Development and Verification of a Down-Hole Penetrometer

Project Report No. TxDOT 5-4372-01-1

Final Report

Texas Department of Transportation

by

C. Vipulanandan, Ph.D., P.E.

Omer F. Usluogullari

Center for Innovative Grouting Materials and Technology (CIGMAT)
Department of Civil and Environmental Engineering
University of Houston
Houston, Texas 77204-4003

Report No. CIGMAT/UH 2008-2

http://tti.tamu.edu/documents/5-4372-01-1

Published: April 2008

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-08/5-4372-01-1		

4. Title and Subtitle	5. Report Date
Development and Verification of a Down-Hole Penetrometer	February 2008 Published: April 2008
	6. Performing Organization Code
7. Author(s) C. Vipulanandan and Omer F. Usluogullari	8. Performing Organization Report No. CIGMAT/UH 2008-2 5-4372-01-1
9. Performing Organization Name and Address University of Houston Department of Civil and Environmental Engineering N107 Engineering Building 1 Houston, Texas 77204-4003	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 5-4372-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered January 2005 to August 2007 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with Texas Department of Transportation
Research Project Title: Development and Verification of a Down-Hole Penetrometer
URL: http://tti.tamu.edu/documents/5-4372-01-1.pdf

16. Abstract

Drilled shafts are increasingly used as foundations to support bridges and transportation structures in geomaterials such as soft-rocks and hard clay. Locating the bottom of the borehole during construction with the required strength is critical. Hence, developing a simple device that could be easily adapted/used with the drilling tool was an interest of this study. Determining the shear strength of the geomaterial in the borehole and at the bottom of the borehole can lead to better designs by identifying the various layers based on strength. In this study, Down-Hole Penetrometer (DHP) was designed, built and tested to determine its effectiveness in measuring the strength of soil/soft rock at the bottom of the borehole. DHP was calibrated in the laboratory by using springs with various stiffnesses and then field tested in clay shale, clay and silty clay in a total of six locations in the Houston and Dallas districts. The test results were used in developing the correlation between undrained shear strength of soil/soft rock and DHP deflection.

17. Key Words	18. Distribution Statement
Correlations, Undrained Shear Strength, Soils, Soft Rock, Unconfined Compression Test, Down-Hole Penetrometer	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

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ENGINEERING DISCLAIMER

PREFACE

In order to support high loads on bridges and other transportation structures and/or based on the near surface geological conditions, more and more drilled shafts are being socketed to soft rocks and clay. During the construction of drilled shafts in soft rock or hard clay, it is critical to identify the soil stratum during the drilling process so that the drilled shaft could be correctly socketed in the soft-rock or hard clay.

Both static and dynamic penetrometers are being used to determine the in situ soil properties for designing deep foundations and slope stability analysis. However, these devices cannot be used to characterize the soil in the drilled shaft borehole due to the difficulty of incorporating the operations during the construction phase. In order to overcome this difficulty at present, a Down-Hole Penetrometer (DHP) was designed and built at the University of Houston, in Houston, Texas, and there is no commercially available tool to characterize the clay and soft-rock strength at the bottom of the borehole of a drilled shaft.

Correlations based on the field test values could be very useful to engineers to determine the undrained shear strength of the soil/rock. In order to correlate the DHP measurements (deflections) to soil/rock strength and TCP values, limited field tests were performed in the Houston District and Dallas District.

ABSTRACT

Drilled shafts are increasingly used as foundations to support bridges and transportation structures in geomaterials such as soft-rocks and hard clay. Locating the bottom of the borehole during construction with the required strength is critical. Hence developing a simple device that could be easily adapted/used with the drilling tool was an interest of this study. Determining the shear strength of the geomaterial in the borehole and at the bottom of the borehole can lead to better designs by identifying the various layers based on strength.

In this study, a Down-Hole Penetrometer (DHP) was designed, built and tested to determine its effectiveness in measuring the strength of soil/soft rock at the bottom of the borehole. Based on limited field tests, correlations between geomaterial strengths and DHP deflection have been developed.

SUMMARY

Defining the soil and rock parameters at the bottom of a borehole in a drilled shaft is not common because of the difficulties of measurement. Hence when developing the DHP, its adoption to the Kelly bar was considered. The key components of DHP are the spring and a ring, which is adjusted to move with the motion of the spring. The working procedure of DHP is based on a concept. Load applied to the DHP provides a deflection at the spring then with the motion of the spring ring, it starts to move. When a failure occurs at the penetrated soil the spring reaches its maximum deflection, although the spring returns to its old position, the ring stands at the point of maximum deflection.

In this project, DHP was calibrated in the laboratory using springs with various stiffnesses and then field tested in clay shale, clay and silty clay at six locations within the Houston and Dallas Districts. Based on the field test results, correlation between undrained shear strength and DHP deflection was developed.

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RESEARCH STATEMENT

This research project was conducted to develop a Down-Hole Penetrometer that could be easily used during construction to determine strength of the geomaterial at the bottom of a borehole.

The report will be a guidance document for TxDOT engineers on using the Down-Hole Penetrometer to determine the strength of the soil/soft rock at the bottom of the borehole. The deflection measured in DHP has been correlated to S_u (shear strength) and TCP values.

The major components of the mechanical DHP system are piston, spring, sliding ring and penetrometer shell. The basic concept of the penetrometer is to fail the geomaterials below the piston and determine the deflection of the spring which in turn is correlated to the S_u of the soil/soft rock.

The DHP can be attached to the Kelly bar and lowered into a borehole, with or without slurry, to determine the strength of the geomaterials at the bottom of the borehole. Based on limited field tests, the shear strength of the geomaterials has been related to the deflection measured.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

For site investigation, in situ tests are increasingly used to determine the soil properties for geotechnical analysis and design. The penetrometers evolved from the need to acquire data on sub-surface soils that were not sampled easily by any other means. Static and dynamic penetration resistances have been used to classify and characterize subsoils. Laboratory testing undisturbed samples requires great care to avoid disturbance during handling, or systematical disturbance during testing, and it may be difficult to relate the laboratory test results to the in situ properties of the soil. There is always a certain degree of disturbance to the samples because the confining pressures, which exist in the ground, are forcibly changed when the sample is collected.

The penetrometer was developed as a handy tool to avoid many drawbacks of sampling and laboratory tests, ant it has become a widely accepted means for the in situ properties. A penetrometer consists of a slender metal rod that is pushed or driven into the ground by jacks, hammer blows or other field instruments (Sanglerat 1972).

In this project, a Down-Hole Penetrometer (DHP) was designed, built and tested in the laboratory and field to determine the ultimate strength of clay and soft rocks. The field tests were conducted using the DHP in the Dallas and Houston Districts, both of which contain clay shale, clay and silty clay.

1.2. Research Objective

The overall objective was to develop and calibrate the DHP for use in soft rocks. Then specific objectives are as follows:

- Design the Down-Hole Penetrometer to cover a range of hard clay to soft rock.
- Calibrate the Down-Hole Penetrometer with field tests.

1.3 Organization

This report has been organized into four chapters. In Chapter 2, literature reviews related to in situ methods used to characterize the soils and rocks have been summarized. In Chapter 3, in addition to design details, field tests have been summarized. By varying the spring, various soil types were investigated. Linear relationships between spring deflections and undrained shear strength have been developed. Also DHP deflection is related to Texas Cone Penetrometer (TCP) values. Conclusions and recommendations are summarized in Chapter 4.

CHAPTER 2 LITERATURE REVIEW

2.1 Penetrometers

Probing with rods through weak ground to locate a firmer stratum has been practiced since 1917 (Meigh 1987). Soil sounding or probing consists of forcing a rod into the soil and observing the resistance to penetration. The penetrometer evolved from the need of acquiring data on sub-surface soils that were not obtainable by any other means.

There are several applications for penetrometers such as: used to establish the thickness of different strata when investigating the suitability of a site for construction works, testing compaction works, and for determining the relative density of fills and naturally deposited non-cohesive soils. In addition, information concerning the physical properties of soils can be obtained, which is used to assess their bearing capacity and to analyze stability problems.

There are two ways to drive the penetrometers into the soil: static and dynamic methods. Each one of these penetrometers have their own purposes and design considerations. In the United States, the most commonly used penetration devices for soil-related applications are the standard penetration test (SPT) and the cone penetration test (CPT). One of the in situ tools commonly used for this process in the State of Texas by the Texas Department of Transportation is the Texas cone penetrometer (TCP).

The SPT originated around 1927 and has been in use for some 80 years. It is being used worldwide and currently the most popular and economical means to obtain subsurface information. It is estimated that 85 to 90 percent of conventional design in North America is made using the SPT (Bowles 2002; Marcuson and Bieganousky 1977; Mayne and Kemper 1984; Mayne 1991; Meyerhof 1956). The method has been standardized as an ASTM D1586 since 1958 with periodic revisions to date.

The CPT is now widely used in lieu of the SPT, particularly in soft clays, soft silts and in fine to medium sand deposits (Kulhawy and Mayne 1990; Mayne and Kemper 1984). The test is not well adopted to gravel deposits or to stiff/hard cohesive deposits. This test has been standardized by ASTM as D 5778. The test consists of pushing a 35.6 mm diameter standard cone into the ground at a rate of 10 to 20 mm/s and recording the resistance. Because of the complexity of soil behavior, empirical correlations are used extensively in evaluating soil parameters (Orchant et al. 1988; Robertson and Campanella 1983).

