

Overburden Stress Normalization and Rod Length Corrections
for the Standard Penetration Test (SPT)

by

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A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

Engineering – Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

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Spring 2014

Abstract

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The Standard Penetration Test (SPT) has been a staple of geotechnical engineering practice for more than 70 years. Empirical correlations based on in situ SPT data provide an important basis for assessment of a broad range of engineering parameters, and for empirically based analysis and design methods spanning a significant number of areas of geotechnical practice. Despite this longstanding record of usage, the test itself is relatively poorly standardized with regard to the allowable variability of specific details of equipment and procedures, and this requires a number of adjustments or corrections to further standardize this “standard” test. In addition, for many engineering purposes, it is also useful or necessary to “normalize” the penetration resistance measured by SPT in order to account for the influence of effective vertical effective overburden stress at the depth where an individual SPT is performed.

This research addressed two of corrections and adjustments that can be applied to SPT: (1) normalization of measured penetration resistances to account for effective overburden stress, and (2) corrections of SPT data for the effects of variations in hammer energy successfully transferred into the rods during driving due to “short rod” effects.

The development of procedures and relationships for normalization of SPT penetration data for effects of effective overburden stress dates back more than 60 years, and a number of top geotechnical experts of the past six decades have weighed in on this issue. Despite this long history, current normalization relationships are not based on very extensive data sets, and they are based largely on data for clean sands only (SW and SP) and so do not necessarily represent a suitable basis for overburden normalization of SPT for silty soils (SP-SM, SP-SC, SM and ML) which can be of significant interest in a number of problem areas including, but not limited to, soil liquefaction engineering. The approach taken here was to first re-evaluate the important data developed by Marcuson and Bieganski (1977) based on large-scale laboratory calibration chamber tests of SPT performed on three clean sands. Then the resulting overburden normalization relationships developed were further examined by cross-comparison with several additional sets of field (in situ) SPT data.

To extend these types of relationships to silty soils, data were next gathered for six silty foundation soil strata beneath major dams, where the overlying (largely trapezoidal) earthen dam embankments provided the needed broad ranges of effective overburden stresses within foundation strata that were judged to be suitably laterally geologically continuous as to provide a basis for development of these types of relationships. In the end, it was found that the new relationships developed for “silty” soils, with suitable fines adjustments (similar to the fines adjustments currently employed in widely used SPT-based liquefaction triggering correlations), match relatively well with the newly developed relationships for overburden stress normalization of SPT data for cleaner sands.

The issue of short rod effects has a shorter history, having first been broached by Schmertmann and his colleagues in the early 1970’s. Considerable additional work has followed, and with ongoing advances in both the availability of improved instrumentation (especially high frequency accelerometers) and of analytical methods, it has become clear that earlier measurement and analytical methods developed prior to about the mid-1980’s overestimated to some extent the reduction in hammer energy delivery for conditions wherein rods were “short” (less than about 45 feet in length). With improved modern accelerometers, we are now able to fully track the very high frequency accelerations produced by steel to steel hammer/anvil impacts, and as a result it is now no longer necessary to make simplifying assumptions that had been intrinsic in pre-1986 measurements and analyses. It is now possible to trace hammer energy (and wave travel) up and down the rods for multiple cycles of wave travel and to account for additional hammer energy transferred into and out from the rods until the entire “event” had been concluded. Debate has ensued as to the magnitude of actual hammer energy correction that is appropriate now that this improved measurement data is becoming available. The approach taken here was to gather instrumented hammer energy data from SPT performed, under closely controlled conditions, for purposes of “calibration” of automatic (mechanical) hammers. The resulting data show that short rods effects are indeed somewhat less significant than had previously been postulated, but that this reduction in short rods effects is less pronounced than has been postulated by a number of recent papers. An additional finding, also of engineering significance, is that “common practice” with regard to performing of SPT for purposes of calibration of automatic hammers often does not properly account for short rod effects, and that this can produce a conservative bias in SPT data when these hammers are subsequently used for actual engineering investigations. Recommendations are presented for (a) new short rod corrections, and (b) for hammer energy calibration testing of automatic SPT hammer systems.

To my family...

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ACKNOWLEDGMENTS

First and foremost I want to thank my advisor Prof. Raymond Seed. It would not have been possible to write this doctoral thesis without the help and support of him. He was a tremendous mentor for me. His advice on both research as well as on my career have been priceless. He has always given me the freedom to pursue different projects and to experience what U.C. Berkeley offers in different fields.

I would also like to thank to my co-advisor Prof. Juan Pestana and my committee member Prof. Douglas Dreger for their time and effort in reviewing this work. Prof. Pestana has been always supportive during my Ph.D. studies, and he has provided insightful discussions about the research. I am deeply grateful. Prof. Dreger was also very supportive throughout this study, and it was a pleasure for me to have the opportunity to work with him.

I also thank to each member of U.C. Berkeley Geoengineering Program, all of whom have contributed immensely to my personal and professional experiences and learning at Berkeley. I was lucky to be a member of such a privileged community. I am grateful to Professors Jonathan Bray, Nicholas Sitar and Michael Riemer for their support. I also wish to thank a number of my fellow graduate students, particularly Joe Weber, Hamed Hamedifar, Justin Hollenback, Julien Waeber, Roozbeh Geraili, Yolanda Alberto, Juan Carlos Andrada and Khaled Chowdhury for their friendship, help and support. I also wish to thank to my officemates Josh Zupan, Sang-min Kim and Nathaniel Wagner for their kindness during these past years.

There are many friends who makes Berkeley better place to live. I thank all my friends, too many to list here but you guys know who you are. In particular, I would like to thank Ferda Ofli, Barlas Oguz, Yasemin Oguz, Ahmet Can Tanyeri, my soccer teammates and all my friends from I-House for their friendships these past years. Special thanks are also given to my dear friends back from Turkey: Aydin Unuvar, Demir Uyanik, Altug Sahin, Can Seckin, Cemre Yardim, and Mert Levendoglu.

I must express my deepest gratitude to my loving, supportive, and patient fiancée Zeynep. Without her love, encouragement and editing assistance, I would not have finished this thesis. There are no words to convey how much I love her.

Last, but by no means least, I would like to thank my family, my parents Gulseren and Guntac, my sister Basak, my brother-in-law Baris and my niece Ada for all their love and encouragement. I am eternally grateful to them for the love and support they have provided me.

CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 Introduction

This research addresses two issues associated with the use and interpretation of the Standard Penetration Test (SPT). The Standard Penetration Test (ASTM D1586-08a) involves the use of a standardized steel sampler to retrieve samples from a borehole. A description of the SPT test details, including equipment and procedures, is presented in Section 2.2. The standard sampler has an outside diameter of 2 inches, and an inside diameter of 1 1/2 or 1 3/8 inches. A standard hammer used to drive the sampler 18 inches into the soil at the bottom of the borehole. The standard hammer has a weight of 140 pounds, and a drop height of 30 inches. The number of hammer blows required to drive the sampler into the soil for each of three 6-inch driving increments is counted. The number of blows required for the second and third of these driving increments are added together, and this constitutes the “blow count” or N-value; the number of standard hammer blows required to drive the standard sampler 12 inches into the soil. N-values (blows/ft) are then taken as characterizing the “penetration resistance” of the soil. Numerous empirical engineering correlations, affecting multiple fields of geotechnical engineering practice and design, are based on these measurements of penetration resistance. The SPT is thus of great importance in a diverse suite of areas including design of both shallow and deep foundations, evaluation of properties for dynamic response analyses, and issues associated with seismically-induced soil liquefaction.

Unfortunately, although the basic rules and intent of the test are clearly understood, there is little that is “standard” about the Standard Penetration Test. Variations in sampler details, variations in hammer details, and variations in the means by which hammers are raised and dropped, variations in borehole diameter, etc., all affect the measured penetration resistance. In addition, the blow count, or N-value, is generally “normalized” for the effects of effective vertical stress on the measured penetration resistance to generate an estimate of the N-value that would have been measured if the vertical effective stress had been equal either to 1 atmosphere, or to 1 ton/ft². Finally, for various correlations, the normalized N-value is often further “corrected” for effects of fines in the soil being sampled.

The investigations described and presented herein are targeted towards helping to further define and characterize two of the correction factors applied in the use and interpretation of SPT data. The first of these is normalization for effective overburden effects, with particular emphasis on silty sands and sandy silts, and the second factor is “short rod” effects. Both of these factors are potentially significant in the development of empirical correlations and analytical methods based on field case histories.

The first section of Chapter 2 describes the Standard Penetration Test in greater detail, and explains the suite of corrections and adjustments often applied in the use and interpretation of SPT data. The remainder of Chapter 2 then discusses laboratory and field data developed to illuminate the issue of effective overburden normalization of SPT N-

values, and also presents and discusses the principal relationships proposed for this normalization.

Chapter 3 presents and re-analyzes in detail, the seminal large-scale laboratory calibration chamber tests performed by Marcuson and Bieganousky (1977a,b) on three test sands to develop overburden correction relationship (C_N curves). All three sands were clean sands, and the resulting C_N relationship is then compared with two limited sets of field data.

Having thus established a baseline C_N relationship for clean sands, Chapter 4 then addresses the problem of developing similar C_N relationships for “silty” soils (silty sands and sandy silts). The principal available laboratory calibration test data do not include SPT performed in silty soils, and useful field data for development of C_N relationships for silty soils has also been sparse. As a result, little is known with good certainty regarding overburden correction for silty soils, and the geotechnical profession has tended simply to use the C_N relationships developed for clean sands and to apply them to silty sands and sandy silts.

Field performance case histories involving silty sands and sandy silts are important components of the case history databases used to develop empirical SPT-based correlations for assessment of the likelihood of triggering of seismically-induced soil liquefaction, and the field performance case history databases used for back-analyses of failures to develop empirical correlations for estimation of post-liquefaction residual strengths actually include more “silty” cases (silty sands and sandy silts) the clean sand cases.

The approach taken in Chapter 4 is to garner field SPT data from a suite of dam investigations in which laterally continuous silty sand and sandy silt strata were subjected to SPT, with N-values obtained within each unit over significant ranges of effective overburden stress due to the non-uniform loading of the overlying (largely trapezoidal) dam embankments. These data are then processed and analyzed to develop C_N relationships for silty soils. The resulting relationships are then compared with the C_N relationship for clean sands developed in Chapter 3, and recommendations are made for use of C_N to normalize SPT data for effective overburden effects for materials ranging from clean sands through silty sands and sandy silts of low plasticity.

Chapter 5 addresses the second issue: short rod effects on measured SPT N-values. When the drill rod length, measured from the point of hammer contact at the top of the drill rods down to the tip of the advancing sampler, is less than about 45 feet the initial tensile reflection wave returning from the base of the rods begins to reach the top of the rods before the full compressive force has been successfully transferred from the hammer to the rods. This reduces the energy transferred. Subsequent tensile and compressive reflecting waves passing up and down within both the rods and the hammer, and potential secondary hammer impacts as the hammer may briefly separate from the top of the rods, further complicate the situation. First noted in the late 1970’s, understanding of these issues, and of the corrections needed to account for them in the use and interpretation of SPT data, has advanced considerably over the several decades that followed. Significant advances have been made over this period in instrumentation capabilities, especially with regard to development of

accelerometers capable of accurately measuring the high accelerations and high frequencies on the rods associated with the metal to metal hammer to anvil contacts, and corollary advances in wave equation-based analyses of these dynamic systems, have also been made.

Early “short rod” corrections widely used in engineering practice were based on simplified analytical assumptions that were necessary in the late 1970’s and the early 1980’s before improved accelerometers were capable of making the accurate acceleration measurements needed from more refined, and more fundamentally correct solutions. The early solutions were not able to track energy transfer after the initial return of the first reflected tensile wave, but more modern instrumentation and analyses are now able to accomplish that. As a result, it is now apparent that early solutions overestimated to some extent the significance of short rod effects. These advances have led to new controversy, however, as to the actual magnitudes of short rod effects, and the corrections appropriate for them.

Chapter 5 presents and discusses the mechanics of this problem, and the history of the evolution of our understanding of it. Then, to help resolve the current controversy, a set of field data is gathered for twenty-four instrumented SPT borings performed for purposes of calibration of automatic (mechanical) hammers. This periodic calibration is performed so that the hammer energy delivered will be known, and the hammers are then used for production work in engineering investigations. The calibration tests for this data set were all performed specifically for either seismic dam investigations, or for the California Central Valley Levee Program (CVLP), and so were performed with high quality instrumentation and good field supervision, and were subsequently analyzed by four different firms with good expertise. The resulting data set leads to interesting insights, and also to an interesting and potentially significant insight with regard to standards of practice for this type of automatic hammer calibration.

Finally, Chapter 6 presents a summary of the findings of these studies, and some recommendations for further work.

CHAPTER 2

OVERVIEW OF C_N OVERBURDEN CORRECTION FACTORS FOR SPT

2.1 Introduction

The behavior of cohesionless soil depends on the relative density and stress state of the soil, and so does penetration resistance of the soil (e.g. the SPT penetration resistance, or N-value). The SPT N-value is a function of a number of different soil characteristics, including particle shapes, particle sizes (gradation), fabric, age, and stress history of the soil deposit, but relative density (D_R) and effective confining stress are the two most influential factors. Penetration resistance increases with increasing relative density and with increasing effective overburden stress. When the main purpose of the Standard Penetration Test is to evaluate the relative density of cohesionless soils, or to correlate N-values with properties or behaviors that are heavily dependent upon relative density, it is required to correct the measured N-values to account for overburden pressure at the test depth. Without proper adjustment for effective overburden stress, the measured N-values would underestimate the relative density at shallow depths and overestimate it at very large depths.

The current practice to address this issue is to normalize in situ N-values to a reference stress level of 1 atmosphere effective vertical stress in order to evaluate relative density and other soil factors. The result is a normalized N_1 value, which represents the hypothetical blow count that would have been measured if the test had been performed at a depth where the vertical effective stress had been equal to 1 atmosphere. Field N-values are corrected to N_1 values by an overburden correction factor (C_N) as shown in Equations 2.1 and 2.1(a).

$$N_1 = C_N \cdot N_{\text{field}} \quad \text{Equation 2.1}$$

$$(N_1)_{60} = C_N \cdot N_{60} \quad \text{Equation 2.1(a)}$$

Overburden correction factors (C_N) are generally empirically derived, based on laboratory chamber test data and/or field data.

2.2 Brief Description of the Standard Penetration Test

The use of the Standard Penetration Test was initiated in the U.S. in the 1920's. Since that time, SPT N-values have been correlated with a wide range of engineering properties and behaviors of cohesionless soils, including relative density, effective friction angle, bearing capacity of shallow foundations, bearing capacity of deep foundations (e.g.: piles and piers), subgrade modulus, dynamic stiffness (e.g. dynamic shear modulus), compressibility and settlement behaviors, soil liquefaction triggering potential, post-liquefaction residual strength, etc.

The Standard Penetration Test is usually performed within boreholes. The test is performed by driving a standard sampler 18 inches into soil using a standard hammer. The numbers of blows required to advance (or “drive”) the sampler into the soil are counted for each of three six-inch driving increments. The sum of the numbers of blows required for the second and third of these six-inch driving increments are combined to produce the “blowcount” or N-value which represents the driving resistance (or N-value) in units of blows per foot.

Figure 2-1 is a schematic illustration of equipment used to perform a Standard penetration test. A variety of hammer types, and hammer lifting and dropping mechanisms are used, and this figure illustrates a “donut hammer” with a rope and cathead system for raising the hammer. ASTM specifications for this test include ASTM D1586-08a.

Figure 2-2 illustrates the standard sampler (or “split spoon sampler”) used in this test. The sampler is required to have an outside diameter of 2.0 inches, an inside diameter of $1 \frac{3}{8}$ (or $1 \frac{1}{2}$) inches, and must have a length of at least 24 inches so that the sampler tube will not be “plugged” by the combination of any slough (disturbed soil material) that settles at the bottom of the borehole plus the sample driven up into the tube during the 18 inches of “driving” (or penetration) during the application of hammer blows. The cutting edge of the tube also has specified dimensions and configuration. A ball valve chamber must be attached at the top of the sampler (between the sampler and the drill rods) so that fluids can exit from the top of the tube during “driving”, but so that the steel ball valve will subsequently settle into place and form a seal so that fluid pressures at the top of the sampler will not drive the sample out of the tube when sample retrieval is then attempted.

The sampler is often called a “split spoon” sampler because the sampler tube is fabricated in two halves, and these are held together at the top of the sampler by the “top section” containing the ball valve chamber and at the base of the sampler by the “cutting shoe”. These top and bottom sections are attached by threaded connections, and when they are removed the main body of the sampler tube separates (splits longitudinally) into two sections to provide access to the sample retrieved.

This standard sampler is to be inserted to the base of a borehole. The sampler is then struck with “standard” blows of a “standard” hammer. Originally, this was a hammer weighing 140 lbs., and dropping 30 inches, so that the total energy delivered by each blow was theoretically $140 \text{ lbs.} \times 30 \text{ inches} = 4,200 \text{ in-lbs./blow}$.

The basic details of the Standard Penetration Test are thus relatively well-defined. Unfortunately, significant variations in equipment and procedural details occur. As a result, it is necessary to make a number of “corrections” or adjustments in order to further standardize the Standard Penetration Test resistance measured to “standardized” N_{60} values. These corrections can be expressed in the form of Equations 2.2 as

$$N_{60} = N \cdot C_S \cdot C_B \cdot C_E \cdot C_R \quad \text{Equation 2.2}$$

In addition, the measured N-values can also be normalized to produce the N-values that hypothetically would have been measured if the SPT test had occurred at a depth at which the in situ effective vertical stress had been equal to 1 atmosphere as shown in Equation 2.1, where C_N is an effective overburden stress normalization factor.

These two sets of “corrections” and normalization adjustments can be performed concurrently as

$$N_{1,60} = N \cdot C_N \cdot C_S \cdot C_B \cdot C_E \cdot C_R \quad \text{Equation 2.3}$$

Various combinations of correction factors, and different normalization factors, are applied for different purposes and different correlations, and by different investigators. As an example, Table 2-1 shows the specific correction factors and normalization factors employed by Cetin et. al (2003) in developing their correlation for evaluation of seismically-induced triggering of soil liquefaction. These are not the only combination of such factors employed, but they will serve well as an illustrative example. An explanation of these factors follows.

The “standard” sampler actually has two common configurations. One is a split steel tube with an inside diameter of $1 \frac{3}{8}$ inches, as specified by ASTM. Many samplers, however, have a slightly larger inside diameter (of approximately 1.5 inches) in order to provide space for insertion of brass “liner” rings. When the liner rings are in place, they fill the “extra” annular space, and bring the inside diameter back to the ASTM-specified $1 \frac{3}{8}$ inches. This is the most common type of sampler in actual use in U.S. practice. Unfortunately, the brass liner rings are costly, and so they have fallen into disuse. Instead, these samplers with “space” for liner rings, but without liner rings occupying that space, have an enlarged diameter that technically violates the original standards. Making matters worse, the sampler cutting shoe at the bottom of the split spoon sampler through which the soil sample enters the sampling tube still has the correct (ASTM-specified) inside diameter of $1 \frac{3}{8}$ inches. As a result, the soil sample sliding up into the sampler tube makes insufficient contact with the inside wall of the tube, reducing penetration resistance somewhat relative to the resistance that would be measured if the inside diameter had, instead, been a constant inside diameter of $1 \frac{3}{8}$ inches.

Three approaches are taken to deal with this variability of sampler configuration and geometry. One approach is simply to ignore this issue, resulting in variability of N-values measured with the different sampler configurations. The second approach is to require the use of a sampler of constant $1 \frac{3}{8}$ - inch inside diameter, as specified by ASTM. That can be accomplished either (a) by using a sampler tube machined to have a constant ASTM-specified diameter of $1 \frac{3}{8}$ inches, or (b) by requiring that brass liner rings be used, if space for liners is present within the split spoon sections. A number of governmental agencies, and engineering firms and organizations, have steel sampler tubes with a constant inside diameter of $1 \frac{3}{8}$ inches specially fabricated to accomplish this. A third approach is to make corrections for the reduced penetration resistance measured due to the reduced inside friction and adhesion within a tube that is sized for brass liner rings, but with the rings absent. This

gives rise to the sampler correction factor (C_S). A common correction, for cohesionless soils, is that of Equation 2.4 (Seed, et al., 1984) as

$$C_S = 1 + \frac{N_{1,60}}{100} \quad \text{Equation 2.4}$$

where $N_{1,60}$ is the measured penetration resistance after correction and normalization for overburden effects. This is the correction employed by Cetin et al. (2003), as shown in Table 2-1.

A second correction is required due to the variability of sizes (diameters) of boreholes in which SPT are performed. Increased borehole diameter increases the depth (and width) of the zone of reduced in situ vertical effective stress immediately underlying the base of the borehole due to removal of overburden (soil) from the closely overlying hole. One of the reasons that the first 6-inch increment of penetration does not have its “blowcount” added into the N-value measured is because the SPT blowcount is intended to be a measure of penetration resistance at in situ effective overburden stress. The “unloading” (reduction in vertical stress) at the base of an open borehole dissipates relatively quickly with increased depth beneath the base of the borehole, but it decreases more slowly for larger diameter boreholes than for smaller diameter holes. Accordingly, a borehole diameter correction factor (C_B) is applied. For the correction factors (C_B) recommended by Cetin et al. (2003), as shown in Table 2-1, the “standard” borehole diameter is taken as 65 mm to 115 mm (2.5 inches to 4.5 inches). Larger borehole diameters therefore require correction with a factor (C_B) that increases with increasing borehole diameter, as shown in this table. Boreholes with diameters greater than 200 mm (8 inches) should not be used for SPT testing.

A third correction is necessitated due to the variability in types of hammers, and hammer lift-and-drop mechanisms, employed. This gives rise to potentially significant differences in the actual impact energy delivered to the sampler, and it is the single greatest source of variability in the ostensibly “Standard” Penetration Test. As a result, it has been relatively well studied. The “60” in the standardized N_{60} -value comes directly from this. It was determined (e.g. Kovacs et al., 1983) that the most common rope and cathead system employed in U.S. practice at that time delivered approximately 60% of the theoretical “free fall” energy of the hammer to the top of the drill rod due to friction between the rope and the spinning cathead and due to friction over the top pulley. This assumes (1) that the operator has a relatively clean, dry, and “un-worn” section of rope wrapped around the rotating cathead, (2) that only two turns of rope are passed around the cathead, (3) that the operator actually raises the hammer the full 30 inches for each blow (no more and no less), and (4) that the “release” is relatively clean (although the rope continues to be wrapped loosely around the spinning cathead). Operator variability (e.g. three turns of the rope about the cathead, or “short” blows with the hammer falling less than 30 inches, etc.) can produce wide variations in actual energy delivered to the drill rods and sampler. Accordingly, good monitoring in the field by an engineer is required. Even better, it is now possible to make direct measurements of the actual energy imparted to the sampler, as will be discussed in more detail in Chapter 5. It is such direct measurements that lead to the types of “typical” energies for different hammer types and lift-and-drop systems shown in Table 2.1.

Operator variability can be largely obviated by the use of an automatic mechanical trip hammer system that imparts essentially the same energy with each blow. Such mechanical systems can be “calibrated” with direct measurements of the energy delivered to the rods, and these calibrations can be periodically repeated to ensure that hammer energy delivery for any individual automatic hammer system is not varying over time. These automatic mechanical hammer systems typically deliver a much larger fraction of the theoretical free fall hammer energy, as shown in Table 2-1.

Three main types of hammers are widely used, and these are illustrated in Figure 2-3. Two of these are used with rope and cathead (manual, operator-dependent) lift-and-drop systems, and these are (a) “donut” hammers which have an annular shape and slide down the drill rod to strike an anvil section on the rod, and (b) “safety” hammers that usually consist of a hollow pipe section with the top end plugged that slides down the drill rod so that the “plug” at the top end strikes the top of the drill rod. This second hammer type acquired the name “safety” hammer because it is not possible for the operator to have a finger get crushed between the falling hammer and the “anvil” or point of impact. The third type of hammer is the class of automatic (mechanical) trip hammers. Some of these actually employ drop elements with weights greater than 140 lbs., but they are generally designed to deliver an approximately “standard” blow. Because these automatic hammers can achieve more nearly free fall, these types of hammers usually strike with a somewhat higher percentage of the theoretical “free fall” energy of 4,200 inch-pounds/blow than do the rope and cathead hammer systems (as shown in Table 2-1.) To this table should be added another line for Automatic Trip Hammers with self-contained internal hammer mechanisms (not safety or donut hammers) which typically strike with energy ratios of approximately 0.6 to 0.9, although energy ratios of slightly greater than 1.0 can sometimes occur when automatic hammers are operated too quickly, resulting in the “lift” part of the operation actually hurling the drop element vertically so that excess drop distance results.

Energy ratio (ER) is defined as the ratio of energy actually delivered to the top of the drill rods divided by the theoretical free fall energy of a 140 lb. hammer dropping 30 inches.

Correction (or normalization) of N-values is performed to develop estimates of the N-values that would have been measured if the hammer energy had been equal to 60% of this theoretical free fall value. It is assumed that N-values will be approximately linearly proportional to the energy actually imparted by the hammer, and the corrections is usually performed as

$$C_E = \frac{ER}{60\%} \quad \text{Equation 2.5}$$

Finally, an additional correction factor (C_R) is often applied to SPT performed at shallow depths. When the length of drill rods from the point of hammer impact to the sampler is relatively short (less than about 30 to 45 feet) the dynamic compressive waves driven down the rod by the hammer impact can reflect back up the rod and these reflections can interfere in variable ways with the still developing compressive waves travelling down the rods. This can reduce the overall energy delivered to the sampler. This is a relatively minor effect, except at relatively shallow depths, and it is currently an issue of some controversy and debate. Accordingly, it will be addressed in more detail in Chapter 5.

Table 2-1, presenting the recommended corrections of Cetin et al. (2003) for SPT compatible with their soil liquefaction triggering relationships refers to “Figure 9” for the short rod correction factor (C_R). Figure 2-4 presents this figure.

2.3 Previous Research Efforts to Develop C_N Relationships

2.3.1 Introduction

One of the earliest and most widely used correlations for material character based on SPT N-values was the one proposed by Terzaghi and Peck (1948) which correlated SPT N-values measured in cohesionless soils with (1) the apparent relative “denseness” (not quite relative density) of the material, and (2) effective friction angle. This early relationship is shown in Table 2-2. However, their relationship lacked any explicit consideration of effective overburden pressure, and as a result it tended to lead to over conservatism with regard to estimation of friction angles for design of shallow foundations, and under conservatism with regard to performance of deeper foundations. Improved correlations, and corrections for effective overburden stress (C_N), rapidly followed.

Initial efforts were made to use field (in situ) data to develop relationships for normalization of SPT N-values to account for effective overburden stress effects. A basic problem with the use of in situ data was the need to perform SPT at various depths (and thus various effective overburden stresses) within a soil deposit that has uniform properties (including mineralogy, gradation, fabric, density, etc.) over the full depth range. It is difficult to find natural soil deposits within which these properties remain sufficiently uniform with depth, and with sufficient reliability. This type of relative uniformity can be achieved with engineered fills, but such fills are generally engineered to provide the desired engineering properties needed to meet project needs; it is natural soils, and heterogeneous (non-engineered fills such as hydraulic fills and tailings, etc.) that poses the greater engineering challenges. It proved difficult to establish reliable effective overburden corrections based on in situ data. Accordingly, the main effort was directed towards large-scale laboratory experimentation.

2.3.2 Laboratory Experimental Work of Gibbs and Holtz (1957)

One of the early efforts was the landmark experimental program performed by Gibbs and Holtz of the U.S. Bureau of Reclamation in the early 1950’s (Gibbs and Holtz, 1957). Their research investigated the influence of effective overburden pressure, SPT rod type, SPT rod length, soil type, and soil moisture content on penetration resistance. Figures 2-5 and 2-6 show their soil testing chamber. They fabricated a heavy steel tank 3 feet in diameter and 4 feet in height, fitted with load plates and loading springs at the top which could be used to apply different vertical loads (effective overburden pressures) to the top of the soils sample. Holes were provided through the top of the tank, and through the top loading plate, so that SPT testing could be performed in the soil contained within the tank. Controlled variation of

applied vertical stress was accomplished by progressive tightening of the top threaded nuts to compress the springs at the top of the tank.

Two different sands were tested. One was a fine, cohesionless sand and the other was a coarse sand. The chamber was filled with samples of each of the two sands at various (controlled) relative densities. Samples were fabricated by pluviation, and control of sample densities was by means of compaction with vibrators. Multiple SPT were then performed within each chamber sample, at four different vertical pressure levels; increasing from zero applied vertical load to progressively higher applied top loads.

The results of this testing program are shown in Figures 2-7(a) and (b) for the fine sand and for the coarse sand, respectively. Each figure shows measured N-values vs. relative density, as a function of effective vertical stress. These data are re-plotted from the original source reference for clarity. Relative density was based on laboratory-determined maximum and minimum densities for the two sands, and by the average density of the samples within the large-scale testing chamber. Relationships were developed between the measured N-values and relative density (D_R), and it was clearly demonstrated that penetration resistance at any given relative density strongly depends on effective overburden pressure, and in a systematic manner.

In Figures 2-7(a) and 2-7(b), the different symbols represent different applied overburden pressure levels as measured by the pressure cells. Based on the data presented in Gibbs and Holtz (1957), curves that fit the data were developed for each different overburden pressure level. The regression curves shown in Figures 2-7(a) and 2-7(b) are modified from the original curves in order to obtain better fit to the data. The blue curves represent the samples tested with no applied overburden pressure and the green curves represent the samples tested with maximum applied top pressure for both sands. It can be clearly seen that penetration resistance strongly depends on overburden pressure at the level of the penetration test, and that *“The relative density of sand cannot be established by penetration resistance unless consideration is given to overburden pressures”* (Gibbs and Holtz, 1957).

