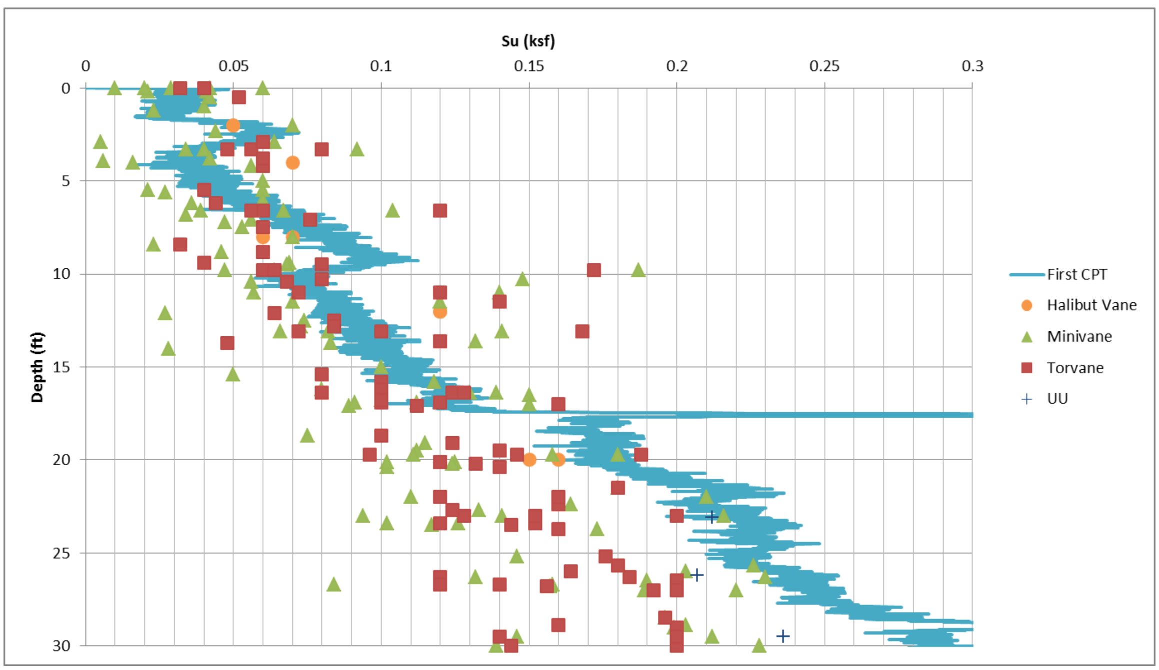


Figure 4.31: Profile of First CPT and Point Data from Region K

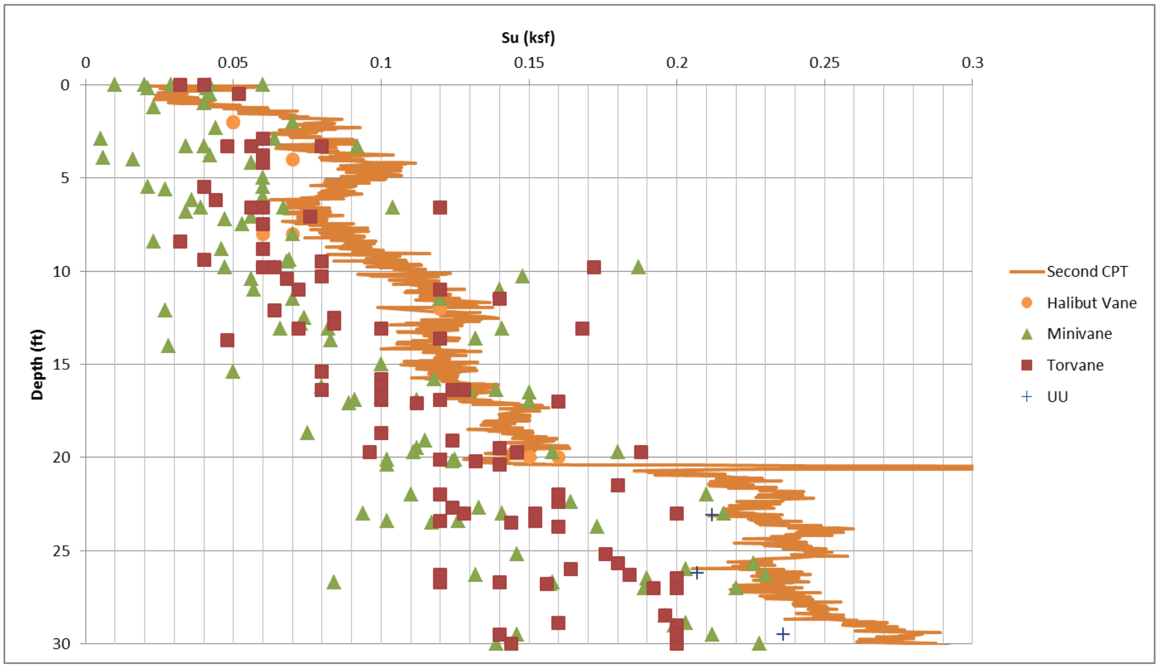


Figure 4.32: Profile of Second CPT and Point Data from Region K

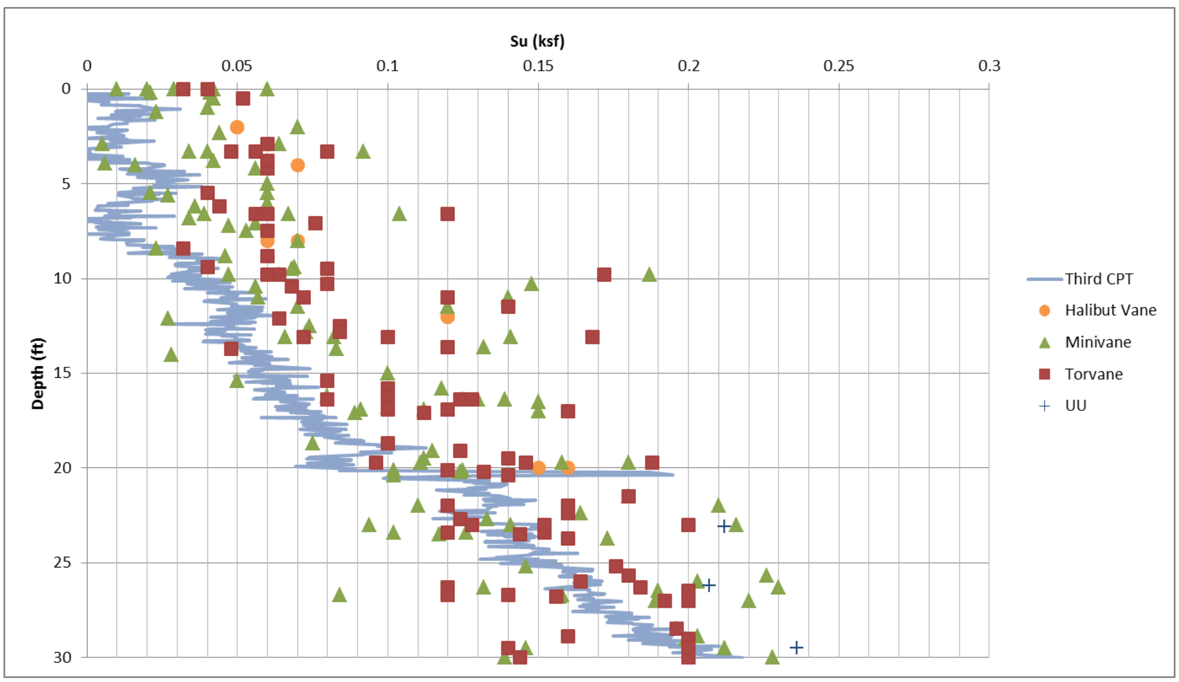


Figure 4.33: Profile of Third CPT and Point Data from Region K

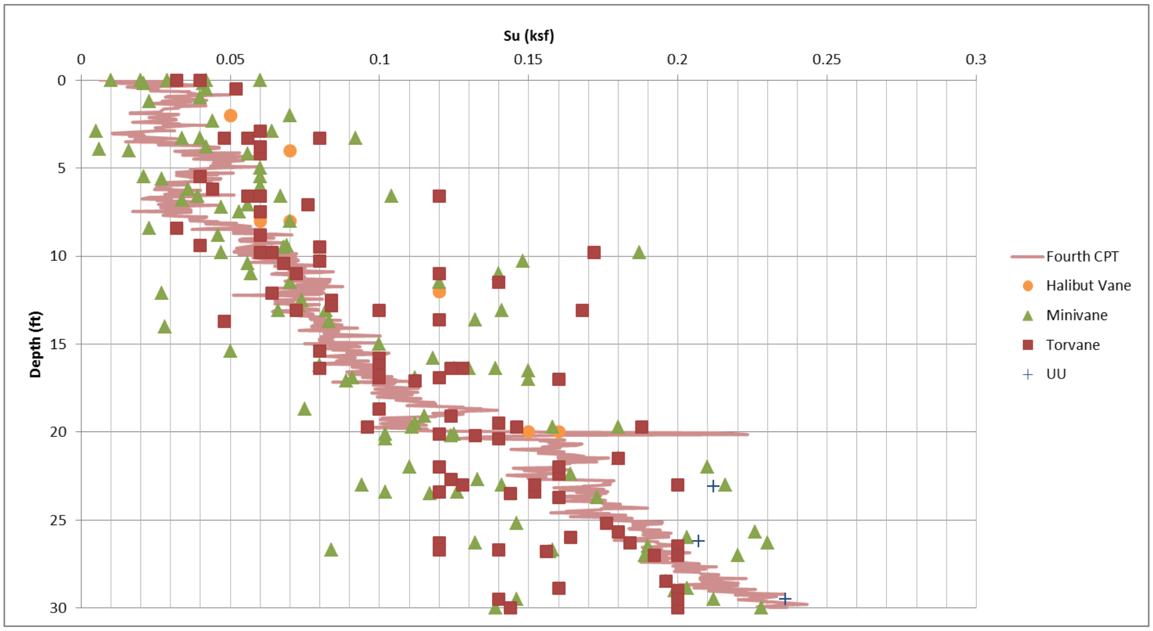


Figure 4.34: Profile of Fourth CPT and Point Data from Region K

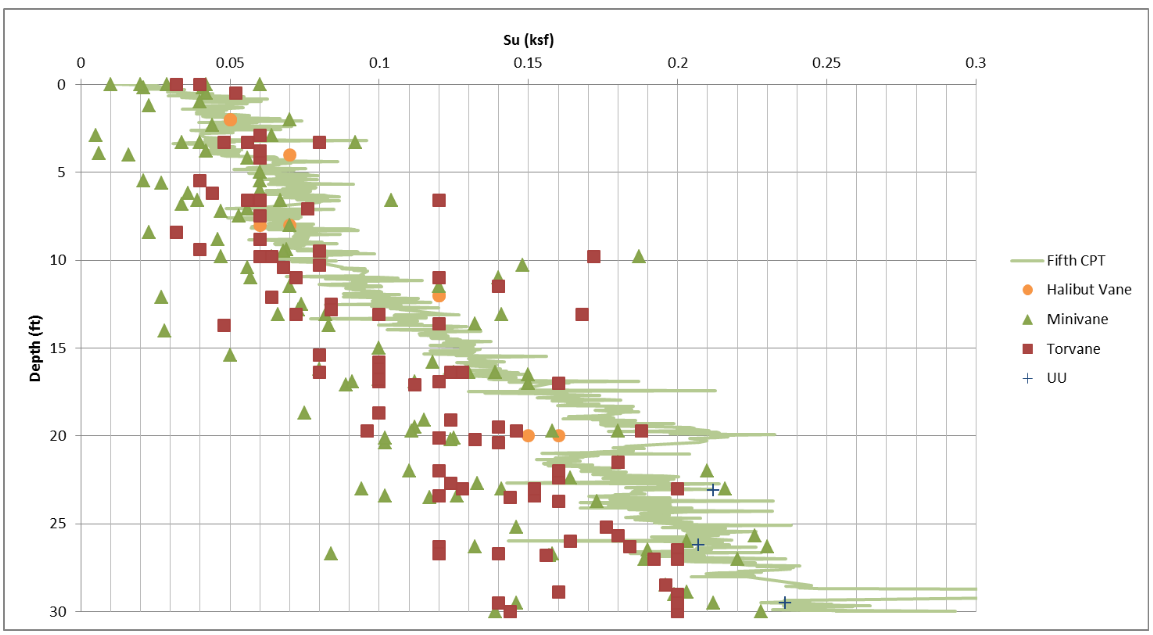


Figure 4.35: Profile of Fifth CPT and Point Data from Region K

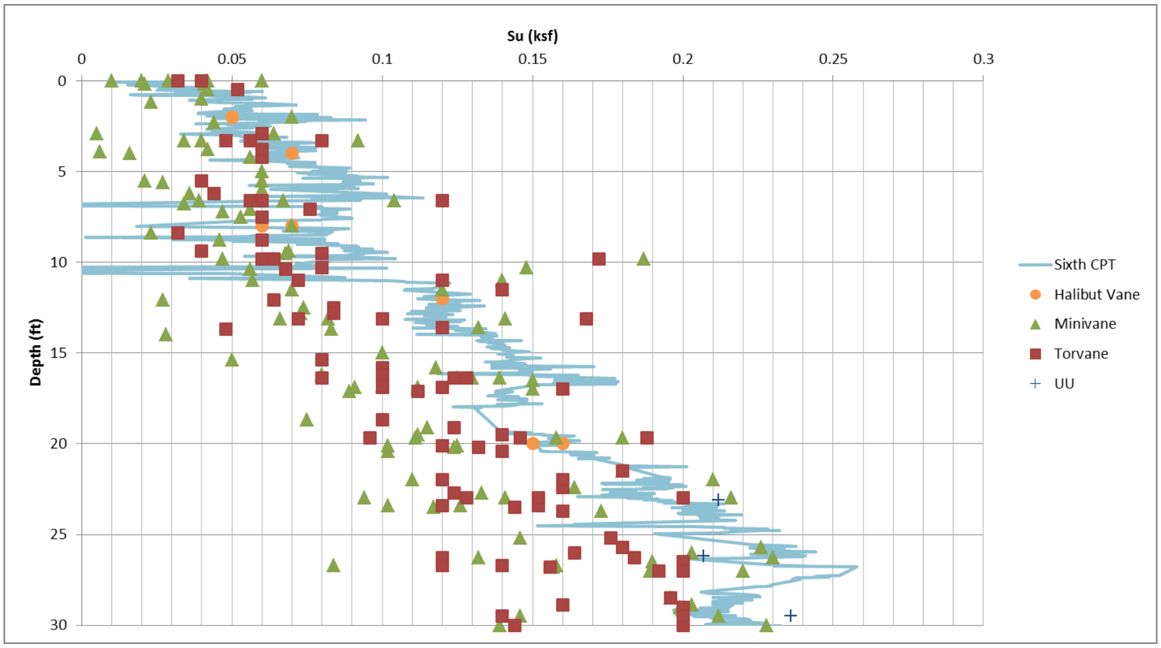


Figure 4.36: Profile of Sixth CPT and Point Data from Region K

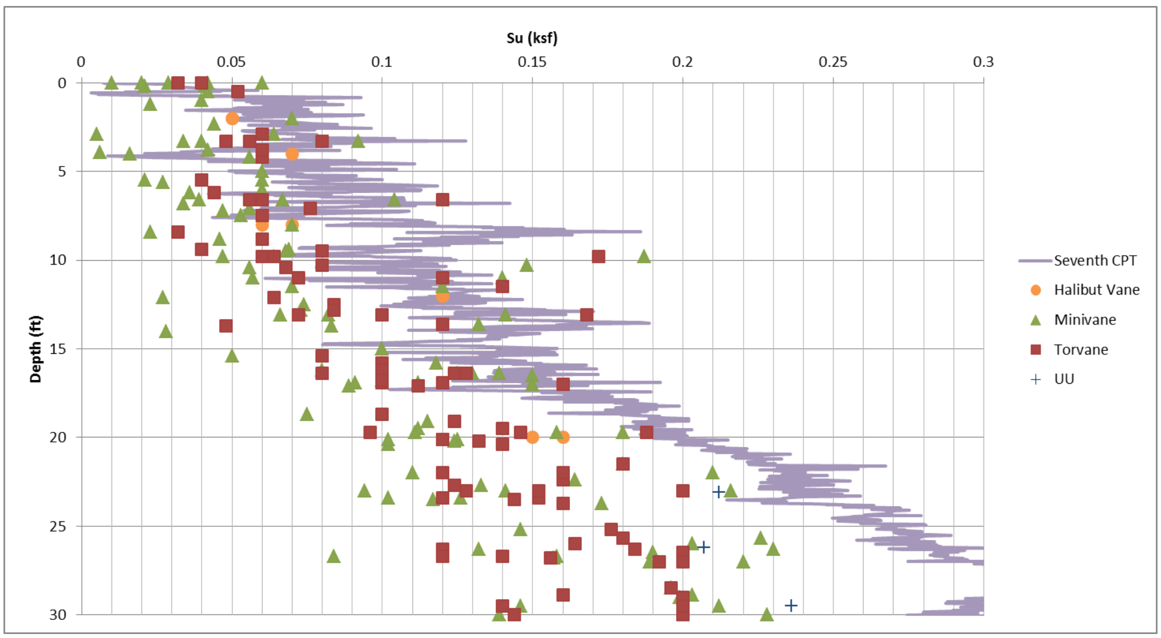


Figure 4.37: Profile of Seventh CPT and Point Data from Region K

In Region N there is also wide scatter in the different CPT profiles (Figure 4.38), although all the profiles share a similar shape including a similar fluctuation at a depth of about 5 ft that occurs in all the profiles. The first CPT (Figure 4.39) includes a drop into the negative strength zone near the mudline and remains at the lower bound of the point data in the shallow region; it appears to follow the Minivane data more closely than the Halibut Vane data. It has an N_{kt} value of 19. The second CPT (Figure 4.40) has a large amount of noise in its profile, which follows the upper bound of the point data in the shallow region and lies closer to the Halibut Vane data. It has an N_{kt} value of 19. The third CPT (Figure 4.41) sits in between the upper and lower bounds of the point data in the shallow region; it lies below the Halibut Vane data but is still in the middle of the rest of the data. It has an N_{kt} value of 19. The fourth CPT (Figure 4.42) sits on the upper bound of the point data and appears to follow the Halibut Vane data. It has an N_{kt} value of 19. The fifth CPT (Figure 4.43) lies within the bounds of the point data but sits more closely to the lower bound. It has an N_{kt} value of 19. The sixth CPT (Figure 4.44) contains a considerable amount of noise in its profile; It is closer to the upper bound and appears to follow the Halibut Vane data. It has an N_{kt} value of 19. The seventh CPT (Figure 4.45) sits right in the middle of the point data. It has an N_{kt} value of 19. The eighth CPT (Figure 4.46) sits near the lower bound. It has an N_{kt} value of 19.

