ESTIMATION OF GRAIN CHARACTERISTICS OF SOILS BY USING CONE PENETRATION TEST (CPT) DATA

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ABSTRACT

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Due to lack of soil sampling during a conventional cone penetration testing (CPT), it is necessary to classify soils based on recorded tip and sleeve friction and pore pressure (if available) values. However, currently available soil classification models are based on deterministic and judgemental determination of soil classification boundaries which do not address the uncertainties intristic to the problem. Moreover, size and quality of databases used in the development of these soil classification models are undocumented and thus questionable. Similar limitations do also exist in the development of

SPT-CPT correlations which are widely used in SPT dominated design such as soil liquefaction triggering.

To eliminate these discussed limitations, within the confines of this study it is attempted to present (1) a new probabilistic CPT- based soil classification methodology, and (2) new SPT-CPT correlations which address the uncertainties intrinsic to the problems. For these purposes, a database composed of 400 CPT/SPT boring data pairs was compiled. It is intended to develop probabilistic models, which will correlate CPT tip and sleeve friction values to actual soil classification and CPT tip resistance to SPT blow count N.

The new set of correlations, model parameters of which estimated by implementing maximum likelihood methodology, presented herein are judged to represent a robust and defensible basis for (1) prediction of soil type based on CPT data and, (2) estimation of SPT-N value for given CPT data.

KEYWORDS: Cone penetration test, soil classification, standard penetration test, correlation, maximum likelihood methodology, limit state models.

ÖZ

KONİK PENETRASYON DENEYİ (CPT) VERİLERİNİ KULLANARAK ZEMİNLERİN DANE ÖZELLİKLERİNİN BELİRLENMESİ

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Konik penetrasyon deneyinde numune alınamaması nedeniyle zeminleri ölçülen uç direnci, zemin sürtünme direnci ve (varsa) boşluk suyu basıncı verilerine dayanarak sınıflandırmak gerekmektedir. Ancak, mevcut ve güncel zemin sınıflandırma modelleri deterministik ve yargısal esaslı olup, probleme ait belirsizlikleri göstermezler. Ayrıca, bu zemin sınıflandırma modellerini geliştirmek için kullanılan veritabanlarının büyüklüğü ve kalitesi belgelenmemiştir. Bu sebepten bu modellerin büyüklüğü ve kalitesi bilinmemektedir. Zemin sıvılaşma potansiyelinin belirlenmesi gibi SPT'ye

dayalı tasarı yöntemlerinde geniş olarak kullanılan mevcut SPT-CPT bağıntılarında da benzer sınırlamalar vardır.

Bu çalışmada, belirtilen sınırlamalardan kurtulmak için (1) yeni bir CPT'ye dayalı zemin sınıflandırma yöntemi ve (2) yeni SPT-CPT ilişkileri sunulmuştur. Sunulan çalışmalar problemlere ait belirsizlikleri göstermektedir. Bu amaçla 400 CPT/SPT sondaj veri çiftinden oluşan bir veri tabanı hazırlanmıştır. CPT uç ve sürtünme direnci verilerini gerçek zemin sınıflandırılması ile ve CPT uç direncini SPT vuruş sayısı, N ile ilişkilendirecek olasılıksal modeller oluşturulmak amaçlanmıştır.

Model değişkenleri, maksimum olasılık yöntemi kullanılarak bulunan yeni bağıntılar, (1) CPT verisi kullanılarak zemin tipi tahmini ve belirli CPT verisi için SPT-N değerinin belirlenmesi çalışmaları için sağlam ve tutarlı bir temel oluşturacak şekilde değerlendirilmiştir.

Anahtar kelimeler: Konik penetrasyon deneyi (CPT), zemin sınıflandırılması, standard penetrasyon deneyi, maximum olasılık yöntemi, limit durum modelleri.

To My Family

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Cone Penetration Test (CPT) is widely used as an in-situ penetration test for site investigation and geotechnical design purposes. Its standardized procedure and instruments, incorporated with modern electronics and technology, offer an in-situ test with many advantages such as simplicity, repeatibility, continuous logging and precision, over other penetration tests. Nevertheless, due to lack of soil sampling in conventional CPT and due to the necessity to use CPT data in Standard Penetration Test (SPT) based design and analysis methods, such as liquefaction susceptibility analysis, a good mapping between CPT and SPT is required.

In the past decades, CPT channel measurements versus soil type correlation and the relationship between CPT tip resistance and SPT blowcount N subjects have been studied by many researchers and several CPT based soil classification charts (Robertson and Wride (1997), Olsen and Mitchell (1995)) and SPT-CPT correlations (Kulhawy and Mayne (1990)) have been recommended.

1.2 RESEARCH STATEMENT

The goal of these studies is to develop probabilistically based correlations i) for the use of CPT to classify subsurface soils, and ii) between SPT-N and CPT channel measurements. For this purpose, a database composed of 400 CPT/boring data components of tip resistance (q_c), friction ratio (R_f), soil classification based on Unified Soil Classification System (USCS), fines content (FC), mean particle size (D_{50}) and SPT blow count value (N) was compiled.

1.3 SCOPE

Following this introduction, Chapter 2 presents an overview of : (1) available CPT-based soil classification charts, and (2) available SPT-CPT correlations. Limitations of existing charts and correlations are also discussed in this chapter.

Chapter 3 presents the procedures followed for processing data from penetration tests to compile a database.

Chapter 4 discusses the development of probabilistically-based (1) CPT soil classification boundary curves, and (2) SPT-CPT correlations.

Finally, a summary of the research, major conclusions, and recommendations for future areas of study are presented in Chapter 5.

CHAPTER 2

AN OVERVIEW OF AVAILABLE SOIL CLASSIFICATION METHODOLOGIES BASED ON CPT DATA AND SPT-CPT CORRELATIONS

2.1 CONE PENETRATION TEST (CPT)

In cone penetration test, a cone penetrometer connected to the tip of series of rods is hydralically pushed into the ground at a constant rate (2 cm/sec) and continuous resistance measurements of the cone penetrometer are recorded. The reference test instrument consist of a cone with 60^o apex angle and a diameter of 35.7 mm (10 cm^2 cross-sectional area) and a 150 cm^2 friction sleeve located above the cone. Resistance values are measured as the combined resistance to penetration of the cone as tip resistance (q_c) and the resistance of friction sleeve as friction resistance (f_s). Attaching additional sensors to CPT system to measure pore water pressure, verticality, shear wave velocity,etc. can also provide relevant data in addition to tip and friction resistances. Figure 2.1 illustrates the schematic view of a cone penetrometer probe.

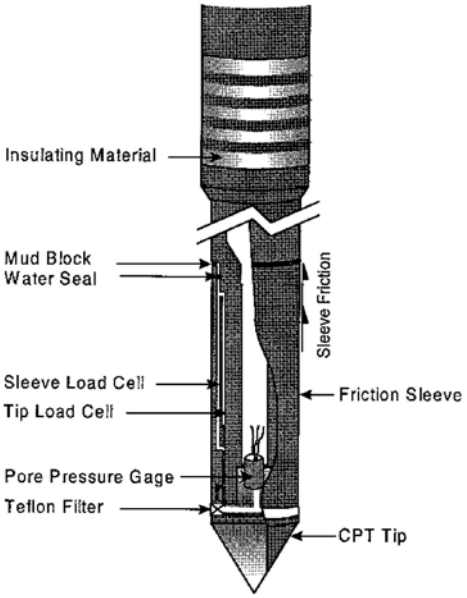


Figure 2.1: Schematic view of a cone penetrometer probe

2.1.1 CPT Corrections

When performing a CPT with pore water pressure measurement, due to the inner geometry of the cone penetrometer, the ambient pore water pressure causes additional resistance on the shoulder area behind the cone. This phenomenon is known as unequal area effect and reduce the measured tip resistance (Campanella et al.(1982)). A correction is necessary to take into account this unequal area effects as given in Equation (2.1):

$$q_t = q_c + u \cdot (1 - a) \tag{2.1}$$

where "q_t" and q_c" are corrected and measured tip resistances, respectively, "u" is pore water pressure acting behind the cone, and "a" is cone area ratio determined using calibration vessel.

Softer soil layers above and below the cone tip also affect the CPT data. Measured CPT tip resistance is smaller in thin layers of granular soils embedded within softer layers than in thicker layers of the same granular soils (Figure 2.2). Vreugdenhil et al. (1994) provided a procedure based on a simplified elastic solution for correcting the cone penetration resistance of thin stiff layers sandwiched between softer layers. According to this work, the error in the measured tip resistance is a function of the thickness and the relative stiffness of the thin stiff layer. Robertson and Fear (1995) recommended a conservative thin layer correction (corresponding to $q_{cA}/q_{cB} = 2$ curve sketched in Figure 2.2) derived based on Vreugdenhil et al. (1994) as:

$$q_c^{\,*} = K_H \cdot q_{cA} \tag{2.2}$$

where K_H is thin layer correction factor, $q_c^{\,*}$ is the corrected tip resistance and q_{cA} is tip resistance of the stiff layer.

According to NCEER (1998), $q_{cA}/q_{cB} = 2$ curve is not adequately conservative. Further analysis of field data by Gonzalo Castro and Peter Robertson for NCEER workshop indicate that the lower bound of the range of

field data plotted by G.Castro in Figure 2.3 provides more conservative K_H values and are used for these studies. The equation of the lower bound of the field curve is:

$$K_H = 0.25 \cdot (((H/d_c)/17) - 1.77)^2 + 1.0 \qquad (2.3)$$

where H is the thickness of the interbedded layer in mm, q_{cA} and q_{cB} is tip resistance of the stiff and soft layers, respectively, and d_c is diameter of the cone in mm.

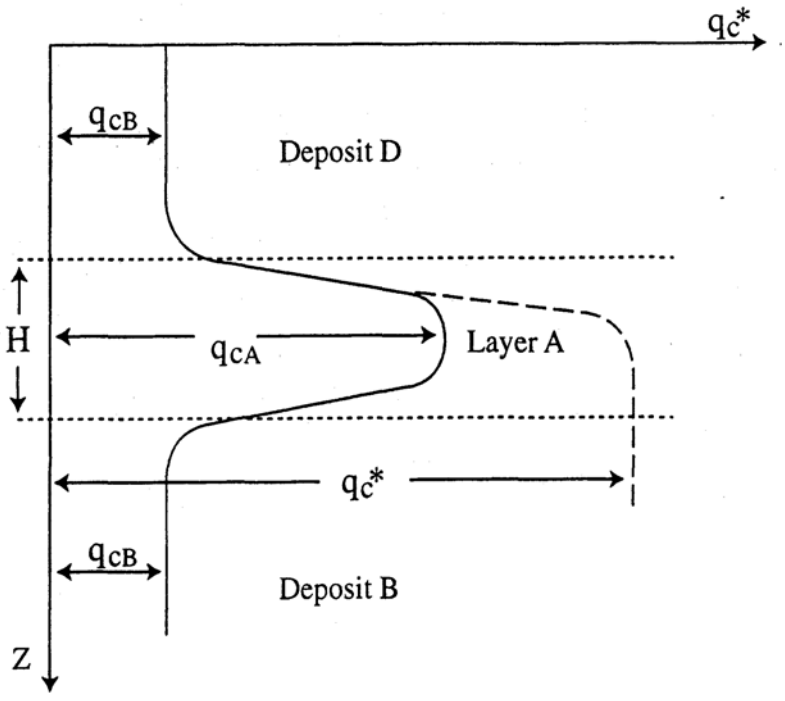


Figure 2.2: Illustration of thin layer correction

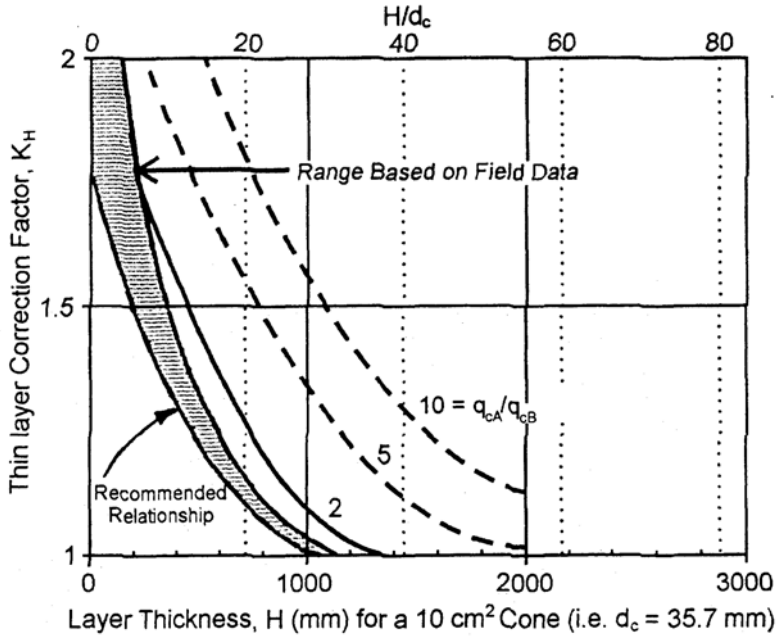


Figure 2.3: Thin-Layer correction factor K_H

2.2 STANDARD PENETRATION TEST (SPT)

The standard penetration test was developed in the United States in 1927 and is used worldwide to a greater extent than any other in-situ test. Ideally, the test is performed by dropping a free-falling hammer weighing 63.5 kg (~ 140 lb) on to the drill rods from a height of 760 mm (~30 in.). The number of blows necessary to achieve a penetration of 30 cm (after a seating drive of 15 cm) of a standard sample tube is defined as the penetration resistance or SPT-N value. Sample of soil, usually obtained during test, can be used to perform laboratory tests for the estimation of soil type, index properties, particle size distribution, etc.

It has been addressed by many researchers that the standard penetration test has been in fact conventionally performed by using different kinds of hammers in different parts of the world, with different energy delivery systems which also have varying degrees of efficiency. Additionally, the borehole diameters and the sampling techniques also differ significantly, which in turn cause a large variability in the measured values depending on the combinations of actual test procedures and equipment used.

Schmertmann (1976) and Kovacs et al. (1983) have shown that the actual energy delivered to the sampler rods in performing SPT in different areas of the world may vary between 40% to 90% of the theoretical free-fall energy intended to be delivered by the falling hammer. Depending on the amount of energy applied by the hammer, the results may differ significantly. Schmertmann (1976), and Palacios (1977), based on theoretical and field studies, summarized the most important factors that may influence the results of a SPT test as: (1) the use of drilling mud vs. casing for supporting the walls of the drill hole; (2) the use of a hollow stem auger versus casing and water; (3) the size of the drill hole; (4) the number of turns of the rope around the drum; (5) the use of a small or a large anvil; (6) the length of the drive rods; (7) the use of nonstandard sampling tubes; (8) the depth range over which the penetration resistance is measured. Additional researchers have since added : (1) varying mechanisms used to raise and drop the hammer, (2) hammer type, and (3) and length and diameter of rods between the impacting hammer and the sampler.

How to correct for all the deviations in the SPT procedures from the "standard" procedure has been resolved after NCEER (1997). A consensus among expert panel members has been achieved and a series of recommendations were presented, which will be discussed later in this chapter.

2.2.1 SPT Corrections

The measured SPT resistance needs to be corrected to account for overburden stress. As a definition, "normalized" SPT blowcounts (N_1-values) correspond to the SPT resistance (N values) corrected to values that would have been measured under 100 kPa vertical effective stress as:

$$N_1 = C_N \cdot N \tag{2.4}$$

where C_N is an effective overburden-based correction factor. This factor is commonly calculated from the equation (Liao and Whitman (1986)) given in Table 2.1.

The length of the drill rods, the diameter of the borehole and sampler type also affect the SPT data. Wave equation studies (Schmertman and Palacios (1979)) show that the theoretical maximum energy ratio decreases with decreasing rod length, especially if rod length is less than about 10 m. This decrease in measured energy is due to the rapid return of the tension wave before all the hammer energy can be transmitted to the rods. Similarly, if borehole diameter larger than the standard borehole diameter of 65-115 mm is

drilled then the SPT measurements can be off as much as 15 %. Removing the liners from SPT sampler designed for liners improves sample recovery but reduces the measured blowcount by about %20 due to higher frictional resistance inside sampler.

As was briefly listed in Section 2.2, any combination of SPT equipment procedures other than the "standardized" ones (Table 2.1) requires a correction for the measured SPT resistance. The NCEER (1997) suggested-corrections need to be performed as stated by:

$$N_{1,60} = N \cdot C_N \cdot C_E \cdot C_B \cdot C_R \cdot C_S \tag{2.5}$$

where N is the in-situ measured SPT blowcounts obtained by driving a standard sampling tube 30 cm into the ground.

Energy delivered from hammer to SPT rods can be measured by instrumenting a portion of rod string with 2 strain gauges and 2 accelerometers between anvil and rods. Using the energy ratio (ER), the ratio of delivered hammer energy to theoretical potential energy of free-falling hammer, and Equation (2.6) as recommended by Seed et al. (1985), the blowcount normalized to 60% of the theoretical energy, N_{60} can be computed as:

$$N_{60} = N_{field} \cdot \frac{ER}{60} \tag{2.6}$$

and as a consequence Equation (2.5) reduces to:

$$N_{1,60} = N_{60} \cdot C_N \cdot C_B \cdot C_S \qquad (2.7)$$

Table 2.1: Summary of the correction factors for SPT measurements (After 1997 NCEER Workshop)

Factor	Term	Equipment Variable	Correction
Overburden Pressure	C_N	-	$(P_a/\sigma'_v)^{0.5}$ $C_N \leq 2$
Energy Ratio	C_E	Safety Hammer Donut Hammer	0.60-1.17 0.45-1.00
Borehole Diameter	C_B	65-115 mm 150 mm 200 mm	1.00 1.05 1.15
Rod Length	C_R	3-4 m 4-6 m 6-10 m 10-30 m > 30 m	0.75 0.85 0.95 1.0 < 1.0
Sampling Method	C_S	Standard Sampler Sampler without liners	1.0 1.15-1.30

2.3 SOIL CLASSIFICATION BASED on CPT DATA

2.3.1 Robertson and Wride (1997) CPT-Based Soil Classification Chart

It is possible to estimate the grain characteristics of soils directly from CPT results using the soil behaviour type chart shown in Figure 2.4 (Robertson (1990)), constructed based on field data and experiences of authors.

The boundaries between soil behaviour type zones 2-7 can be approximated as concentric circles (Jefferies and Davies (1993)). The radius of these circles, termed the soil behavior type index I_C (Robertson and Wride (1997)) is calculated from the following equation:

$$I_C = \left[(3.47 - \log Q)^2 + (\log F + 1.22)^2\right]^{0.5} \tag{2.8}$$

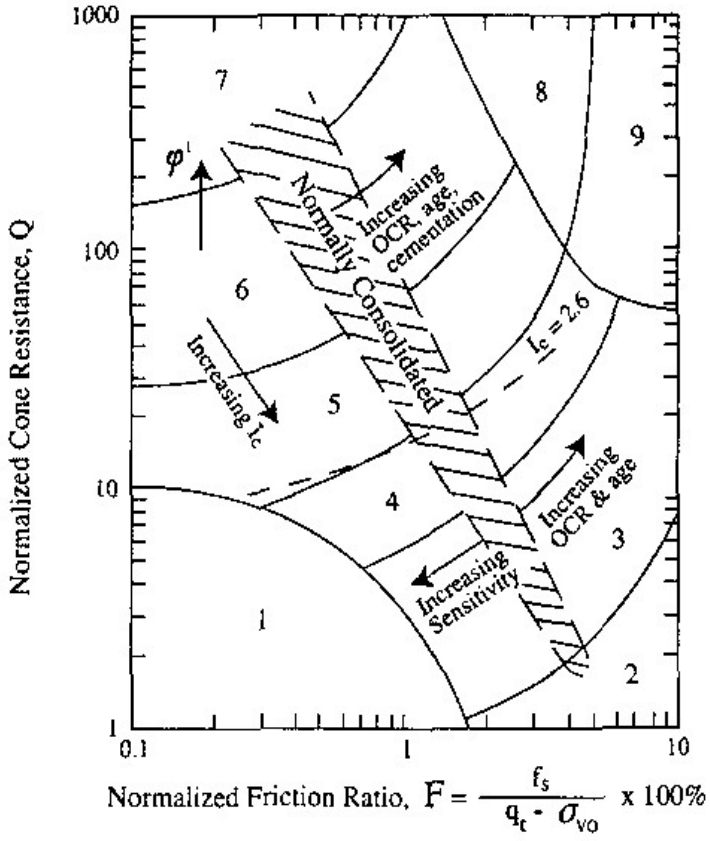
where

$$Q = (q_c - \sigma_{vo})/Pa \times (Pa / \sigma'_{vo})^n \tag{2.9}$$

and

$$F = \left[f_s/(q_c - \sigma_{vo})\right] \times 100\,\% \tag{2.10}$$

where Q is the normalized tip resistance, dimensionless; F is the normalized friction ratio, in percent; σ_{vo} and σ'_{vo} are the total and effective overburden stresses, respectively; Pa is the reference pressure, equal to 100 kPa.



1. Sensitive, fine grained
2. Organic soils - peats
3. Clays - silty clay to clay
4. Silt mixtures - clayey silt to silty clay
5. Sand mixtures - silty sand to sandy silt
6. Sands - clean sand to silty sand
7. Gravelly sand to dense sand
8. Very stiff sand to clayey sand*
9. Very stiff, fine grained*

**Heavily overconsolidated or cemented*

Figure 2.4: CPT-based soil classification chart (Robertson (1990))

The value of the exponent "n" in Equation (2.9) varies from 0.5 to 1.0 depending on the grain characteristics of soils (Olsen (1997)). However, the soil behavior chart in Figure 2.4 was developed using an exponent of 1.0, which is the appropriate value for clayey soil types. For clean sands an exponent value of 0.5 is more appropriate, and a value intermediate between

0.5 and 1.0 would be appropriate for silts and sandy silts. Robertson and Wride (1997) recommended the following procedure for calculating the soil behavior type index I_C. The first step is to differentiate soil types characterized as clays from soil types characterized as sands and silts. The recommended procedure is performed by assuming an exponent n of 1.0 and calculating the dimensionless normalized tip resistance Q and the initial value of I_C. If calculated I_C is greater than 2.6, the soil is classified as clayey. This value of I_C is used to estimate soil type. However, if the I_C calculated with exponent of 1.0 is less than 2.6, Q should be recalculated using an exponent n of 0.5. I_C should then be recalculated using Equation (2.7). If recalculated remains I_C less than 2.6, the soil is defined as nonplastic and granular. This I_C is used to estimate soil type. However, If I_C iterates above and below a value of 2.6, the soil is likely to be very silty and possibly plastic. At this instant, normalized, dimensionless cone tip resistance (q_{c1N}) should be recalculated by using Equation (2.11) using an intermadiate exponent n of 0.7 as given in Equation (2.12).

$$q_{c1N} = C_Q (q_c / Pa) \tag{2.11}$$

where

$$C_Q = (Pa / \sigma'_{vo})^n \tag{2.12}$$

and where C_Q is the normalization factor for cone tip resistance (At shallow depths C_Q becomes large because of low overburden pressure; however, values >1.7 should not be applied for design purposes). I_C is then recalculated from Equation (2.8) using recalculated value of q_{c1N}. This intermediate I_C is then used to predict soil type.

The boundaries of soil behavior type are given in terms of the index, I_C, as shown in Table 2.2. The soil behavior type index does not apply to zones 1,8 and 9.

Table 2.2: Boundaries of soil behavior type (after Robertson (1990))

Soil Behavior Type Index, I_C	Zone	Soil Behavior Type
I_C <1.31	7	Gravelly sand to dense sand
1.31< I_C <2.05	6	Sands: clean sand to silty sand
2.05< I_C <2.60	5	Sand Mixtures: silty sand to sandy silt
2.60< I_C <2.95	4	Silt Mixtures: clayey silt to silty clay
2.95< I_C <3.60	3	Clays: silty clay to clay
3.60< I_C	2	Organic soils: peats

2.3.2 Olsen and Mitchell (1995) CPT-Based Soil Classification Chart

The CPT soil classification chart in Figure 2.5, developed by Olsen and Mitchell (1995) using a large database of CPT/boring database, is based on a new cone penetration resistance normalization technique.

According to the new normalization technique, based on stress focus concept, the trends of cone resistance with effective stress can be described using a variable stress exponent which provides a better undestanding of the exponential relationship of cone resistance with vertical effective stress(Olsen (1994)). Normalized tip and friction resistances, recommended to be used in Figure 2.5, are described as:

$$q_{c1e} = \frac{(q_c - \sigma_{vo})}{(\sigma'_{vo})^c} = \frac{(q_c)_{net}}{(\sigma'_{vo})^c} \tag{2.13}$$

$$f_{s1e} = \frac{f_s}{(\sigma'_{vo})^s} \tag{2.14}$$

$$FR = \frac{f_{s1e}}{q_{c1e}} \times 100 \cong \frac{f_s}{q_c} \times 100 \tag{2.15}$$

where σ_{vo} and σ'_{vo} are the total and effective overburden stresses; q_{c1e} is the normalized tip resistance; f_{s1e} is the normalized friction resistance; FR (or R_f) is friction ratio; c is cone resistance stress exponent; s is sleeve stress exponent (approximately equal to c).

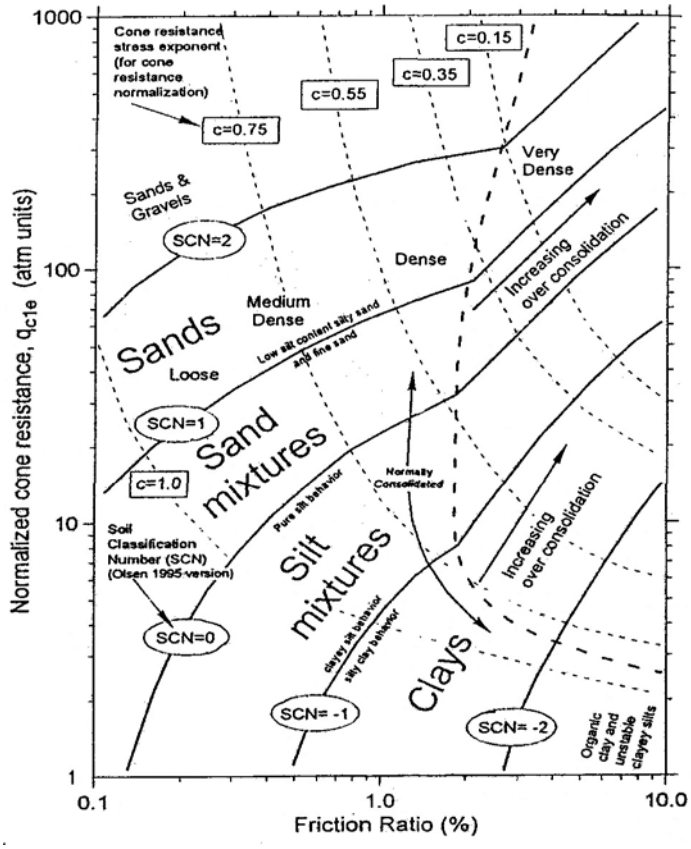


Figure 2.5: CPT-based soil classification chart (Olsen (1994))

Stress exponent contours, given in Figure 2.5, are used to determine the stress exponent for normalization of tip resistance given in (2.13). These cone resistance stress exponent contours exhibit several predictable trends; (1) high values for loose sands, (2) very low values for over-consolidated sands, (3) values of approximately 1.0 for normally consolidated clays, (4) values slightly below unity (0.75-0.9) for slightly over-consolidated clays, (5) values as high as 1.2 for unstable silty clay mixtures. An iterative solution is required for

normalization procedure. Initially, a stress exponent is assumed and the q_{c1e} is calculated using Equation (2.13). The resulting q_{c1e} and calculated friction ratio are used to determine the chart-based contour stress exponent from Figure 2.5. If chart-based stress exponent is not equal to the assumed stress exponent, a new assumed value must be tried. About 3 to 9 iterations are usually required until the chart-based value is sufficiently close to the assumed value. Completing iterations, final q_{c1e} value and friction ratio is used to predict soil classification from Figure 2.5.

In Figure 2.5, soil classification number (SCN) = 0 represents a pure silt, SCN = 1 represents a fine sand or low silt content silty sand, and finally SCN = -1 represents the boundary between silty clay and clayey silt. As a result, SCN's greater than 1 represent sand and SCN's less than –1 represent clay. The boundary between normally consalidated and over consalidated soils are also shown in Figure 2.5 together with the trends for increasing over consalidation. Soil classification descriptions are also shown near SCN boundaries.

2.3.3 Limitations of Available CPT-Based Soil Classification Charts

To eliminate the disadvantage of CPT stated as lack of soil sampling, researchers have tried to develop a standard CPT-based soil classification technique. Normalized CPT data-based soil classification charts presented in Section 2.3 (Robertson and Wride (1997) and Olsen and Mitchell (1995))

largely dominate the current practice in the use of CPT to predict soil classification. Presented charts have been widely accepted and used in practice, however suggested deterministic soil classification zones in both charts do not address the uncertainties in the locations and the forms of these boundaries. Also in both charts, soil classification boundaries, separating soil classification zones, are determined based on engineering judgements and experiences of authors which provide no quantifiable insight into the problem. Moreover, size and quality of data bases of both charts, used to produce soil classification boundaries, are unknown and questionable since CPT/boring databases were not presented with proposed soil classification methods.

2.4 SPT-CPT CORRELATIONS

A number of studies have been presented over years to relate the SPT-N value to CPT tip resistance. Robertson et al. (1983) reviewed these correlations and presented the relationship shown in Figure 2.6 relating $(q_c / Pa) / N_{60}$ ratios with the mean particle size, D_{50}. q_c values are normalized by reference pressure Pa (100 kPa). It is observed that $(q_c / Pa) / N_{60}$ ratio exponentially increases with increasing particle size.

Kulhawy and Mayne (1990) gathered the databases of Robertson and Campanella (1983), Zervogiannis and Kalteziotis (1988), Chin et al. (1988), Jamiolkowski et al. (1985), Andrus and Youd (1987), Kasim et al. (1986), Seed and deAlba (1986) and Muromachi (1981) and proposed a $(q_c / Pa) / N$ - D_{50} correlation, given in Figure 2.7.

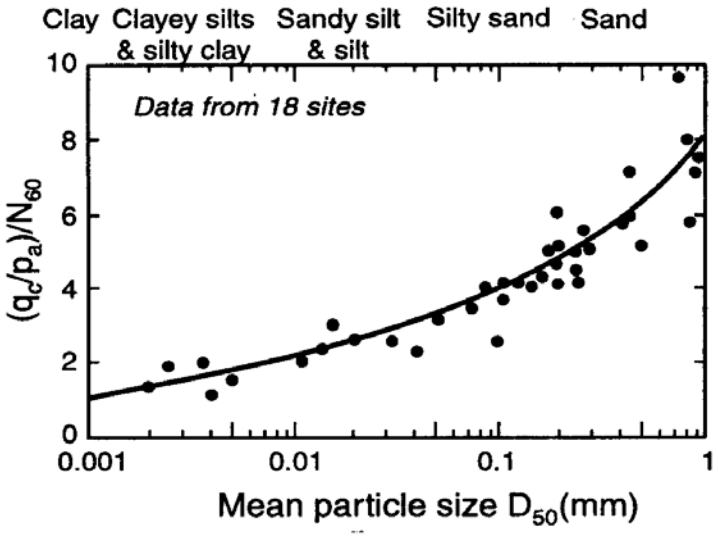


Figure 2.6: CPT-SPT correlation with grain size

(Robertson et al.(1983))

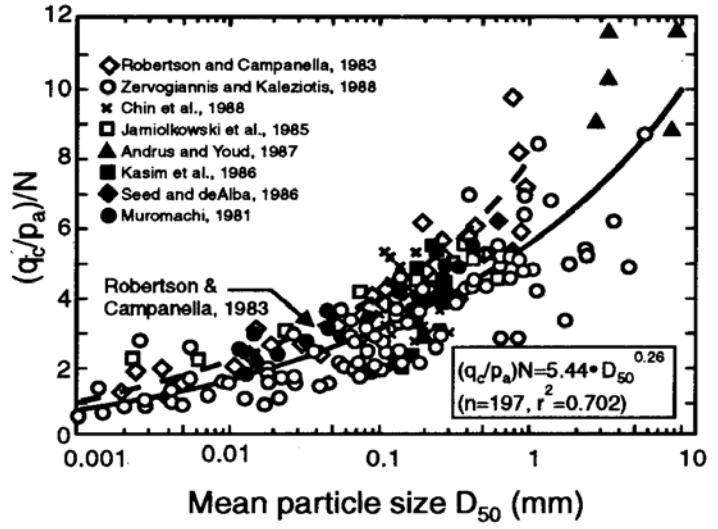


Figure 2.7: CPT-SPT correlation with grain size

(Kulhawy and Mayne (1990))

In other studies, relationship between $(q_c / Pa) / N$ ratio and fines content (FC) investigated by Jamiolkowski et al. (1985), Kasim et al. (1986), Muromachi (1981), Chin et al. (1988). Kulhawy and Mayne (1990) also gathered the databases of these studies and presented a correlation relating $(q_c / Pa) / N$ ratios with the fines contect. As seen in Figure 2.8, $(q_c / Pa) / N$ ratio decreases with increasing fines content.

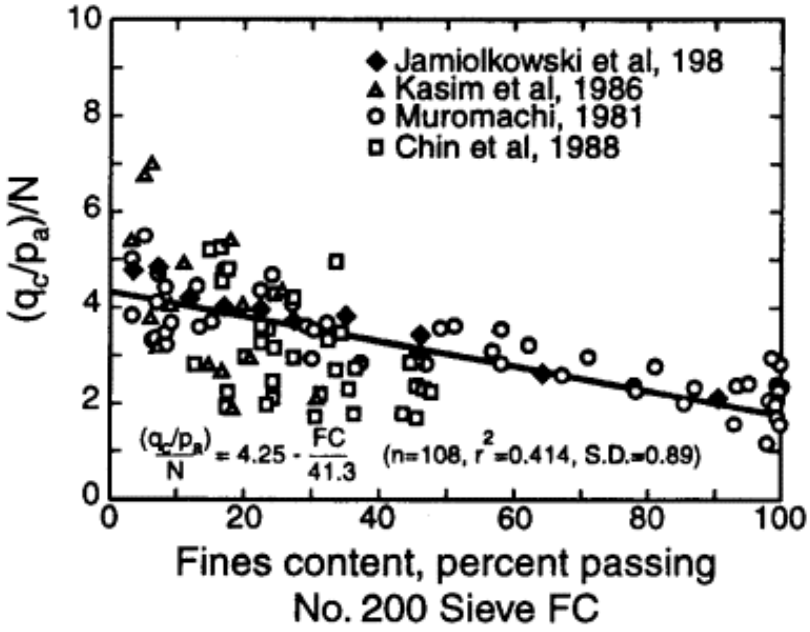


Figure 2.8: CPT-SPT correlation with fines content

(Kulhawy and Mayne (1990))

Inspired by Jefferies and Davies (1993), Peter Robertson combined the soil classification chart shown in Figure 2.4 and the correlation given in Figure 2.6 to provide a continuous variation of $(q_c / Pa) / N_{60}$ with soil type as given in Equation (2.13).

$$(q_c / Pa) / N_{60} = 8.5(1 - I_C / 4.6) \tag{2.16}$$

where I_C is soil behavior type index as defined in Equation (2.8)

This equation (2.16) suggests a simple method to estimate the SPT-N value from CPT results. Jefferies and Davies (1993) suggested that the SPT values estimated by using Equation (16) and CPT data are more reliable than SPT-N values obtained after a SPT.

2.4.1 Limitations of Available SPT-CPT Correlations

Due to the necessity to use CPT data in Standard Penetration Test (SPT) data based design and analysis correlations, SPT-CPT correlations have been a topic of considerable interest in the past decades. In general, assuming a linear relationship between q_c and N, variation of $(q_c / Pa) / N$ ratio as a function of grain charateristics has been searched.

Kulhawy and Mayne (1990) compiled a database from past SPT-CPT correlation studies and recommended a SPT-CPT correlation with D_{50} (Figure 2.7) and a SPT-CPT correlation with fines content (Figure 2.8).

However, compiled database did not define the energy ratio of SPT data. In other words, in proposed correlations SPT-N values do not correspond to an energy ratio of 60 % (that is N_{60}). Moreover, correlation shown in Figure 2.7 relating $(q_c / Pa) / N$ ratios with the mean particle size has relatively little data for the soils with D_{50} values of 1 to 10. Similary, SPT-CPT correlation in Figure 2.8 suffers the same problem for soils with 55 to 90 %fines content values. All these limitations address the need to develop a probabilisticly-based SPT-CPT correlation based on “high quality” database.

CHAPTER 3

CPT-BASED SOIL CLASSIFICATION AND SPT-CPT CORRELATION DATABASES

3.1 EVALUATION OF CPT AND SPT MEASUREMENTS

For assessing the CPT-based soil classification and SPT-CPT correlation models, a database of 400 CPT/SPT-boring data pairs composed of tip resistance (q_c), friction ratio (R_f) and soil classification based on Unified Soil Classification System (USCS), fines content (FC), mean particle size (D_{50}) and SPT blow count value (N) was compiled. CPT and SPT data was obtained from 3 different databases that are: (1) Pasific Earthquake Researh Center (PEER), Turkey Ground Failure (August 1999 Earthquakes) Database, (2) Karaca (2001) and, (3) Buski-East Waste Water Treatment Plant Project.

Pasific Earthquake Researh Center (PEER), Turkey Ground Failure (August 1999 Earthquakes) Database was originated from site investigation studies performed in Adapazari and İzmit Bay after 17 August 1999 Kocaeli Earthquake as a consequence of the joint research supported by University of California, Berkeley, Brigham Young University, University of California, Los

Angeles, ZETAŞ, SAU and METU. A rope and 2 1/4 turns on a clockwise rotating cathead system was used to perform the standard penetration test. The driving energy was delivered by the 76 cm-high drop of a safety hammer weighing approximately 63.5 kgf. CPT's were performed using an electronic cone penetrometer probe. Soil classification was performed based on Unified Soil Classification System (USCS) as discussed in Wagner (1957) by laboratory testing of the disturbed samples retrieved from the boreholes. Mean grain size and percent fines content values of retrieved samples were estimated by sieve analysis as described in ASTM D-442-63.

Karaca (2001) performed site investigation studies composed of 8 SPT and 6 CPT, performed by ZMG corp., to study the large vertical displacements experienced by structures in Adapazari during 17 August 1999 Kocaeli Earthquake. SPT was performed by a rope and cathead system and a donut hammer and CPT was performed using an electronic cone penetrometer probe.

Finally, Buski-East Waste Water Treatment Plant Project Database was originated from site investigation studies performed in Bursa. In situ and laboratory tests were performed by ERBEY and PROTEST. An electronic cone penetrometer probe was used to perform CPT. SPT results and CPT profiles are presented in Appendix B and Appendix C, respectively.

In order to develop a good mapping between SPT and CPT, after a sensitive study, 65 CPT logs were matched with 65 boreholes within 2 m of each CPT hole to form data pairs, tabulated in Appendix A. 50 out of 65 data

pairs were gathered from PEER, Turkey Ground Failure (August 1999 Earthquakes) Database, 13 from Buski-East Waste Water Treatment Plant Project Database and 2 from Karaca (2001). After having compiled data pairs, necessary correction were applied to CPT and SPT data as described in Section 2.1.1 and Section 2.2.1, respectively.

Since cone penetration test responds to soil and delivers data approximately every 2 cm, whereas data obtained in SPT (soil classification based on (USCS), fines content (FC), mean particle size (D_{50})) are defined over a 30 cm length, to smooth the detail in CPT and to determine representative CPT values for corresponding SPT pair, measured CPT data is algebraically averaged over the depth internal corresponding to the SPT (that is, 30 cm) on all two CPT data channels, tip resistance (q_c), friction ratio (R_f) as shown in Figure 3.1.

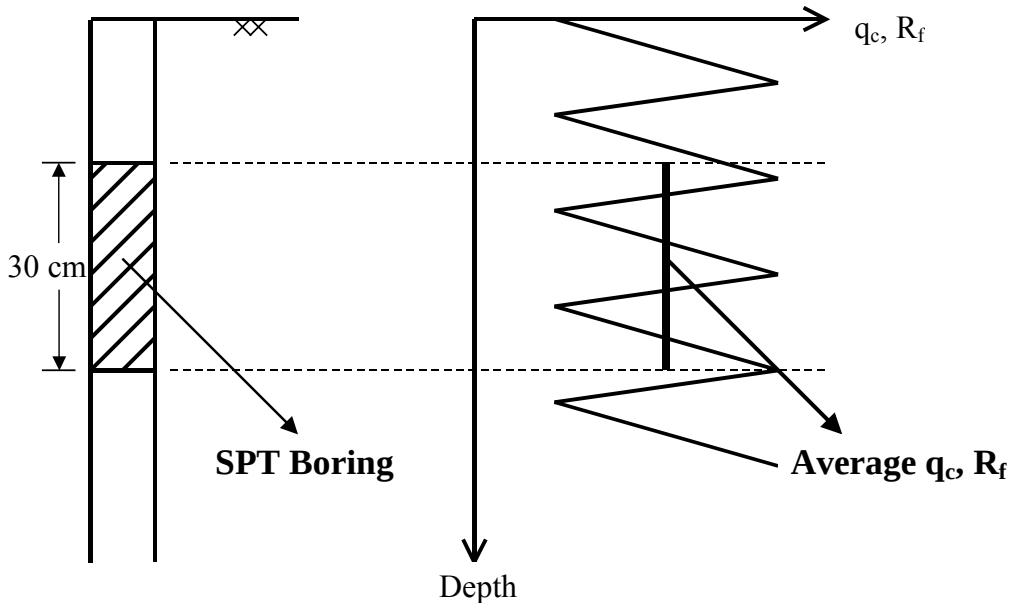


Figure 3.1: Illustration of determining representative CPT measurements

Figure 3.2 summarizes compiled CPT/boring database. Circles represent clayey soils, triangles represent silt and silt mixtures, and finally squares represent sand and sand mixtures. Database presented in Figure 3.2 is used to determine soil classification boundaries by using maximum likelihood methodology, which will be discussed in Chapter 4.

Figure 3.3 presents the distribution of $(q_c / Pa) / N_{60}$ ratio with mean particle size D_{50}, varying between 0.001 and 10 mm. $(q_c / Pa) / N_{60}$ increases with increasing D_{50}. Moreover, the distribution shows an increasing scatter with increasing D_{50}, especially for greater than about 0.1 mm.

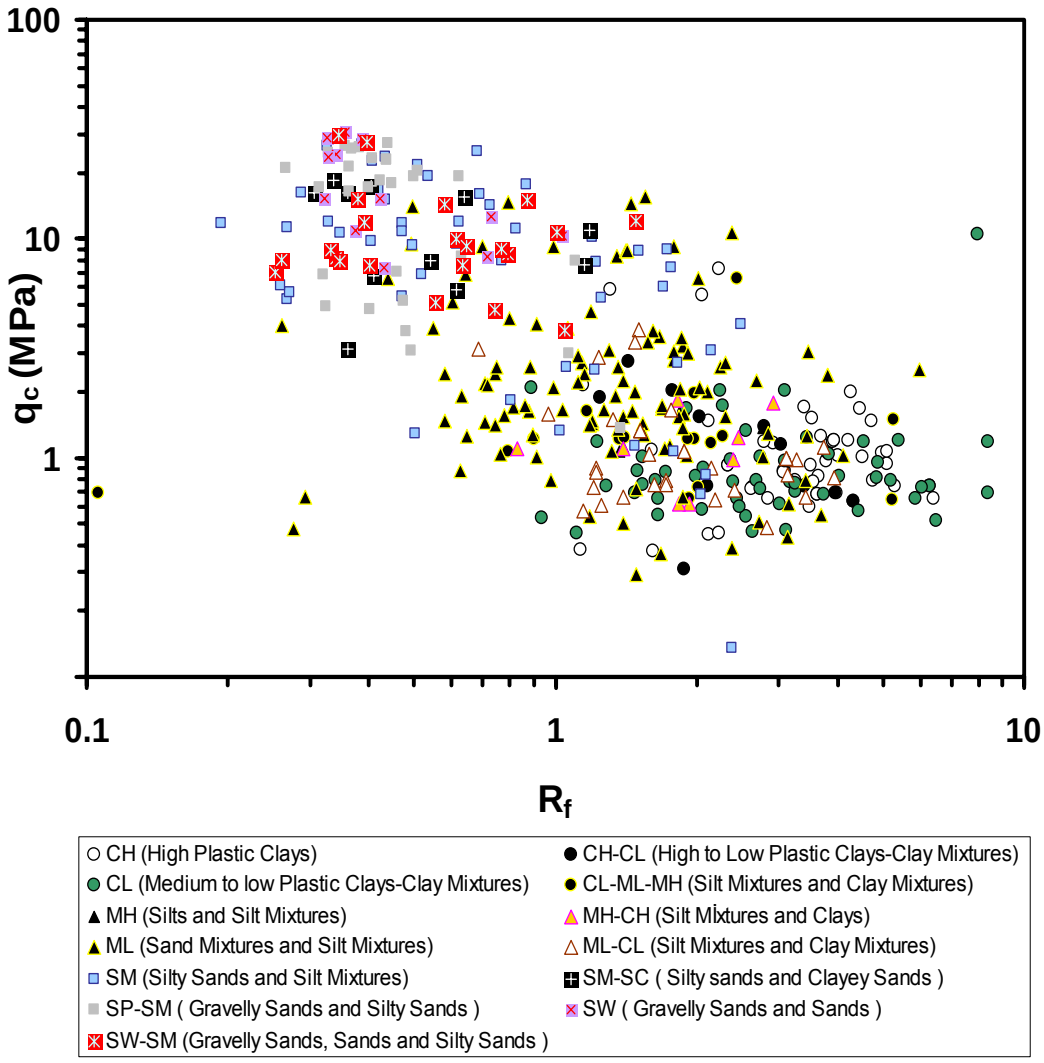


Figure 3.2: Database for CPT-based soil classification used in this study

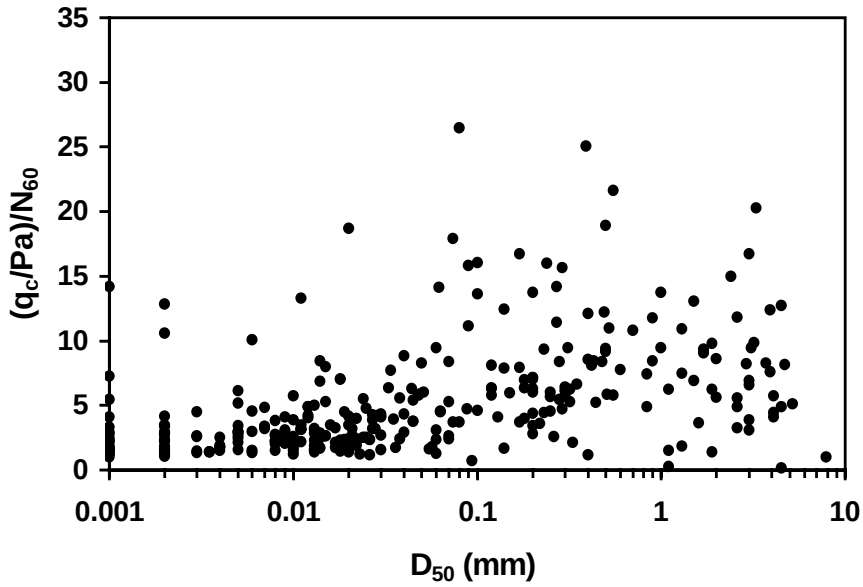


Figure 3.3: Database for SPT-CPT-correlation with D_{50} used in this study

In Figure 3.4, the distribution of $(q_c / Pa) / N_{60}$ ratio with percent fines content is illustrated. $(q_c / Pa) / N_{60}$ ratio decreases as a function of increasing FC. There is also scatter in this figure, but a decrease of $(q_c / Pa) / N_{60}$ with increasing FC is clear.

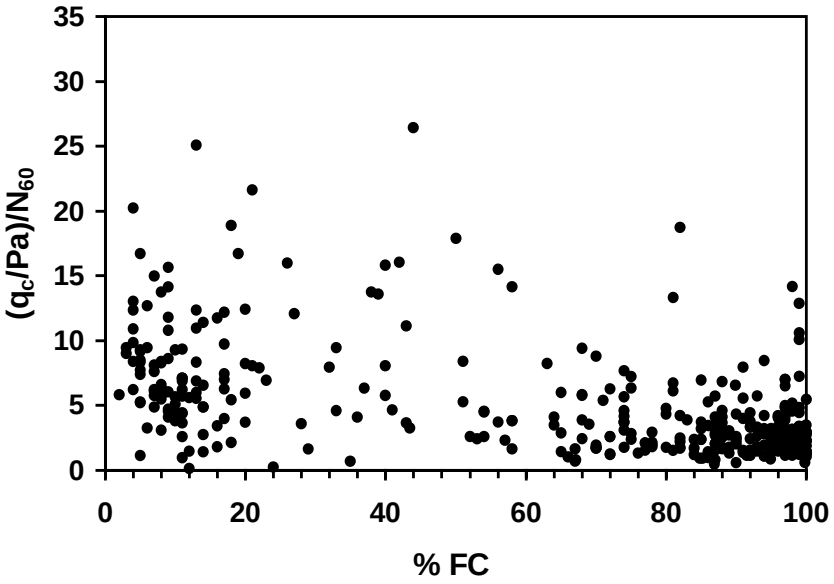


Figure 3.4: Database for SPT-CPT-correlation with FC used in this study

CHAPTER 4

DEVELOPMENT OF CPT-BASED SOIL CLASSIFICATION MODEL AND SPT-CPT CORRELATIONS

4.1 DEVELOPMENT OF CPT-BASED SOIL CLASSIFICATION MODEL

For the development of CPT-based soil classifcation model, compiled database, including CPT-boring pairs as shown in Figure 3.2 in Section 3.1, was used. Having developed representative limit state models, the maximum likelihood (ML) method was implemented. Development of limit state models and implementation of ML method is discussed in the following sections.