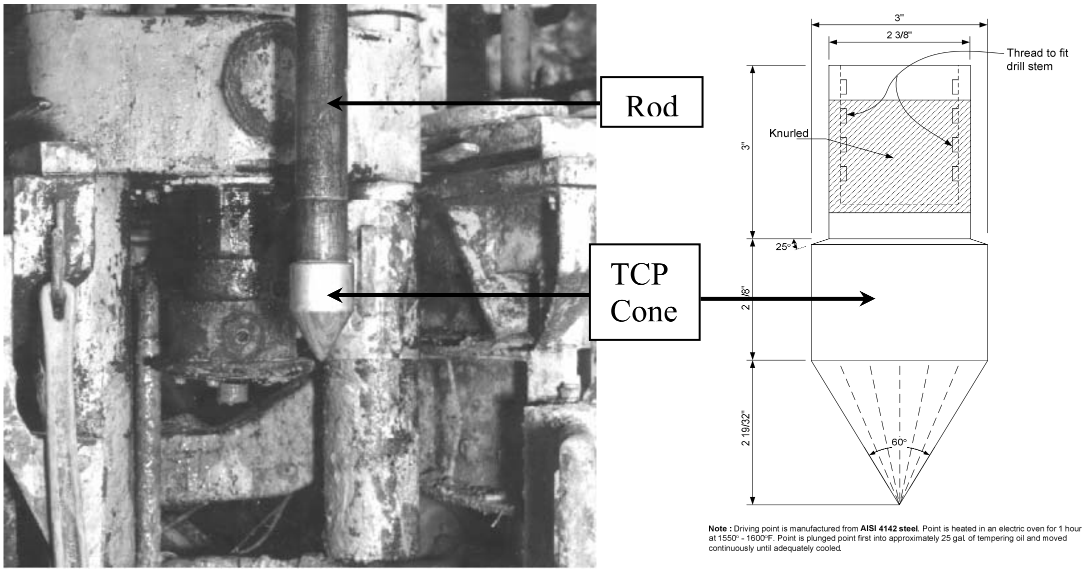
In addition to these devices, University of Houston recently developed a Down-Hole Penetrometer to characterize the soil in the borehole due to the difficulty of incorporating the operations during the construction phase. Also, there are other penetrometers that have been developed for in situ tests: Multiple-Purpose Borehole Testing Device (Huang et al. 2002), Danish Pocket Penetrometer (Godskesen 1936).

2.1.1 Texas Cone Penetrometer (TCP)

The Texas Cone Penetrometer is commonly used for site investigation by the Texas Department of Transportation (Figures 2.1 and 2.2). The TCP test involves driving a hardened conical point into the soil and hard rock by dropping a 170 lb (77 kg) hammer a height of 2 feet (0.6 m) (Tex-132-E). From the soil test, a penetration resistance or blow count (N_{TCP}) is obtained which equals the number of blows of the hammer for 12 inches (300 mm) of penetration.

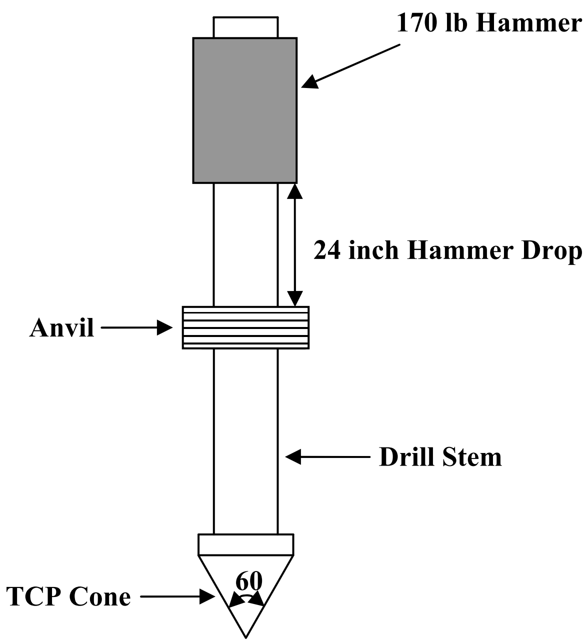
According to the Geotechnical Manual (2000), TCP was developed by the bridge foundation group in the bridge division with the help of several other divisions in the TxDOT. This was an effort to bring consistency in soil testing to determine soil and rock load carrying capacity in foundation design, which was lacking prior to the 1940s. The first use of TCP dates back to 1949, and the correlation charts and test procedure was first published in the Foundation Exploration and Design Manual in 1956. These correlations were modified slightly in 1972 and 1982 based on accumulated load test data for piling and drilled shafts (Geotechnical Manual 2000).

A recent study on TCP has further verified the correlations between CL and CH soil Undrained Shear Strength and TCP values (Kim et al. 2007; Vipulanandan et al. 2007b; Vipulanandan et al. 2007)



(a) Actual view
(TxDOT Geotechnical Manual, 2000)

(b) Texas Cone Schematic



(c) Details of the Texas Cone Penetrometer (Not to Scale)

Figure 2.1 Texas Cone Penetrometer (TCP)

(a) Fully Automatic **(b) Automatic Trip**

Figure 2.2 TCP Hammers (TxDOT Geotechnical Manual 2000)

2.1.2 Danish Pocket Penetrometer

The Danish or Swedish pocket penetrometer was developed by the Danish railroads in 1931. It has a spring placed on a cone, and it is driven into the soil by hand or with suspension (Figure 2.3). It has been satisfactorily used for determining cohesion and allowable bearing pressures of soils (Godskesen 1936).

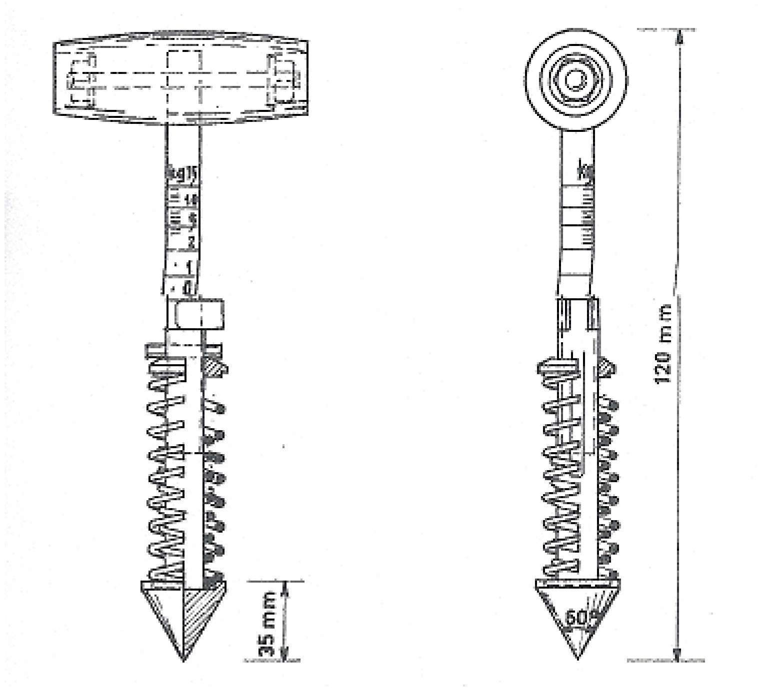


Figure 2.3 The Danish Pocket Penetrometer (Sanglerat 1972)

2.1.3 Multiple-Purpose Borehole Testing Device (BTD)

This in situ testing device was developed to provide design parameters for shallow or deep foundations in soft rock (Huang et al. 2002). This device consists of two measuring instruments; one is a pressuremeter and the other is a plate-loading device (Figure 2.4). It can be used to perform a borehole jacking test, plate-loading test and borehole shear test in the same borehole.

The BTD consisted of three major compartments, as described in Figure 2.4, with a total height of 1900 mm. It was designed to perform tests in a 200 mm diameter borehole. The top compartment could be expanded laterally against the borehole wall, performing a borehole jacking test. This lateral expansion jams the top compartment against the borehole wall, provides a reaction to the plate-loading test at the bottom of the borehole and exerts a normal stress against the borehole wall for performing a shear wave test at the same time. The central compartment offered waterproofed housing for the electronic signal processing system.

A series of field tests have been performed in a soft rock formation at a test site in Miaoli County, which is located in northern Taiwan. Silty sandstone with occasional layers of shale and mudstone were the major rock formations in this region.

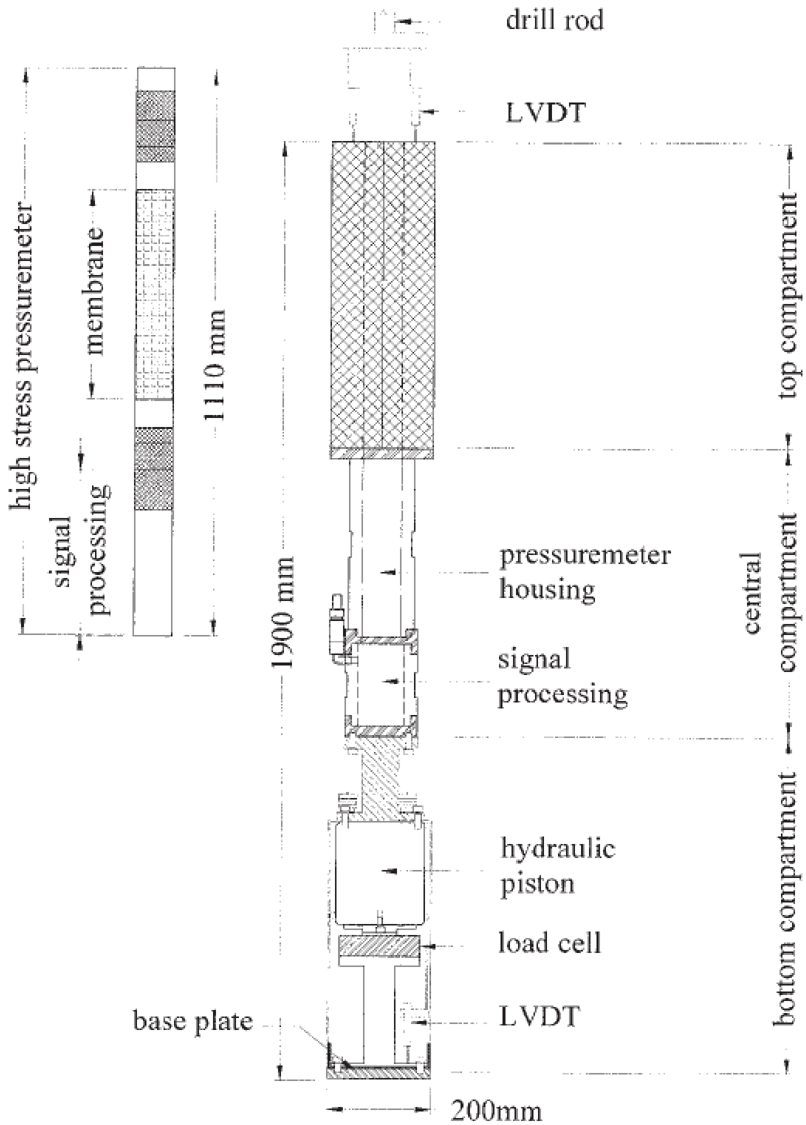


Figure 2.4 Schematic View of the BTD System (Huang et al. 2002)

Field coring can cause significant disturbance to soft rock samples and result in low stiffness measurements. This device reduced the disturbance effects. It would be more desirable to derive design parameters directly from field load tests. However, a full-size load test can be time consuming and costly. Like the DHP, this device was also developed for foundations in soft rock. On the other hand, DHP has the advantage that it can be attached to the Kelly bar during construction, and also the DHP has the option of changing springs in case different types of soils are encountered.