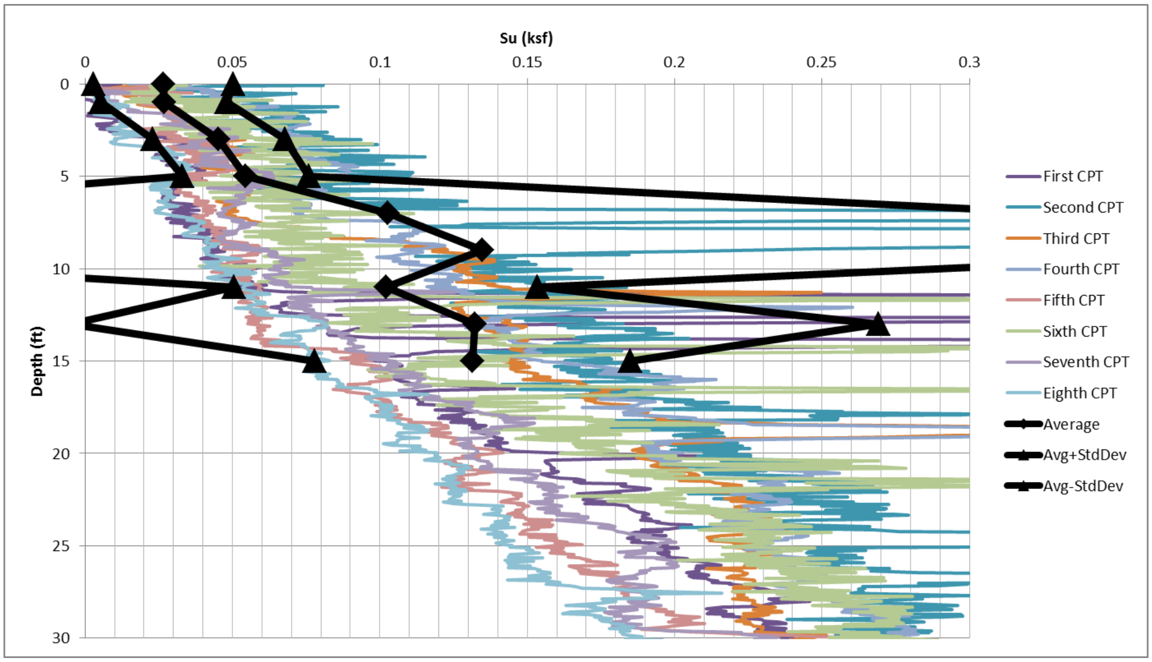


Figure 4.38: All CPT Profiles from Region N

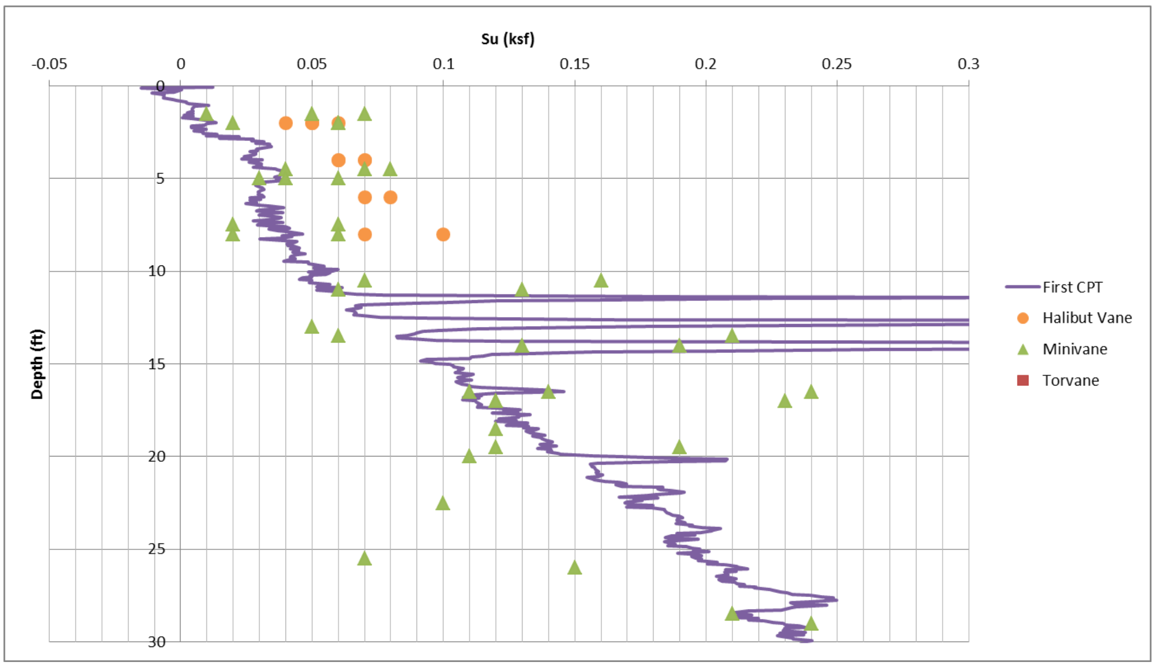


Figure 4.39: Profile of First CPT and Point Data from Region N

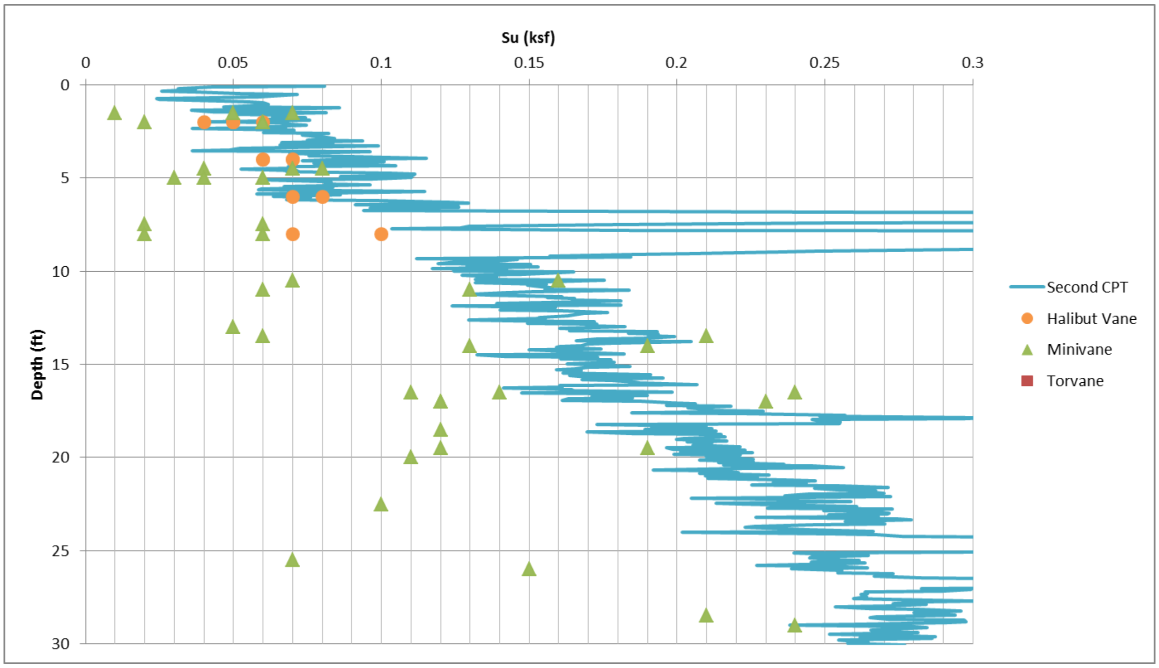


Figure 4.40: Profile of Second CPT and Point Data from Region N

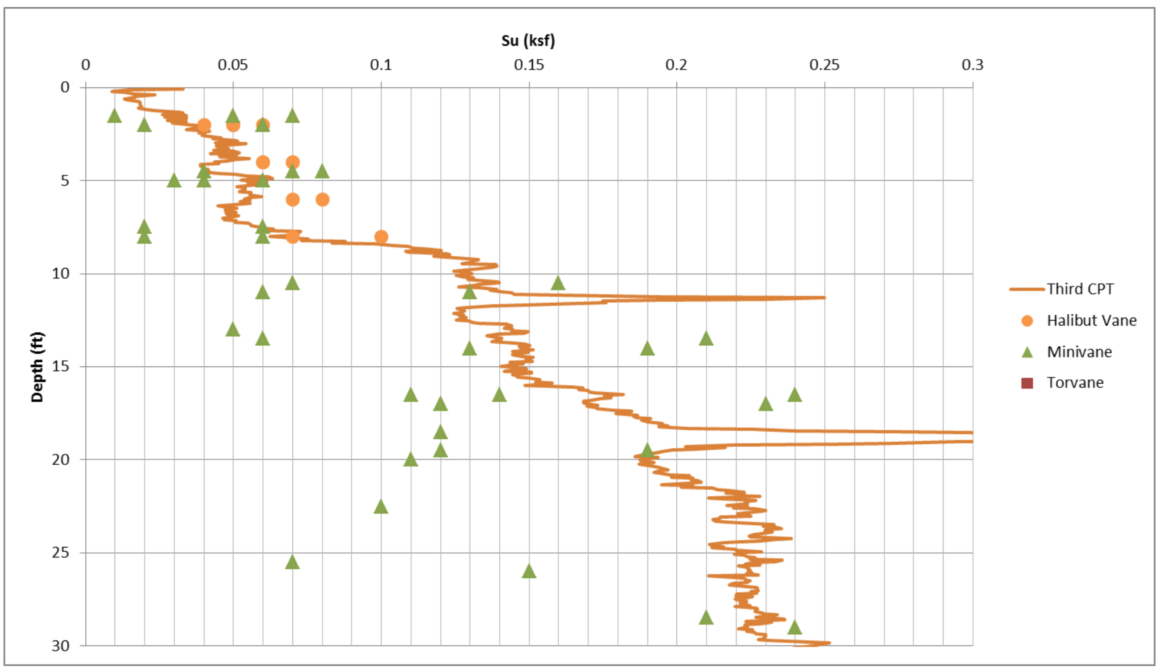


Figure 4.41: Profile of Third CPT and Point Data from Region N

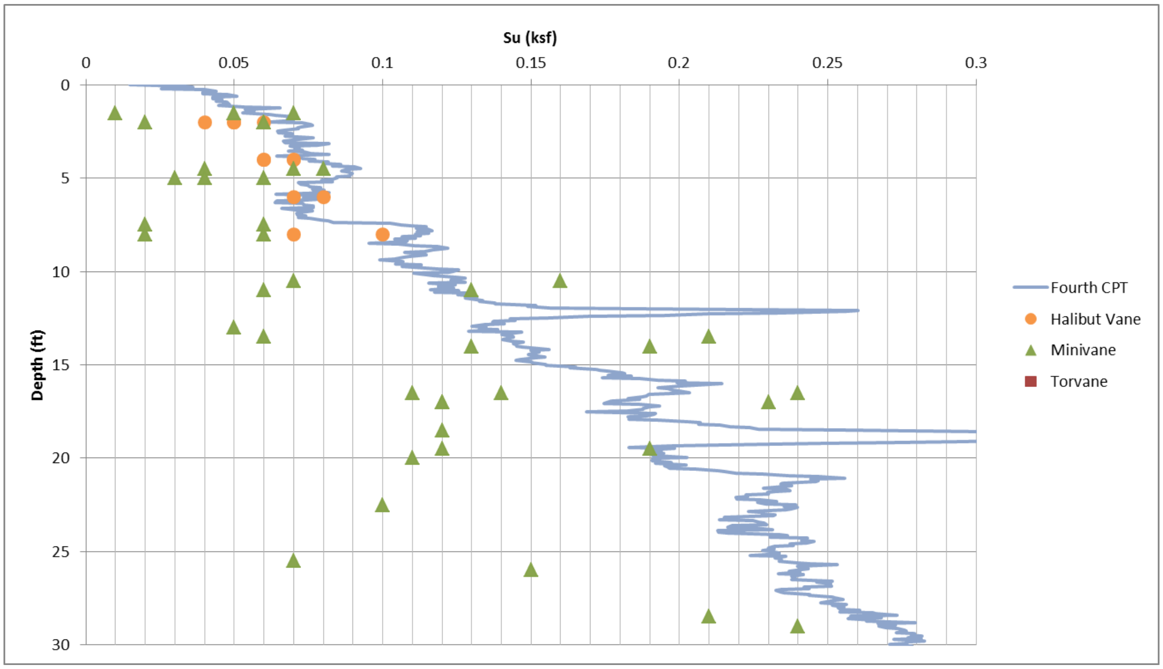


Figure 4.42: Profile of Fourth CPT and Point Data from Region N

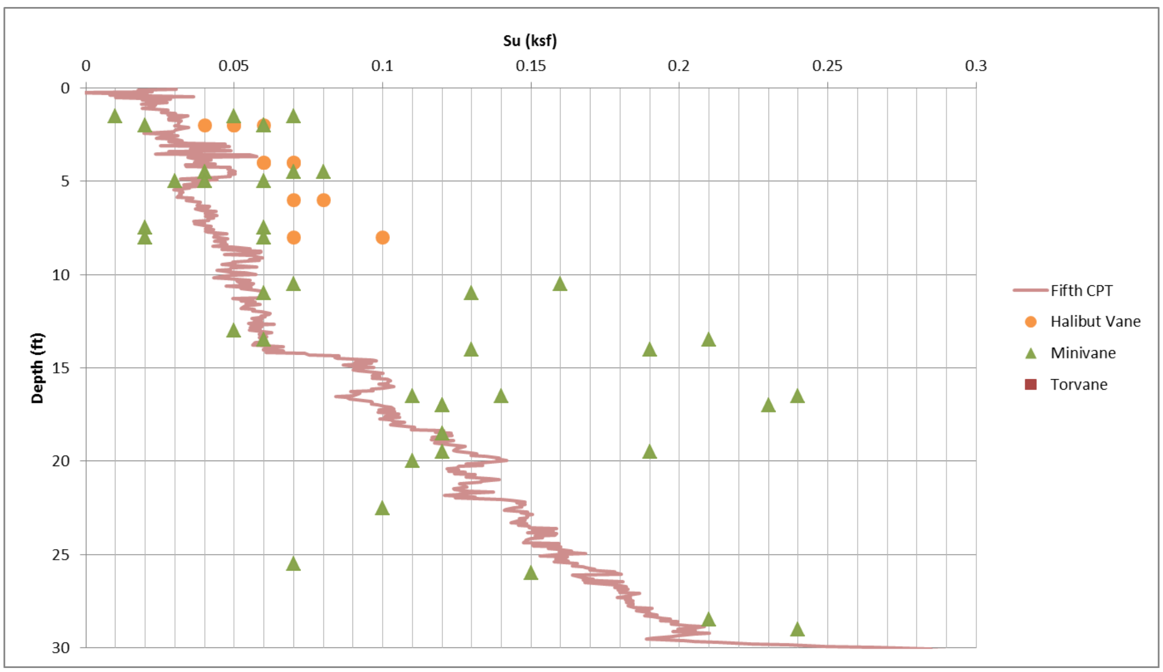


Figure 4.43: Profile of Fifth CPT and Point Data from Region N

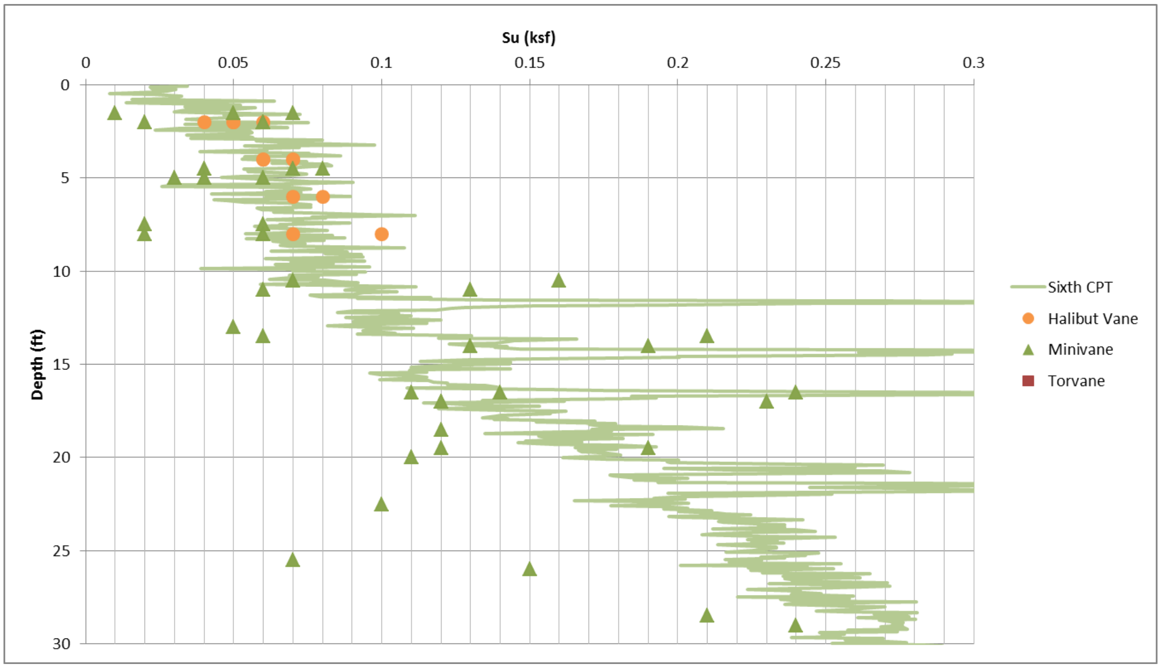


Figure 4.44: Profile of Sixth CPT and Point Data from Region N

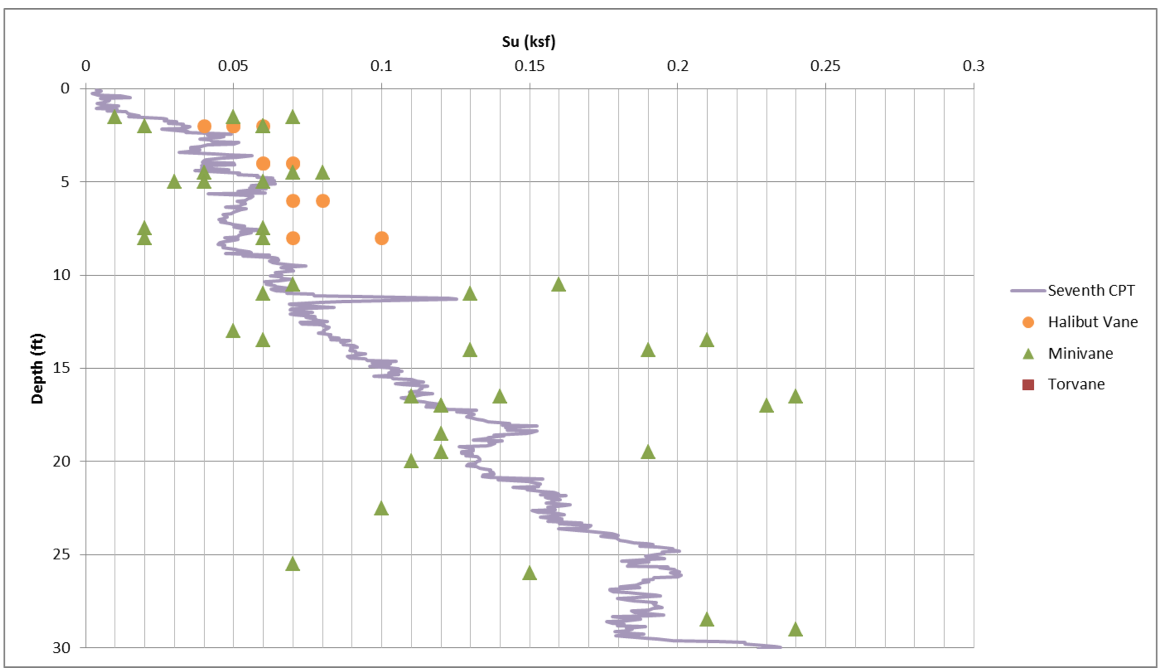


Figure 4.45: Profile of Seventh CPT and Point Data from Region N

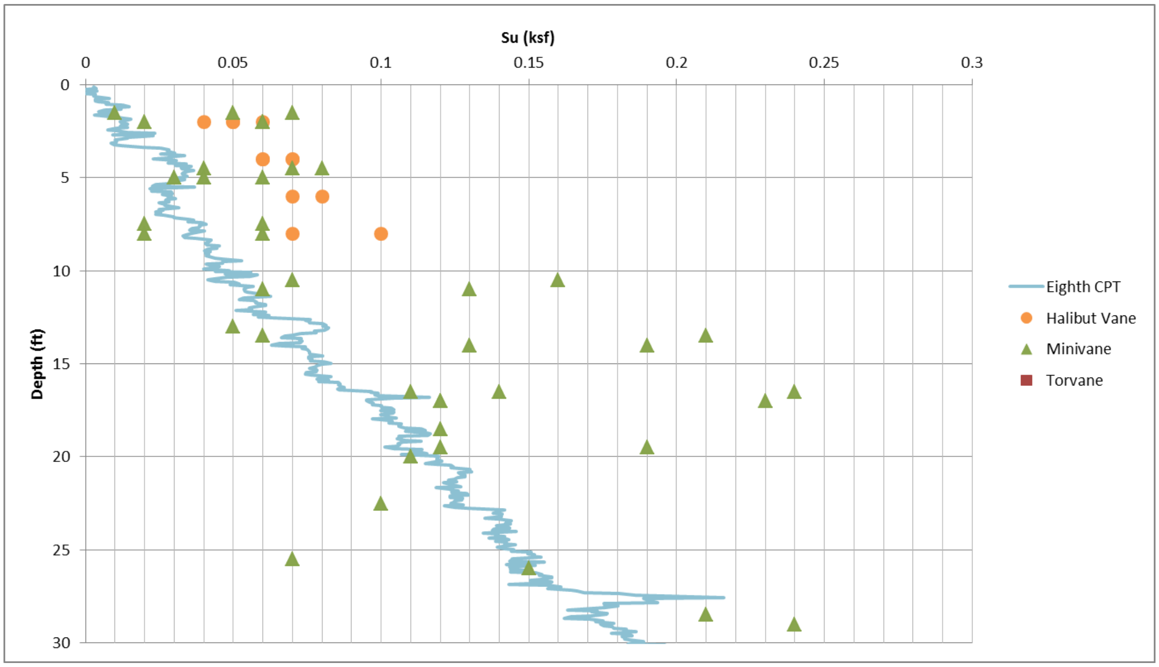


Figure 4.46: Profile of Eighth CPT and Point Data from Region N

Region Q is very curious in that there is an incredibly small amount of scatter among the CPT profiles (Figure 4.47); they are very tightly grouped together. As a result, and also due to their very similar shapes, the CPT profiles give a very clear and consistent picture of the behavior of the soil in the shallow region and beyond. This behavior includes a well defined bump in strength that would indicate a crust at a depth of about 4 ft. Because all of the CPT profiles are so similar in shape and magnitude they all have very similar relationships to the point data (Figure 4.48 through 4.59). They all tend toward the lower bound of the point data in the shallow region but converge with the point data at a depth of between 15 and 20 ft. They also all follow the shape of the point data in the upper 5 ft, which also indicates the presence of a crust. And they all have an N_{kt} of 18.