Although the experimental program of Gibbs and Holtz (1957) was an important pioneering study of the effects of the overburden pressure on penetration resistance, there were some important limitations to this work. These included the following:

1. The rigid walls of the test chamber provided rigid lateral restraint during SPT penetration. In the field (in situ), the soil at a radius corresponding to the perimeter of the tank can move laterally (against the adjacent soil) with the adjacent soil providing stiffness but not full lateral rigidity. Significant subsequent research has been performed to evaluate the effects of lateral rigidity of laboratory calibration chambers on penetration resistances (including SPT and CPT penetration resistances), and it has been found that (a) the diameter of the calibration chamber required to provide a negligible effect of this rigid lateral boundary increases with increased relative density, and (b) the required diameter is significantly larger than that provided by Gibbs and Holtz's chamber (e.g.: Holden, 1991; Clayton et al., 1995; Salgado et al., 1998; etc.). Most of these studies of chamber diameter effects are based on

penetrometers with 100% insertion ratios (the full penetrated area is “filled” by the inserted sampler or probe and so soil must be displaced). It is difficult to generalize these results to an SPT split spoon penetrometer with an insertion ratio of approximately 53 percent, but it must be recognized that it is likely that the rigid lateral boundary of the test chamber significantly affected the measured N-values, and that this effect increased at increasing relative densities.

2. The penetration tests were performed by means of the access provided by six uniformly spaced holes around the loading plate at the top of the chamber. As a result, the SPT were performed in relatively close proximity to the rigid lateral boundary of the steel chamber walls.
3. The rigid walls of the steel chamber also raised questions with regard to the actual effective vertical stresses that were present within the soils at the locations at which the SPT testing was performed. The soils could be expected to “hang up” to some extent by frictional contact with the rigid walls of the chamber, producing “arching” that reduces the actual effective vertical stresses somewhat (relative to the “apparent” vertical stresses, as applied at the top of the soil specimen). For this reason, Gibbs and Holtz installed four earth pressure cells within each fabricated soil sample; two at a depth of 6 inches and two at a depth of 18 inches. These allowed evaluation of vertical stress across the depth range of the SPT penetration. The upper load cells consistently measured higher vertical stress than the lower cells, and the vertical stresses that Gibbs and Holtz reported as compatible with the N-value data produced were the averages of these two sets of load cells.
4. An additional boundary condition problem was the rigid steel base underlying the sample. The presence of a rigid base increases the bearing capacity (and driving resistance) of piles as they approach a stiffer/stronger underlying soil stratum, and so does the penetration resistance measured in calibrated “penetrometers” including SPT and also cone penetrometers (e.g. CPT). Similarly, a stiffer overlying stratum in close proximity can also affect penetration resistance. The top loading plate was not fully rigid, as it was loaded with springs that could yield slightly in the vertical direction, but it was an artificial boundary not fully representative of what would ordinarily have been overlying soil. With a total sample depth of only 4 feet, it was not possible to perform SPT in a position far enough from the rigid base as to avoid potentially significant “thin layer” effects on the penetration resistances measured. The effects of these boundary conditions, especially the rigid base, on the test results of Gibbs and Holtz are unknown.
5. Finally, the maximum vertical pressure that could be applied at the top of the testing chamber limited the maximum effective vertical stress to only 3.4 atmospheres.

There were also some limitations due to the equipment and procedures employed in performing SPT testing. These included the following:

1. Although the effects of different rod types and rod lengths were investigated as another part of the overall research program, the SPT testing performed for the tests investigating effective overburden effects were conducted using no rod at all. The hammer struck directly upon the top of the penetrometer, which is not standard practice.
2. Hammer efficiency, or hammer energy ratio (ER), was not defined, since the potential effects of variations in hammer efficiency had not yet been properly recognized at the time (see Chapter 5). This should, however, be a relatively minor issue while evaluating the effects of the overburden pressure for these tests, as long as energy ratio delivered by the hammer was relatively consistent throughout the testing program.

Notwithstanding the limitations associated with the early experimental work of Gibbs and Holtz (1957), theirs was an important investigation and it led to the development of early relationships for normalization of SPT N-values for effective overburden effects.

2.3.3 Field Data Compiled by Zolkov & Wiseman (1965) and Bazaraa (1967)

A number of investigators attempted to develop relationships for normalization of SPT N-values based on field data. As discussed previously, this posed difficulties with regard to ascertaining whether the soils in a given stratum or deposit had uniform properties, and especially uniform density, over any significant range of depths.

One of the interesting early efforts here included the work of Zolkov and Wiseman (1965), who collected SPT data during progressive excavation at a site where clean sands could be evaluated. As the effective overburden stresses were progressively reduced by soil removal, SPT were performed at essentially the same locations (same elevations) so that it could be inferred that (1) soil properties (e.g. gradation, mineralogy, etc.) were the same, and (2) densities were at least very similar due to minor rebound upon unloading of the cohesionless soils tested. Figure 2-8 shows these data. A drawback to this work was the fact that progressive excavation and removal of overburden loads resulted in a progressive increase in the overconsolidation ratio (OCR) within the soils being tested, and progressively increased the ratio of lateral effective to remaining vertical effective stress, so that the properties (and penetration resistance) would not have been truly constant at the depth(s) at which the SPT were performed. As a result, the decrease in measured SPT N-values was less than expected despite removal of approximately 30 tons/meter² of overburden load, as shown in Figure 2-8. This was explained largely by the residual horizontal stress that remained after removing the surcharge. Unloading of sand increased the K_0 value and that, in turn, limited the decrease in horizontal stress compared to the decrease in vertical stress. They concluded that consideration should be given to stress history, and thus to the lateral pressure in interpreting Standard Penetration Tests.

There are others (e.g. Mansur and Kaufman, 1958; Philcox, 1962; etc.) that also reported measurements of standard penetration resistance before and after excavation, and found similar behaviors.

Another significant early effort to make use of in situ data during this period was that of Bazaraa (1967) who collected SPT data from ten sites of different geology and locations. Figure 2-9 shows the data collected by Bazaraa. It was Bazaraa's view that the soil conditions from these sites were sufficiently variable that they could, on average, be assessed to extract the effects of effective overburden stress on SPT N-values. The relatively large data set assembled here made this a noteworthy early effort of its type. Figure 2-10 shows approximate C_N values (normalized to an effective overburden stress of 1 ton/ft²) based on the ten sites for which Bazaraa collected SPT data, with the data interpreted to back-calculate C_N values for this current study. The resulting apparent relationship between C_N and vertical effective stress must be considered to be an approximate one, owing to uncertainties as to soil consistency over the depth ranges sampled, but it is noted that these generally (at least approximately) conform to the types of shapes (and values) of C_N vs. effective vertical stress developed by other laboratory and field studies.

2.3.4 Laboratory Experimental Work of Marcuson and Bieganousky (1977)

Following the massive liquefaction-induced slope failure of the upstream side of the Lower Van Norman Dam during the 1971 San Fernando Earthquake, the U.S. Army Corps of Engineers' took a lead role in the new U.S. Seismic Dam Safety Program. This led to a renewed interest in liquefaction potential of dams and their foundations, an extensive laboratory studies were conducted in U.S. Army Engineer Waterways Experiment Station (WES) by Marcuson and Bieganousky in order to (1) develop improved C_N factors for normalization of SPT N-values for effective overburden effects, and (2) investigate the reliability of the SPT as an index of relative density.

Specimens 4 ft. in diameter and 6 ft. in height were constructed to varying relative densities in calibration chamber and SPT were performed on these specimens under three effective vertical stress levels (10 psi, 40psi, and 80 psi). Fine sands (Reid Bedford Model sand and Ottawa sand) and coarse sands (Platte River sand and Standard Concrete sand) were used to prepare the specimens in Phase I and Phase II, respectively. The results of calibration chamber tests, which correlated relative density with SPT N values and overburden pressure, are presented in Figure 2-13.a and Figure 2-13.b for fine and coarse sands respectively (Marcuson and Bieganousky 1977a, 1977b). Interpretations of their data will be presented in Section 2.4 and Section 3.3.

The testing program of Marcuson and Bieganousky (1977a, b) had many advantages and improvements relative to the earlier tests of Gibbs and Holtz (1957). They performed a higher number of tests, and these tests were performed in a larger chamber with better boundary conditions.

Figures 2-11 and 2-12 illustrate the testing chamber used by Marcuson and Bieganousky. The chamber had a diameter of 4 feet, and a sample height of 6 feet. Controlled loading applied at the top of the chamber by means of hydraulic rams was used to control effective vertical stresses within the soil samples.

To reduce risk of soil “hanging up” (arching) on the sides of the steel chamber, and thus reducing the actual vertical effective stresses within the soil samples tested, the walls of the chamber were comprised of stacked steel rings with rubber spacing separators. Because rubber is compressible, vertical stresses would not be carried by arching and were instead able to pass into the soil. To reduce “rigid base” effects, the base of the sample chamber was not steel, but rather compacted sand in order to provide some degree of soil-like compliance. The cylindrical opening of the foundation was backfilled with highly compacted sand. The foundation material, which was used instead of rigid base, provided a semi-compliant base to the specimen. This calibration chamber appears likely to have largely eliminated arching effects, and to have at least greatly minimized rigid base effects. Effects of rigidity of lateral confinement of the soils being tested were reduced by the larger diameter chamber, but were likely not fully eliminated, especially for samples of higher relative density

Although, the overall boundary conditions provided by the WES calibration chamber were greatly improved, the test results were still subjected to some degree of lateral confinement against expansion, and the proximity of the peripheral holes through which SPT were performed to the laterally rigid sides of the soil container likely also had some unknown influence on the tests performed.

Overall, this larger chamber provided significantly improved boundary conditions relative to the earlier chamber of Holtz and Kovacs. As a result, the data produced by this important testing program continues to be a principal basis for most modern C_N relationships for cohesionless soils.

Figure 2-13 presents a summary of the data produced by Marcuson and Bieganousky, and Figure 2-14 shows the C_N relationships originally proposed by Marcuson and Bieganousky based on these data. Further discussion of these tests, and further analysis of the data produced, will be presented in Sections 2.4 and 3.3.

2.4 Previous Overburden Correction Relationships

Using the data from the laboratory calibration chamber tests performed by Gibbs and Holtz (1957), Meyerhof (1957) proposed his well-known relationship to correlate SPT N blow count with the square of the relative density, with a linear relationship with effective stress as

$$N = 1.7 D_R^2 (\sigma'_v + 10) \quad \text{Equation 2.6}$$

where σ'_v is units of lbs/in²

Although Gibbs and Holtz (1957) and Meyerhof (1957) both related N -values (blow count) to effective overburden stress, Teng (1962) can essentially be named as the first to develop an actual C_N overburden correction factor in a form largely recognizable as being compatible with the types of implementation represented by Equations 2.1 and 2.1(a). Teng used the data of Gibbs and Holtz to develop his correction factor, but he normalized the penetration resistance to a reference stress of 40 lbs/in² (40 lbs/in² = 2.88 tons/ft²) instead of 1 ton/ft² or 1 atmosphere, which means that Teng's value of C_N is equal to 1.0 at an effective vertical overburden stress of 40 psi. Teng's relationship can, however, be re-normalized to a reference vertical stress of 1 tsf, and it can then be compared directly with other C_N relationships proposed by others. This re-normalized version of Teng's relationship is shown in Figure 2-15. Teng's re-normalized relationship is essentially the relationship recommended by Tokimatsu and Yoshimi (1983), which continues to be widely used in Japanese geotechnical engineering practice.

Similar early efforts were made to develop overburden correction relationships using the field data of Bazaraa (1967). Based on his data, Bazaraa developed two piecewise equations (one for stresses higher than his selected reference stress level, and one for stresses lower than the reference stress level), which used 1.5 ksf (3,000 lbs/ft²) as the reference stress level. Because he believed that low C_N values at high overburden pressure might lead to the underestimation of relative density, especially for very dense sands, two equations were proposed one for below and one for above the reference stress level, in order to apply a smaller correction (i.e. higher C_N) at high effective overburden stresses. This relationship can be approximately re-normalized to a reference stress level of 1 tsf, and this re-normalized relationship is also shown in Figure 2-15.

Later on, Peck et al. (1974) proposed setting the effective overburden pressure of 1 tsf as the standard reference stress level, and proposed one continuous equation to approximate the two piecewise equations of Bazaraa (1967). 1 tsf (≈ 1.06 atm) is a reasonable reference stress level, being mathematically simple and corresponding to a reasonable "medium" depth for geotechnical engineering problems. This relationship proposed by Peck et al. (1974) is also shown in Figure 2-15.

Seed (1976) proposed a C_N relationship analogous to the mathematical form proposed by Peck et al. (1974). However, the Seed (1976) C_N relationship was based on the results of the laboratory calibration chamber tests of Gibbs and Holtz, while the Peck et al. (1974) relationship was based on the field data compiled by Bazaraa. This relationship is also shown in Figure 2-15.

The C_N curves proposed by Seed (1976) and by Teng (1962) provide for much lower normalized N_1 values at high effective overburden stresses than do the relationships proposed by Bazaraa (1967) and by Peck (1974). These produced very low N_1 values at significant depths, and this was problematic with regard to the burgeoning interest in using SPT data for evaluations of seismic dam safety in the 1980's, and this led directly to the funding and performance of the larger-scale calibration chamber testing performed at the Waterways Experiment Station of the U.S. Army Corps of Engineers by Marcuson and Bieganousky, as described previously in Section 2.3.

Based on the new test data of Marcuson and Bieganousky (1977a,b), new C_N relationships were proposed by Marcuson and Bieganousky (1977 a, b) and Seed (1979). The relationships proposed by Marcuson and Bieganousky were presented previously in Figure 2-14, and the relationship proposed by Seed (1979) is presented in Figure 2-16. Seed's relationship essentially compresses to some extent the range of variability of C_N as a function of varying N -value relative to the relationships proposed by Marcuson and Bieganousky.

Liao and Whitman (1986) considered the difference between the two curves proposed by Seed (1979) to be relatively insignificant, and they recommended one single curve with simple mathematical form, which approximated the average of two relative density dependent C_N relationships of Seed (1979). This proposed relationship of Liao and Whitman (1986) is

$$C_N = \left(\frac{1}{\sigma'_v} \right)^{0.5} \quad \text{Equation 2.6}$$

where σ'_v is in units of tons/ft². Being simple, the Liao and Whitman (1986) C_N relationship quickly became a widely used overburden correction factor.

Kayen et al. (1992) next proposed a C_N relationship, which modified the Seed (1979) C_N relationship in a way to limit maximum C_N to a maximum value to 1.7 at shallow depth. The 1998 NCEER/NSF workshop participants (Youd et al., 2001) suggested the use of the Liao and Whitman (1986) C_N relationship for $\sigma'_v \leq 2$ tsf, and the Kayen et al. (1992) C_N relationship for $\sigma'_v \leq 3$ tsf.

Boulanger (2003) re-evaluated the large scale calibration chamber data of Marcuson and Bieganousky, and proposed a C_N relationship that was dependent upon corrected $N_{1,60}$ values as

$$C_N = \left(\frac{1}{\sigma'_v} \right)^m \quad \text{Equation 2.7}$$

$$\text{where } m = 0.784 - (0.521 \frac{N_1}{46})^{0.5} \quad \text{Equation 2.7(a)}$$

A summary of C_N relationships published in the literature is listed in Table 2-3. Figure 2-18 illustrates post-1979 C_N relationships that use reference effective overburden pressure level of either 1 tsf or 1atm. At effective overburden stresses greater than approximately 1 tsf or 1 atm there is good general compatibility between these relationships, though it must be noted that at great depths (very high effective overburden stresses) the variations between the various relationships can have significant engineering consequences. At lower effective overburden stresses, variations between the various proposed relationships is significantly higher; this is an area of volatility, and it is a range of effective overburden

stresses of significant importance for purposes of back-analyses of (typically shallow) field performance case histories for purposes of developing empirical liquefaction triggering correlations.

Castro (1995), on the other hand, pointed out that variability associated to C_N appears to be potentially higher than is suggested by the relationships shown in Figure 2-18. Figure 2-19 shows C_N curves back calculated by Castro for a number of the sands tested in the laboratory by Marcuson and Bieganousky, as well for select additional field sands. Variability is greater among the field sands, and it must be noted that this may reflect, in part, actual changes in density, ageing effects, etc. in the case of the field sands in which case these back-calculated C_N curves would not be fully accurate. Nonetheless, Castro makes a good point in observing that variability may be greater for individual sands than is suggested by the families of curves shown in Figure 2-18.

2.5 Project-Specific C_N for Dams

In the view of their interest in the resistance to triggering of liquefaction, and of potential post-liquefaction strengths, for a critical foundation soil unit beneath at Duncan Dam, B.C. Hydro carried out extensive field, laboratory and analytical investigations in late 1980s and early 1990s. The layer of concern was a uniformly graded, fine, loose sand layer, described as Unit 3c, beneath the dam. A typical cross section of the dam showing the location of Unit 3c is shown in Figure 2-20. SPT were performed under the crest of the dam, beneath the mid-slope, and at the toe providing N-values obtained under widely varying effective overburden stresses. These measured N-values were plotted vs. effective overburden stress, as shown in Figure 2-21. An interpreted relationship between N and effective overburden stress is also shown. It can be observed that the field N values increase with increasing effective overburden stress for the same soil layer, unit 3c.

Empirical SPT-based soil liquefaction triggering correlations were used to assess the liquefaction resistance for this soil unit. However, available C_N correction factors in the literature were considered to be uncertain for effective overburden stresses higher than 3 atm, so it was decided that C_N needed to be estimated by other means. Because the effective overburden stress encountered during SPT testing in Unit 3c ranged from approximately 1 atm to 12 atm, Pillai and Stewart (1994) developed a site-specific overburden correction factor for Duncan by inverting the relationship between N and σ'_v shown in Figure 2-21. The resulting back-calculated, site-specific C_N relationship is shown in Figure 2-22 (Curve B). This site-specific C_N curve is then compared with the relationships proposed by Seed et al. (1984), Skempton (1986) and Liao and Whitman (1986). The site-specific curve agrees fairly well with the curves of Seed et al. and of Liao and Whitman.

Like in the case of Duncan Dam, the simplified C_N overburden correction factor was considered to be a source of high uncertainty at high effective overburden stresses for Perris Dam, a high earthfill dam in California. The California Department of Water Resources (DWR) carried out comprehensive field and laboratory testing in four phases to evaluate foundation liquefaction potential and overall seismic dam safety. SPT were performed out

along the crest, downstream face, bench and toe of Perris Dam. Because the overburden pressure encountered during SPT within the soils units of principal interest ranged from 0.2 atm to 10 atm, DWR developed site-specific field based C_N relationship for the shallow alluvium (DWR, 2005, Wehling and Rennie, 2008).

This case will be discussed in greater detail, and also re-analyzed, in Chapter 4. For now, Figure 2-23 presents a summary of the SPT N_{60} -values measured at various effective overburden stresses within the critical strata, and Figure 2-24 presents a summary of the site-specific C_N curves generated by back-analyses of these data by DWR.

2.6 Inferences of SPT Overburden Normalization from CPT Normalization

Another approach to developing C_N for SPT is to infer that Cone Penetration Test (CPT) tip resistance is “similar” to SPT penetration resistance, and that similar C_N behaviors would occur. Effective overburden stress corrections are much better developed for CPT than for SPT, because (1) the CPT is a smaller diameter penetrometer, and can thus be usefully tested in smaller laboratory calibration chambers, and (2) there is a well-developed analytical framework (cavity expansion theory) available for analysis and interpolation/extrapolation of CPT tip resistance performance, while there is no suitable analytical framework yet for analysis of SPT. There are number of C_N overburden correction relationships for CPT proposed (e.g. Salgado et al., 1997, Boulanger, 2003, Moss et al., 2006, etc.) and each of these is based on cavity expansion theory and more 400 laboratory calibration chamber tests done with CPT. Figure 2-25 presents a typical example, in this case the proposed C_q (analogous to C_N for SPT) relationship proposed by Moss et al. (2006).

CPT calibration chamber tests vastly outnumber the limited number of large-scale calibration tests performed with SPT. SPT data are not only limited but they are also more severely affected by the chamber size and boundary conditions. The ratio of chamber diameter D_c to penetrometer diameter d_p should be large enough to prevent the boundary from influencing the penetration tests (Clayton et al., 1985, Salgado et al., 1998). The required ratio D_c/d_p should be especially higher for dense specimens because dense soils are more dilatant.

In addition, SPT does not have a reliable analytical framework like cavity expansion for CPT. The insertion ratio of cone is 100 percent which is ideal for the assumptions of cavity expansion where the hole made in the soil by the advancing cone tip expands to displace the soil as cone is pushed into the ground. A number of well-developed analytical models now exist for cavity expansion-based analysis of CPT, each with their own internal constitutive models, but all operating within a cavity expansion-based framework.

Idriss and Boulanger (2008) have proposed a suite of C_N correction curves based on either SPT N -values or CPT q_c values, as shown in Figure 2-26. Boulanger and Idriss (2010) developed SPT-based C_N relationships based on the large-scale laboratory test data of Marcuson and Bieganousky (1977a,b), and Boulanger (2003) had previously developed C_N curves for CPT tip resistance. Both were based on the power type of model of equation suggested by Liao and Whitman (1986), as shown in Table 2-3, with the exponent power

being a variable as a function of density or measured resistance. As both sets of curves (SPT and CPT) had identical form, exact similarity can be achieved by simply matching $N_{1,60}$ values with $q_{c,1}$ values to delineate the different curves.

It is not clear, however, whether these two sets of curves would retain this similarity across varying ranges of fines contents and fines character, as (1) the SPT relationships are based only on the limited available large-scale calibration test data of Marcuson and Bieganousky who tested only four sands, all of the clean sands, and (2) it is not straightforward to convert SPT N -values to equivalent CPT q_c -values.

2.7 Conclusions

C_N relationships are reasonably well developed for making corrections to SPT data for the effects of variable effective overburden stress. The actual data upon which these C_N relationships are based is more sparse than most engineers understand, and most current relationships are based entirely, or at least largely, upon the limited set of large-scale laboratory calibration chamber test data developed by Marcuson and Bieganousky (1977a,b). They tested only three sands, and all three were clean sands, and all samples were fabricated by dry pluviation and then vibrated to the target relative density. As a result, there can be no full assurance that these data fully capture the ranges of gradations, fabrics, depositional mechanisms, etc. represented by field conditions. There is some good general additional support from field data, but this also tends to involve clean fine to medium sands.

What is lacking is data, and C_N relationships, for silty sands and sandy silts. These “silty” soils, especially when the silt fines are of low plasticity, are potentially vulnerable to seismically-induced soil liquefaction. The field performance case history data bases currently used for development of SPT-base empirical liquefaction triggering correlations include many silty soils, and the field performance case history data base available for back-analyses of failures to generate empirical SPT-based correlations for assessment of post-liquefaction residual strengths actually contains more cases involving “silty” soils than clean sands. It is therefore important to garner further insight as to appropriate C_N -type corrections for silty sands and sandy silts.

Table 2-1: Examples of Correction Factors for the Standard Penetration Test
As Recommended by Seed et al. (2003)

C _R	(See Fig. 9 for Rod Length Correction Factors)																
C _S	For samplers with an indented space for interior liners, but with liners omitted during sampling, $C_s = 1 + \frac{N_{1.60}}{100}$ (Eq. T-1) With limits as $1.10 \leq C_S \leq 1.30$																
C _B	<u>Borehole diameter</u> 65 to 115 mm 150 mm 200 mm	<u>Correction (C_B)</u> 1.00 1.05 1.15															
C _E	$C_E = \frac{ER}{60\%}$ (Eq. T-2) where ER (efficiency ratio) is the fraction or percentage of the theoretical SPT impact hammer energy actually transmitted to the sampler, expressed as % • The best approach is to directly measure the impact energy transmitted with each blow. When available, direct energy measurements were employed. • The next best approach is to use a hammer and mechanical hammer release system that has been previously calibrated based on direct energy measurements. • Otherwise, ER must be estimated. For good field procedures, equipment and monitoring, the following guidelines are suggested: <table><tr><td><u>Equipment</u></td><td><u>Approximate ER (see Note 3)</u></td><td><u>C_E (see Note 3)</u></td></tr><tr><td>-Safety Hammer¹</td><td>0.4 to 0.75</td><td>0.7 to 1.2</td></tr><tr><td>-Donut Hammer¹</td><td>0.3 to 0.6</td><td>0.5 to 1.0</td></tr><tr><td>-Donut Hammer²</td><td>0.7 to 0.85</td><td>1.1 to 1.4</td></tr><tr><td>-Automatic-Trip Hammer (Donut or Safety Type)</td><td>0.5 to 0.8</td><td>0.8 to 1.4</td></tr></table> • For lesser quality fieldwork (e.g.: irregular hammer drop distance, excessive sliding friction of hammer on rods, wet or worn rope on cathead, etc.) further judgmental adjustments are needed.		<u>Equipment</u>	<u>Approximate ER (see Note 3)</u>	<u>C_E (see Note 3)</u>	-Safety Hammer ¹	0.4 to 0.75	0.7 to 1.2	-Donut Hammer ¹	0.3 to 0.6	0.5 to 1.0	-Donut Hammer ²	0.7 to 0.85	1.1 to 1.4	-Automatic-Trip Hammer (Donut or Safety Type)	0.5 to 0.8	0.8 to 1.4
<u>Equipment</u>	<u>Approximate ER (see Note 3)</u>	<u>C_E (see Note 3)</u>															
-Safety Hammer ¹	0.4 to 0.75	0.7 to 1.2															
-Donut Hammer ¹	0.3 to 0.6	0.5 to 1.0															
-Donut Hammer ²	0.7 to 0.85	1.1 to 1.4															
-Automatic-Trip Hammer (Donut or Safety Type)	0.5 to 0.8	0.8 to 1.4															

Table 2-2: Relative Density versus SPT N-Value (From Terzaghi and Peck, 1948)

N-Value	Relative Density
Below 4	Very Loose
4 to 10	Loose
10 to 30	Medium Dense
30 to 50	Dense
Over 50	Very Dense

Table 2-3: Summary of C_N Relationships (Modified from Liao & Whitman 1986)

Reference	C_N Relationship	Units
Teng (1962)*	$C_N = \frac{50}{(10 + \sigma'_v)}$	lbs/in ²
Bazaraa (1967)*	$C_N = \frac{4}{1 + 2 \sigma'_v}$ for $\sigma'_v < 1.5$ $C_N = \frac{4}{3.25 + 0.5 \sigma'_v}$ for $\sigma'_v > 1.5$	kips/ft ²
Peck et al. (1974)	$C_N = 0.77 \log_{10} (20/\sigma'_v)$	tons/ft ²
Seed (1976)	$C_N = 1 - 1.25 \log_{10} (\sigma'_v)$	tons/ft ²
Seed (1979)	$C_N =$ See Fig. 2.11	tons/ft ²
Tokimatsu & Yoshimi (1983)	$C_N = \frac{1.7}{0.7 + \sigma'_{vn}}$	kg/cm ²
Liao & Whitman (1986)	$C_N = \left(\frac{P_a}{\sigma'_v} \right)^{0.5}$	Units of P_a
Skempton (1986)	$C_N = \frac{2}{1 + \sigma'_v}$ for Fine Sand $C_N = \frac{3}{2 + \sigma'_v}$ for Coarse Sand	kg/cm ²
Kayen et al. (1992)	$C_N = \frac{2.2}{(1.2 + \sigma'_v/P_a)}$	Units of P_a
Boulanger (2003)	$C_N = \left(\frac{P_a}{\sigma'_v} \right)^m$ $m = 0.784 - 0.0768 \sqrt{(N_1)_{60}}$	Units of P_a

* Correlations that use a reference stress level other than 1 tsf or 1 atm.