Summary

Based on the literature review, the following observation can be advanced:

(1) In situ methods currently used cannot be easily adopted with the drilled shaft construction to determine the strength of the hard soil/soft rock at the bottom of the borehole.

CHAPTER 3 DOWN-HOLE PENETROMETER (DHP)

3.1 DHP Design

During the development of DHP, Kelly bar was considered for attaching the device. The parts used in the DHP are listed in Table 3.1 and the cross sections of the DHP. The piston and Kelly bar adaptor are shown in Figures 3.1, 3.2 and 3.3. Once assembled, the DHP weight about 30 lb. The key components of DHP are the spring and a ring, which is adjusted to move with the motion of the spring. The working procedure of the DHP is based on a simple concept. Load-applied DHP provides a deflection at the spring then with the motion of the spring ring starts to move. By applying the weight of the Kelly bar the soil/soft rock below the piston fails and compresses the spring to represent the failure load. At soil/soft rock the spring reaches its maximum deflection. Although the spring returns to its old position when DHP is lifted off the ground, the ring stands at the point of maximum deflection (δ_{max}).

If the failure load on the piston was q_{ult} and the spring stiffness was k, it can be represented as follows (bearing capacity relationship):

$$q_{ult} = \frac{k \times \delta_{max}}{A_p} = N \times S_u \qquad (1)$$

where δ_{max} = maximum deflection, A_p = area of piston, S_u = undrained shear strength and N is the bearing capacity factor.

Table 3.1 Down-Hole Penetrometer Materials List (All dimensions in inches)

Part No	Description	Material	Qty
1	Square tube, 5.37 (OD) × 0.50 (wall) × 9.5 (length)	Mild Steel	1
2	Square plate, 6.12 × 6.12 × 0.75	Mild Steel	1
3	Die Spring, linear, 125 lb/in. – 2100 lb/in.	Treated Steel	1
4	Circular bar piston, 1.50 (OD) × 4.87 (long)	Mild Steel	1
5	Circular tube, 6.00 (long) × 0.25 (wall)	Mild Steel	1
6	Piston Head, 0.50 (high) × 2.00 (OD) × 0.25 (wall)	Mild Steel	1
7	Flathead screws w/ Allen-head-wrench slot, 0.20 (Diameter) × 1.00 (long)	Mild Steel	2
8	Flat ring bushing, 0.5 (high) × 2.0 (OD) × 0.25 (wall)	Mild Steel	1
9	Flat ring protector plate, 0.50 (high) × 2.50 (ID) × 1.00 × 1.00 (wall)	Mild Steel	1
10	Reading ring / slider ring. Slider ring made of Teflon tubing, 2.50 (diameter) × 0.50 (height) × 0.12 (wall thickness). Reading ring (fits over slider ring) made of slotted mild steel tubing, 0.50 (height) × 0.06 (wall thickness) (to hold slide ring snugly in place but free to slide).	Mild Steel / Teflon	1