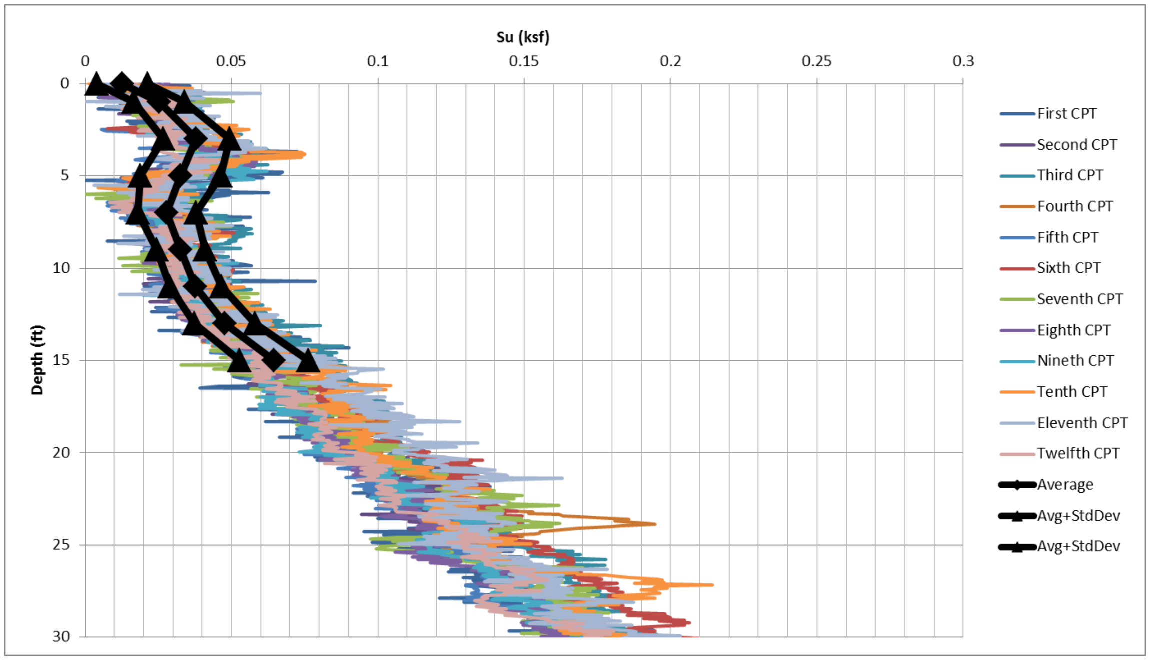


Figure 4.47: All CPTs Profiles from Region Q

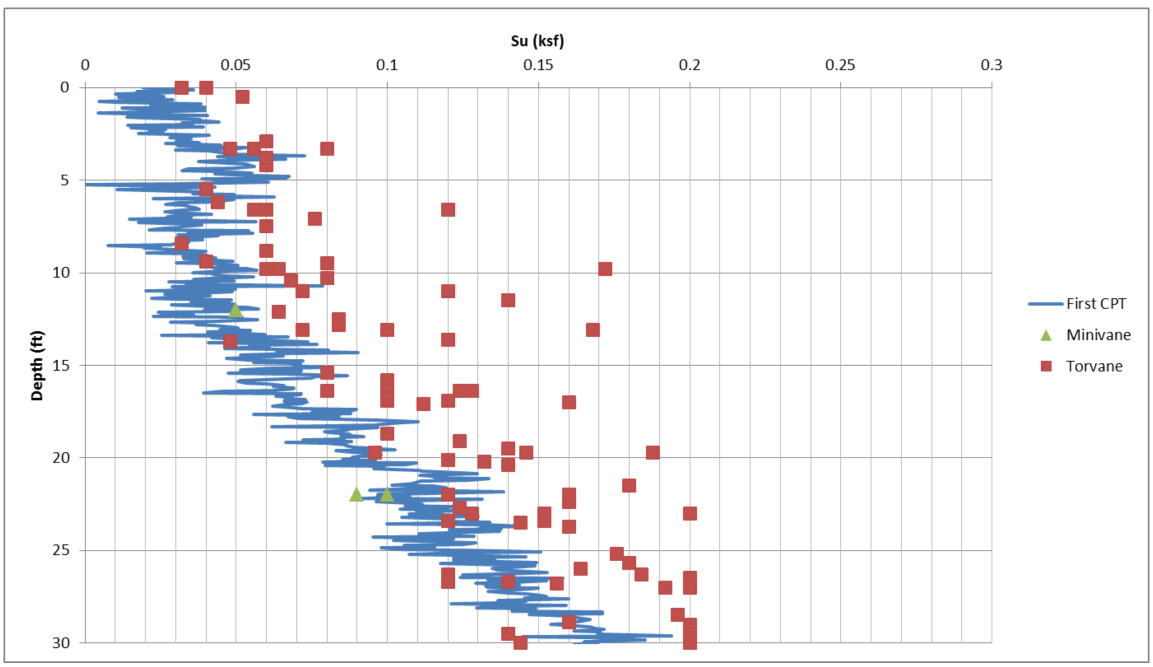


Figure 4.48: Profile of First CPT and Point Data from Region Q

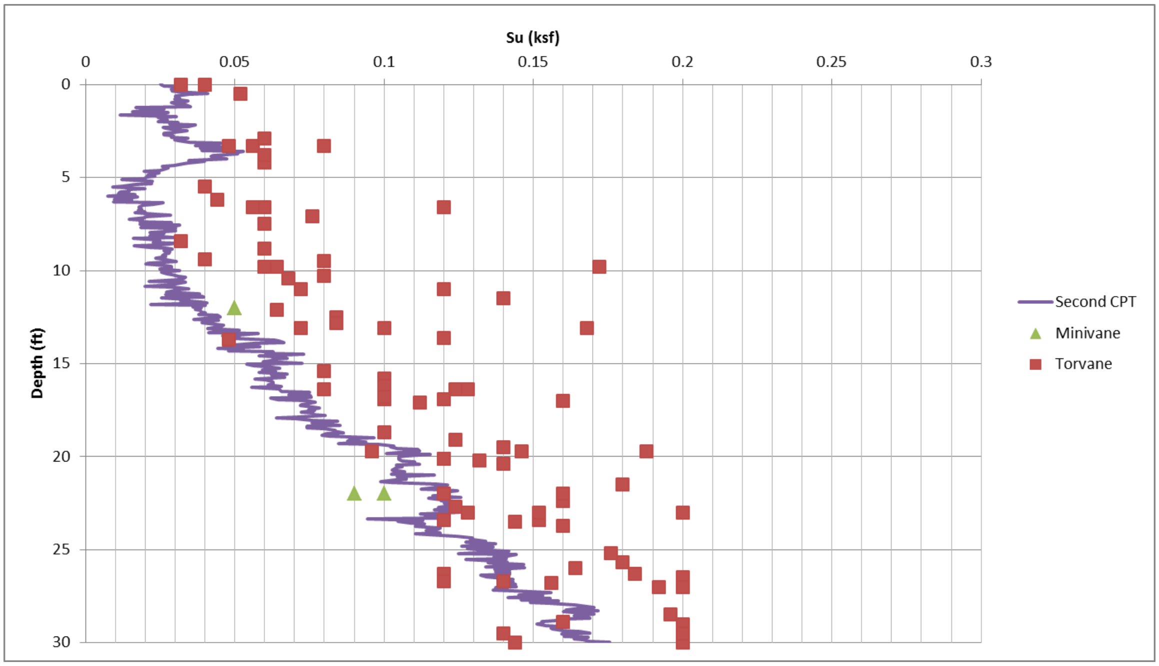


Figure 4.49: Profile of Second CPT and Point Data from Region Q

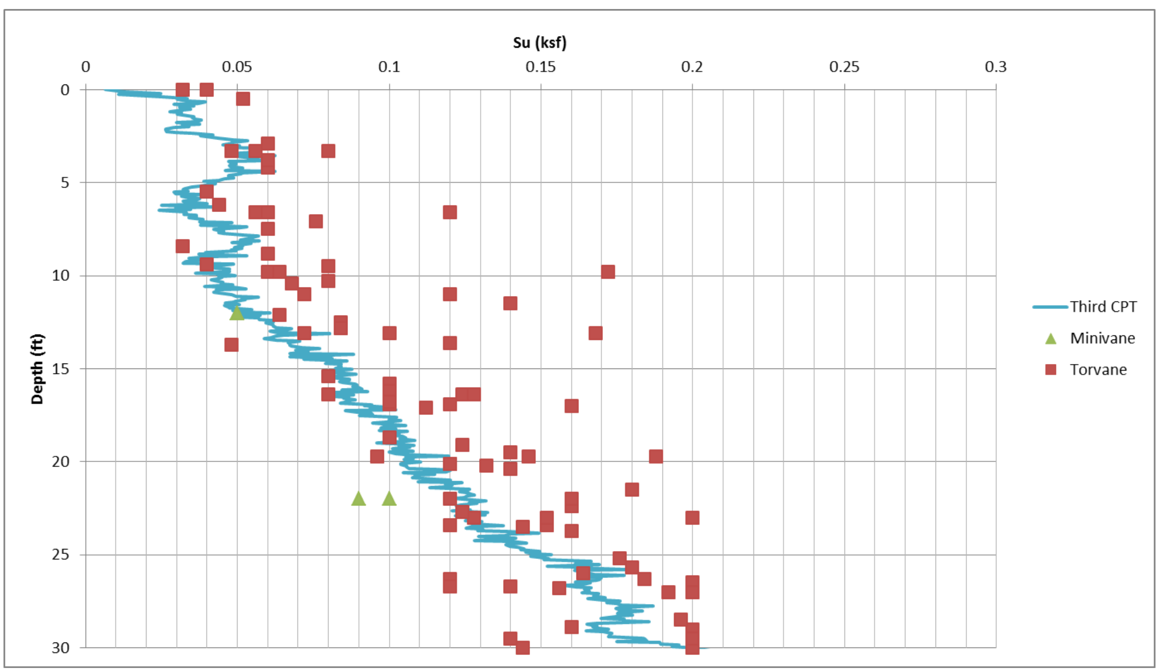


Figure 4.50: Profile of Third CPT and Point Data from Region Q

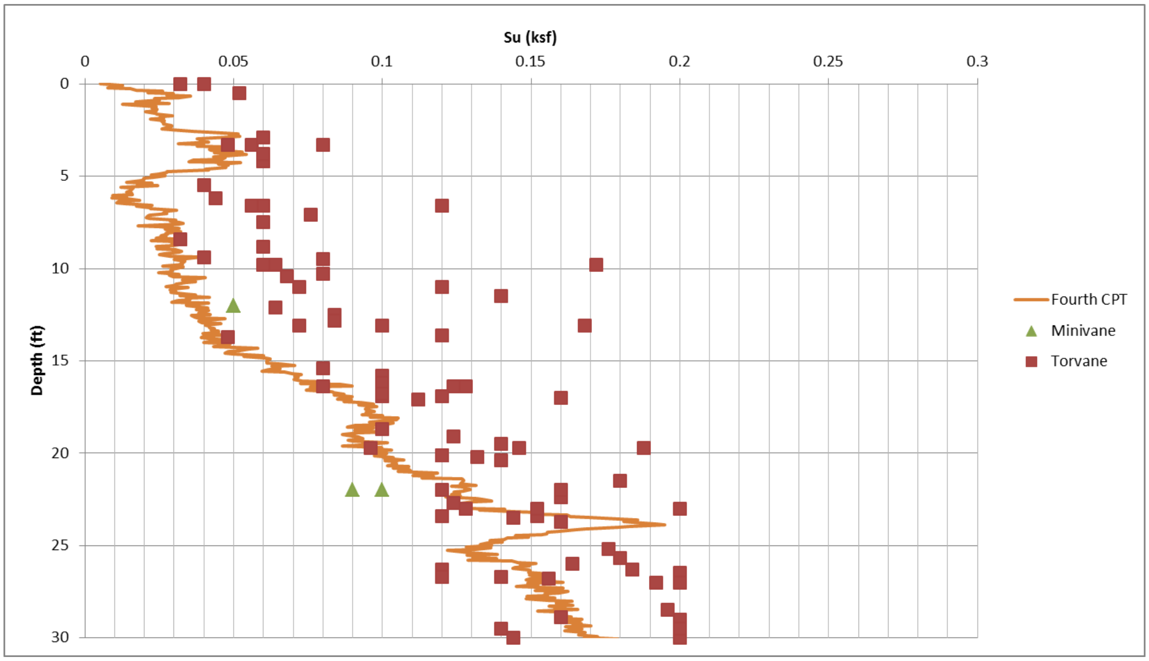


Figure 4.51: Profile of Fourth CPT and Point Data from Region Q

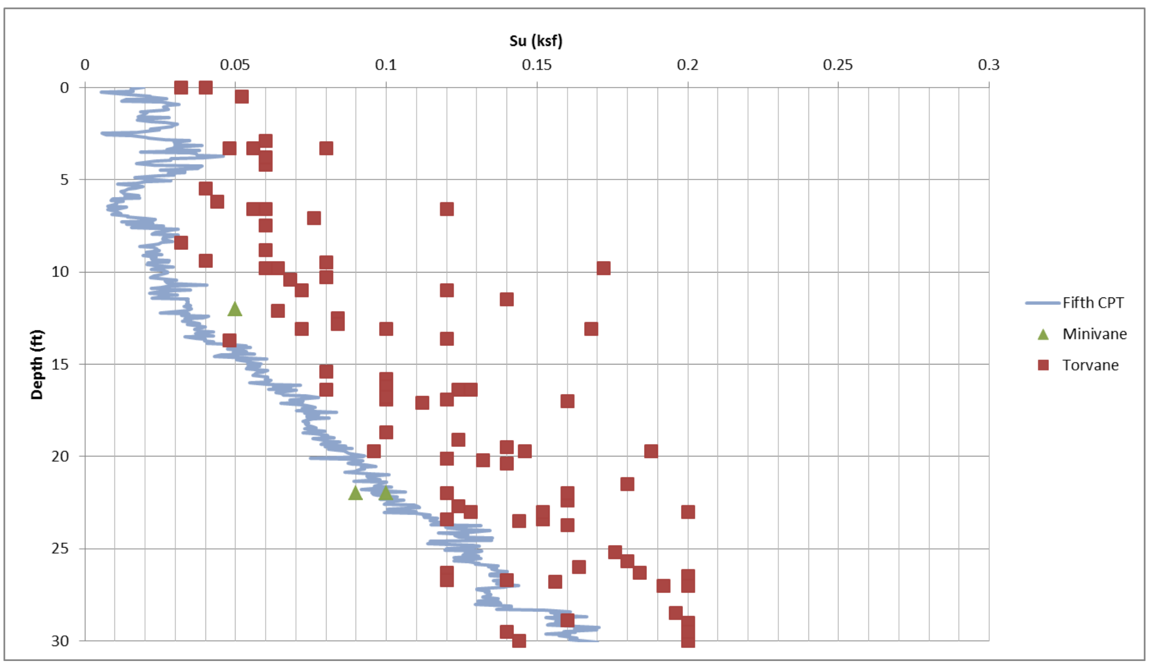


Figure 4.52: Profile of Fifth CPT and Point Data from Region Q

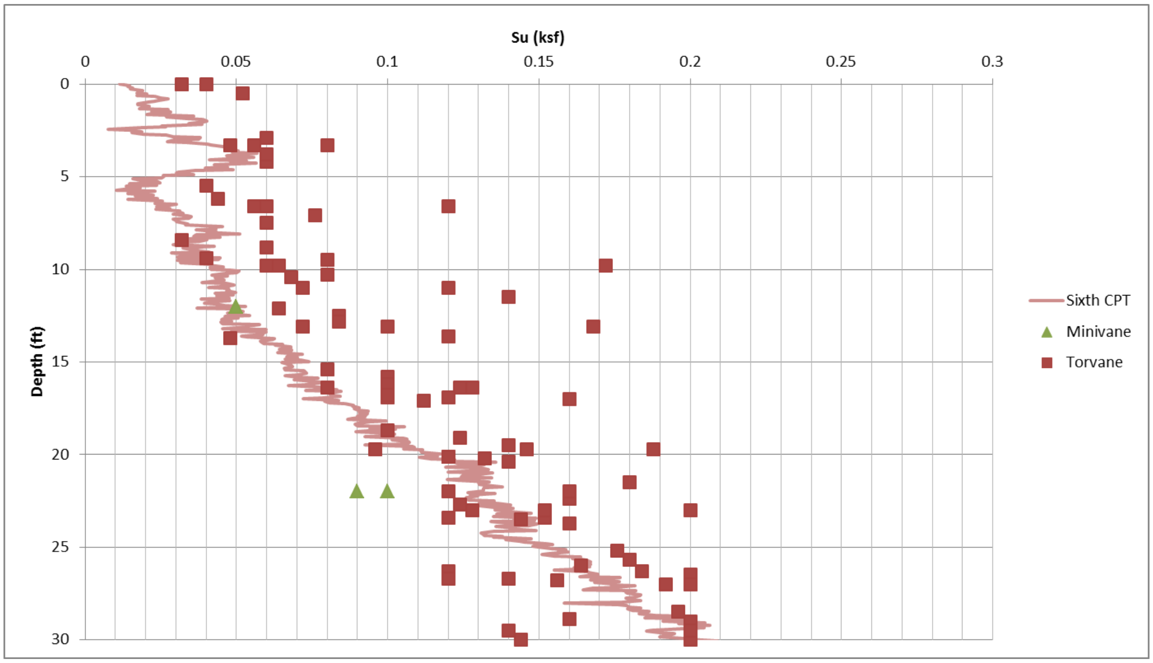


Figure 4.53: Profile of Sixth CPT and Point Data from Region Q

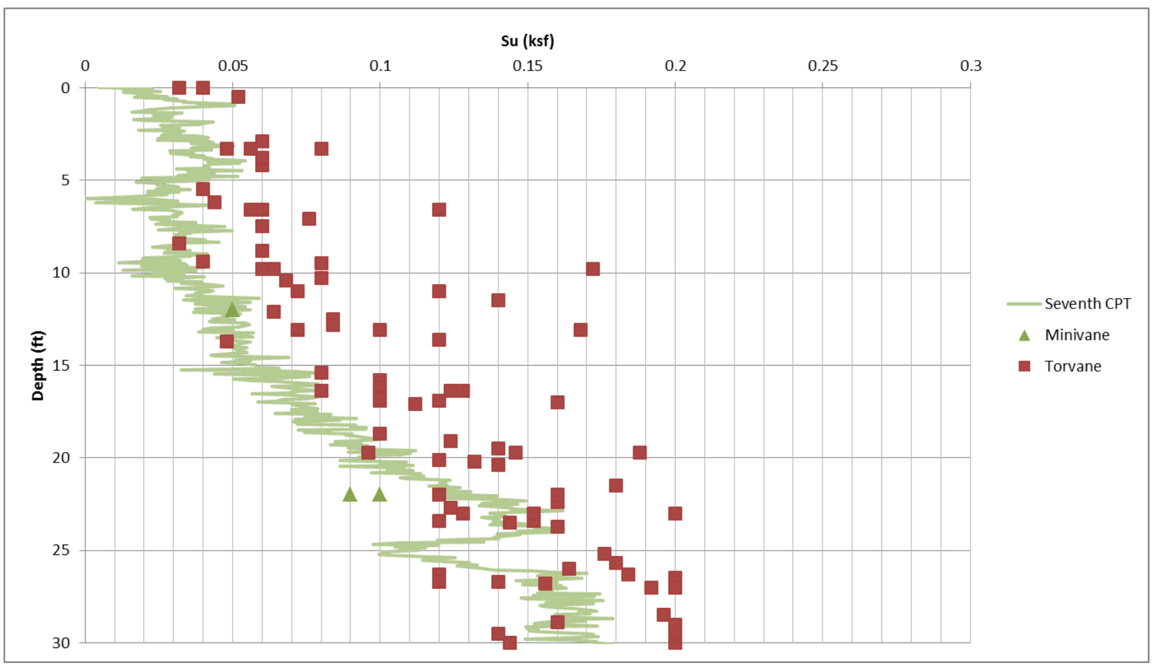


Figure 4.54: Profile of Seventh CPT and Point Data from Region Q

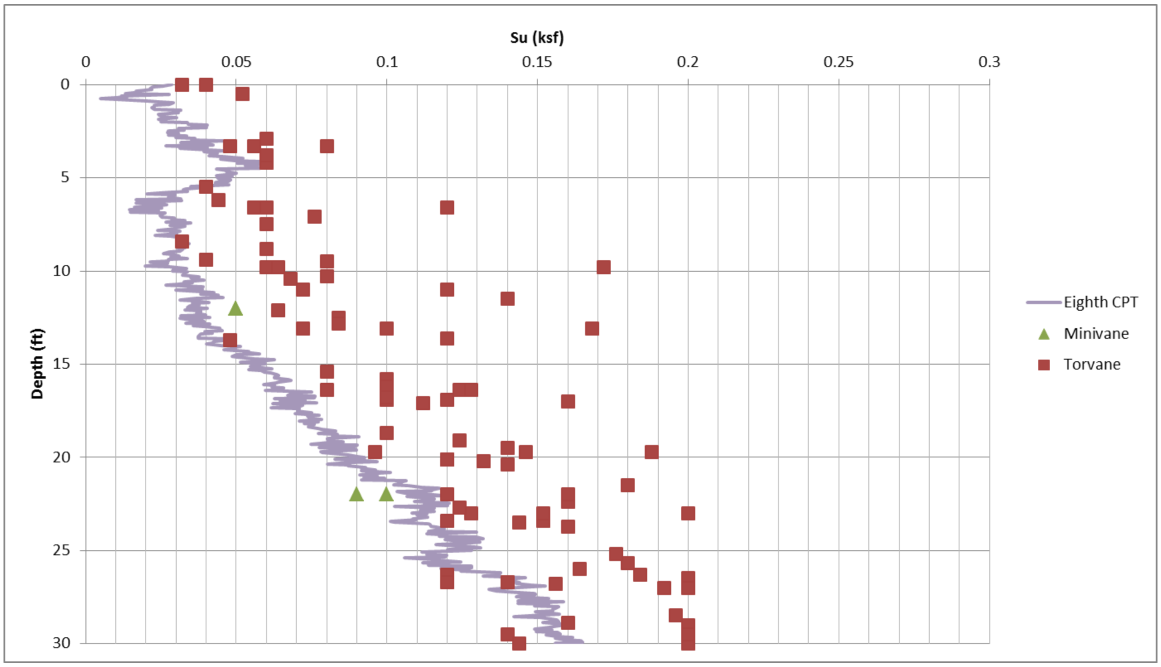


Figure 4.55: Profile of Eighth CPT and Point Data from Region Q