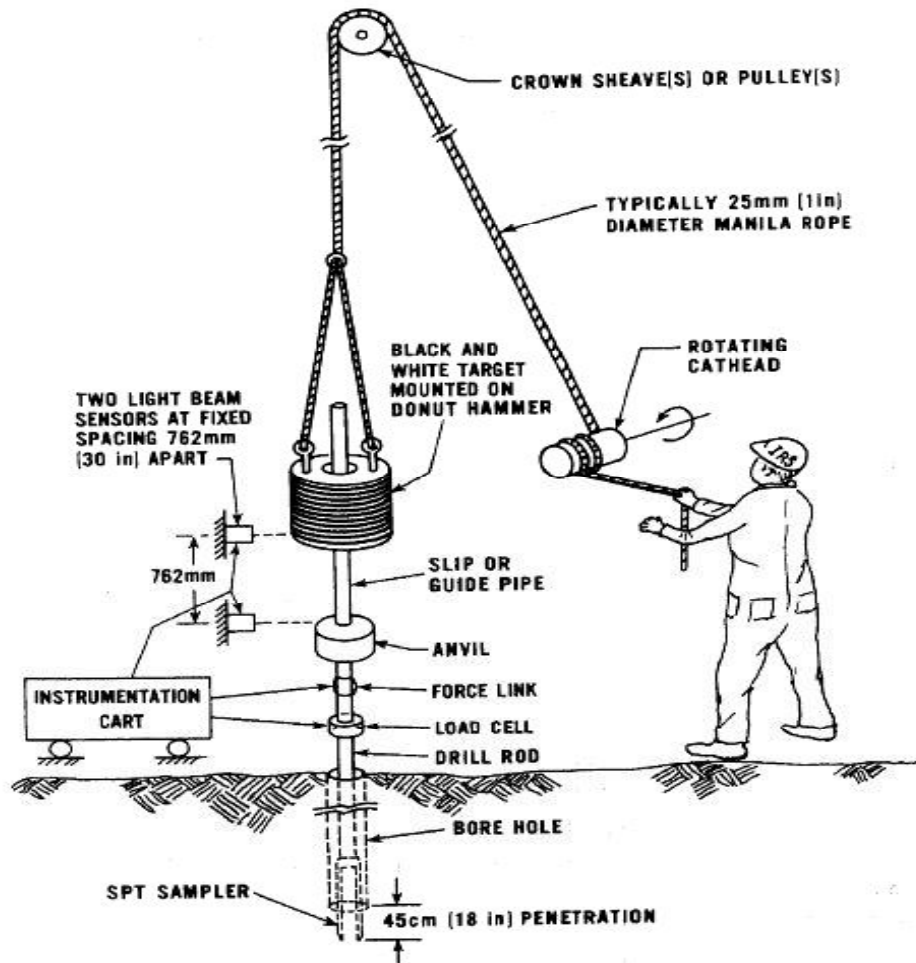
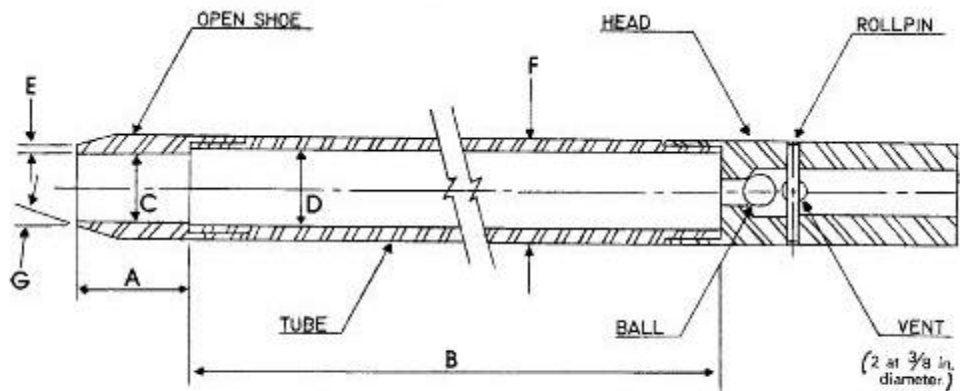


Figure 2-1: Schematic Illustration of Equipment Used to Perform a Standard Penetration Test (from Kovacs and Salomone, 1982)



A= 1.0 to 2.0 in.
 B= 18.0 to 30.0 in.
 C= 1.375 ± 0.005 in.
 D= 1.50 ± 0.05 in.
 E= $0.10 \pm .02$ in.
 F= 2.00 ± 0.05 in.
 G= 16.0° to 23.0°

Figure 2-2: Sampler Configuration for the Standard Penetration Test
(from ASTM D1586-08a)

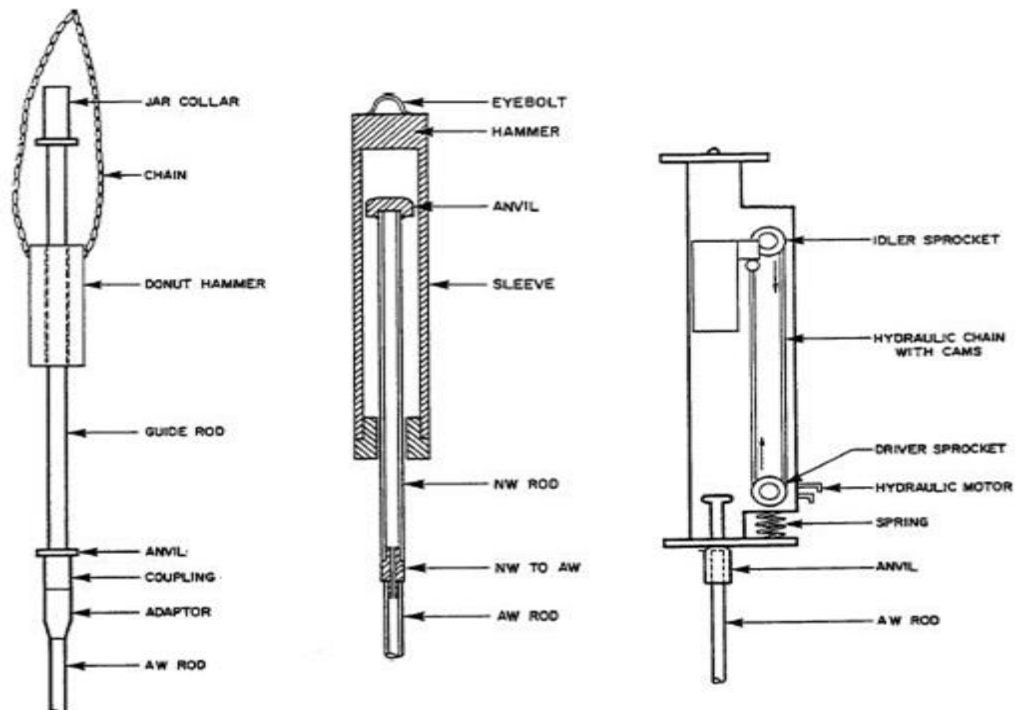


Figure 2-3: Three Common Hammer Types Used for the Standard Penetration Test
(from Sy, 1993)

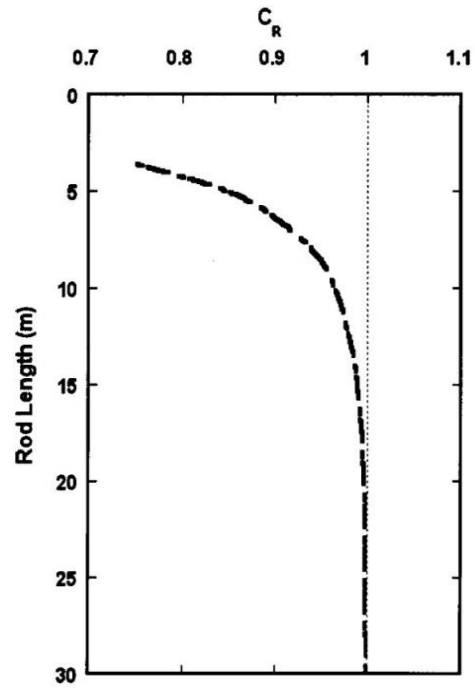


Figure 2-4: “Figure 9” Referred to in Table 2-1 Showing the Short-Rod Correction Factor C_R Recommended by Cetin et al. (2003)

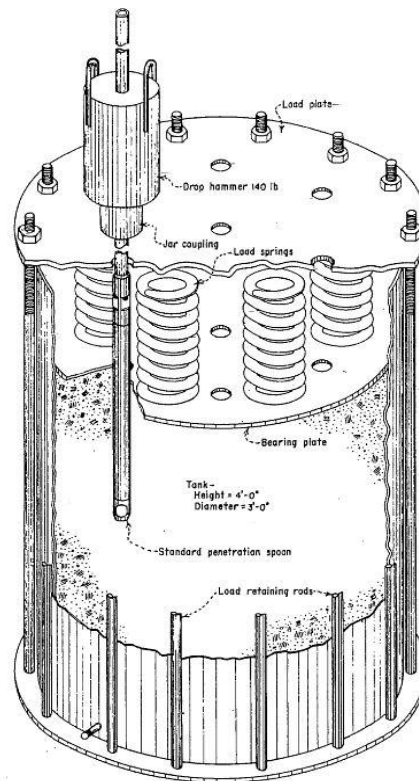


Figure 2-5: Schematic Illustration of the Test Chamber of Gibbs and Holtz
(from Gibbs and Holtz, 1957)

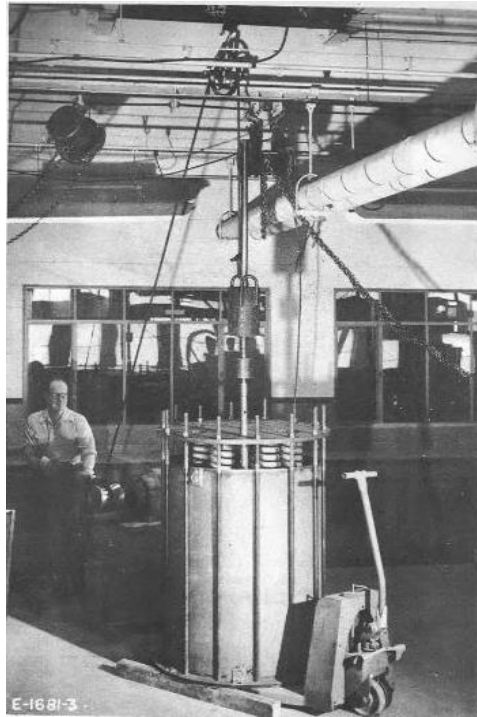


Figure 2-6: Photographs of the Test Chamber of Gibbs and Holtz
(from Gibbs and Holtz, 1957)

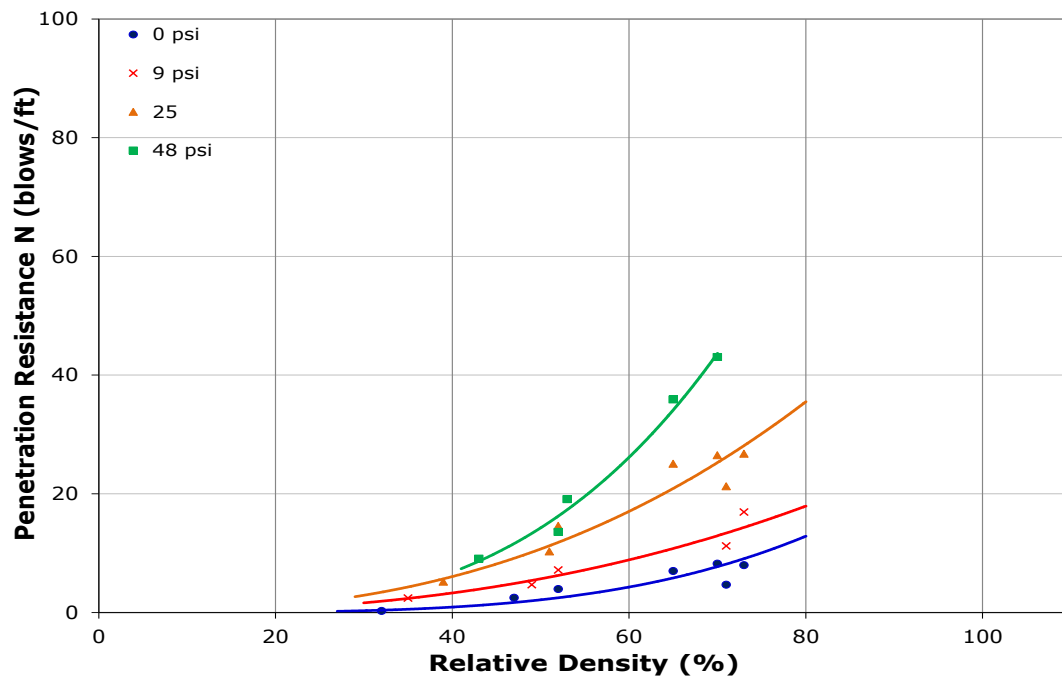


Figure 2-7(a): Results of Penetration Tests for Fine Sand (Re-Plotted from Gibbs and Holtz, 1957)

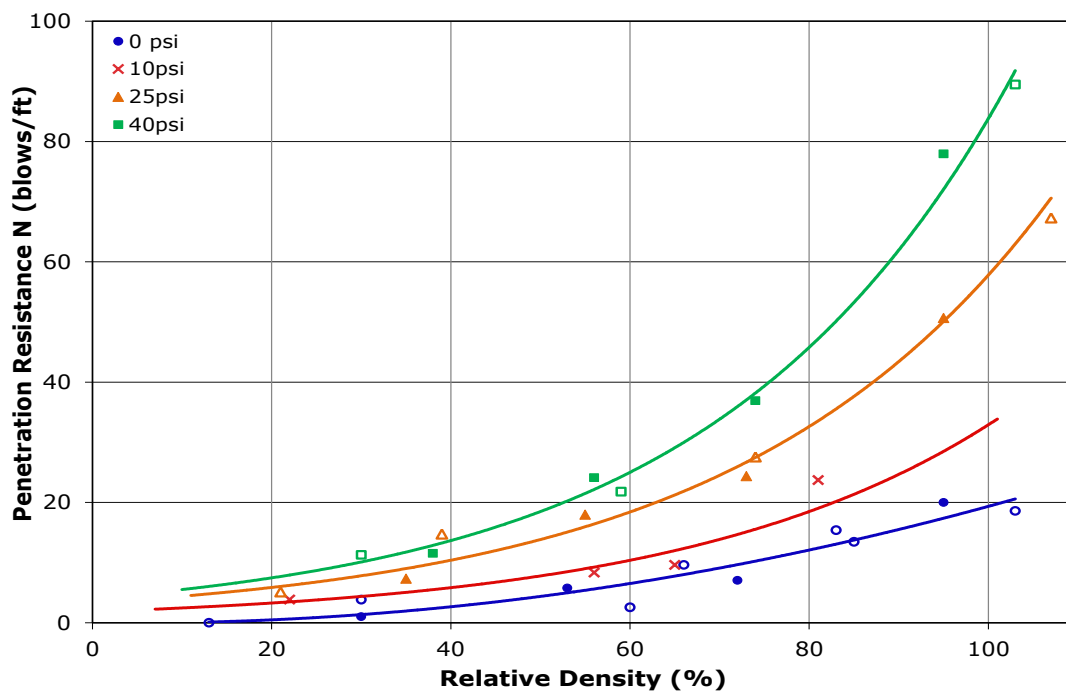


Figure 2-7(b): Results of Penetration Tests for Coarse Sand (Re-Plotted from Gibbs and Holtz, 1957)

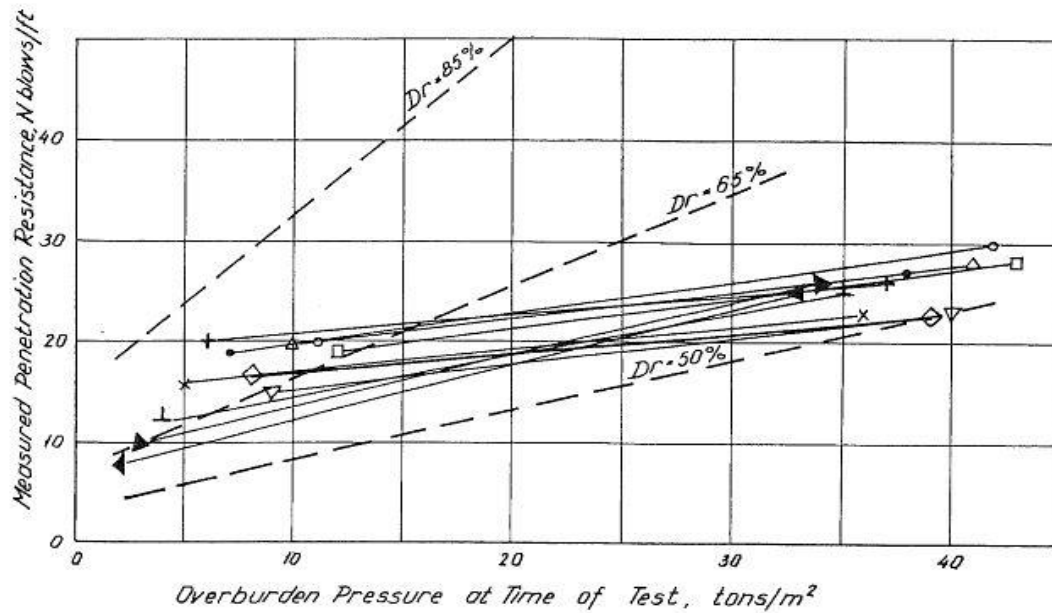


Figure 2-8: Measured Penetration Resistances both Before and After Excavation
(from Zolkov and Wiseman, 1965)

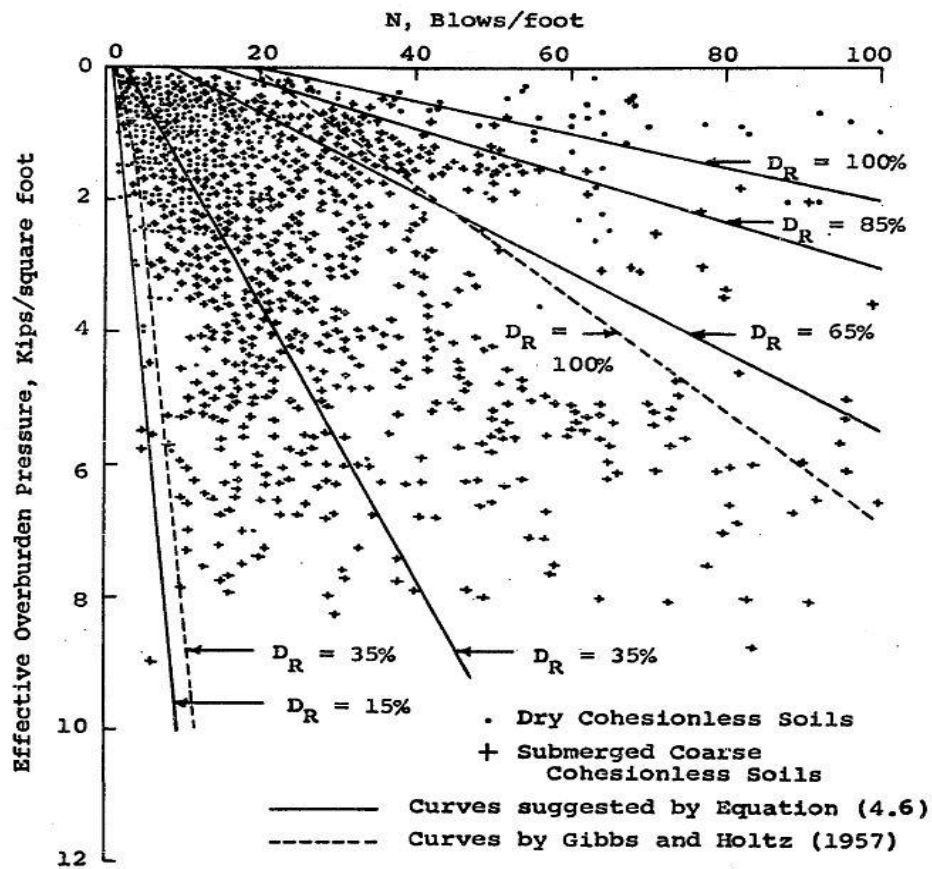


Figure 2-9: SPT Field Data Compiled by Bazaraa (1967)

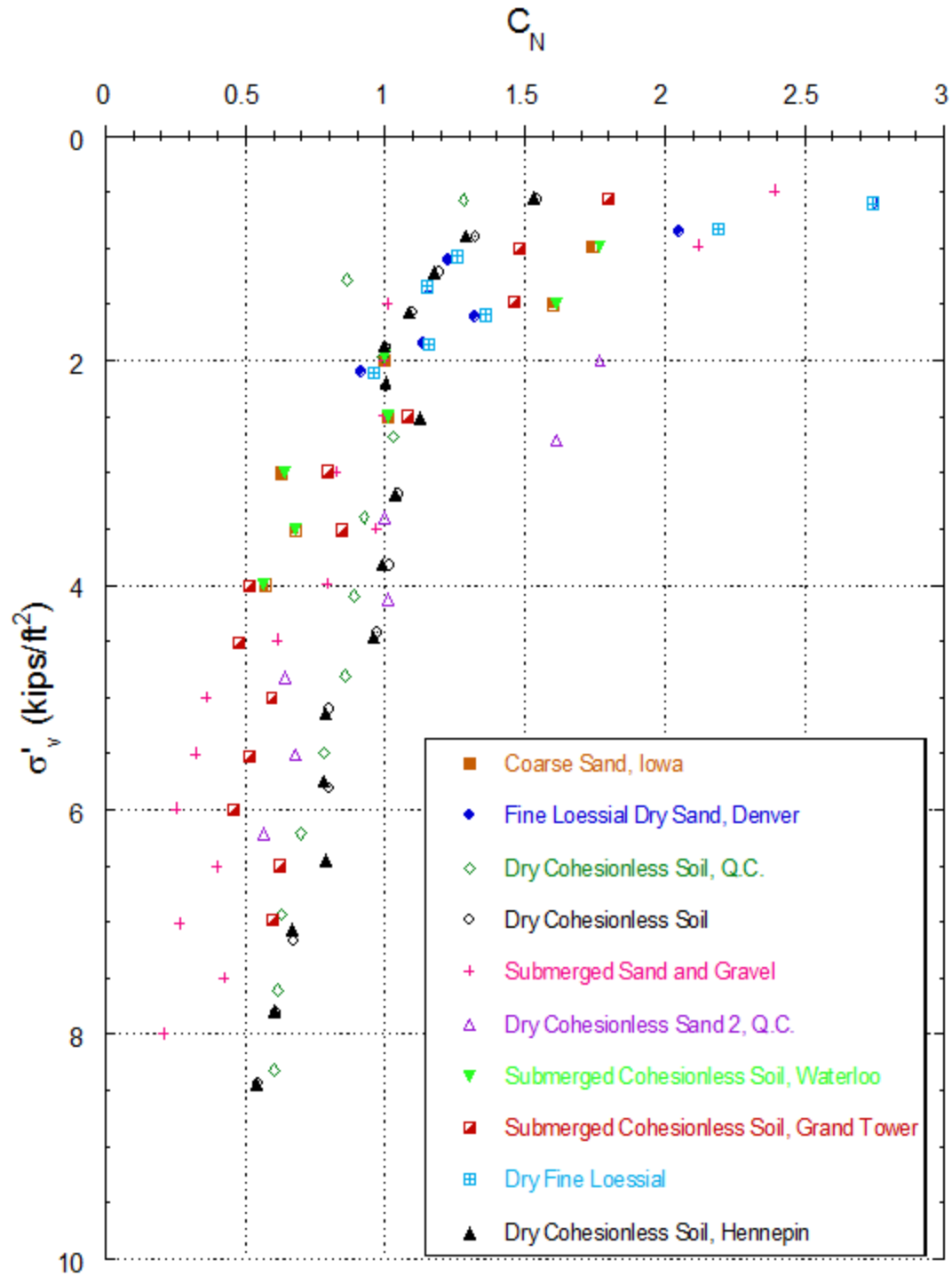


Figure 2-10: Overburden Correction Factor C_N , Back-Calculated from the In Situ Data of Bazaraa (1967) Normalized to a Reference Effective Vertical Stress of 1 ton/ft²

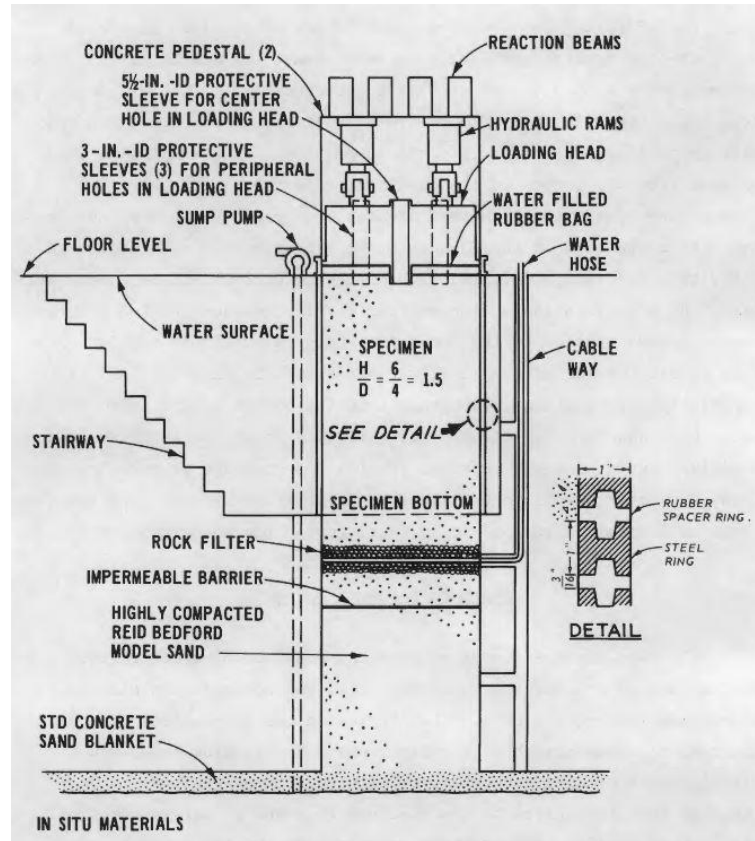


Figure 2-11: Sectional View of Test Chamber of Marcuson and Biegansky
(from Marcuson and Biegansky, 1977a)

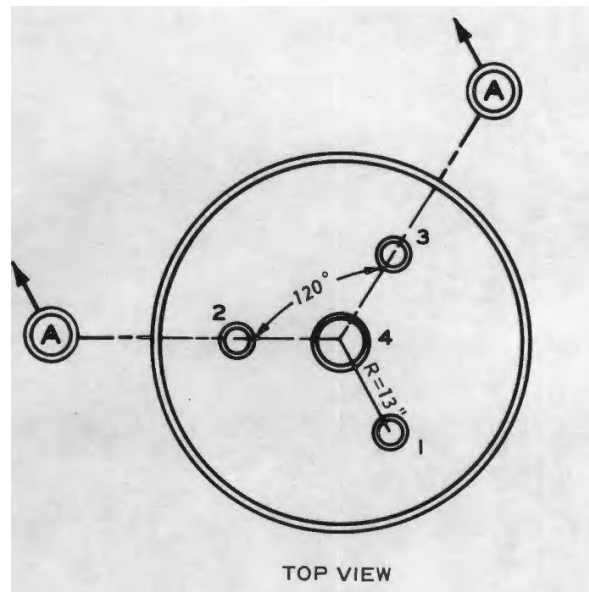


Figure 2-12: Plan View of Top Loading Plate of the Test Chamber Showing
Locations of Access Ports for Performing SPT Within the
Chamber (from Marcuson and Biegansky, 1977)

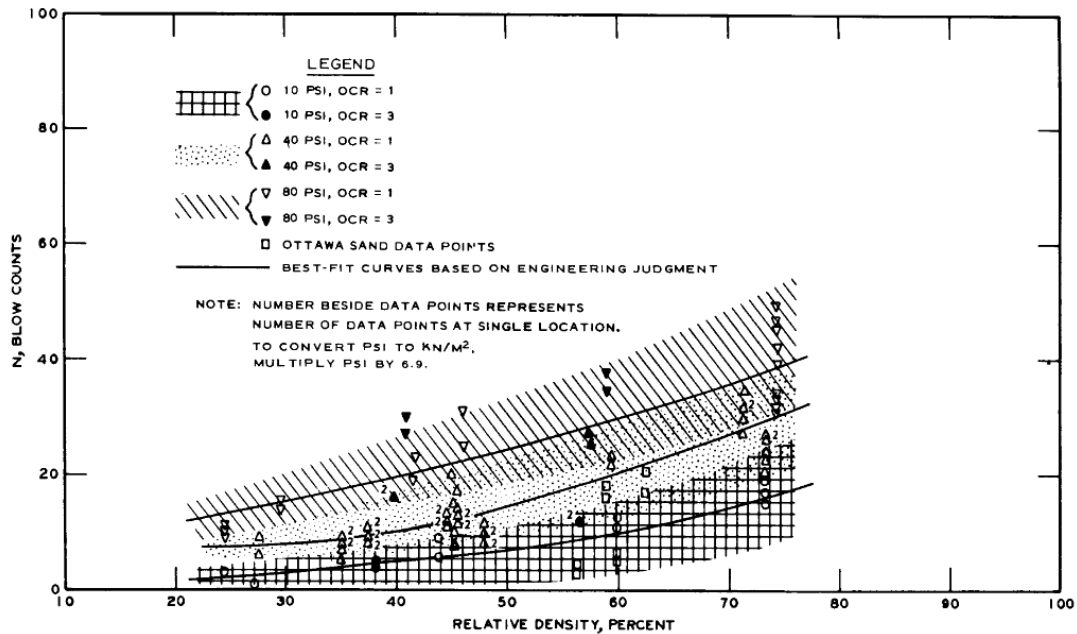


Figure 2-13(a): Results of WES Laboratory Standard Penetration Tests at Three Overburden Pressures for Two Fine Sands (from Marcuson and Biegansky, 1977a)

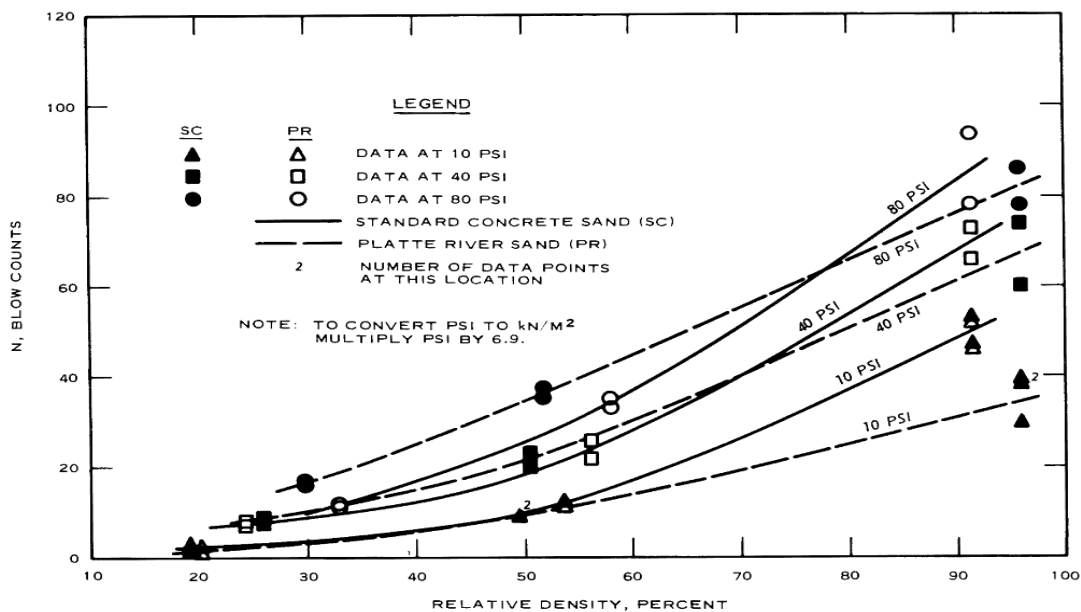


Figure 2-13(b): Results of WES Laboratory Standard Penetration Tests at Three Overburden Pressures for Two Coarse Sands (from Marcuson and Biegansky, 1977b)