*See Figures 3.1-3.2-3.3

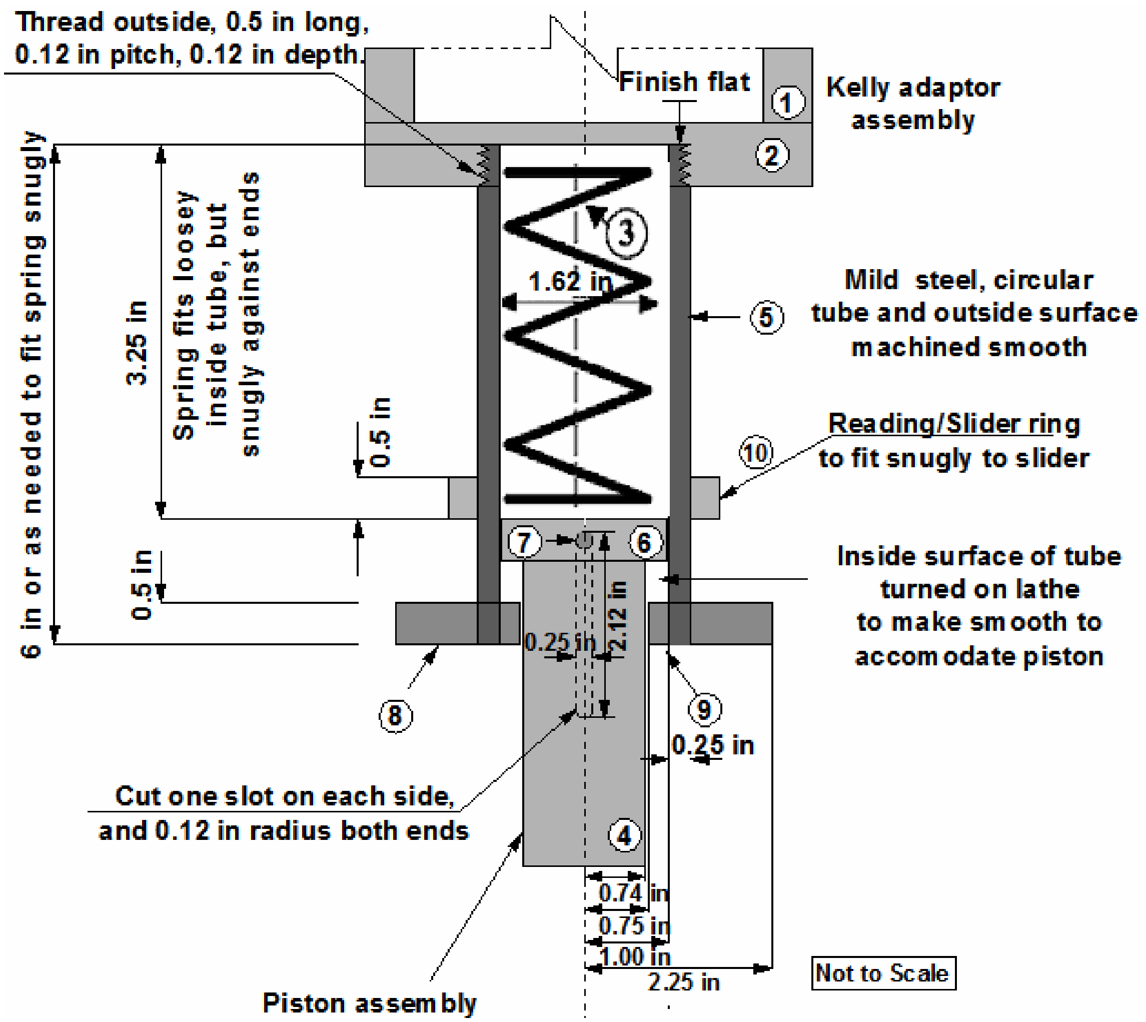


Figure 3.1 Body of Down-Hole Penetrometer

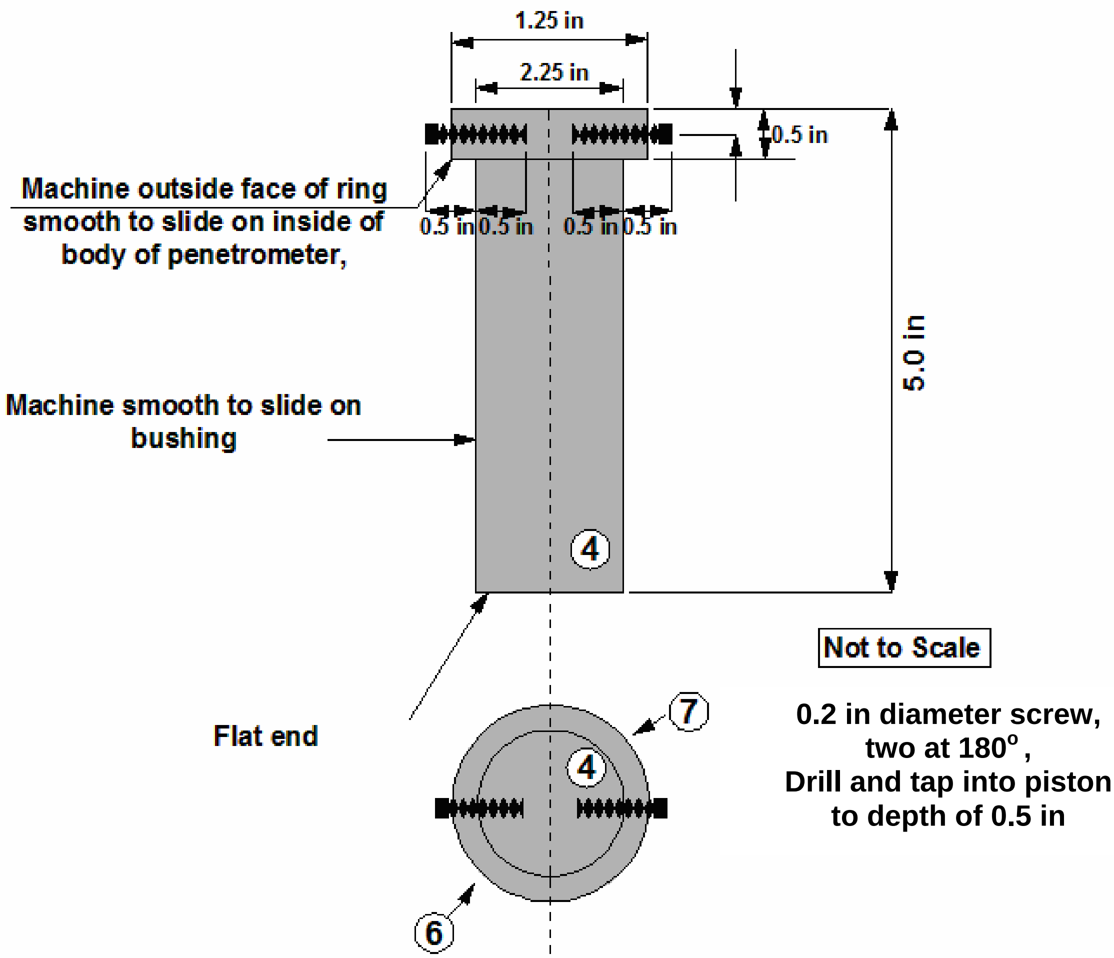


Figure 3.2 Details of the Piston

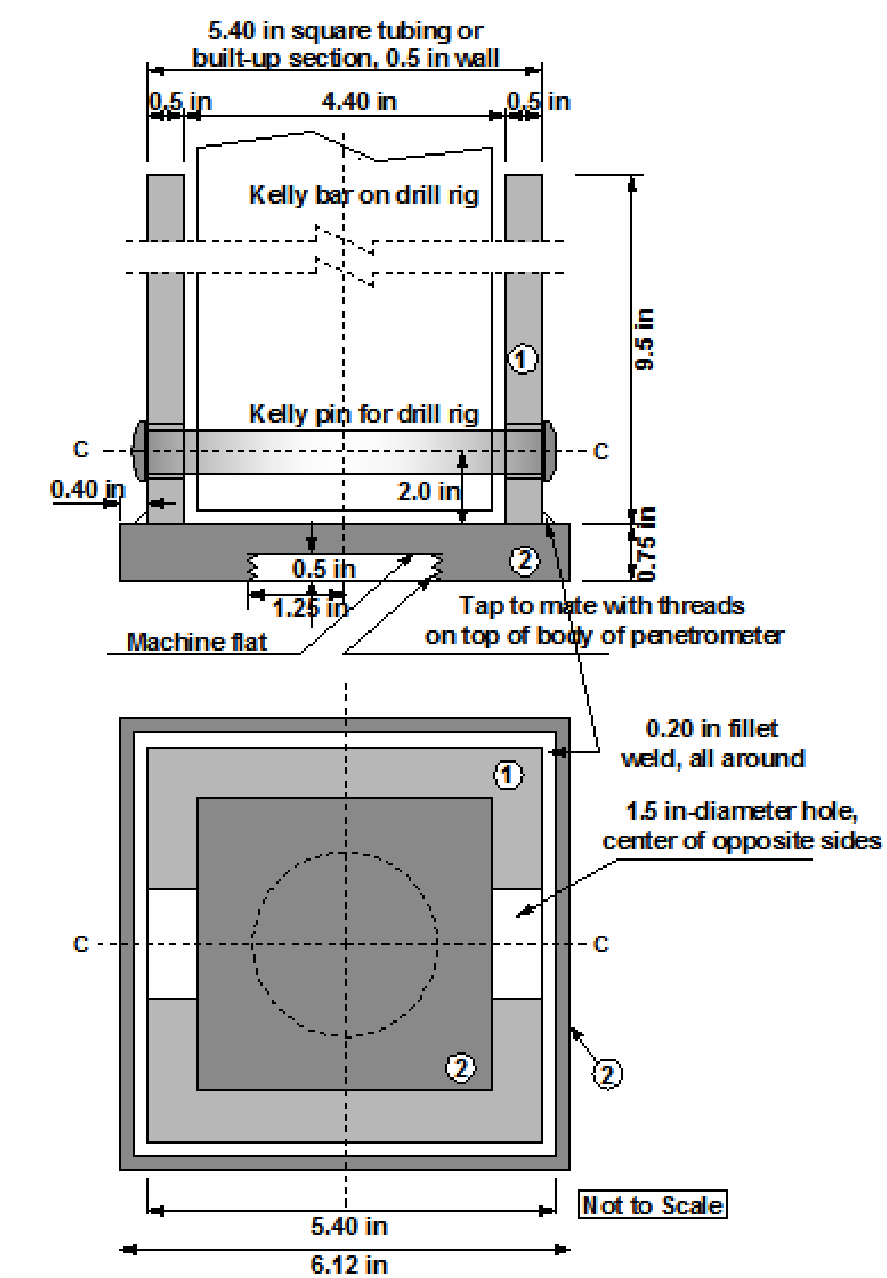
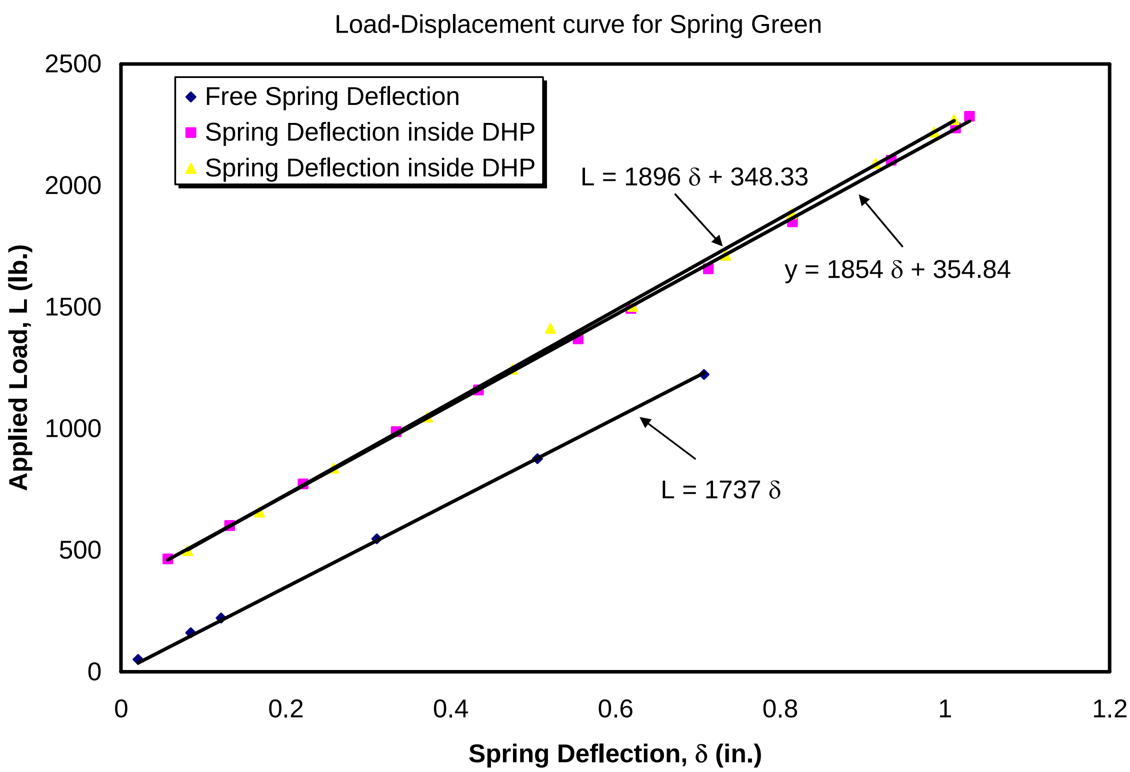


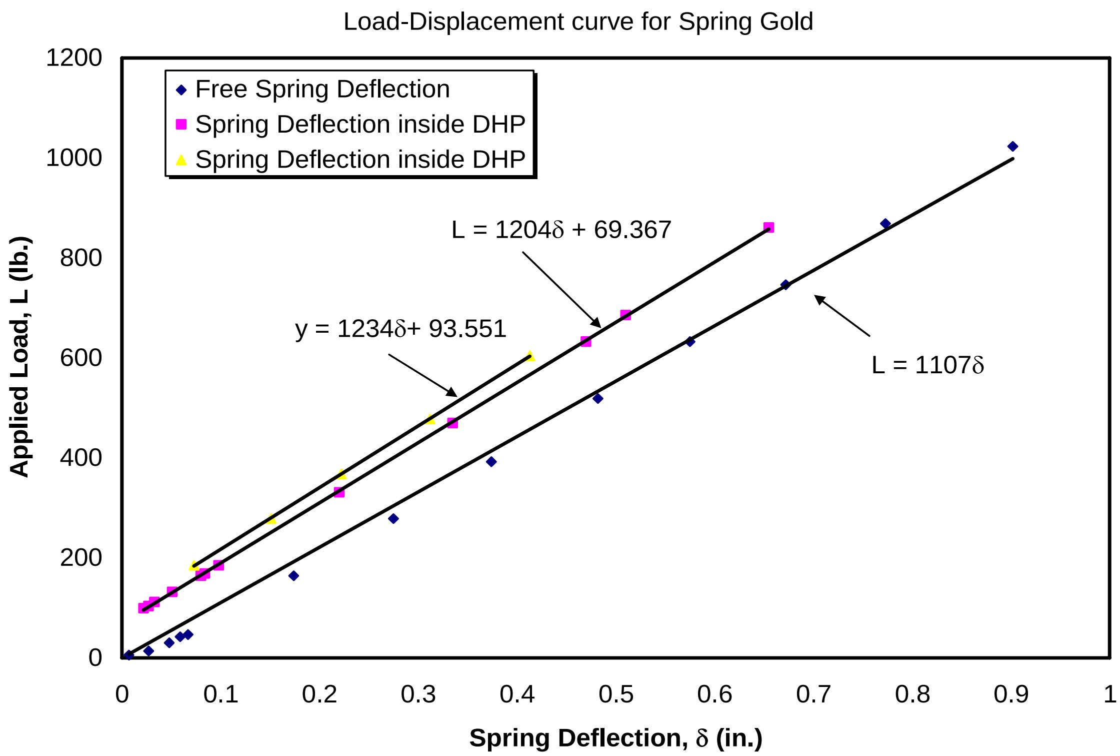
Figure 3.3 Details of the Kelly Adaptor

3.2 Calibration

Springs of different stiffnesses were used to test the DHP in the field. The springs were calibrated in the laboratory using the Universal Test Machine (UTM). The applied load (L) and corresponding deflection (δ) were recorded. The springs were calibrated inside and outside (free) the DHP. The load-deflection curves for each of the springs are given in Figure 3.4 (a-b).



(a)



(b)

Figure 3.4 Spring Constants Inside and Outside the DHP for a) Green Spring b) Gold Spring

Table 3.2 lists the different springs used in this study.

Table 3.2 Spring Constants of the Springs Used in the DHP

Spring	Manufacturer's Spring Constant (lb/in.)	Calibrated Spring Constant of Free Spring (in compression) (lb/in.)	Average Calibrated Spring Constant of Spring in DHP (in compression) (lb/in.)
Green	1728	1737	1875
Gold	1100	1107	1219

As summarized in Table 3.2 the free spring constants (in compression) varied by 7 percent and 1 percent of the manufacturer's supplied spring constants. This variation may occur because the manufacturer's spring constant is not found by calibrating each spring, but only a statistical estimation of a particular type of spring. Also, the manufacturer may have tested the springs in tension, while for this study the springs were tested in compression. Calibration results show two stiffness constants for each spring. In analyzing the spring constants it was found that the springs, when calibrated inside the DHP, gave a higher value than when calibrated outside. The increase in value of the spring constant in the DHP can be attributed to two factors: (a) friction between the plunger and penetrometer walls increases with spring deflection, and/or (b) the spring expands laterally when it is compressed, rubbing against the side of the chamber.