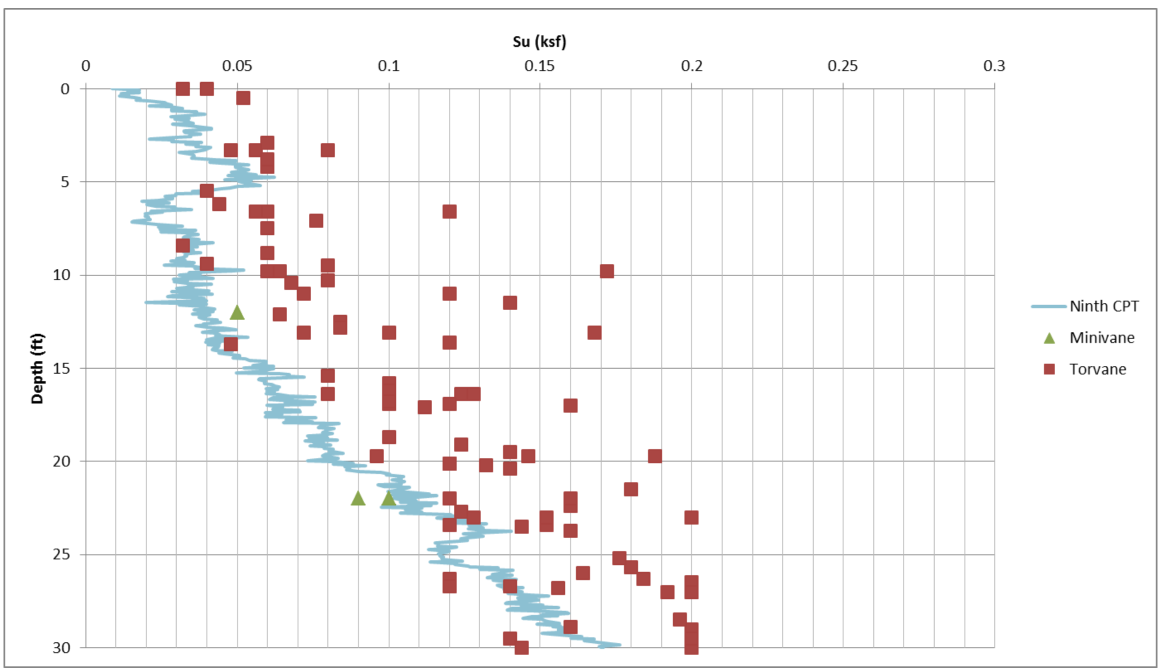


Figure 4.56: Profile of Ninth CPT and Point Data from Region Q

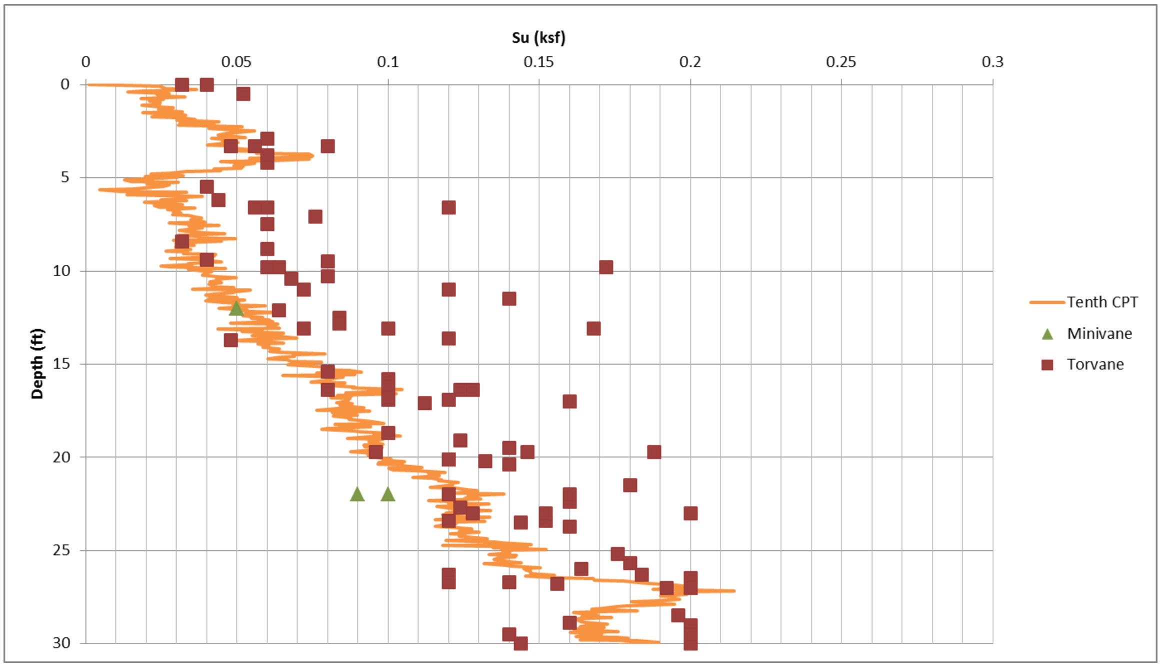


Figure 4.57: Profile of Tenth CPT and Point Data from Region Q

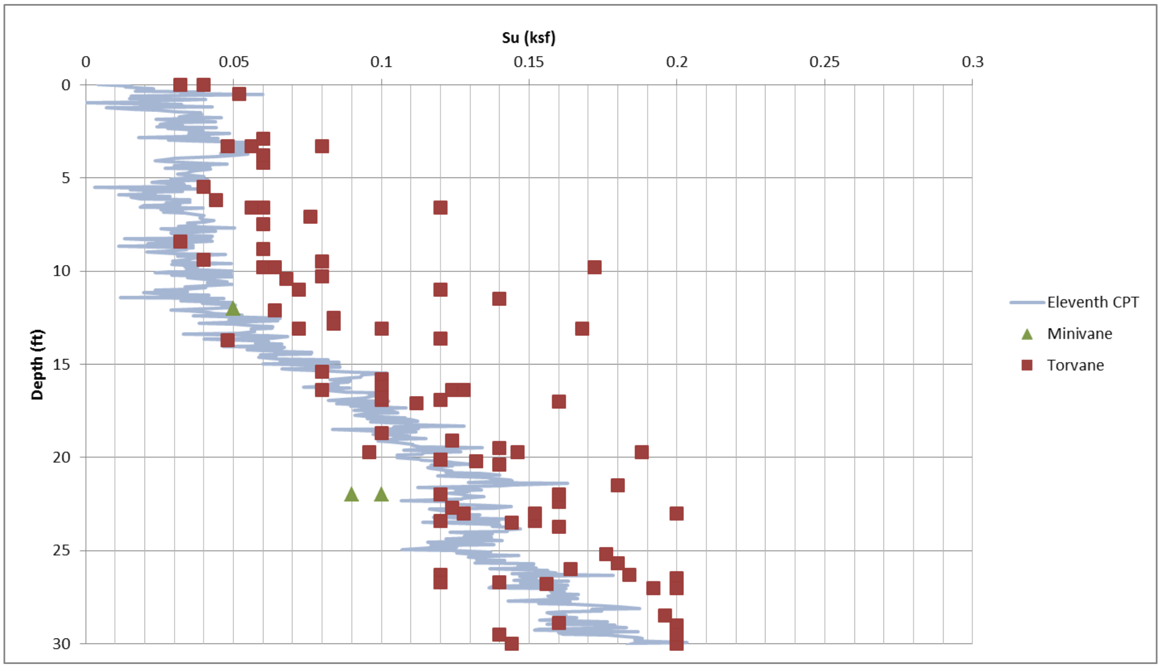


Figure 4.58: Profile of Eleventh CPT and Point Data from Region Q

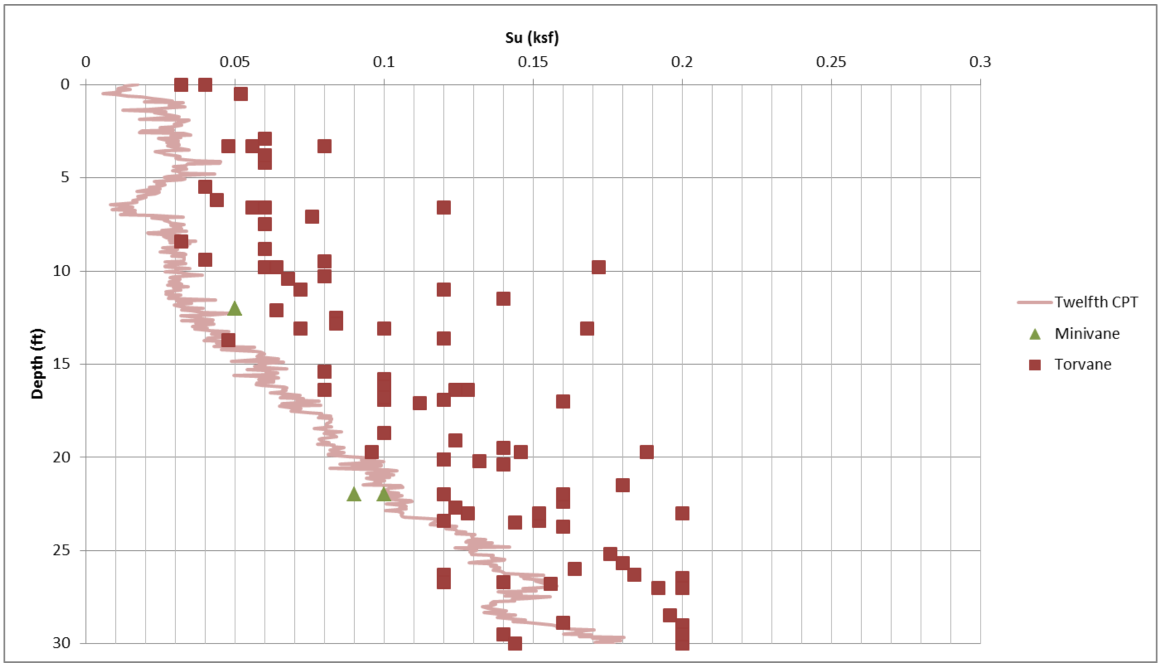


Figure 4.59: Profile of Twelfth CPT and Point Data from Region Q

In figure 4.60, the average of the CPT data from each region is plotted. This figure shows the variability that can be found in the CPT data. Whereas the average for Region Q seems to maintain a shape similar to the shape of the CPT profiles from the region, the other two profiles from Regions K and N are not as similar to the CPT profiles from those regions. This is likely due to the variability of strengths represented by the CPT profiles. There might be evidence of a crust in the region, as with Region K, but it is not