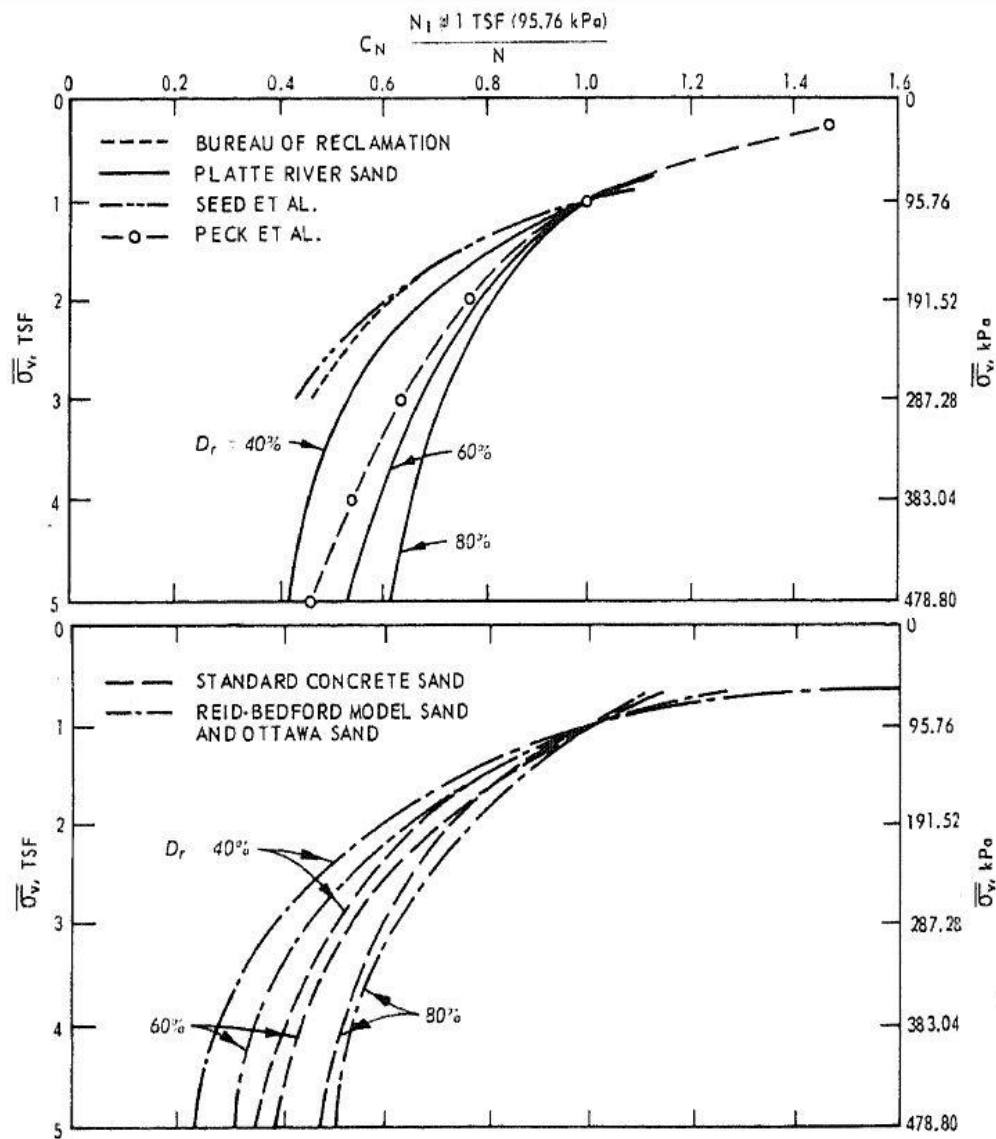


Figure 2-14: C_N Recommendations of Marcuson and Bieganousky (1977b)

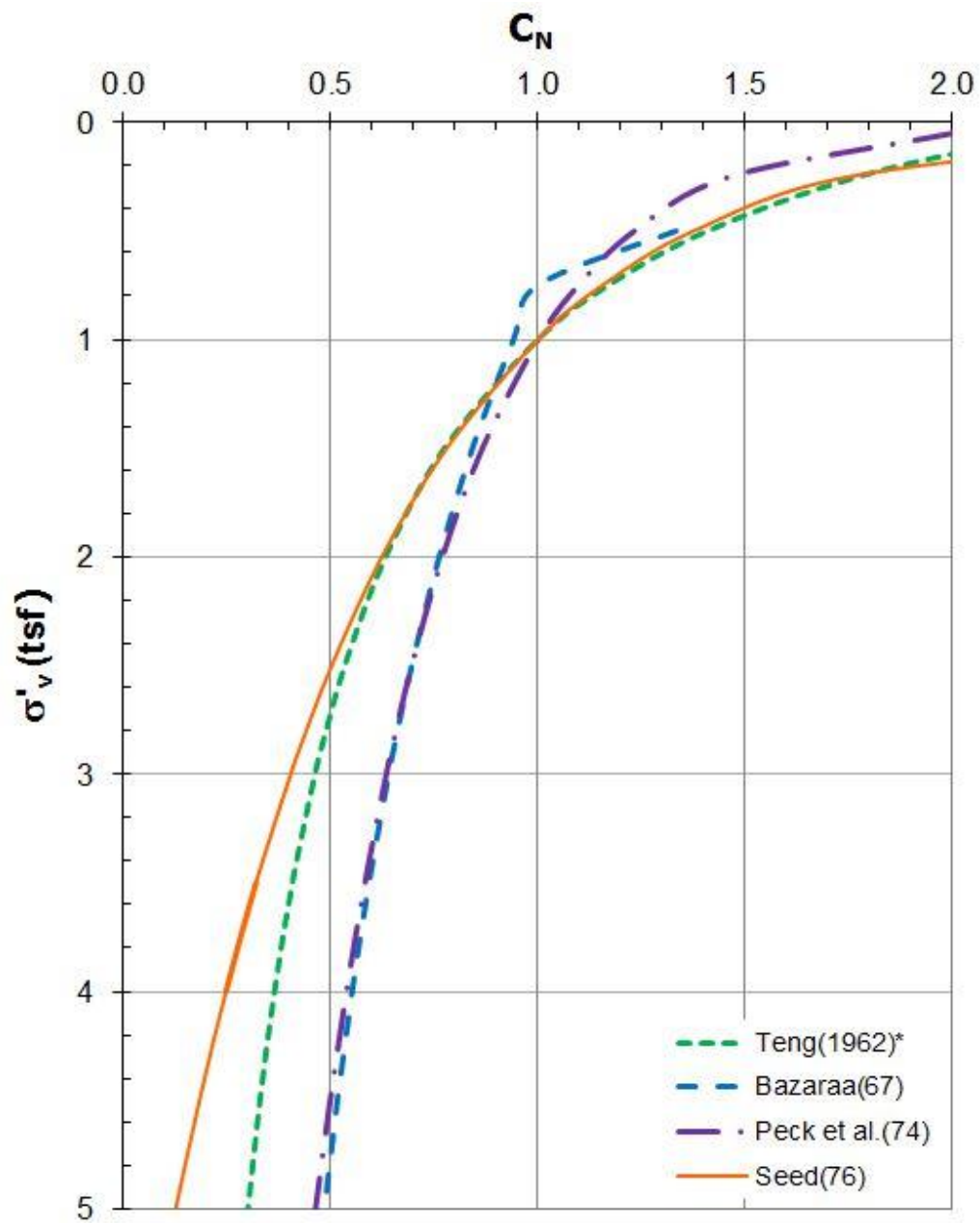


Figure 2-15: Early C_N Relationships of Teng (1962), Bazaraa (1967), Peck et al. (1974) and Seed (1976)

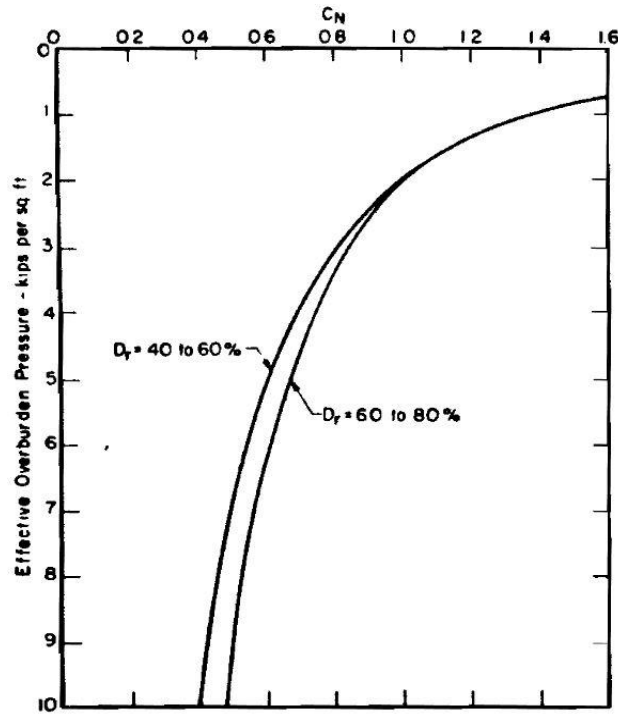


Figure 2-16: Recommended C_N Relationship of Seed (1979) Based on WES Data

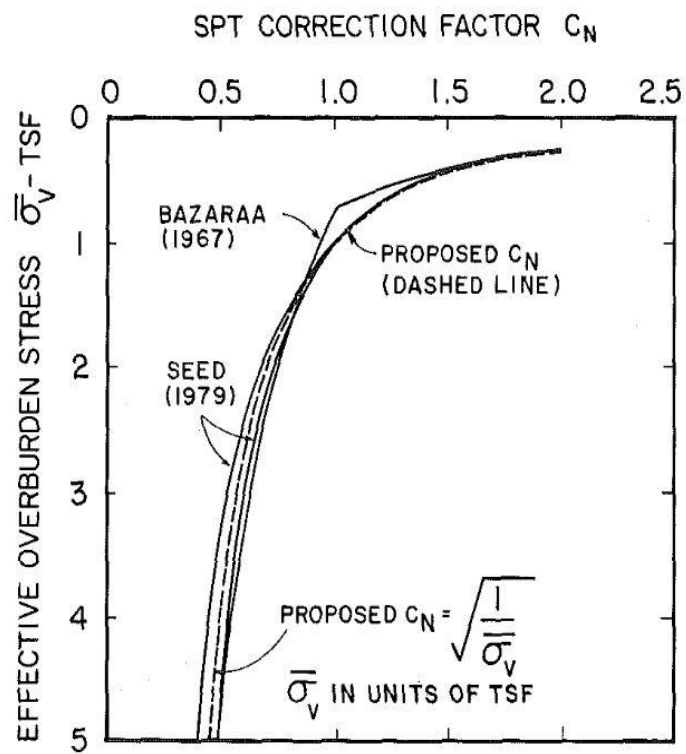


Figure 2-17: Recommended C_N Relationship of Whitman and Liao (1986)

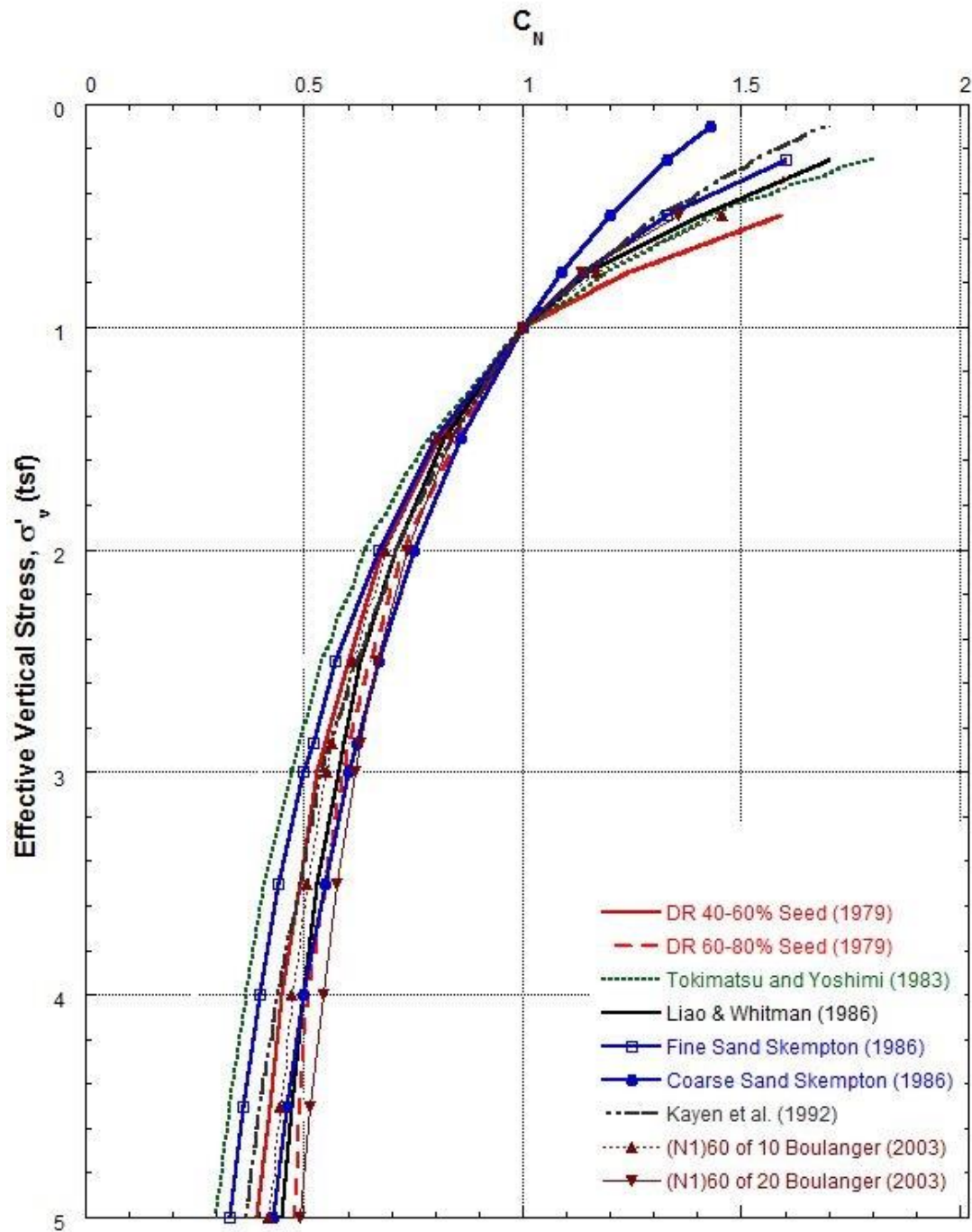


Figure 2-18: Comparison of Post-1977 Published C_N Relationships with Reference Stress Level of 1 tsf ($\approx 1\text{atm}$)

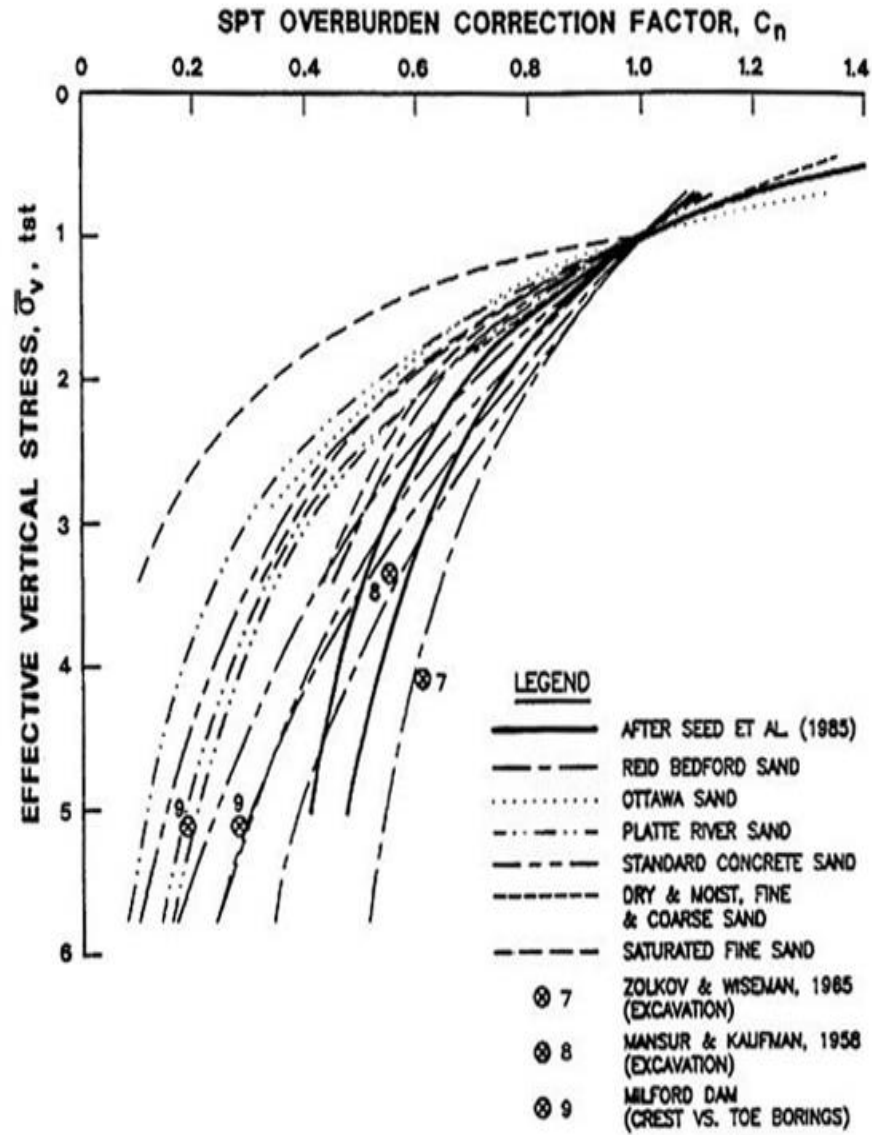


Figure 2-19: Variation of SPT Overburden Correction Factor, C_N for Various Sands (from Castro, 1995)

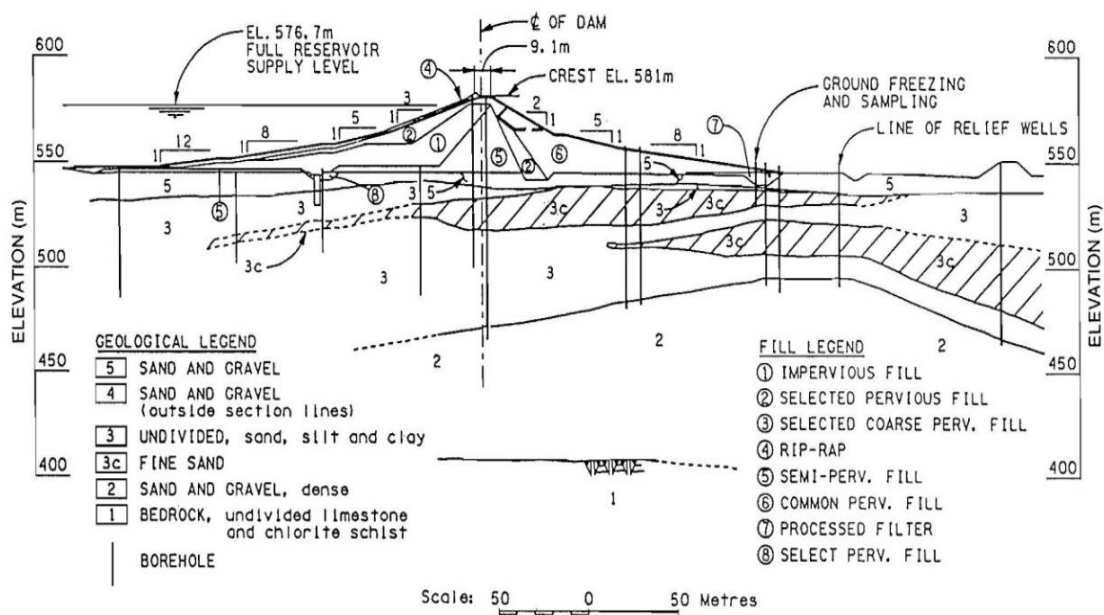


Figure 2-20: Typical Cross-Section of Duncan Dam (from Pillai and Stewart, 1994)

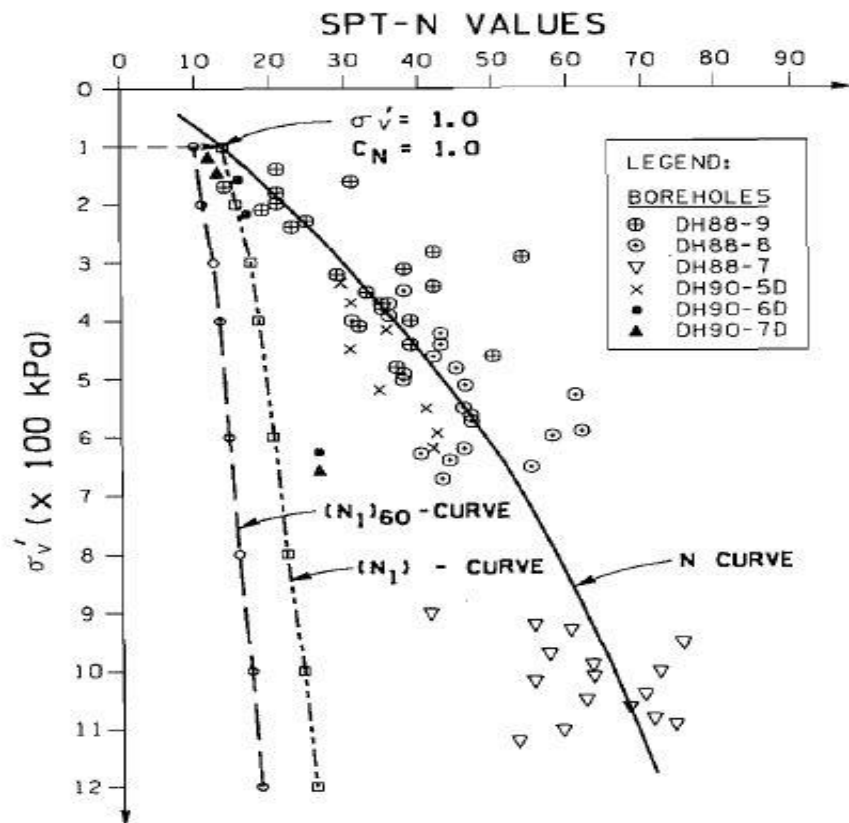


Figure 2-21: SPT-N and $(N_1)_{60}$ Values vs. Effective Vertical Overburden Stress for Unit 3c Sand at Duncan Dam (from Pillai and Stewart, 1994)

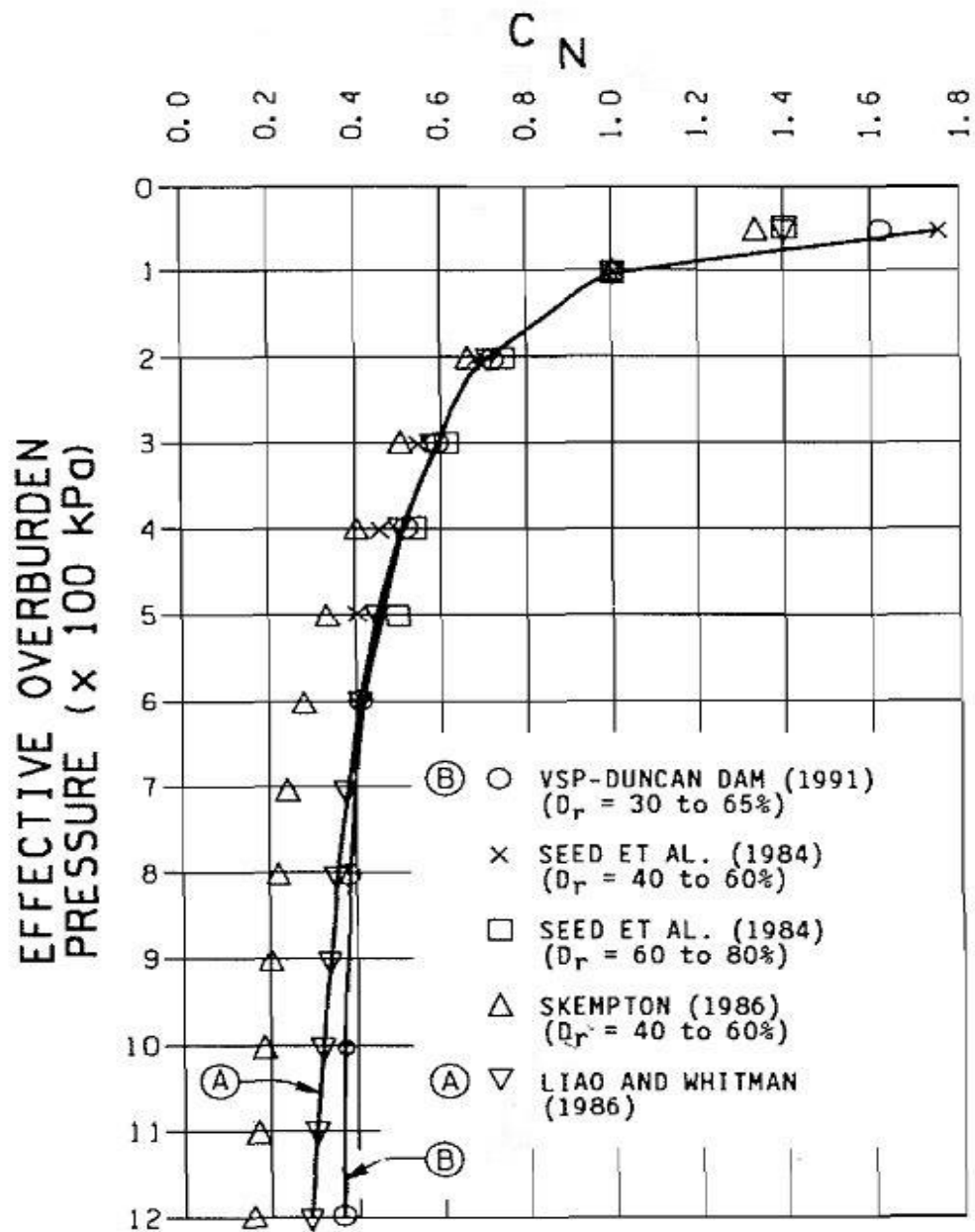


Figure 2-22: Duncan Dam Back-Calculated Relationship Between C_N and σ'_v
(from Pillai and Stewart, 1994)

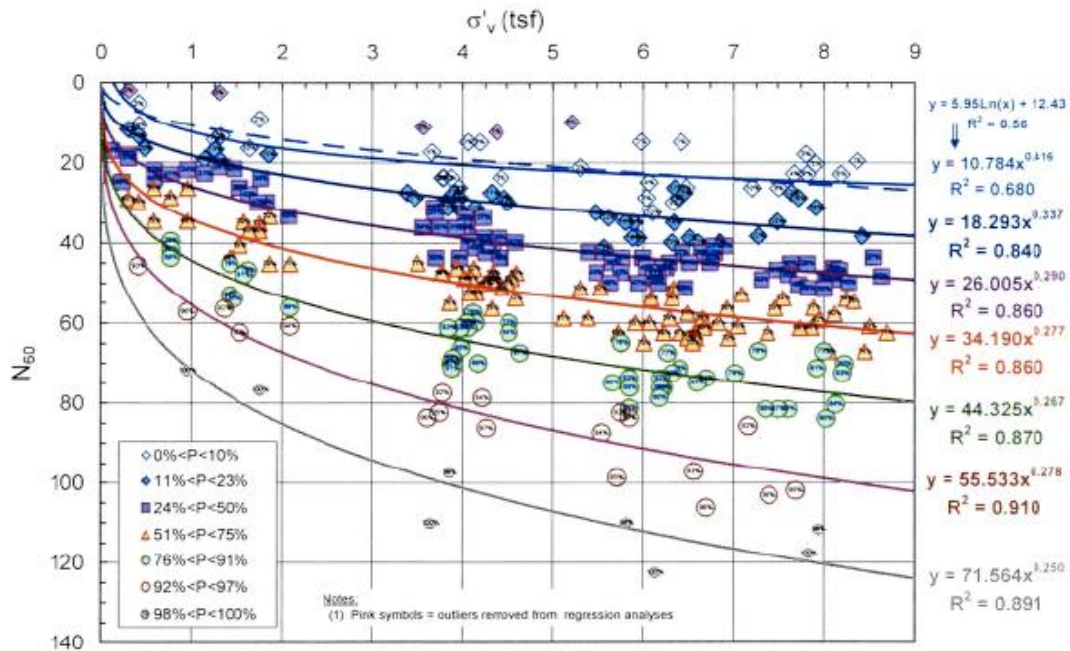


Figure 2-23: N_{60} vs. σ'_v and Regression on Percentile Bins for Perris Dam
(from Wehling and Rennie, 2008)

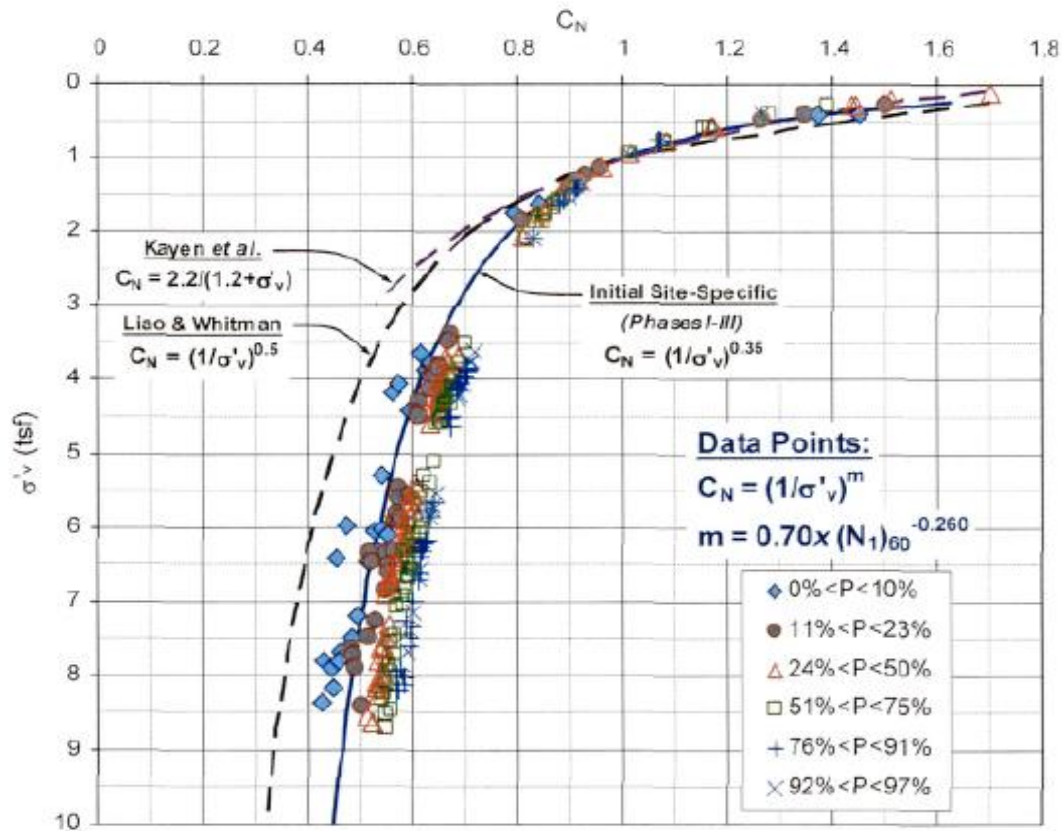


Figure 2-24: Site-Specific C_N vs. Effective Stress for Perris Dam (from CDWR, 2005)