3.3 Field Tests

a) Location 1 & 2 (I-10 West, I-10 East, Houston B1, B2, B3, B4) (July 2006)

Table 3.2 summarizes the information from the locations where field tests were completed. Clay samples were obtained from four locations in Houston, Texas. Three of the locations were along Interstate Highway 10 close to Beltway 8 and have been designated as B1, B2, and B3. The fourth location was at the junction of Wallisville and Maxey Road, and has been designated as B4. Figures 3.5 and 3.6 illustrate the maps of the four locations.

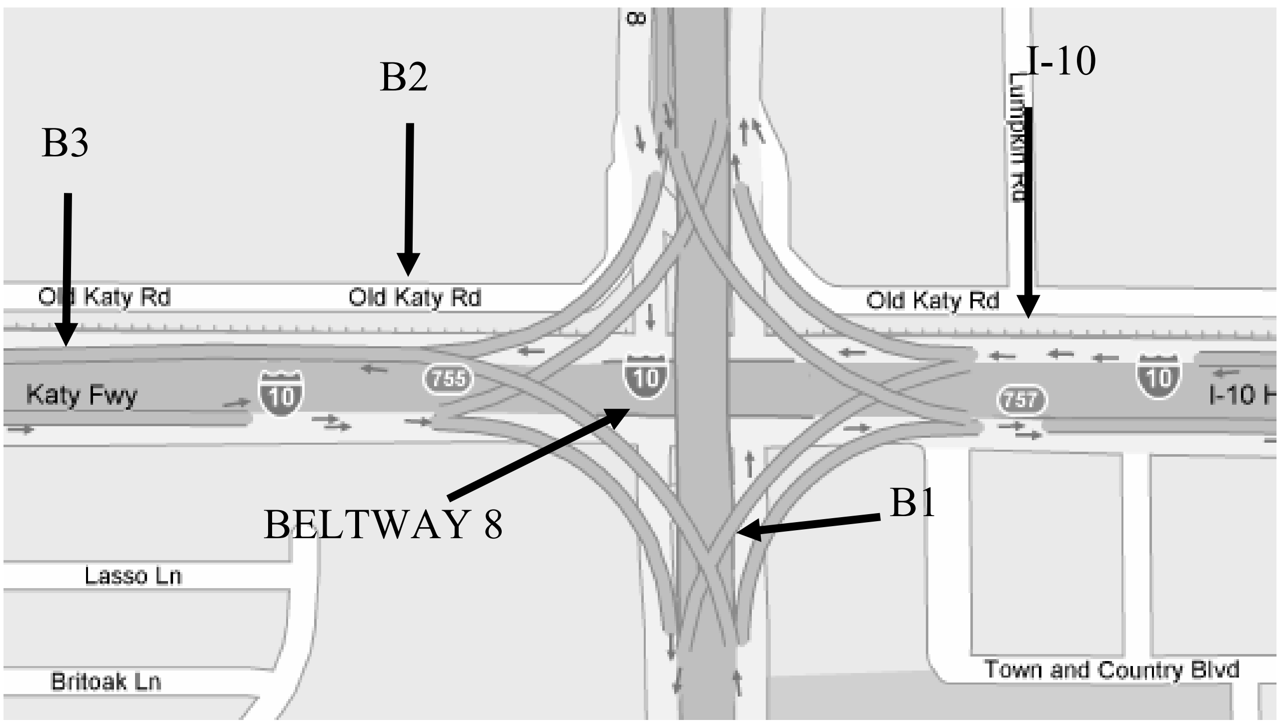


Figure 3.5 The First Location of the DHP Test in Houston.
(Map courtesy of \ Google Maps)

Figure 3.6 The Second Location of the DHP Tests in Houston.
(Map courtesy of Google Maps)

Table 3.3 summarizes the details of the four drilled shafts at the test sites.

Table 3.3 Details on the Four Boreholes in Which DHP Tests Were Conducted

Location	Length of Borehole (ft)	Diameter of Borehole (in.)	Soil Description	TCP blow count	Slurry
B1	50	60	Reddish Brown	10 (6) 25 (6)	Yes
B2	63	60	Reddish Brown	34 (6) 40 (6)	No
B3	53	48	Reddish Brown	39 (6) 50 (6)	No
B4	54	36	Reddish Brown	18 (6) 21 (6)	Yes

Material properties of the clay samples obtained from the four locations are summarized in Table 3.4

Table 3.4 Geotechnical Properties of Natural Clay from Various Boreholes

Location	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Soil Classification
B1	21	53	32	CH
B2	20	59	39	CH
B3	22	42	20	CL
B4	27	72	45	CH

b) Location 3 (Intersection of Memorial Dr. and Beltway 8, B5) (03/23/07)

The field was located near the intersection of Memorial Dr. and B 8 (Figure 3.7). The soil was composed of silt and clay, and these materials make soil extremely sticky. In order to prevent soil sticking to auger during drilling, slurry is being used.

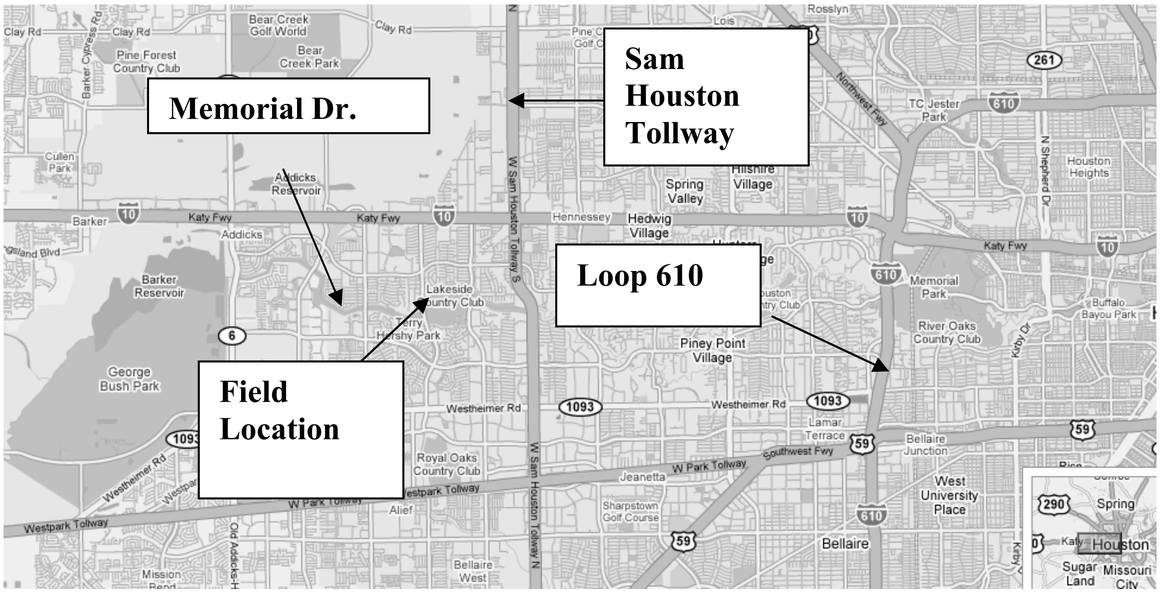


Figure 3.7 The Third Location of the DHP Test at Memorial Dr., Houston.
(Map courtesy of Google Maps)

Slurry is a mixture of bentonite and water to make drilling easy in clay soils. Because of slurry, the field conditions were really difficult for current penetrometers, but DHP can be easily handled in slurry conditions with the help of the steel box, which goes into the borehole (Figure 3.8).

DHP tests began with a spring that had 370 lb/in. stiffness. With this spring, the reader ring didn't move, meaning that the soil was softer than the capacity of this spring (Figure 3.9). The spring was replaced with another spring with a stiffness of 290 lb/in. (Figures 3.9 and 3.10). The spring produced a 1.35 inch deflection, and when the DHP test was repeated with the same spring a deflection of 1.21 was produced. Springs with a stiffness of 140 lb/in. and 110 lb/in. were used for other DHP tests (Figures 3.11 and 3.12). Two samples with a 20 in. height and 2.8 in. diameter were obtained for unconfined compression tests (Figures 3.13 and 3.14).