4.1.1 Limit State Models and Maximum Likelihood Method for CPT-Based Soil Classification

The first step in developing a limit state model for the CPT-based soil classification is to select a mathematical model, which will capture the essentials of the problem. The model for the limit-state function has the general form $\hat{g} = g(x, \Theta)$, where x is a set of descriptive variables and Θ is the set of unknown model parameters. The limit-state surfaces $g_j(x, \Theta) = 0$ denotes the

boundaries between soil classification zones in our specific problem. Inspired by currently available method of Robertson and Wride (1997), classifying soils as sands, silts, clays etc. based on the relative position of the CPT data in normalized tip resistance (q_{c1}) as given in Equation (2.11) and friction ratio (R_f) domain as shown in Figure 4.1, it was decided to identify soil classification zones as the circles with varying unknown radii (θ_3, θ_4, θ_5, θ_6) drawn from the same central coordinates of (θ_1, θ_2).

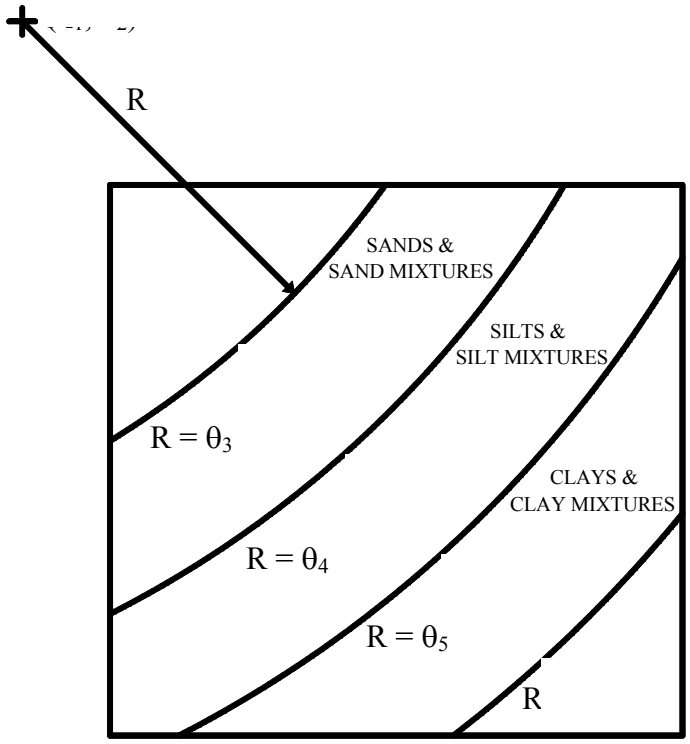


Figure 4.1: A Schematic representation of soil classification zones based on CPT-data (Robertson and Wride (1997))

The following model was adopted for the limit state function for CPT-based soil classification:

$$\hat{g}_j(R,\theta) = R - \theta_j \qquad j = 3,4,5,6 \tag{4.1}$$

where,

R: Soil behavior type index expressed as:

$$R = \sqrt{(\log(R_f) - \theta_1)^2 + (\log(q_c \cdot C_N) - \theta_2)^2} \tag{4.2}$$

R_f: Friction Ratio expressed as:

$$R_f = \frac{f_s}{q_c} \times 100\ \% \tag{4.3}$$

C_N: Normalization factor for vertical effective overburden stress expressed as:

$$C_N = \left(\frac{100}{\sigma'_v}\right)^n \qquad n = \begin{cases} R < \theta_4 & 0.5 \\ \theta_4 < R < \theta_5 & 0.5 \cdot (1 + \frac{R - \theta_4}{\theta_5 - \theta_4}) \\ R > \theta_5 & 1 \end{cases} \tag{4.4}$$

q_c: Measured CPT tip resistance in units of MPa,

f_s: Measured CPT sleeve resistance in units of MPa,

n: Normalization stress exponent which varies from 0.5 to 1.0 depending on the grain characteristics of soils (Olsen (1997))

In addition to q_c and R_f, vertical effective stress (σ'_v) was also chosen as one of the descriptive variables to better characterize the boundaries between soil classification zones. $\theta = (\theta_1, K, \theta_6)$ is the set of unknown model parameters.

The limit state function given in equation (4.1) assumes that the boundaries between soil zones can be completely explained by the three descriptive variables of q_c, R_f and σ'_v. Obviously other variables exist which may influence classification of soils. Even if the selected descriptive variables were to fully classify soils, the adopted mathematical expression may not have the ideal form. Hence, equation (4.1) is an imperfect model of the limit-state function. This is signified by use of a superposed hat on g. To account for the influences of the missing variables and the possible incorrect model form, a random model correction term, ε, is introduced and the corrected limit state function is written as:

$$g_j(q_c, R_f, \sigma'_v, \varepsilon, \theta) = \sqrt{(\log(R_f) - \theta_1)^2 + (\log(q_c \cdot (\frac{100}{\sigma'_v})^n) - \theta_2)^2} - \theta_j + \varepsilon \qquad (4.5)$$

It is reasonable and also convenient to assume that ε has the normal distribution. With the aim of producing an unbiased model (i.e., one that, in the average, makes the correct prediction), the mean of ε is set to zero. The standard deviation of ε, denoted σ_ε, however is unknown and must be

estimated. The set of unknown parameters of the model, therefore, is $\Theta = (\theta, \sigma_\varepsilon)$.

For the sake of brevity, in the following the notation q, F and E to denote the descriptive variables q_c, R_f and σ'_v will be used, respectively. With this definition, the limit-state function takes the form:

$$g_j(q, F, E, \varepsilon, \theta) = \sqrt{(\log(F) - \theta_1)^2 + (\log(q \cdot (\frac{100}{E})^n) - \theta_2)^2} - \theta_j + \varepsilon \qquad (4.6)$$

4.1.2 Formulation of Likelihood Function for CPT-Based Soil Classification

Let q_i, F_i, and E_i be the values of q_c, R_f and σ'_v at the i^{th} CPT data pair observation, respectively, and let ε_i be the corresponding realization of the model correction term. If the i^{th} CPT data pair is proved to be obtained from a layer of sand and sand mixture by laboratory testing of obtained soil samples, then $g_3(q_i, F_i, E_i, \varepsilon_i, \theta) > 0$ and $g_4(q_i, F_i, E_i, \varepsilon_i, \theta) \le 0$, if from a layer of silt and silt mixture, then $g_4(q_i, F_i, E_i, \varepsilon_i, \theta) > 0$ and $g_5(q_i, F_i, E_i, \varepsilon_i, \theta) \le 0$, if from a layer of clay and clay mixture, then $g_5(q_i, F_i, E_i, \varepsilon_i, \theta) > 0$ and $g_6(q_i, F_i, E_i, \varepsilon_i, \theta) \le 0$.

Assuming the observations compiled from different sites to be statistically independent, the likelihood function can be written for “n” sand and sand mixture cases, “k” silt and silt mixture cases and “m” clay and clay mixture cases as the product of the probabilities of the observations, i.e.,

$$
\begin{aligned}
L(\theta,\sigma_\varepsilon) = & \prod_{\substack{\text{Sand and}\\ \text{Sand Mixture}}} P\left[g_4(q_i,F_i,E_i,\varepsilon_i,\theta)\le 0\right] I\ P\left[g_3(q_i,F_i,E_i,\varepsilon_i,\theta)>0\right]\times \\
& \prod_{\substack{\text{Silt and}\\ \text{Silt Mixture}}} P\left[g_5(q_i,F_i,E_i,\varepsilon_i,\theta)\le 0\right] I\ P\left[g_4(q_i,F_i,E_i,\varepsilon_i,\theta)>0\right]\times \\
& \prod_{\substack{\text{Clay and}\\ \text{Clay Mixture}}} P\left[g_6(q_i,F_i,E_i,\varepsilon_i,\theta)\le 0\right] I\ P\left[g_5(q_i,F_i,E_i,\varepsilon_i,\theta)>0\right]
\end{aligned}
\tag{4.7}
$$

Suppose the measured values q_i, F_i, and E_i at each observation are exact, i.e., no measurement or estimation error is present. Then, noting that:

$$
g(q_i,F_i,E_i,\varepsilon_i,\theta) = \hat{g}(q_i,F_i,E_i,\theta) + \varepsilon_i \tag{4.8}
$$

has the normal distribution with mean $\hat{g}(q_i,F_i,E_i,\varepsilon_i,\theta)$ and standard deviation σ_ε, the likelihood function (4.8) can be written as:

$$
\begin{aligned}
L(\theta,\sigma_\varepsilon) = & \prod_{\substack{\text{Sand and}\\ \text{Sand Mixture}}} \Phi\left[-\frac{\hat{g}_4(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right] - \Phi\left[-\frac{\hat{g}_3(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right] \times \\
& \prod_{\substack{\text{Silt and}\\ \text{Silt Mixture}}} \Phi\left[-\frac{\hat{g}_5(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right] - \Phi\left[-\frac{\hat{g}_4(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right] \times \\
& \prod_{\substack{\text{Clay and}\\ \text{Clay Mixture}}} \Phi\left[-\frac{\hat{g}_6(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right] - \Phi\left[-\frac{\hat{g}_5(q_i,F_i,E_i,\theta)}{\sigma_\varepsilon}\right]
\end{aligned}
\tag{4.9}
$$

where $\Phi[\cdot]$ is the standard normal cumulative probability function. Note that the above is a function of the unknown parameters θ and σ_ε.

Having formulated the likelihood function, unknown model parameters $\theta = (\theta_1, K, \theta_6)$ and standard deviation σ_ε of the model error term ε are estimated as the point estimates of those parameters, which maximize the likelihood function.

Table 4.1 summarizes the model parameters of the CPT-based soil classification limit state model.

Table 4.1: Maximum likelihood estimates of model parameters for CPT-based soil classification

θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	σ_ε
-12.835	8.064	2.175	14.540	15.350	17.589	0.307

4.2 DEVELOPMENT OF SPT-CPT CORRELATIONS

Database, used to develop correlation between SPT-N value and CPT tip resistance, q_c, as a function of mean grain size (D_{50}) and fines content (FC), is shown in Figure 3.4 and Figure 3.5, respectively, in Section 3.1. Additionally, for assessing SPT-CPT correlation with soil behavior type index (R), R values were determined as described in Section 4.1 and are tabulated in Appendix 4. To develop correlations, an appropriate probabilistic model was developed and the maximum likelihood method was implemented. Development of probabilistic model and implementation of ML method is discussed next in this chapter.

4.2.1 Probabilistic Model and Maximum Likelihood Method

Maximum likelihood approach for developing a model for the SPT-CPT correlations begins with the selection of a mathematical model. The model for the correlation is going to have functional form of $\hat{g} = g(x, \Theta)$ where x is a set of descriptive variables and Θ is the set of unknown model parameters.

Following a fastidious sensitivity study and a deep literature survey, the representative functional form to be used in analysis is determined as:

$$\hat{g} = g(N_{60}, D_{50}, FC, R, \theta, \varepsilon) \tag{4.10}$$

$\theta = (\theta_1, K, \theta_7)$ is the set of model parameters different for each model, and ε is the error term to account for the influence of the missing variables and the possible incorrect model form.

For the error terms in all models, it is reasonable and also convenient to assume that ε has the normal distribution. With the aim of producing an unbiased model (i.e., one that, in the average, makes the correct prediction), the mean of ε is set to zero. The standard deviation of ε, denoted σ_ε, however is unknown and must be estimated. The set of unknown parameters of the model, therefore, is $\Theta = (\theta, \sigma_\varepsilon)$.

4.2.2 Formulation of the Likelihood Function for SPT-CPT Correlation with Mean Grain Size (D_{50})

Figure 4.2 illustrates the distribution of q_c with mean grain size, D_{50}, varying between 0.001 mm to 10 mm. It is observed from the figure that for D_{50} less than 0.1 mm, q_c falls between about 0.1 and 5 MPa and for coarser mean grain size values, there is a sudden increase in q_c, values of which goes up to 30 MPa.

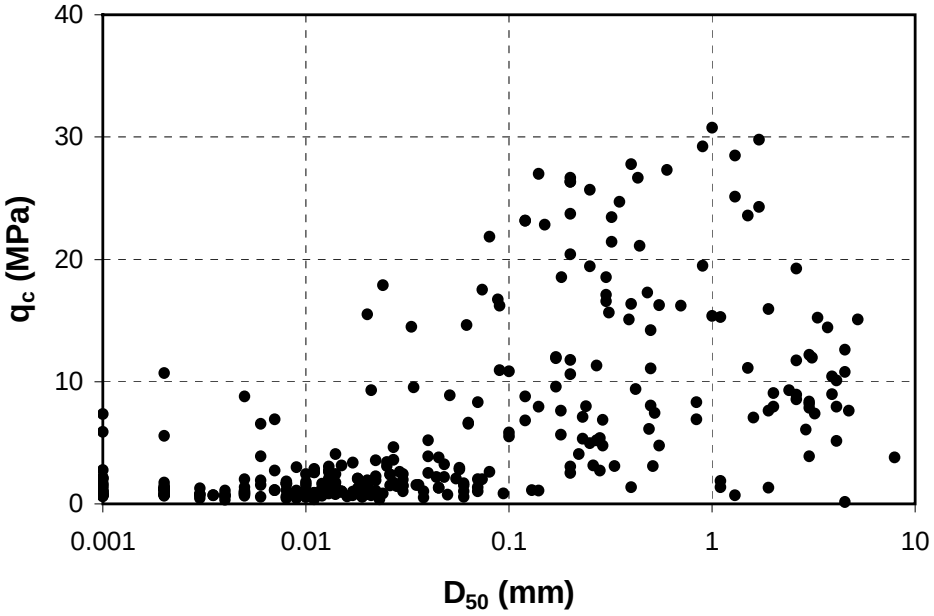


Figure 4.2: Distribution of q_c with mean grain size, D_{50}

After a sensitivity analysis, following form of equation was found to be representative for all data pairs and appropriate to assess a probabilistic model:

$$q_c = \theta_1 \times N_{60}^{\theta_3} \times D_{50}^{\theta_2} \pm \sigma_{\varepsilon q} \quad (4.11)$$

In Figure 4.2, there is an increasing scatter with increasing D_{50}, particularly for D_{50} greater than 0.1 mm. It is more reasonable to use variable $\sigma_{\varepsilon,q}$, increasing with increasing D_{50}:

$$\sigma_{\varepsilon,q} = \theta_4 + \theta_5 \times (3 + \log D_{50}) \quad (4.12)$$

Having formulated the likelihood function, unknown model parameters $\theta = (\theta_1, K, \theta_5)$ are estimated as the point estimates of those parameters, which maximize the likelihood function.

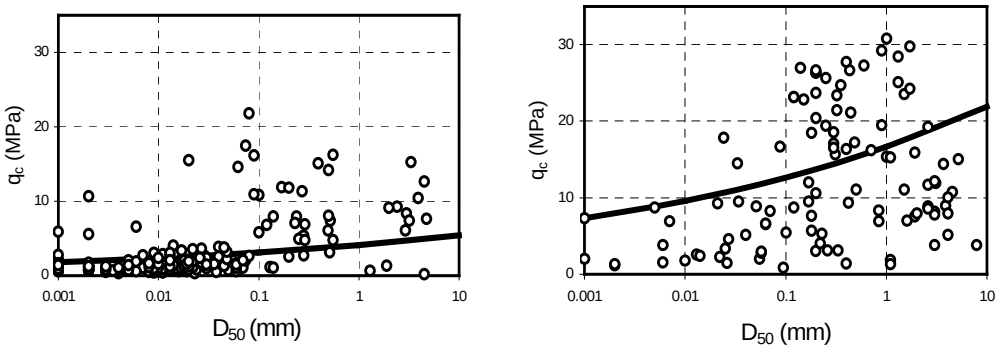
Table 4.2 summarizes the model parameters of SPT-CPT correlation with D_{50}.

Table 4.2: Maximum likelihood estimates of model parameters for SPT-CPT correlation with D_{50}

θ_1	θ_2	θ_3	θ_4	θ_5
0.7175	0.1193	0.9773	1.2165	1.4758

Complied data points with the suggested closed form solution are shown in Figure 4.3. The curves in the Figures 4.3(a) and (b) show the predictions by the proposed closed form solution and the points represent the compiled database. Both the curves and the data points were drawn for varying bins of input parameters to observe sensitivity of results. In Figure 4.3(a),

ranges of parameters are that: N_{60} is less than 11 and in Figure 4.3(b) N_{60} was changed to more than 11. Changing the parameter, it was intended to understand the variation of q_c with the changes in model parameters. It can be concluded from these figures that q_c is proportional to N_{60} and according to maximum likelihood estimates of model parameters for SPT-CPT correlation with D_{50}, there is a linear relationship between q_c and N_{60} for varying D_{50}.



(a) $N_{60} < 11$ **(b) $N_{60} > 11$**

Figure 4.3: Variation of q_c-D_{50} with changes in variable N_{60}

4.2.3 Formulation of the Likelihood Function for SPT-CPT Correlation with Percent Fines Content (FC)

In Figure 4.4, database, used to develop relationship between SPT-N and q_c as a function of percent fines content (FC) is presented. In this figure, it can be seen that q_c increases with decreasing FC.

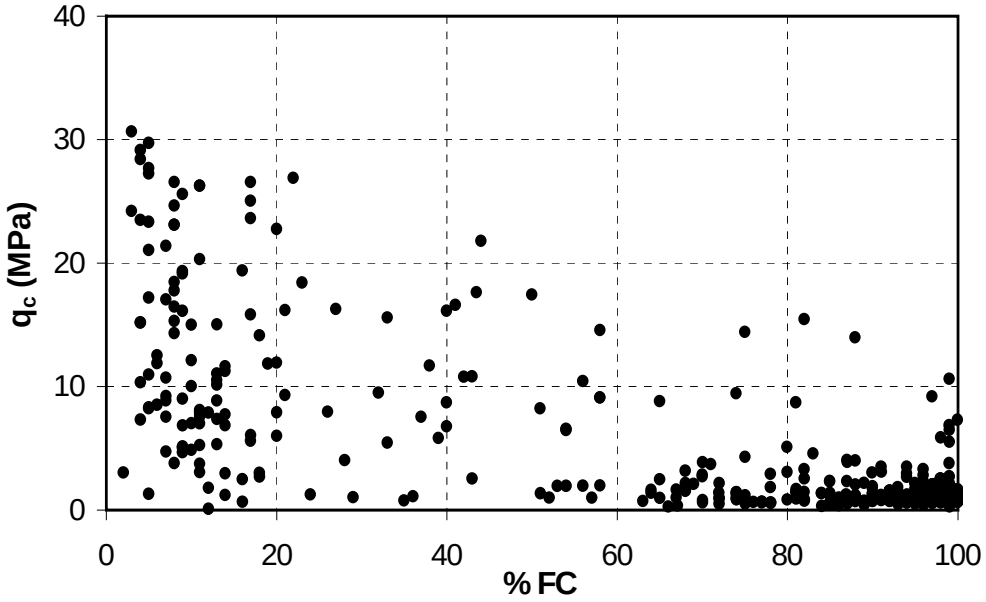


Figure 4.4: Distribution of q_c with fines content, FC

A sensitivity analysis was carried out and consequently, linear equation given below was found to be appropriate and representative for emprical model:

$$q_c = N_{60}{}^{\theta_3} \times (\theta_1 \times FC + \theta_2) \pm \sigma_{\varepsilon,q} \tag{4.13}$$

Since there is wide scatter in q_c versus FC plot shown in Figure 4.5, particularly for lower FC values,. $\sigma_{\varepsilon,q}$ is defined as variable, linearly decreasing with increasing FC as:

$$\sigma_{\varepsilon,q} = \theta_4 + \theta_5 \times (100 - FC) \tag{4.14}$$

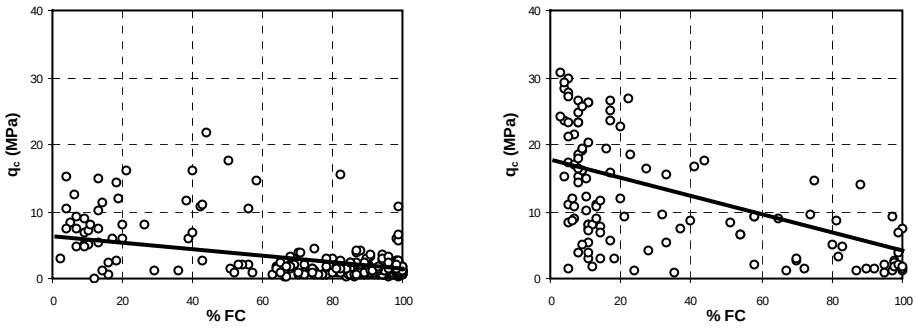
Model parameters $\theta = (\theta_1, K, \theta_5)$ are estimated as the point estimates of those parameters, which maximize the likelihood function.

Table 4.3 summarizes the model parameters of SPT-CPT correlation with FC.

Table 4.3: Maximum likelihood estimates of model parameters for SPT-CPT correlation with FC

θ_1	θ_2	θ_3	θ_4	θ_5
-0.0131	1.7293	0.7250	1.3521	0.0496

Complied data points with the suggested closed form solution are shown in Figure 4.5. In Figure 4.5(a), ranges of parameters are that: N_{60} is less than 11 and in Figure 4.5 (b) N_{60} was changed to more than 11. It is observed that q_c is proportional to N_{60} and according to maximum likelihood estimates of model parameters for SPT-CPT correlation with FC, there is a non-linear relationship between q_c and N_{60} for varying FC.



(a) $N_{60} < 11$ **(b) $N_{60} > 11$**

Figure 4.5: Variation of q_c-FC with changes in variable N_{60}

4.2.4 Formulation of the Likelihood Function for SPT-CPT Correlation with Soil Behavior Type Index (R)

The distribution of q_c with soil behavior type index, R, calculated for all data points as discussed in Section 4.1 is illustrated in Figure 4.6. As shown in this figure, for R greater than about 15, q_c varies between 0.1 and 5 MPa and, q_c increases up to 30 MPa as R decreases for R less than 15.

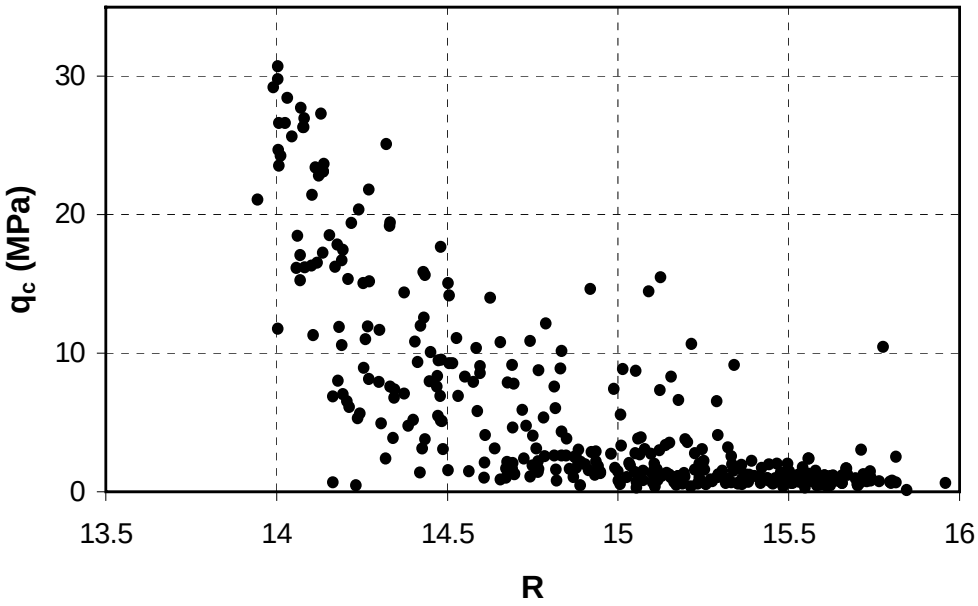


Figure 4.6: Distribution of q_c with soil behavior type index, R

After a sensitivity study, for assessing a probabilistic model of SPT-CPT correlation with soil behavior type index (R), the equation given below was found to be appropriate.

$$q_c = \theta_1 \times N_{60}{}^{\theta_3} \times \exp(\theta_2 \times R) \pm \sigma_{\varepsilon,q} \tag{4.15}$$

Scatter in q_c versus R plot, presented in Figure 4.7, increases with decreasing R, particularly for R less than about 15.3. Since scatter in Figure 4.7 varies with R, a variable $\sigma_{\varepsilon,q}$ equation, linearly increasing with decreasing R, was defined as:

$$\sigma_{\varepsilon,q} = \theta_4 + \theta_5 \times (16 - R) \tag{4.16}$$

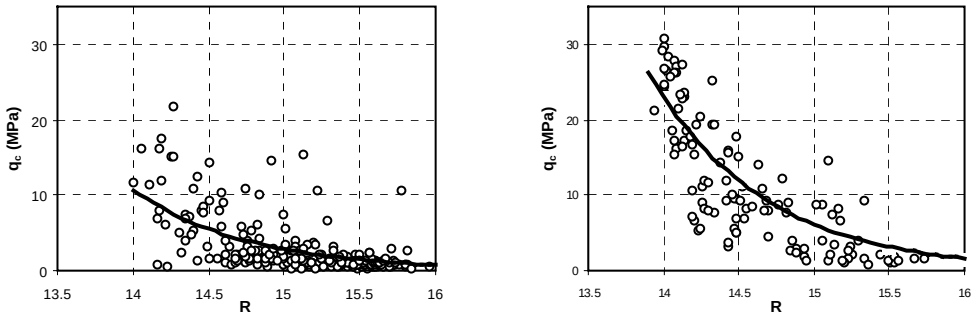
Employing maximum likelihood methodology, unknown model parameters $\theta = (\theta_1, K, \theta_5)$ are estimated as the point estimates of those parameters.

Table 4.4 summarizes the estimated model parameters of SPT-CPT correlation with R.

Table 4.4: Maximum likelihood estimates of model parameters for SPT-CPT correlation with R

θ_1	θ_2	θ_3	θ_4	θ_5
4.8E+08	-1.3240	0.5117	0.7905	1.7249

Complied data points with the suggested closed form solution are shown in Figure 4.8. In Figure 4.8(a), ranges of parameters are that: N_{60} is less than 11 and in Figure 4.8(b) N_{60} is more than 11. From these figures and from maximum likelihood estimates q_c and N_{60} is proportional and there is a non-linear relationship between q_c and N_{60} for varying R.



(a) $N_{60} < 11$ **(b) $N_{60} > 11$**

Figure 4.7: Variation of q_c-R with changes in variable N_{60}

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 SUMMARY

The purpose of these studies was to develop robust and defensible probabilistically-based correlations i) for the use of CPT in soil classification, and ii) between SPT blowcount value, N and CPT tip resistance measurement, q_c. To develop proposed correlations, a database composed of 400 CPT/boring data pairs of tip resistance (q_c), friction ratio (R_f), soil classification based on USCS, fines content (FC), mean particle size (D_{50}) and SPT blowcount value (N) was compiled.

Having compiled the CPT/boring database, probabilistically based empirical models were developed and maximum likelihood method was implemented for the unbiased estimation of i) CPT-based soil classification boundary curves and, ii) SPT-CPT corrrelations.

As a conclusion, main research findings can be summarized as:

- For CPT-based soil classification boundaries:

Figure 5.1 presents the boundary curves drawn by using the parameters summarized in Table 4.1 in Section 4.1.2. Also on the same figure, there are the normalized CPT tip resistance and friction ratio values with soil classification descriptions. In this figure, soil behavior type index, R, given in Equation 5.1, defines soil types. Table 5.1 presents soil behavior types.

$$R = \sqrt{(\log(R_f) + 12.835)^2 + (\log(q_c \cdot C_N) - 8.064)^2} \qquad (5.1)$$

C_N: Normalization factor for vertical effective overburden stress expressed as:

$$C_N = \left(\frac{100}{\sigma'_v}\right)^n \qquad n = \begin{cases} R < 14.54 & 0.5 \\ 14.54 < R < 15.35 & 0.5 \cdot (1 + \dfrac{R - 14.54}{15.35 - 14.54}) \\ R > 15.35 & 1 \end{cases} \qquad (5.2)$$

q_c: Measured CPT tip resistance in units of MPa,

f_s: Measured CPT sleeve resistance in units of MPa,

R_f: Friction Ratio

n: Normalization stress exponent which varies from 0.5 to 1.0 depending on the grain characteristics of soils (Olsen (1997))

- For SPT-CPT Correlation with Mean Grain Size (D_{50}):

  Following closed form solution, given in Equation (5.1), was proposed.

$$q_c = 0.717 \times N_{60}^{0.977} \times D_{50}^{0.119} \pm \sigma_{\varepsilon,q} \quad (5.3)$$

$$\sigma_{\varepsilon,q} = 1.217 + 1.476 \times (3 + \log D_{50})$$

- For SPT-CPT Correlation with Percent Fines Content (FC)

  Following closed form solution, given in equation (5.2), was proposed.

$$q_c = N_{60}^{0.7250} \times (-0.0131 \times FC + 1.7293\ ) \pm \sigma_{\varepsilon,q} \quad (5.4)$$

$$\sigma_{\varepsilon,q} = 1.3521\ + 0.0496 \times (100 - FC)$$

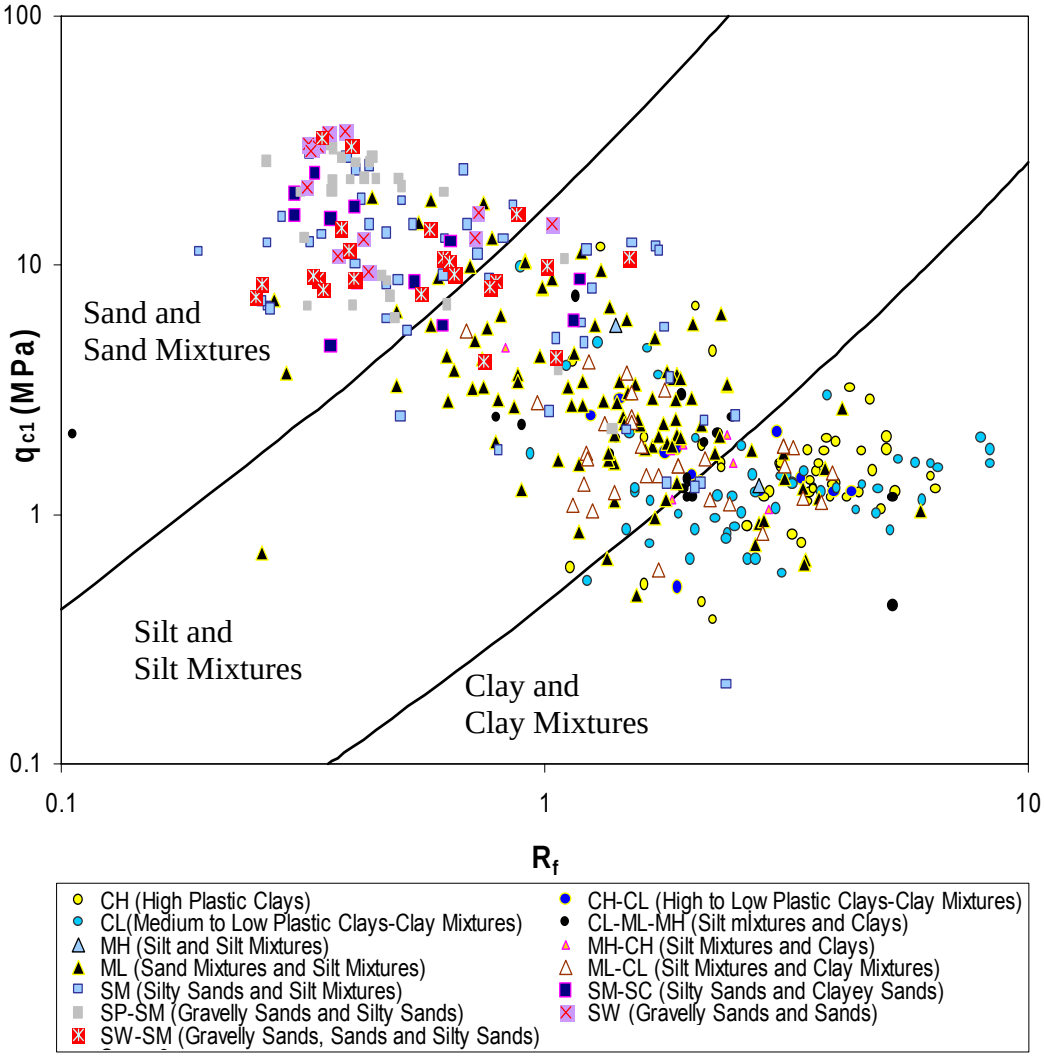


Figure 5.1: Proposed CPT-based soil classification chart

Table 5.1: Boundaries of soil behavior type

Soil Behaviour Type Index, R	Soil Type
R<14.54	Sand and Sand Mixtures
14.54<R<15.35	Silt and Silt Mixtures
R>15.35	Clay and Clay Mixtures

- For SPT-CPT Correlation with Soil Behavior Type Index (R)

  Following closed form solution, given in equation (5.3), was proposed.

$$q_c = 4.8E+08 \times N_{60}^{0.5117} \times \exp(-1.324 \times R) \pm \sigma_{\varepsilon,q} \quad (5.5)$$

$$\sigma_{\varepsilon,q} = 0.7905 + 1.7249 \times (16 - R)$$

All currently available SPT-CPT correlations, discussed in Chapter 2, had been developed for the variation of $(q_c / Pa)/N$ ratio with grain characteristics, such as mean grain size, percent fines content and soil behavior type index, assuming a linear relationship between q_c and N. Figure 5.2 through Figure 5.4 present a comparison of, predictions by proposed emprical models with the compiled database. Figures are plotted in $(q_c / Pa)/N_{60}^{\theta_3}$ versus grain characteristics (D_{50}, FC and R, respectively) domain to ease the comparison with currently available correlations and mean prediction equations are also provided in each figure.

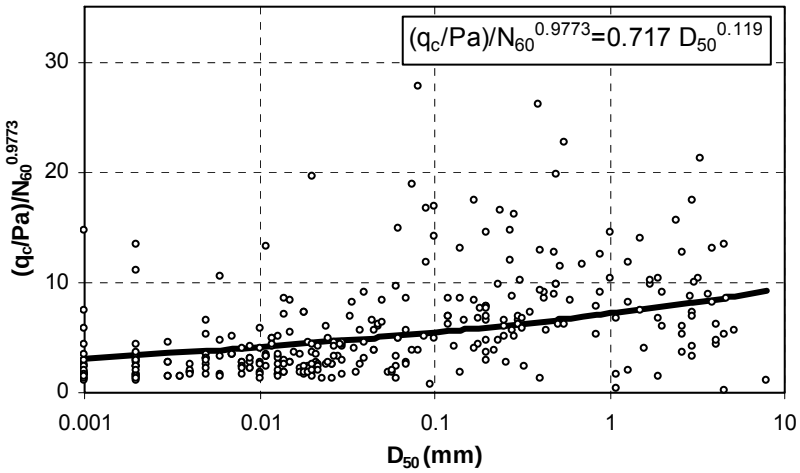


Figure 5.2: Variation of $(q_c / Pa) / N_{60}^{\theta_3}$ ratio with D_{50}

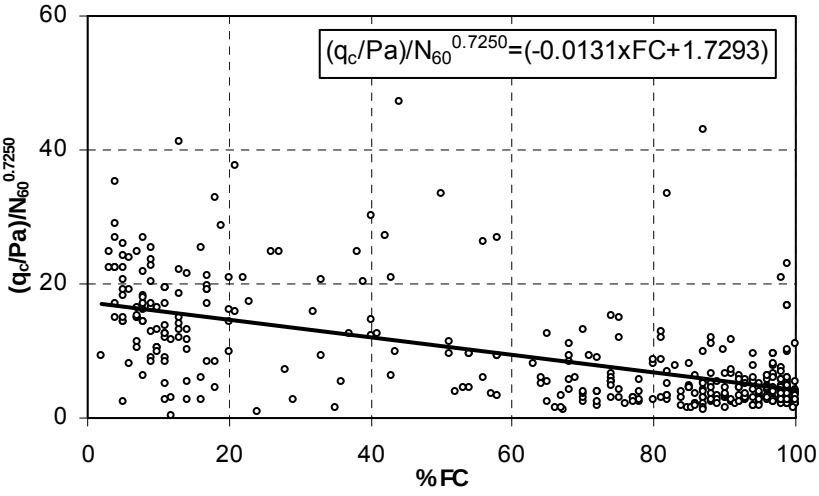


Figure 5.3: Variation of $(q_c / Pa) / N_{60}^{\theta_3}$ ratio with FC

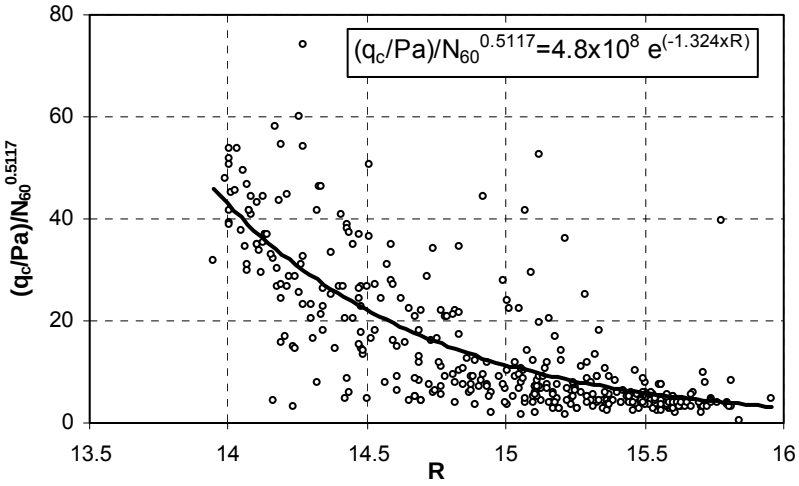


Figure 5.4: Variation of $(q_c / Pa) / N_{60}^{\theta_3}$ ratio with R

5.2 CONCLUSIONS

As a part of these studies followings can be concluded:

- For CPT-based soil classification:

Proposed CPT-based soil classification method provides a quantifiable insight in to the problem. As shown in Figure 5.1, new set of soil classification boundaries clearly identify various soil classification zones which adress the uncertainties in the locations and the forms of these boundaries. Presently, three available soil zones of i) sand, ii) silt and iii) clay mixtures can be extended to a more detailed and finer classification zones once more CPT and soil classification data pairs become available.

- For SPT-CPT correlations:

More advanced probabilistic tools, maximum likelihood methodology, were used to develop and evalute correlations and probabilistic models are based on significantly more number of data pairs than currently available methods. The resulting correlations provide a significantly improved basis and unbiased estimates for SPT-CPT correlations. For variation of q_c with D_{50}, there is a linear relationship between q_c and N_{60} as offered by currently available correlations but q_c and N_{60} have non-linear trend for varying fines content, FC and varying soil behavior type index, R.

APPENDIX A

SPT-CPT DATA PAIRS

In Appendix A, site names, SPT log and CPT log names of data pairs are tabulated. In addition, a name is given to each data pair which is also tabulated.

Table A.1: SPT-CPT pairs from Pasific Earthquake Researh Center (PEER), Turkey Ground Failure (August 1999 Earthquakes) Database

Phase	Site Name	CPT Log Name	SPT Log Name	Name of SPT-CPT Pair
1	Site A	CPT-A3	SPT-A1	A-1
		CPT-A1	SPT-A2	A-2
	Site B	CPT-B1	SPT-B1	B-1
		CPT-B3	SPT-B2	B-2
	Site C	CPTC3	SPTC2	C-1
		CPT-C2	SPT-C5 AND SPT-C6	C-2
		CPT-C7 AND CPT-C1	SPT-C1	C-3
		CPT-C4	SPT-C3 AND SPT-C4	C-4
	Site D	CPT-D3	SPT-D2	D-1
		CPT-D2	SPT-D1	D-2
		CPT-D1	SPT-D3	D-3
	Site E	CPT-E1	SPT-E1	E-1
	Site F	CPT-F1	SPT-F1	F-1
	Site G	CPT-G1	SPT-G2	G-1
		CPT-G3	SPT-G1	G-2
	Site H	CPT-H2	SPT-H1	H-1
	Site I	CPT-I2	SPT-I1	I-1
	Site J	CPT-J4	SPT-J2	J-1
		CPT-J2	SPT-J1	J-2

Table A.1 (cont.): SPT-CPT pairs from Pasific Earthquake Researh Center (PEER), Turkey Ground Failure (August 1999 Earthquakes) Database

Phase	Site-Line	CPT Log Name	SPT Log Name	Name of SPT-CPT Pair
1	Site K	CPT-K2	SPT-K1	K-1
	Site L	CPT-L1	SPT-L1	L-1
2	Line 1	CPT-1-11	SPT-1-11	L1-1
		CPT-1-42	SPT-1-42	L1-2
		CPT-1-41	SPT-1-41	L1-3
		CPT-1-32	SPT-1-32	L1-4
		CPT-1-16	SPT-1- 16	L1-5
		CPT-1-24	SPT-1-24	L1-6
		CPT-1-02	SPT-1-02	L1-7
	Line 2	CPT-2-10	SPT-2-10	L2-1
		CPT-2-3	SPT-2-3	L2-2
	Line 3	CPT-3-3	SPT-3-3	L3-1
		CPT-3-6	SPT-3-6	L3-2
	Line 4	CPT-4-13	SPT-4-13	L4-1
		CPT-4-3	SPT-4-3	L4-2
		CPT-4-22	SPT-4-22	L4-3

Table A.1 (cont.): SPT-CPT pairs from Pasific Earthquake Researh Center (PEER), Turkey Ground Failure (August 1999 Earthquakes) Database

Phase	Site Name	Name of CPT Log	Name of SPT Log	Name of SPT-CPT Pair
4	Çark Canal	CPT-1-24-cc	SPT-1-24-cc	CC-1
	Cumhuriyet Avenue	CPT-4-22-ca	SPT-4-22-ca	CA-1
	Değirmendere Nose	CPT-DN1	SPT-DN1	DN-1
		CPT-DN2	SPT-DN2	DN-2
	Hotel Sapanca	CPT-SH2	SPT-SH2	HS-1
		CPT-SH4	SPT-SH4	HS-2
		CPT-SH7	SPT-SH7	HS-3
		CPT-SH11	SPT-SH11	HS-4
	Police Station	CPT-PS3	SPT-PS3	PS-1
		CPT-PS4	SPT-PS4	PS-2
	Soccer Field	CPT-SF5	SPT-SF5	SF-1
	Yakin Street	CPT-A3-ys	SPT-A1-ys	YS-1
		CPT-A1-ys	SPT-A2-ys	YS-2
	Yalova Harbor	CPT-YH4	SPT-YH3	YH-1
		CPT-YH3	SPT-YH1	YH-2--50

Table A.2: SPT-CPT pairs from Karaca (2001) Database

Site Name	Name of CPT Log	Name of SPT Log	Name of SPT-CPT Pair
Tigcilar District (Site A)	CPT-Tigcilar-1A	SPT-TSK-1	TD-1
Cumhuriyet Disrict (Site E)	CPT-CUM-3	SPT-CSK-1	CD-1

Table A.3: SPT-CPT pairs from Buski East Waste Water Treatment Plant Project Database

Site Name	CPT Log Name	SPT Log Name	Name of SPT-CPT Pair
Demirtas	CPT-1	SK7	BCP-1
	CPT-2	S104	BCP-2
	CPT-3	S102	BCP-3
	CPT-7	S105	BCP-4
	CPT-8	S103	BCP-5
	CPT-14	S110	BCP-6
	CPT-15	S101	BCP-7
	CPT-16	S106	BCP-8
	CPT-17	SK5	BCP-9
	CPT-18	S107	BCP-10
	CPT-19	S108	BCP-11
	CPT-20	SK1	BCP-12
	CPT-21	S109	BCP-13

APPENDIX B

SPT LOG AND
LABORATORY TEST RESULTS

In Appendix B, STP log and laboratory test results of borings tabulated in Appendix A is presented.