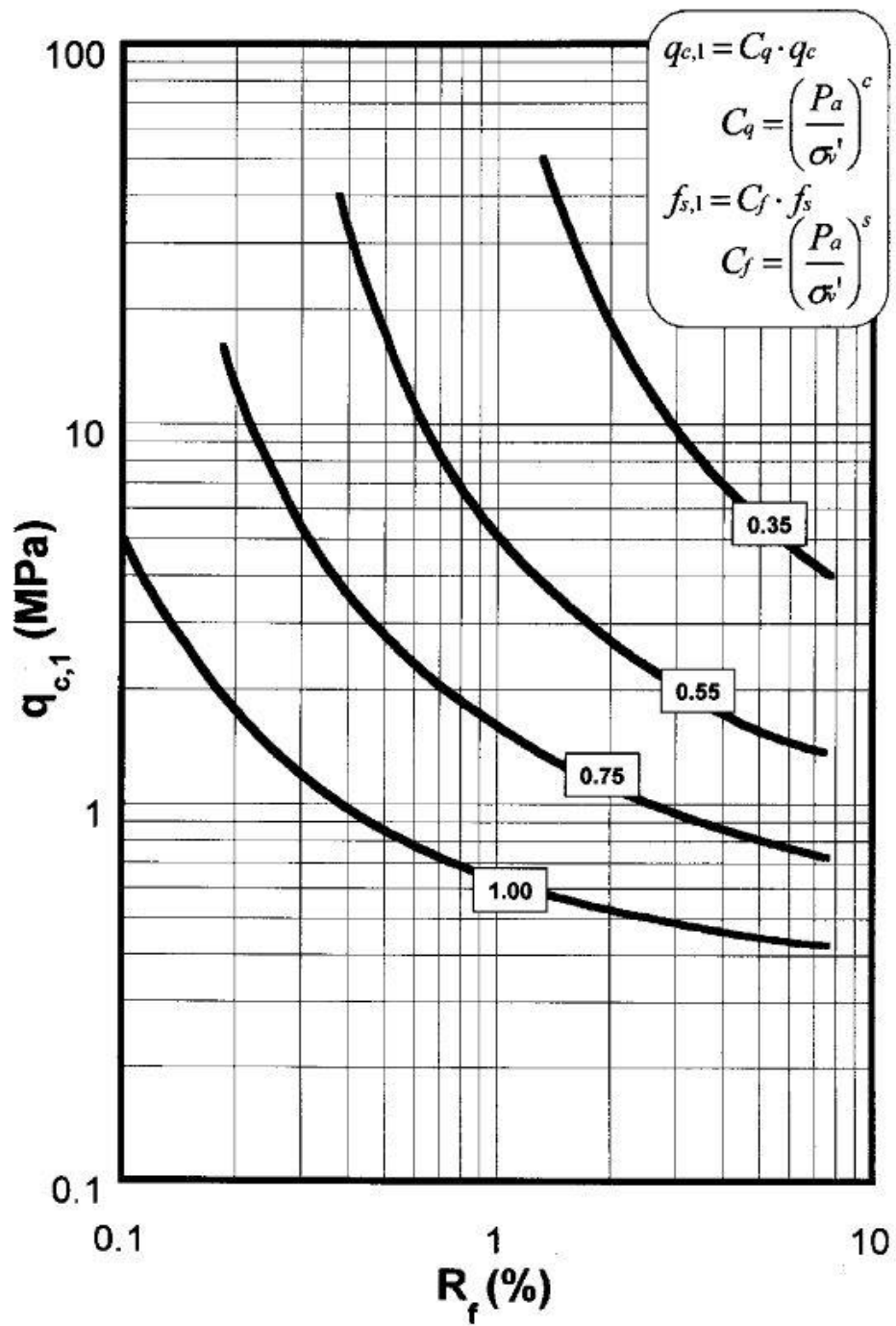


Figure 2-25: CPT Cone Tip and Cone Sleeve Normalization Coefficients Recommended by Moss et al. (2006)

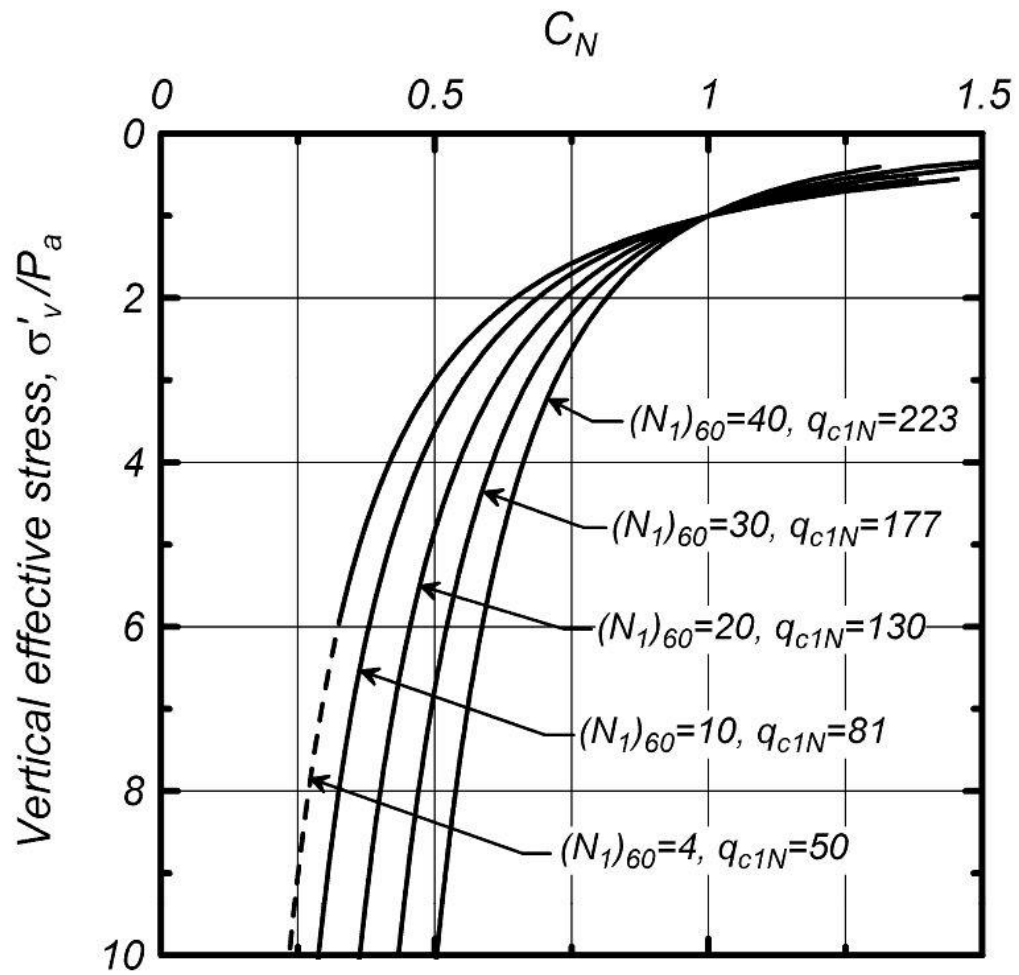


Figure 2-26: Effective Overburden Correction Factors C_N Recommended by Idriss and Boulanger (2008) for Normalization of Both SPT N-Values and CPT Cone Tip Resistance (q_c)

CHAPTER 3

RE-EVALUATION OF OVERBURDEN CORRECTION FOR CLEAN SANDS

3.1 Introduction

The large-scale laboratory chamber tests conducted at the U.S. Army Corps of Engineers Waterways Experiment Station (WES) by Marcuson and Bieganousky (1977a, b) were briefly discussed previously in Chapter 2 of this thesis. These data, for four clean sands, are the principal basis for many of the current C_N relationships in common use. Re-evaluation of this important data set is thus warranted as the first step in developing a baseline for C_N relationships for clean sands.

3.2 Characteristics of the Sands Tested

Laboratory tests were conducted in two phases on four different sands in order to evaluate the effects of particle size, gradation and angularity on penetration resistance. Grain size distributions of the four sands tested are shown in Figure 3-1. Phase I consisted of testing of two fine sands; Reid Bedford Model Sand (RBMS) and Ottawa Sand (OS). RBMS and OS are poorly graded (uniformly graded), clean, fine sands with median particle sizes (D_{50}) of 0.25mm and 0.21 mm, respectively. RBMS is characterized as subangular to subrounded, while OS is classified as subrounded to rounded. Phase II consisted of testing of two coarse sands; Platte River Sand (PRS), and Standard Concrete Sand (SCS). PRS and SCS are poorly graded, clean, coarse sands with median particle sizes of 2mm and 0.5mm, respectively. PRS is classified as subrounded, while SCS is classified as subrounded to well rounded.

3.3 Testing Procedures

Samples 4 feet in diameter by 6 feet high were fabricated to various relative densities in the large calibration chamber, and SPT were performed at three effective overburden stress levels (0.72 tsf, 2.88 tsf, and 5.76 tsf) on samples of each type of sand, except Ottawa sand (OS) which was only tested at only two overburden stress levels. Consequently, OS was not included in this reevaluation since the range of overburden stress levels was not wide enough to develop overburden correction curves. Samples were fabricated by dry pluviation, and vibration was then used to create the desired initial relative density of each specimen.

Specimens were placed using three different preparation methods. RBMS specimens were constructed by pluviation using either a rotating rainer or a stationary circular rainer, while most of the rest of the samples (of the other sands) were placed using the rotating rainer. Test results associated with the circular rainer are not included in these current re-analyses because there are not enough tests to reliably develop overburden correction curves based only on samples prepared with the circular rainer. It was decided not to analyze and

regress RBMS circular rainer data jointly with the rotating rainer data because different preparation methods might be expected to lead to variations in N-values at the same relative density due to fabric effects. PRS and SCS samples were all prepared using the single hose rotating rainer.

Testing was performed using a split spoon SPT sampler that conformed to ASTM D1586-67, however no interior liner was used. N-weight drill rod was used for all tests, and the length of drill rod varied between 5 to 11 feet. The split spoon sampler was driven by a hydraulically operated 140-lb trip automatic hammer lifted to 30 inch drop height. The rate of driving was approximately 15 blows per minute (Bieganousky and Marcuson 1976, 1977). Schmertmann later measured hammer energy for the WES hammer, and it was reported as averaging 83 percent of the theoretical free fall energy of 350 feet-pounds (Skempton, 1986).

3.4 Re-Evaluation of the WES Data

The data set employed in this re-evaluation consists of SPT conducted on specimens of three of the test sands. A majority of the tests were performed on normally consolidated specimens, but two RBMS specimens were overconsolidated to $OCR = 3$ to test the effects of overconsolidation. Because the specimens were laboratory fabricated, relative density and overburden pressure are the principal variants that affected the penetration resistances of the individual samples, and the influence of overburden pressure on SPT N values can be clearly deduced from the compiled data.

The approach taken with regard to analysis of these data was to compile SPT data from each specimen that was tested at all three overburden pressure levels into separate specimen-specific bins, and then to evaluate how penetration resistance varied over a range of effective overburden pressures for each specimen. Although every SCS and PRS specimen was tested at three effective overburden stress levels, some of the RBMS specimens were only penetrated at one or two overburden pressure levels. This re-evaluation will only utilize data for specimens that were tested at all three overburden pressure levels. The sole exception for that is the “dense” bin of RBMS sand because there is not one single dense RBMS specimen that was tested at all three applied overburden pressure levels, so it was necessary to combine data from multiple specimens for this sand. SPT data for RBMS were compiled from three different specimens of consistent relative density, each of which was tested at one of the three pressure levels, and they are grouped into one single bin. The data employed in this re-evaluation, and the bins used, are shown in Tables 3-1 to 3-3 for RBMS, PRS and SCS.

Raw SPT N-values were plotted versus effective overburden pressure, as shown in Figure 3-2, for all three sands. SPT N-values can be seen to increase with increasing overburden pressure, and the relationships between N-values and overburden stress can be empirically derived by regressing the data over the range of applied overburden pressure using the relatively straightforward method of non-linear least squares regression. Because a non-linear power function form was chosen to describe the data, the nonlinear least square method was preferred instead of the linear least square method for regression. Both methods

were actually employed, and the differences between linear and nonlinear regression were found to be within small (and reasonable) ranges except for two of the “loose” bins. Linear least square regression was found to be more sensitive to outliers, and loose specimens were found to be less stable for regression because of their low N-values, because even small changes in these N-values lead to significant percentage change.

The influence of effective overburden pressure on SPT N-values can be expressed in terms of regressed power function stress exponents (m) for each of the bins. The overburden correction factor is the ratio of N_1 (hypothetical SPT N-value that would have been measured if the effective overburden pressure at the depth of SPT had been equal to either 1 atm or 1tsf) to the SPT-N value actually measured at any depth, as in Equation 3.1 below. If a general form of power function is used, the overburden correction factor C_N can be taken as;

$$C_N = \frac{N_1}{N} = \left(\frac{1}{\sigma'_v} \right)^m \quad \text{where } \sigma'_v \text{ is in tsf or atm.} \quad \text{Equation 3.1}$$

as suggested by Liao and Whitman (1986) and Boulanger (2003).

By inverting this, the N-value (and the energy, equipment and procedurally corrected N_{60} -value) can be expressed as

$$N = N_1 \cdot (\sigma'_v)^m \quad \text{Equation 3.2.a}$$

$$N_{60} = N_{1,60} \cdot (\sigma'_v)^m \quad \text{Equation 3.2.b}$$

These forms of relationships can then be used to regress the large-scale calibration test data to develop estimates of the power function exponent m as a function of either N_1 or $N_{1,60}$, as shown in Figures 3-2 and 3-3 for raw (uncorrected) N-values, and for corrected N_{60} values, respectively.

As shown in these two figures, the data was found to be well described by the nonlinear power functions with coefficients of determination, R^2 , ranging from 88 percent to 99 percent for the various sands and density bins.

Adjustment of raw N-values to develop corrected N_{60} -values in Figure 3-2 required the application of several corrections. Rod lengths varied from 5 to 11 feet, and the efficiency of the automatic hammer was measured as 83 percent. A rod length correction of $C_R = 0.75$, and a hammer energy correction factor of $C_E = 1.38$, were applied to the N-values measured. A sampler correction was also required because no liner was used. Accordingly every bin was assigned with a sampler correction of 1.1 to 1.3 (Cetin et al., 2004) based on the relative density of specimens within the bin. The corrections used, and the resulting N_{60} values, are presented in Tables 3-1 through Table 3-3. The effects of these corrections for variations in SPT equipment and procedures are not a significant factor in the determination of m values for these data because the equipment and procedures were internally self-consistent within the testing program, so that N-values within each bin were affected by these corrections in largely the same manner. All N-values within a particular bin were multiplied

by the same correction factors, and m remained the same. However, the application of these correction factors is necessary to accurately determine the $N_{1,60}$ values associated with each of the bins, and thus the $N_{1,60}$ -values associated with each of the m values.

Based on the results of nonlinear least square regression with no constraints, m values could be regressed directly, and the results are shown in Figures 3-2 and 3-3. Figures 3-4(a) and 3-4(b) show the variation of the overburden correction exponent m versus N_1 , and $N_{1,60}$, respectively. As shown in these figures, m is not constant; it varies from sand to sand, and it also varies with density for each of the sands tested. The back-calculated m values range from 1 to 0.27, as N_1 -values progressively increase from 2.8 to 53.6 blows/ft, and as $N_{1,60}$ values progressively increase from 3.2 to 72.1 blows/ft.

It can be observed that m values decrease with increasing $N_{1,60}$, and thus with increasing relative density. This agrees in general with the conclusions of Marcuson and Bieganousky (1977b), and with other previous re-evaluations of the WES study (e.g.: Seed et al., 1979; and Boulanger, 2003). These regressions performed for these current studies differ a bit from the recommendations of Seed (1979), and are in closer agreement with the recommendations of Boulanger (2003).

There is a systematic relationship between m and either $N_{1,60}$ or N_1 , and an additional regression was performed to develop a correlation representing this relationship. The relationship between m and normalized penetration resistance was found, based on nonlinear least squares regression, to be well modelled in the form of an exponential decay function, as shown in Figures 3-4(a) and (b). Regression over the available ranges of data led to the overburden pressure exponent relationships presented in Equations 3.3a and 3.3b. These relationships are then jointly plotted with the data in Figures 3-4(a) and 3-4(b), respectively. As shown in Figures 3-4(a) and 3-4(b), and by the R^2 values of the regressions for Equations 3.3a and 3.3b, these regressed correlations well explain the data, with R^2 values of 87 to 88 percent. According to these equations, the relationship between effective overburden pressure and penetration resistance is close to linear (m values nearly equal to 1.0) at very low relative density, and m gradually decreases with increasing relative density and converges to $m \approx 0.31$ at high relative density.

$$m = 0.30 + 0.74 \cdot e^{(-0.081 \cdot N_1)} \quad \text{with } R^2 = 0.87 \quad \text{Equation 3.3.a}$$

$$m = 0.31 + 0.71 \cdot e^{(-0.068 \cdot N_{1,60})} \quad \text{with } R^2 = 0.88 \quad \text{Equation 3.3.b}$$

3.5 Densification Adjustments for SPT N-Values

A majority of the specimens fabricated by Marcuson and Bieganousky were tested at three different overburden pressures in order to obtain the maximum amount of useful data from each of these very large specimens. Specimens were placed at specifically targeted initial densities, but the subsequent applications of overburden pressure caused densification of specimens, resulting in changes in these relative densities. Marcuson and Bieganousky

(1977a, b) performed one-dimensional consolidation tests to estimate the influence of densification, and corrected the relative densities reported for these effects of densification.

For this current re-evaluation, it was decided to examine the likely effects of this progressive densification on C_N relationships as increased overburden stresses were applied.

It was assumed in the previous section (Section 3.4) that a particular specimen that was tested at three different stress levels had consistent relative density during the performance of SPT at all of these three overburden pressures. Consequently, each specimen bin was also considered as having the same average or representative relative density throughout. If there was not any densification, this would have been correct. However, any densification of specimens due to increased applied overburden pressure will cause some resulting increase in relative density, and SPT N-values obtained at higher applied effective overburden pressures would correspond to higher relative densities. For example, let us consider loose specimen bins. The loose RBMS specimen was initially placed at a relative density $D_R = 18.3$ percent. Then an effective overburden pressure of 0.72 tsf was applied, which increased the relative density of the specimen to 24.3 percent, and SPT were performed at this density level. Then the applied effective overburden pressure was increased to 2.88 tsf, and the relative density of the specimen increased from 24.3 to 27.8 percent. Again SPT were performed. Then, the relative density again increased, this time to $D_R = 29.5$ percent, after the final effective overburden pressure of 5.76 tsf was applied.

Similar trends were observed in the loose and medium dense specimens of SCS and PRS. The relative density of the loose SCS specimen increased in three increments of increasing applied effective overburden stress from $D_R = 20.1$ percent at $\sigma'_v = 0.72$ tsf, to $D_R = 29.7$ percent at $\sigma'_v = 2.88$ tsf. This is a potentially significant increase in relative density for this case of a very loose specimen. Consequently, the m value regressed ignoring this densification will reflect the compound effects of both densification and overburden pressure increases, instead of solely the effect of increased overburden pressure. It is thus important to examine whether this may unacceptably damage the C_N (and exponent m) relationships developed.

To assess the influence of densification on m values, the influence of densification on SPT N-values needed to be accounted for by first adjusting the N-values for densification effects, and then using the adjusted N values to perform regressions over the available range of applied effective overburden pressures to develop new m values based on density-adjusted penetration resistances.

The density adjustment employed herein to approximately adjust (or “correct”) the N-values for minor densification effects is based on empirical relationships for estimation of N as a combined function of (1) D_R and (2) effective overburden pressure. Skempton (1986) had developed these types of relationships for these specific materials (RBMS, PRS and SCS), and these are shown in Figures 3-5, 3-6 and 3-7, respectively. Changes in relative density due to applied overburden pressure had been already quantified by Marcuson and Biegounosky (1977a, b) based on one-dimensional consolidation test data. Then, the

resulting changes in N-value (ΔN) can be inferred for an incremental relative density change (ΔD_R). Figures 3-5 through 3-7 illustrate density adjustment for SPT N-values for RBMS, PRS, and SCS, respectively. For each specimen bin, a middle relative density (at the middle of the three applied effective stresses) was chosen as the “pivotal” (or representative) relative density, and then adjustments ΔN were determined for SPT N-values obtained in looser and denser states of the same specimen. ΔN is literally the difference between the hypothetical N-value (the density adjusted N-value) that would have been measured if relative density had been equal to the pivotal relative density during SPT) and the actual N-value obtained during the test at the actual relative density tested.

The resulting density adjusted SPT N values (N_{DA}) are presented in Tables 3-1 to 3-3 for RBMS, SCS and PRS. Adjustments range from $\Delta N = -3.4$ blows/ft to $\Delta N = +2.0$ blows/ft. These density adjustments in penetration resistance are dependent upon both relative density and overburden stress. For loose specimens, which are more highly compressible, the same amount of relative density change leads to higher proportional penetration resistance adjustment (relative to the unadjusted N-value) than for denser samples. Denser specimens were found to undergo relatively minor densification with increases in effective stress, and these produced (proportionally) relatively minor adjustments in N-values. Interested readers can refer Appendix A for more details of these density adjustment calculations.

The influence of effective overburden pressure on density adjusted SPT N-values can now be quantified in terms of the power function stress exponent “m” for each bin, once again using the same procedures and regression techniques that were used for non-adjusted N-values in Section 3.4. The resulting regressed relationships between density adjusted SPT N_{DA} values, and SPT $N_{60,DA}$ values, versus applied overburden pressure are shown in Figures 3-8 and 3-9, respectively, for RBMS, PRS and SCS. Resulting overburden stress exponents m obtained from nonlinear regressions are shown for both cases in Figures 3-10(a) and (b). The relationship between m and penetration resistance was again defined in the form of an exponential decay function based on nonlinear least squares regression. Regression over the ranges of $N_{1,DA}$ and $N_{1,60,DA}$ led to the overburden pressure exponent relationships shown in Figure 3-10, and these are given in Equations 3.4.a and 3.4b.

$$m = 0.30 + 0.60 \cdot e^{(-0.077 \cdot N_1)} \quad \text{Equation 3.4a}$$

$$m = 0.30 + 0.58 \cdot e^{(-0.066 \cdot N_{1,60})} \quad \text{Equation 3.4b}$$

R^2 values were equal to 0.91 for both equations.

Overburden correction factor exponents m based on the adjusted SPT N_{DA} or $N_{60,DA}$ are slightly smaller than the overburden correction factor exponent m based on SPT N or SPT N_{60} values. As applied effective vertical stress increased, the specimens became a bit denser. Any measured increases in SPT N values were thus compound effects of (1) increase in applied overburden pressure, and (2) increase in relative density. Ignoring of densification effects will incorrectly associate all of the increase in SPT N-values with increased overburden pressure, and this results in some overestimation of m values.

Consequently, these nonlinear regressions based on density adjusted SPT $N_{60,DA}$ were judged to be closer to the true m values for this overall data set.

Density adjustment led to one unreasonable m value in the loosest specimen of PRS, and this had to be excluded as an outlier. The first bin (loosest) of PRS was relatively more compressible compared to the loosest specimens of RBMS and SCS. Increases in the applied overburden pressure level caused larger increases in relative density, and this produced an m value of slightly greater than 1.0, which was judged to be physically unreasonable. This is likely due to the approximate nature of the density adjustment, and to the large “step” or increase in relative density applied for this specimen. It is also because this particular specimen, even without adjustment for densification effects, evidenced an m -value of approximately 1.0 (see Figure 3-4) at very low N .

Comparing Figures 3-4 vs. 3-10, it can be seen that there are negligible differences between the calculated m -values, except at very low N -values (where the one adjusted data point was omitted). These two sets of curves agree very closely except at m -values, and $N_{60,DA}$ values, of less than about 5 blows/ft, and in these very low penetration resistance ranges the moderate differences will not likely be significant for engineering applications.

Accordingly, it is concluded that for this data set, adjustment for the effects of minor increases in relative density as effective overburden stresses were incrementally increased had little significant impact on the resulting regressed C_N (and m) relationships.

3.6 Overconsolidation Effects on the Overburden Correction Factor Exponent

It has been recognized that overconsolidation ratio (OCR) appears to have an effect on the relationship between N -values and (1) relative density and (2) effective overburden stress. But there has been little data available with which to quantify these effects. It should be noted, however, that the fact that OCR affects the relationship between N -values and (1) relative density and (2) effective overburden stress, does not necessarily mean that OCR has a significant influence on C_N relationships if OCR is constant over the full depth of a soil unit or stratum of interest.

Marcuson and Bieganousky developed the most useful data that can help to address this question. Two of their specimens were prepared using RBMS at two different relative densities. These specimens were initially subjected to three times the intended eventual testing vertical effective stress pressure for one-half hour, and the applied pressure was then reduced back to the SPT testing pressure. This resulted in $OCR = 3.0$ for these specimens as SPT were performed. The SPT N -values obtained from these overconsolidated specimens are shown in Table 3.4. Using the same types of procedures discussed in Sections 3.4 and 3.5, and nonlinear least squares regression, the relationships between SPT N -values, and N_{60} -values, and effective overburden pressure were determined for specimens with $OCR = 3$ in the form of Equation 3.2. Figure 3-11 shows the results of the nonlinear regressions of N vs effective overburden stress, and of N_{60} vs. effective overburden stress for these overconsolidated specimens. Figures 3-12(a) and 3-12(b) then show the resulting m -values

calculated, and compares these overburden correction factor exponents from overconsolidated RBMS specimens (OCR of 3) with overburden correction factor exponents from normally consolidated RBMS specimens, and all normally consolidated specimens, respectively.

For the First Bin (lowest N -value), the m value for RBMS having OCR = 3 is perhaps a bit higher than the relationships developed based on normally consolidated specimens. The m value for Second RBMS Bin with OCR = 3 is just on the previous relationship developed based on normally consolidated specimens. Clearly these two data points are not sufficient to fully assess OCR effects on overburden correction factor exponents, but this does appear to show that the relationships developed between $N_{1,60}$ and m in this study for normally consolidated clean sands may also provide a potentially useful basis for overburden correction of moderately overconsolidated clean sands, within a useful range of engineering accuracy, at least for these two overconsolidated RBMS specimens.

3.7 Overburden Correction at Shallow Depths

The large-scale laboratory calibration chamber test SPT data set developed by Marcuson and Bieganousky provides good insight regarding overburden normalization for clean sands, but the data set is limited inasmuch as the smallest effective overburden stresses at which SPT were performed in their large-scale chamber was $\sigma'_v = 0.72$ atmospheres. As a result, their data set does not well serve to define C_N for very shallow SPT performed at depths wherein effective vertical stresses are less than about 0.7 atmospheres.

The previous C_N relationships discussed in Chapter 2 differ significantly in this shallow depth range, and this is an important range of (low) effective overburden stresses for normalization of SPT data for both (a) shallow foundation design and (b) back-analyses of soil liquefaction triggering field performance case histories for purposes of development of empirical triggering correlations.

One approach for dealing with this would be to simply extrapolate the power function relationships developed in Sections 3.5 and 3.6 to this lower effective stress range. Another approach would be to analyze field SPT data and to develop C_N -type relationships based on those field data.

As an interim step, the field data set of Bazaraa (1967) will be examined. This was an interesting early field data set, and it was discussed in Section 2.3.3. This field data set was a principal basis for the early C_N relationship proposed by Peck et al. (1974). Bazaraa collected field SPT data over varying depths for cohesionless soils at ten sites, and his data are presented in Figure 2-9. Figure 2-10 presented a summary re-plotting of those data in which the SPT data for each of these 10 soils within finite depth ranges were first averaged (for the specific soil), and then “normalized” so that the correction factor C_N for that soil would have a correction factor of 1.0 at an effective overburden stress of 1 ton/ft².

Figure 3-13 shows regression of these data to develop material-specific estimates of C_N relationships with the power function form of Equation 3.1. The resulting calculated m -values are plotted in Figure 3-14 (the red triangles), where they are compared with (a) m -values for clean sands developed based on the WES large-scale laboratory calibration chamber test data, (b) m -values for clean sands developed based on field data for dam foundation strata (see Chapter 4), and (c) m -values developed for silty soils (see Chapter 4). In both Figures 3-13 and 3-14, it can be seen that three of Bazaraa's soils exhibit C_N behavior unlike that of the other soils evaluated, inasmuch as they exhibit essentially linear normalization of SPT N -values vs. increasing effective vertical stress, and for $N_{1,60}$ values of approximately 20 to 22 blows/ft. This type of nearly linear normalization (with m approaching 1.0) would not be surprising for materials with very low N -values, but these three soils (indicated with a large "A" in Figure 3-14) all appear to have corrected N_1 -values of slightly greater than 20 blows/ft. One could hypothesize about densification with increasing depth due to periodic seismic activity, or ageing effects, or cementation, etc. for these in situ soils, but there is no clear indication that any of these would serve to explain this. Neglecting these three soils, however, the remaining seven soils exhibit similar C_N (and m) behaviors as the rest of the soils. Overall, this exercise illustrates the difficulties, but also the potential benefits, of attempting to garner insight as to C_N behavior at shallow depths based on field data.

Finally, Figure 3-15 shows the field SPT data for Bazaraa's ten soils, and a comparative plotting of the C_N relationships developed herein based on the m vs. $N_{1,60,CS}$ relationship for both clean sands and also silty sands and sandy silts (see Chapter 4) of Figure 4-37. This serves to help address the important question as to whether or not the C_N relationships continue to increase to very high C_N values at low effective stresses, or whether they should be "truncated" at some limiting maximum value of C_N . Based on these data, it appears that there is no physical limitation for C_N , but that truncation at some level may be warranted because SPT N -values may become unreliable at very shallow depths.

Finally, it is noted that Bazaraa's field data set is interesting, and that it was of some historic interest in the early development of C_N relationships, but that it is only one limited data set. There is ample room for more research effort here. Additional field SPT data could be collected and analyzed to shed further light on C_N at shallow depths.

3.8 Conclusions

Marcuson and Bieganousky (1977a, b) conducted large-scale laboratory calibration chamber tests with SPT performed at different stress levels on a total of thirty-two specimens built to various densities using clean sands with different grain size distributions. Of these thirty-two specimens, eleven specimens were found appropriate to evaluate in the format of this study. These represented three different sands. The influence of effective overburden pressure on SPT N -values was deduced for each specimen (at each particular relative density) by regressing N -values over the ranges of applied overburden pressures. A power function relationship was developed, based on effective overburden stress and a power exponent m . It was observed that the overburden correction factor exponent m depends on

relative density defined in terms of either N or $N_{1,60}$. An empirical relationship was proposed to model the correlation between $N_{1,60}$ and the effective overburden stress correction factor exponent m . This relationship appears to provide a suitable basis for making overburden corrections to SPT performed in relatively clean sands for many engineering purposes.