visible in the average profile because the range of strengths in the various CPT profiles covers it up. In figure 4.61, the standard deviation of the CPT data from each region is plotted. In Regions K and Q the standard deviation remains relatively constant at a value of about 0.02 ksf. However in Region N the standard deviation spikes at depths of approximately 9 and 13 ft. This makes sense when looking at the CPTs from the region. A few of the CPTs in the region show large spikes in strength that may or may not be anomalies. However, these spikes are large enough to greatly increase the average of the region. Variability notwithstanding, the average strengths from Region K are greater than the average strengths from Regions N and Q in the upper 5 ft.

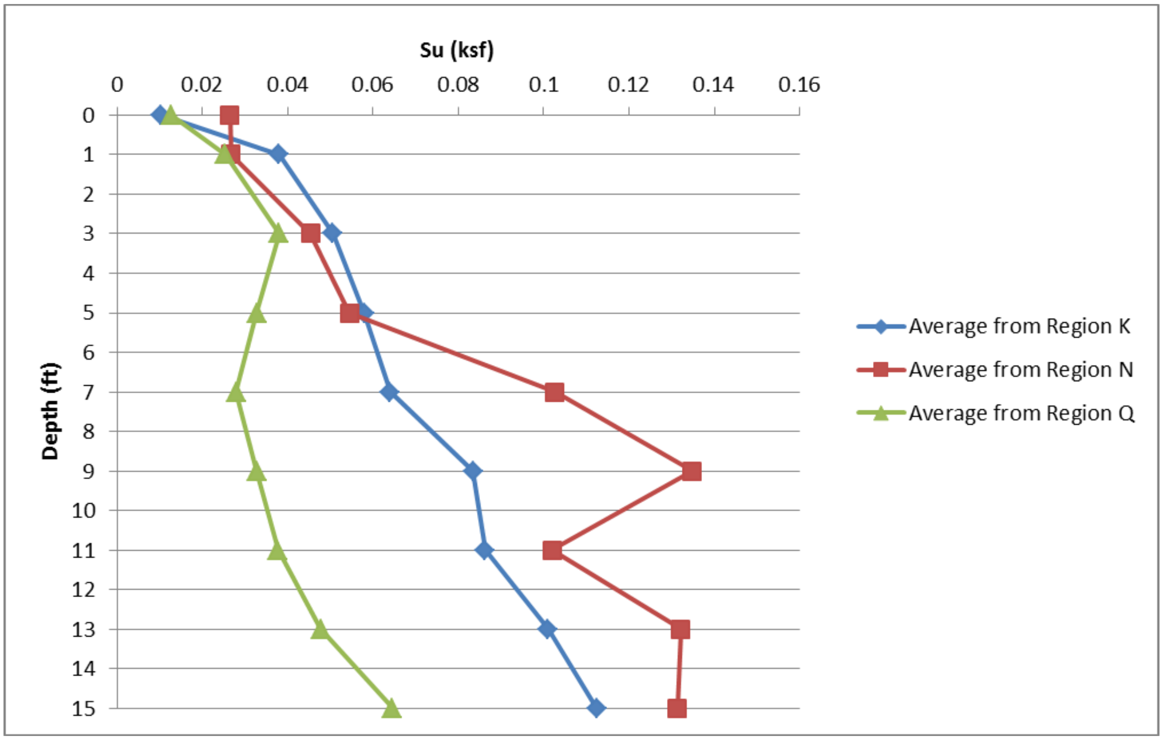


Figure 4.60: Average of CPT Profiles from Regions K, N, and Q

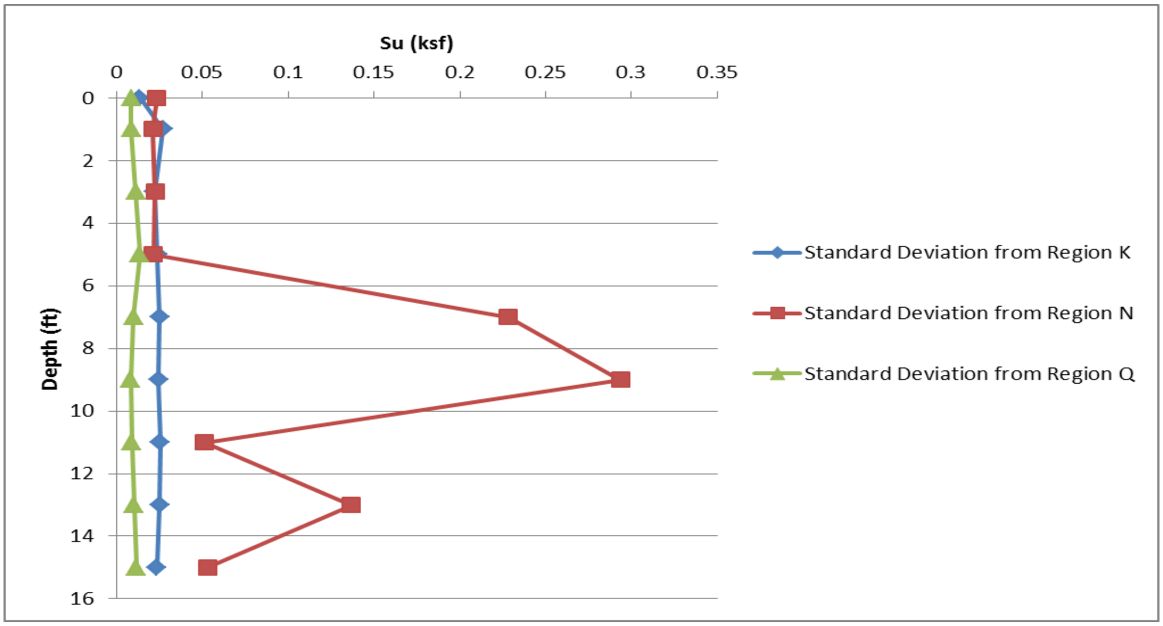
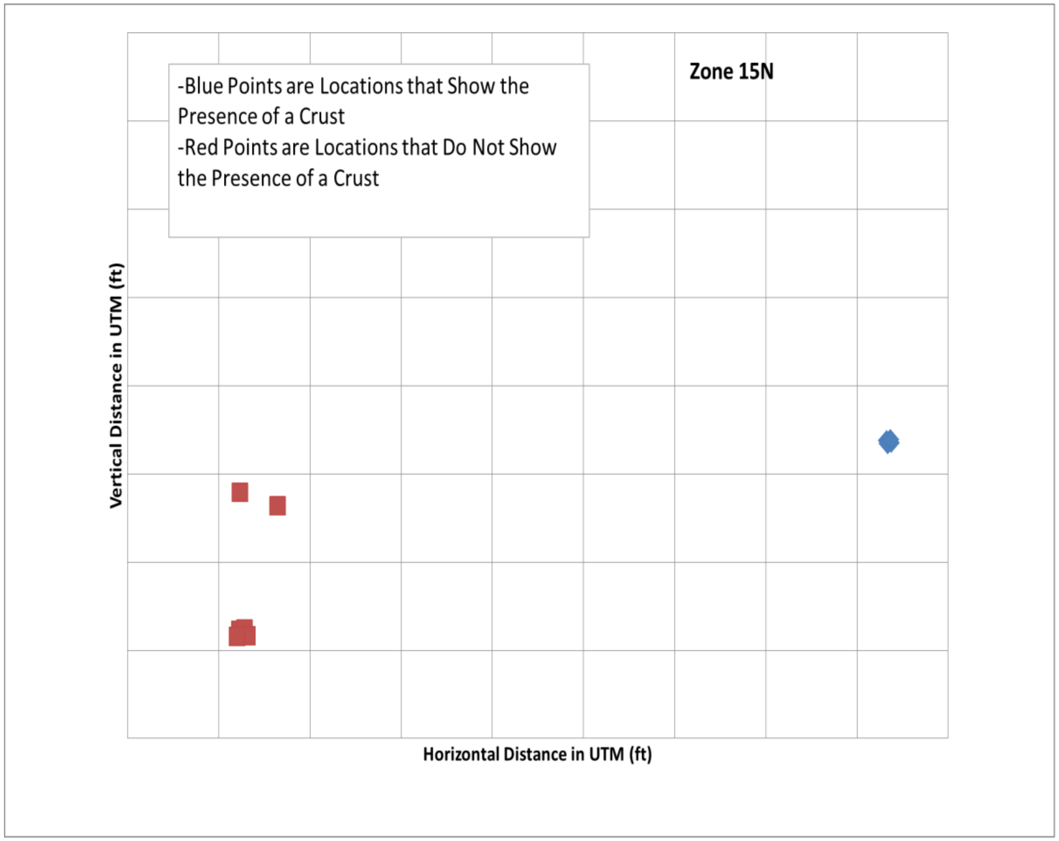