Table B.2 : SPT Results and laboratory test result of Buski East Waste Water Treatment Plant Project Database

Sample		Depth (m)		N_{60}	LL	PI	%FC	D_{50}	USCS
Boring Name	Sample No	From	To						
SK101	SPT-1	1.65	1.95	7	70	50	95		CH
	SPT-2	3.65	3.95	8	NP	NP	54		ML
	SPT-5	9.65	9.95	10	NP	NP	50	0.074	SM-ML
SK102	SPT-4	7.7	8	4	26	7	39	0.1	SM-SC
	SPT-5	9.5	9.8	11	NP	NP	8	1	SW-SM
	SPT-7	13.7	14	17	19	5	33	0.31	SM-SC
	SPT-8	15.7	16	17	NP	NP	16	0.9	SM
SK103	SPT-3	5.65	5.95	6	35	15	74		CL
	SPT-4	7.65	7.95	7	NP	NP	19	0.17	SM
	SPT-5	9.65	9.95	7	28	13	56		CL
	SPT-7	13.65	13.95	8	NP	NP	44	0.08	SM
	SPT-8	15.65	15.95	7	NP	NP	42	0.1	SM
	SPT-11	21.6	21.9	8	NP	NP	13		SM
SK104	SPT-1	1.7	2	4	42	27	77		CL
	SPT-2	3.7	4	7	30	11	68	0.014	CL
	SPT-3	5.7	6	6	NP	NP	29	0.14	SM
	SPT-4	7.7	8	7	48	33	86	0.001	CL
	SPT-5	9.7	10	14	21	6	27	0.4	SM-SC
	SPT-6	11.7	12	14	NP	NP	18	0.33	SM
SK105	SPT-1	1.65	1.95	7	32	11	65		CL
	SPT-2	3.65	3.95	6	NP	NP	13	0.28	SM
	SPT-3	5.65	5.95	5	NP	NP	18	0.28	SM
	SPT-5	9.65	9.95	12	NP	NP	32	0.17	SM
	SPT-7	13.65	13.95	12	17	6	37	0.18	SM-SC
	SPT-8	15.65	15.95	11	NP	NP	28	0.22	SM
SK106	SPT-1	1.65	1.95	7	74	52	98		CH
	SPT-2	3.7	4	5	45	29	88	0.001	CL
	SPT-3	5.7	6	5	NP	NP	17	0.49	SM
	SPT-4	7.7	8	9	NP	NP	11	0.5	SW-SM
	SPT-5	9.7	10	7	20	6	21	0.55	SM-SC

Table B.2 (cont.) : SPT Results and laboratory test result of Buski Counselin Project

Sample		Depth (m)		N_{60}	LL	PI	%FC	D_{50}	USCS
Boring Name	Sample No	From	To						
SK107	SPT-1	1.7	2	4	61	40	95		CH
	SPT-2	3.7	4	5	40	24	76		CL
SK108	SPT-1	1.7	2	5	40	22	80		CL
	SPT-2	3.7	4	4	44	25	88	0.001	CL
	SPT-3	5.7	6	4	40	25	75	0.001	CL
	SPT-5	9.7	10	6	NP	NP	13	0.39	SM
	SPT-7	13.7	14	8	NP	NP	4	3.3	SW
SK109	SPT-1	1.65	1.95	4	33	15	70		CL
	SPT-2	3.65	3.95	4	38	20	70		CL
	SPT-4	7.65	7.95	10	NP	NP	14	0.27	SM
	SPT-5	9.65	9.95	12	NP	NP	5	0.5	SW
	SPT-6	11.65	11.95	8	NP	NP	7	0.55	SW-SM
	SPT-7	13.65	13.95	10	27	6	43	0.09	SM-SC
SK110	SPT-1	1.7	2	5	35	17	88		CL
	SPT-4	7.7	8	5	23	5	26	0.24	SM-SC
	SPT-7	13.7	14	7	NP	NP	13	0.52	SM
	SPT-8	15.7	16	8	NP	NP	18	0.5	SM
SK1	SPT-5	7.65	7.95	9	23		38	0.2	SM
SK5	SPT-12	18.15	18.45		34	16	53	0.004	CL
	SPT-5	7.65	7.95				9	0.7	SM
SK7	SPT-4	6.65	6.95				39	0.14	SM

Table B.1 : SPT Results and laboratory test result of Karaca (2001) Database

SAMPLE			W_n (%)	G_s	ATTERBERG LIMITS			% FINES CONTENT				USCS	N	N_{field}
Boring Name	Sample No	Depth (m)			LL	PL	PI	4 (%)	10 (%)	40 (%)	200 (%)			
TSK-1	SPT-1	1.50-1.95	34.8		34	26	8	100.0	100.0	100.0	89.9	ML	3 -3 -4	7
	SPT-2	3.00-3.45	18.0	2.581	NP			100.0	98.9	96.4	40.0	SM	3 -4 -5	9
	SPT-3	4.50-4.95	31.9	2.585	33	24	9	100.0	100.0	97.5	87.0	ML	3 -4 -5	9
	SPT-4	6.00-6.45	16.0		NP			98.9	97.9	73.3	13.8	SM	4 -5 -7	12
	SPT-5	7.50-7.95	19.2		NP			97.1	96.1	89.7	14.9	SM	9 -19 -33	52
	SPT-6	9.00-9.45	17.1	2.577	NP			100.0	97.5	84.7	21.5	SM	8 -30 -39	69
	SPT-7	10.50-10.95	16.4		NP			100.0	100.0	77.1	12.2	SM	9 -27 -38	65
	SPT-8	12.00-12.45	31.2		NP			100.0	100.0	98.5	29.2	SM	16 -17 -20	37
	SPT-9	13-50-13.95	23.2		NP			100.0	100.0	97.8	41.2	SM	15 -19 -25	44
	SPT-10	15.00-15.42	38.6	2.673	39	26	12	98.3	96.2	92.5	86.9	ML	10 -15 -17	32
	SPT-11	16.50-16.95	34.6		36	24	11	100.0	98.8	96.5	90.0	ML	8 -12 -15	27
CSK-1	SPT-1	1.50-1.95	29.0	2.624	32	24	8	100.0	96.5	86.6	67.1	ML	3 -3 -4	7
	SPT-2	3.00-3.45	33.9		47	22	25	100.0	98.2	95.7	85.2	CL	3 -3 -4	7
	SPT-3	5.00-5.45	35.6	2.620	44	22	22	100.0	97.0	92.2	84.8	CL	2 -3 -3	6
	SPT-4	6.00-6.45	36.9	2.627	37	21	16	100.0	100.0	100.0	94.9	CL	3 -5 -9	14
	SPT-5	7.50-7.95	35.1	2.631	42	23	19	100.0	100.0	98.2	91.5	CL	5 -6 -7	13
	SPT-6	9.00-9.45	30.4	2.571	NP			100.0	100.0	98.0	43.5	SM	12 -26 -39	65
	SPT-7	10.50-10.95	17.7		NP			96.5	92.5	65.5	5.8	SM-SW	8 -18 -36	54

Figure B.1: SPT log: SPT-A1

Figure B.2: SPT log: SPT-A2

Figure B.3: SPT log: SPT-B1

Figure B.3(cont.): SPT log: SPT-B1

Figure B.4: SPT log: SPT-B2

Figure B.5: SPT log: SPT-C1

Figure B.6: SPT log: SPT-C2

Figure B.7: SPT log: SPT-C3

Figure B.8: SPT log: SPT-C4

Figure B.9: SPT log: SPT-C5

Figure B.10: SPT log: SPT-C6

Figure B.11: SPT log: SPT-D1

Figure B.12: SPT log: SPT-D2

Figure B.13: SPT log: SPT-D3

Figure B.14: SPT log: SPT-E1

Figure B.15: SPT log: SPT-F1

Figure B.15(cont.): SPT log: SPT-F1

Figure B.16: SPT log: SPT-G1

Figure B.17: SPT log: SPT-G2

Figure B.17(cont.): SPT log: SPT-G2

Figure B.18: SPT log: SPT-H1

Figure B.19: SPT log: SPT-I1

Figure B.20: SPT log: SPT-J1

Figure B.21: SPT log: SPT-J2

Figure B.22: SPT log: SPT-K1

Figure B.23: SPT log: SPT-L1

Figure B.24: SPT log: SPT-1-11

Figure B.25: SPT log: SPT-1-42

Figure B.26: SPT log: SPT-1-41

Figure B.27: SPT log: SPT-1-32

Figure B.28: SPT log: SPT-1-16

Figure B.29: SPT log: SPT-1-24

Figure B.30: SPT log: SPT-1-02

Figure B.31: SPT log: SPT-2-10

UCB-BYU-UCLA
ZETAS-SaU-METU
Joint Research
Sponsored by:
NSF, Caltrans
CEC, PG&E

Project Name: CPT Liquefaction Investigations, Adapazari, Turkey
Location: 1.5 m away from CPT-2-03, in Migros parking lot
Date: July 13, 2000
Field Log by: Rodolfo B. Sancio
Operator: ZETAS (Zemin Teknolojisi, A. S.)
Drilling Method: Rotary wash with 9 cm-diameter tricone bit
Water Table Elevation: GWL = 0.92 m 07/13/00
Notes: The accelerometers malfunctioned and recorded high values

Test ID: SPT-2-03
GPS Coordinates: 40.77969°N 30.39469°E
Elevation: 28.407 m
Drilling Equipment: Custom made, equivalent to Crealius XC90H
Responsible Engineers: J. D. Bray and R. B. Sancio, U. C. Berkeley
SPT System: Rope, pulley and cathead method. AWJ rods.
Hammer Type: Safety Hammer (per Kovacs et al. 1983)

Depth Scale (m)	Lithology	USCS	Sample Type and No.	Recovery/ Length (cm)	SPT Blows/15 cm	Casing Depth (m)	Rod Length (m)	Energy Ratio (%)	Description	Pocket Pen (q_u) (kPa)	Torvane (s_u) (kPa)	Moisture Content (%)	Liquid Limit	Plasticity Index	% fines < 75 µm	< 5 µm (%)	< 2 µm (%)	D50 (mm)	D10 (mm)	Remarks
0									Fill: Gravel pack for parking lot followed by sandy clayey soil											
1		CH	S-2-3-1	30/45	1-2-2	0.5	4.27		CH: Brown gray high plasticity silty clay	140	52	38	64	38	97	64	48	0.002	<1µm	Roots in the tip of the sampler
2		ML	S-2-3-2	22/45	1-1-1	1.95	5.80		CLAYEY SILT: Tan brown clayey silt with traces of fine sand	25		31	33	-	87	30	23	0.016	<1µm	
3		ML	S-2-3-3	33/45	2-2-3	2.95	5.80			60		37	34	-	90	20	15	0.022	<2µm	
4		ML	S-2-3-4	25/45	3-2-3	3.95	7.32		SILTY CLAY: Brown stiff silty clay			37	47	18	96	38	29	0.009	<1µm	
5		CH ML	S-2-3-5A S-1-3-5B	32/45	1-1-2	4.85	8.84		CLAYEY SILT: Gray clayey silt with fine sand	75	42	43 30	67 37	42 -	100 85	66 27	54 20	0.001 0.018	<1µm <1µm	
6		CL/ML ML	S-2-3-6A S-2-3-6B	32/45	2-3-3	5.75	8.84					32 31	37 36	13 9	88 86	36 25	26 21	0.009 0.019	<1µm <1µm	
7		CH/MH CL	S-2-3-7A S-2-3-7B	34/45	2-2-2	6.55	10.37		SILTY CLAY: Gray high plasticity silty clay			39 36	58 39	28 16	98 97	47 55	36 40	0.006 0.004	<1µm <1µm	
8		CH	S-2-3-8	29/45	2-2-4	7.95	11.29			45		40	65	40	100	72	61	<2µm	-	
9		SM	S-2-3-9	37/45	5-12-19	9.15	13.42		SAND: Gray silty fine sand to fine sand with silt			23	-	-	20	10	8	0.17	0.005	
10		SP-SM	S-2-3-10	42/45	11-17-28	9.95	12.82					21	-	-	11	-	-	0.20	0.07	

Legend
S: Spit Spoon (SPT) SH: Shelby tube * Estimated Energy Ratio

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Figure B.32: SPT log: SPT-2-03

Figure B.33: SPT log: SPT-3-3

Figure B.34: SPT log: SPT-3-6

Figure B.35: SPT log: SPT-4-13

Figure B.36: SPT log: SPT-4-3

Figure B.37: SPT log: SPT-4-22

Figure B.38: SPT log: SPT-1-24-cc

Figure B.39: SPT log: SPT-4-22-ca

Figure B.40: SPT log: SPT-DN-1

Figure B.41: SPT log: SPT-DN-2

Figure B.42: SPT log: SPT-SH2

Figure B.43: SPT log: SPT-SH4

UCB-BYU-UCLA
ZETAS-SaU-METU
Joint Research
Sponsored by:
NSF, Caltrans
CEC, PG&E

Project Name: Geotechnical Site Investigations at Lateral Spread Sites
Location: Sapanca Hotel, Sapanca
Date: August 22, 2000
Field Log by: K. Ö. Çetin
Operator: ZETAS (Zemin Teknolojisi, A. S.)
Drilling Method: Rotary wash with 9 cm-diameter tricone bit
Water Table Elevation: 0.50 m
Notes:

Test ID: SPT-SH4
GPS Coordinates: 40.698852°N 30.265636°E
Elevation:
Drilling Equipment: Custom made, equivalent to Crealius XC90H
Responsible Engineers: K. Ö. Çetin and M. T. Yilmaz, M.E.T.U.
SPT System: Rope, pulley and cathead method. AWJ rods.
Hammer Type: Safety Hammer (per Kovacs et al. 1983)

Depth Scale (m)	Lithology	USCS	Sample Type and No.	Recovery/ Length (cm)	SPT Blows/15 cm	Casing Depth (m)	Rod Length (m)	Energy Ratio (%)	Description	Pocket Pen (kPa) q_u	Torvane (kPa) s_u	Moisture Content (%)	Liquid Limit	Plasticity Index	% fines < 75 μm	< 5 μm (%)	< 2 μm (%)	D50 (mm)	D10 (mm)	Remarks
		SW-SM	S-SH4-10	18/45	6-6-14	11.00	14.94	66					NP	NP	7	-	-	4.5	0.19	

Legend
S: Spit Spoon (SPT) SH: Shelby Tube * Estimated Energy Ratio NP: Nonplastic

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Figure B.43(cont.): SPT log: SPT-SH4

Figure B.44: SPT log: SPT-SH7

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Joint Research

Sponsored by:
NSF, Caltrans
CEC, PG&E

Project Name: Geotechnical Site Investigations at Lateral Spread Sites
Location: Sapanca Hotel, Sapanca
Date: August 21, 2000
Field Log by: K. Ö. Çetin
Operator: ZETAS (Zemin Teknolojisi, A. S.)
Drilling Method: Rotary wash with 9 cm-diameter tricone bit
Water Table Elevation: 1.25 m
Notes:

Test ID: SPT-SH7
GPS Coordinates: 40.698852°N 30.265636°E
Elevation:
Drilling Equipment: Custom made, equivalent to Crealius XC90H
Responsible Engineers: K. Ö. Çetin and M. T. Yilmaz, M.E.T.U.
SPT System: Rope, pulley and cathead method. AWJ rods.
Hammer Type: Safety Hammer (per Kovacs et al. 1983)

Depth Scale (m)	Lithology	USCS	Sample Type and No.	Recovery/ Length (cm)	SPT Blows/15 cm	Casing Depth (m)	Rod Length (m)	Energy Ratio (%)	Description	Pocket Pen (kPa) q_u	Torvane (kPa) s_u	Moisture Content (%)	Liquid Limit	Plasticity Index	% fines < 75 μm	< 5 μm (%)	< 2 μm (%)	D50 (mm)	D10 (mm)	Remarks
12		SP-SM	S-SH7-12	22/45	2-5-6	11.80	14.94	61					NP	NP	5	-	-	0.84	0.24	
13		SM	S-SH7-13	11/45	3-8-5	13.50	16.46	65					NP	NP	14	-	-	0.84	<0.07	

Legend
S: Spit Spoon (SPT) SH: Shelby Tube * Estimated Energy Ratio NP: Nonplastic

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Figure B.44(cont.): SPT log: SPT-SH7

Figure B.45: SPT log: SPT-SH11

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Joint Research
Sponsored by:
NSF, Caltrans
CEC, PG&E

Project Name: Geotechnical Site Investigations at Lateral Spread Sites
Location: Police Station, eastern edge of Izmit Bay
Date: August 26, 2000
Field Log by: K. Ö. Çetin
Operator: ZETAS (Zemin Teknolojisi, A. S.)
Drilling Method: Rotary wash with 9 cm-diameter tricone bit
Water Table Elevation: 1.40 m
Notes:

Test ID: SPT-PS3
GPS Coordinates: 40.72120°N 29.73733°E
Elevation:
Drilling Equipment: Custom made, equivalent to Crealius XC90H
Responsible Engineers: K. Ö. Çetin and M. T. Yilmaz, M.E.T.U.
SPT System: Rope, pulley and cathead method. AWJ rods.
Hammer Type: Safety Hammer (per Kovacs et al. 1983)

USCS	Sample Type and No.	Recovery/ Length (cm)	SPT Blows/15 cm	Casing Depth (m)	Rod Length (m)	Energy Ratio (%)	Description	q_u Pocket Pen (kPa)	s_u Torvane (kPa)	Moisture Content (%)	Liquid Limit	Plasticity Index	% fines < 75 μm	< 5 μm (%)	< 2 μm (%)	D50 (mm)	D10 (mm)	Remarks
							FILL: Brown silty clay.											
SM	S-PS3-1	14/45	8-20->30	1.70	5.20	55*	FILL: Brown gravelly silty sand.				NP	NP	24	-	-	1.1	<0.07	
SM	S-PS3-2	0/45	3-1-2	2.20	5.20	55*	SM: Gray silty sand.				NP	NP	36	-	-	0.13	<0.07	
CL	SH-PS3-3	45/50		3.70			CL: Gray clay.			35	45	23	89	24	17	0.02	<1μm	
CL	SH-PS3-4	45/50		5.70						40	41	18	99	32	18	0.014	<1μm	
SM CL	S-PS3-5	40/45	4-3-3	8.00	12.82	65*	SM: Gray silty sand. CL: Gray clay.				NP	NP	26 89	- -	- -	0.98 <0.07	<0.07 <0.07	
	SH-PS3-6	42/50		9.30														
	SH-PS3-7	45/50		10.40														

Depth Scale (m): 0 – 11

Legend
S: Spit Spoon (SPT) SH: Shelby Tube * Estimated Energy Ratio NP: Nonplastic

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Figure B.46: SPT log: SPT-PS3

Figure B.46(cont.): SPT log: SPT-PS3

Figure B.47: SPT log: SPT-PS4

Figure B.48: SPT log: SPT-SF5

Figure B.49: SPT log: SPT-A1-YS

Figure B.50: SPT log: SPT-A2-YS

Figure B.51: SPT log: SPT-YH3

Figure B.52: SPT log: SPT-YH1

APPENDIX C

CPT PROFILES

In Appendix C, CTP profiles of tests tabulated in Appendix A are presented.