It was observed that the multi-stage testing procedures employed in these calibration chamber tests caused incremental densification of the specimens with each increase in applied effective overburden stress, thus producing some level of variation (increase) in relative density throughout the application of different overburden pressure levels. To assess the influence of this densification on m values, density adjustments for SPT N -values were developed and employed. Although overburden correction factor exponent m values obtained by neglecting this incremental densification are promising, they jointly reflect the compound effects of both densification and increasing overburden pressure, instead of separately reflecting only the effects of overburden pressure. As a result, the densification-corrected analysis (which more successfully isolates just the effective overburden stress effects) produces slightly lower m values with density adjusted SPT N_{DA} values. Differences are more pronounced for loose specimens. Overall, however, differences between density adjusted m values, and m values developed without accounting for density changes with increased applied effective overburden stress, are relatively minor except at very low N -values, and both appear to represent a suitable basis for making overburden corrections (overburden normalization) for SPT performed in clean sands for most engineering purposes.

Finally, it is important to emphasize that there are only a limited number of large-scale calibration chamber tests results, and that they are all limited to tests on laboratory-fabricated sand specimens. Although three different sands were used, they were all clean sands, and of fairly uniform gradations. Effects of gradation, fines content and character, fabric, depositional process, cyclic (seismic) loading history, ageing, etc. were not investigated in these calibration chamber studies. Despite two overconsolidated specimens tested, effects of stress history (or OCR) also have not yet been thoroughly well explored. It must be expected that variations of these types of properties and characteristics for soils in situ may potentially lead to more overall variability in C_N behavior than is reflected by these important large-scale laboratory data.

In addition, it should be noted that the smallest effective overburden stresses applied to these large-scale calibration chamber specimens were on the order of $\sigma'_v = 0.72$ atmospheres, so that these data do not fully address questions as to the C_N -type of behavior of soils at very shallow depths (with effective overburden stresses of less than 0.7 atm). Field data provides some basis for extrapolation of the C_N relationships developed based on the large-scale laboratory chamber test data to lesser effective overburden stresses, but there is room for more work to be done here.

Table 3-1: Summary of Data for Reid Bedford Model Sand, RBMS (Based on Original Data of Marcuson and Bieganousky, 1979a)

Bin	Specimen No	D _R (%)	σ'_v (tsf)	N-value (bpf)	Density Adjusted N-value	C _E	C _R	C _S	N ₆₀	Density Adjusted N _{60,DA}
1 st Bin Average D _R 27.2%	4	24.3	0.72	3	3.5	1.38	0.75	1.10	3.4	4.0
	4	24.3	0.72	3	3.5	1.38	0.75	1.10	3.4	4.0
	4	27.8	2.88	6	6.0	1.38	0.75	1.10	6.8	6.8
	4	27.8	2.88	9	9.0	1.38	0.75	1.10	10.3	10.3
	4	29.5	5.76	14	12.9	1.38	0.75	1.10	16.0	14.7
	4	29.5	5.76	16	14.9	1.38	0.75	1.10	18.3	17.0
2 nd Bin Average D _R 45.1%	2	43.8	0.72	6	6.4	1.38	0.75	1.10	6.8	7.3
	2	43.8	0.72	9	9.4	1.38	0.75	1.10	10.3	10.7
	2	45.3	2.88	15	15	1.38	0.75	1.10	17.1	17.1
	2	45.3	2.88	20	20	1.38	0.75	1.10	22.8	22.8
	2	46.1	5.76	25	24.2	1.38	0.75	1.10	28.5	27.6
	2	46.1	5.76	31	30.2	1.38	0.75	1.10	35.4	34.5
3 rd Bin Average D _R 73%	12	71.5	2.88	35	36.6	1.38	0.75	1.20	43.6	45.6
	12	71.5	2.88	32	33.6	1.38	0.75	1.20	39.8	41.8
	12	71.5	2.88	27	28.6	1.38	0.75	1.20	33.6	35.6
	12	71.5	2.88	31	32.6	1.38	0.75	1.20	38.6	40.6
	12	71.5	2.88	30	31.6	1.38	0.75	1.20	37.4	39.3
	12	71.5	2.88	32	33.6	1.38	0.75	1.20	39.8	41.8
	17	73.2	0.72	17	17	1.38	0.75	1.20	21.2	21.2
	17	73.2	0.72	24	24	1.38	0.75	1.20	29.9	29.9
	17	73.2	0.72	15	15	1.38	0.75	1.20	18.7	18.7
	17	73.2	0.72	19	19	1.38	0.75	1.20	23.7	23.7
	17	73.2	0.72	15	15	1.38	0.75	1.20	18.7	18.7
	17	73.2	0.72	19	19	1.38	0.75	1.20	23.7	23.7
	18	74.4	5.76	33	31.0	1.38	0.75	1.20	41.1	38.6
	18	74.4	5.76	42	40.0	1.38	0.75	1.20	52.3	49.8
	18	74.4	5.76	39	37.0	1.38	0.75	1.20	48.6	46.1
	18	74.4	5.76	45	43.0	1.38	0.75	1.20	56.0	53.5
	18	74.4	5.76	46	44.0	1.38	0.75	1.20	57.3	54.8
	18	74.4	5.76	49	47.0	1.38	0.75	1.20	61.0	58.5

Notes: a) OCR=1 for all of the specimens.

b) Specimens 2 and 4 were placed using Rotating Rainer, while Specimens 12, 17 and 18 were placed using Rotating Rainer, Tamped

Table 3-2: Summary of Data for Platte River Sand, PRS (Based on Original Data of Marcuson and Bieganousky, 1977b)

Bin	D _R (%)	σ'_v (tsf)	N (bpf)	Density Adjusted N (bpf)	C _E	C _R	C _S	N ₆₀	Density Adjusted N ₆₀
1 st Bin Average D _R =25.4%	19,2	0,72	3	N/A	1,38	0,75	1,10	3,4	N/A
	19,2	0,72	2	N/A	1,38	0,75	1,10	2,3	N/A
	24,2	2,88	7	N/A	1,38	0,75	1,10	8,0	N/A
	24,2	2,88	8	N/A	1,38	0,75	1,10	9,1	N/A
	32,9	5,76	11	N/A	1,38	0,75	1,10	12,6	N/A
	32,9	5,76	12	N/A	1,38	0,75	1,10	13,7	N/A
2 nd Bin Average D _R =56%	53,7	0,72	11	12,3	1,38	0,75	1,15	13,1	14,7
	53,7	0,72	12	13,3	1,38	0,75	1,15	14,3	15,9
	56,2	2,88	22	22	1,38	0,75	1,15	26,2	26,2
	56,2	2,88	26	26	1,38	0,75	1,15	31,0	31,0
	58,1	5,76	33	29,6	1,38	0,75	1,15	39,4	35,3
	58,1	5,76	35	31,6	1,38	0,75	1,15	41,8	37,7
3 rd Bin Average D _R =91.4%	91,4	0,72	53	53	1,38	0,75	1,30	71,5	71,5
	91,4	0,72	52	52	1,38	0,75	1,30	70,1	70,1
	91,4	0,72	47	47	1,38	0,75	1,30	63,4	63,4
	91,4	0,72	46	46	1,38	0,75	1,30	62,0	62,0
	91,4	2,88	73	73	1,38	0,75	1,30	98,5	98,5
	91,4	2,88	66	66	1,38	0,75	1,30	89,0	89,0
	91,4	5,76	94	94	1,38	0,75	1,30	126,8	126,8
	91,4	5,76	78	78	1,38	0,75	1,30	105,2	105,2

Notes: a) OCR=1 for all of the specimens.

b) Preparation Method; 1st Bin: Single Hose Rainer, 2nd and 3rd Bin: Single Hose Rainer, vibrated

Table 3-3: Summary of Data for Standard Concrete Sand, SCS (Based on Original Data of Marcuson and Bieganousky, 1977b)

Bin	D _R (%)	σ'_v (tsf)	N (bpf)	Density Adjusted N (bpf)	C _E	C _R	C _S	N ₆₀	Density Adjusted N ₆₀
1 st Bin Average D _R =25.2%	20,1	0,72	2	3,0	1,38	0,75	1,10	2,3	3,4
	20,1	0,72	1	2,0	1,38	0,75	1,10	1,1	2,3
	25,9	2,88	9	9,0	1,38	0,75	1,10	10,3	10,3
	25,9	2,88	8	8,0	1,38	0,75	1,10	9,1	9,1
	29,7	5,76	16	12,6	1,38	0,75	1,10	18,3	14,4
	29,7	5,76	17	13,6	1,38	0,75	1,10	19,4	15,5
2 nd Bin Average D _R =50.5%	49,3	0,72	9	9,5	1,38	0,75	1,15	10,7	11,3
	49,3	0,72	9	9,5	1,38	0,75	1,15	10,7	11,3
	50,5	2,88	20	20,0	1,38	0,75	1,15	23,9	23,9
	50,5	2,88	23	23,0	1,38	0,75	1,15	27,4	27,4
	51,7	5,76	35	33,1	1,38	0,75	1,15	41,8	39,4
	51,7	5,76	37	35,1	1,38	0,75	1,15	44,1	41,8
3 rd Bin Average D _R =95.9%	95,9	0,72	38	38,0	1,38	0,75	1,30	51,3	51,3
	95,9	0,72	38	38,0	1,38	0,75	1,30	51,3	51,3
	95,9	0,72	30	30,0	1,38	0,75	1,30	40,5	40,5
	95,9	0,72	39	39,0	1,38	0,75	1,30	52,6	52,6
	95,9	2,88	60	60,0	1,38	0,75	1,30	80,9	80,9
	95,9	2,88	74	74,0	1,38	0,75	1,30	99,8	99,8
	95,9	5,76	78	78,0	1,38	0,75	1,30	105,2	105,2
	95,9	5,76	86	86,0	1,38	0,75	1,30	116,0	116,0

Notes: a) OCR=1 for all of the specimens.

b) Preparation Method; 1st Bin: Single Hose Rainer, 2nd and 3rd Bin: Single Hose Rainer, vibrated

Table 3-4: Summary of Data for Reid Bedford Model Sand (RBMS) Specimens With OCR = 3 (Based on Original Data of Marcuson and Bieganousky, 1979a)

Bin	D _R (%)	σ'_v (tsf)	N-value (bpf)	Density Adjusted N (bpf)	C _E	C _R	C _S	N ₆₀ (bpf)	Density Adjusted N ₆₀
1 st Bin Average D _R =39.5%	38	0,72	5	N/A	1,38	0,75	1,10	5,7	N/A
	38	0,72	4	N/A	1,38	0,75	1,10	4,6	N/A
	39,7	2,88	16	N/A	1,38	0,75	1,10	18,3	N/A
	39,7	2,88	16	N/A	1,38	0,75	1,10	18,3	N/A
	40,9	5,76	27	N/A	1,38	0,75	1,10	30,8	N/A
	40,9	5,76	30	N/A	1,38	0,75	1,10	34,2	N/A
2 nd Bin Average D _R =57.3%	56,3	0,72	12	N/A	1,38	0,75	1,15	14,3	N/A
	56,3	0,72	12	N/A	1,38	0,75	1,15	14,3	N/A
	57,3	2,88	25	N/A	1,38	0,75	1,15	29,9	N/A
	57,3	2,88	27	N/A	1,38	0,75	1,15	32,2	N/A
	59	5,76	35	N/A	1,38	0,75	1,15	41,8	N/A
	59	5,76	38	N/A	1,38	0,75	1,15	45,3	N/A

Notes: a) OCR=3 for all of the specimens.
b) Specimen 6 and 7 was placed using Rotating Rainer

Table 3-5: Regressed C_N Relationships for the 10 Field SPT Data Sets for the Cohesionless Soils of Bazaraa (1967)

Site	N_1	m
Coarse Sand, Iowa	21.6	0.85
Fine Loessial Dry Sand, Denver	10.5	0.70
Dry Cohesionless Soi, Q.C.	28.2	0.25
Dry Cohesionless Soil	25.4	0.32
Submerged Sand and Gravel	21.3	0.85
Dry Cohesionless Sand 2, Q.C.	27.9	0.20
Submerged Cohesionless Soil, Waterloo	22.0	0.86
Sub. Cohesionless Soil, Grand Tower	14.4	0.49
Dry Fine Loessial	10.0	0.70
Dry Cohesionless Soil, Hennespin	25.4	0.31

$$N = N_1 \cdot (\sigma'_v)^m$$

$$C_N = \left(\frac{1}{\sigma'_v}\right)^m$$

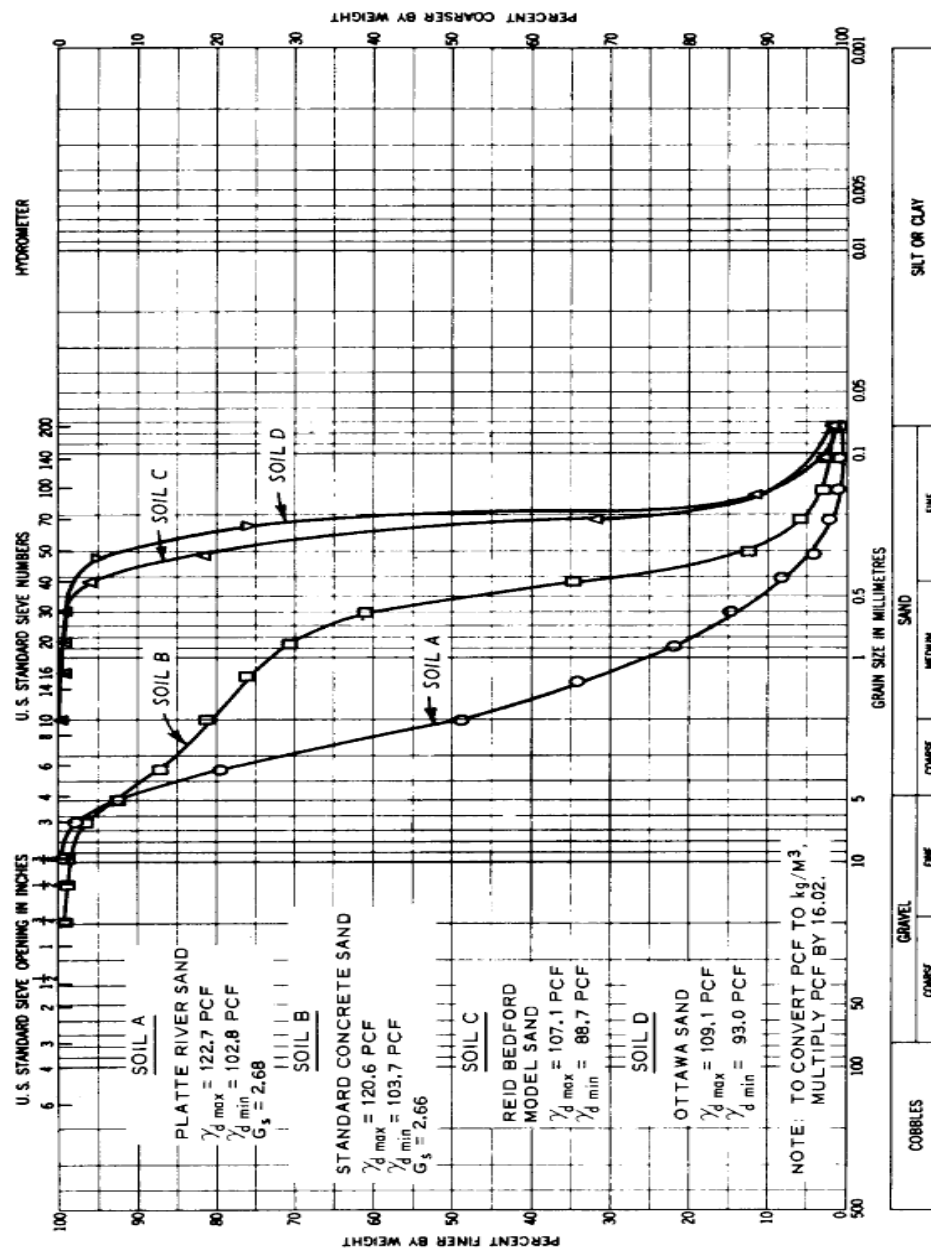


Figure 3-1: Grain Size Distributions of Tested Sands (from Marcuson, 1977)

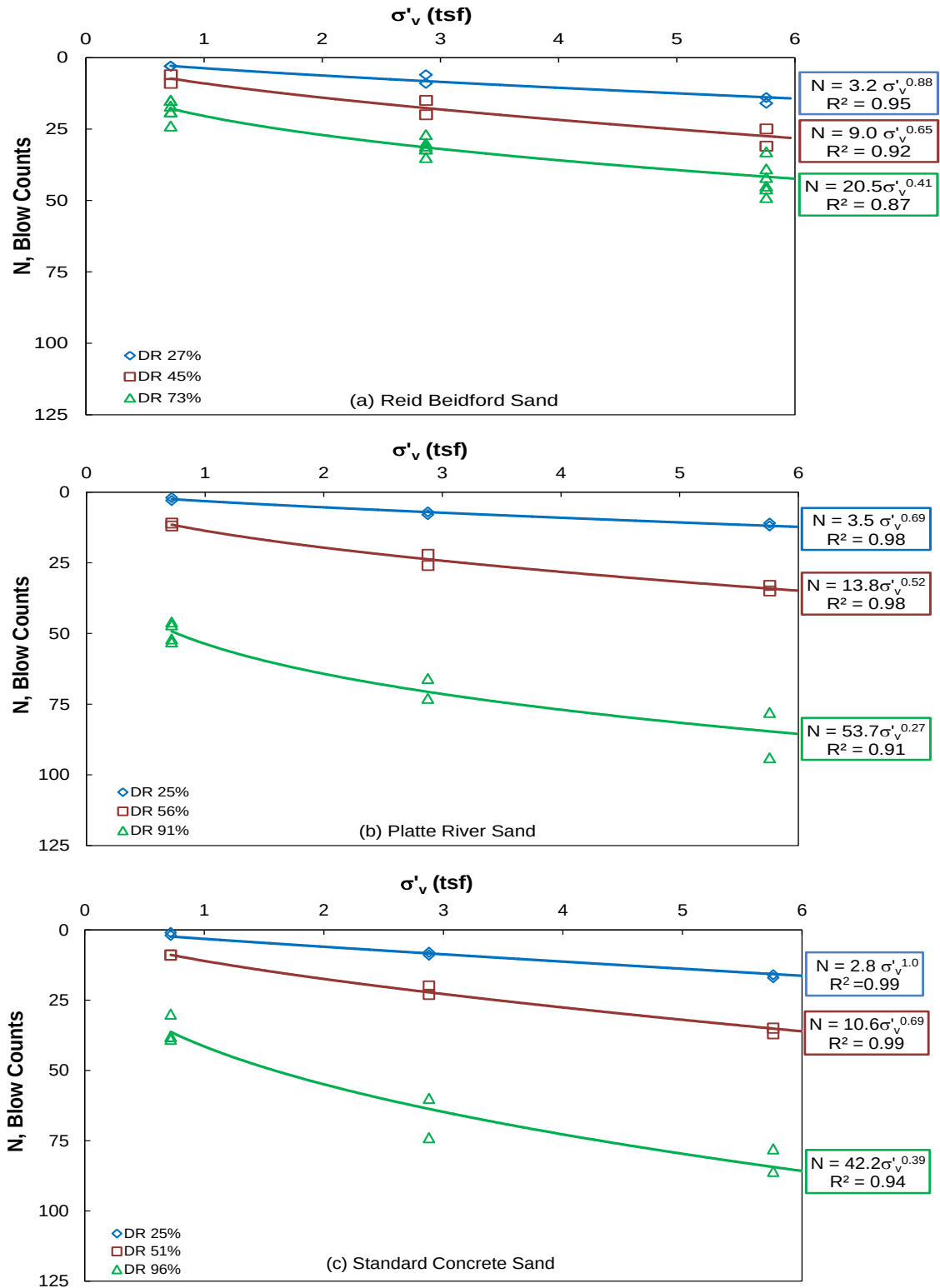


Figure 3-2: Raw SPT N-Values Over the Range of Effective Overburden Stress for RBMS, PRS, SCS at Three Relative Densities, and Results of Nonlinear Regression (Based Marcuson and Bieganousky 1977a, 1977b)

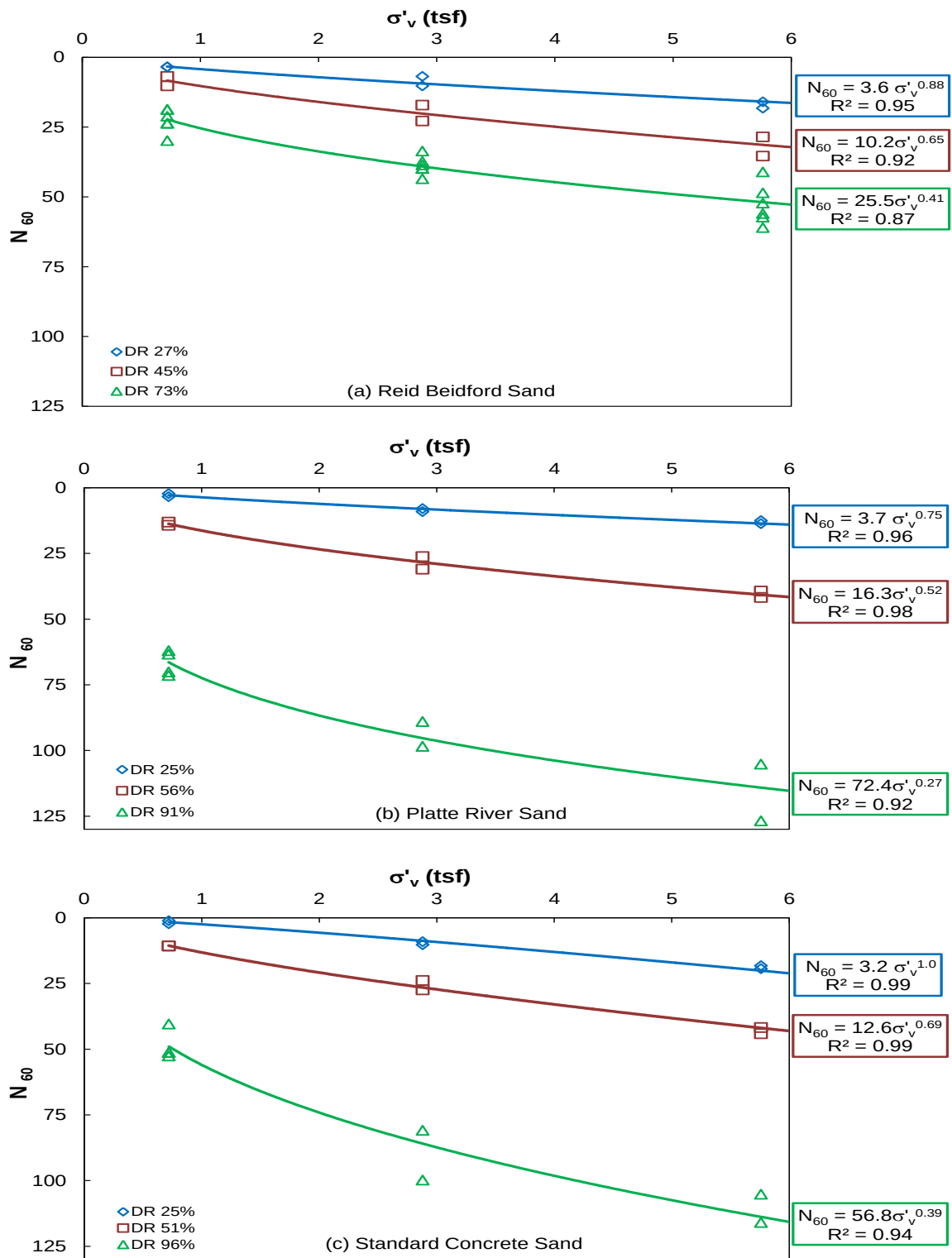


Figure 3-3: SPT N_{60} values Over the Range of Effective Overburden Stress for RBMS, PRS, SCS at Three Relative Densities, and Results of Nonlinear Regression (Based on Marcuson and Bieganousky 1977a, 1977b)

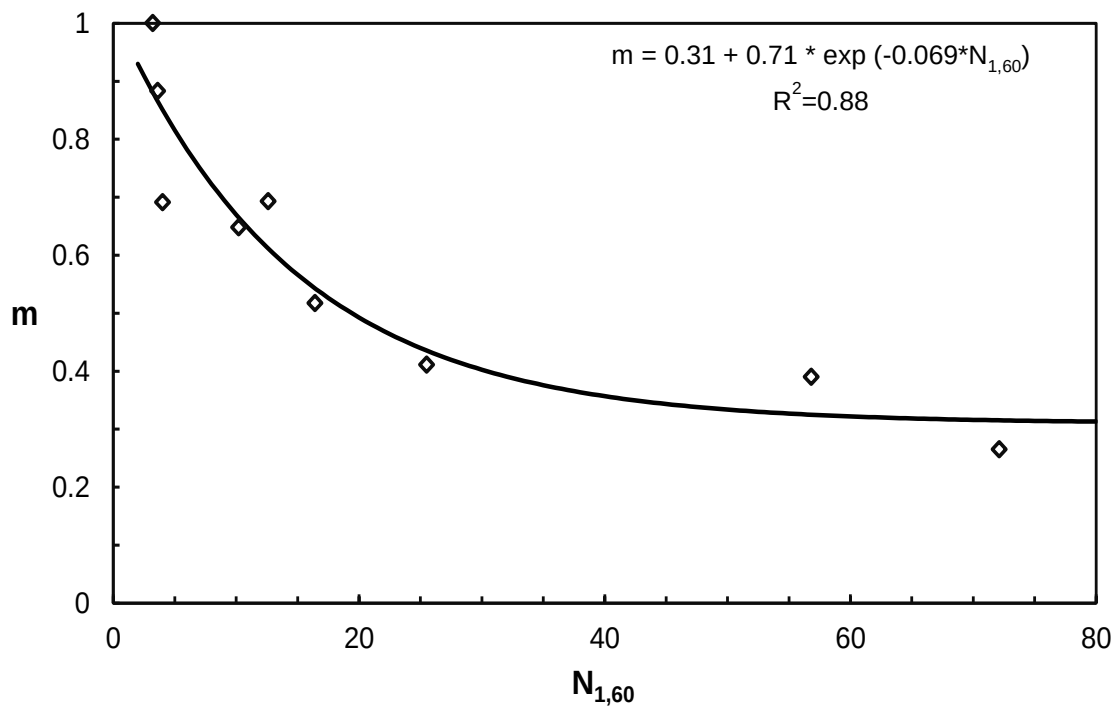
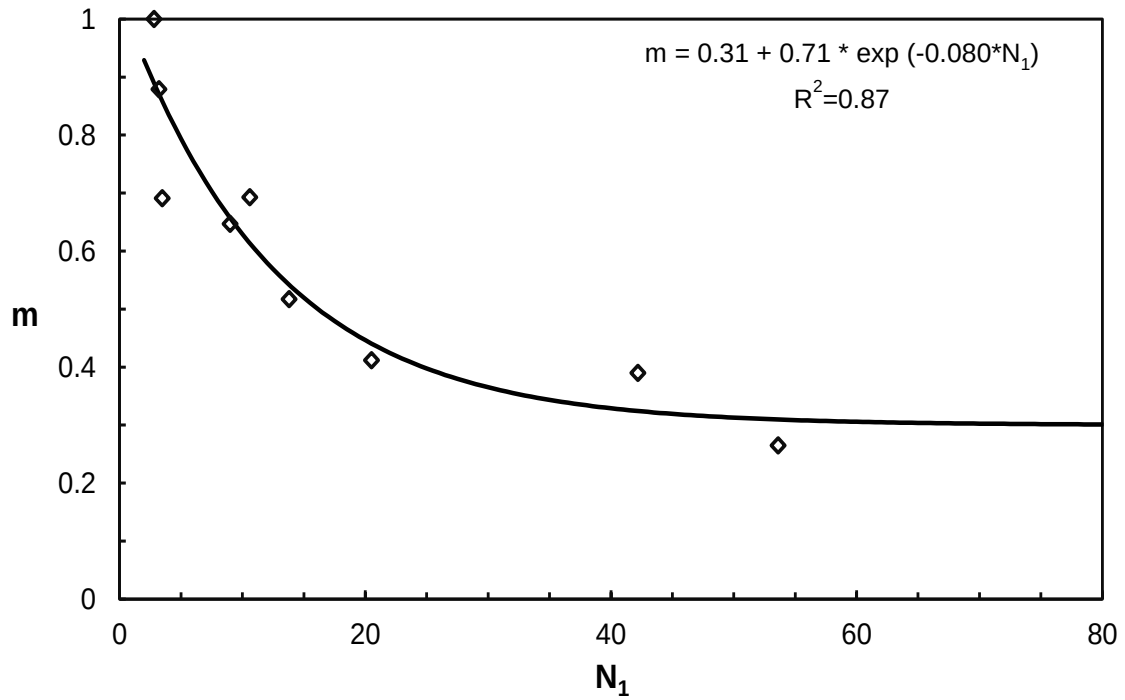


Figure 3-4: Variation of SPT Overburden Correction Factor Exponent m from Re-Evaluation of SPT Calibration Chamber Tests (Based on Marcuson and Bieganousky 1977a, b) based on N_1 and $N_{1,60}$