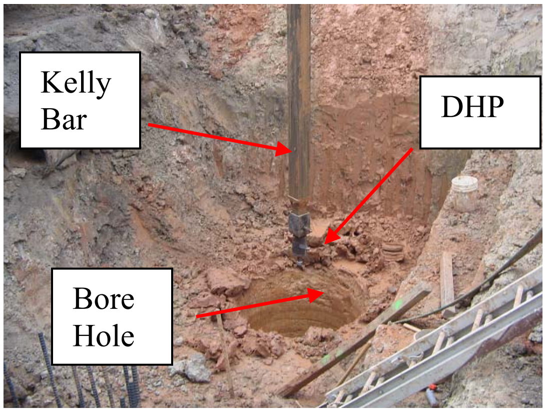


Figure 3.8 The DHP Going into the Borehole

Figure 3.9 After the test, changing the DHP for the Other Test

Figure 3.10 Spring Is Hooked on DHP

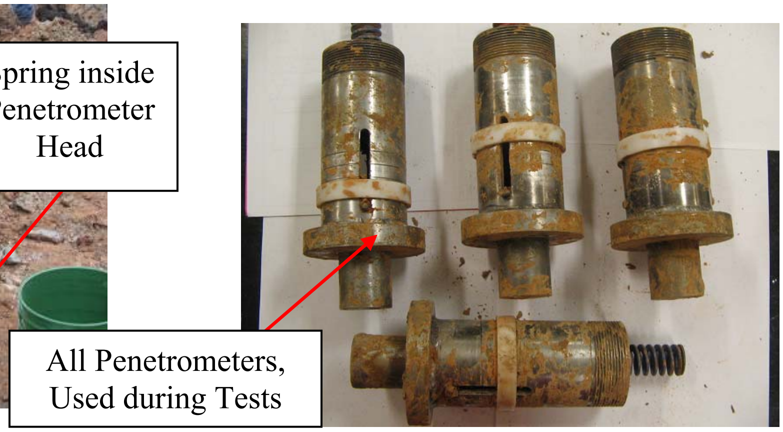


Figure 3.11 All DHPs Used in the Field Tests

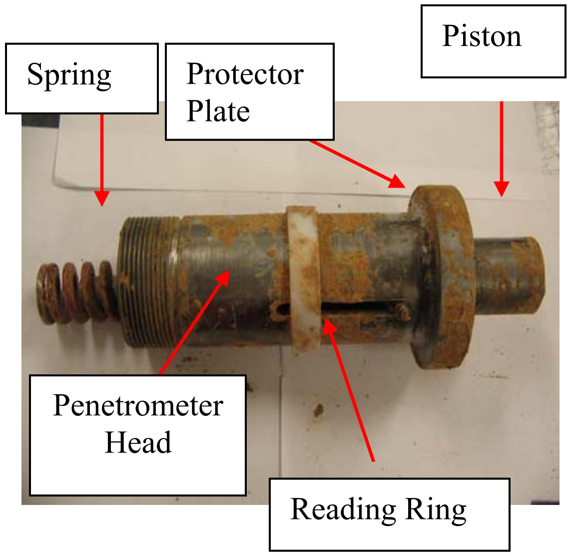


Figure 3.12 Schematic of a DHP after the Field Test

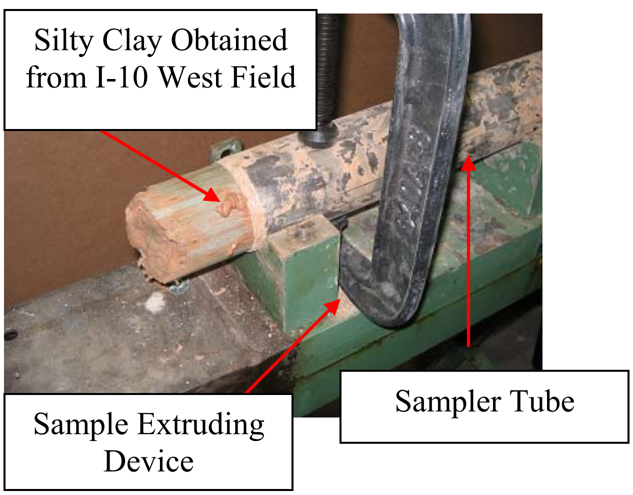


Figure 3.13 Extruding the Soil Samples

Figure 3.14 Extruded Sample

c) Location 4 (Houston Field at Goodyear Dr. (B6) (04/20/07))

The field test location was near the intersection of Loop 610 and Highway 225 (Figure 3.15). The soil was stiff clay. In order to prevent the collapse of the borehole during drilling, slurry was used. Slurry is a mixture of bentonite and water, and nothing can be seen in the borehole below the level of the slurry. The DHP was lowered through the slurry to perform the test (Figures 3.16 and 3.17).

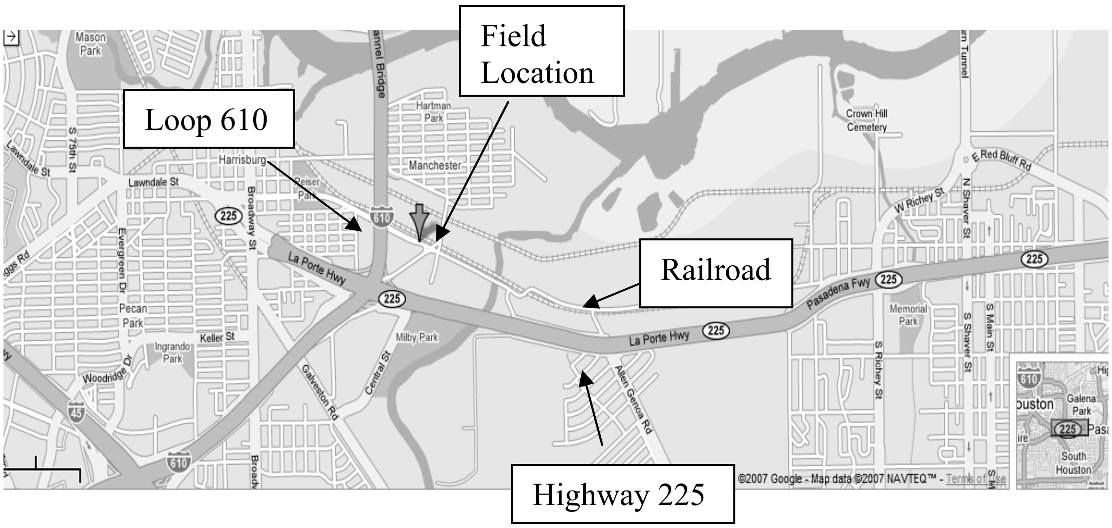


Figure 3.15 The Fourth Location of the DHP Test (Lawndale St., Houston).
(Map courtesy of Google Maps)

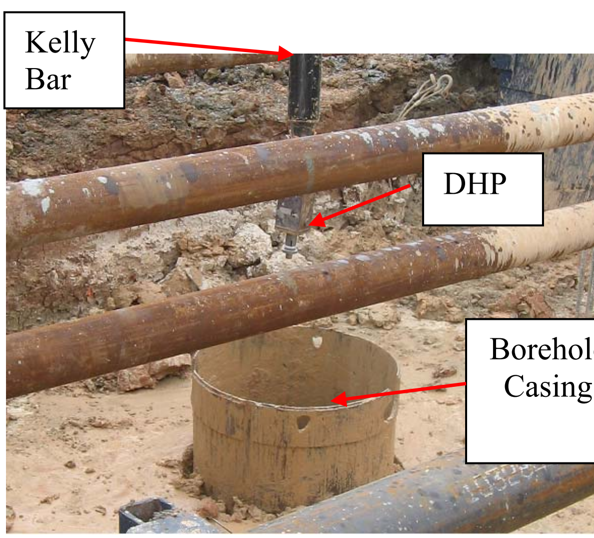


Figure 3.16 The DHP Being Lowered into the Borehole

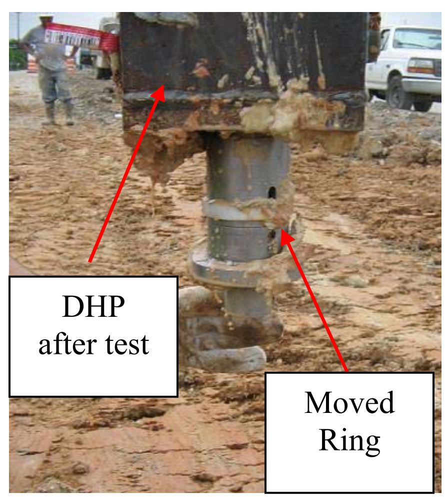


Figure 3.17 Moved Ring after Test.

Soil samples were collected from the bottom of the borehole. The extruded samples were trimmed to a size of 2.5 x 6 inches (Figure 3.18). Unconfined compression tests were performed using a standard triaxial test machine without confinement (Figure 3.19). The soil sample failed in shear (Figure 3.20).

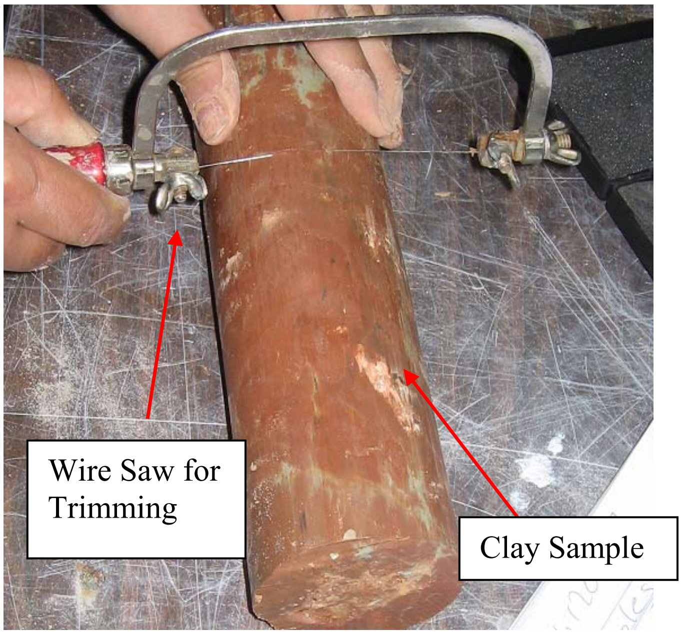


Figure 3.18 Trimming Clay Sample

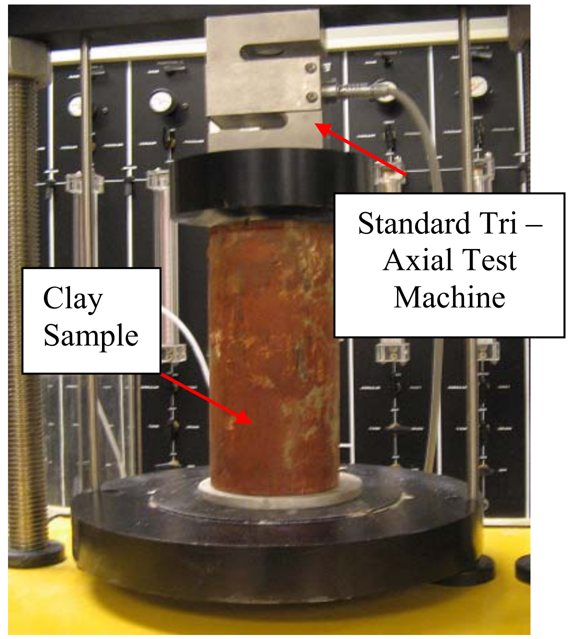


Figure 3.19 Clay Sample before Compression Test.

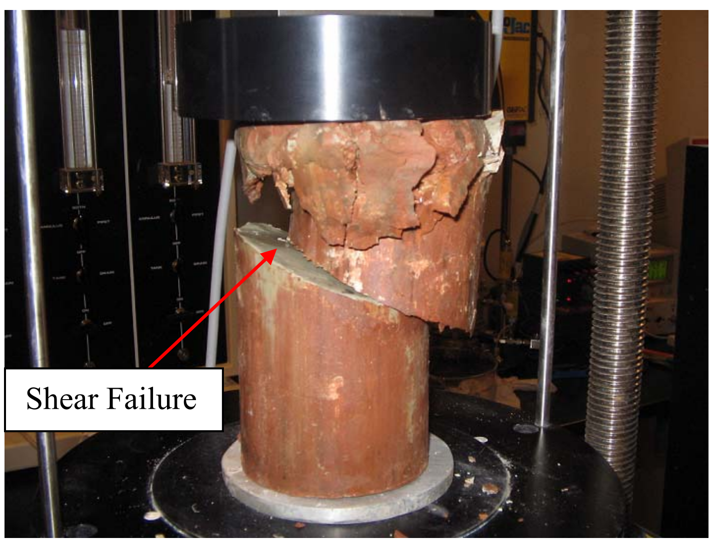


Figure 3.20 Clay Sample after failure

d) Location 5 (Intersection of I-30 and Loop 12 in Dallas (B7) (09/21/06 – 09/23/06))

The locations of the field tests were at the intersection of I-30 and Loop 12 and have been designated as B6 (Figures 3.21 and 3.22). Clay shale samples were obtained from these locations, and compression tests were conducted to obtain undrained shear strength.