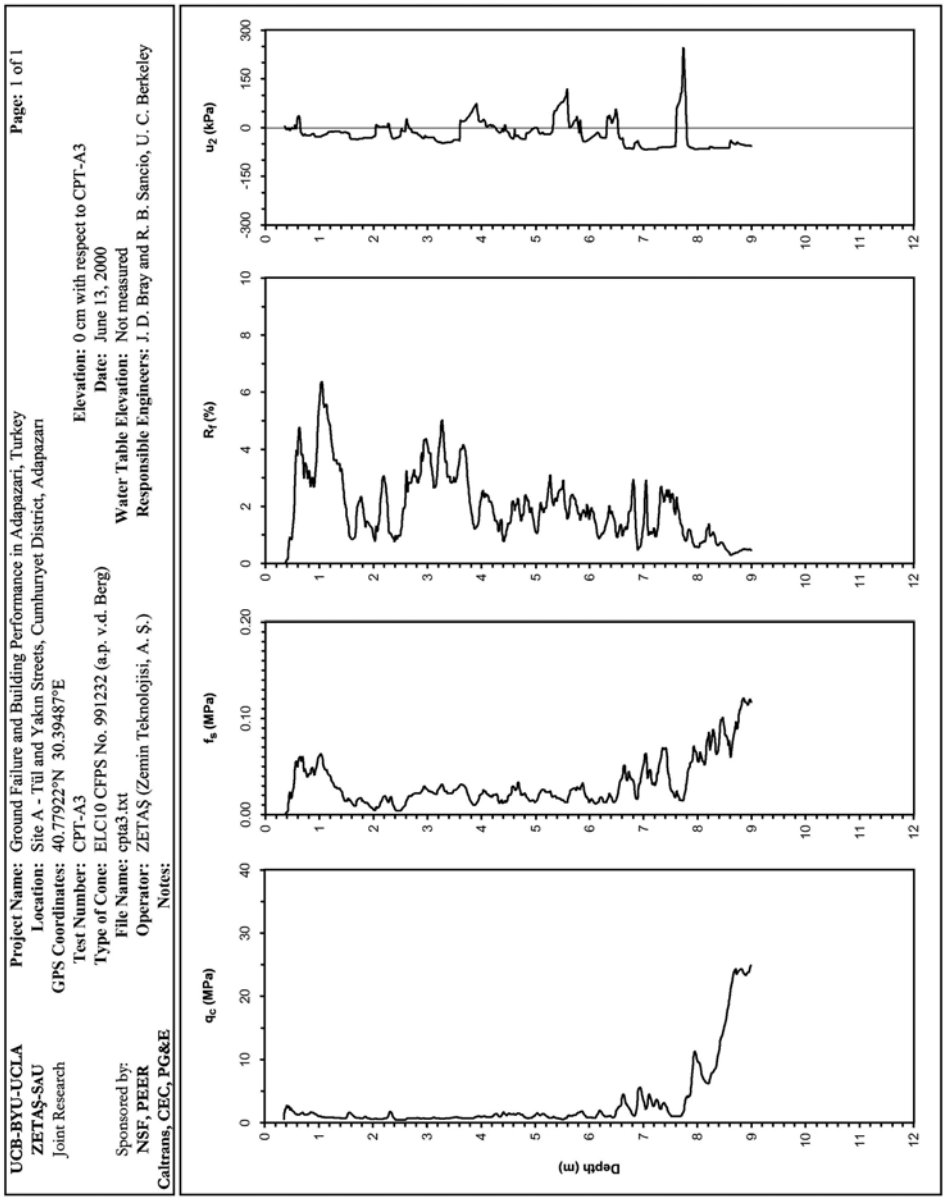


Figure C.1: CPT Profile: CPT-A3

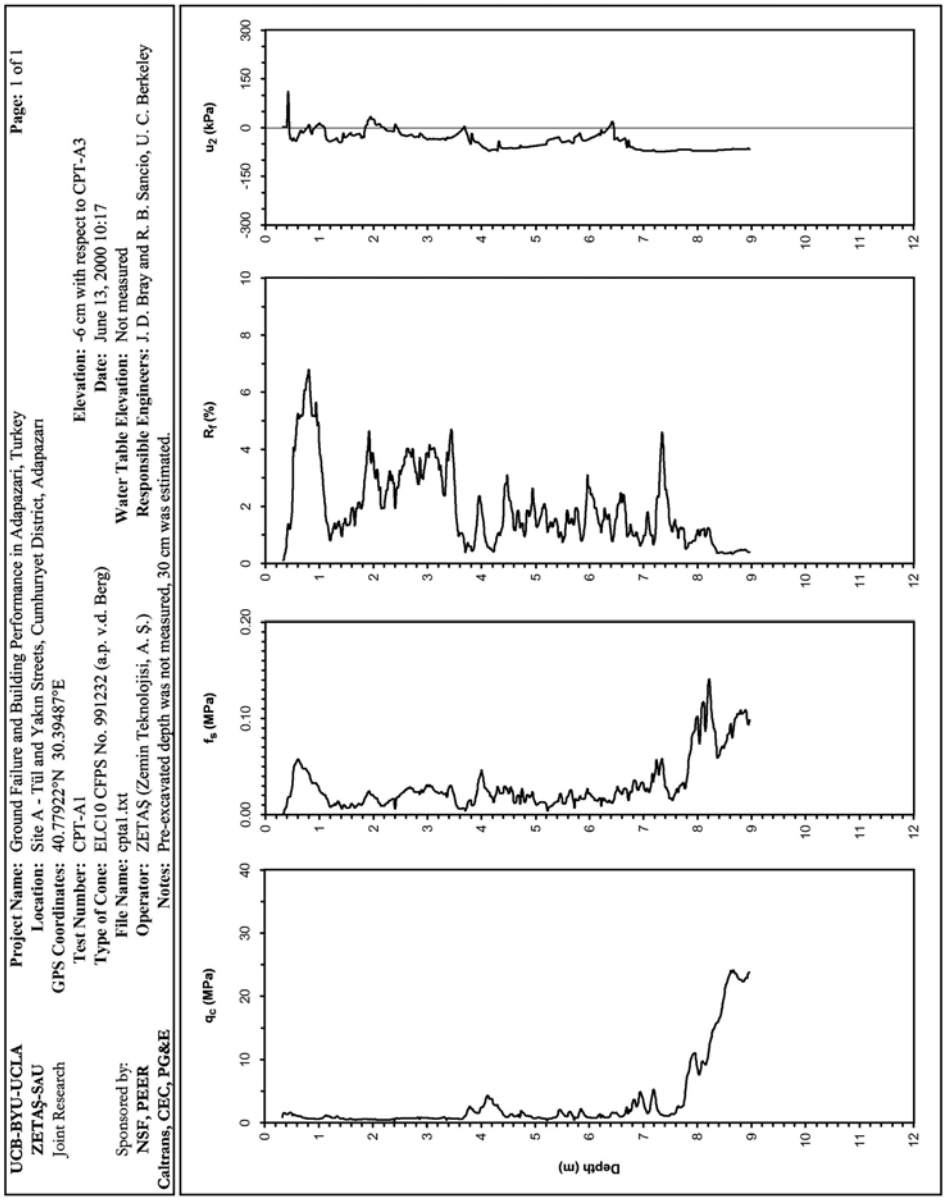


Figure C.2: CPT Profile: CPT-A1

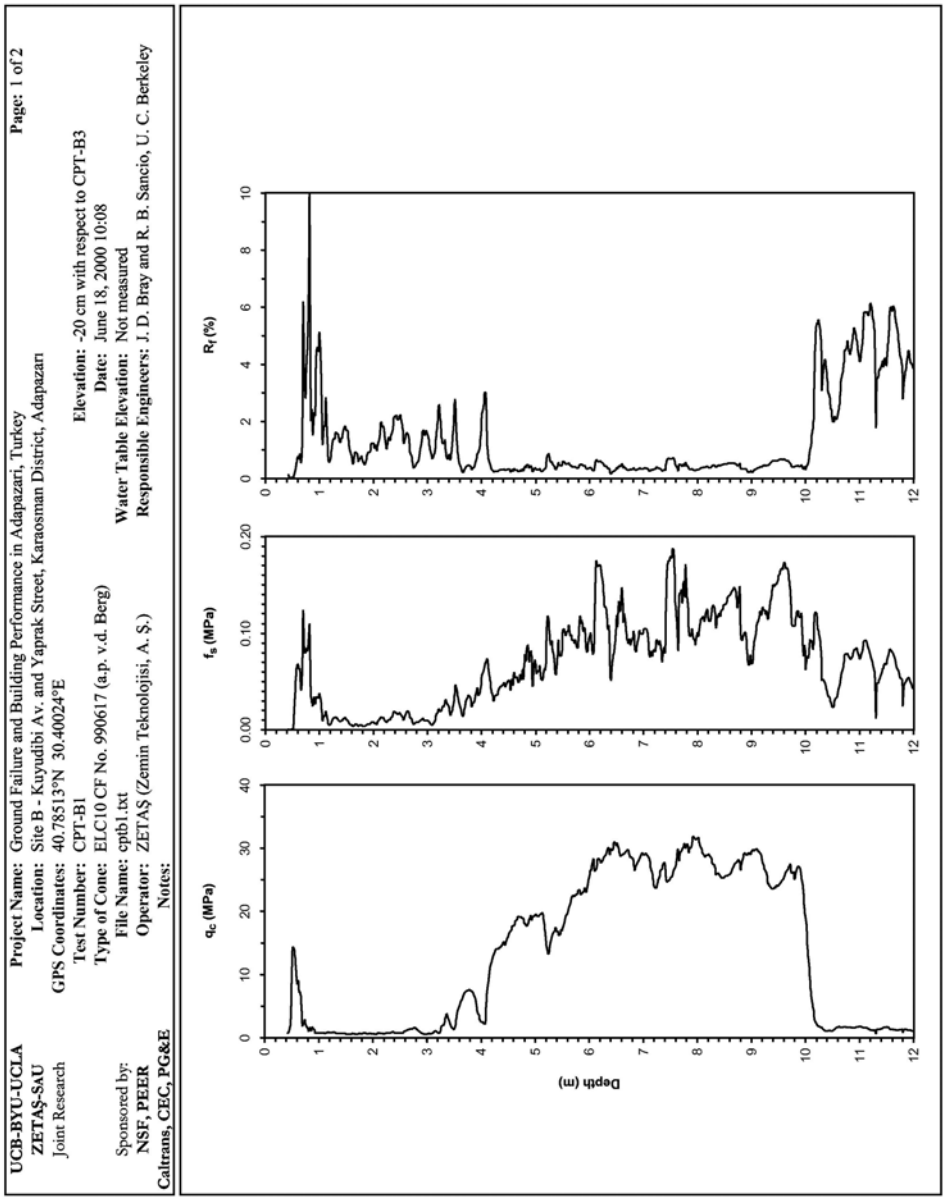


Figure C.3: CPT Profile: CPT-B1

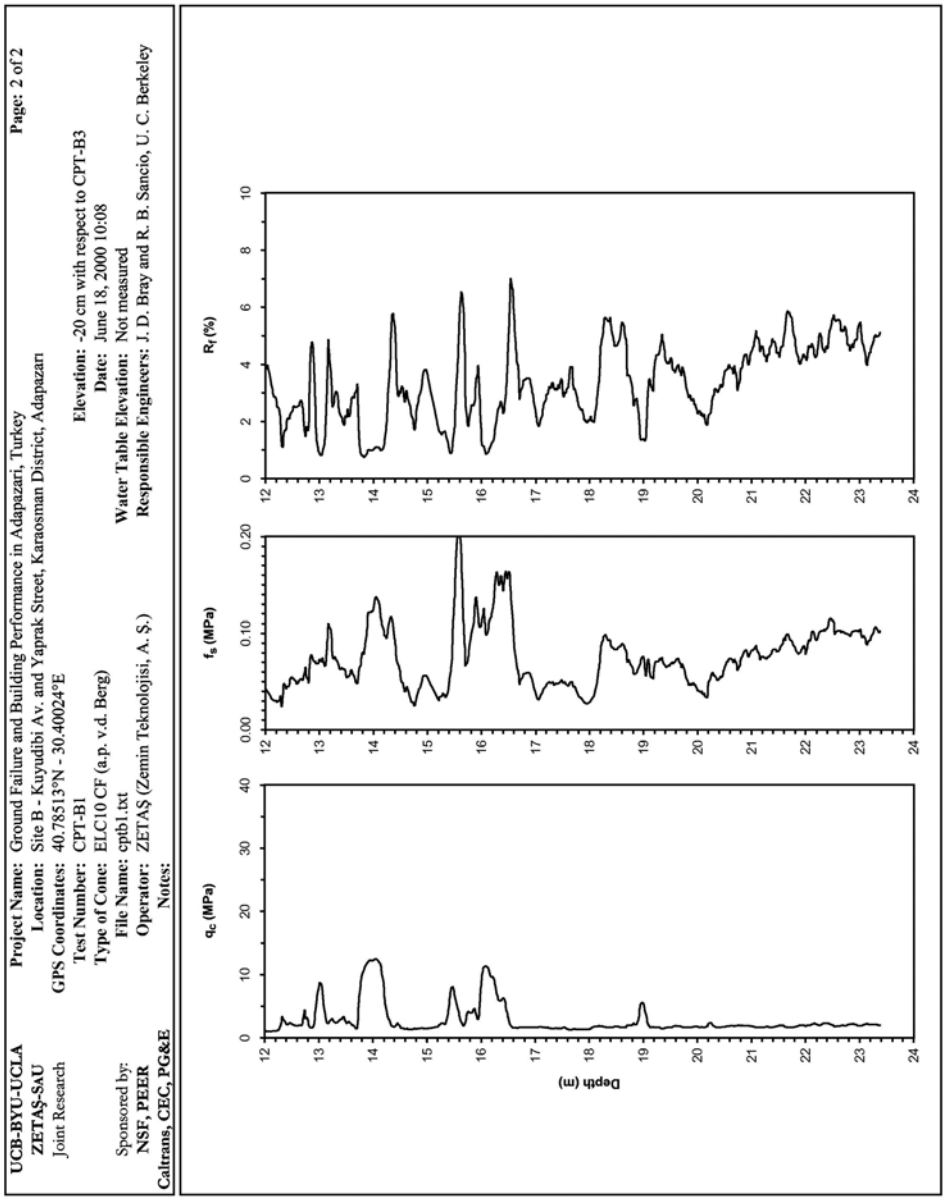


Figure C.3(cont.): CPT Profile: CPT-B1

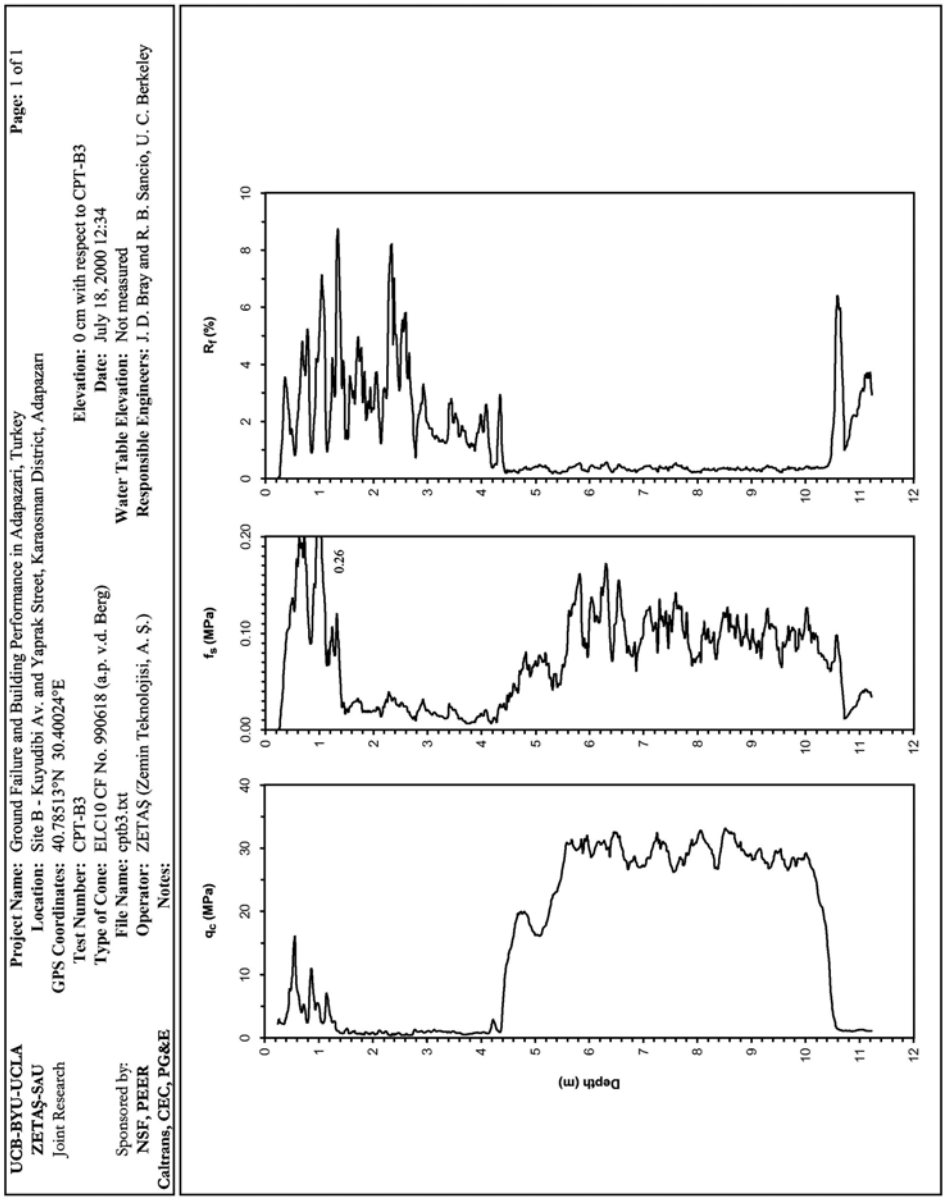


Figure C.4: CPT Profile: CPT-B3

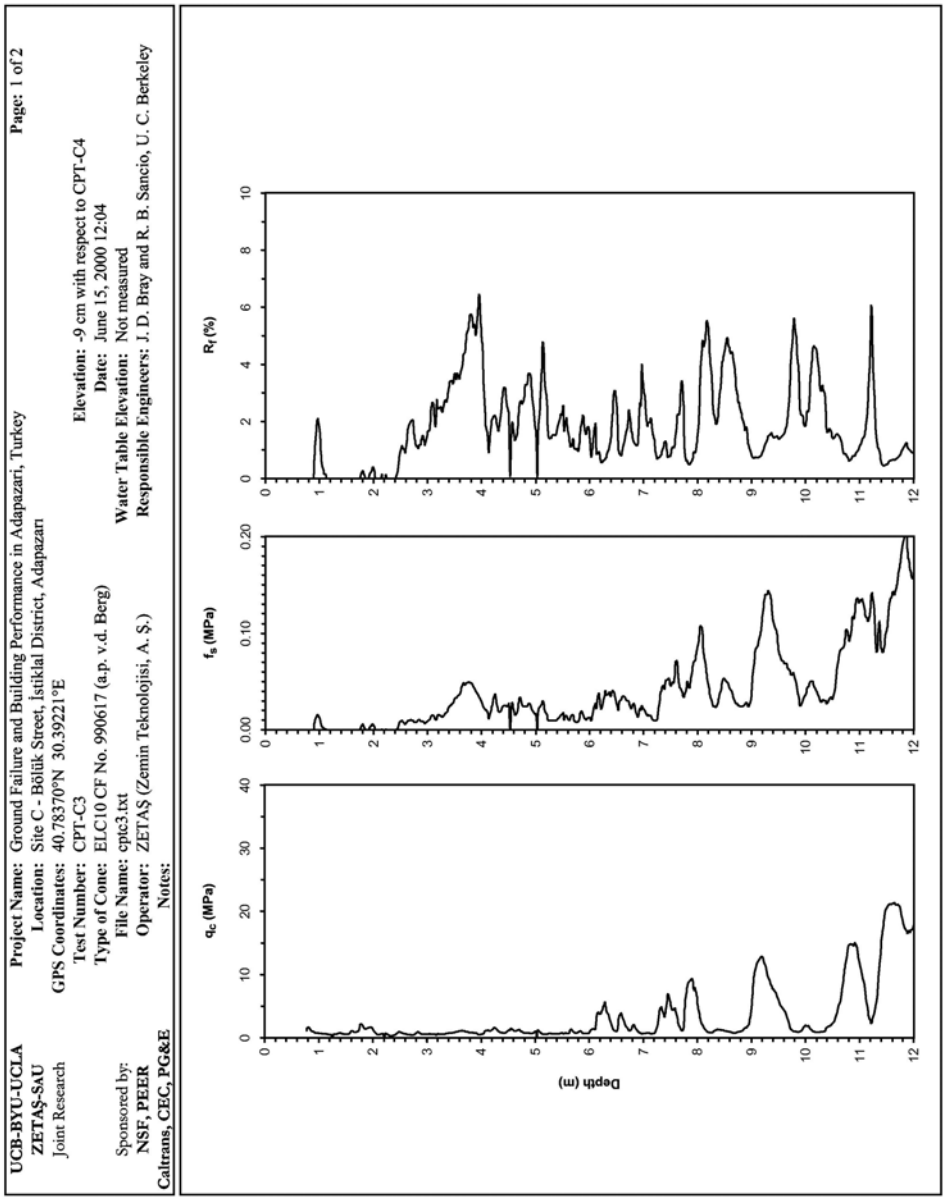


Figure C.5: CPT Profile: CPT-C3

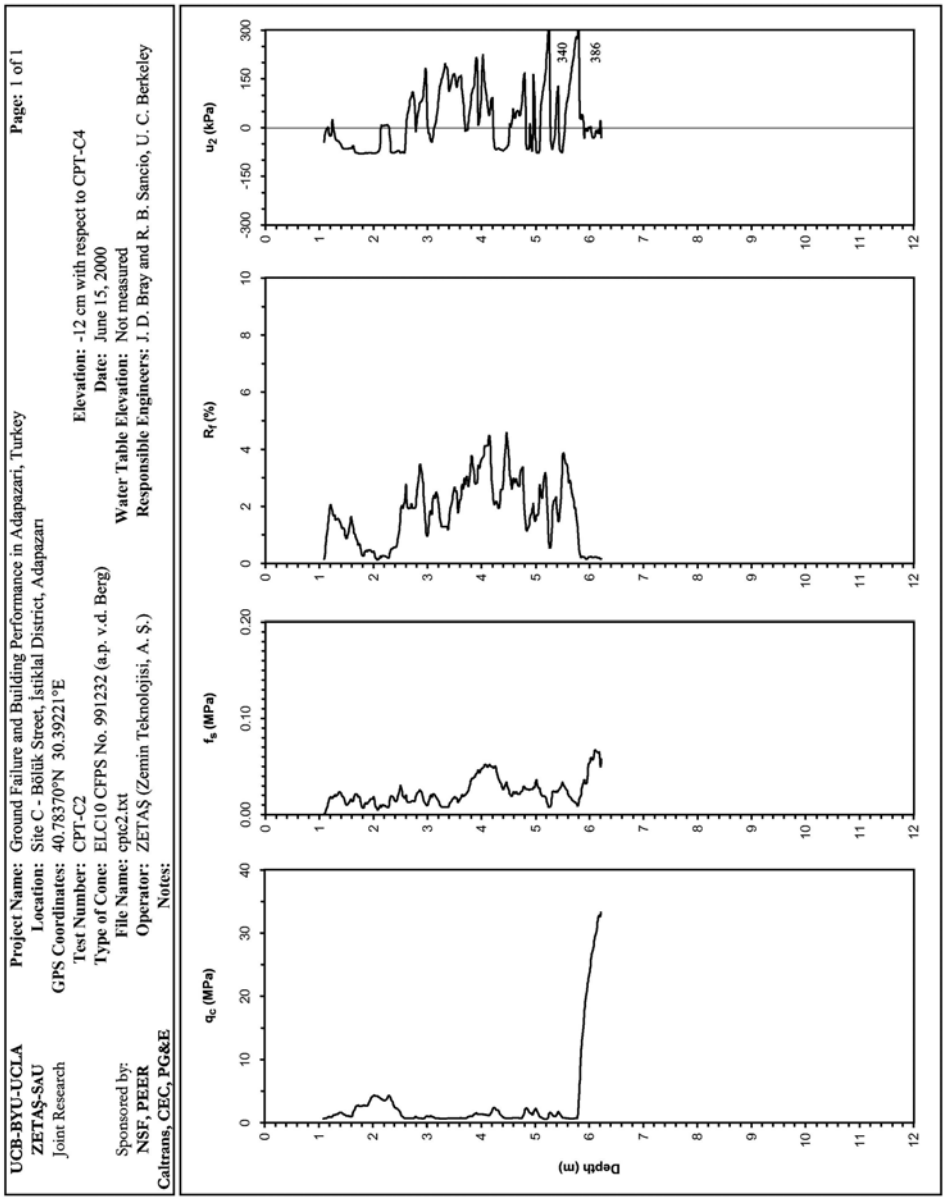


Figure C.6: CPT Profile: CPT-C2

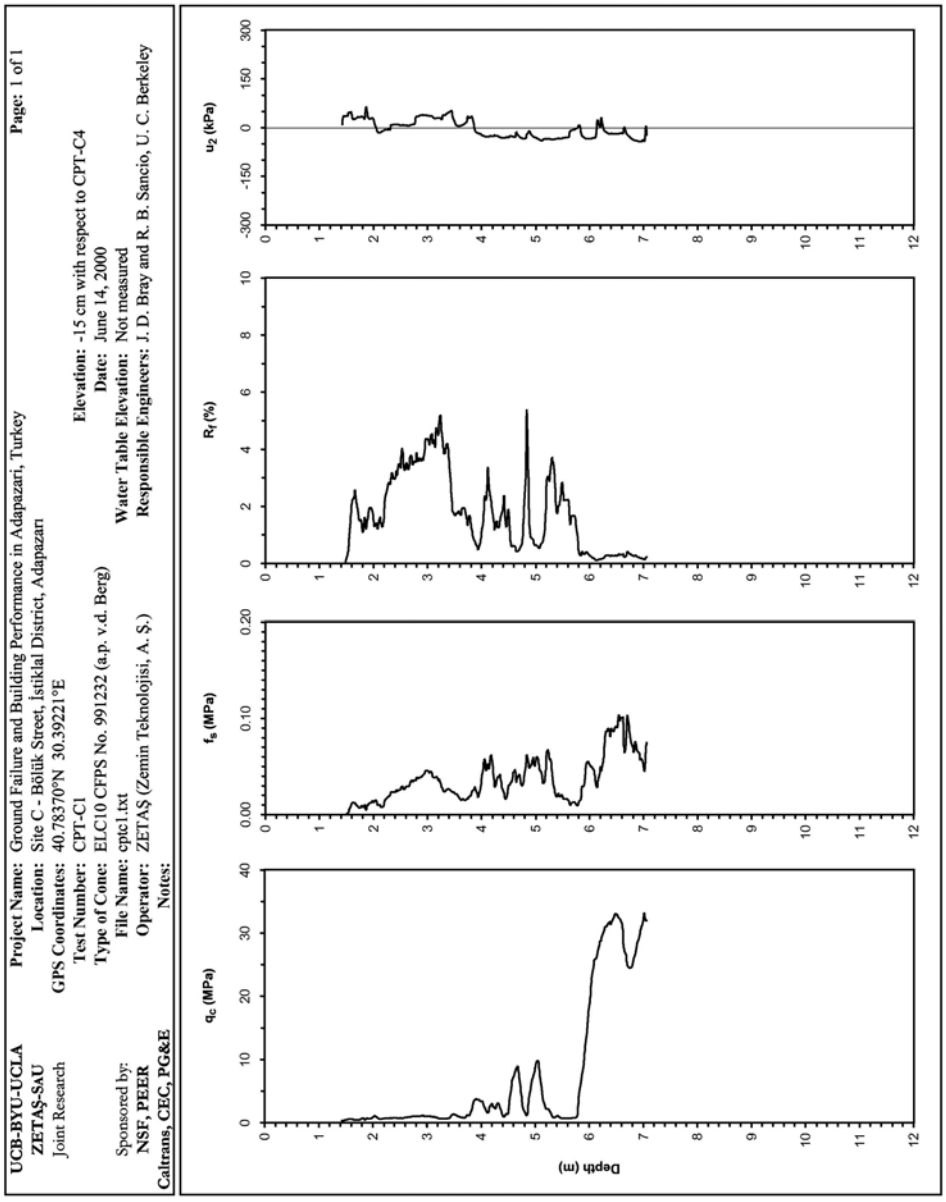


Figure C.7: CPT Profile: CPT-C1

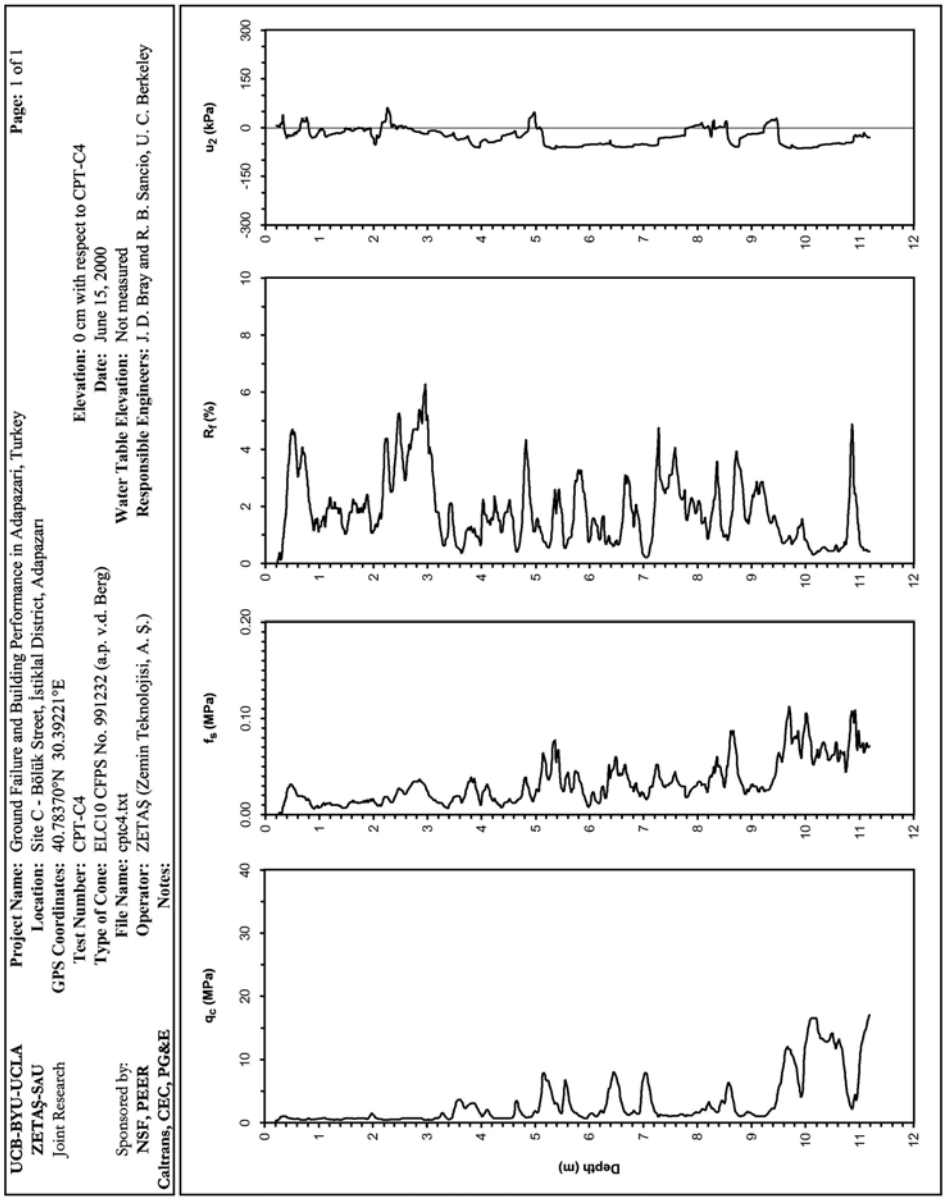


Figure C.8: CPT Profile: CPT-C4

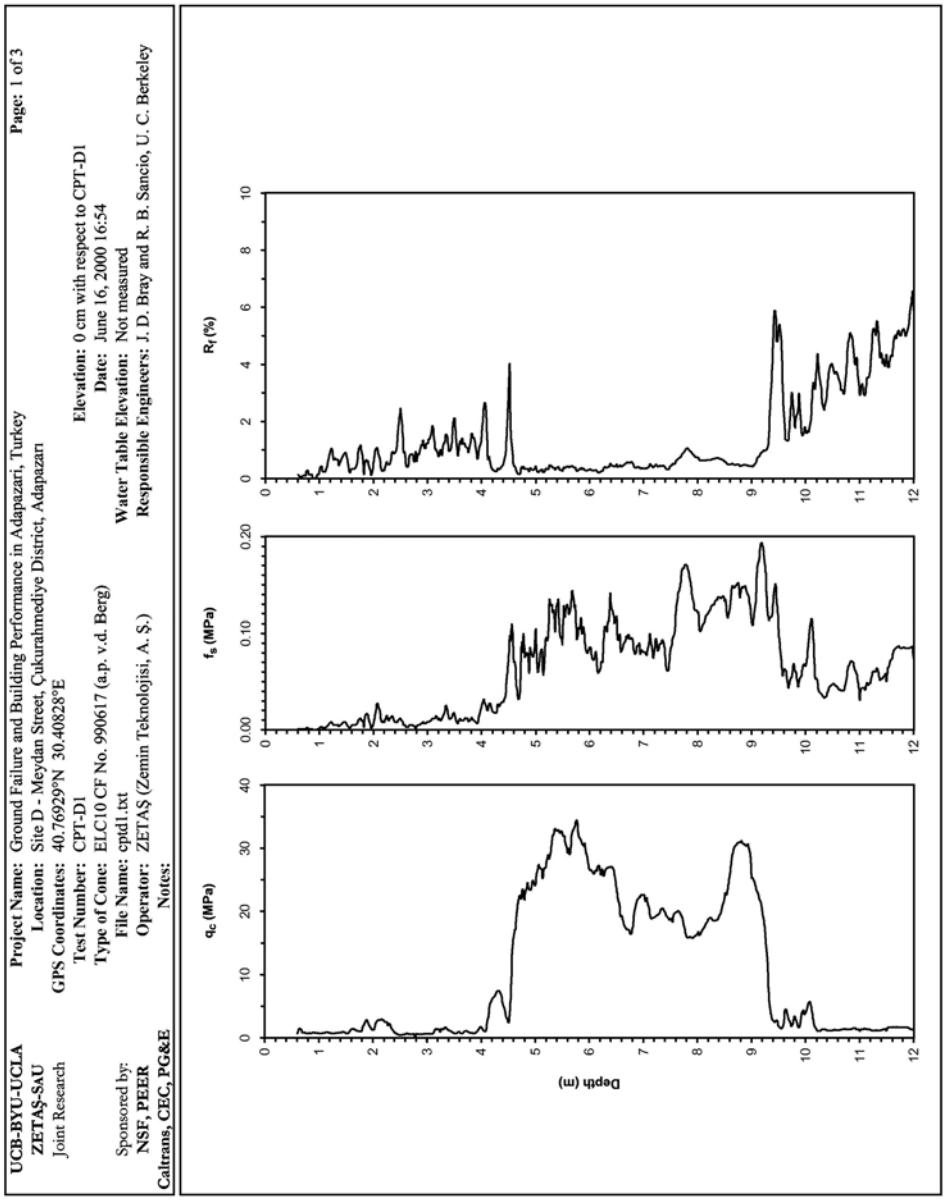


Figure C.9: CPT Profile: CPT-D1

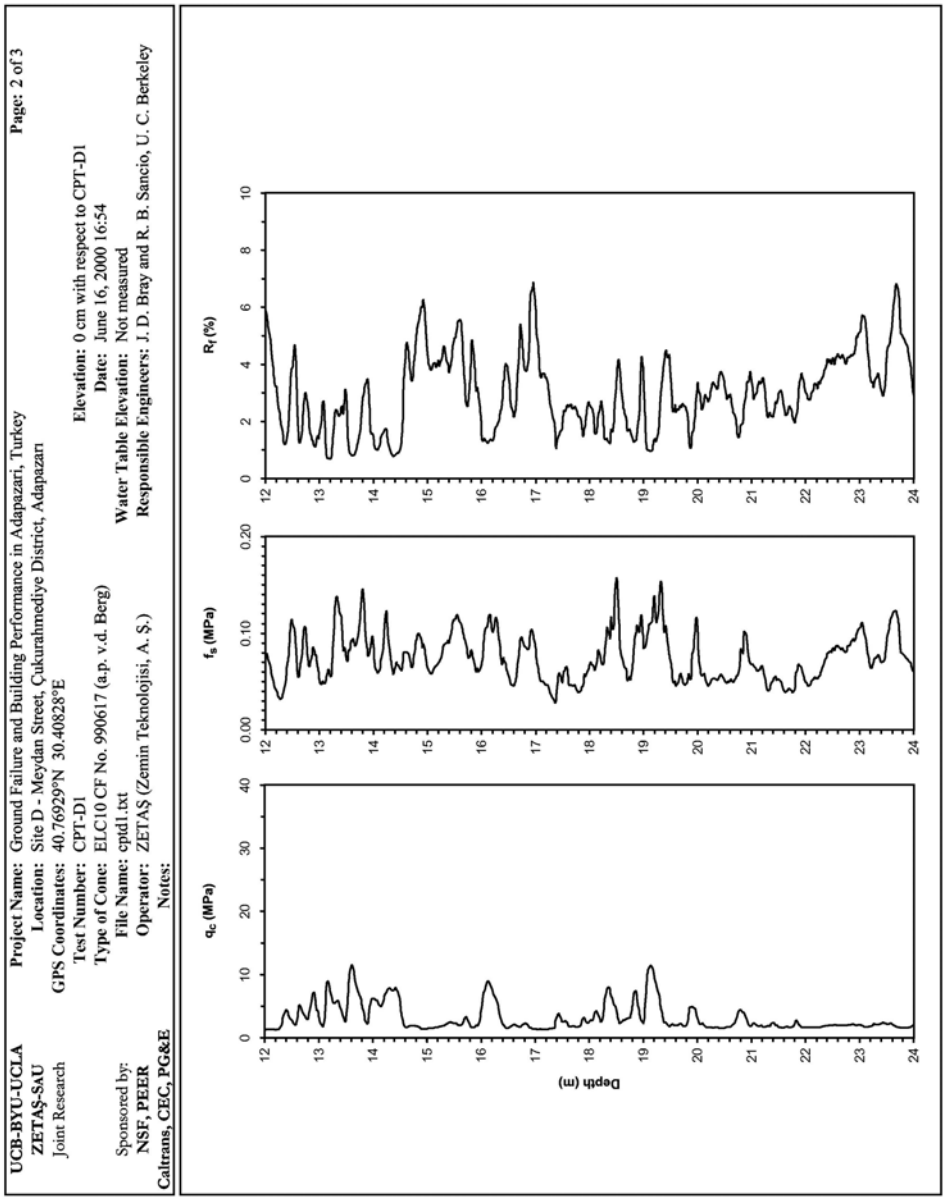


Figure C.9(cont.): CPT Profile: CPT-D1

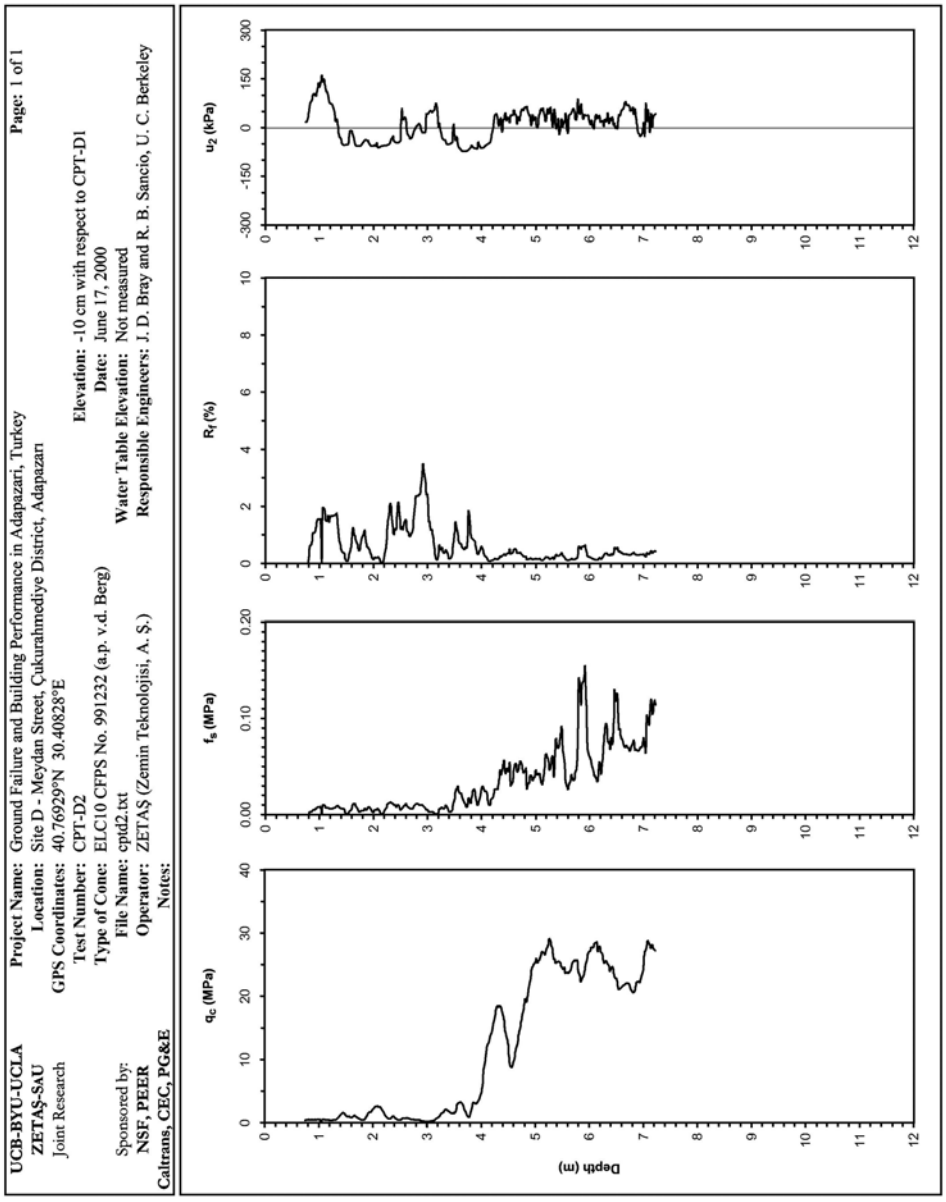


Figure C.10: CPT Profile: CPT-D2

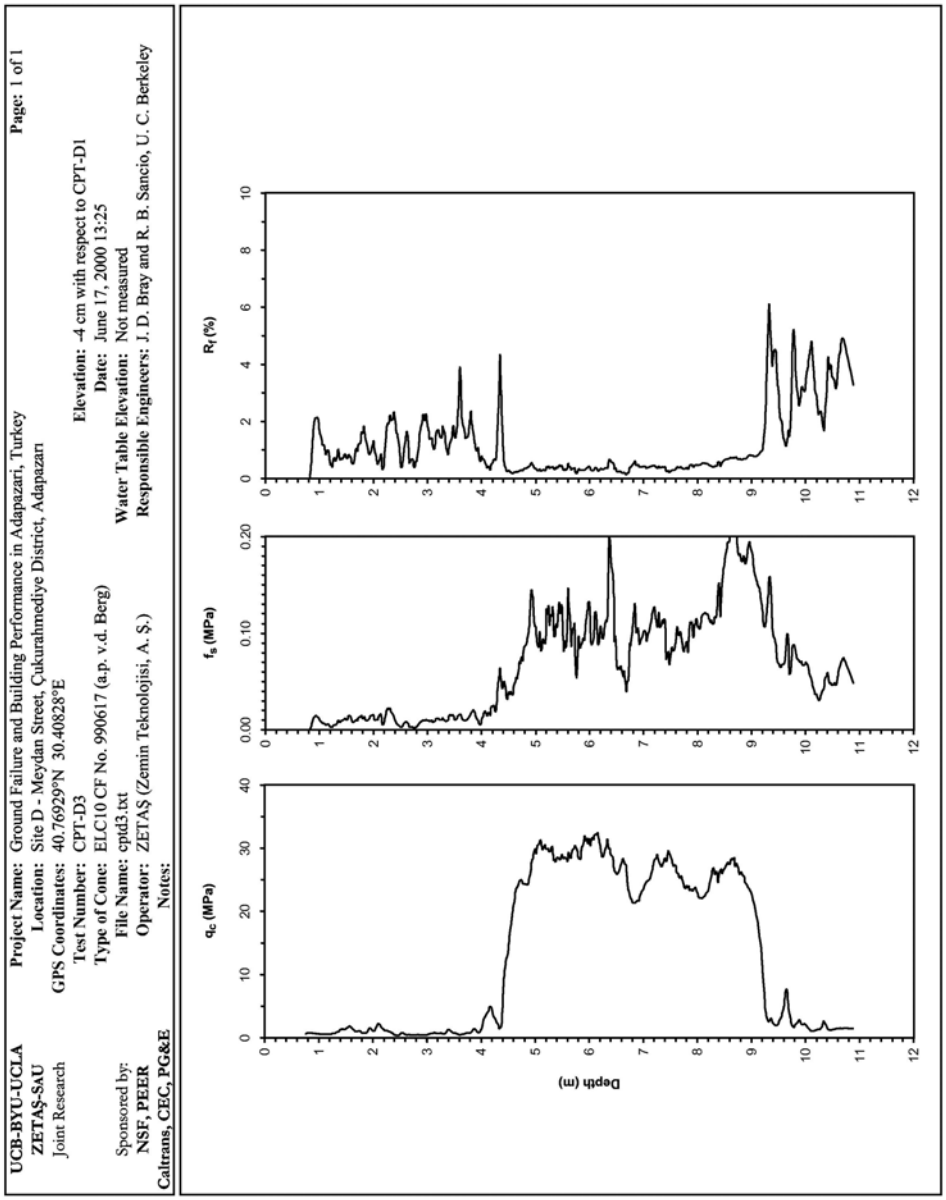


Figure C.11: CPT Profile: CPT-D3

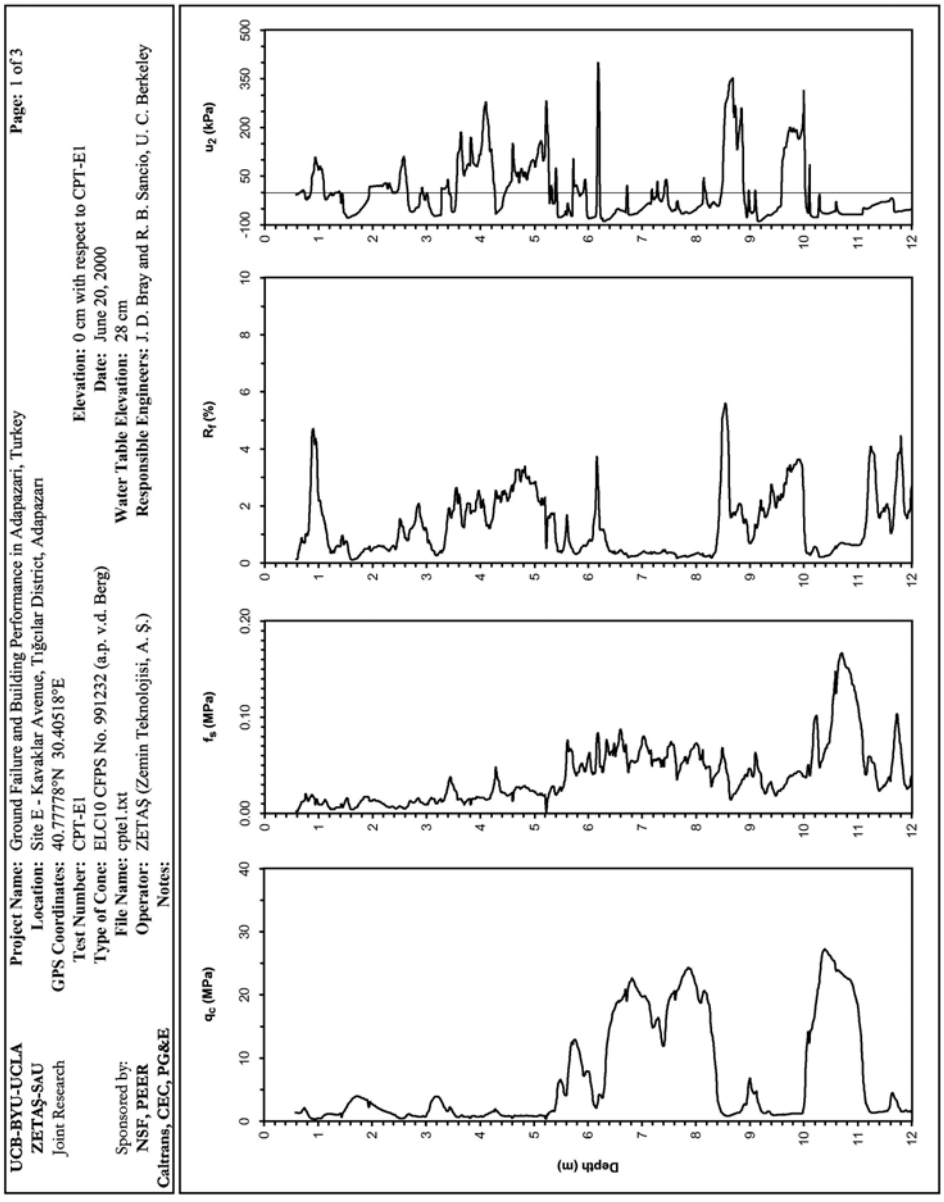


Figure C.12: CPT Profile: CPT-E1

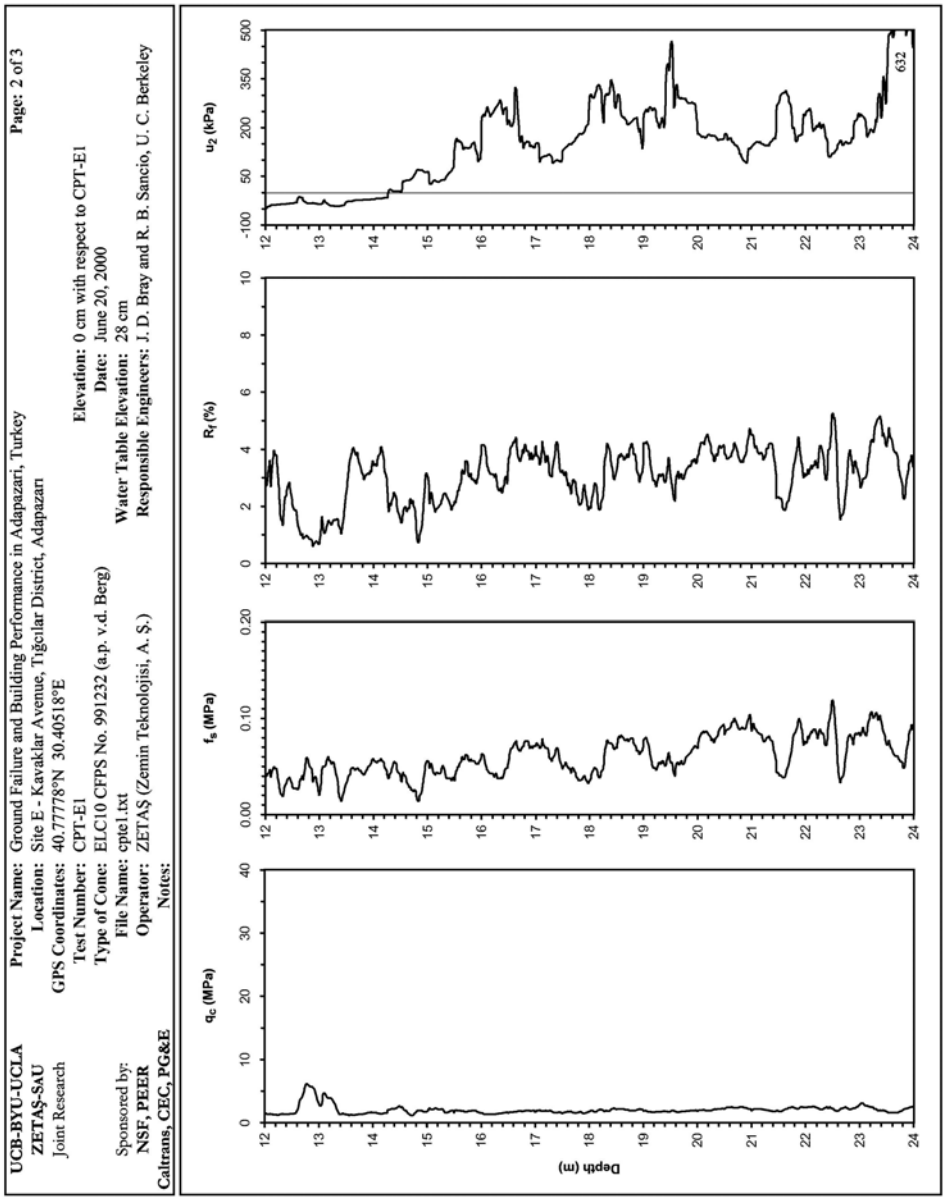


Figure C.12(cont.): CPT Profile: CPT-E1

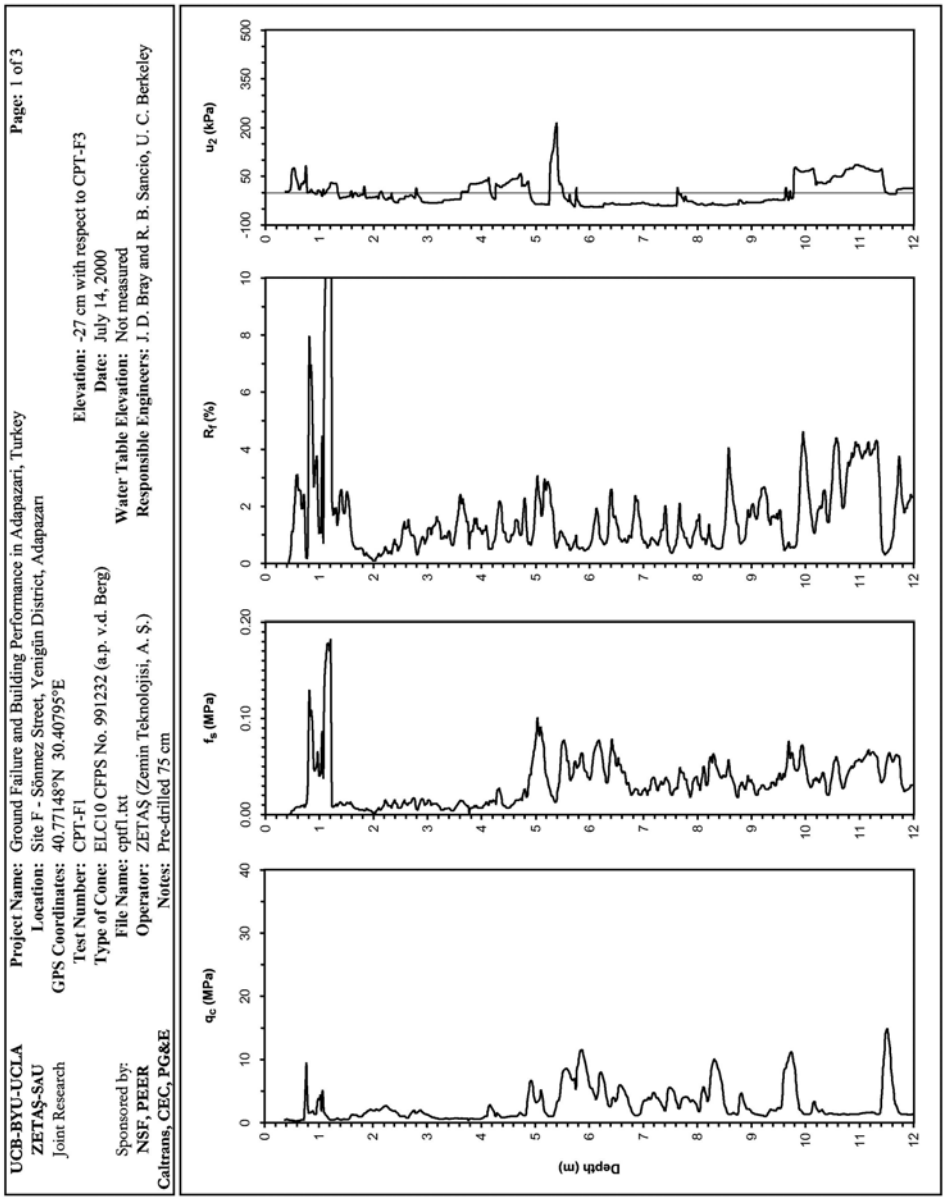


Figure C.13: CPT Profile: CPT-F1

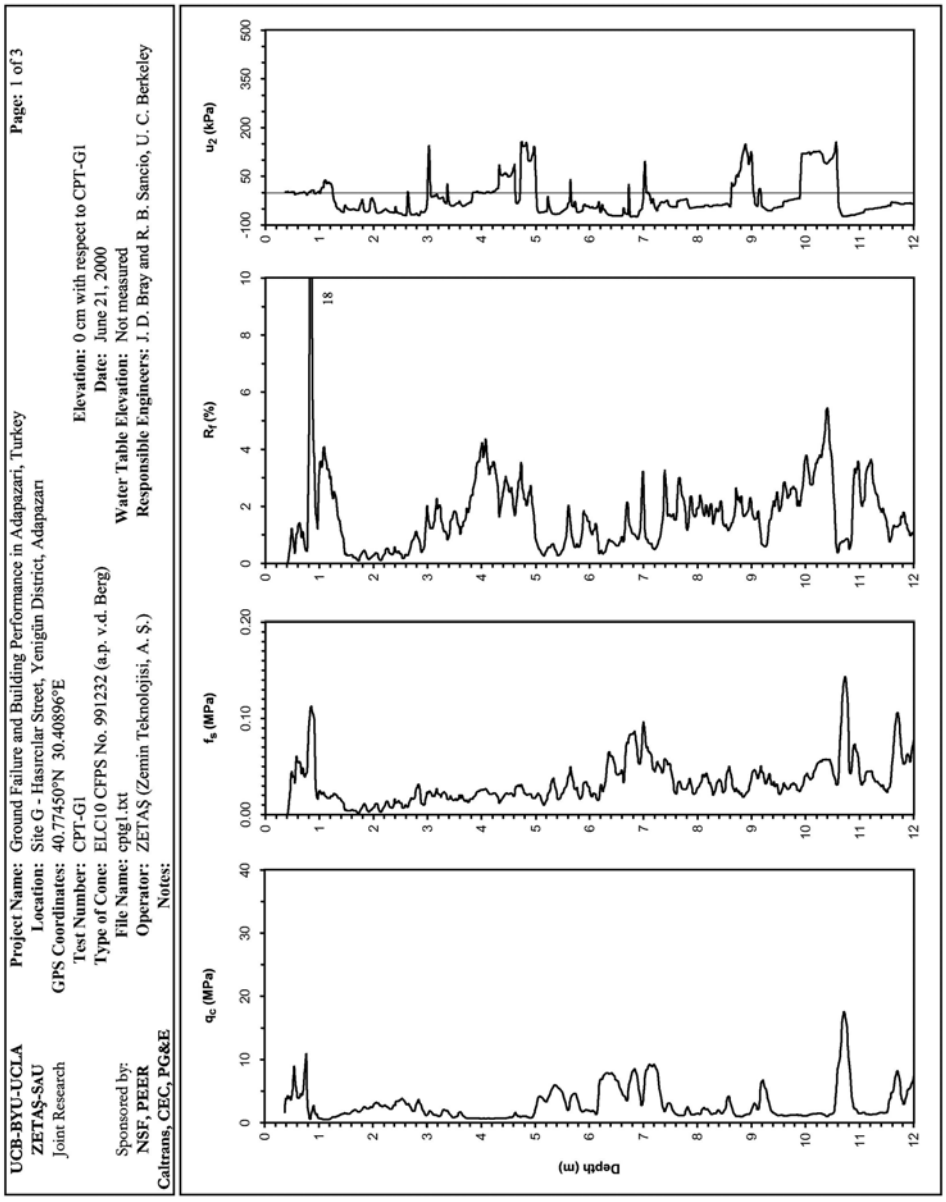


Figure C.14: CPT Profile: CPT-G1

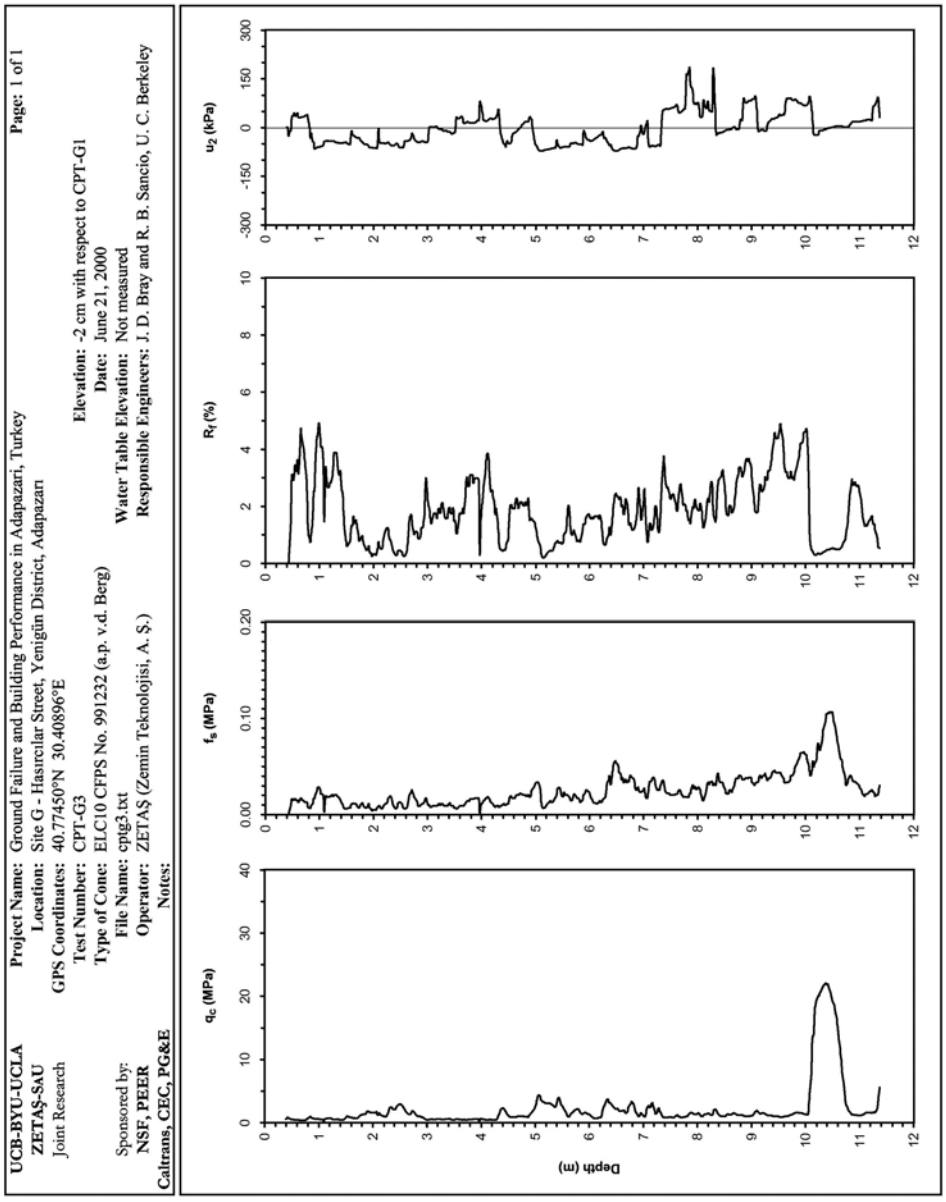