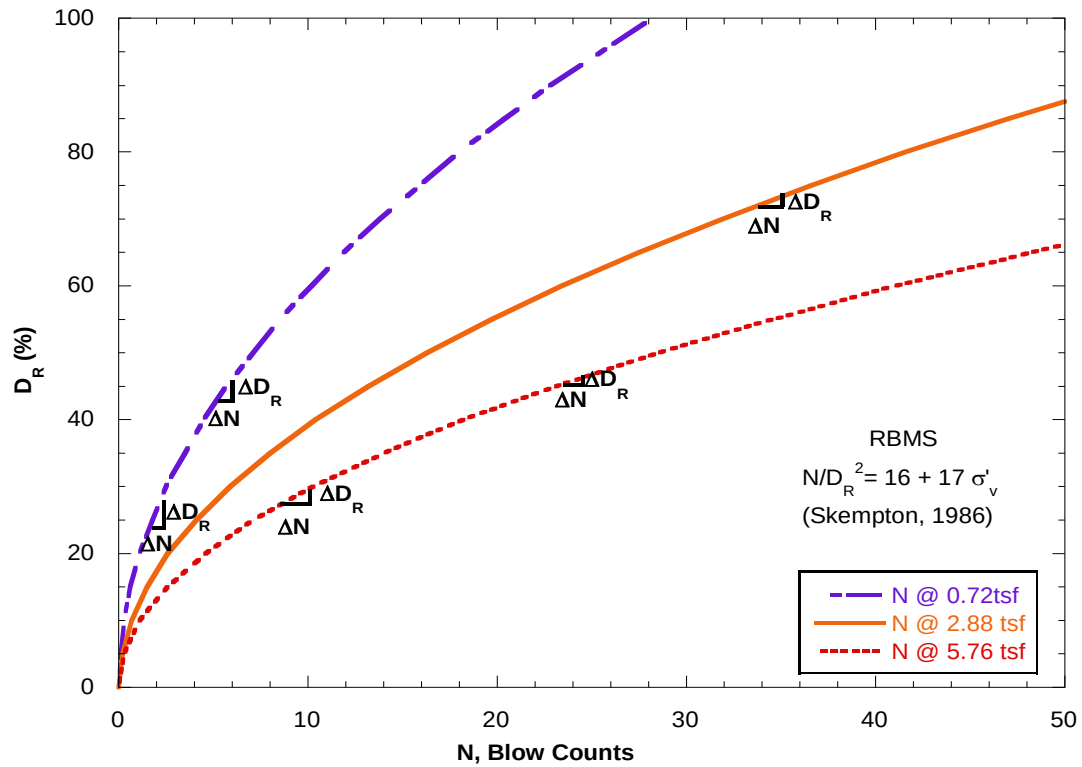


Figure 3-5: Illustration of Density Adjustments in SPT N-Values for Reid Bedford Model Sand (RBMS)

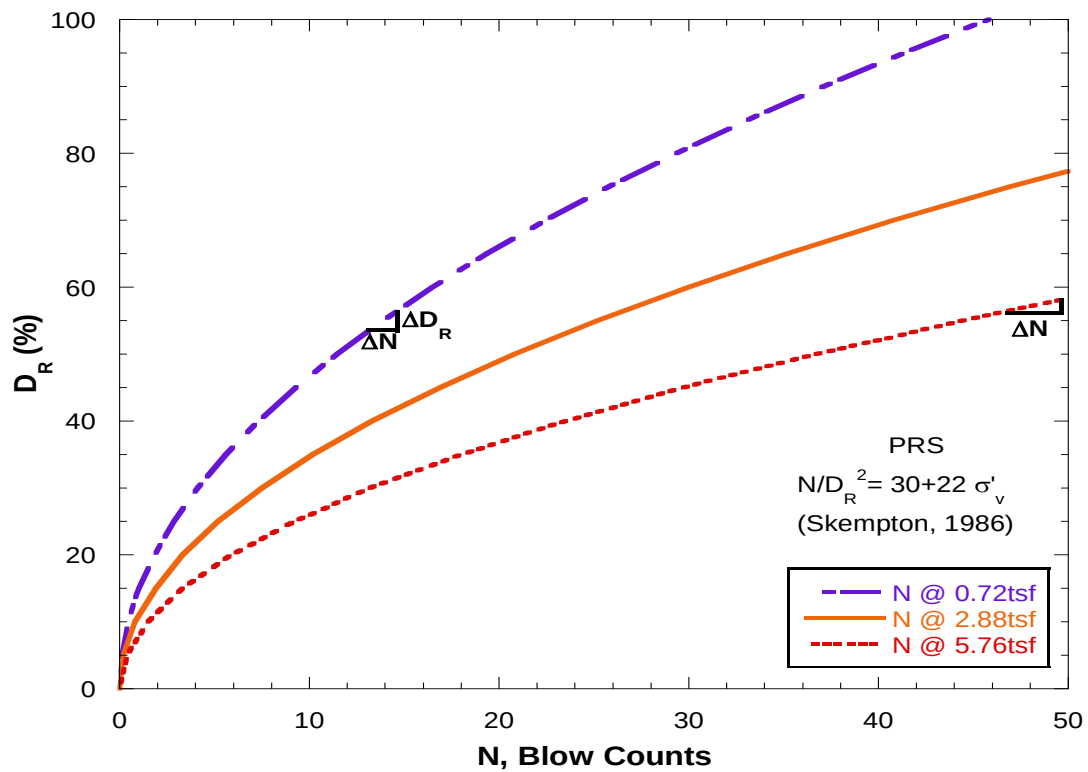


Figure 3-6: Density Adjustments in SPT N-Values for Platte River Sand (PRS)

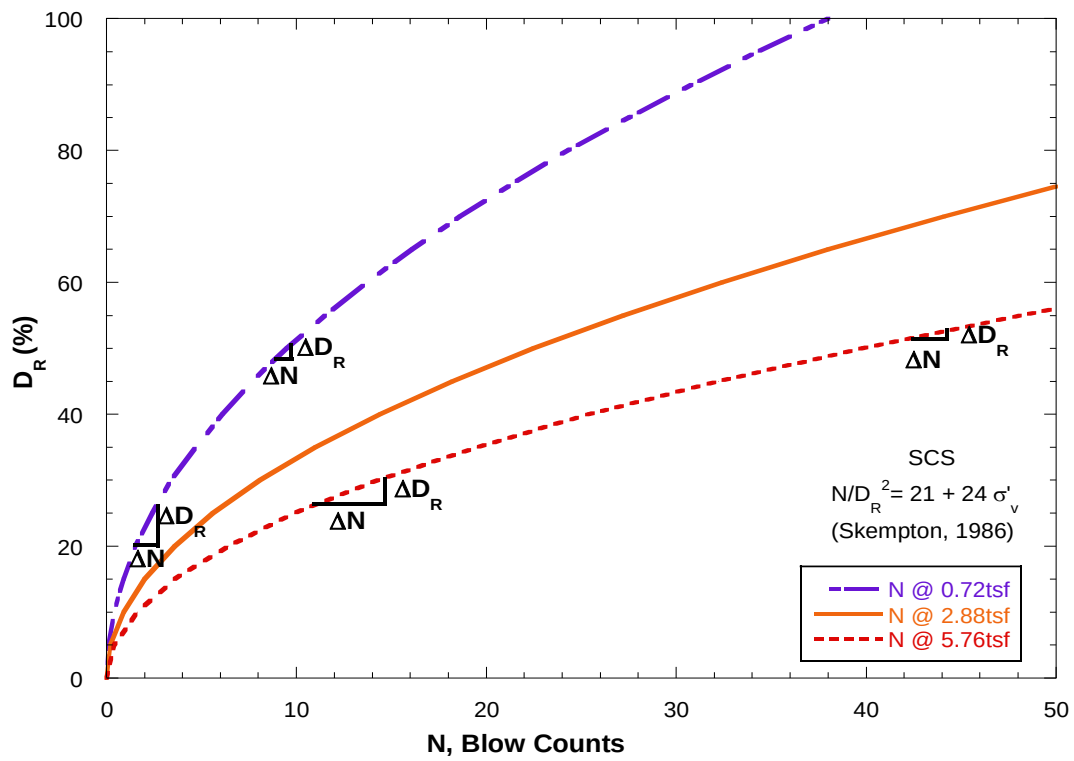


Figure 3-7: Illustration of Densification Adjustments in SPT N-Values for Standard Concrete Sand (SCS)

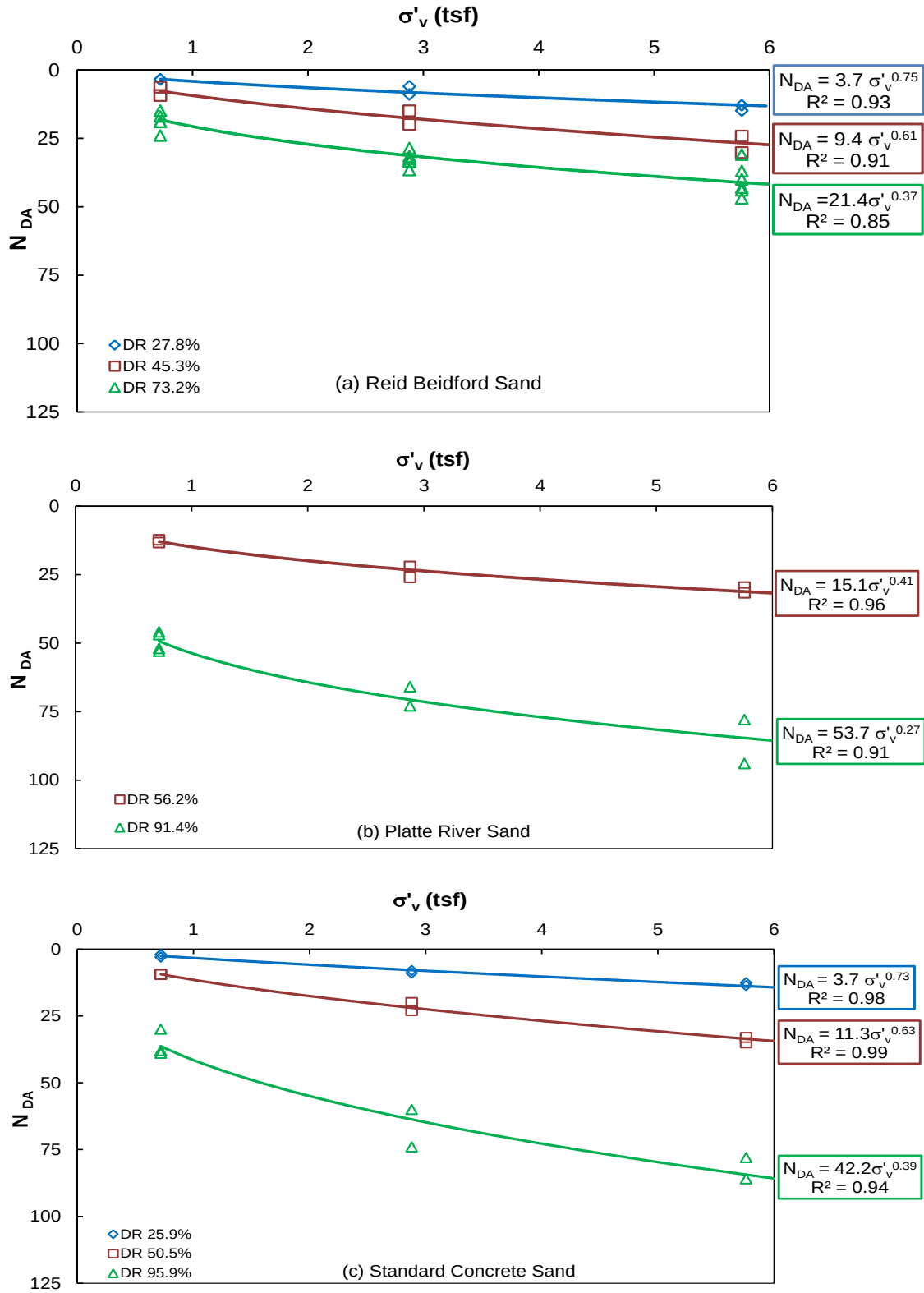


Figure 3-8: Adjusted Raw SPT N values Over the Range of Effective Overburden Stress for RBMS, PRS, SCS at Three Relative Densities and Results of Nonlinear Regression (Based on Marcuson and Bieganski 1977a, 1977b)

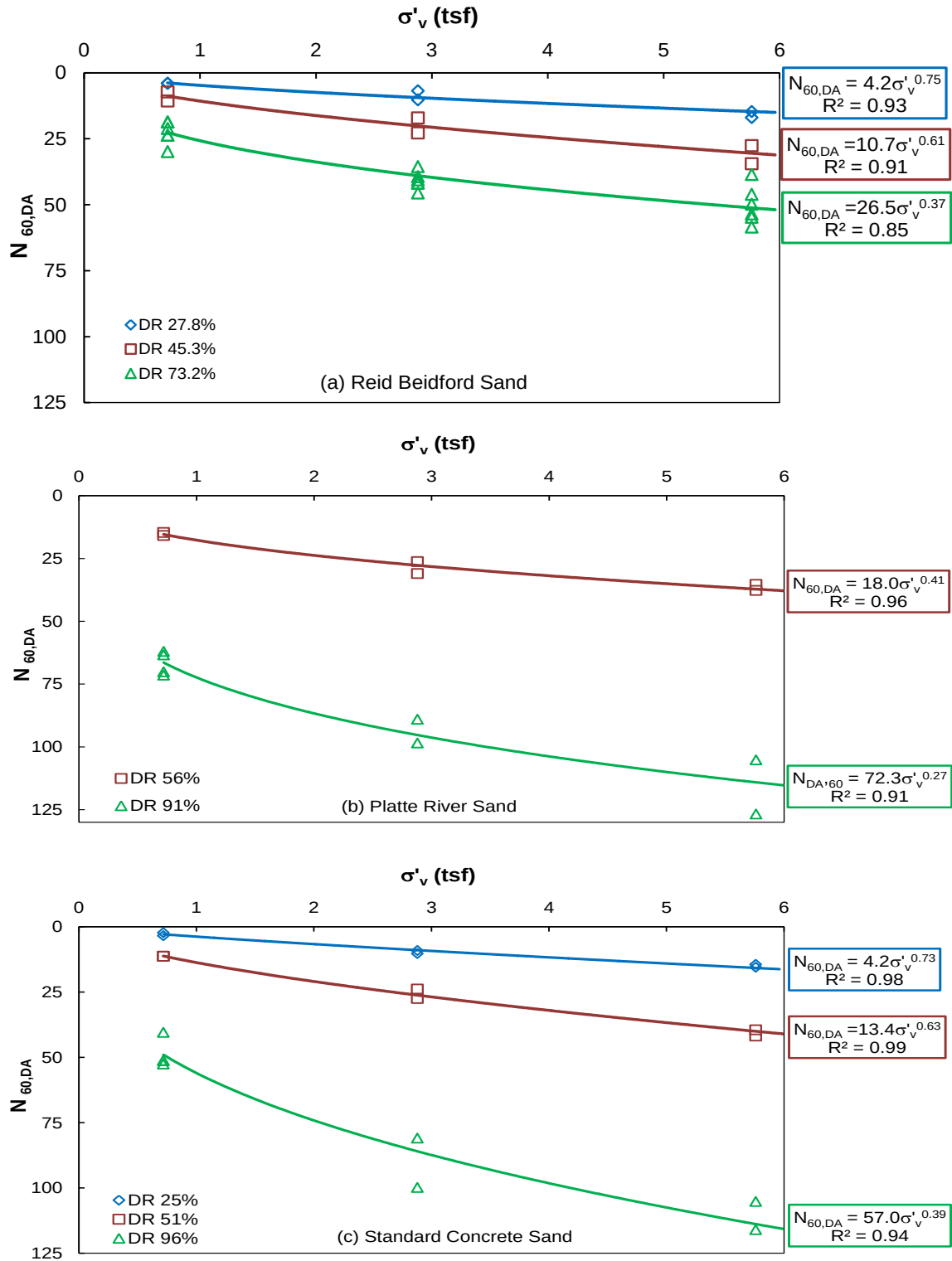


Figure 3-9: Adjusted N_{60} values Over the Range of Effective Overburden Stress for RBMS, PRS, and SCS at Three Relative Densities and Results of Nonlinear Regression (Based on Marcuson and Bieganousky 1977a, 1977b)

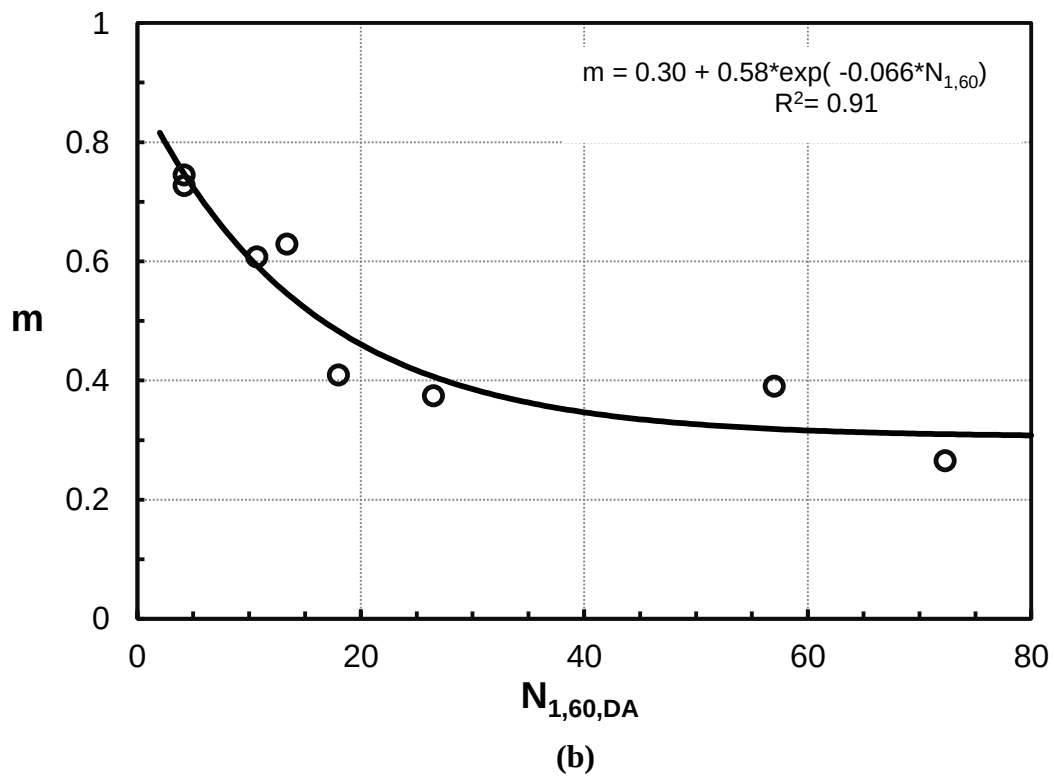
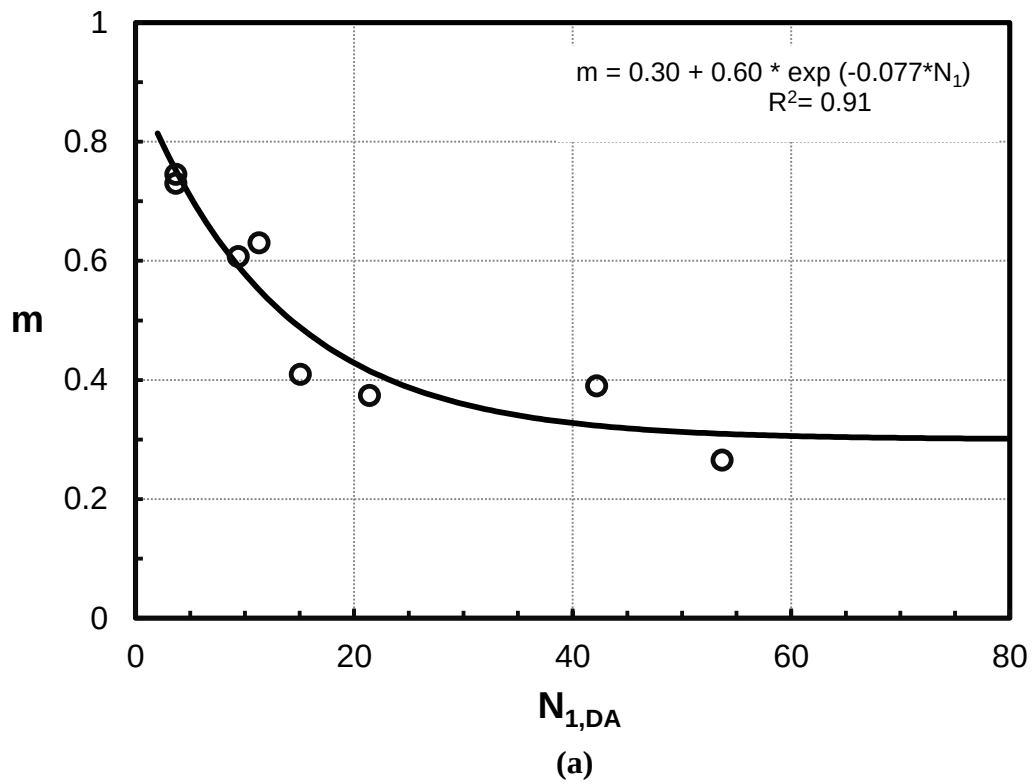


Figure 3-10: Variation of SPT Overburden Correction Factor Exponent m based on Density Adjusted SPT $N_{1,DA}$ and $N_{1,60,DA}$ of Calibration Chamber Tests (Based on Marcuson and Bieganski 1977a, b)

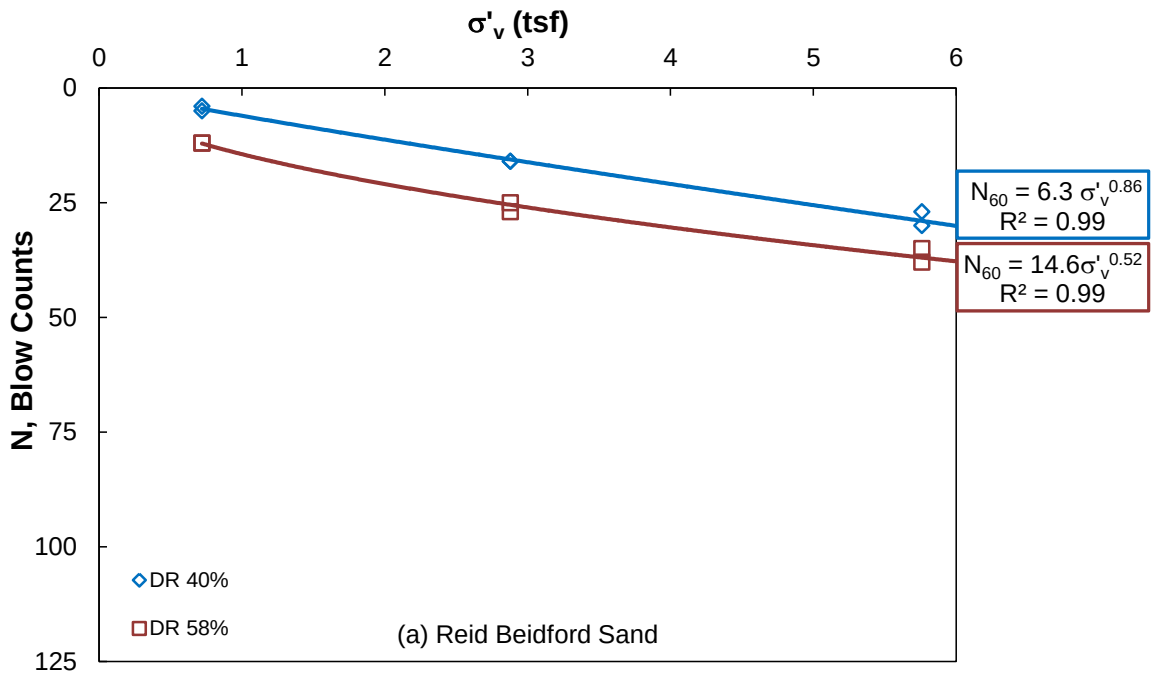
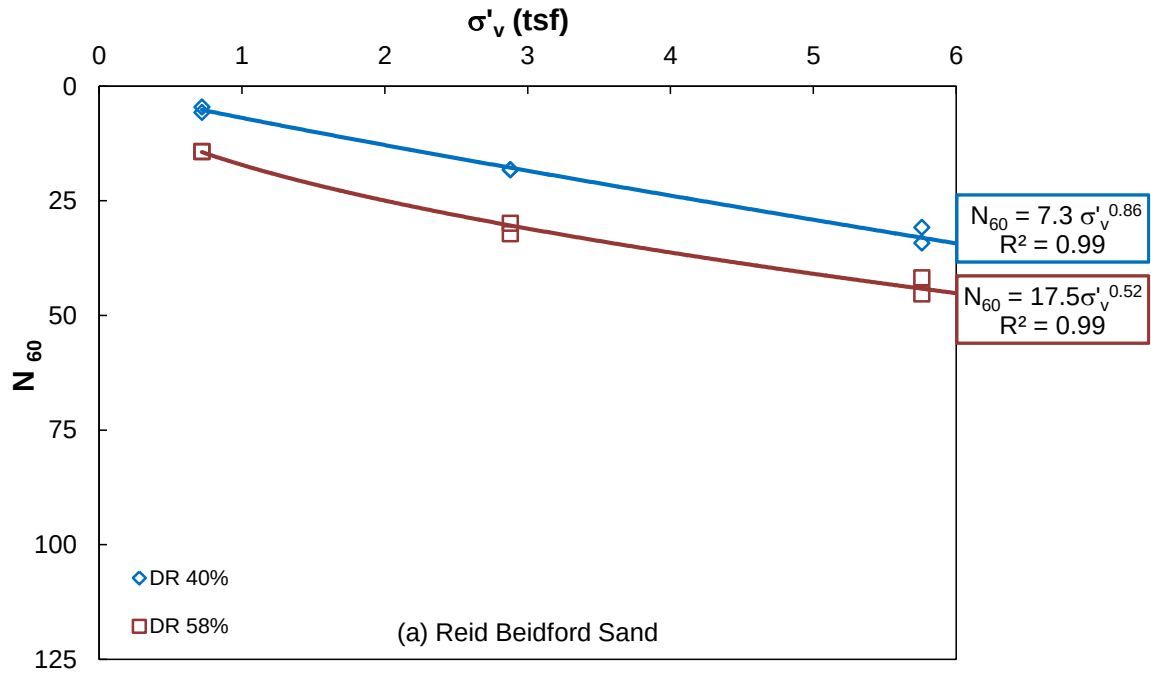


Figure 3-11: SPT N and N_{60} values Over the Range of Effective Overburden Stress for RBMS Having **OCR of 3** at Two Relative Densities and Results of Nonlinear Regression (Based on Marcuson and Biegounsky 1977a)

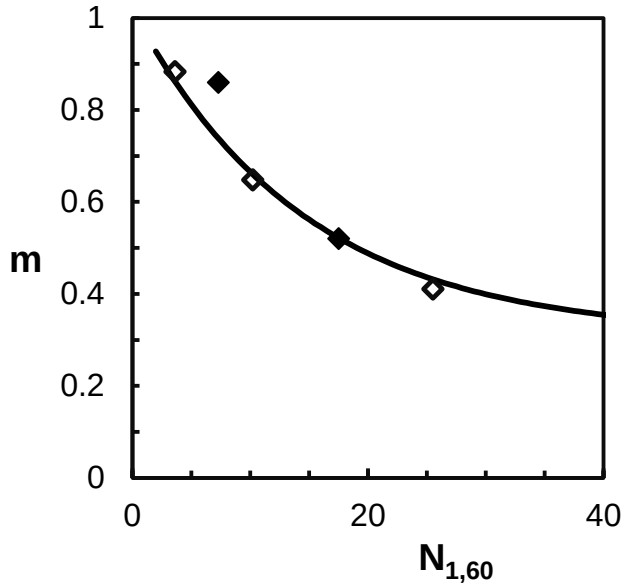


Figure 3-12(a): Comparison of Overburden Correction Factor Exponents m for Normally Consolidated RBMS Specimens and RBMS Specimens with OCR = 3 (Based on Marcuson and Bieganousky 1977a)

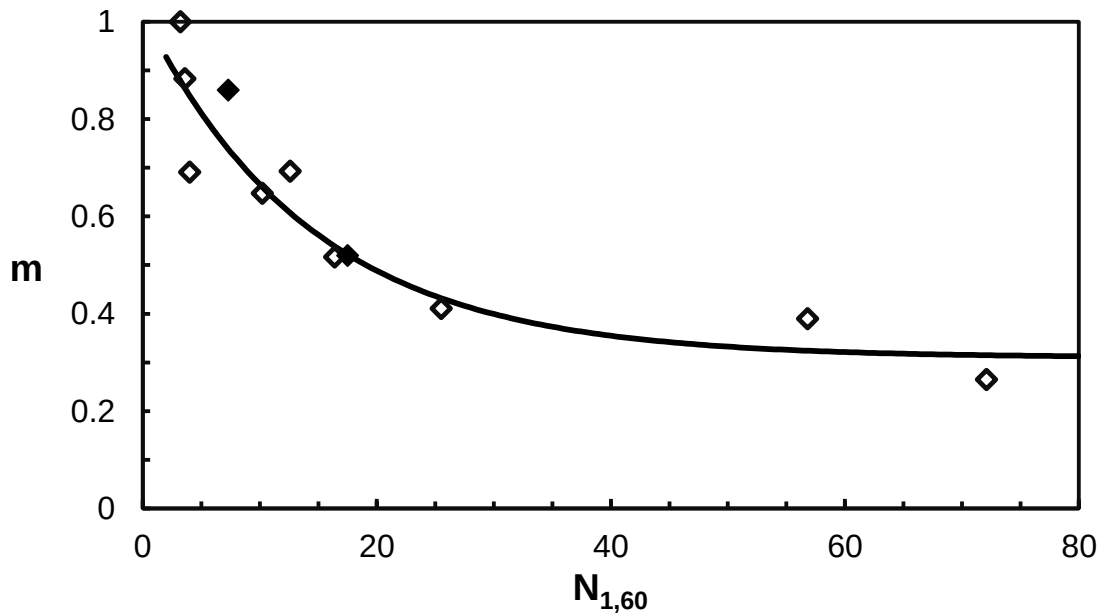


Figure 3-12(b): Comparison of Overburden Stress Exponents m for All of the Normally Consolidated Specimens and RBMS Specimens with OCR = 3 (Based on Marcuson and Bieganousky, 1977a,b)