Figure 4.61: Standard Deviation of CPT Profiles from Regions K, N, and Q

4.6 Conclusions Regarding Shallow Data

There are several important conclusions that can be made after considering the shallow soil strength data within the existing database.

First of all, the high resolution data in conjunction with the CPTs containing shallow data make it clear that there is a crust near the mudline in deep water Gulf of Mexico at certain locations. The properties of the crust vary from location to location, but it is approximately 1 ft thick and sits at a depth between 2 and 5 ft. Strength also varies, much more widely than any other characteristic, but the c/p ratio of the crust ranges from 0.308 to 3.250 with an average of 1.204 and a standard deviation of 0.697. The location of the crust is also questionable, but based on the data used in this thesis it appears to be located along the bottom of the continental shelf slope in the deep water region closer to zone 16 (Figure 4.62). These characteristics are based on the 18 high resolution studies and the 25 CPTs discussed in this thesis.



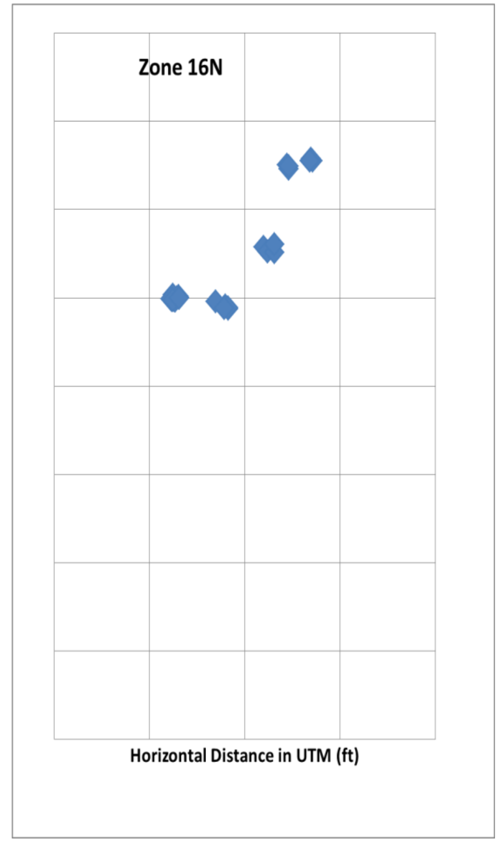


Figure 4.62: Locations of High Resolution Studies and CPTs with Shallow Data that Do or Do Not Show a Crust

Another major conclusion is that there is less data currently available for the shallow region than for deeper soils. The spatial variability analysis method that was originally produced in Cheon's dissertation uses all 115 boreholes, JPCs and CPTs from all over the deep water Gulf of Mexico to predict undrained shear strengths at new locations. Of the 115 corresponding design profiles, 111 use only 1 or 2 points to indicate strength behavior in the shallow region of the soil. There are only 4 locations, all in Region P and 3 of which have the exact same profile, where the engineers who designed the undrained shear strength profile versus depth used more than 2 points to indicate strength behavior in the shallow region of the soil.

There are 18 locations in the existing database that correspond to a high resolution study of the shallow region and 25 CPTs with shallow data. This means that if a future user of the database were to re-evaluate the undrained shear strength design profile at the locations with high resolution studies of the shallow region, she would be able to add 43 profiles to the database. That would bring the total of design profiles with high resolution in the shallow region to a total of 47. This is less than half of the total number of design profiles in the existing database.

The CPTs within the database offer the highest resolution of data for understanding the behavior of the soil strength in the shallow. But of the 44 CPT profiles within the database, almost half of them either do not have data in the shallow region or do not make sense in the shallow region. The remaining CPTs are incredibly valuable for understanding the soil in the shallow region, but they are limited to only 3 regions in the Gulf.

4.9 Summary

The point data within the existing database can be divided into coming from two categories of study: high resolution studies and low resolution studies. The resolution level of the study is defined by the number of points of data in the shallow region (a boundary of 10) and the variety of test types available there (2 types of tests).

Only 18 locations in the existing database correspond to high resolution studies, and 15 of those 18 give evidence of a crust. They offer a clear picture of the soil behavior in the shallow region. The design profiles, however, either gloss over the raw data, ignore the in-situ data in favor of more recognizable patters in the non in-situ data, or stick to the lower bound of the data in favor of conservatism.

The majority of the data, 48 locations, in the existing database come from low resolution studies. Low resolution studies are subdivided into two more categories: adequate and poor. This subdivision describes the amount of additional data that must be collected at these locations to make them high resolution, and thus useful for shallow soil analysis. Adequate studies have more than 5 points of data in the shallow region, and poor studies have fewer than 5 points of data in the shallow region.

By comparing in-situ test data and non in-situ test data it becomes apparent that there is considerably more scatter in the in-situ test data but that it is also the more accurate method of attaining data as it does not involve removing the soil and disturbing it. Engineers in the past have focused on non in-situ test data because it is easier to recognize the patterns in non in-situ test data and because it has been less important for deep foundation design.

CPTs offer the highest resolution picture of soil strength behavior in the shallow region because they are a continuous strength profile. However, many of the CPT profiles in the existing database do not start until after the shallow region. All the CPT profiles are calibrated with point data using a value called N_{kt}. For the three regions with CPT profiles in the shallow region the same N_{kt} value is applied to all locations within the same region and is applied over the entire depth of the test. The result of these N_{kt} values is that the CPT profile for a given locations is more likely to be below the point data in the shallow region. This is because the CPT profiles are typically calibrated to be closer to the deeper soil strength data and are not focused on the shallow soil strength data.

The data shows that there is a crust in deep water Gulf of Mexico. It is located in the shallow region of the soil near the mudline, is about one foot thick, and has a c/p ratio between 0.3 and 3.3 with an average of 1.2 and a standard deviation of 0.7. It appears to be located primarily along the bottom of the continental shelf in or near zone 16.

Finally, more data would be helpful in creating a database for spatial variability analysis of shallow soils in deep water Gulf of Mexico.

Chapter 5: Conclusions

5.1 Introduction

This thesis presents the findings of a study of the characteristics of undrained shear strength in shallow soils in deep water Gulf of Mexico. Data were collected from the database of Cheon (2011), which contains data on undrained shear strengths in deep water Gulf of Mexico. These data comes from a number of reports on the marine clay that generally makes up the soil in deep water Gulf of Mexico. The motivation of this research is to help future users of the existing database to better locate data within the database that will be useful for the purpose of shallow soil analysis and shallow foundation design. The various types of data found within the existing database, including undrained shear strength, remolded undrained shear strength, and unit weight profiles, were in the upper 10 to 20 ft of soil. The sources of data were examined including the reports that originally contained the data and the types of tests used to acquire the data. Examples of the usefulness of data that focuses on the shallow region were described for two separate regions. The data within the database were categorized based on usability and split into categories of having come from high or low resolution studies as well as point data versus Cone Penetration Test data. Comparisons were made between in-situ data and non in-situ data as well as point data and Cone Penetration Test data. The product of this research can be used by future users of the database to better locate data within the database that will be useful for the purpose of shallow soil analysis and shallow foundation design.

5.2 Conclusions

1. There are 18 locations of point data within the existing database with enough data in the shallow region to be able to properly characterize the soil behavior there. The data comes mostly from Halibut Vane, Minivane, and Torvane tests.
2. There are 25 CPTs in the existing database whose data points were reported in the upper 10 to 20 ft and provide an understanding of the behavior of the undrained shear strength of the soil in the shallow region.
3. Shallow soils are best characterized by studies performed with the express intent of focusing on the shallow region. Studies focused on deep soils tend to overlook important characteristics of soils in the shallow region because they are less important to deep foundation design.
4. There is a crust at certain locations in deep water Gulf of Mexico. The majority of these locations lie along the bottom of the slope of the continental shelf in UTM zone 16 in the Gulf of Mexico. The crust lies at a depth of between 2 and 5 ft below the mudline and has a thickness of about 1 ft. Its strength is much higher than the soil above or below it, and the c/p ratio ranges from 0.3 to 3.3 with an average of 1.2 and a standard deviation of 0.7.
5. In-situ tests are more variable in their characterization of the undrained shear strength of the soil in the shallow region of deep water Gulf of Mexico, whereas non in-situ tests are less variable.
6. For Cone Penetration Tests, the ratio of the undrained shear strength from lab and in-situ tests to the actual cone resistance is larger in most cases in the shallow region than it is in the deeper region. This results in a Cone Penetration Test profile that is lower in strength than the lab and in-situ test data from the same location. This ratio should be lowered to increase similarity between the Cone

Penetration Test strength profile and the lab and in-situ strength test data in the shallow region.

5.3 Recommendations for Future Work

In the future work, the following activities are suggested to build upon this research:

1. Re-evaluate the design profiles at the 43 locations described in this report at which high resolution studies have been performed in the shallow region. For most of these locations, the design profile originally created was not intended to be used for shallow foundation design, nor is it effective for this. Therefore, the design profiles at these locations must be altered to better represent the actual undrained shear strength behavior of the soil in the shallow region.
2. Collect the data from the existing database as well as any new data that can be acquired and put it into a new database specifically created to analyze soils in the shallow region.
3. Generate a new generic profile based on the data within the new database using the method outlined by Cheon (2011).
4. Create a new spreadsheet following the model of Cheon (2011) that uses spatial variability analysis to calculate undrained shear strengths at new locations based on the data in the database.

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