Figure C.15: CPT Profile: CPT-G3

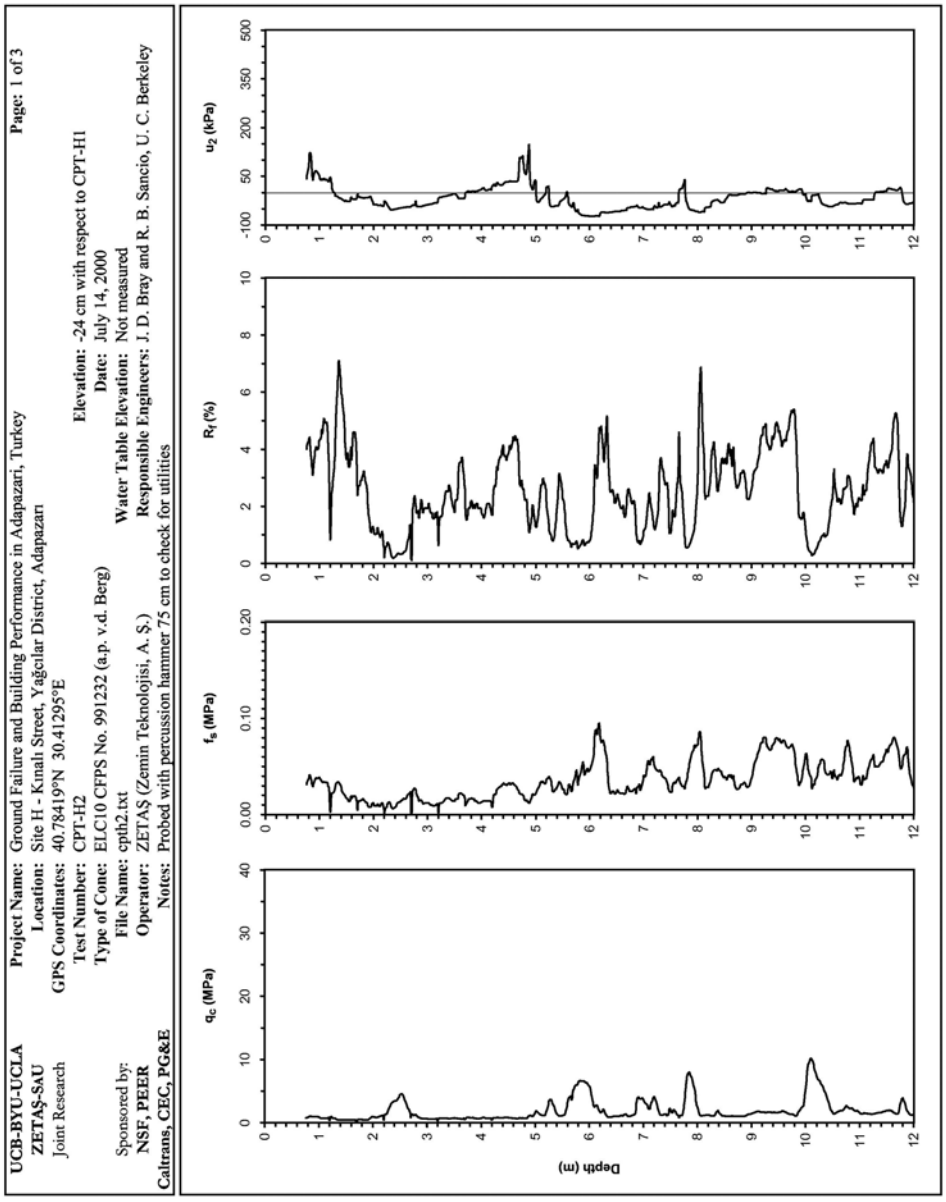


Figure C.16: CPT Profile: CPT-H2

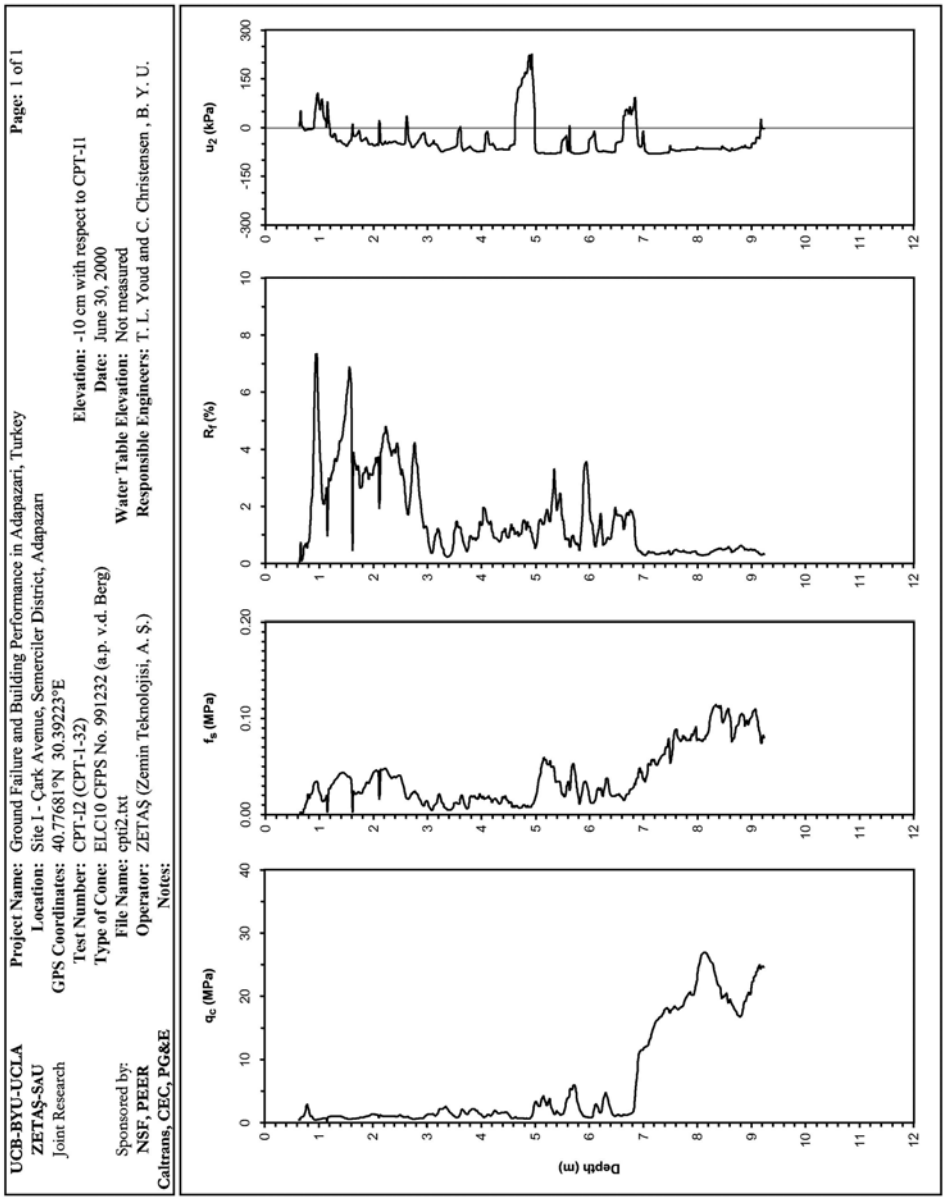


Figure C.17: CPT Profile: CPT-I2

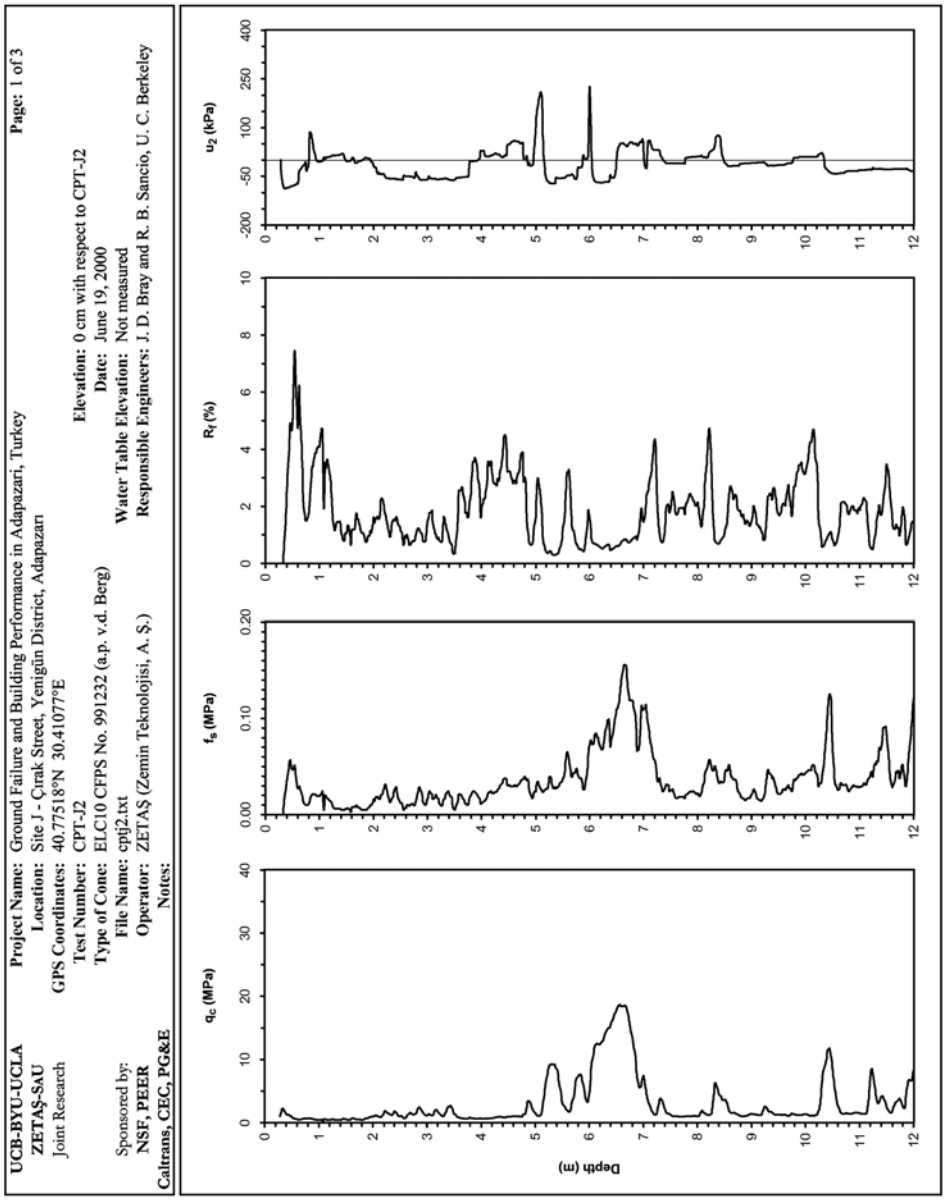


Figure C.18: CPT Profile: CPT-J2

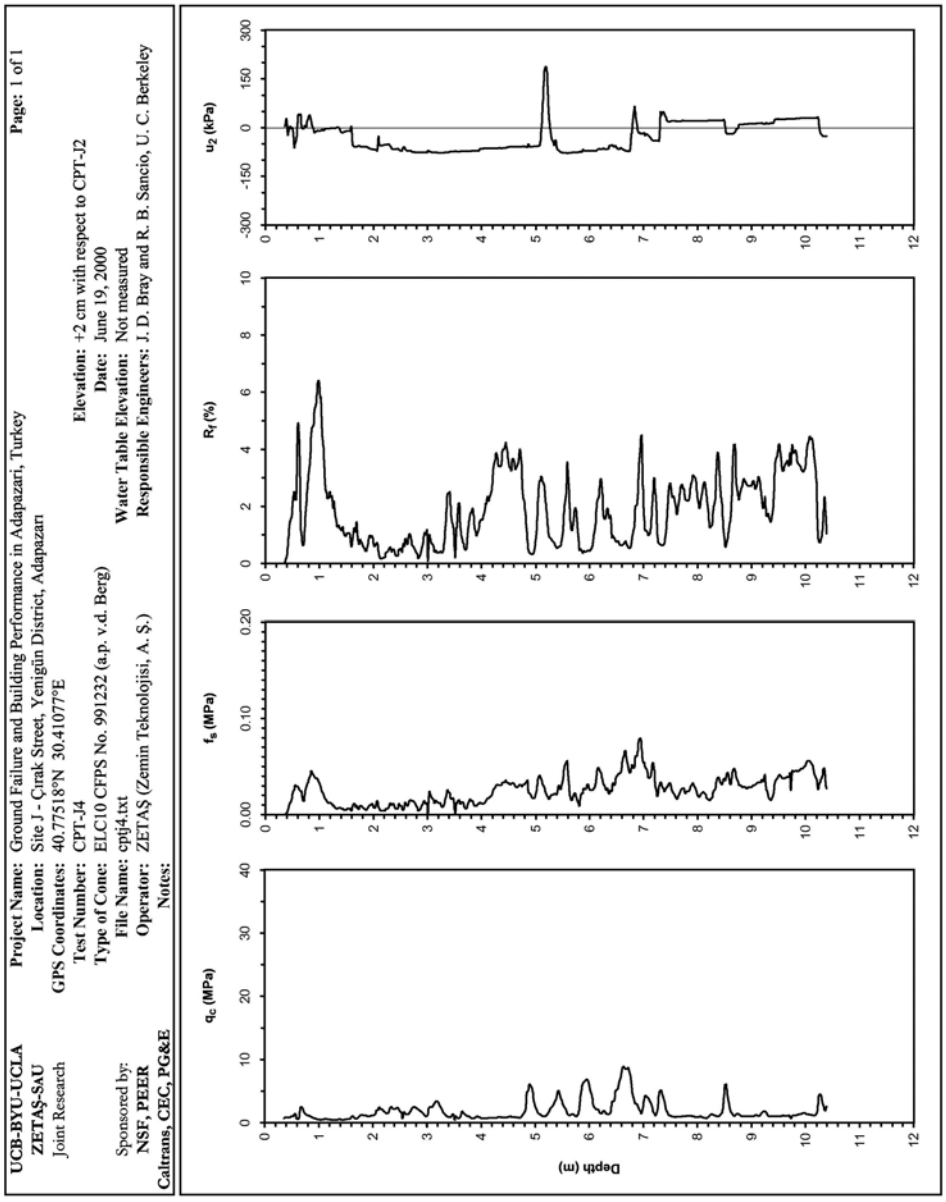


Figure C.19: CPT Profile: CPT-J4

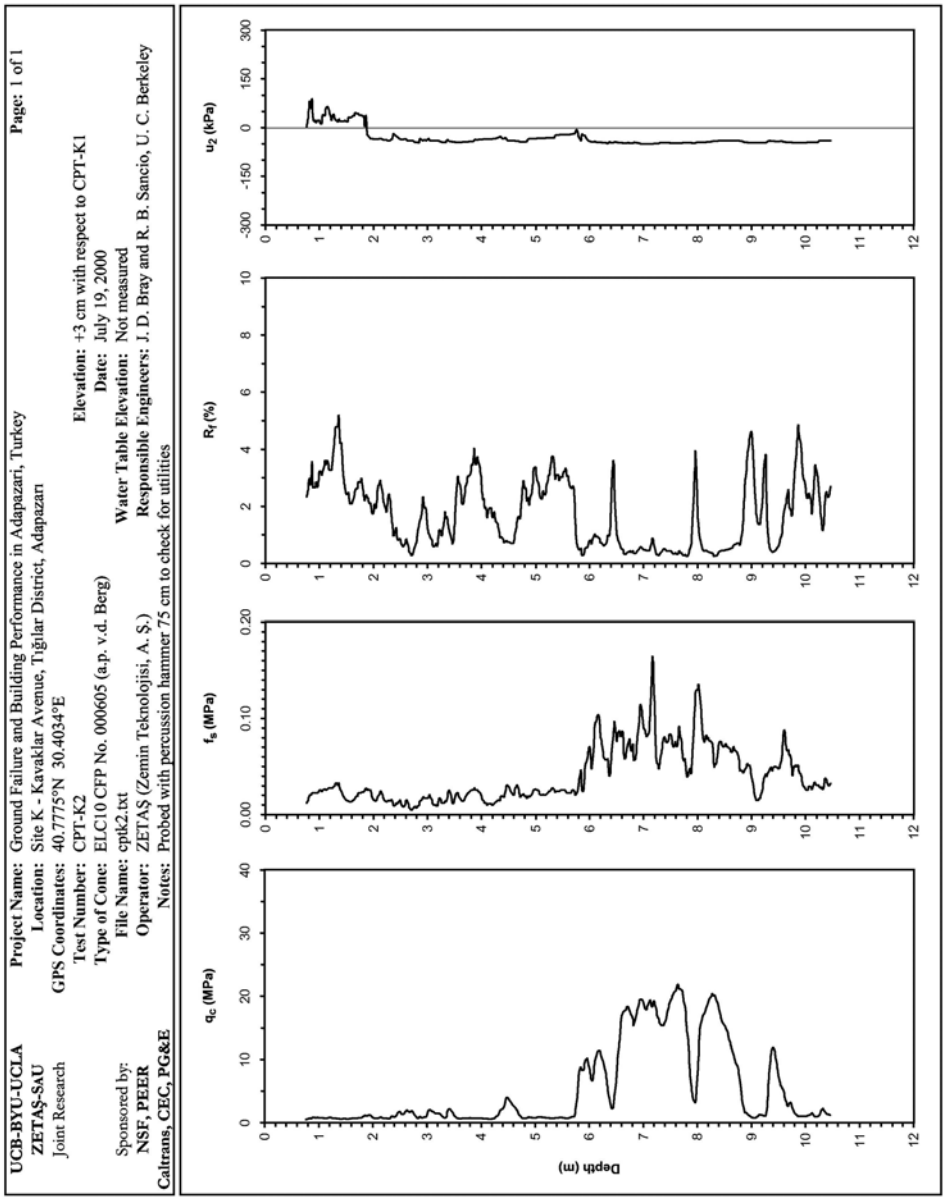


Figure C.20: CPT Profile: CPT-K2

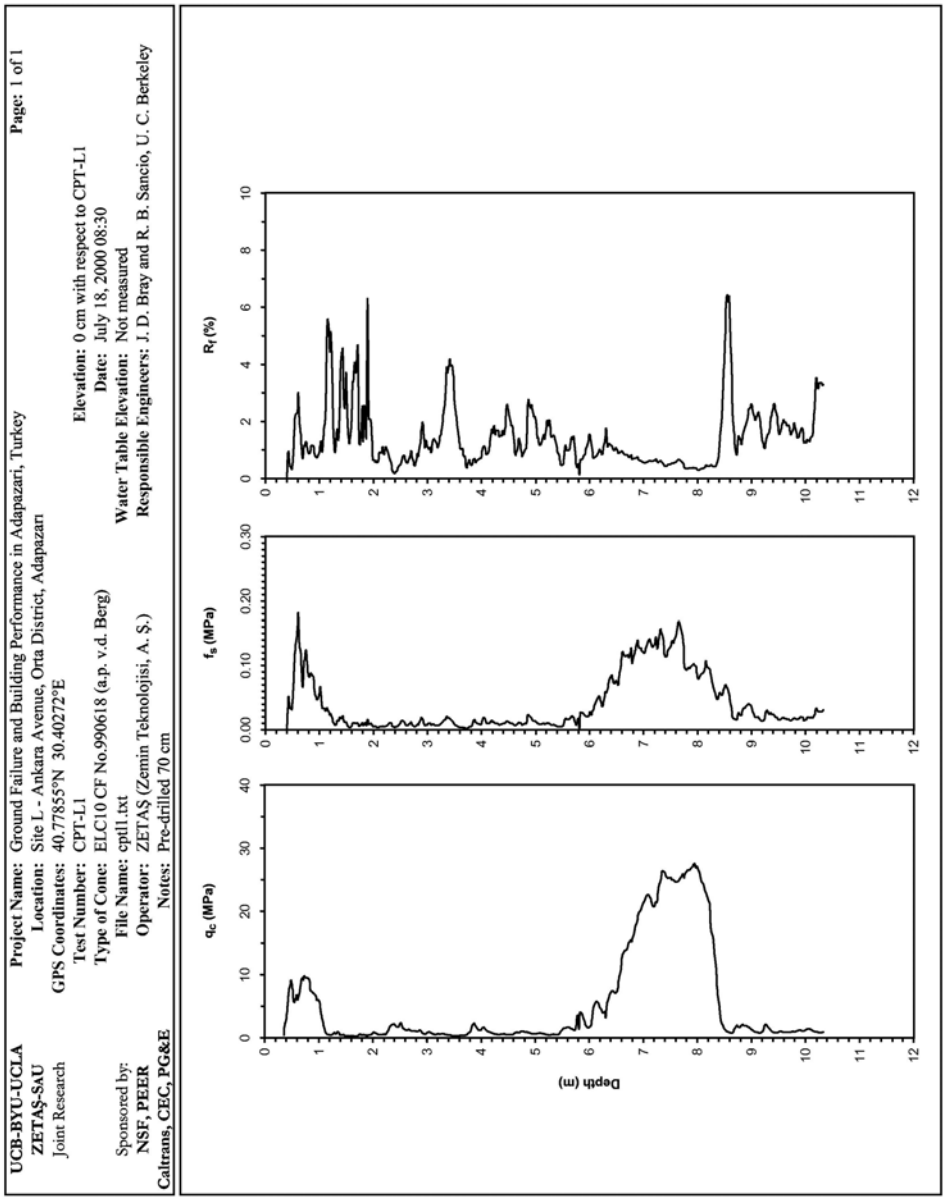


Figure C.21: CPT Profile: CPT-L1

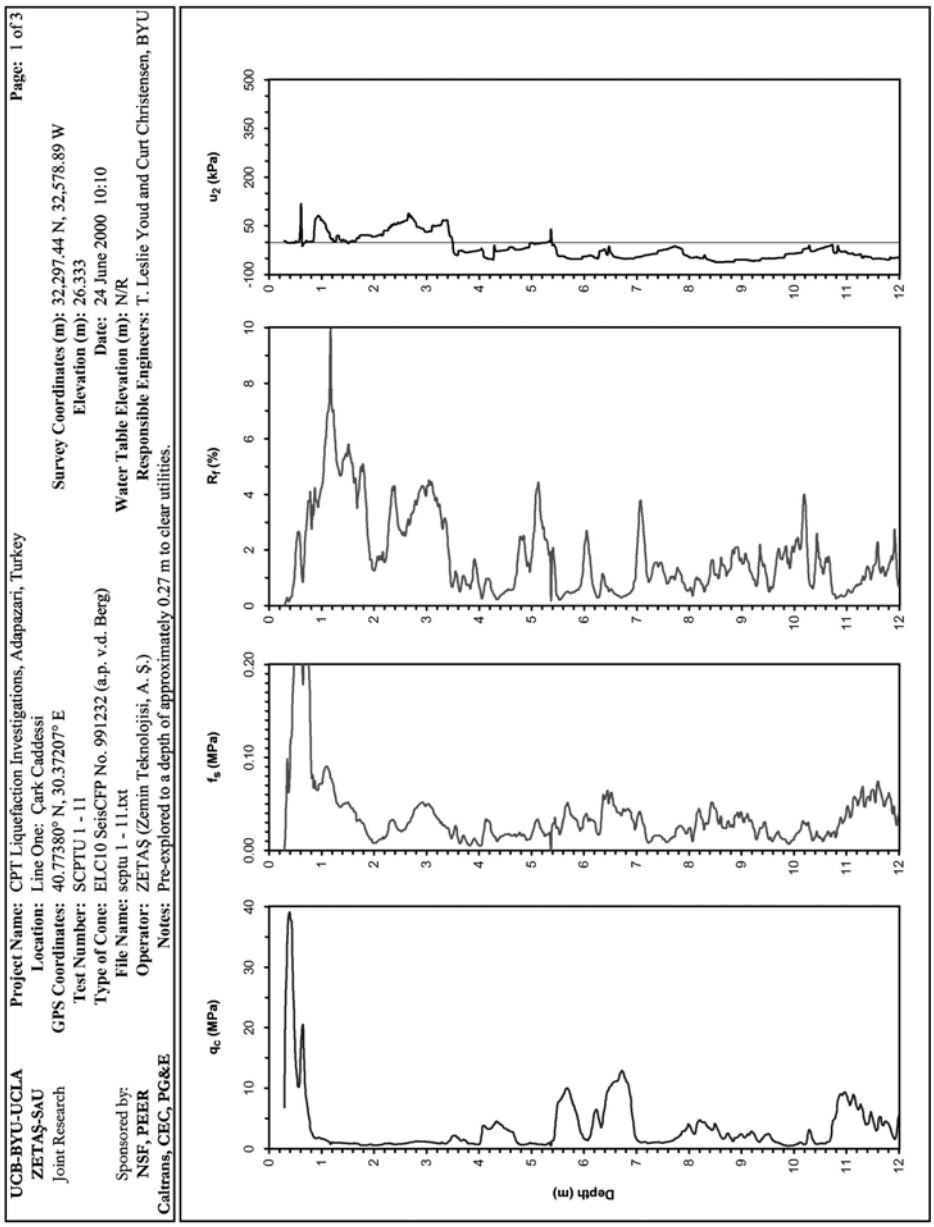


Figure C.22: CPT Profile: CPT-1-11

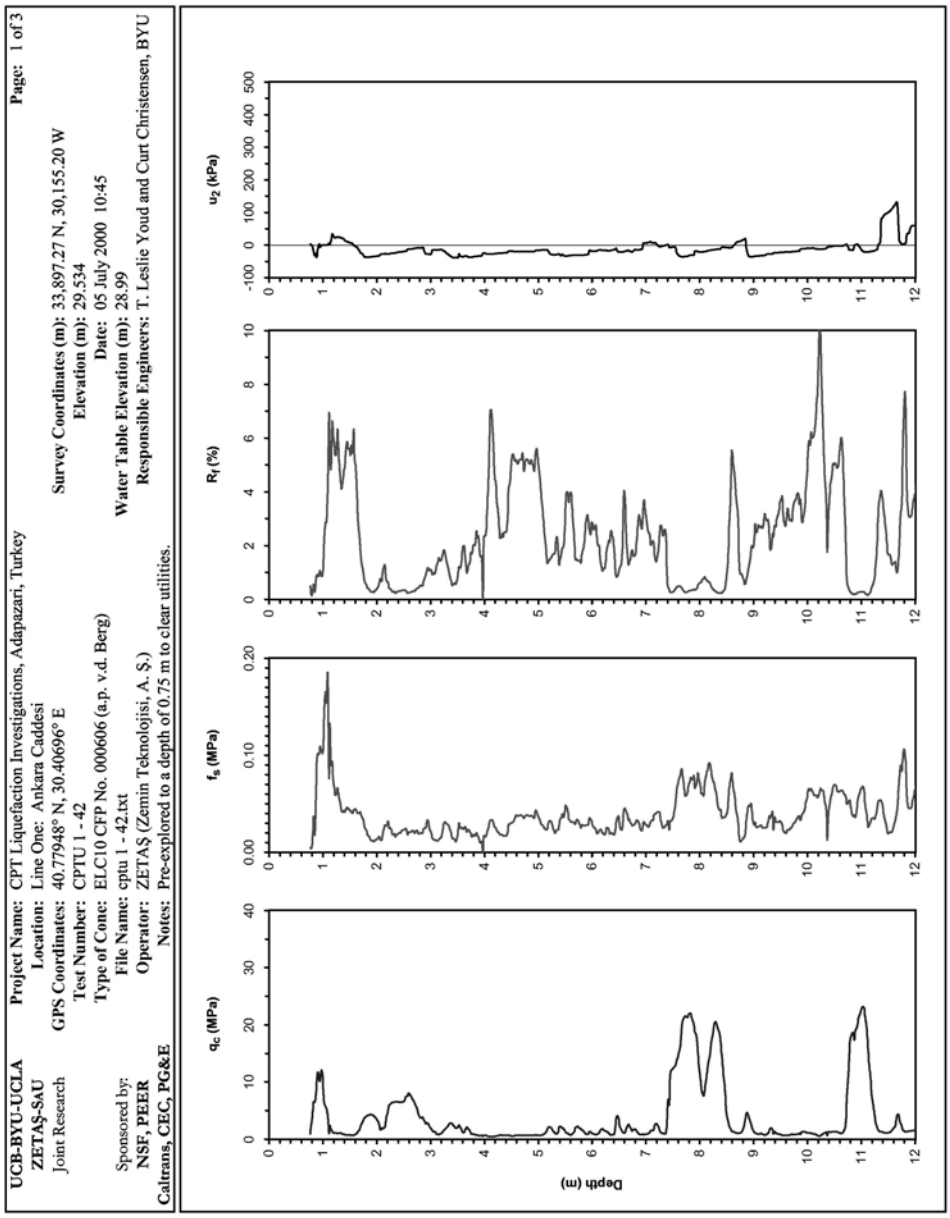


Figure C.23: CPT Profile: CPT-1-42

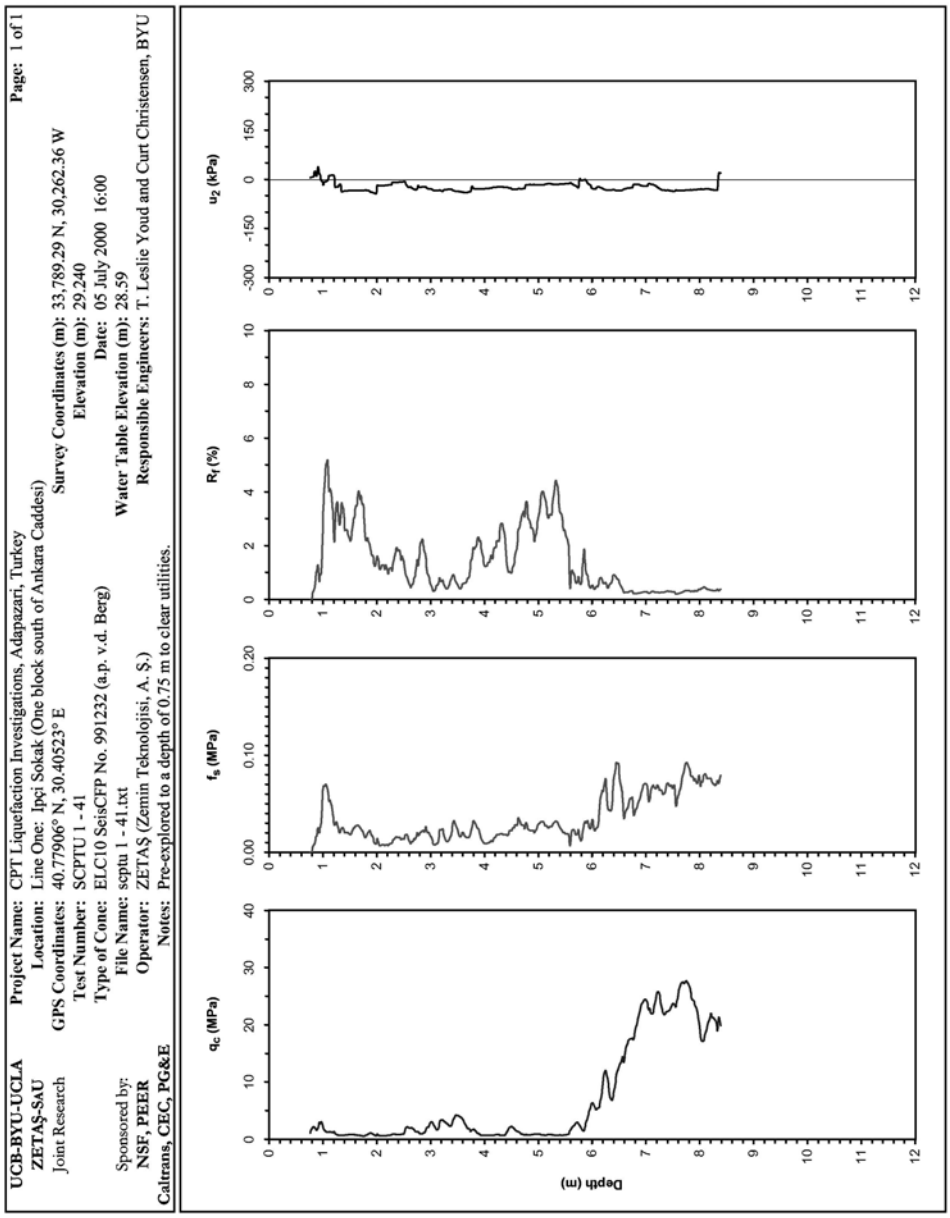


Figure C.24: CPT Profile: CPT-1-41

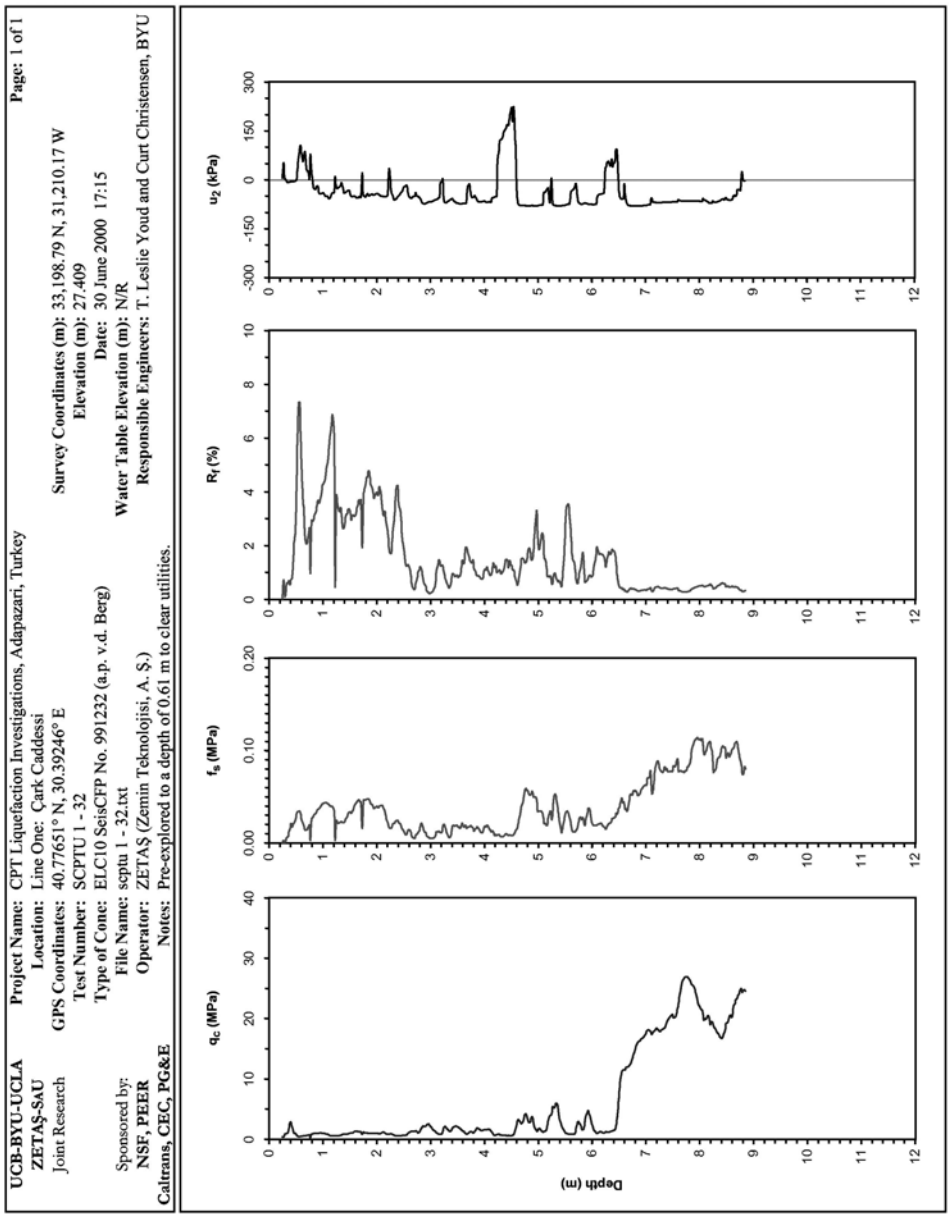


Figure C.25: CPT Profile: CPT-1-32

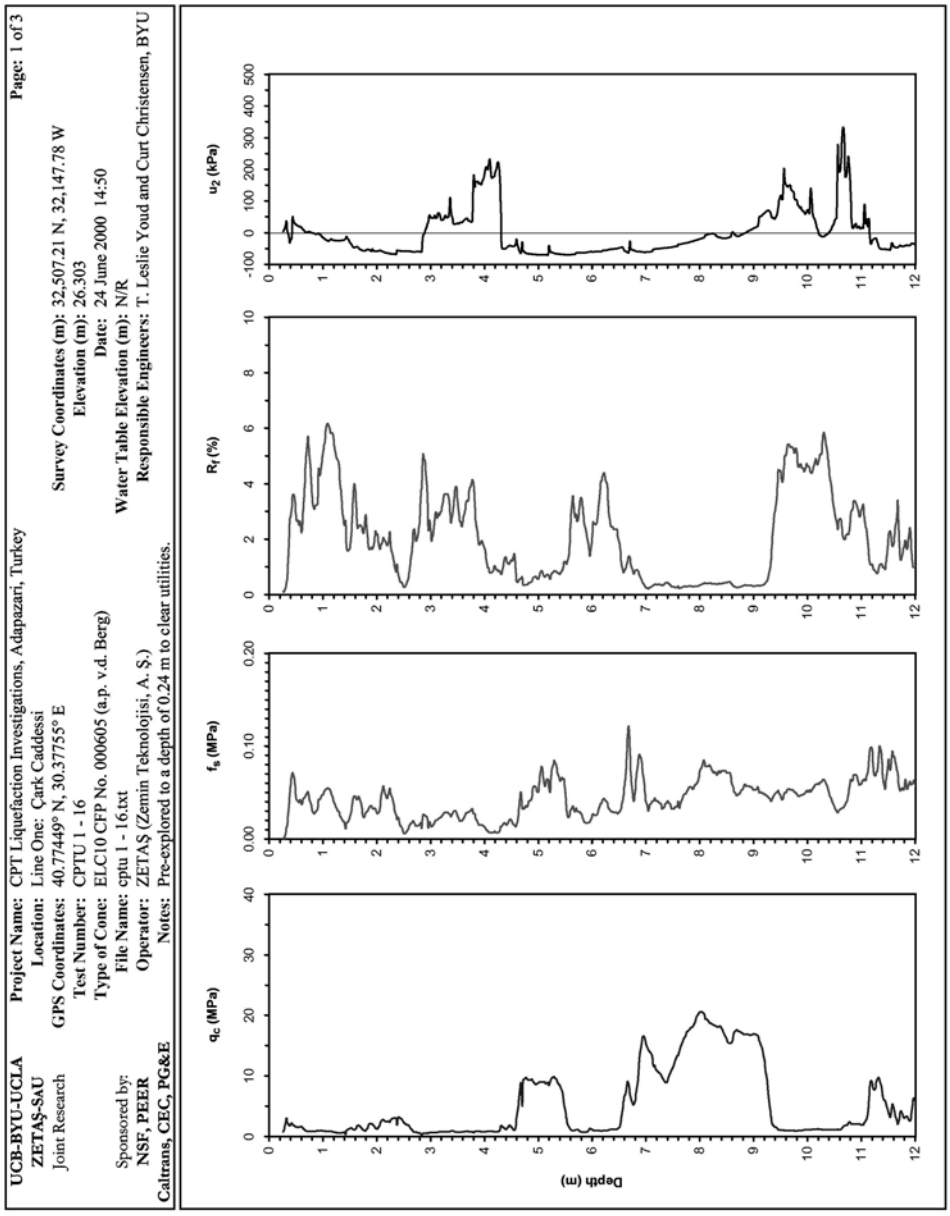


Figure C.26: CPT Profile: CPT-1-16

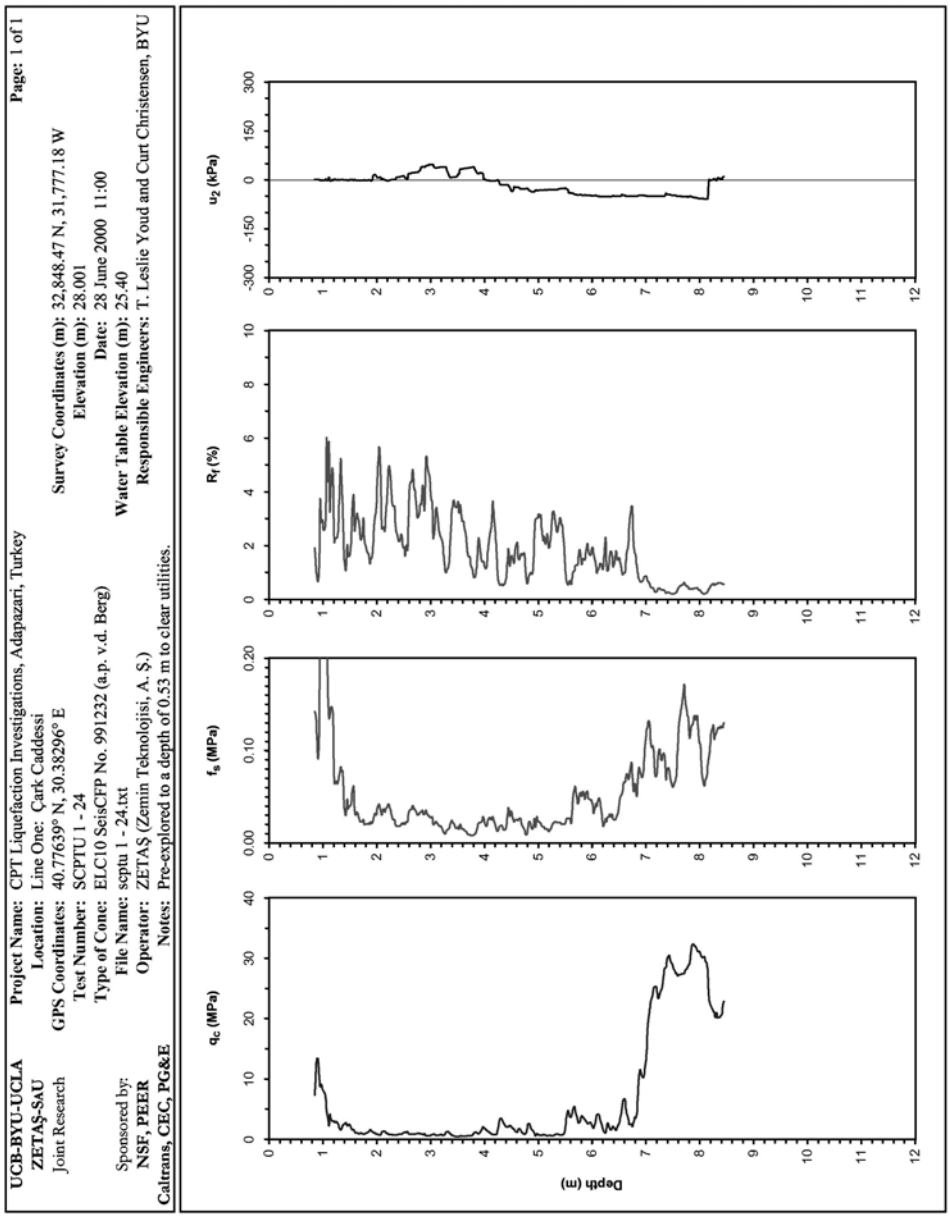


Figure C.27: CPT Profile: CPT-1-24

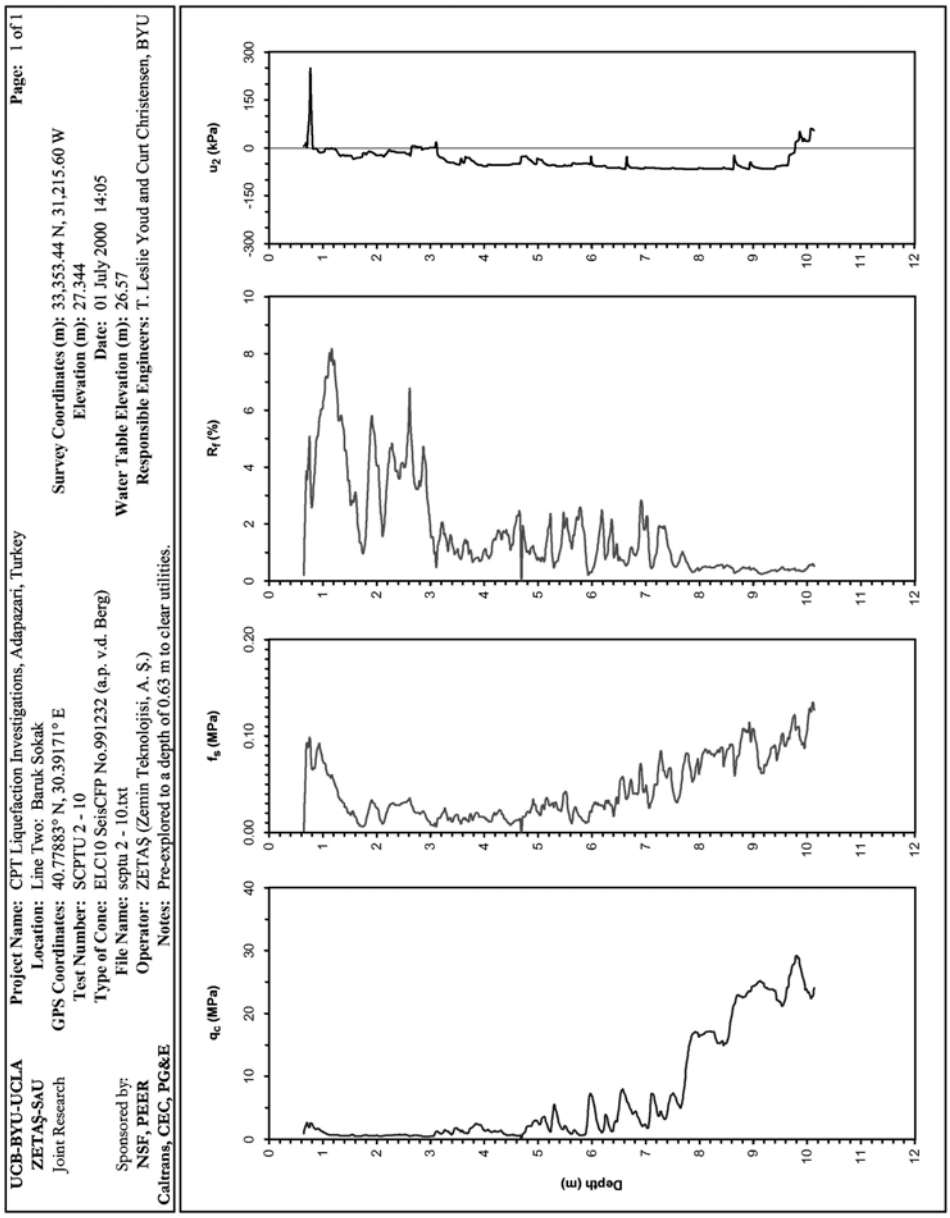


Figure C.28: CPT Profile: CPT-2-10

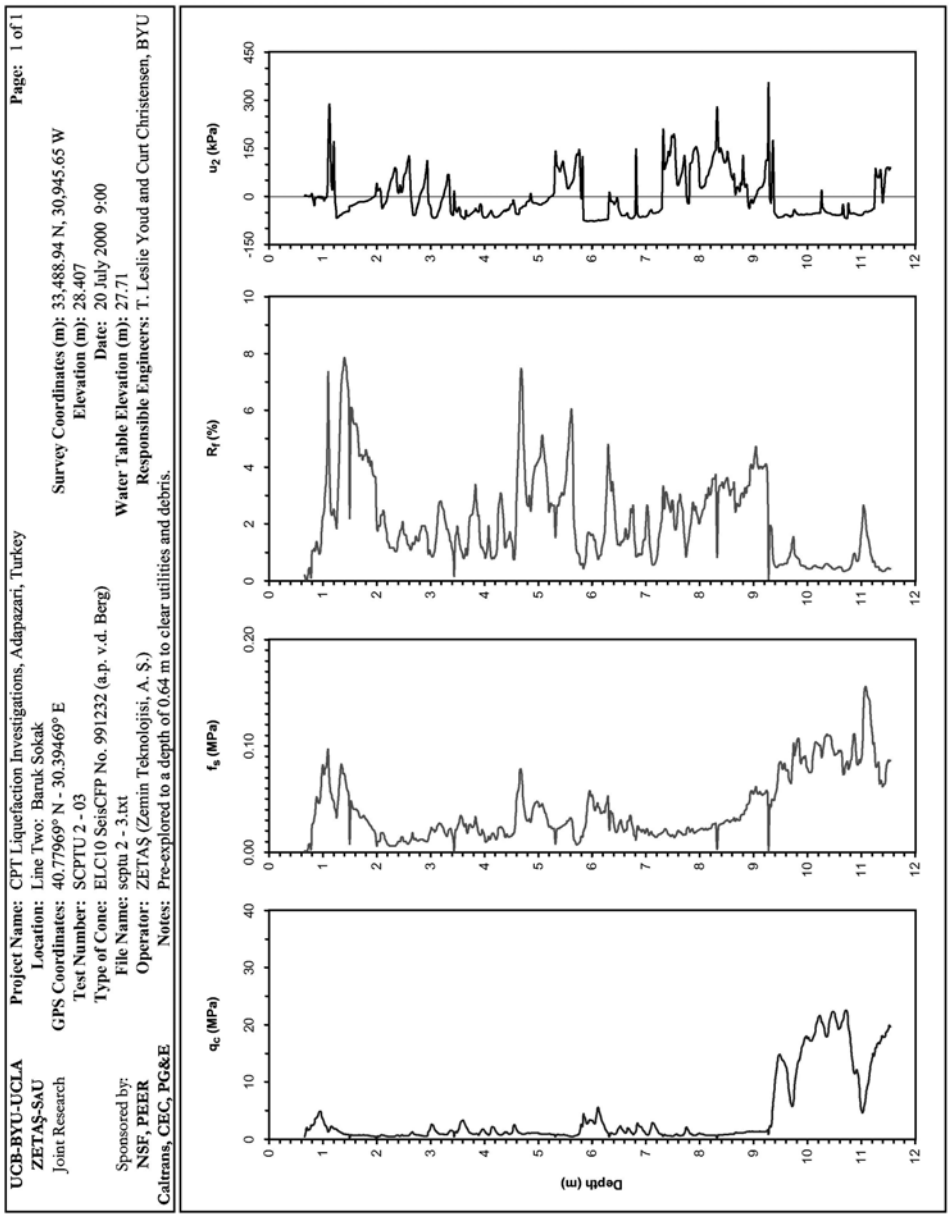


Figure C.29: CPT Profile: CPT-2-3

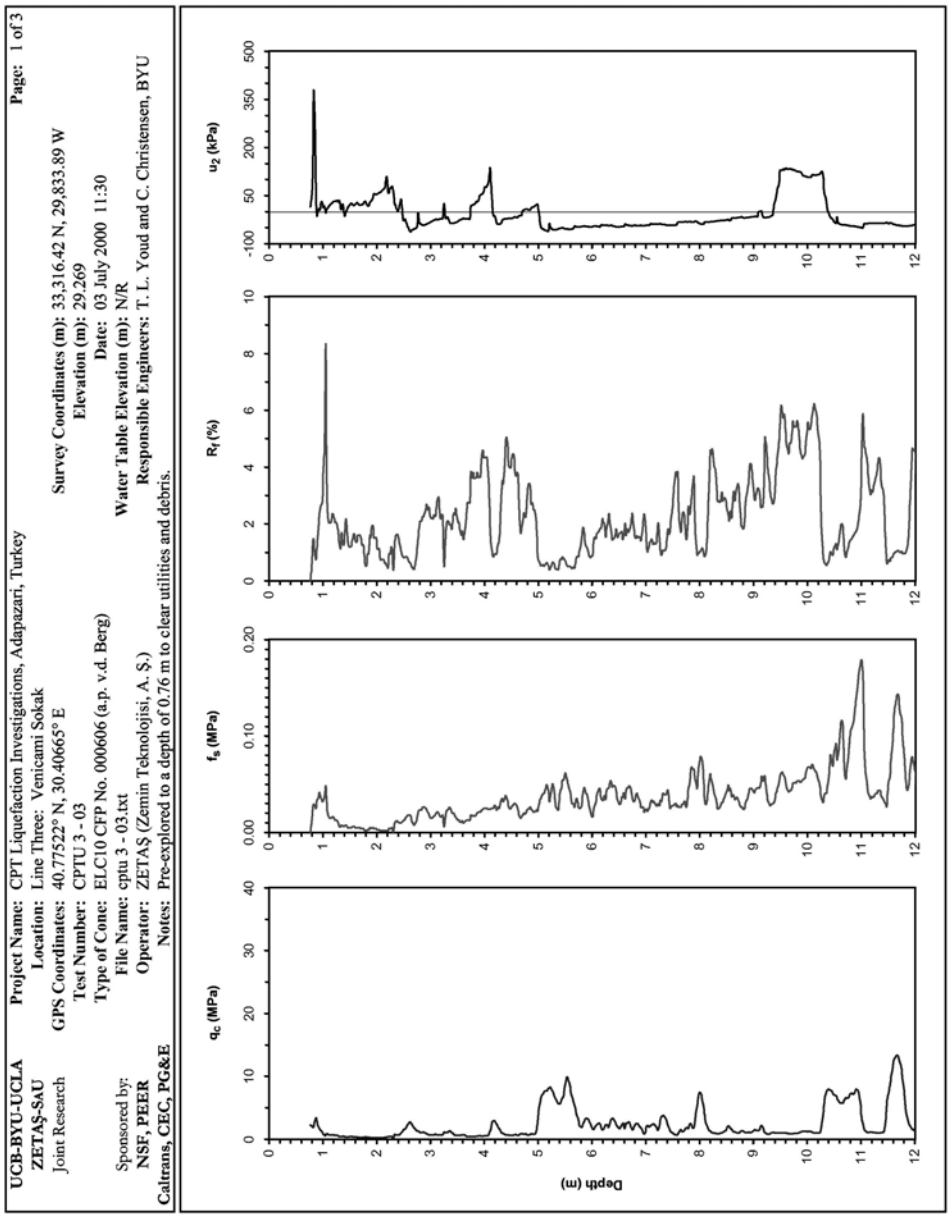


Figure C.30: CPT Profile: CPT-3-3

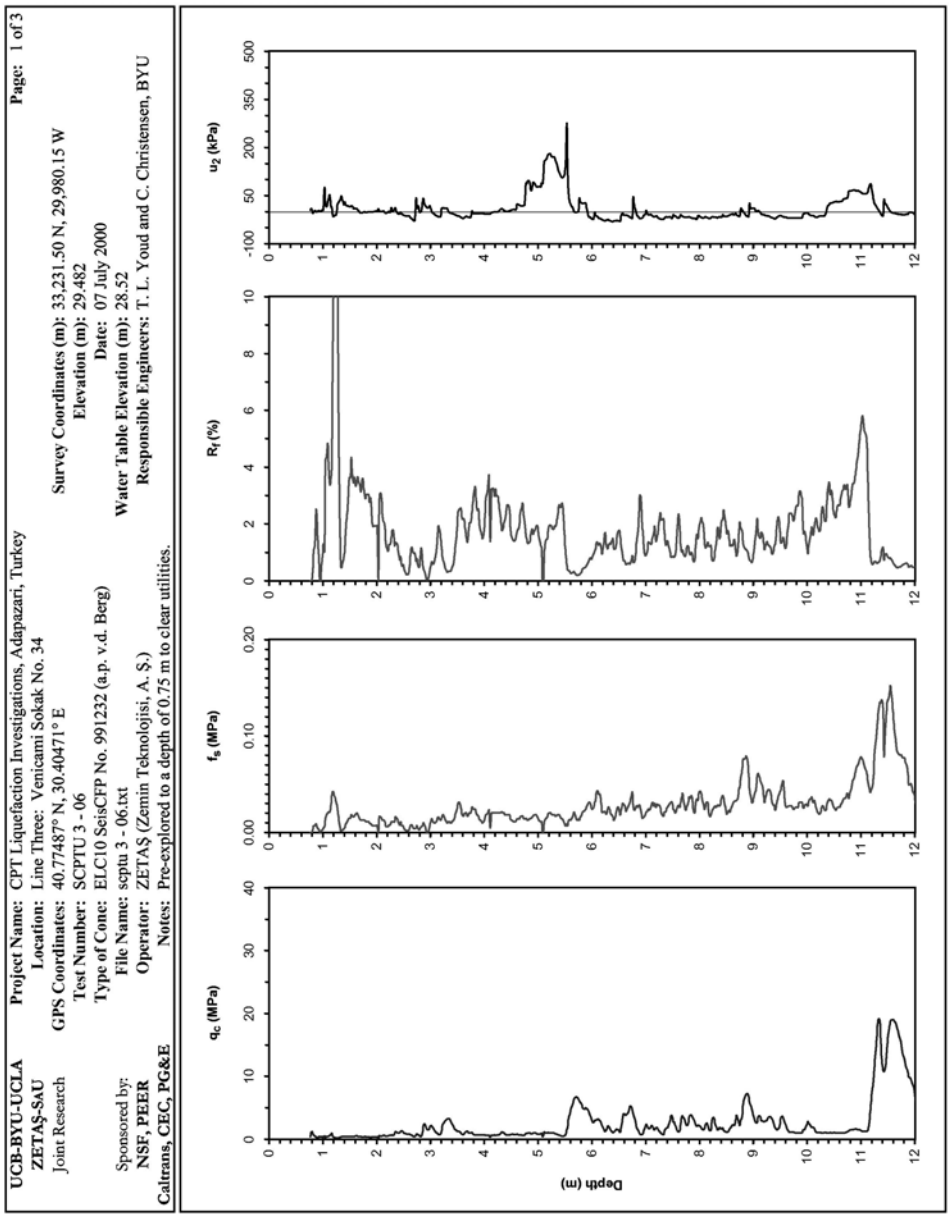


Figure C.31: CPT Profile: CPT-3-6

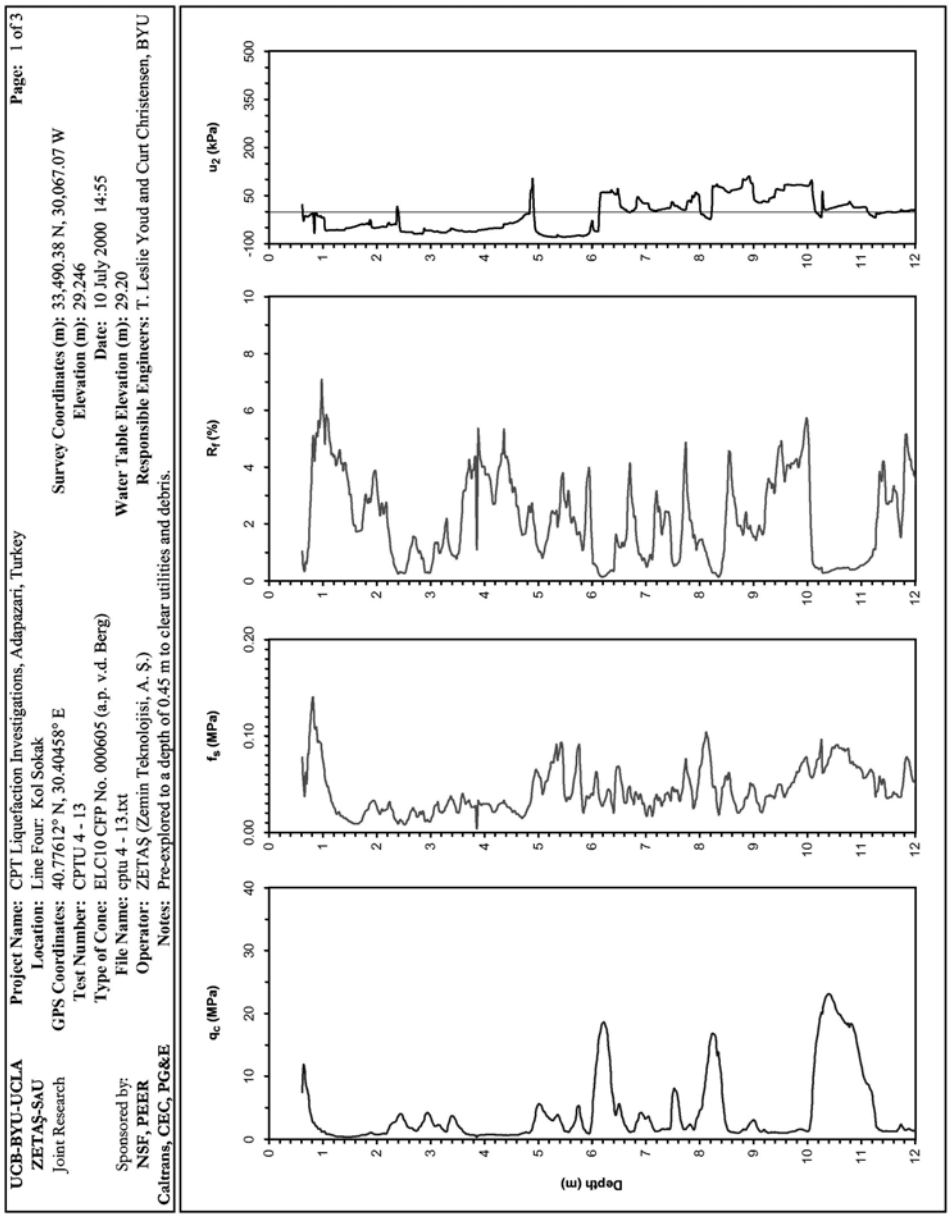


Figure C.32: CPT Profile: CPT-4-13