Figure 3.21 Location of the DHP Test at the Intersection of I-30 and Loop 12, Dallas. (Map courtesy of Google Maps)

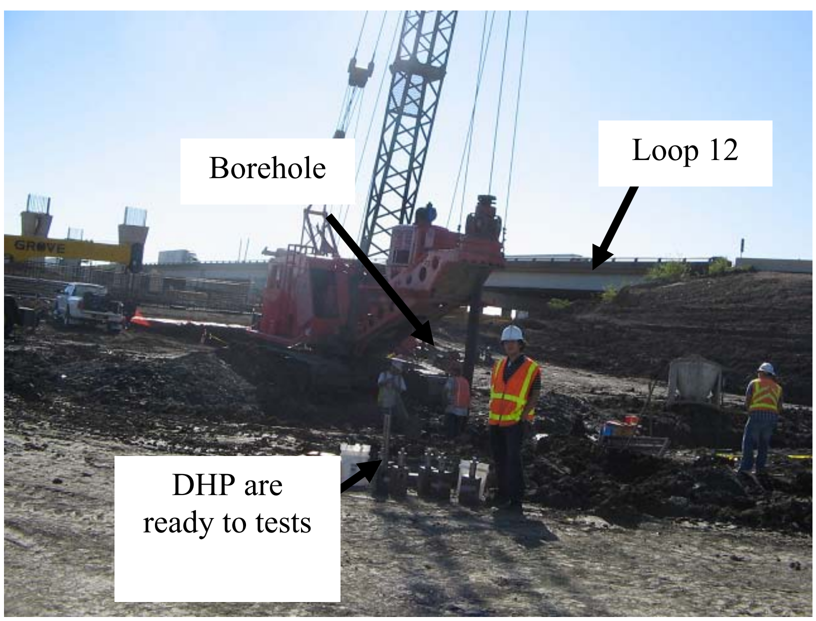


Figure 3.22 Dallas Field Location and Prepared DHP before Test

e) Location 6 (Dallas Field at Trinity Bridge (B8) (03/14/07 – 03/16/07))

The drilled shafts were being constructed for the reconstruction of Trinity Bridge at North Hampton, in Dallas (Figure 3.23). Because of the heavy rain on the previous day, the boreholes were filled with water so the construction was stopped for one day.

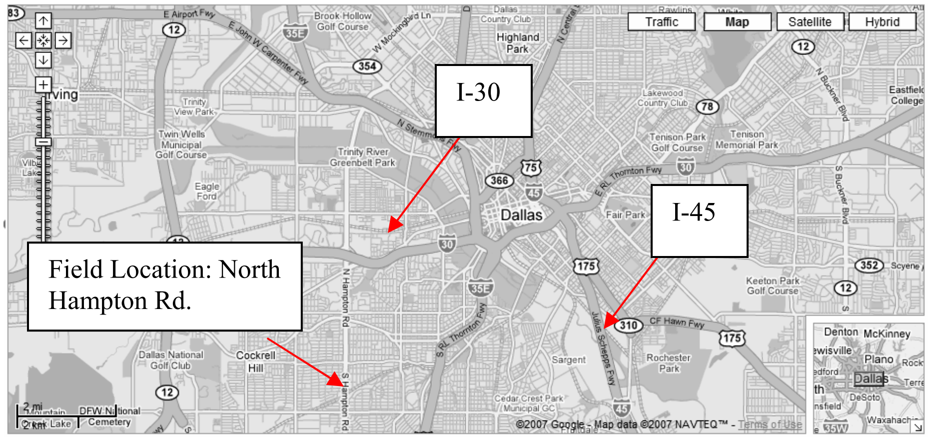


Figure 3.23 Location of the DHP Tests, at the Trinity Bridge, Dallas.
(Map courtesy of Google Maps)

Drilling began with a washer auger, where the water from the top level was taken away, and the auger was switched to a drilling auger. The clay shale layer was founded at 17 feet and for construction purposes, at least 30 foot of shaft was required to be in the clay shale. But, the soil was harder than expected so they had to use mirrors and ropes to keep the digging aligned to center, this precaution repeated for every movement of the auger. Two DHP tests were completed (Figure 3.24), and one sample was collected. After finishing the first borehole, DHP tests were conducted with the help of the construction crew (Figure 3.25).

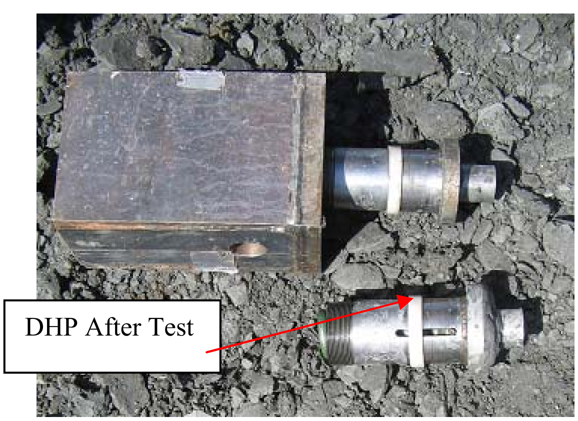


Figure 3.24 The DHP after Tests

Figure 3.25 DHP Taken Out of the borehole

Details of the drilled shafts at the test sites (Houston Field at the intersection of Memorial Dr. and Beltway 8 and Houston Field at Goodyear Dr., Dallas Field at the intersection of I-30 and Loop 12, Dallas Field at Trinity Bridge) are summarized in Table 3.5.

Table 3.5 Details of Four Boreholes in Which DHP Tests were Conducted

Location	Length of Borehole (ft)	Diameter of Borehole (in.)	Soil Description	TCP Blow Count	Slurry
B5	54	45	Silty Clay, Reddish Brown	18 (6) 24 (6)	Yes
B6	100	60	Silt, Reddish Brown	39 (6) 50 (6)	Yes
B7	56	45	Shale, Dark Gray	50 (1) 50 (3)	No
B8	53	48	Shale, Dark Gray	50 (4) 50 (4)	No

Table 3.6 illustrates the material properties of the clay samples obtained from the four locations.

Table 3.6 Geotechnical Properties of Natural Clay from Various Boreholes

Location	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Soil Classification
B5	35	69	34	CH
B6	19	50	31	CH
B7	24	56	32	CH
B8	24	54	30	CH

3.4 Correlations

(a) Undrained Shear Strength

The main focus of this study was to investigate the relationship between the undrained shear strength of soil/soft rock and the deflection obtained from DHP.

Figures 3.26 and 3.27 show the correlations of DHP deflection and undrained shear strength (S_u) of the geomaterials. Because of relatively high, stiffness the Green spring (1800 lb/in) was used for soft rocks and hard soils. Based on the linear regression analysis of the data, the following correlation was obtained for DHP deflection and undrained shear strength of soil:

$$s_u = 54.4\ \delta \qquad \text{(N=15 data)} \qquad (2)$$

The coefficient of variation (R^2) for this relationship was 0.57.

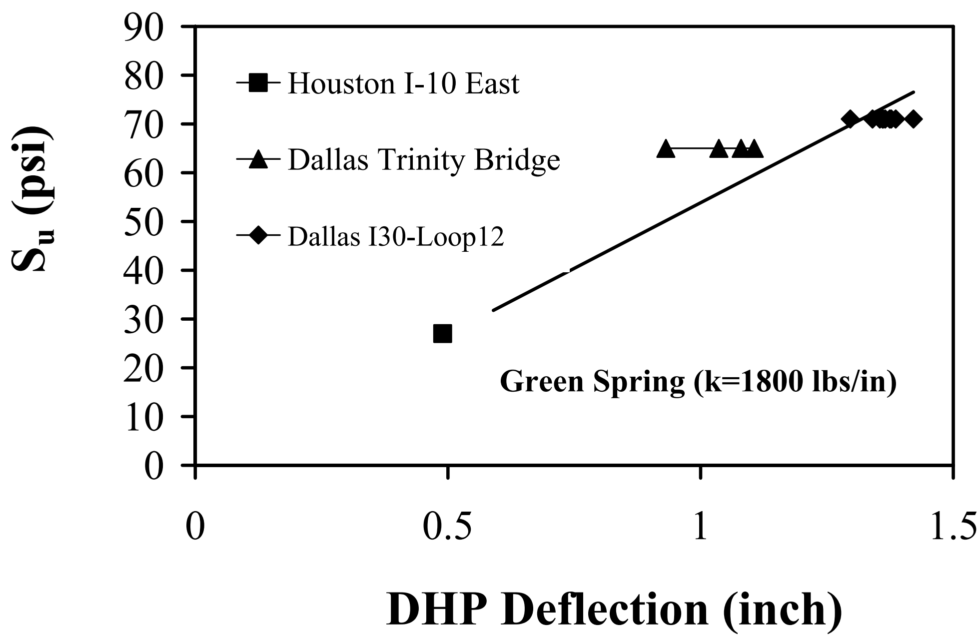


Figure 3.26 Undrained Shear Strength versus DHP Spring Deflection for Green Spring. (k=1800 lb/in.)

The Gold Spring had a stiffness (k) of 1100 lb/in. and was used for clay soils. Based on the linear regression analysis of the data, the following correlation was obtained for DHP deflection and undrained shear strength of soil:

$$S_u = 33.2\ \delta \qquad \text{(N=3 data)} \qquad (3)$$

The coefficient of variation (R^2) for this relationship was 0.91.