Figure C.33: CPT Profile: CPT-4-3

Figure C.34: CPT Profile: CPT-4-22

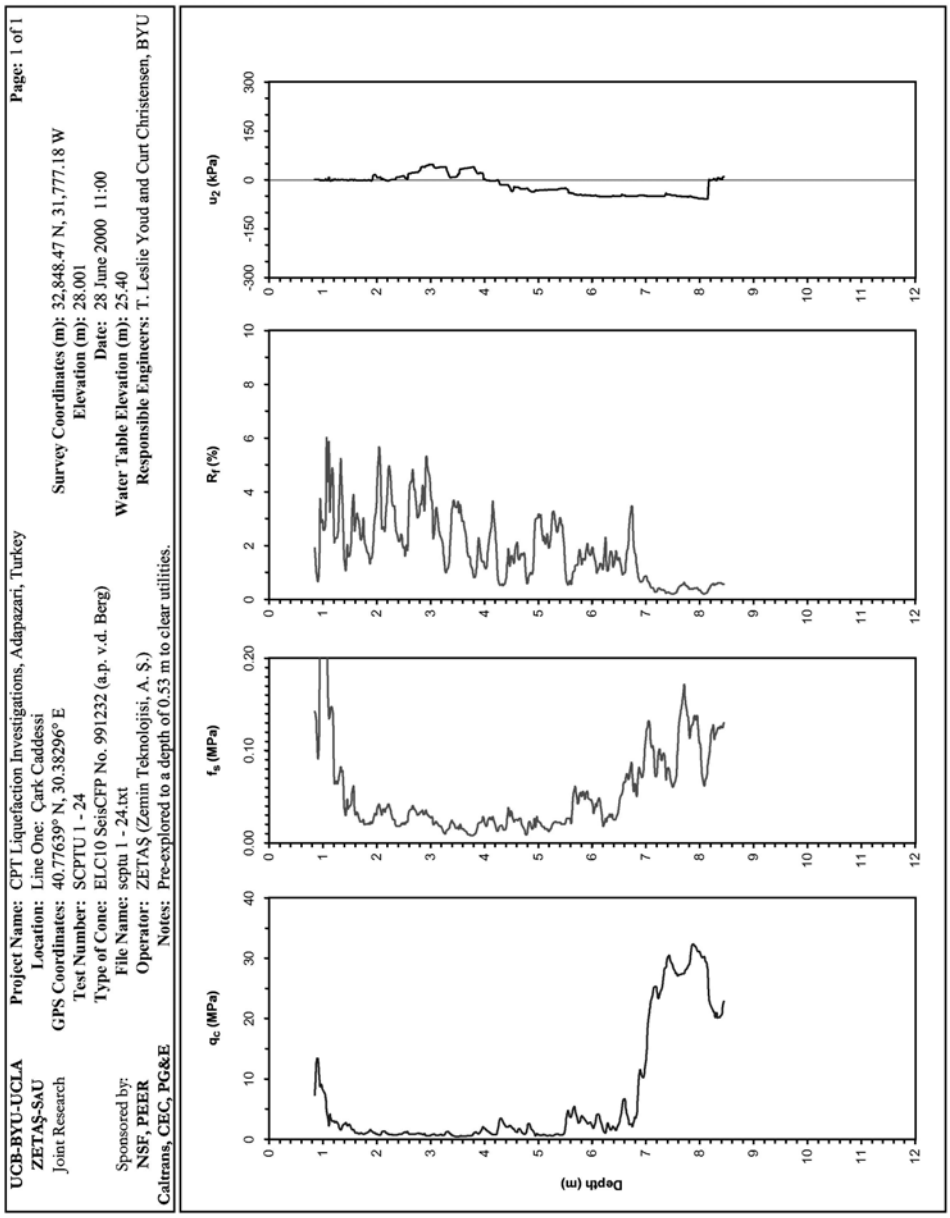


Figure C.35: CPT Profile: CPT-1-24-cc

Figure C.36: CPT Profile: CPT-4-22-ca

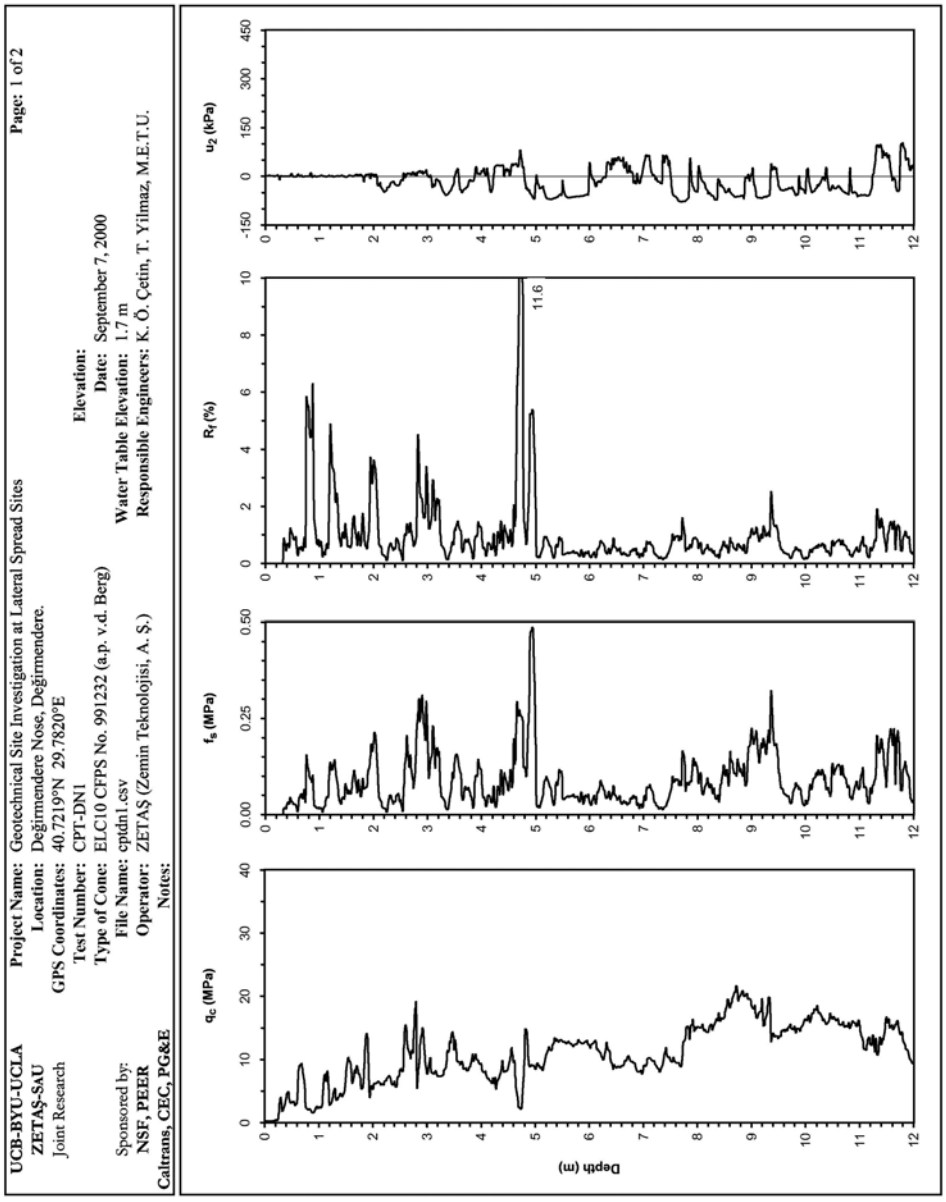


Figure C.37: CPT Profile: CPT-DN1

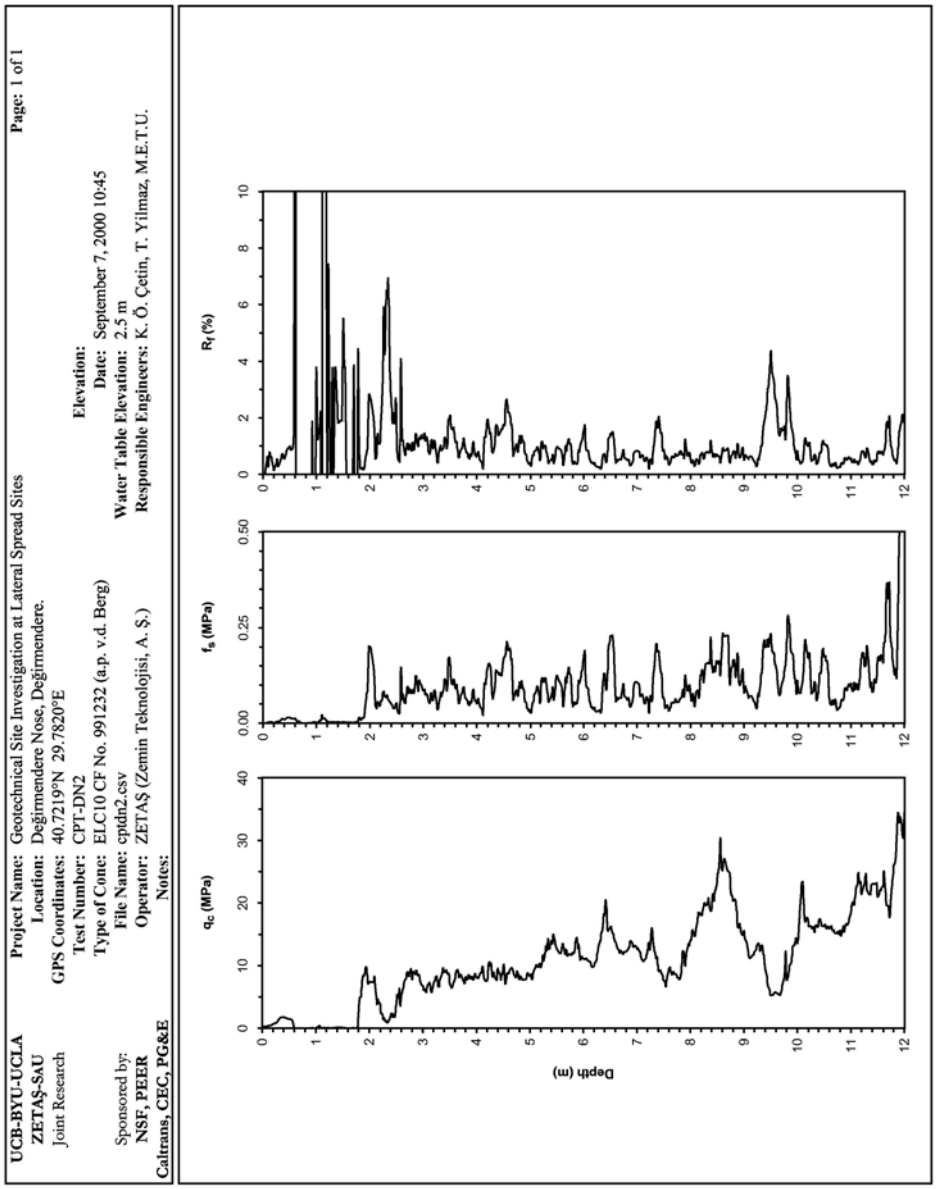


Figure C.38: CPT Profile: CPT-DN2

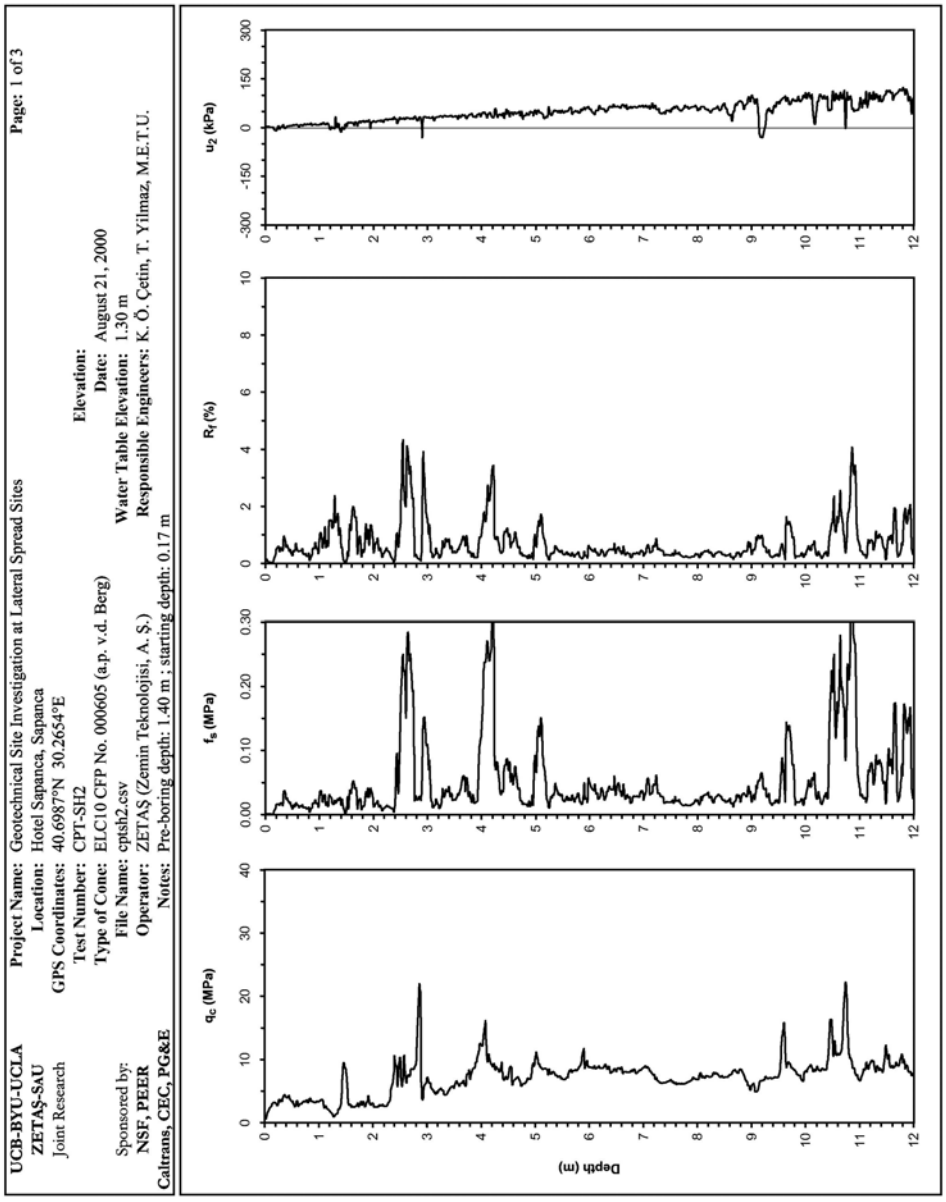


Figure C.39: CPT Profile: CPT-SH2

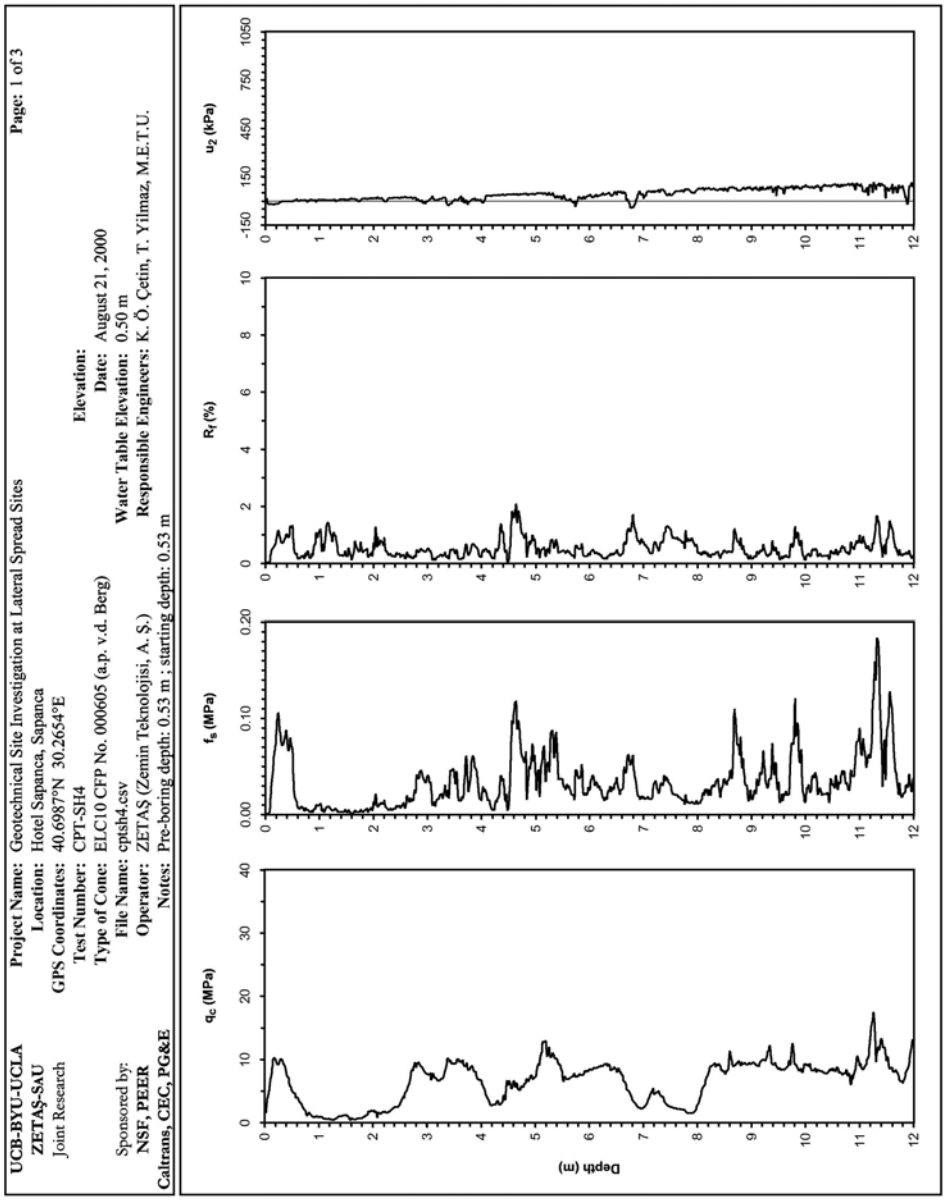


Figure C.40: CPT Profile: CPT-SH4

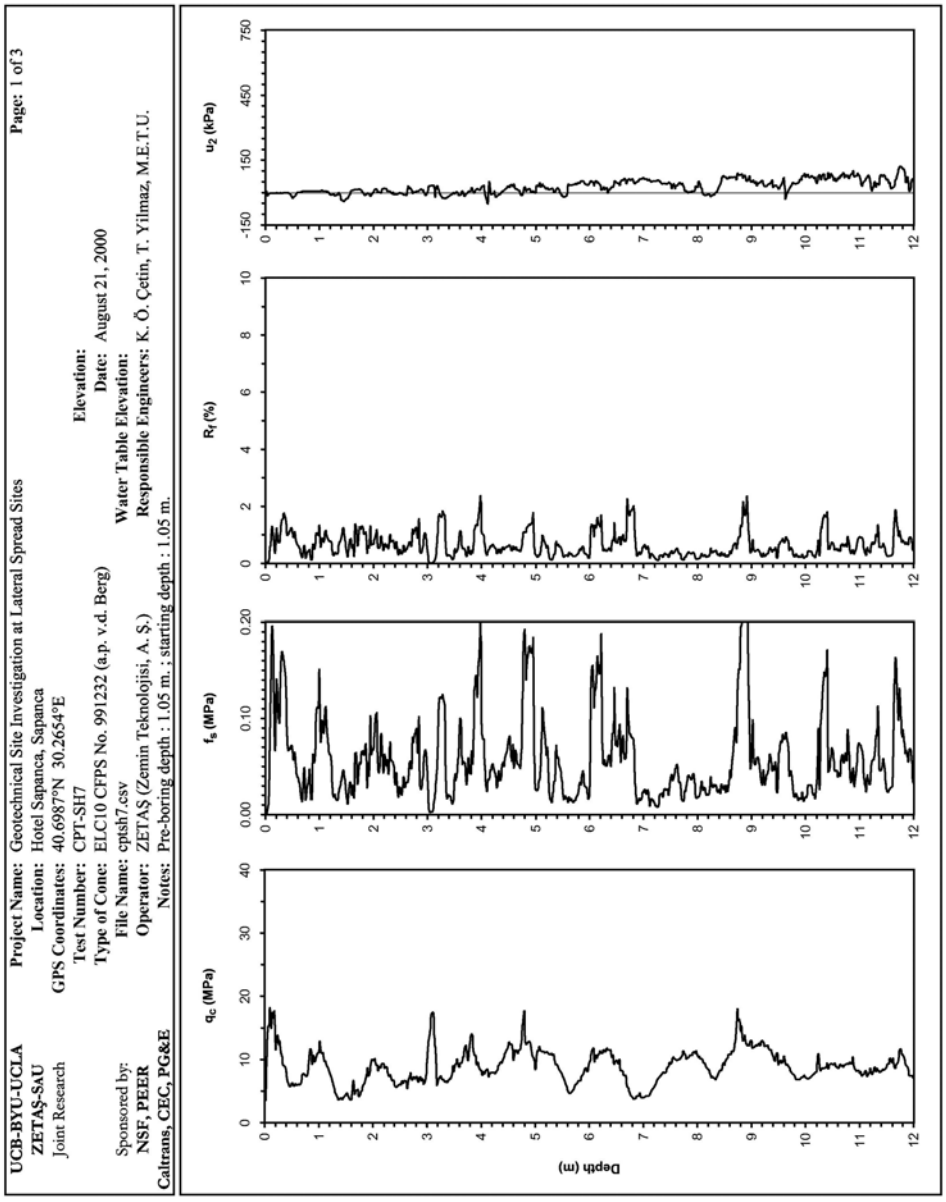


Figure C.41: CPT Profile: CPT-SH7

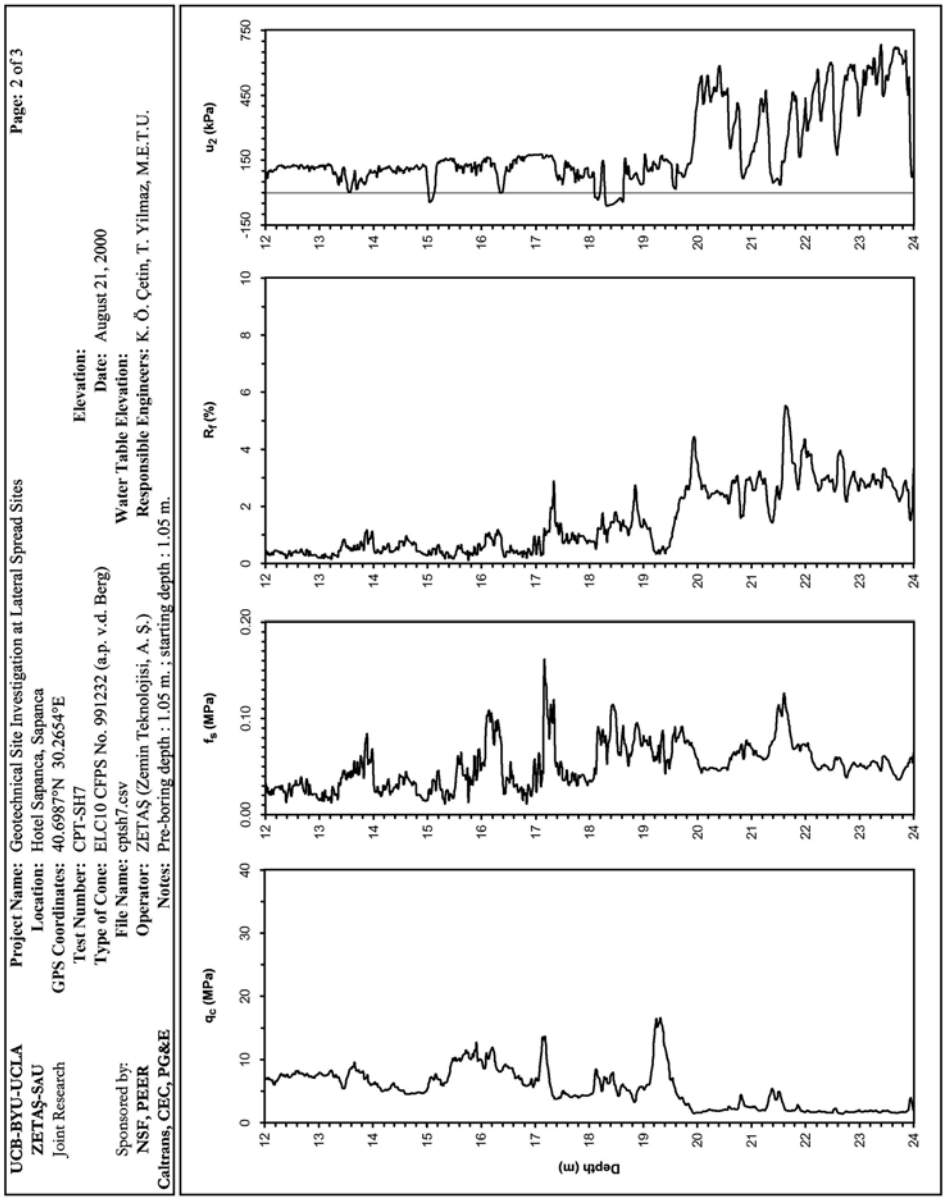


Figure C.41(cont.): CPT Profile: CPT-SH7

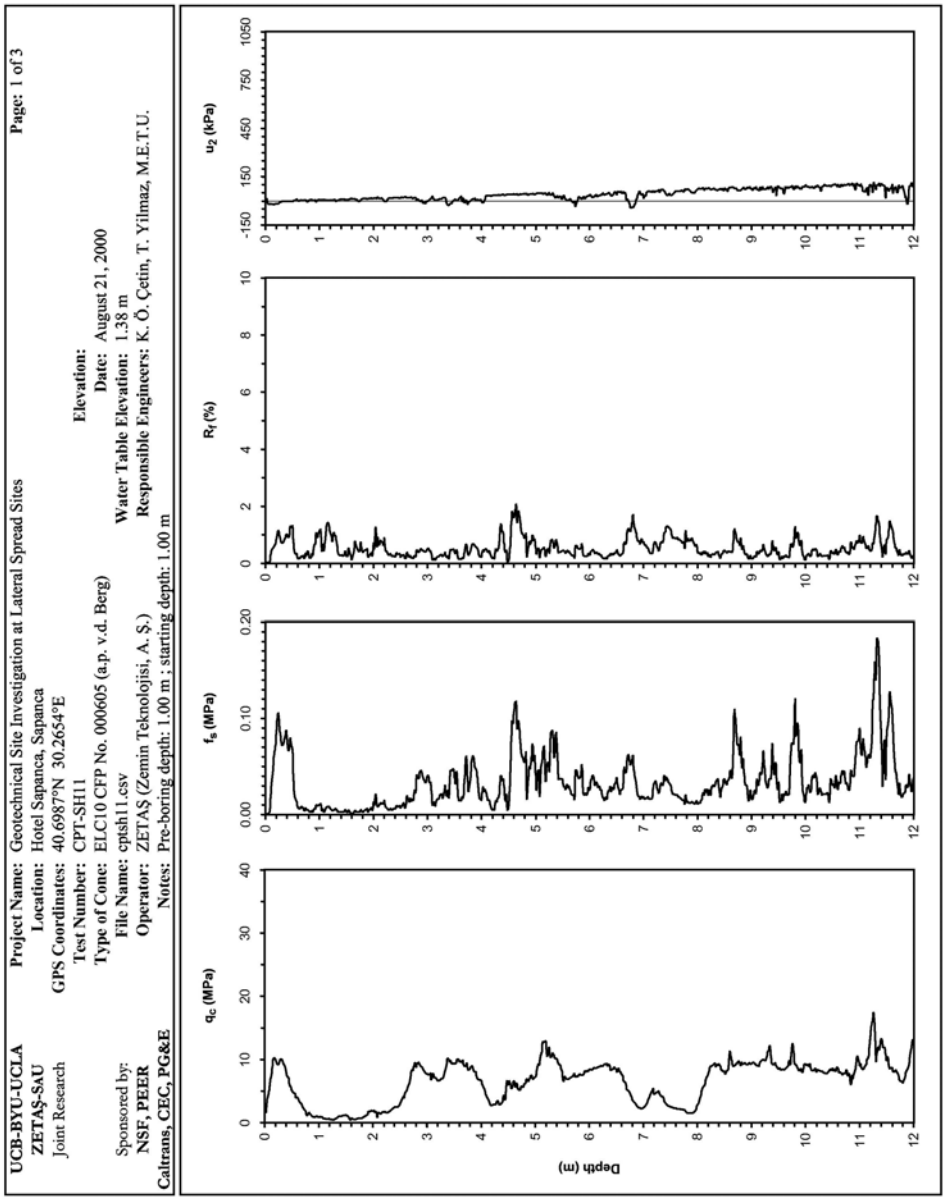


Figure C.42: CPT Profile: CPT-SH11

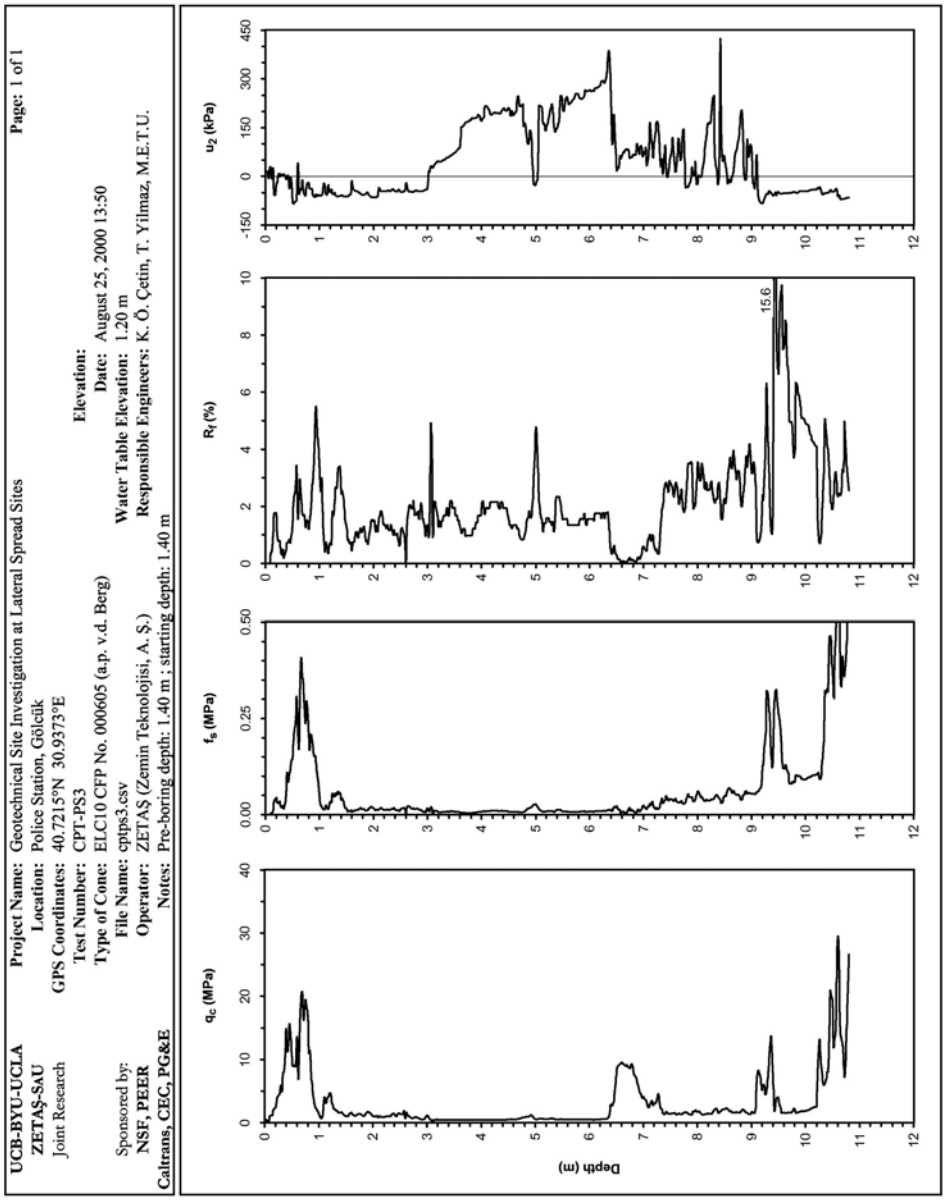


Figure C.43: CPT Profile: CPT-PS3

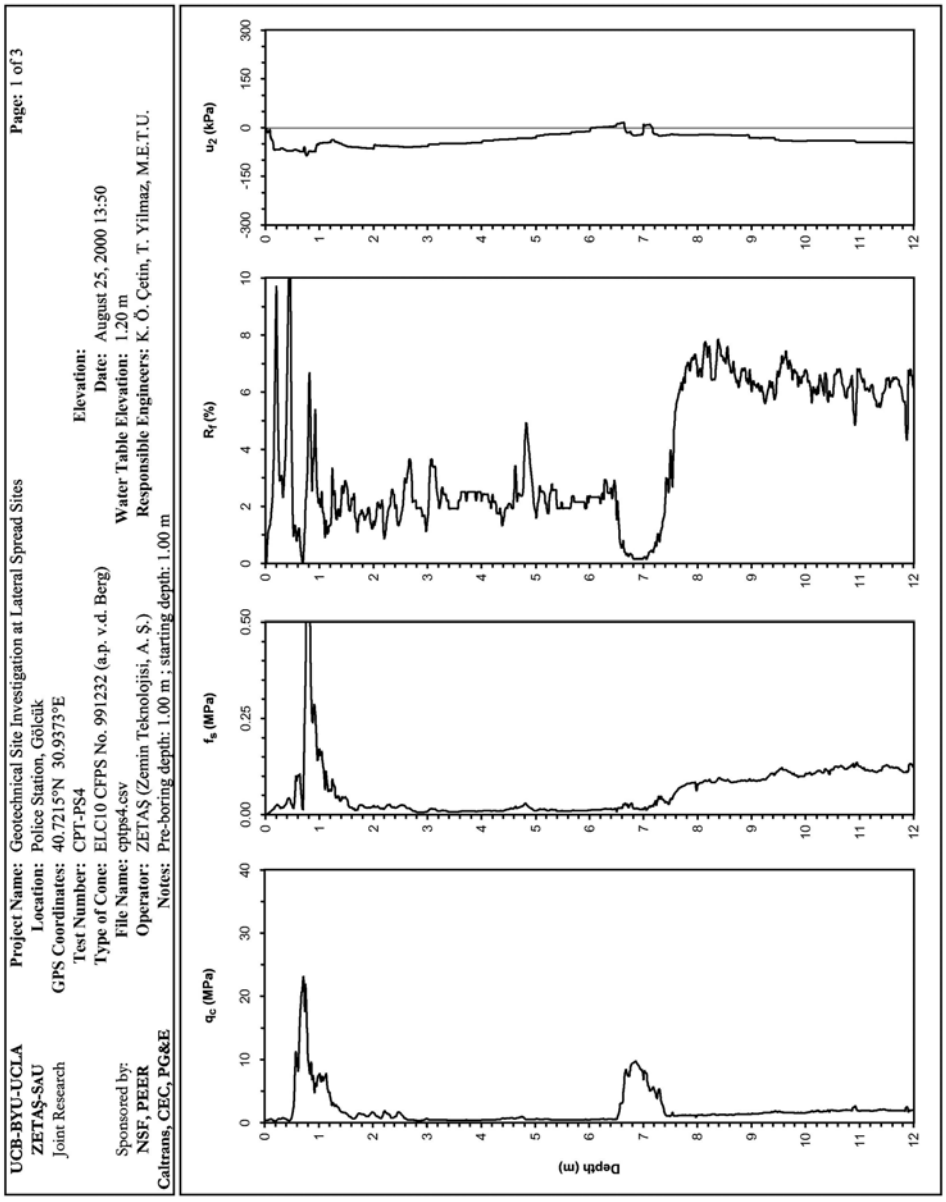


Figure C.44: CPT Profile: CPT-PS4

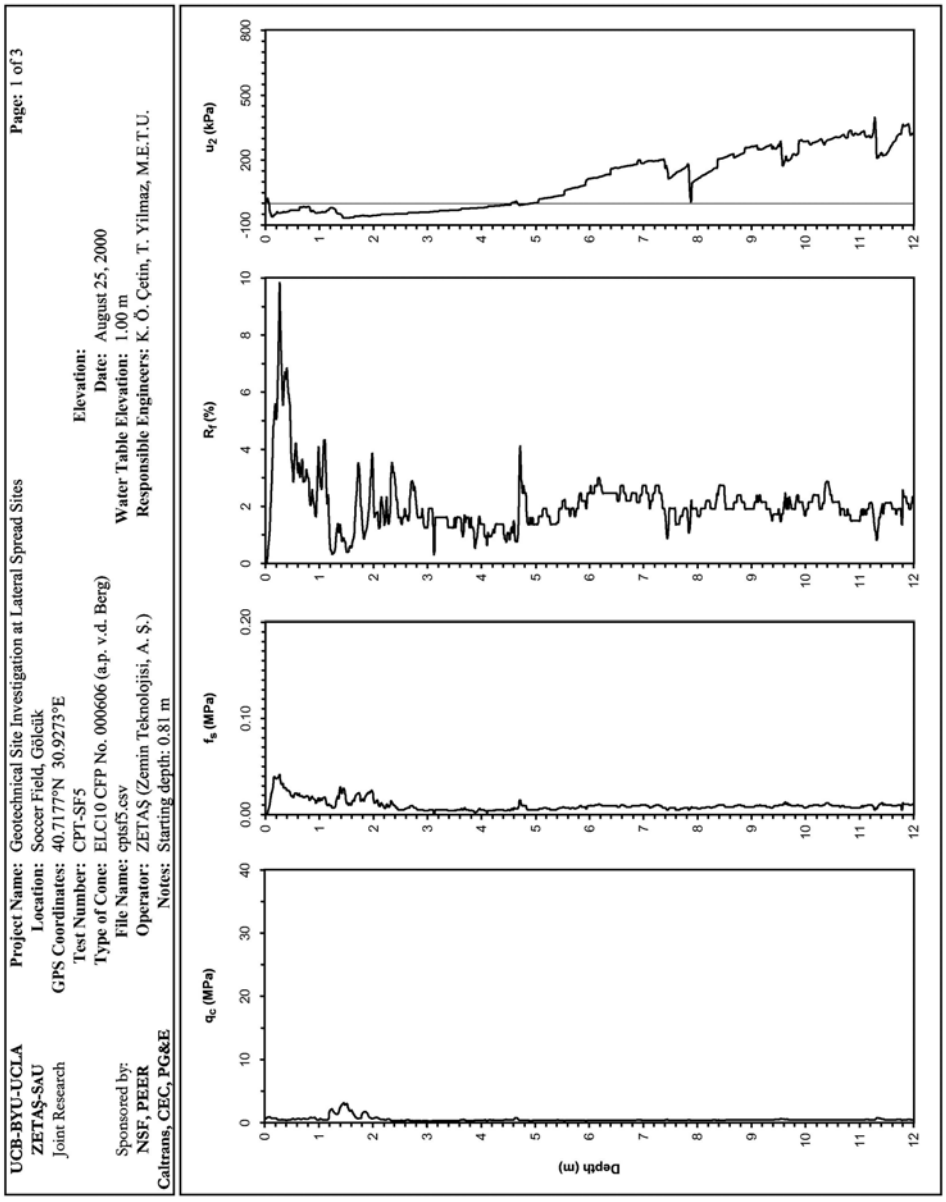


Figure C.45: CPT Profile: CPT-SF5

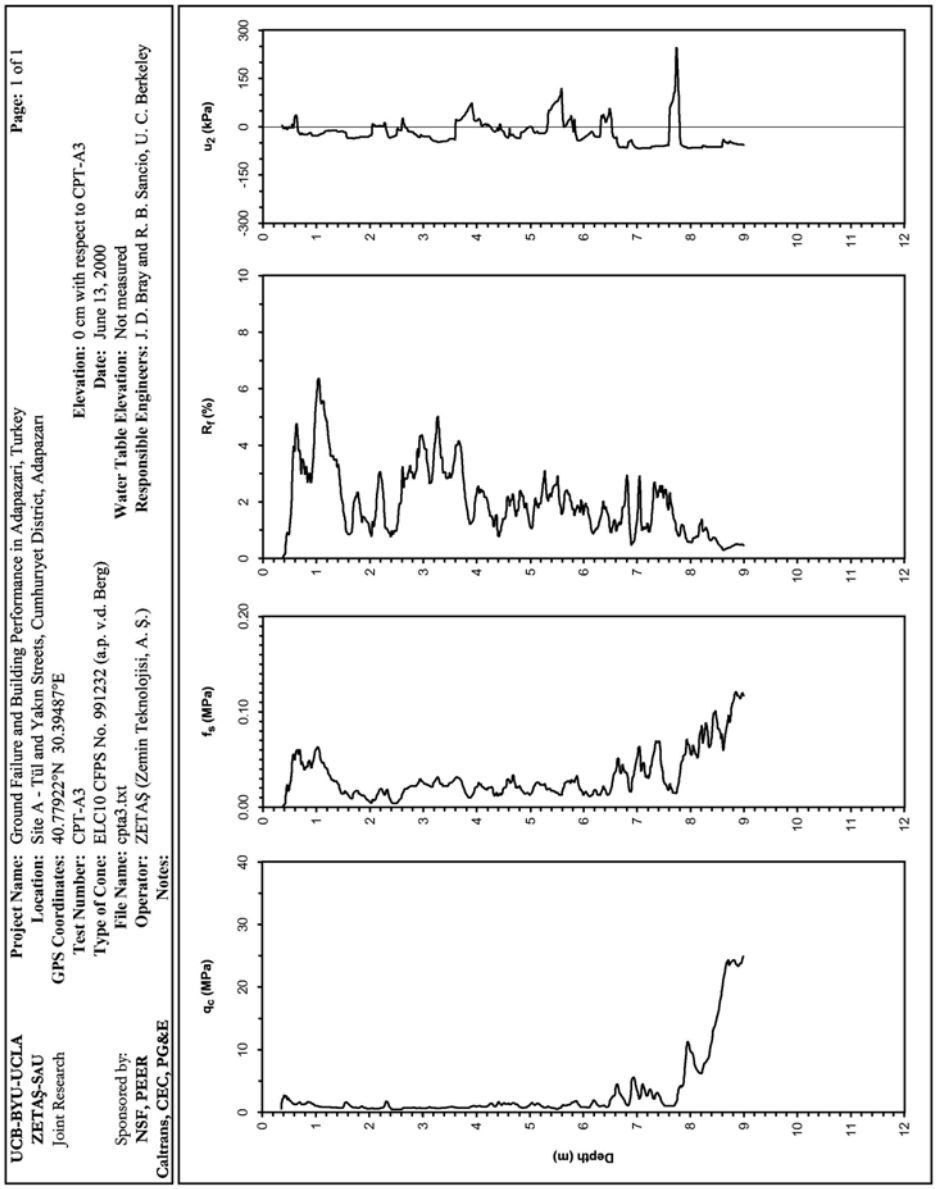


Figure C.46: CPT Profile: CPT-A3-ys

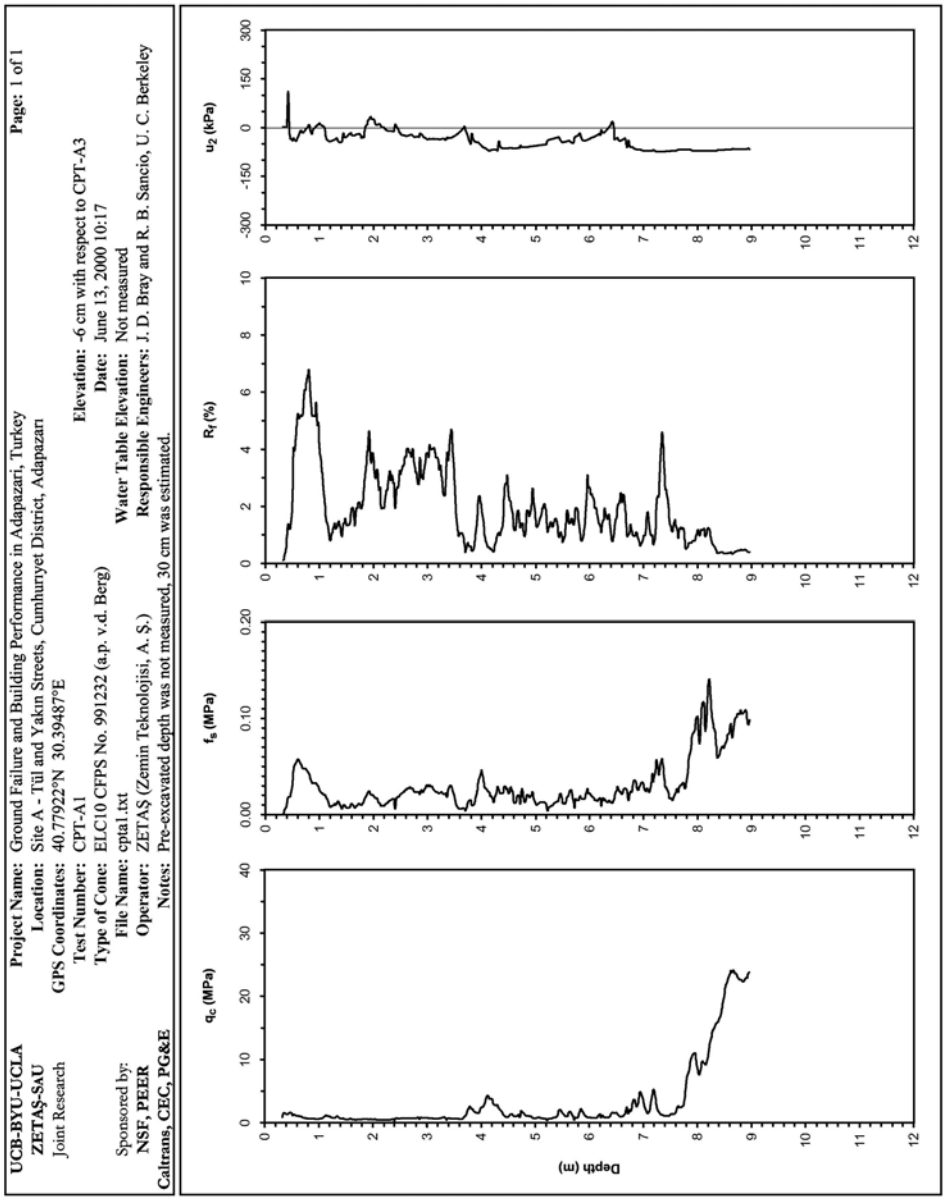


Figure C.47: CPT Profile: CPT-A1-ys

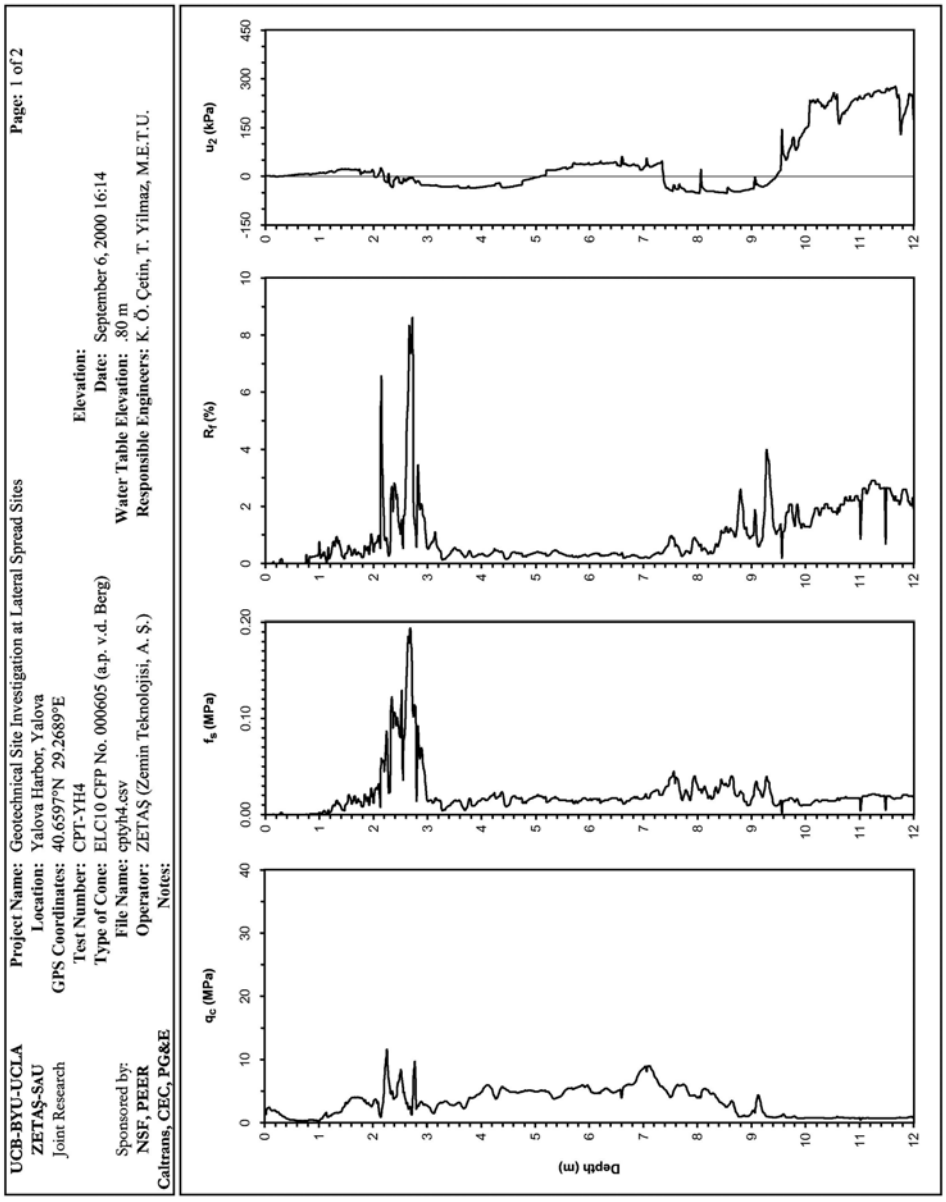


Figure C.48: CPT Profile: CPT-YH-4

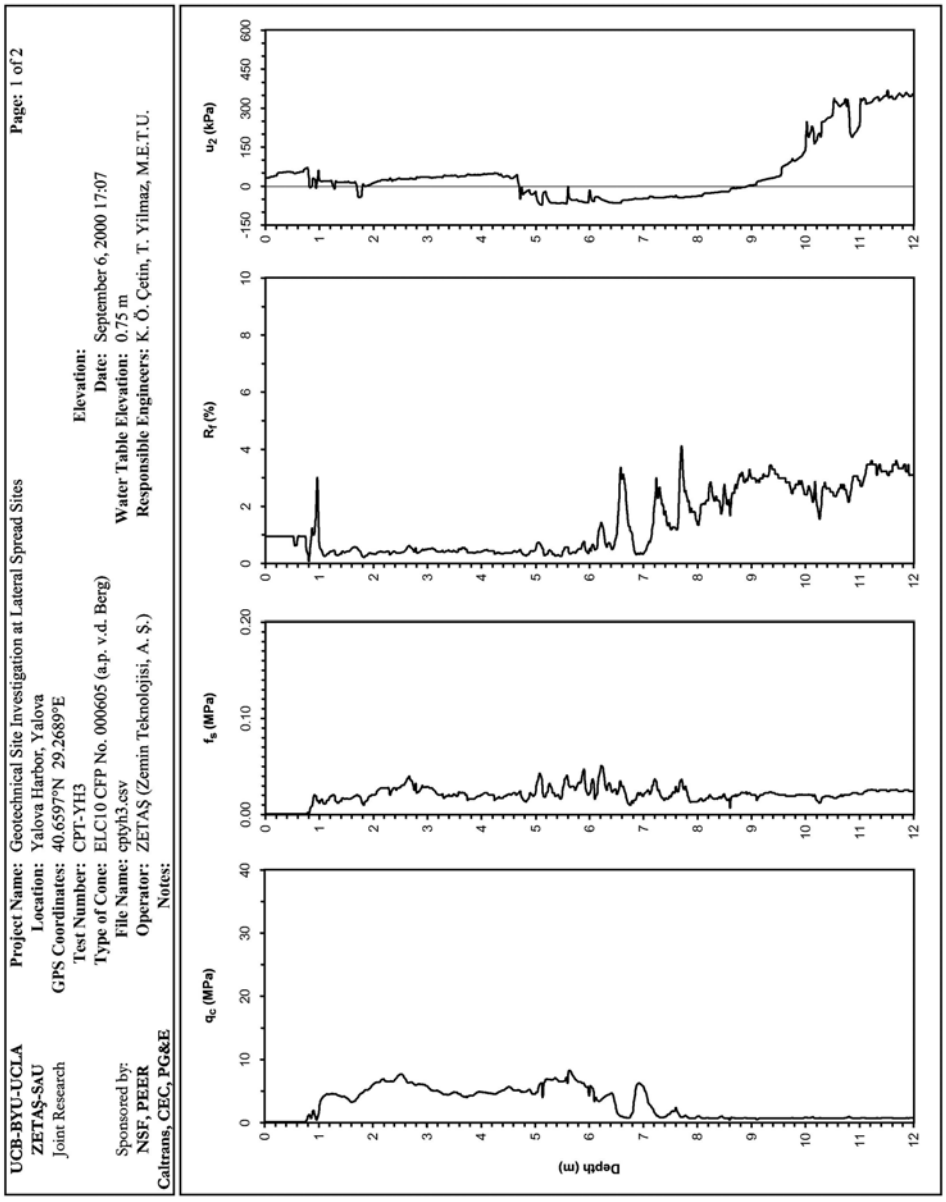
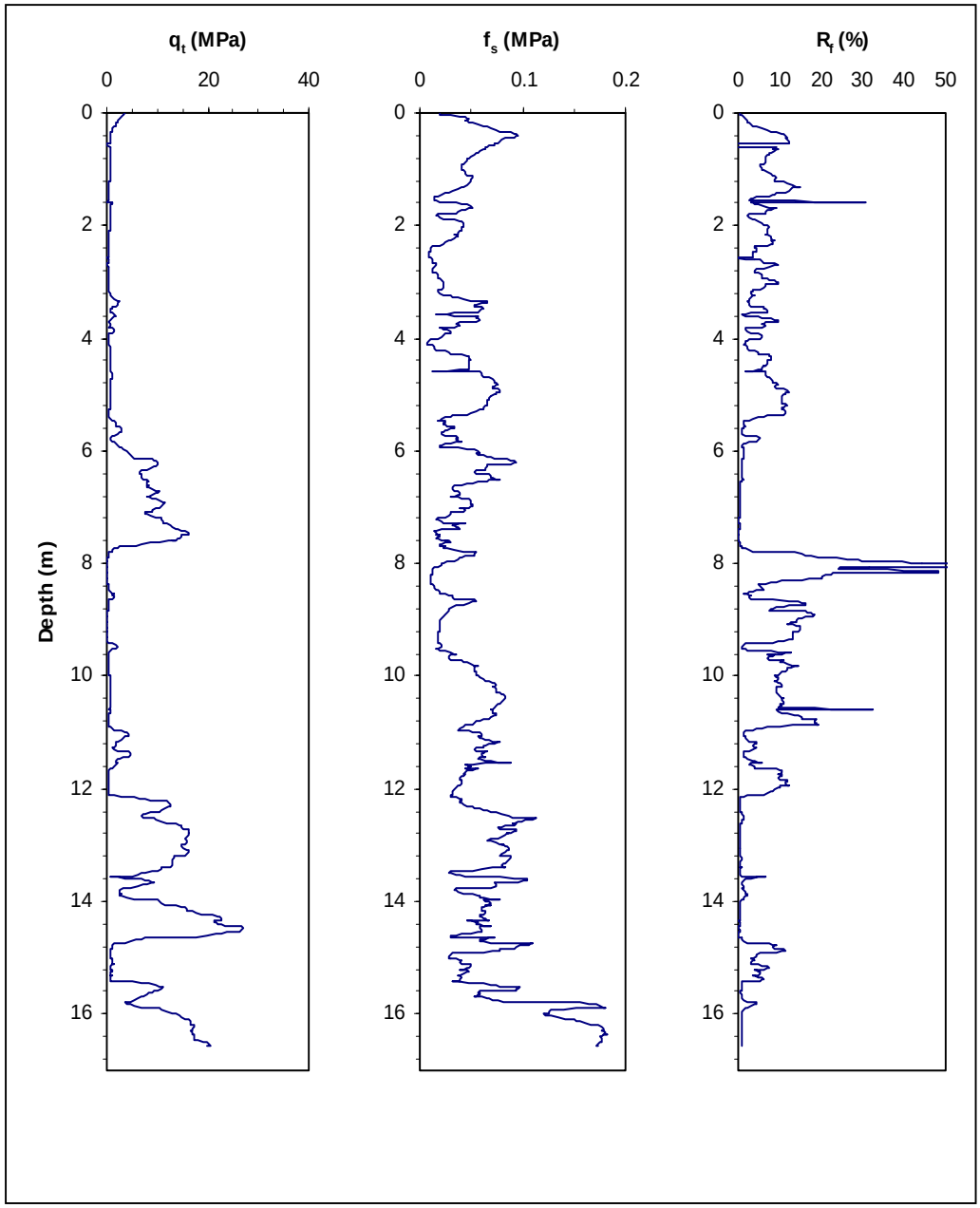
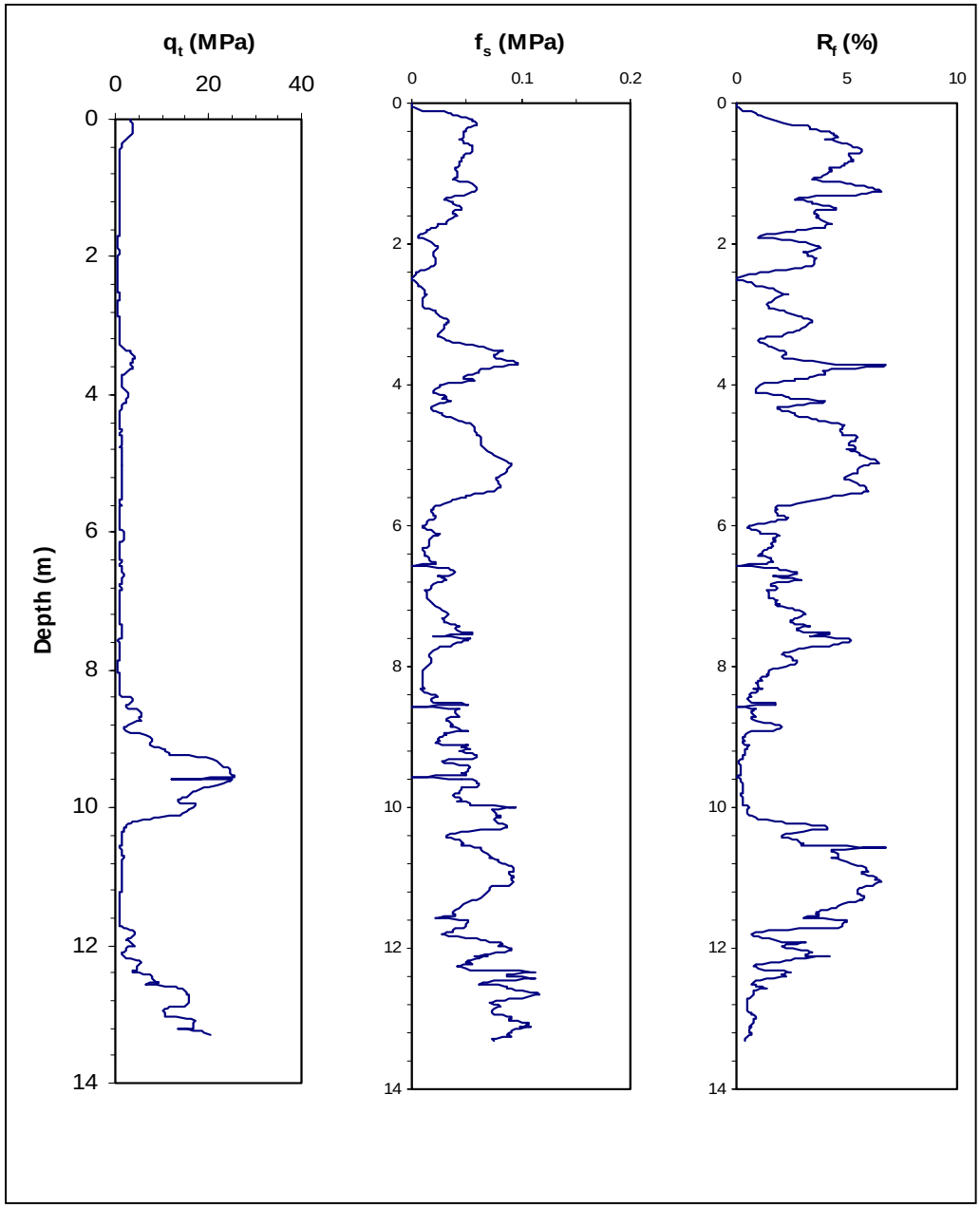


Figure C.49: CPT Profile: CPT-YH-3



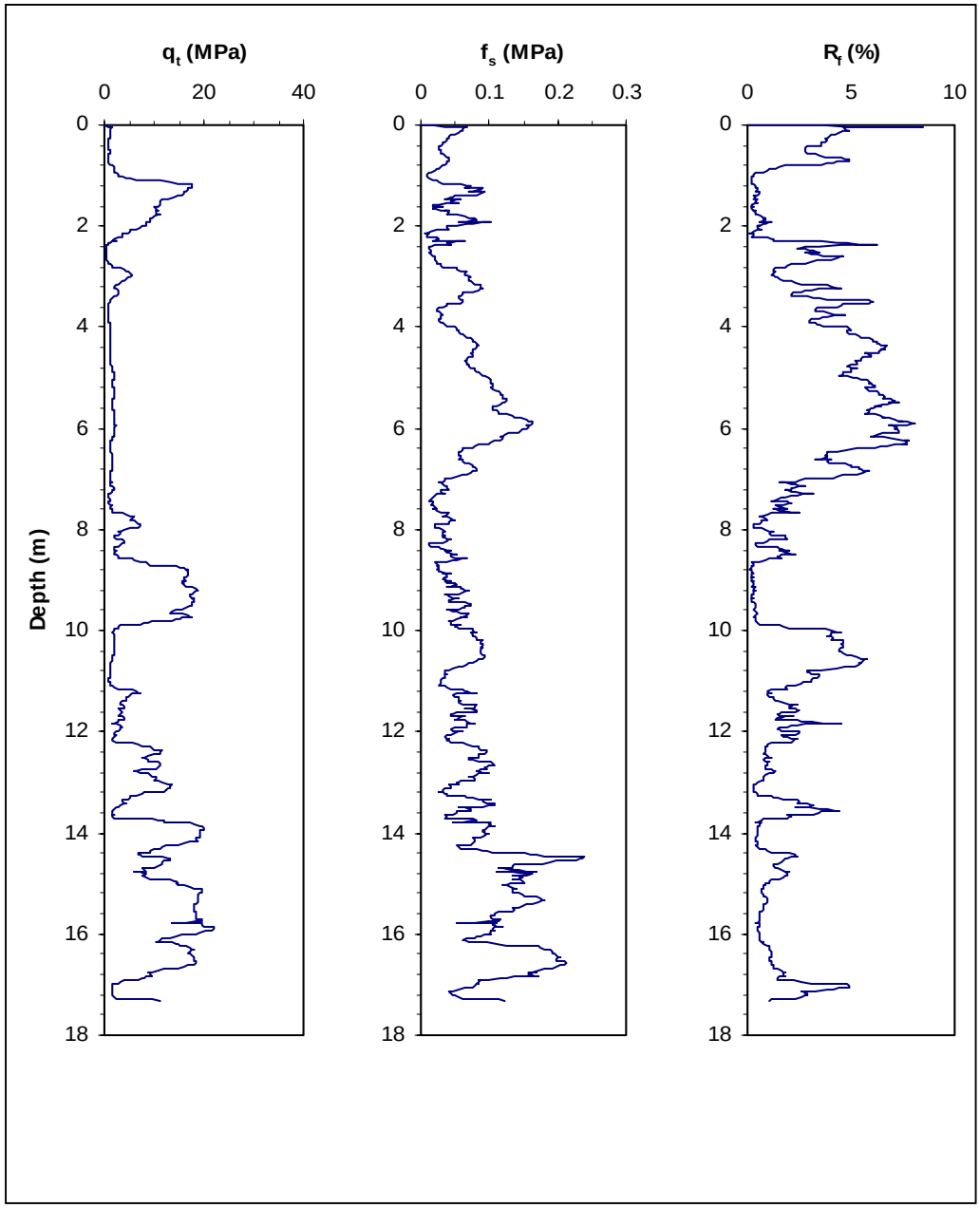
Project:	Buski-East Waste Water Treatment Plant
Operator:	ERBEY Mühendislik Müş. İnş. San. ve Tic. Ltd.Şti
Location:	Demirtas-BURSA
Test Name:	CPT-1

Figure C.50: CPT Profile: CPT-1



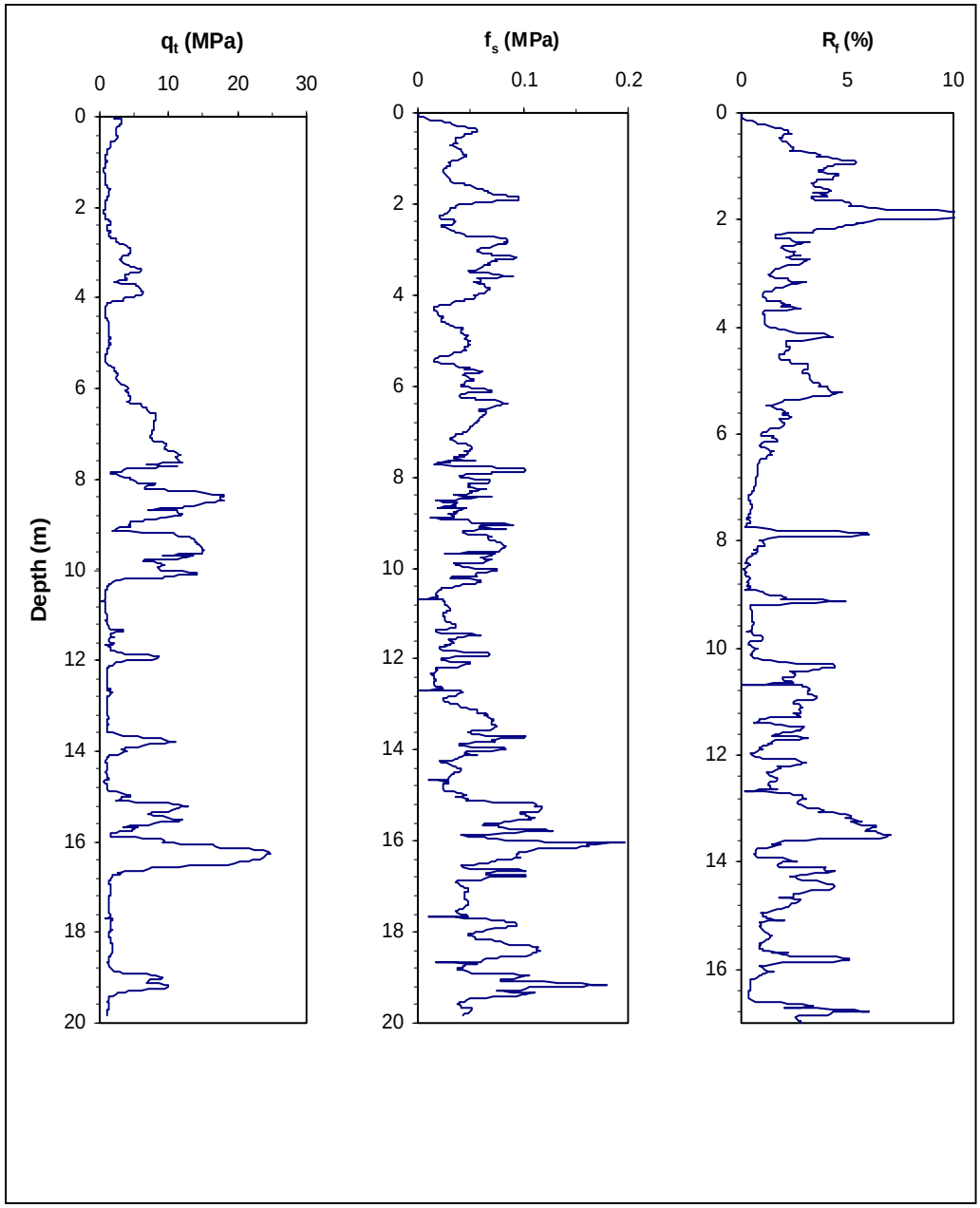
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-2

Figure C.51: CPT Profile: CPT-2



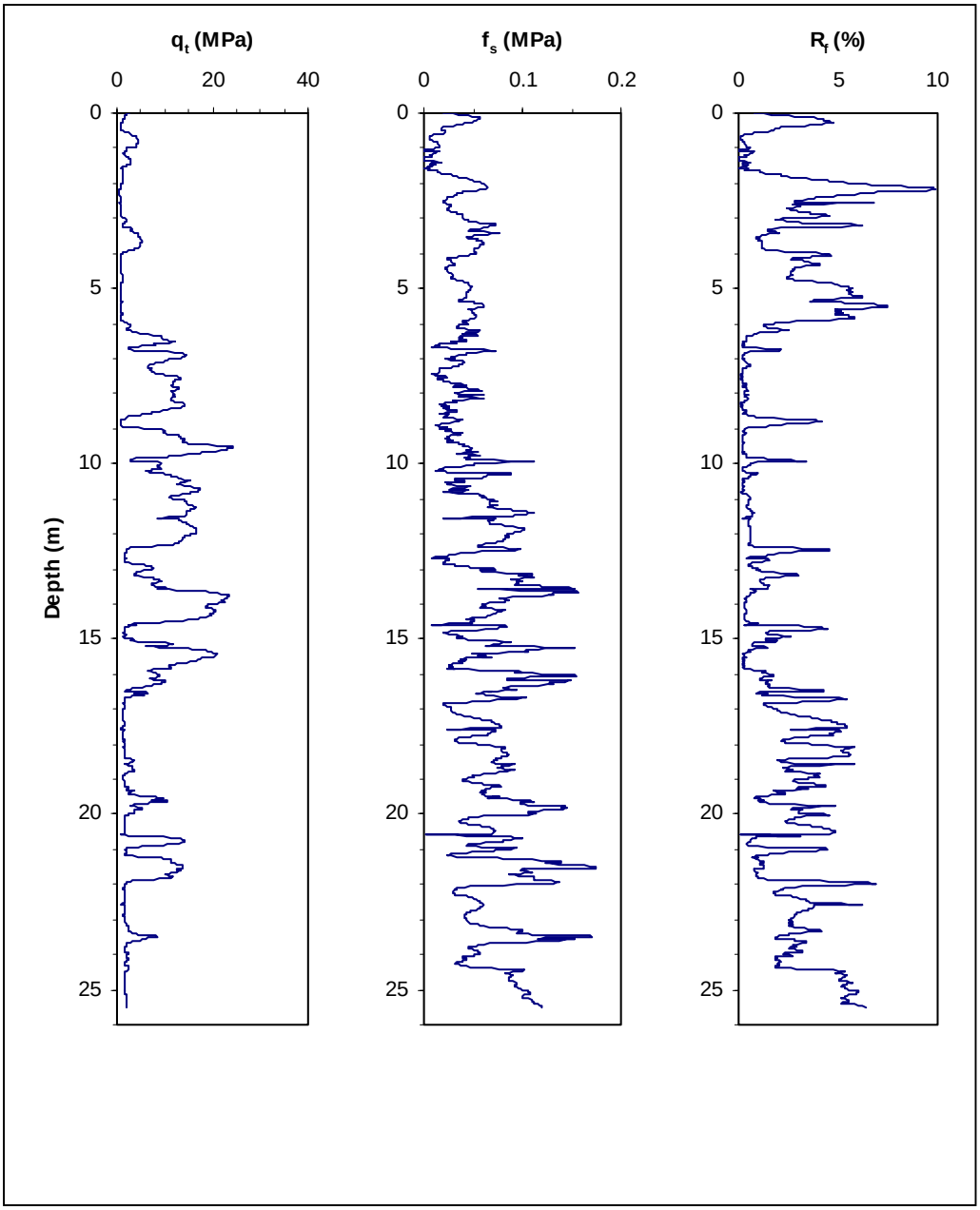
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-3

Figure C.52: CPT Profile: CPT-3



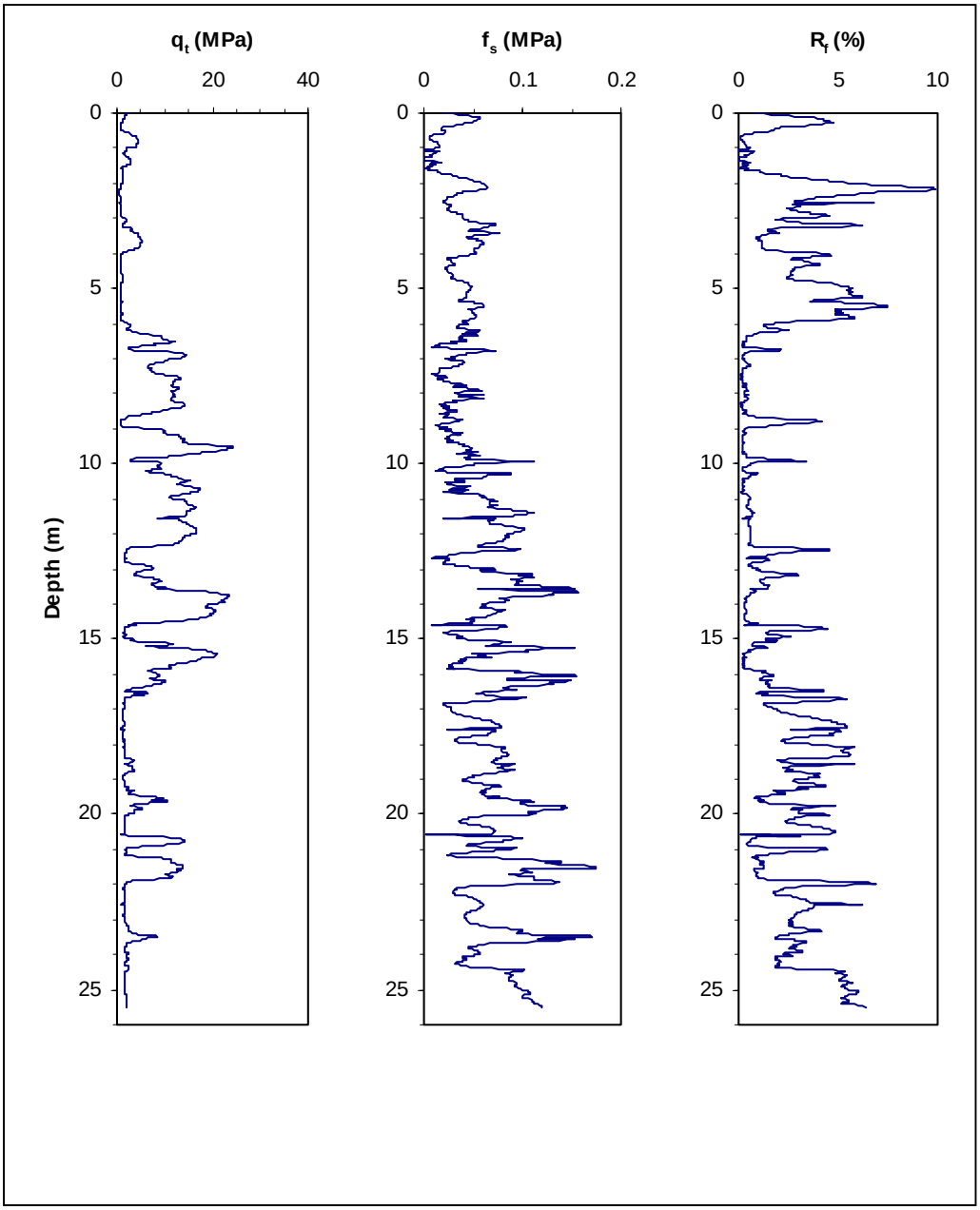
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-7

Figure C.53: CPT Profile: CPT-7



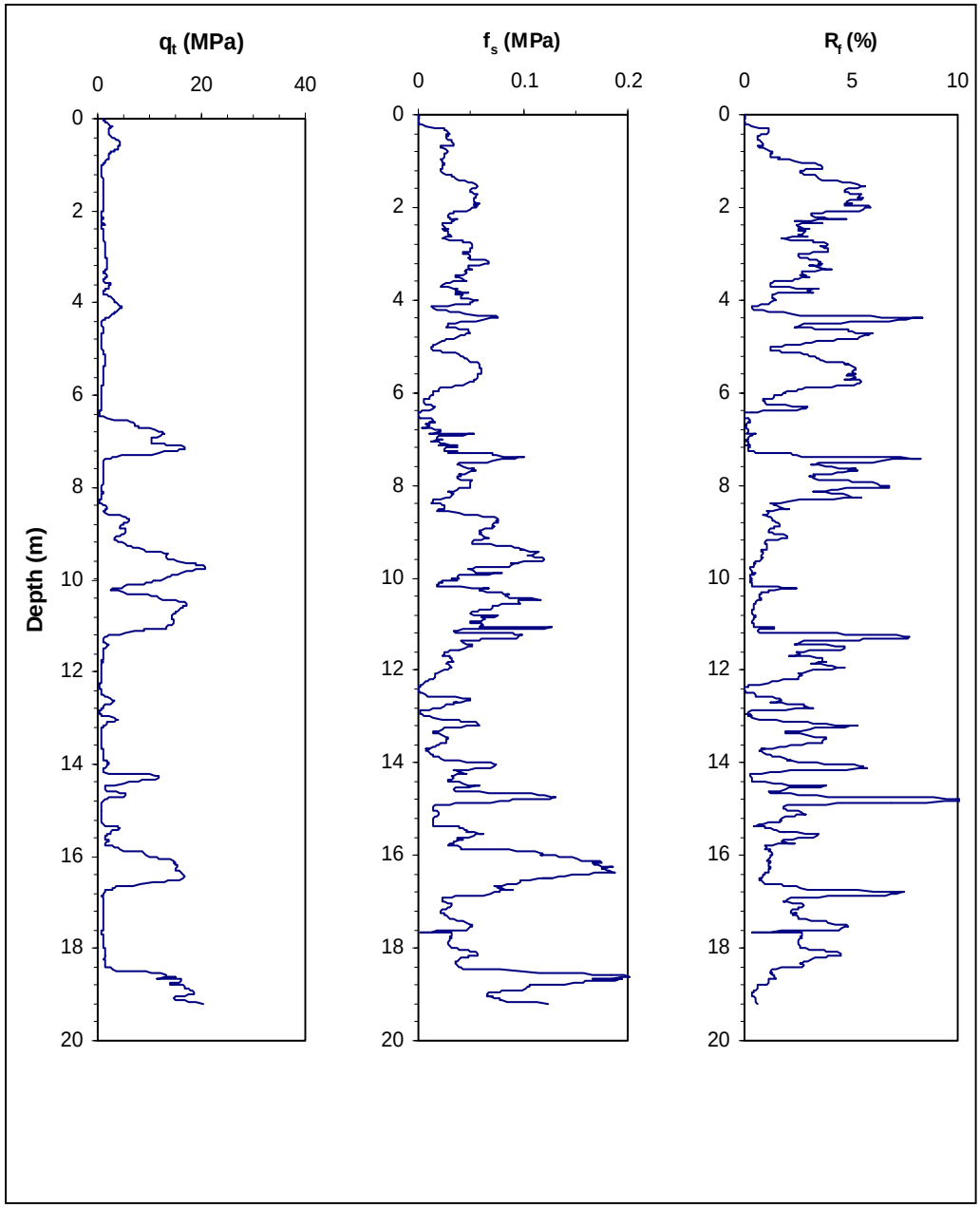
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-8

Figure C.54: CPT Profile: CPT-8



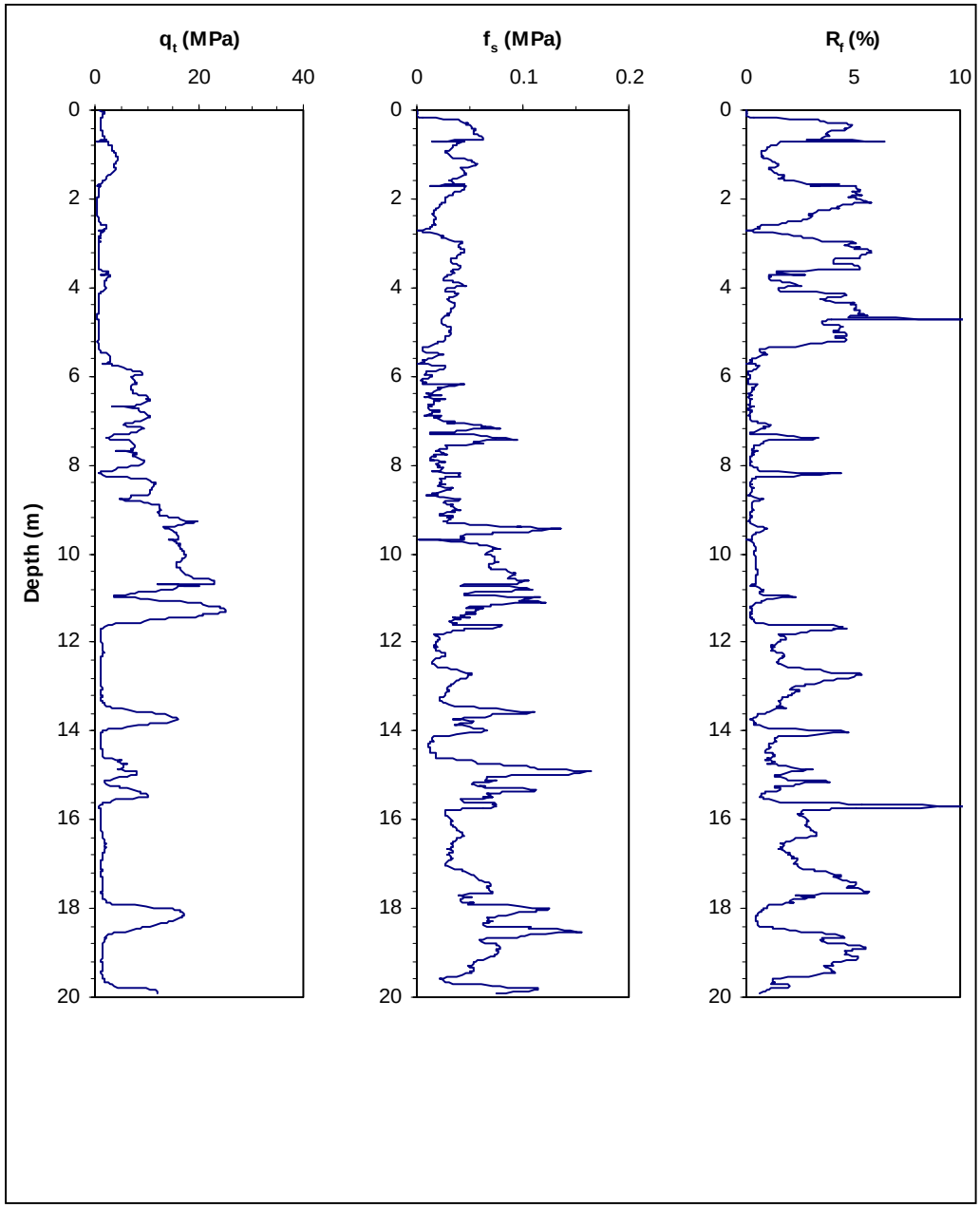
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-14

Figure C.55: CPT Profile: CPT-14



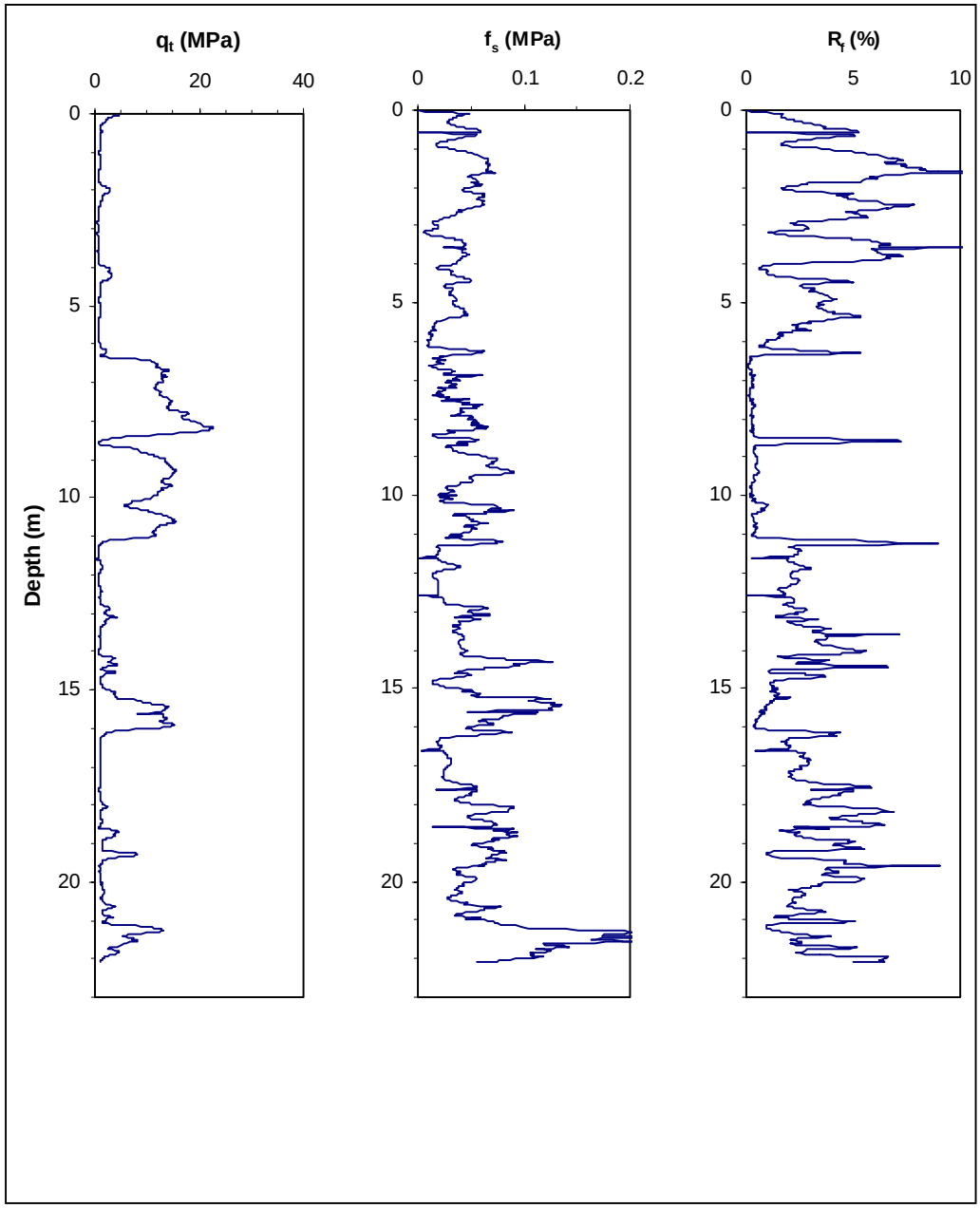
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-15

Figure C.56: CPT Profile: CPT-15



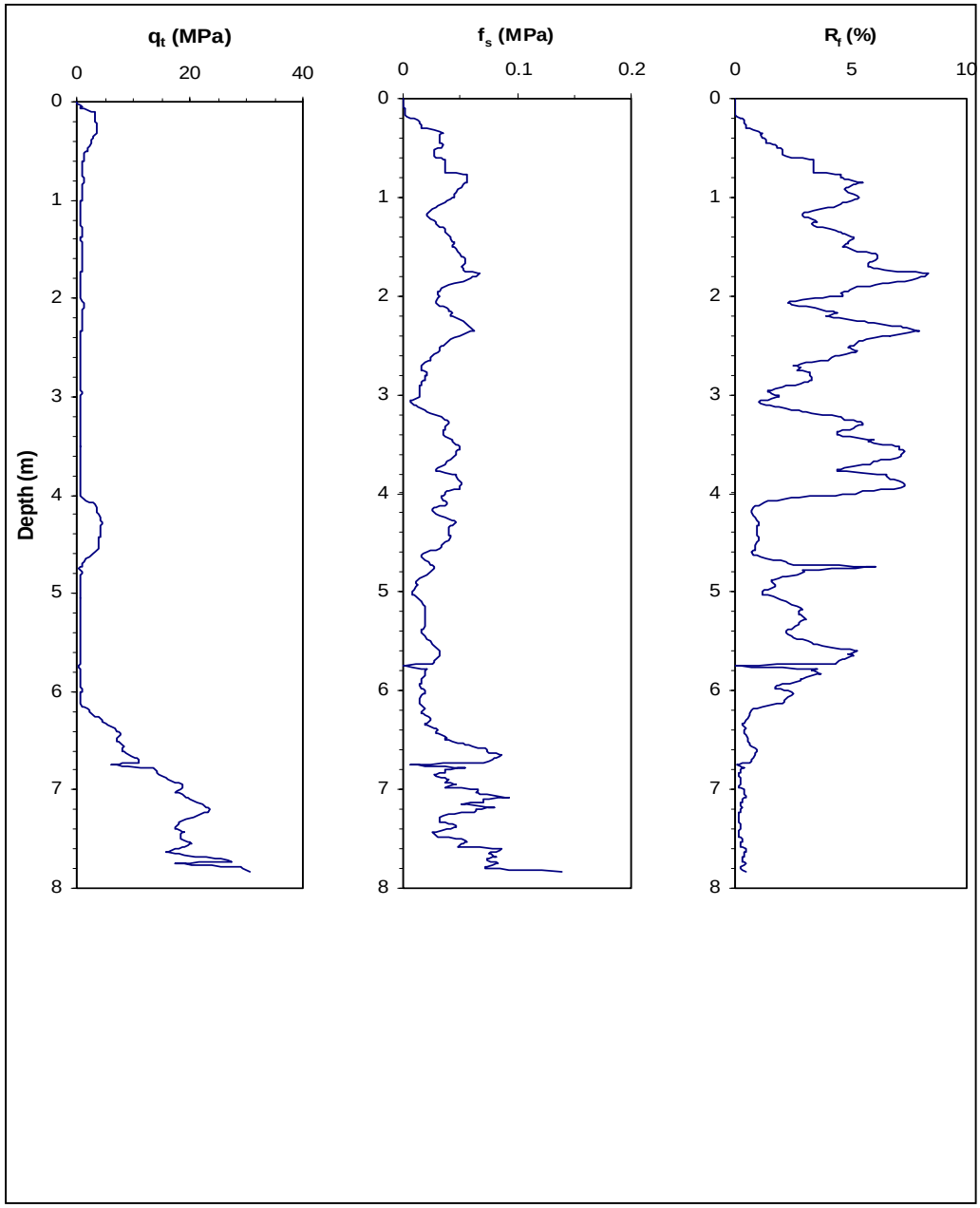
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-16

Figure C.57: CPT Profile: CPT-16



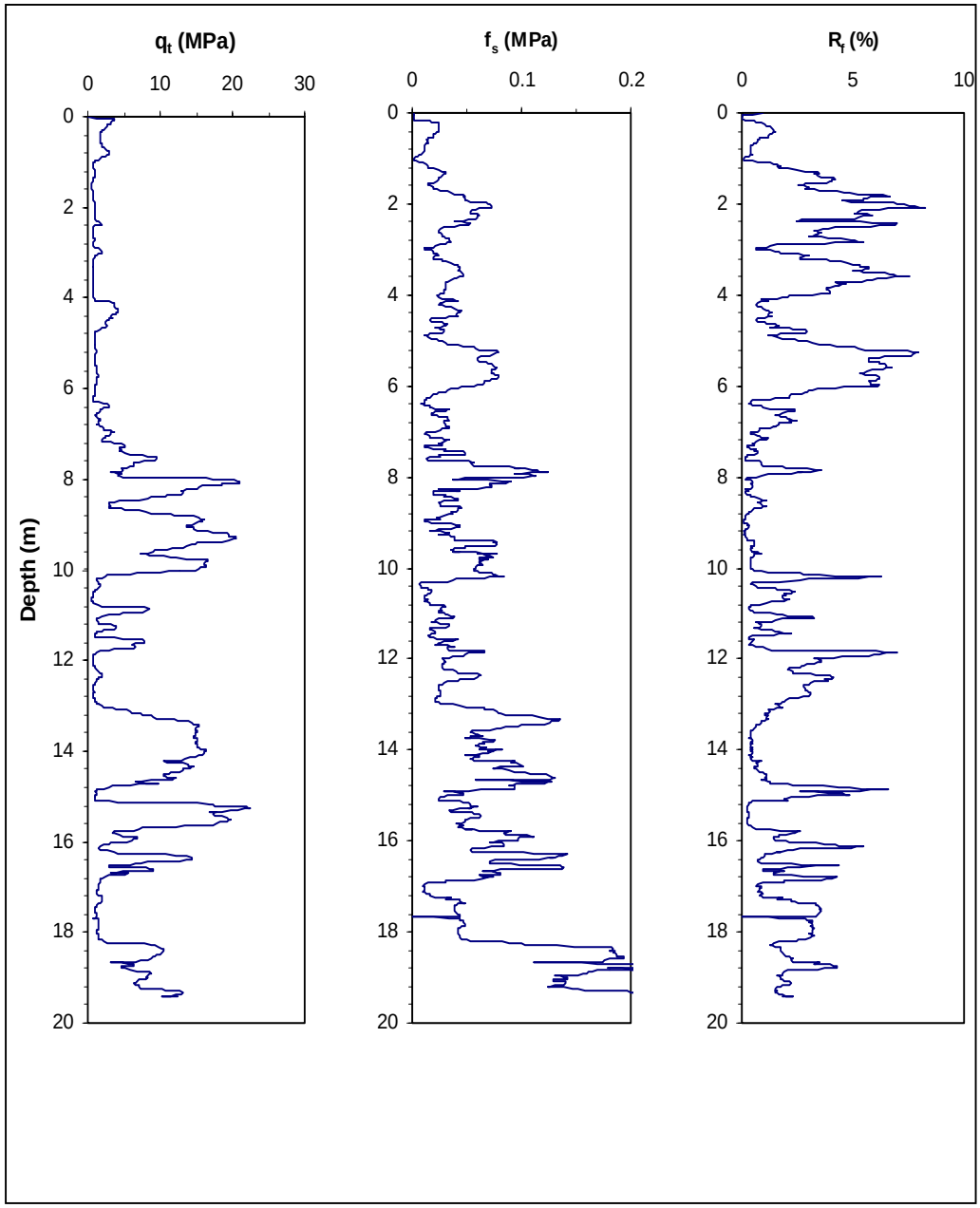
Project:	Buski-East Waste Water Treatment Plant
Operator:	ERBEY Mühendislik Müş. İnş. San. ve Tic. Ltd.Şti
Location:	Demirtas-BURSA
Test Name:	CPT-17

Figure C58: CPT Profile: CPT-17



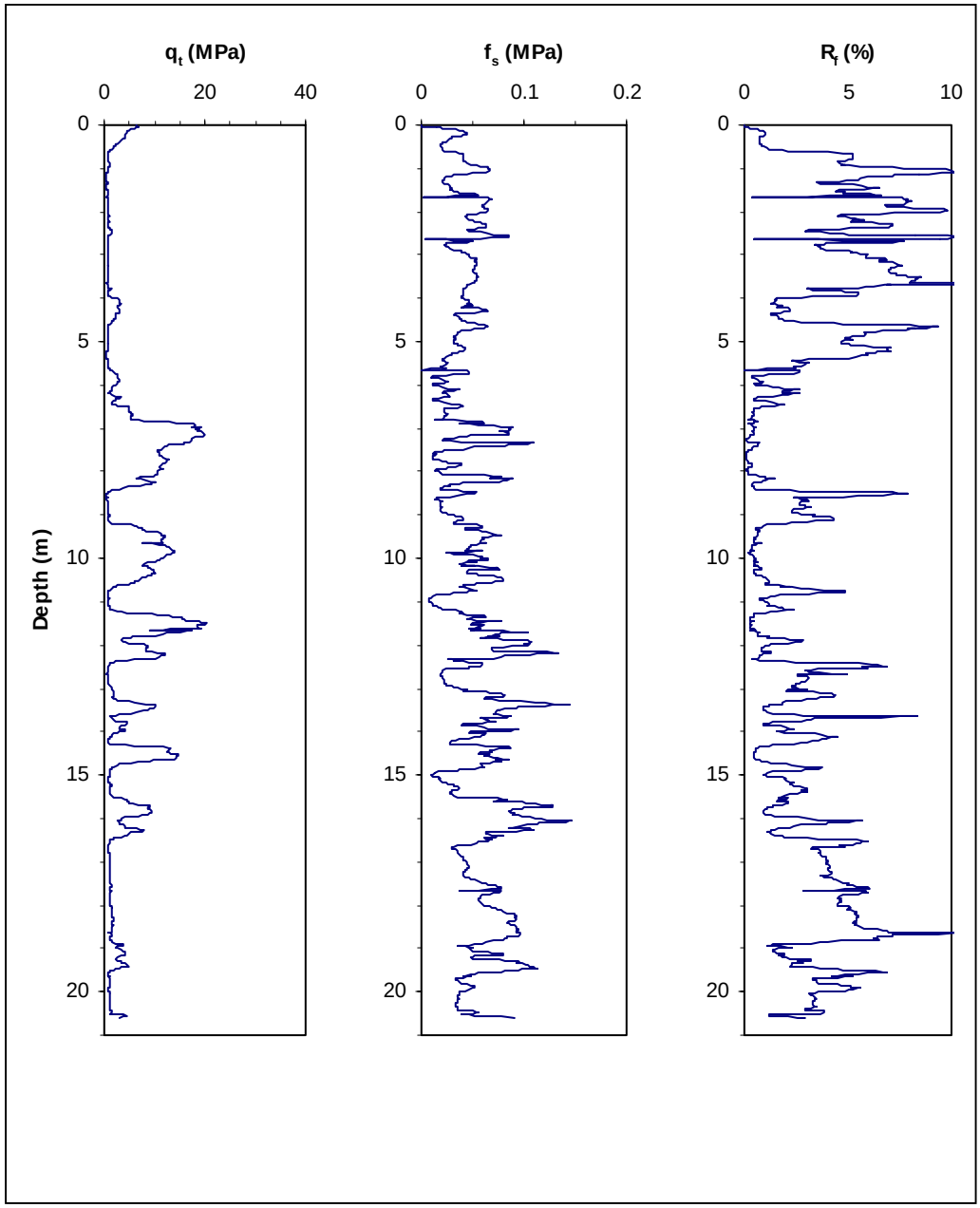
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-18

Figure C.59: CPT Profile: CPT-18



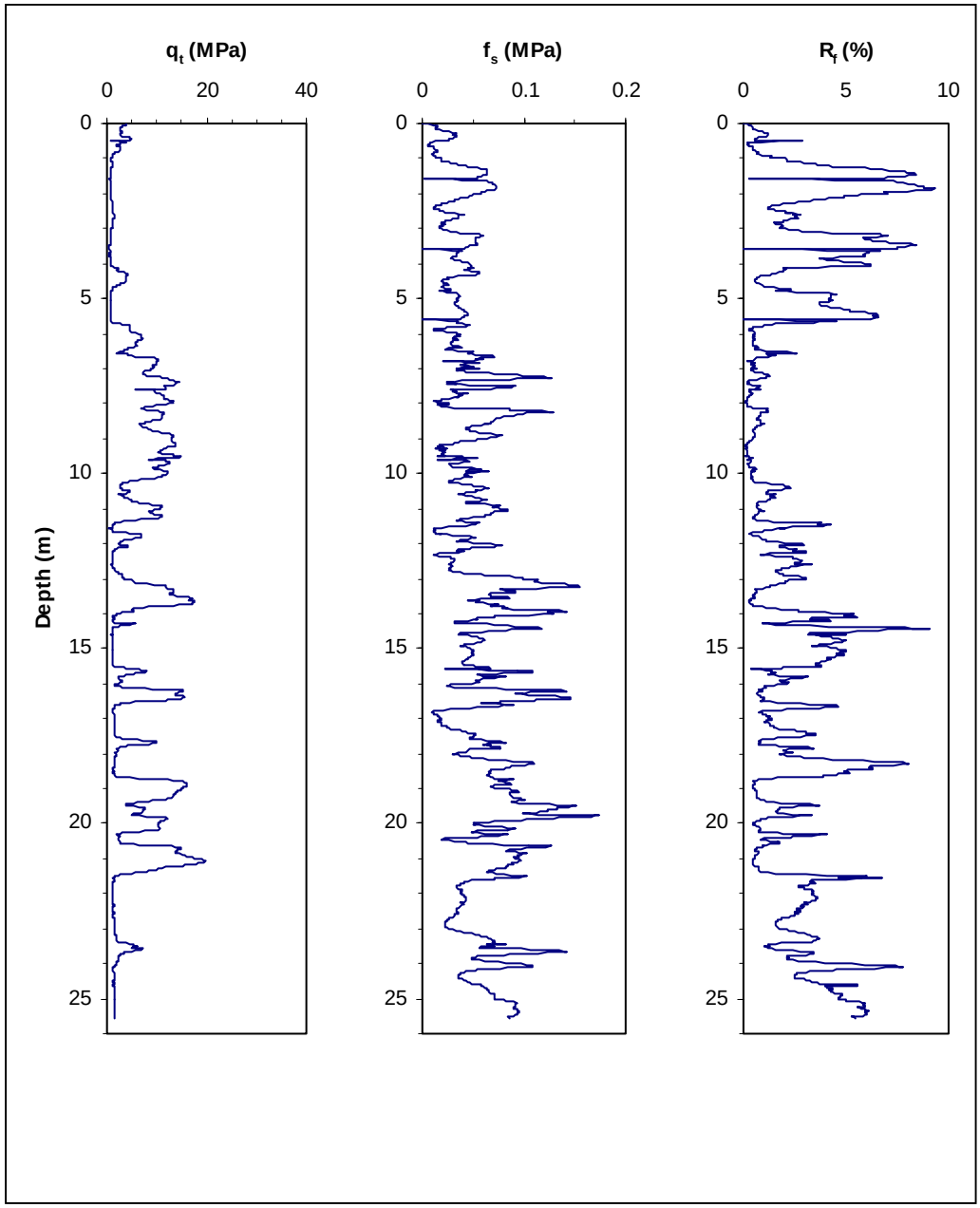
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-19

Figure C.60: CPT Profile: CPT-19



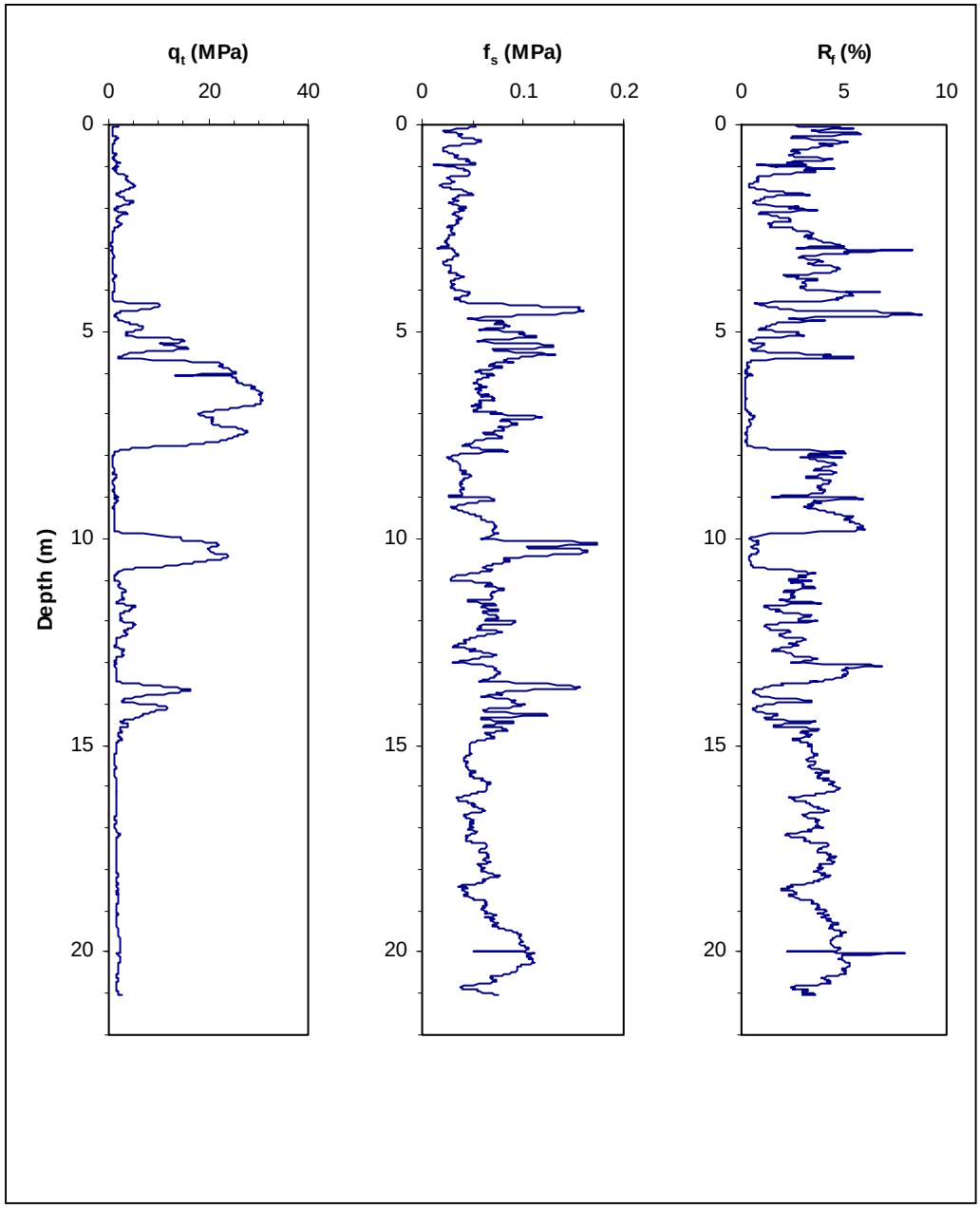
Project:	Buski-East Waste Water Treatment Plant
Operator:	ERBEY Mühendislik Müş. İnş. San. ve Tic. Ltd.Şti
Location:	Demirtas-BURSA
Test Name:	CPT-20

Figure C.61: CPT Profile: CPT-20



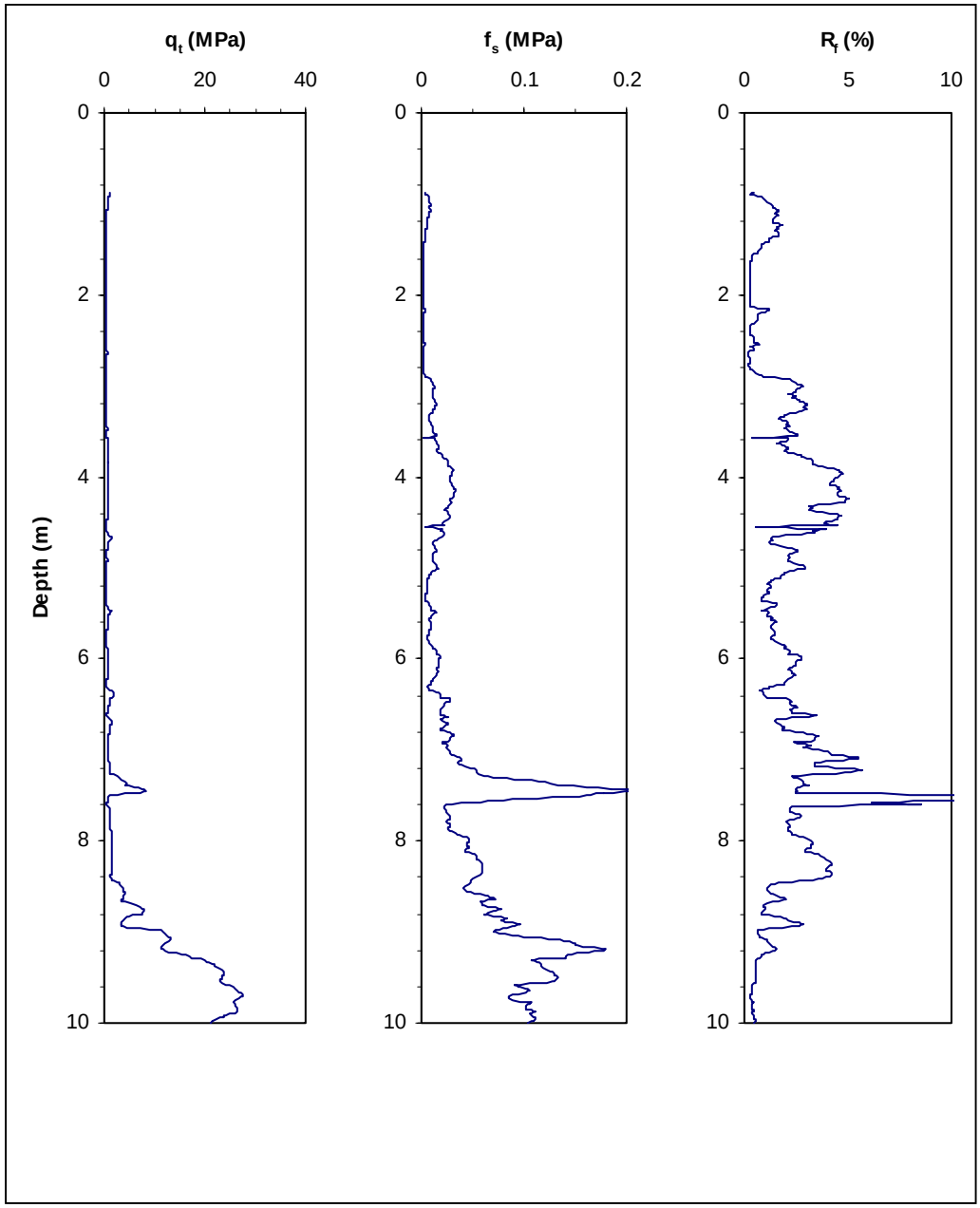
Project:	Buski-East Waste Water Treatment Plant
Operator:	PROTEST Yapı Araştırmaları ve Test Merkezi San ve Tic A.Ş.
Location:	Demirtas-BURSA
Test Name:	CPT-21

Figure C.62: CPT Profile: CPT-21



Project:	Karaca (2001)
Operator:	ZMG Müşavirlik Proje Enstrümantasyon Tic. Ve İnş. Lmt. Şti.
Location:	Tıgcilar Disrict
Test Name:	CPT-Tigcilar-1A

Figure C.63: CPT Profile: CPT-Tigcilar-1A



Project:	Karaca (2001)
Operator:	ZMG Müşavirlik Proje Enstrümantasyon Tic. Ve İnş. Lmt. Şti.
Location:	Cumhuriyet Disrict
Test Name:	CPT-CUM-3

Figure C.64: CPT Profile: CPT-CUM-3

APPENDIX D

COMPILED DATABASE

In Appendix D, compiled database is presented.