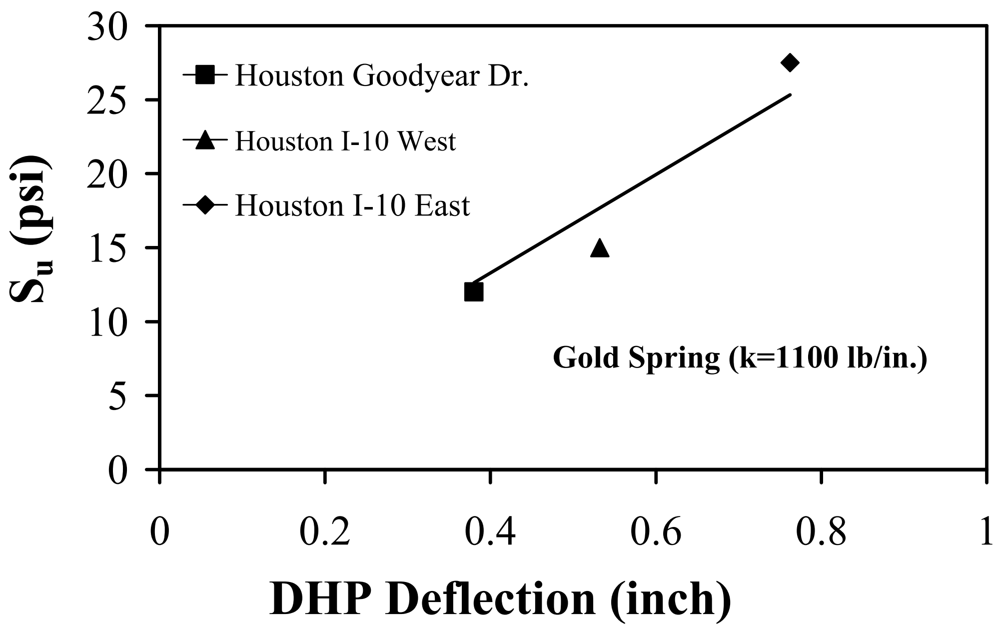


Figure 3.27 Undrained Shear Strength versus DHP Ultimate Strength Gold Spring (k=1100 lb/in.).

(b) TCP Value

The correlation between Texas Cone Penetrometer and DHP deflection was also investigated. Field tests performed in the Dallas and Houston areas were used for developing this relationship. Correlation between TCP blow counts (per 12 in penetration) to DHP deflection, obtained from the Houston District is shown in Figure 3.28. The relationship was represented with the following equation with a R^2 value of 0.63.

$$N_{TCP} = 65.5\ \delta, \quad (N = 4 \text{ data}) \tag{4}$$

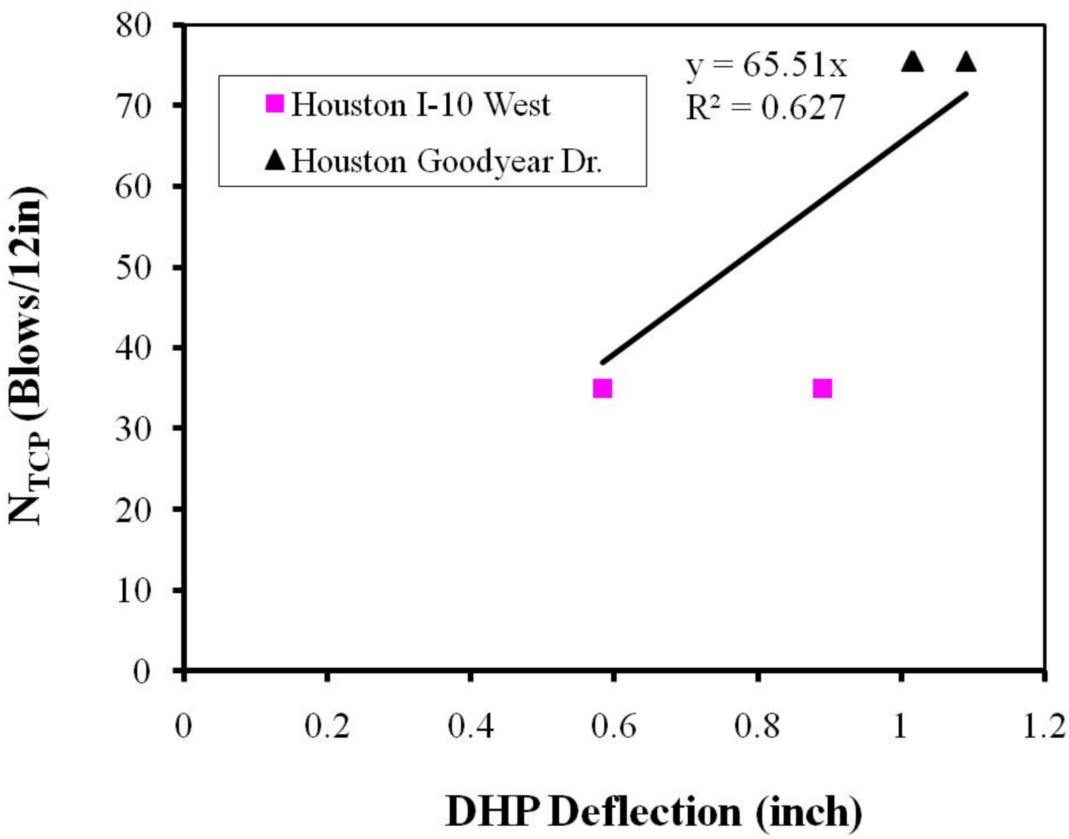


Figure 3.28 Correlation between DHP Deflection and N_{TCP} (Blows/12 in.)

Both linear and nonlinear correlations between TCP penetration per 100 blows to DHP deflection obtained from the Dallas District are shown in Figures 3.29 and 3.30 and represented as follows:

$$N_{TCP} = -3.9 \times \delta + 10.5, \qquad R^2 = 0.42, \qquad (N=14 \text{ data}) \qquad (5)$$

$$N_{TCP} = 6.6\ \delta^{-1.05}, \qquad R^2 = 0.51, \qquad (N=14 \text{ data}) \qquad (6)$$

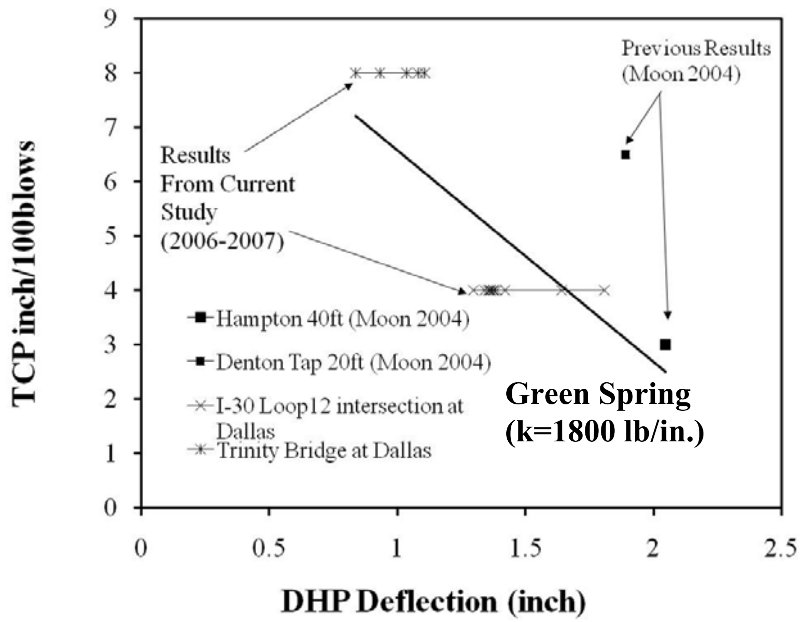


Figure 3.29 Correlation between DHP Deflection and N_{TCP} (in./100 blows)

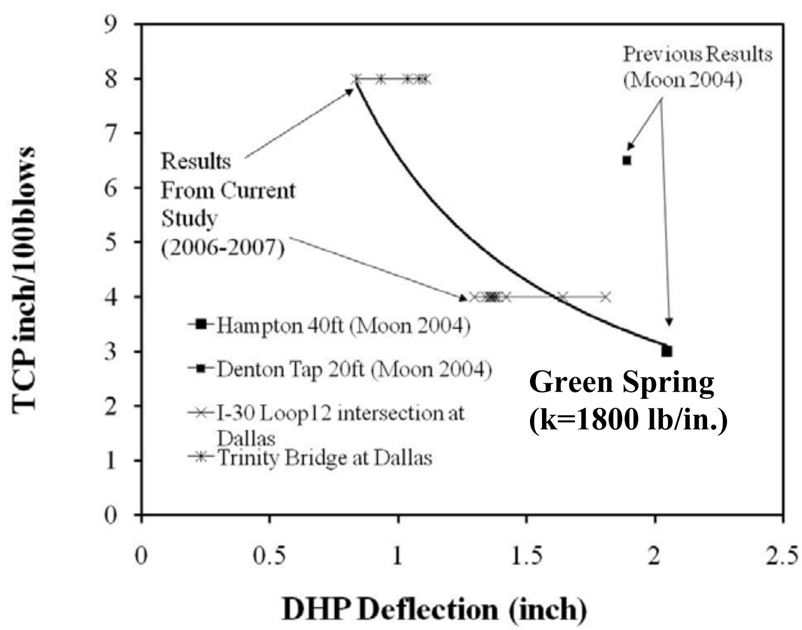


Figure 3.30 Correlation between Deflection and N_{TCP} (in./100 blows)

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The main focus of this study was to develop a new penetrometer, Down-Hole Penetrometer (DHP), for identifying the transition from hard soil to rock and measuring the ultimate strength of the geomaterials during drilled shaft constructions. DHP can be used to determine the undrained shear strength of soil from the ring displacement. Also, a correlation between TCP blow count and DHP spring deflection was developed based on the data collected from the Houston and Dallas Districts.

Based on the analyses of raw data and average values, the following relationships were developed for soils in the Houston District and soft rocks in the Dallas District.

a) Correlations of DHP deflections and undrained shear strength of the soil (28 psi $< S_u <$ 71 psi):

$S_u = 54.4\ \delta$ for Green Spring (k=1800 lb/in.) (N=15 data) (1)

b) for the soils with (12 psi $< S_u <$ 27 psi):

$S_u = 33.2\ \delta$ for Gold Spring (k=1100 lb/in.) (N=3 data) (2)

c) Least square fit of the data resulted in the following relationship between TCP blow count and DHP spring deflection (in soil):

$\delta = 65.5\ N_{TCP}$, $R^2 = 0.63$ (N=4 data) (3)

d) Linear correlation between TCP penetration per 100 blows to DHP deflection (soft rock):

$N_{TCP} = -3.9 \times \delta + 10.5$, $R^2 = 0.42$, (N=14 data) (4)

e) Nonlinear correlation between TCP penetration per 100 blows to DHP deflection (soft rock):

$N_{TCP} = 6.6\ \delta^{-1.05}$, $R^2 = 0.51$, (N=14 data) (5)

4.2 Recommendations

1. Correlations for DHP were developed based on limited testing. The researchers recommend additional field tests various soils and soft rocks to further improve the correlations.

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