Table D.1: Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
CD-1	SPT-1	1.8	5	32	8	67.1		ML	0.386	0.001	0.260	0.386	15.213
	SPT-2	3.3	5	47	25	85.2		CL	0.467	0.011	2.371	0.467	15.701
	SPT-3	5.26	5	44	22	84.8		CL	0.461	0.006	1.228	0.461	15.608
	SPT-4	6.3	11	37	16	94.9		CL	0.980	0.014	1.656	0.980	15.529
	SPT-5	7.8	10	42	19	91.5		CL	1.188	0.027	2.272	1.188	15.377
	SPT-6	9.3	54	NP	NP	43.5		SM	17.683	0.137	0.866	17.683	14.481
L1-7	s-1-02-1	1.24	4	69	39	98	0.001	CH	5.896	0.064	1.309	5.896	14.720
	s-1-02-2	2.49	5	58	35	98	0.002	CH	1.034	0.043	4.007	1.030	15.523
	s-1-02-3	3.74	7	24		71	0.045	ML	3.488	0.019	0.581	3.780	15.197
	s-1-02-4	4.84	6	79	51	97	0.001	CH	1.004	0.046	4.530	1.006	15.590
	s-1-02-5	5.79	15	75	50	99	0.001	CH	1.998	0.085	4.267	1.999	15.442
	s-1-02-6	7.36	9	65	43	100	0.003	CH	1.260	0.046	3.693	1.265	15.540
	s-1-02-7	8.36	3	44	25	99	0.005	CL	0.952	0.024	2.553	0.967	15.496
	s-1-02-8	9.35	5	29		95	0.027	ML	1.733	0.021	1.356	1.741	14.991
L1-1	s-1-11-1	1.49	8	63	39	99	0.001	CH	0.939	0.048	5.086	0.939	15.629
	s-1-11-2	2.51	3	40	26	88	0.024	ML-CL	0.834	0.026	3.126	0.834	15.478
	s-1-11-3	3.27	6	40	27	88	0.017	ML-CL	0.982	0.032	3.274	0.982	15.461
	s-1-11-4	4.16	5	40		68	0.048	ML	3.222	0.020	0.629	3.222	15.322
	s-1-11-5	5.2	4	39	21	94	0.004	CL	0.788	0.023	3.002	0.788	15.442
	s-1-11-6	6.04	9	37		99	0.007	ML	2.730	0.031	1.425	2.730	14.979
	s-1-11-7	6.85	6			20	0.14	SM	7.946	0.038	0.768	7.946	14.576
	s-1-11-8	7.99	7	34		80	0.025	ML	3.104	0.023	0.747	3.104	14.761
	s-1-11-9	8.79	9	33		78	0.022	ML	1.902	0.030	1.617	1.902	14.750
	s-1-11-10	9.79	4	32		82	0.02	ML-CL	0.784	0.013	1.719	0.784	15.477

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L1-5	s-1-16-1	1.31	3						0.729	0.029	4.018	0.724	
	s-1-16-2	2.2	6	31		82	0.029	ML	2.618	0.044	1.690	2.602	14.834
	s-1-16-3	3.19	3	48	26	98	0.001	CL	0.755	0.023	3.088	0.768	15.532
	s-1-16-4	4.1	4	34	6	82	0.011	ML	0.822	0.010	1.180	0.870	14.655
	s-1-16-5	5.31	15	39		65	0.051	ML	8.874	0.069	0.778	8.858	15.015
	s-1-16-6	6.42	12	34	22	72	0.026	CL ML	1.498	0.032	2.439	1.485	15.739
	s-1-16-7	7.42	18			13	0.2	SM	10.611	0.036	0.346	10.600	14.191
	s-1-16-8	8.78	28			7	0.3	SP- SM	17.105	0.053	0.313	17.105	14.069
	s-1-16-9	9.63	6	68	44	99	0.001	CH	1.015	0.050	4.968	1.049	15.740
L1-6	s-1-24-3	2.6	4	37	24	72	0.015	ML-CL	0.988	0.029	3.109	0.992	15.437
	s-1-24-4	3.65	3	41	18	78	0.019	CL	0.607	0.013	2.246	0.616	15.551
	s-1-24-6	5.31	5	61	35	99	0.002	CH	0.738	0.019	2.639	0.731	15.540
	s-1-24-7	6.11	8	37	8	98	0.011	ML	2.597	0.037	1.490	2.585	14.785
	s-1-24-8	7.18	38			17	0.2	SM	23.713	0.100	0.433	23.701	14.138
	s-1-24-9	8.14	37			11	0.2	SP- SM	26.355	0.095	0.382	26.347	14.078
L1-4	s-1-32-1	1.29	5	73	48	99	0.001	CH	0.701	0.027	3.981	0.694	15.604
	s-1-32-2	2.16	6						0.981	0.030	3.006	0.972	
	s-1-32-3	3.19	4	29		64	0.02	ML	1.421	0.011	0.862	1.408	15.113
	s-1-32-4	4.34	4	39	13	90	0.019	ML-CL	0.712	0.009	1.207	0.738	15.164
	s-1-32-5	5.08	9	43	33	94	0.013	ML	2.730	0.037	1.636	2.714	15.064
	s-1-32-6	6.33	10	35		96	0.01	ML	1.544	0.023	1.571	1.553	14.502
	s-1-32-7	7.28	29			8	0.3	SP- SM	18.532	0.078	0.423	18.515	14.155
	s-1-32-8	8.19	42			9	0.25	SP- SM	19.450	0.097	0.499	19.433	14.219
L1-3	s-1-41-1	1.65	1	27		63	0.05	ML	0.735	0.023	3.140	0.727	15.054

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L1-3	s-1-41-2	2.77	4	30		74	0.03	ML	1.473	0.017	1.319	1.467	14.563
	s-1-41-3	3.6	4	29		91	0.015	ML-CL	3.150	0.020	0.687	3.141	14.639
	s-1-41-4	4.44	4	44		96	0.012	ML-CL	1.431	0.021	1.765	1.654	15.112
	s-1-41-5	5.29	5	54	30	92	0.005	CH	0.781	0.028	3.552	0.778	15.558
	s-1-41-7	6.86	40			5	0.44	SP- SM	21.105	0.056	0.266	21.100	13.945
	s-1-41-8	7.85	37			8	0.35	SP- SM	24.718	0.080	0.327	24.710	14.005
L1-2	s-1-42-1	1.61	2	26		51	0.07	ML	1.359	0.042	4.115	1.358	15.142
	s-1-42-2	2.59	4			9	0.29	SP- SM	6.883	0.022	0.320	6.880	14.165
	s-1-42-3	3.54	4	39	14	98	0.005	CL	2.039	0.021	1.110	2.030	15.466
	s-1-42-4	4.31	3	62	27	98	0.002	ML-CL	0.670	0.022	3.418	0.664	15.578
	s-1-42-5	5.3	5	39		100	0.002	ML	1.725	0.028	1.673	1.719	14.878
	s-1-42-6	6.19	8	40	18	96	0.013	CL/ML	1.242	0.022	1.930	1.238	15.126
	s-1-42-7	7.04	11	40	16	97	0.002	CL	1.333	0.031	2.553	1.334	15.499
	s-1-42-9	9.34	4	54	27	98	0.002	CH	1.184	0.032	2.786	1.178	15.494
L2-1	s-2-10-1	1.28	3	64	36	95	0.001	CH	0.653	0.043	6.427	0.650	15.799
	s-2-10-2	2.15	3	70	44	99	0.001	CH	0.605	0.021	3.479	0.601	15.594
	s-2-10-3	3.18	3	33	16	88	0.013	CL/ ML	1.073	0.015	1.407	1.068	14.869
	s-2-10-4	4.33	2	39	22	86	0.015	ML-CL	1.056	0.017	1.584	1.043	15.184
	s-2-10-6	6.4	13	32		82	0.025	ML	3.403	0.034	1.151	3.387	15.139
	s-2-10-7	7.98	35			41	0.088	SM	16.718	0.070	0.419	16.702	14.191
	s-2-10-8	8.79	38			20	0.15	SM	22.844	0.093	0.408	22.830	14.124
	s-2-10-9	9.75	34			22	0.14	SM	26.972	0.105	0.388	26.971	14.081
L2-2	s-2-3-1	1.3	4	64	38	97	0.002	CH	1.473	0.059	4.721	1.469	15.502
	s-2-3-2	2.34	2	33		87	0.016	ML	0.604	0.009	1.395	0.613	15.507

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L2-2	s-2-3-3	3.29	4	34		90	0.022	ML	1.073	0.020	1.906	1.072	15.026
	s-2-3-4	4.37	5	47	18	96	0.009	ML	1.034	0.018	1.839	1.022	15.468
	s-2-3-6	6.11	6	37	11	88	0.014	ML	3.445	0.044	1.399	4.042	14.751
	s-2-3-7	7	4	48.5	22	98	0.006	CH/ MH CL	1.909	0.020	1.247	1.894	15.035
	s-2-3-8	8.35	6	65	40	100	0.002	CH	0.755	0.025	3.251	0.789	15.636
	s-2-3-9	9.54	32			20	0.17	SM	12.012	0.073	0.623	11.998	14.421
	s-2-3-10	10.32	47			11	0.2	SP- SM	20.400	0.103	0.509	20.388	14.241
L3-1	s-3-3-1	1.64	3	29		84	0.023	ML	0.356	0.005	1.343	0.362	15.109
	s-3-3-3	3.2	4	35	15	90	0.018	ML-CL	0.907	0.019	2.147	0.902	15.323
	s-3-3-4	4.45	5	31		91	0.013	ML-CL	0.823	0.031	3.935	0.817	15.580
	s-3-3-6	6.29	14	34	10	98	0.014	ML	2.425	0.044	1.846	2.414	14.878
	s-3-3-7	7.39	12	35		95	0.022	ML	2.248	0.033	1.861	2.238	15.251
	s-3-3-8	8.09	5	53	27	99	0.002	CH	3.915	0.054	2.063	5.574	15.007
	s-3-3-9	9.32	7	43	15	100	0.008	ML-CL	1.118	0.041	3.726	1.120	15.621
L3-2	s-3-6-1	1.29	2	42	20	89	0.008	CL	0.448	0.019	5.203	0.453	14.890
	s-3-6-2	2.46	4	27		57	0.06	ML	1.027	0.008	0.792	1.026	15.238
	s-3-6-3	3.41	3	69	40	99	0.001	CH	2.147	0.018	1.146	2.146	14.891
	s-3-6-4	4.19	3	34	12	92	0.005	CL/ ML	0.729	0.020	2.779	0.729	15.381
	s-3-6-5	5.36	12			35	0.094	SM	0.797	0.016	2.102	0.833	15.366
	s-3-6-6	6.39	9	30		82	0.036	ML	1.538	0.021	1.394	1.531	15.240
	s-3-6-7	7.35	10	31		93	0.02	ML	1.926	0.026	1.556	1.922	15.362
	s-3-6-8	8.3	12	33		58	0.055	ML	2.051	0.028	1.459	2.047	15.106
	s-3-6-9	9.38	8	57	28	99	0.001	CH/ MH	2.773	0.038	1.429	2.769	15.050
L4-1	s-4-13-1	1.26	4	39	19	87	0.006	CL	0.556	0.025	4.430	0.542	15.363

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L4-1	s-4-13-2	2.32	7			43	0.08	SM	2.611	0.019	1.057	2.602	14.814
	s-4-13-4	4.33	4	47	25	89	0.01	CH/CL	0.706	0.028	3.962	0.695	15.622
	s-4-13-5	5.26	9	33		91	0.022	ML	3.561	0.070	2.030	3.542	15.151
	s-4-13-6	6.3	10			58	0.062	ML	12.818	0.038	0.440	14.630	14.918
	s-4-13-7	7.29	9	30		93	0.019	ML	1.544	0.035	2.300	1.545	15.114
	s-4-13-8	8.16	8	26		82	0.02	ML	12.237	0.073	0.746	15.500	15.124
	s-4-13-9	9.16	7	39		100	0.008	ML	1.632	0.033	2.250	1.641	15.107
	s-4-13-10	10.35	34			7	0.32	SP- SM	21.442	0.077	0.364	21.444	14.103
L4-3	s-4-22-1	1.2	4	53	30	99	0.004	CH/ CL	0.630	0.028	4.331	0.634	15.656
	s-4-22-2	2.01	4						1.329	0.013	1.025	1.319	
	s-4-22-3	2.87	4	29		72	0.044	ML	2.227	0.019	0.976	2.216	14.935
	s-4-22-4	3.95	3	55	28	100	0.005	CH	0.843	0.026	3.067	0.868	15.469
	s-4-22-5	5.05	3	34		97	0.018	ML	2.088	0.023	1.118	2.074	15.032
	s-4-22-6	6.05	4	40	15	99	0.009	ML-CL	1.040	0.019	1.884	1.064	15.291
	s-4-22-7	7	14	36		54	0.063	ML	4.791	0.037	0.989	6.553	14.207
	s-4-22-8	8.29	5	60	36	100	0.002	CH	1.158	0.042	3.934	1.194	15.605
	s-4-22-9	9.33	8	65	38	99	0.002	CH	1.183	0.046	3.905	1.191	15.629
L4-3	s-4-3-1	1.46	6			89	0.003	CL	0.794	0.052	6.491	0.788	15.803
	s-4-3-2	2.18	2						0.818	0.017	2.464	0.808	
	s-4-3-3	3	4						0.770	0.033	4.238	0.775	
	s-4-3-4	3.81	4	28		68	0.035	ML	1.540	0.025	2.019	1.539	15.305
	s-4-3-5	4.95	5	59	35	97	0.001	CH	0.732	0.038	5.290	0.740	15.728
	s-4-3-6	6.09	26			23	0.181	SM SP- SM	18.519	0.062	0.337	18.509	14.061
	s-4-3-7	7.3	8	29		84	0.014	ML	1.428	0.041	3.119	1.413	14.420

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L4-3	s-4-3-8	8.59	10	35	18	96	0.017	ML-CL	3.353	0.044	1.474	3.353	15.009
A-1	s-a1-1	1.3	3	41	13	90		ML	0.794	0.031	3.807	0.791	15.558
	s-a1-2	2.1	5	53	23	94		MH/ CH	0.614	0.011	1.839	0.612	15.256
	s-a1-3	2.91	5	65	35	100	0.0035	CH	0.692	0.025	3.612	0.686	15.580
	s-a1-4	3.67	4	46	23	87		CL	0.781	0.025	3.168	0.784	15.001
	s-a1-5	4.5	4	29	6	74	0.045	ML-CL	1.329	0.020	1.513	1.325	15.107
	s-a1-6	5.3	3	55	28	92		CH	0.919	0.021	2.334	0.922	15.363
	s-a1-7	6.29	3	47	20	97	0.012	CL/ ML	1.220	0.016	1.367	1.219	14.931
	s-a1-8	7.31	16	30		70	0.057	ML	2.798	0.050	1.874	2.782	15.225
	s-a1-9	8.31	24	29		58		ML	9.197	0.079	0.913	9.181	15.341
	s-a1-9	8.31	24	29		58		ML	9.197	0.079	0.913	9.181	14.689
A-2	s-a2-1	1.28	2	31	8	74		ML-CL	0.909	0.011	1.221	0.899	15.104
	s-a2-2	2.11	4	35	8	86		ML	0.499	0.014	2.773	0.501	15.171
	s-a2-3	2.85		51	23	100	0.001	CH/ MH	0.755	0.026	3.401	0.748	15.537
	s-a2-4	3.6	2	49	25	85		CL/ CH	0.646	0.013	1.974	0.642	15.959
	s-a2-5	4.5	8	35	7	93	0.018	ML	1.143	0.023	1.876	1.127	15.177
	s-a2-6	5.26		43	20	95		CL	0.750	0.011	1.538	0.740	14.896
	s-a2-7	6.3	3	51	22	99	0.007	MH/ CH	1.103	0.015	1.392	1.101	14.742
	s-a2-8	7.29	10	39	11	85	0.026	ML	2.412	0.042	2.386	2.394	15.558
	s-a2-9	8.8	37			8	0.12	SP- SM	23.171	0.101	0.436	23.155	14.137
B-1	s-b1-1	1.91	2	37		96	0.012	ML	0.664	0.006	0.896	0.664	15.102
	s-b1-2	2.88	2	35		87	0.03	ML	1.007	0.009	1.065	1.007	14.607
	s-b1-3	3.75	8			40	0.12	SM-ML	6.811	0.028	0.409	6.811	14.344
	s-b1-4	4.49	10	27		40	0.09	SM-ML	16.186	0.049	0.305	16.186	14.058

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
B-1	s-b1-6	6.5	32			5	1.7	SW- SM	29.792	0.103	0.346	29.792	14.004
	s-b1-7	8.3	35			5	0.6	SP- SM	27.311	0.120	0.439	27.311	14.130
	s-b1-8	10.8	9	62	40	100	0.001	CH	1.676	0.075	4.460	1.676	15.668
	s-b1-9	12.7	14						2.363	0.057	2.606	2.363	
	s-b1-11	16.32	13	58	34	100	0.001	CH	7.197	0.147	2.235	7.345	15.123
B-2	s-b2-1	1.7	3	42	18	87	0.014	CL	0.777	0.026	3.450	0.777	15.504
	s-b2-2	2.5	3						0.552	0.026	4.995	0.552	
	s-b2-3	3.28	2	37	9	91	0.038	ML	1.007	0.017	1.667	1.007	15.552
	s-b2-4	4.19	12			5	0.4	SP- SM	1.371	0.014	1.379	1.371	15.100
	s-b2-5	5	21			5	0.48	SP- SM	17.248	0.068	0.398	17.248	14.136
	s-b2-6	5.8	34						30.597	0.121	0.397	30.597	
	s-b2-7	7.31	32			3	1	SW	30.752	0.109	0.356	30.752	14.004
	s-b2-8	8.3	35			4	0.9	SW	29.235	0.095	0.325	29.235	13.990
C-3	s-c1-1	2.1	2	44	17	99		ML-CL	0.757	0.013	1.721	0.757	15.276
	s-c1-2	2.86	3	64	42	99	0.002	CH	1.044	0.040	3.819	1.052	15.501
	s-c1-3	3.67							1.103	0.018	1.686	1.107	
	s-c1-4	4.49	8	33	8	94	0.027	ML	3.583	0.032	1.273	3.576	15.203
	s-c1-5	5.34	15	26		67		ML	1.103	0.038	2.684	1.094	15.196
C-1	s-c2-1	1.99	2	40	15	97		CL/ ML	1.175	0.002	0.106	1.175	15.293
	s-c2-2	2.71		42	15	94	0.013	ML-CL	0.661	0.009	1.396	0.661	15.235
	s-c2-3	3.56	7	74	45	99		CH	0.961	0.037	3.774	0.961	15.520
	s-c2-4	4.36		73	28	99	0.003	MH	1.120	0.026	2.389	1.120	14.895
	s-c2-5	5.21	9	42	15	87		ML-CL	0.709	0.017	2.405	0.709	15.460
	s-c2-7	6.79	14	34		92		ML	1.500	0.024	1.715	1.585	15.225

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
C-1	s-c2-8	7.85	7	49	26	99	0.006	CL/ CH	6.553	0.056	1.166	6.553	15.290
	s-c2-9	9.25	8	37		99	0.002	ML	10.669	0.122	1.191	10.669	15.216
C-4	s-c3-3	4.89	3	40	15	88		CL/ ML	1.221	0.025	2.280	1.222	15.148
	s-c3-5	7.03	12	31		83	0.027	ML	4.646	0.023	0.762	4.633	14.692
	s-c3-6	7.98	5	67	36	98		CH/ MH	1.597	0.029	1.885	1.598	15.252
	s-c3-7	10.12	23	28		75	0.033	ML	14.493	0.074	0.549	14.478	15.090
	s-c4-1	2.76	2	45	22	99	0.003	CL	0.704	0.032	4.559	0.702	15.530
	s-c5-4	4.59		48	27	91		CL	0.748	0.024	3.255	0.752	15.267
C-2	s-c5-5	5.39	4	42	18	100	0.002	CL	1.224	0.023	2.065	1.230	15.528
	s-c6-1	1.36	1	40		94	0.014	ML	1.275	0.018	1.449	1.265	15.064
	s-c6-2	2.1	1	31		87	0.015	ML	3.925	0.011	0.276	3.915	15.068
D-2	s-d1-1	1.38	1	33	14	81	0.011	CL	0.906	0.006	0.937	0.904	15.271
	s-d1-2	2.2	2	28		68	0.06	ML	1.680	0.007	0.709	1.667	14.858
	s-d1-3	3.01	2	50	26	99	0.004	CH/ CL	0.302	0.005	1.885	0.309	15.547
	s-d1-4	3.7	7	28		89		ML	2.264	0.018	0.877	2.248	15.391
	s-d1-5	4.74	25			4	1.1	SW	15.271	0.045	0.322	15.282	14.070
	s-d1-6	5.76	27			3	1.7	SW	24.267	0.081	0.341	24.278	14.012
D-1	s-d2-1	1.56							1.418	0.011	0.794	1.418	
	s-d2-2	2.37		36	12	94	0.02	ML-CL	0.756	0.013	1.626	0.756	15.257
	s-d2-3	2.81	2	42	13	99		ML	0.476	0.006	1.180	0.476	14.233
	s-d2-4	3.6	3	35	12	95	0.021	CL/ ML	0.694	0.013	1.935	0.694	14.165
	s-d2-6	5.5	26			4	1.3	SW	28.469	0.110	0.387	28.469	14.032
	s-d2-7	7.3	32			5	0.4	SW- SM	27.750	0.110	0.397	27.750	14.070
D-3	s-d3-1	2.51	4						0.687	0.008	1.185	0.687	

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
D-3	s-d3-2	3.48	4	30		52	0.07	ML	1.032	0.014	1.353	1.032	14.672
	s-d3-3	4.09	9	31	12	96	0.011	ML-CL	2.864	0.022	1.237	2.864	14.922
	s-d3-4	4.86	18			4	1.5	SW	23.552	0.077	0.328	23.552	14.006
DN-1	s-dn1-1	2.09	7	NP	NP	20	2.9	SM	6.051	0.098	1.704	6.046	14.817
	s-dn1-3	4.5	15	NP	NP	40	0.12	SM	8.755	0.117	1.510	8.762	14.767
	s-dn1-4	6.13	24	NP	NP	14	2.6	SM	11.717	0.054	0.471	11.715	14.301
	s-dn1-5	7.51	23	NP	NP	10	4.1	SW- SM	10.093	0.061	0.617	10.091	14.452
	s-dn1-6	8.63	16	NP	NP	9	2.6	SP- SM	19.238	0.119	0.621	19.225	14.331
	s-dn1-7	9.6	17	NP	NP	8	3.7	SW- SM	14.408	0.082	0.580	14.401	14.374
	s-dn1-8	10.64	16	NP	NP	17	1.9	SM	15.904	0.110	0.691	15.894	14.429
DN-2	s-dn2-1	1.65	8	NP	NP	12	4.5	SM	0.135	0.003		0.135	15.845
	s-dn2-2	2.73	12	NP	NP	14	3	SM	7.828	0.087	1.220	7.828	14.695
	s-dn2-3	3.68	14	NP	NP	11	4.1	SP- SM	7.914	0.085	1.105	7.914	14.677
	s-dn2-4	4.55	16	NP	NP	13	2.6	SM	8.918	0.153	1.729	8.918	14.831
	s-dn2-5	6.56	29	NP	NP	10	5.2	SW- SM	15.066	0.134	0.873	15.066	14.502
	s-dn2-6	7.57	26	NP	NP	6	2.6	SW- SM	8.562	0.068	0.793	8.562	14.596
	s-dn2-7	8.61	34	NP	NP	17	1.3	SM	25.123	0.170	0.680	25.123	14.321
	s-dn2-8	9.9	31	NP	NP	10	3	SW- SM	12.171	0.155	1.492	12.171	14.789
E-1	s-e1-1	1.94	5			2	0.51	SP	3.088	0.015	0.492	3.086	14.488
	s-e1-2	3.21	4	30		70	0.04	ML	3.180	0.014	0.493	3.878	14.341
	s-e1-3	4.05	3	52	22	99		MH/ CH	0.938	0.016	1.820	0.979	15.316
	s-e1-4	4.77		61	33	95	0.005	CH	0.863	0.027	3.086	0.878	15.473
	s-e1-7	7.69	35						21.715	0.055	0.256	21.702	
F-1	s-f1-1	1.34	4	28		72	0.06	ML	0.541	0.031	5.986	0.543	15.257

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
F-1	s-f1-2	2.1	4	27		68	0.048	ML	2.198	0.007	0.292	2.195	14.767
	s-f1-3	2.88	4	31		92	0.008	ML	1.628	0.013	0.799	1.623	14.818
	s-f1-4	3.86	3	47	19	97	0.008	ML-CL	0.597	0.008	1.252	0.603	15.233
	s-f1-5	4.73	10	33	13	81	0.03	ML-CL	1.493	0.018	1.327	1.502	15.074
	s-f1-6	5.7	16	28		51	0.07	ML	8.305	0.052	0.643	8.298	15.156
	s-f1-9	8.3	12	31		74	0.034	ML	7.268	0.047	0.699	9.498	14.474
	s-f1-10	9.3	11	53	27	100	0.006	CH/CL/ ML	1.542	0.029	2.028	1.536	15.339
	s-f1-11	10.29	10	48	29	98	0.013	CH/ MH	2.028	0.034	1.773	2.037	15.237
G-2	s-g1-1	1.81	3	41	16	97	0.013	ML	1.269	0.009	0.795	1.258	15.719
	s-g1-2	2.59	6	29		69		ML	2.149	0.014	0.743	2.138	14.675
	s-g1-3	3.39	4	33		95		ML	0.550	0.009	1.693	0.548	15.607
	s-g1-4	4.28	4	53	33	97	0.005	CH	1.086	0.011	1.610	1.089	15.175
	s-g1-5	5.05	10	37	25	78	0.009	ML	3.006	0.021	0.829	2.994	15.121
	s-g1-7	7.29	10	27		67		ML	1.708	0.030	2.105	1.705	14.671
	s-g1-8	8.37	6	58	22	99	0.005	MH	1.368	0.032	2.461	1.373	15.476
	s-g1-9	9.32	8	52	22	99		MH/ CH	1.234	0.041	3.427	1.237	15.384
G-1	s-g2-1	1.59	4						1.661	0.005	0.316	1.649	
	s-g2-2	2.8	9	25		65	0.04	ML	2.546	0.018	0.718	2.531	15.814
	s-g2-3	4.05		37	10	77	0.022	ML	0.660	0.024	3.694	0.660	14.405
	s-g2-4	5.51	6	30		75		ML	4.354	0.029	0.813	4.343	14.835
	s-g2-5	6.29	14	44	13	99	0.007	ML	6.930	0.042	0.602	6.916	14.479
	s-g2-6	7.75		58	31	99	0.001	CH	1.490	0.030	2.123	1.482	15.291
	s-g2-7	8.81	9	40	18	95	0.02	CL/ ML	1.230	0.024	1.976	1.251	15.294
	s-g2-8	9.76		48	24	99	0.006	CL	1.181	0.029	2.446	1.177	15.661

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
G-1	s-g2-9	11.24	9	51	30	98	0.001	CH/ CL	1.411	0.039	2.796	1.399	15.491
	s-g2-10	12.28	29	30		97	0.021	ML	9.266	0.095	1.033	9.269	14.515
	s-g2-11	14.25	13	47	18	99	0.006	ML-CL	3.865	0.047	1.510	3.856	15.059
BCP-7	SK101-1	1.8	7	70	50	95		CH	1.069	0.054	5.088	1.069	15.601
	SK101-2	3.8	8	NP	NP	54		ML	2.005	0.034	1.914	2.005	14.905
	SK101-5	9.8	10	NP	NP	50	0.074	SM-ML	17.493	0.071	0.405	17.493	14.194
H-1	s-h1-1	1.39	2	43	23	75	0.038	CL	0.535	0.025	4.843	0.531	15.005
	s-h1-3	3.3	2	43	17	98	0.009	CL/ ML	0.652	0.013	2.020	0.648	15.350
	s-h1-4	4.13	3	70	37	100	0.002	CH/ MH	0.742	0.016	2.113	0.745	15.369
	s-h1-5	5.23	5	36	17	90	0.03	CL/ ML	1.975	0.033	1.917	1.973	15.333
	s-h1-6	5.98	12	33		80	0.04	ML	5.176	0.056	1.360	5.158	14.481
	s-h1-7	6.86	7	41	21	90	0.008	MH-ML	1.841	0.026	1.757	1.829	15.246
	s-h1-8	7.6	8	49	22	99	0.008	CL/ MH	1.643	0.031	2.147	1.639	14.768
	s-h1-9	8.81	7	68	32	98	0.004	MH	1.076	0.031	2.911	1.075	15.154
	s-h1-11	11.29	7	70	46	98	0.001	CH	1.526	0.053	3.519	1.524	15.579
I-1	s-i1-1	1.29	5	73	48	99	0.001	CH	0.933	0.034	3.512	0.927	15.491
	s-i1-2	2.01	6						1.161	0.039	3.374	1.150	
	s-i1-3	3.17	4	29		64	0.02	ML	1.677	0.011	0.708	1.662	14.690
	s-i1-4	4.34	4	39	13	92	0.019	ML-CL	1.598	0.015	0.968	1.582	14.913
	s-i1-5	5.1	9	43	33	94	0.013	ML	3.048	0.040	1.286	3.035	15.712
	s-i1-6	6.39	10	35		96	0.01	ML	2.430	0.024	1.197	2.414	14.725
	s-i1-7	7.3	29			8	0.3	SP- SM	16.574	0.060	0.363	16.554	14.119
	s-i1-8	8.19	42			9	0.25	SP- SM	25.699	0.093	0.367	25.683	14.044
	s-i1-9	9.12	44			5	0.32	SP- SM	23.430	0.094	0.407	23.423	14.113

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
J-2	s-j1-1	1.55	1	43	15	97	0.01	ML-CL	0.571	0.007	1.145	0.572	15.189
	s-j1-2	2.35	4	37	10	93		ML	1.470	0.021	1.410	1.456	14.766
	s-j1-3	3.11	6	32		84	0.02	ML	1.437	0.017	1.201	1.423	14.949
	s-j1-4	3.96	2	55	29	96	0.005	CH	0.650	0.019	2.846	0.652	15.511
	s-j1-5	4.7	4	62	32	94		CH/ MH	1.145	0.033	3.029	1.156	15.399
	s-j1-7	6.29	30	28		88		ML	14.044	0.081	0.580	14.028	14.626
	s-j1-9	8.79	9	30		91	0.013	ML	1.263	0.024	1.873	1.260	14.696
J-1	s-j2-1	2.1	2	32		81		ML	1.703	0.007	0.495	1.689	15.358
	s-j2-2	2.99	8	28		53	0.07	ML	2.029	0.012	0.648	2.010	15.247
	s-j2-3	4.34	3	75	44	99	0.002	CH	0.840	0.031	3.648	0.824	15.548
	s-j2-6	7.43	11	36		98	0.013	ML	2.599	0.028	1.540	2.604	14.847
	s-j2-7	8.8	11	66	40	100	0.002	CH	1.162	0.034	2.916	1.162	15.506
BCP-3	SK102-4	7.85	4	26	7	39	0.1	SM-SC	5.830	0.034	0.615	5.830	14.587
	SK102-5	9.65	11	NP	NP	8	1	SW-SM	15.365	0.058	0.379	15.365	14.210
	SK102-7	13.85	17	19	5	33	0.31	SM-SC	15.653	0.086	0.638	15.653	14.434
	SK102-8	15.85	17	NP	NP	16	0.9	SM	19.459	0.104	0.535	19.459	14.333
BCP-5	SK103-3	5.8	6	35	15	74		CL	1.014	0.048	4.893	1.014	15.623
	SK103-4	7.8	7	NP	NP	19	0.17	SM	11.918	0.039	0.328	11.918	14.182
	SK103-5	9.8	7	28	13	56		CL	10.490	0.054	0.890	10.490	15.776
	SK103-7	13.8	8	NP	NP	44	0.08	SM	21.841	0.108	0.508	21.841	14.270
	SK103-8	15.8	7	NP	NP	42	0.1	SM	10.849	0.042	0.472	10.849	14.405
	SK103-11	21.75	8	NP	NP	13		SM	10.194	0.105	1.200	10.194	14.835
BCP-2	sk104-1	1.85	4	42	27	77		CL	0.648	0.017	2.729	0.648	15.315
	sk104-2	3.85	7	30	11	68	0.014	CL	1.736	0.061	3.841	1.736	15.421

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
BCP-2	sk104-3	5.85	6	NP	NP	29	0.14	SM	1.073	0.019	1.790	1.073	15.307
	sk104-4	7.85	7	48	33	86	0.001	CL	0.722	0.020	2.731	0.722	15.482
	sk104-5	9.85	14	21	6	27	0.4	SM-SC	16.354	0.050	0.305	16.354	14.103
	sk104-6	11.85	14	NP	NP	18	0.33	SM	3.086	0.057	2.148	3.086	15.247
BCP-4	SK105-1	1.8	7	32	11	65		CL	1.044	0.077	7.967	1.044	15.417
	SK105-2	3.8	6	NP	NP	13	0.28	SM	5.347	0.063	1.252	5.347	14.782
	SK105-3	5.8	5	NP	NP	18	0.28	SM	2.723	0.048	1.820	2.723	15.097
	SK105-5	9.8	12	NP	NP	32	0.17	SM	9.548	0.056	0.615	9.548	14.483
	SK105-7	13.8	12	17	6	37	0.18	SM-SC	7.611	0.069	1.151	7.611	14.814
	SK105-8	15.8	11	NP	NP	28	0.22	SM	4.079	0.079	2.486	4.079	15.291
BCP-8	SK106-1	1.8	7	74	52	98		CH	0.784	0.037	4.761	0.784	15.646
	SK106-2	3.85	5	45	29	88	0.001	CL	2.103	0.034	1.721	2.103	14.609
	SK106-3	5.85	5	NP	NP	17	0.49	SM	6.105	0.015	0.260	6.105	14.213
	SK106-4	7.85	9	NP	NP	11	0.5	SW-SM	8.034	0.020	0.260	8.034	14.180
	SK106-5	9.85	7	20	6	21	0.55	SM-SC	16.238	0.059	0.360	16.238	14.171
BCP-10	SK107-1	1.85	4	61	40	95		CH	0.741	0.047	6.294	0.741	15.764
	SK107-2	3.85	5	40	24	76		CL	0.691	0.042	6.066	0.691	15.814
BCP-11	SK108-1	1.85	5	40	22	80		CL	0.862	0.047	5.406	0.862	15.074
	SK108-2	3.85	4	44	25	88	0.001	CL	0.739	0.030	4.032	0.739	15.796
	SK108-3	5.85	4	40	25	75	0.001	CL	1.206	0.071	5.865	1.206	15.672
	SK108-5	9.85	6	NP	NP	13	0.39	SM	15.058	0.064	0.434	15.058	14.253
	SK108-7	13.85	8	NP	NP	4	3.3	SW	15.218	0.064	0.422	15.218	14.272
BCP-13	SK109-1	1.8	4	33	15	70		CL	0.823	0.069	8.361	0.823	15.621
	SK109-2	3.8	4	38	20	70		CL	0.654	0.034	5.248	0.654	15.711

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
BCP-13	SK109-4	7.8	10	NP	NP	14	0.27	SM	11.296	0.029	0.268	11.296	14.108
	SK109-5	9.8	12	NP	NP	5	0.5	SW	11.040	0.041	0.374	11.040	14.261
	SK109-6	11.8	8	NP	NP	7	0.55	SW-SM	4.779	0.032	0.746	4.779	14.731
	SK109-7	13.8	10	27	6	43	0.09	SM-SC	10.900	0.085	1.181	10.900	14.742
BCP-6	SK110-1	1.85	5	35	17	88		CL	0.952	0.080	8.355	0.952	15.695
	SK110-4	7.85	5	23	5	26	0.24	SM-SC	7.978	0.038	0.541	7.978	14.448
	SK110-7	13.85	7	NP	NP	13	0.52	SM	7.415	0.046	1.769	7.415	14.988
	SK110-8	15.85	8	NP	NP	18	0.5	SM	14.198	0.102	0.727	14.198	14.506
K-1	s-k1-1	1.39	3	46	23	99	0.004	CL	0.644	0.024	3.735	0.650	15.452
	s-k1-2	2.41	4						1.136	0.012	1.243	1.128	
	s-k1-3	3.3	4	35	9	85	0.028	ML	1.435	0.016	1.138	1.425	15.049
	s-k1-4	4.1	3	41	14	95	0.019	ML-CL	0.655	0.014	2.194	0.647	15.417
	s-k1-5	4.9	3	46	21	98	0.003	CL	0.819	0.022	2.693	0.810	15.740
	s-k1-7	6.85	32			8	0.024	SP- SM	17.879	0.081	0.449	17.867	14.179
	s-k1-9	9.35	14	37	10	81	0.005	ML	6.798	0.044	1.304	8.758	15.051
BCP-12	SK1-5	7.8	9	23		38	0.2	SM	11.766	0.023	0.193	11.766	14.004
BCP-9	SK5-12	18.3		34	16	53	0.004	CL	1.182	0.062	5.224	1.182	15.847
	SK5-5	7.8	15			9	0.7	SM	16.207	0.046	0.288	16.207	14.083
BCP-1	SK7-4	6.8				39	0.14	SM	9.718	0.039	0.405	9.718	14.307
L-1	s-l1-1	1.27	3	46	24	77	0.009	CL	0.684	0.020	3.250	0.684	15.596
	s-l1-2	2.61	5	26		74	0.06	ML	1.477	0.009	0.632	1.477	14.999
	s-l1-3	3.35	2	41	15	93	0.003	ML-CL	0.482	0.013	2.819	0.482	15.582
	s-l1-6	5.85	9	33	6	87	0.03	ML	2.415	0.020	0.881	2.415	14.319
	s-l1-8	7.9	31			8	0.43	SP- SM	26.633	0.095	0.356	26.633	14.024

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
L-1	s-l1-9	8.85	14	51	22	98	0.01	MH/ CH	1.786	0.031	1.793	1.786	15.541
PS-1	s-ps3-1	1.8	46	NP	NP	24	1.1	SM	1.350	0.014	1.022	1.337	14.949
	s-ps3-2	2.65	3	NP	NP	36	0.13	SM	1.143	0.016	1.478	1.132	15.128
	s-ps3-3	4.15		45	23	89	0.02	CL	0.466	0.010	2.053	0.516	15.759
	s-ps3-4	6.12		41	18	99	0.014	CL	0.532	0.009	1.656	0.601	15.519
PS-2	s-ps4-2	3.15		NP	NP	78	0.04	ML	0.450	0.012	2.726	0.437	15.453
	s-ps4-3	4.36	1	39	17	93	0.01	CL	0.587	0.011	1.902	0.578	15.453
	s-ps4-4	5.05		39	19	96	9.9	CL	0.551	0.013	2.396	0.545	15.406
	s-ps4-6	10.07		39	19	82	0.009	CL	1.690	0.106	6.292	1.680	15.396
SF-1	s-sf5-1	2.07	4	NP	NP	16	1.3	SM	0.696	0.014	2.048	0.683	15.365
	s-sf5-2	3.11	3	NP	NP	66		ML	0.304	0.005	1.545	0.294	15.054
	s-sf5-3	4.13		57	32	96	0.009	CH	0.386	0.004	1.132	0.382	15.317
	s-sf5-4	5.23	1	58	32	86	0.011	CH	0.370	0.006	1.617	0.376	15.484
	s-sf5-5	6.14							0.370	0.010	2.632	0.400	
	s-sf5-6	7.34	1	56	32	96	0.009	CH	0.399	0.008	2.117	0.445	15.622
	s-sf5-7	8.55		55	34	96	0.009	CH	0.402	0.009	2.237	0.457	15.680
HS-4	s-sh11-1	1.88	9	NP	NP	14	1.9	SM	1.289	0.006	0.502	1.292	14.697
	s-sh11-4	4.77	2	NP	NP				6.148	0.068	1.144	6.159	
	s-sh11-5	5.8	12	NP	NP	11	1.9	SW- SM	7.588	0.030	0.403	7.591	14.332
	s-sh11-6	6.81	12	NP	NP	8	3	SW- SM	3.852	0.041	1.052	3.854	14.850
	s-sh11-7	7.79	12	NP	NP	12	1.1	SM	1.829	0.015	0.804	1.845	14.941
	s-sh11-8	8.67	6	NP	NP	7	2.4	SW- SM	9.271	0.060	0.649	9.290	14.506
	s-sh11-9	9.7	12	NP	NP	21	0.42	SM	9.353	0.048	0.497	9.374	14.414
	s-sh11-10	10.88	19	NP	NP				8.278	0.051	0.608	8.302	

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
HS-1	s-sh2-1	3.33	12	NP	NP	9	4.1	SW- SM	5.117	0.028	0.556	5.125	14.484
HS-2	s-sh4-2	2.5	5	NP	NP				3.307	0.010	0.287	3.312	
	s-sh4-5	4.95	9	NP	NP	7	4.7	SW- SM	7.593	0.047	0.633	7.604	14.470
	s-sh4-6	5.74	7	NP	NP	4	3.2	SW	7.369	0.032	0.432	7.370	14.346
	s-sh4-7	6.75	10	NP	NP				4.772	0.044	1.000	4.774	
	s-sh4-8	8.25	12	NP	NP	11	3	SW- SM	8.141	0.027	0.340	8.160	14.270
	s-sh4-9	9.59	12	NP	NP	7	3.9	SW- SM	8.930	0.030	0.332	8.949	14.255
	s-sh4-10	11.45	22	NP	NP	7	4.5	SW- SM	10.772	0.105	1.009	10.793	14.655
HS-3	s-sh7-3	2.92	5	NP	NP	5	3	SW	8.361	0.050	0.717	8.363	14.471
	s-sh7-4	3.89	8	NP	NP	4	3.9	SW	10.398	0.101	1.038	10.402	14.585
	s-sh7-5	4.7	10	NP	NP	6	4.5	SW	12.588	0.096	0.731	12.591	14.431
	s-sh7-6	5.5	10	NP	NP				7.540	0.034	0.428	7.542	
	s-sh7-7	6.31	16	NP	NP	13	1.5	SM	11.094	0.090	0.822	11.100	14.528
	s-sh7-8	7.3	19	NP	NP	11	1.6	SW- SM	7.041	0.018	0.253	7.053	14.194
	s-sh7-9	8.3	14	NP	NP	12	2	SW- SM	7.934	0.027	0.348	7.936	14.300
	s-sh7-10	9.27	13	NP	NP	6	3.1	SW- SM	11.927	0.046	0.393	11.938	14.267
	s-sh7-11	10.52	11	NP	NP	9	2	SW- SM	9.052	0.070	0.770	9.070	14.596
	s-sh7-12	11.94	11	NP	NP	5	0.84	SP- SM	8.288	0.054	0.630	8.306	14.551
	s-sh7-13	13.44	14	NP	NP	14	0.84	SM	6.894	0.035	0.519	6.909	14.532
YH-2	s-yh1-1	1.61	37	NP	NP	11	7.9	SP- SM	3.787	0.018	0.481	3.787	14.434
	s-yh1-2	3.13	4	NP	NP	9	0.27	SP- SM	5.186	0.025	0.474	5.194	14.399
	s-yh1-3	4.24	10	NP	NP	9	0.29	SP- SM	4.742	0.019	0.403	4.754	14.386
	s-yh1-4	5.67	8	NP	NP	10	0.23	SP- SM	7.087	0.032	0.458	7.074	14.375
	s-yh1-5	6.8	11	NP	NP	14	0.2	SP- SM	3.038	0.017	1.070	3.026	14.884

Table D.1 (cont.): Compiled Database used for this study

Pair Name	Boring Name	Depth (m)	N_{60}	LL	PI	%FC	D_{50} (mm)	USCS	q_c(MPa)	f_s(MPa)	R_f	q_t(MPa)	R
YH-2	s-yh1-7	9.25	3	41	21	77	0.017	CL	0.686	0.021	3.104	0.693	15.332
	s-yh1-8	9.97		43	24	72	0.018	CL	0.785	0.021	2.635	0.823	15.506
YH-1	s-yh3-1	3	7	NP	NP	16	0.2	SM	2.529	0.032	1.210	2.522	14.873
	s-yh3-2	3.68	12	NP	NP	11	0.26	SM SP- SM	3.128	0.011	0.361	3.120	14.427
	s-yh3-3	4.76	9	NP	NP	10	0.25	SP- SM	4.952	0.016	0.324	4.947	14.307
	s-yh3-4	5.65	12	NP	NP	11	0.23	SM	5.320	0.014	0.268	5.328	14.237
	s-yh3-5	6.68	14	NP	NP	17	0.18	SM	5.656	0.015	0.271	5.666	14.244
	s-yh3-6	7.72	12	NP	NP	33	0.1	SM	5.505	0.026	0.471	5.495	14.473
	s-yh3-7	8.71	5	31	19	56	0.074	CL	2.030	0.027	1.496	2.019	15.497
	s-yh3-8	9.65		35	17	90	0.026	CL	0.985	0.014	1.479	1.004	15.263
	s-yh3-9	10.64		36	18	80	0.028	CL	0.821	0.016	1.996	0.874	15.138
TD-1	tsk1-1	1.8	5	34	8	89.9		ML	3.068	0.037	1.480	3.068	15.079
	tsk1-10	15.3	27	39	12	86.9		ML	1.297	0.045	3.462	1.297	15.558
	tsk1-11	16.8	23	36	11	90		ML	1.362	0.047	3.445	1.362	15.193
	tsk1-12	18.3	28	52	25	99.8		CH	1.703	0.058	3.392	1.703	15.669
	tsk1-3	4.8	7	33	9	87		ML	4.103	0.071	2.310	4.103	14.610

REFERENCES

Andrus, R.D. and Youd, T.L. (1987), "Susurface investigation of a liquefaction-inducedlateral spread, Thousand Springs Valley, Idaho", Miscellaneous Paper GL-87-8, Us Army Engineer Waterways Experiment Station, Vicksburg, USA, 131.

ASTM D-422-63 (2002), Standard Test Method for Particle-Size Analysis of Soil

Campanella, R.G., Gillespie, D. and Robertson, P.K. (1982), "Pore Pressures During Cone Penetration Testing", Proceedings, 2nd European Symposium on Penetration Testing, ESOPT II, pp.507-512

Chin, C.T., Duann, S.W. and Kao, T.C. (1988), "SPT-CPT Correlations for Granular Soils", International Symposium on Penetration Testing, ISOPT-1, Orlando, 1, 335-9.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. and Lancellotta, R. (1985), "New developments in field and laboratory testing of soils", State of art report, Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, 1, 57-153, Balkema Pub., Rotterdam.

Jefferies, M.G. and Davies M.P. (1993)," Use of CPTu to estimate equivalent SPT N_{60}", Geotechnical Testing Journal, 16(4):458-467.

Karaca, G (2001), “An Investigation into the Large Vertical Displacements Experienced by the Structures in Adapazari During 17 August 1999 Earthquake”, M.S. Dissertation, Middle East Technical University.

Kasim, A.G., Chu, M.Y. and Jensen, C.N.(1986), “Field Correlation of Cone and Standard Penetration Tests”, Journal of Geotechnical Engineering, ASCE, 112(3), 368-72.

Kovacs, W. D., Salamone, L. A., Yokel, F. Y. (1983), “Comparison of Energy Measurements in the Standard Penetration Test Using the Cathead and Rope Method”, National Bureau of Standards, Report to the U.S. Nuclear Regulatory Commission, November 1983.

Kulhawy, F.H. and Mayne, P.H. (1990), “Manual on Estimating Soil Properties for Foundation and Design”, Electric Power Research Institute, EPRI, August.

Liao, S. S. C., Whitman, R. V. (1986), “Overburden Correction Factor for SPT in Sand”, Journal of Geotechnical Engineering, ASCE, Vol. 112, No. 3, March 1986, pp. 373-377.

Muromachi, T. (1981), “Cone Penetration Testing in Japan”, Proceedings of ASCE National Convention: Cone Penetration Testing and Experience, St. Louis, 49-75, American Society of Engineers (ASCE).

NCEER (1997), “Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils”, Edited by Youd, T. L., Idriss, I. M., Technical Report No. NCEER-97-0022, December 31, 1997.

Olsen, R.S. (1994), “Normalization and Prediction of Geotechnical Properties using Cone Penetration Test (CPT)”, Ph.D. Dissertation, University of California, Berkeley, CA.

Olsen, R.S. (1997), “Cyclic Liquefaction based on the Cone Penetration Test”, Proceedings of NCEER Workshop on Evaluation of Liquifaction Resistance of Soils, National Center For Earthquake Engineering Research State University of New York at Buffalo.

Olsen, R.S. and Mitchell, J.K. (1995), “CPT stress normalization and prediction of soil classification.”, Proceedings of the International Symposium on Cone Penetration Testing, CPT’95, Linköping, Sweden, 2, 257-62, Swedish Geotechnical Society.

Palacios, A. (1977), "The Theory and Measurement of Energy Transfer During Standard Penetration Test Sampling”, Dissertation Submitted in Partial Fulfillment of Doctoral of Philosophy Degree, University of Florida.

Robertson, P.K. and Fear, C.E. (1997), “Liquefaction of Sands and its Evaluation”, 1stInternational Conference on Earthquake Geotechnical Engineering.

Robertson, P.K. and Wride, C.E. (1997), “Cyclic Liquefaction and its Evaluation Based on the SPT and CPT”, Proceedings of NCEER Workshop on Evaluation of Liquifaction Resistance of Soils, National Center For Earthquake Engineering Research State University of New York at Buffalo.

Robertson. P.K. (1990), “ Soil classification using the cone penetration test”. Canadian Geotechnical Journal,27(1),151-8.

Robertson. P.K., Campanella, R.G., Wightman, A. (1983), " SPT-CPT correlations", Journal of Geotechnical Engineering, ASCE,109(11), 1449-59.

Schmartmann, J. H. (1976), "Predicting the q_c/N Ratio Interpreting the Dynamics of the Standard Penetration Test", University of Florida Report to the Department of Transportation, Florida, October, 1976.

Schmartmann, J. H. and Palacios, A. (1979), "Energy Dynamics of SPT", ASCE Journal of Geotechnical Engineering Division, 105(GT8): 909-926.

Seed, H.B. and De Alba, P. (1986), "Use of SPT and CPT Tests for Evaluationg the Liquefaction Resistance of Sands", Proceedings of ASCE Speciality Conference In Situ'86: Use of In Situ Tests in Geotechnical Engineering, Blacksburg, 281-302

Seed, H.B., Tokimatsu, K., Harder, L.F. and Chung, R.M. (1985),"Influence of SPT procedures in soil liquifaction resistance evaluations". ASCE , Journal of Geotechnical Engineering 111:1425-1445.

Vreugdenhil, R., Davis, R. and Berrill, J. (1994), "Interpretation of cone penetration results in multilayared soils", International Journal for Numerical and Analytical Methods in Geomechanics, 18(9),585-99

Wagner, A.A. (1957), "The use of the Unified Classification System by the Bureau of Reclamation", Proceedings, 4th International Conference SMFE, London, Vol. 1, Butterworths, London, pp.125-34

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Fİnn, W.L.D., Harder Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson III, W.F., Martin,.G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B. and Stokoe II, K.H. (2001)," Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils", Journal of Geotechnical and Geoenvironmental Engineering, ASCE,127(10): 817-833

Zervogiannis, C.S. and Kalteziotis, N.A. (1988), "Experience and Relationships from Penetration Testing in Greece", International Symposium on Penetration Testing, ISOPT-1, Orlando, 2, 1063-71, Balkema Pub., Rotterdam.