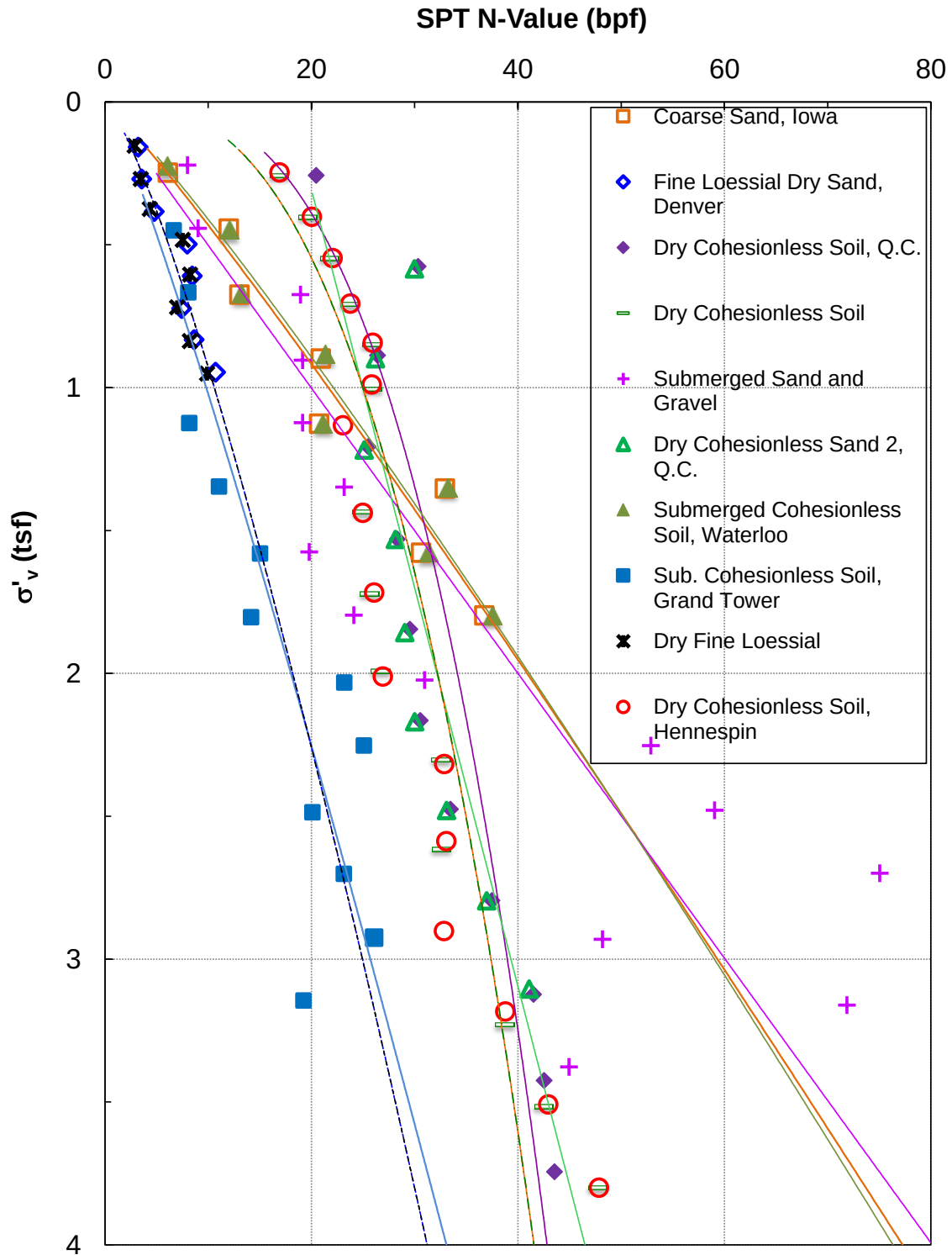


Figure 3-13: SPT N Values vs. σ'_v of the Ten Field Data Sets for Cohesionless Soils by Bazaraa (1967) based on which C_N Relationships in Table 3-5 were Regressed

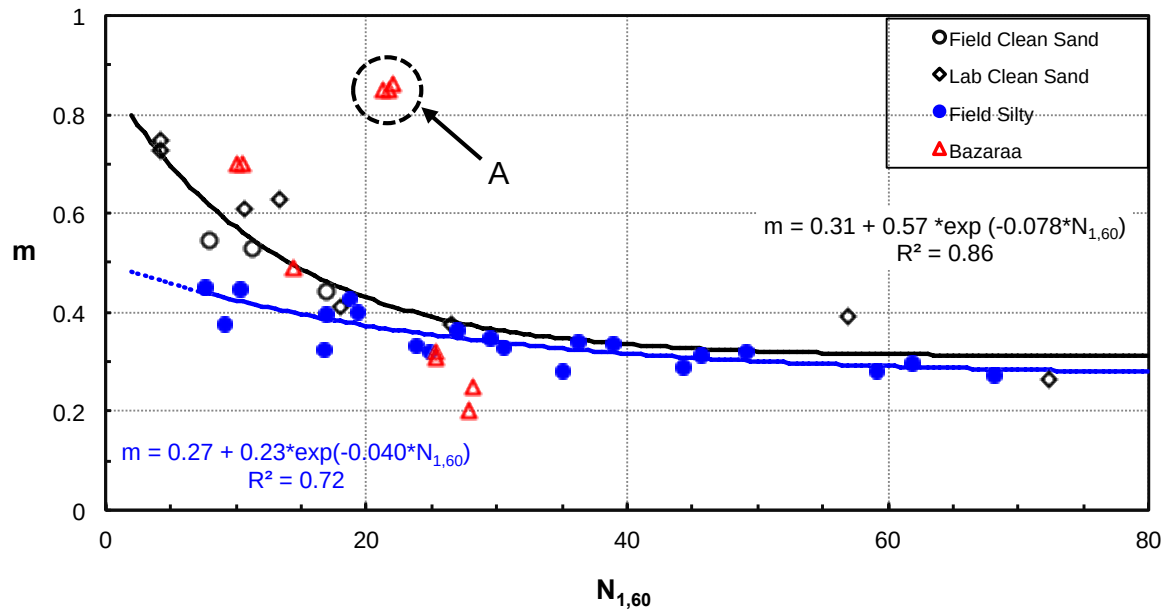


Figure 3-14: Comparison Between Overburden Correction Power Exponents m for Bazaraa's Field Data vs. m Values Developed for Bot Clean Sands and Silty Soils Based on Large-Scale Laboratory Data and Back-Analyses of Field Data from Dam Foundations

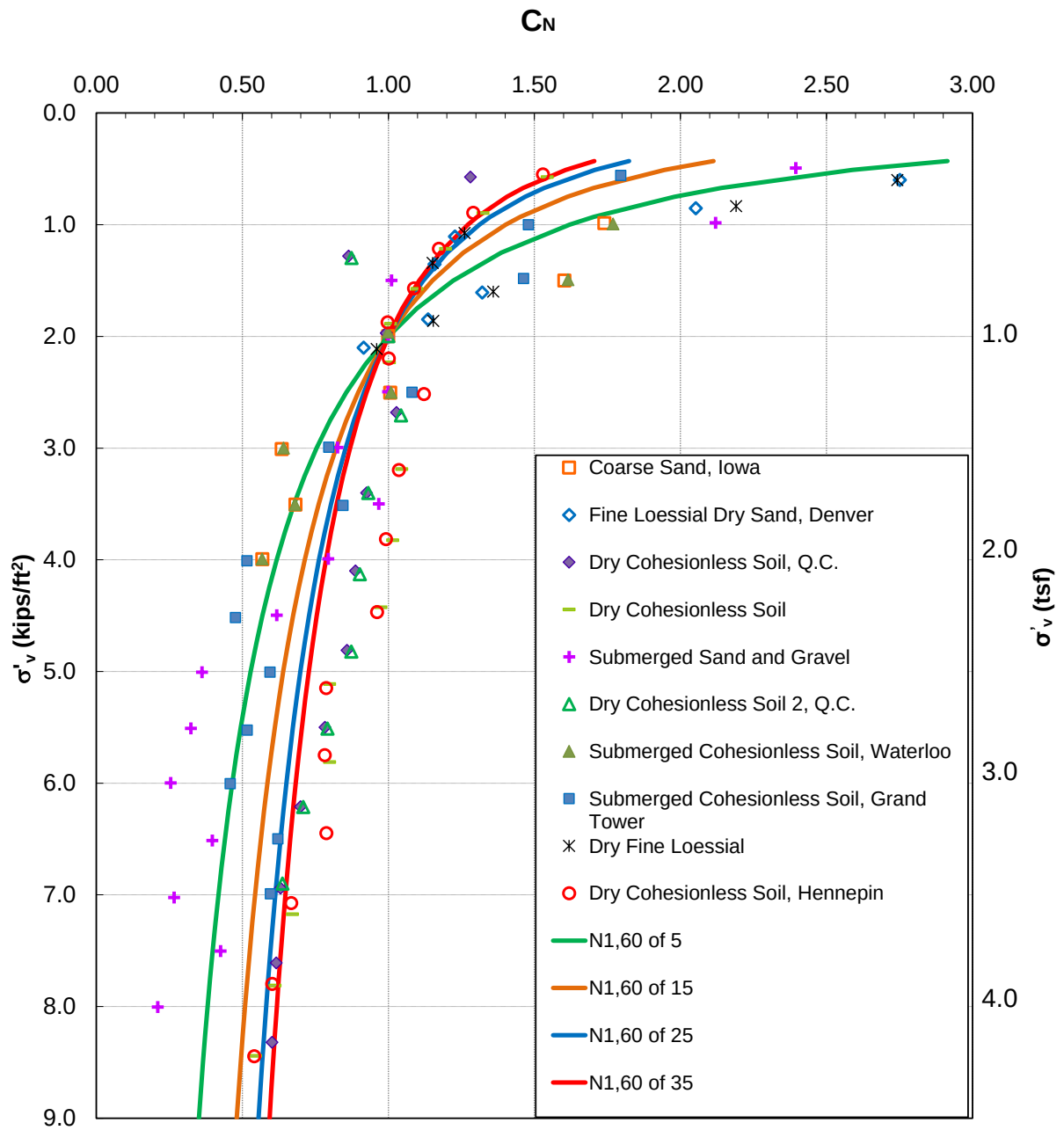


Figure 3-15: Comparison between Seven of the Field SPT Data Sets for Cohesionless Soils Developed by Bazaraa (1967) with the C_N Relationships Based on the Power Function Relationships Developed Based on the WES Calibration Chamber Test Data

CHAPTER 4

OVERBURDEN CORRECTION FACTORS FOR SPT IN SANDY AND SILTY SOILS BASED ON FIELD DATA

4.1 Introduction

The overburden C_N relationships established in Chapter 3 provide a generally suitable basis for overburden normalization of SPT in clean sands. But there is far less that is known with good certainty about overburden normalization of silty soils (silty sands, sandy silts, and silts of low plasticity). These silty soils are an important class of materials with regard to seismically induced soil liquefaction hazard, and so it is necessary to address them. The approach taken to date has generally been to assume that C_N relationships appropriate for clean sands (usually based on the large-scale calibration chamber tests of Marcuson and Beiganousky) can be extrapolated and used for silty soils as well. Good evidence, and data, to support this is largely lacking however.

The approach that will be taken here will be to garner field SPT data from silty foundation soil strata beneath earth dams. Strata will be targeted wherein the geologic conditions appear to provide for good lateral similarity of the deposits studied. Variations in applied effective overburden stress will then be provided by the trapezoidal overlying earthen embankments.

A challenge here is the nature of silty soils. Silty soils are seldom deliberately selected for placement of carefully controlled engineered fills, and so it is natural deposits that are of principal interest. These natural deposits are usually transitional materials with regard to depositional processes, and as a result these silty deposits tend to be both laterally and vertically variable in terms of both material gradations and fines contents, as well as fabric and density, etc. Accordingly, it is difficult to find significant deposits that are “uniform” over any significant lateral expanse. Instead, deposits that are locally variable, but lateral relatively continuous in their variability, will be targeted.

Soil units from the foundations of 30 dams were initially targeted and examined as candidate soil strata. These were recommended as potential candidate units by the engineers and geologists of two governmental agencies with oversight authority over significant numbers of dams: the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (BuRec). From among these 30 dam sites and their foundation soil strata, six foundation soil strata from the foundations of four dams were eventually selected as having the highest degree of apparent continuity of similarity across a sufficient lateral extent as to provide data for a broad range of effective overburden stresses (with the variable vertical stresses being provided by the overlying earth dams) to provide a basis for development of C_N relationships.

It must be emphasized that these strata do not necessarily provide for ideal uniformity of material character and of density, as would be the case for large-scale laboratory calibration chamber tests. Instead these primarily silty strata tend to be highly variable on a very localized basis, both laterally and vertically, but they were selected as being laterally relatively consistent in this variability, with no distinct apparent trends, over the lateral extents needed to provide SPT data under different ranges of effective overburden stress.

4.2 Selection and Processing of Field Cases

A relatively large number of silty soil strata from the foundations beneath 30 dams were initially examined as candidate strata. Each candidate case was examined thoroughly, and suitable cases to develop site-specific overburden correction factor were selected as being those soil units for which the lateral variability of the materials was judged to be relatively small (good laterally uniformity of variability) over a sufficient lateral extent as to provide SPT data under a wide range of effective vertical effective overburden stresses due to varying overburden loading provided by the trapezoidal overlying earth dam embankments. Candidate strata were eliminated if geological information and/or data suggested that changes in depositional conditions caused systematic changes in the materials deposited over the lateral distances that needed to be evaluated. Systematic lateral non-uniformity of the geologic formation, unsuitable soil types of foundation alluvium, high gravel content that might bias SPT data, inadequate effective vertical overburden stress ranges, inadequate SPT data, undefined or non-standard SPT equipment and/or procedures, or lack of hammer energy calibration data, were causes for deletion of the cases not selected. In the end, overburden correction factors were developed for six different foundation geologic units from beneath four different dams.

For each field site, SPT N-values obtained at different effective vertical overburden stresses were collected. Then SPT N-values were grouped into relatively consistent density bins (of similar penetration resistance) for each case. The overburden correction factor (C_N) is the ratio of N_1 (hypothetical SPT N-value that would have been measured if the effective vertical overburden stress at the depth of SPT had been 1 atm or 1 tsf) to SPT-N value at any depth as given in Equation 4.1. If a general form of power function as given in Equation 4.2 is used to relate SPT N-value and vertical effective overburden stress, the influence of effective vertical overburden pressure on SPT N-values can then be quantified by regression of the data in terms of the overburden correction factor power exponent m for each of the apparent density bins.

$$C_N = \frac{N_1}{N} = \left(\frac{1}{\sigma'_v} \right)^m \quad \text{Equation. 4.1}$$

$$N = N_1 \cdot (\sigma'_v)^m \quad \text{Equation 4.2.a}$$

$$N_{60} = N_{1,60} \cdot (\sigma'_v)^m \quad \text{Equation 4.2.b}$$

SPT N-values would be plotted versus effective vertical overburden stresses, and the relationships between N-values and overburden stresses would be empirically derived by regressing the data over the ranges of effective vertical overburden stress available using the method of non-linear least squares regression.

4.3 Duncan Dam

The first case analyzed was a sandy foundation soil stratum beneath Duncan Dam in western Canada. This is a relatively clean sand stratum, and it was selected as providing a basis for assessing whether SPT data from foundation soil strata could produce C_N relationships generally consistent with the C_N relationships developed and presented in Chapter 3 for clean sands.

Duncan Dam is a 39 m high zoned earthfill dam, situated on the Duncan River in southeastern British Columbia, Canada. It was constructed between 1965 and 1967 to provide hydroelectric power generation and flood control. Foundation stratigraphy includes alluvial flood-plain deposits underlain by an interlayered sequence of glaciofluvial deposits, glacial drift, and metamorphic bedrock (Little et al., 1994). Figure 4-1 shows a cross section of the right half of the dam and the underlying foundation stratigraphy. The layer focused on for this study is sandy Unit 3c, within the alluvial and glaciofluvial deposits beneath the right half of the dam. The Unit 3c is relatively clean, uniform, fine sand with about 5 to 8 percent fines, and sand grains are generally angular to subangular. A representative grain size distribution curve for this material is presented in Figure 4-2.

B.C. Hydro carried out field investigations in 1988 (Phase I) and 1990 (Phase II) to characterize the foundation soils beneath the dam. Phase I included ten SPT boreholes and three CPT soundings. Phase II studies included three additional SPT boreholes and four CPT soundings. Details of the SPT procedures employed in the Phase I and Phase II investigations are explained by Plewes et al. (1994), and these can be summarized as given below:

Drill Rig: Mayhew-1000

Sampler Type: Standard SPT Split-Spoon Sampler with the inner liners in place

Hammer Type: Donut-Type Hammer (two turns of the rope about a rotating cathead)

Average Energy Ratio: Average Energy Ratio $\approx 43\%$. (Energy calibration testing was performed to a depth of 40.5m, at another site in Richmond, British Columbia, using the same drill rig and operator)

Figure 4-3 is a plan view of the dam, showing the boring locations. SPT borings were performed along the crest, beneath the midslope, and near the toe of the dam; providing good variability in effective overburden stresses. Six SPT borings were performed beneath the right half of the dam, three at the downstream toe (boring DH88-9, DH99-6D, DH90-7D), two at the midslope of the dam embankment (borings DH88-8, DH90-5D) and one at crest of the dam

(boring DH88-7), and it is the SPT data from foundation soil Unit 3c (see Figure 4-1) in these borings that will be analyzed.

A total of 73 SPT N_{60} values with varying effective vertical overburden stresses ranging from 1.3 tsf to 12 tsf were collected from Unit 3c. These SPT data are presented in Table B-1 of Appendix B. Figure 4-4 shows these data plotted as N_{60} versus effective vertical overburden.

Nonlinear least squares regressions were performed, using the same methods as described previously in Chapter 3, to develop C_N relationships based on the type of power function presented in Equation 4.1 for the SPT data within each of the density bins shown in Figure 4-4. Creation of these density bins was an iterative process. SPT N_{60} values were grouped into density bins based on $N_{1,60}$ values obtained through iterations until the obtained m value, and the m value used to calculate $N_{1,60}$ for that iteration, closely matched each other. As shown in Figure 4-4 (and Table B-1) the selected density bins (or bins of similar penetration resistance) were bins of data with final, overburden-corrected $N_{1,60}$ -values of (a) 5 to 10 blows/ft, (b) 10 to 15 blows/ft, and (c) 15 to 25 blows/ft.

Figure 4-4 shows the final binning of the SPT data, and it also shows the final C_N relationships fitted to these data. As shown in this figure, the resulting C_N relationships have R^2 values of 0.89, 0.95 and 0.80 respectively for the three bins of SPT data. Resulting m values range from 0.55 to 0.44, while average $N_{1,60}$ values range from 7.9 to 17.0 among the three density bins.

These m values obtained based on SPT data from the relatively clean sands of Unit 3c provide an opportunity to compare m values obtained from field data using these procedures with the m values previously obtained for relatively clean sands based on the large-scale laboratory calibration chamber test data of Marcuson and Bieganski from Chapter 3. Figure 4-5 makes this comparison, and it can be seen that the two sets of data match well.

The next five sections (Sections 4.4 through 4.8) will employ similar approaches to evaluate effective overburden stress corrections for SPT in silty soils.

4.4 Perris Dam Left Reach, Shallow Alluvium

Perris Dam is a zoned earthfill dam located in northeastern Riverside County, California. The major portion of the dam is founded on an alluvium filled valley, and alluviums in the valley are stream channel and slope wash deposits derived from weathering of the local granitic rocks. The alluvium reaches to its greatest thickness of about 290 feet at about Station 91+30 on the left reach of the Perris Dam. The historic stream channel crossed the dam axis between Stations 85+00 and 105+00. The valley alluvium is stream channel deposits in this section, and it has a high degree of apparent continuity perpendicular to the dam axis as this unit extends from beneath the dam crest towards the downstream bench and toe (CDWR, 2005).

The California Department of Water Resources (CDWR) performed SPT during four phases of field investigation (drilling and testing) performed between 1996 and 2004 in order to characterize the foundation alluvium. Then 14 additional SPT boreholes were drilled along the toe of the dam in 2007 to further investigate alluvium along the toe. During these investigations, SPT were defined as “refusal” if more than 50-60 blows were required to advance the SPT sampler through any of three 6-inch test intervals. For all of the first four phases of field investigation, six-inch diameter holes were drilled by the mud rotary wash method beyond the toe, and 4-inch diameter mud rotary wash boreholes were drilled beneath the bench and crest. SPT were performed using a split soon sampler and NW-J rods. The sampler was driven with a CME automatic hammer. The hammer energy transfer ratio was determined based on actual field hammer energy measurements obtained by use of an instrumented rod section and a pile driving analyzer (PDA) during performance of SPT on the site. The hammer used in Phase I was calibrated in boreholes SS-17A and SS-17C, and the hammer used in Phases II-IV was calibrated in borehole SS40ML at the site. Hammer drop rates ranged from 30 to 40 blows per minute for all phases. Equipment used in different phases are listed below:

Phase I

Drill Rig: Ingersoll-Rand A-400

Penetrometer: 1-1/2 inch inner-diameter (I.D.) split-barrel samplers with the brass liners omitted

Rod Type: A-size rods at test depth less than 50ft and N-size rods at test depth below 50ft

Hammer Type: Manual 140-lb mobile hammer

Drill Rod Energy Ratio (ER): 45.7 percent for rod lengths of >17feet and 40.6 percent for rod lengths of less than 17feet (Compound correction for hammer and drill rod energy correction)

Phase II:

Drill Rig: CME 750

Penetrometer: 1-1/2 inch inner-diameter (I.D.) split-barrel samplers with the brass liners omitted

Rod Type: N-size rods

Hammer Type: CME 140-lb automatic hammer

Drill Rod Energy Ratio (ER): 72 percent

Phase III:

Drill Rig: CME 750

Penetrometer: Constant 1-3/8 inch I.D. sampler

Rod Type: N-size rods

Hammer Type: CME 140-lb automatic hammer

Drill Rod Energy Ratio (ER): 72 percent

Phase IV:

Drilling Rig: CME 750 (in foundation)

Penetrometer: 1-3/8 inch constant I.D. sampler

Drilling Method: Auger drilling in the embankment and rotary drilling with bentonite water mix in foundation

Rod Type: N-size rods

Hammer Type: 140-lb Automatic Hammer

Drill Rod Energy Ratio (ER): 75 percent

2007 Fieldwork:

Drilling Rig: Mobile B-53

Penetrometer: 1-3/8 inch constant I.D. sampler

Drilling Method: 4.5 inch diameter Mud Rotary

Rod Type: N-size rods

Hammer Type: 140-lb Automatic Hammer

Drill Rod Energy Ratio (ER): 84 percent

A typical cross section of the left reach of the Perris Dam is shown in Figure 4-6. Consistent geologic deposition on the left reach of the dam led to relatively uniform and continuous character of the stream channel alluvium beneath the crest through the toe, perpendicular to the dam axis. Consequently, the relationship between effective vertical overburden stresses and standard penetration resistance can be deduced from collected SPT N_{60} values with varying effective vertical overburden stresses.

This does not mean that conditions within these alluvial deposits were uniform or consistent. Local variability was high within these braided stream channel deposits. But the variability was judged to be consistent, statistically and geologically, over the perpendicular (upstream/downstream) direction, and binning of the data was employed so that looser and denser portions of the alluvium were processed within bins at various (differing) effective overburden stresses.

The comprehensive field investigations of the shallow foundation alluvium beneath the left reach of Perris Dam provide an opportunity to develop overburden correction factors based on an extensive set of field SPT data for silty soils. A total of 346 SPT were performed in 48 boreholes between Stations 85+00 and 112+00. SPT were performed in the shallow alluvium underneath the crest, the upper bench, the lower bench, and the toe of the dam with effective vertical overburden stresses ranging from 0.25 tsf up to 9 tsf. Figure 4-7 shows a plan view of the dam with boring locations along the left reach of the dam. Table B-2 of Appendix B presents a summary of SPT data and results of laboratory tests. SPT “refusal”, and SPT values associated with the Waste Strip and unstripped alluvium, were not included in the data set presented in Appendix B. According to field and laboratory classifications, approximately 36 percent of the SPT samples were classified as non-plastic silty sand (SM), about 22 percent as low-plasticity clayey sand (SC), about 16 percent as low-plasticity silty clayey sand (SC-SM and/or SM/SC), about 9 percent as low-plasticity silt (ML), about 7 percent as low-plasticity clay (CL), and the rest is poorly graded sand with silt (SP-SM, SM-SP), well graded sand with silt (SW-SM), and poorly graded sand (SP). Soil gradations of representative samples are shown in Figure 4-8.

SPT N_{60} -values for this shallow alluvium are plotted versus vertical overburden stress in Figure 4-9. Because of the variability within this alluvial soil unit, the SPT data were iteratively separated into discrete bins with similar $N_{1,60}$ values, and effective overburden correction relationships were then regressed for each bin using nonlinear least squares regression. The collected SPT N_{60} values are grouped into different “apparent density” bins of similar $N_{1,60}$. Groupings for these bins were progressively re-selected through multiple iterations until the overburden correction factor exponents resulting from the overall regressions converged to the overburden stress exponents m used to select the density bins. This was similar to the approach taken in selecting “bins” for these data by Wehling and Rennie (2008), except that optimization schemes for final selection of bins differed, and the scheme used here produced a higher degree of overall “fit” as expressed by R^2 values for the overburden correction curves (and especially for the overburden corrections curves for relatively low $N_{1,60}$ -values), as shown in Figure 4-9, and in the previous Figures 2-23 and 2-24.

Figure 4-9 shows the final overburden correction factors (C_N relationships) based on nonlinear least squares regression for the final six different apparent density bins of the shallow alluvium, and regressed C_N equations (and R^2 values) for these relationships. As shown in this figure, average $N_{1,60}$ -values range from 7.9 to 59.8 blows/ft for the six bins, while overburden correction factor exponents range from $m = 0.44$ to 0.28 . Goodness of fit is represented by R^2 values of $R^2 = 0.82$ to 0.96 for the six bins regressed.

The correlations presented in Figure 4-9 between N_{60} and effective vertical overburden pressure lack any consideration of the effects of fines contents on penetration resistance. The fines contents of samples of the shallow alluvium tested ranged from 8 percent to 65 percent, with a median fines content of 31 percent. To assess the effects of fines content, N_{60} values were next corrected to $N_{60,CS}$ -values, using the fines correction of Cetin et al (2004), and the resulting $N_{60,CS}$ values (instead of N_{60}) were then regressed over the range of effective vertical overburden stresses. Because these overburden correction factors are dependent upon corrected and normalized $N_{1,60}$ values, this required additional iterative loops of regression. The fines content corrected $N_{60,CS}$ values are presented in Table B-2 of Appendix B. Correlations between $N_{60,CS}$ and effective vertical overburden pressure were developed using the same iterative optimization of bins as described previously, and the resulting regressed overburden correction relationships (C_N curves) are presented in Figure 4-10, along with the resulting R^2 values. Goodness of fit was again excellent, with $R^2 = 0.84$ to 0.96 for the six bins of data. Application of this correction for fines was found to have only a modest effect on the m values calculated by this regression, with the differences being a bit more noticeable at very low N -values.

As overburden correction factor will be mainly used in assessment of liquefaction resistance of sandy and silty soils, further regressions were performed excluding SPT N -values associated with clayey materials (CL and SC). All soils classified as SC and CL were deleted (scalped) from the data to be regressed, and the processes described above were again repeated. For this scalped dataset, silty sand (SM) constitutes about 51 percent of the samples, while low plasticity silty clayey sand (SC-SM), low plasticity silt and poorly graded silty sand (SP-SM) constitute about 23 percent, 13 percent, and 8 percent of the samples, respectively.

The remaining 240 SPT $N_{60,CS}$ -values were iteratively binned and regressed over the range of effective vertical overburden stresses using the nonlinear least squares method. Correlations between $N_{60,CS}$ and effective vertical overburden stresses based on the scalped dataset were developed for six different density bins. Figure 4-11 and Figure 4-12 present the resulting regressed overburden correction relationships between N_{60} vs. σ'_v , and $N_{60,CS}$ vs. σ'_v , respectively. These overall results are again similar, and good R^2 values of $R^2 = 0.81$ to 0.97 again indicate good overall fit for these C_N relationships. Representative $N_{1,60,CS}$ values of the six apparent density bins range from 9.7 to 66.7 blows/ft., while the associated overburden correction factor exponents m range from 0.47 to 0.30.

The California Department of Water Resources (CDWR, 2005) had previously developed site-specific overburden correction factors (C_N) for this shallow alluvium underneath of left reach of Perris Dam in 2005. They collected 316 SPT N values from the upper 25 ft between Stations 85+00 and 112+00 where they judged that the depositional environment exhibits the highest degree of continuity. They grouped the data into seven “percentile” bins, then they statistically regressed SPT N -values over the range of overburden stress. The results of this were presented by CDWR (2005), and by Wehling and Rennie (2008), were briefly discussed previously in Chapter 2.

This current study re-evaluated SPT blow counts collected from the shallow alluvium underneath the left reach of Perris Dam, with some modifications. Firstly, there were additional SPT performed along the downstream toe of the dam since the work of Wehling and Rennie. Eleven additional SPT borings were performed between Stations 85+00 and 112+00, and the resulting additional SPT blow counts were added to the dataset. Selection of bins also differed between this study and the previous work of CDWR. This current study preferred to bin the data based on actual relative density ($N_{1,60}$ bins) while CDWR selected “percentile” bins (placing a similar percentile of the overall data at each range of binned effective overburden stresses into the bins) with bin percentiles selected to maximize the overall fit to the data (as expressed by the regressed correlation coefficients’ and their resulting R^2 values.). Notwithstanding these differences, the results of this study and the study of CDWR (2005) are within the same ranges (see Fig. 2-24), with overburden correction factor exponents (m -values) found to systematically decrease as penetration resistance increases.

4.5 Perris Dam, Left Reach, Deep Alluvium

The alluvial foundation in Perris Dam foundation is primarily Pleistocene and younger moderately consolidated to unconsolidated shallow alluvium. There is an apparent age distinction in the alluvium due to the regional depositional history. Therefore, the foundation alluvium was divided into two distinct units; the shallow upper alluvium (the surficial alluvial unit, Q_{sal}) in the upper 20 feet or so of the alluvium, and older (deeper) alluvium (Q_{al}) underneath it. Site-specific C_N relationships for the older, deeper alluvium had not been needed for the engineering evaluations of CDWR, but this deeper alluvium unit provides an additional opportunity for development of material-specific C_N relationships for silty soils.

Consistent geologic deposition on the left reach of the Perris Dam and how it led to continuous and uniform shallow alluvium had been already discussed in Section 4.4.2. Similarly, it has been assumed that this consistent geologic deposition led to relatively good geologic uniformity (relatively uniform heterogeneity) of the uniform deep alluvium unit, perpendicular to the dam axis beneath the left reach of Perris Dam. Consequently, effective vertical overburden stresses and SPT N-values can be correlated within this unit.

A total of 237 SPT N-values were obtained within the upper twenty feet of deep alluvium between Stations 85+00 and 112+00 underneath the crest, upper bench, lower bench and toe, with effective vertical overburden stresses ranging from 0.9 tsf to 9.4 tsf. Table B-3 of Appendix B presents a summary of SPT data collected from this deep alluvium, and results of corollary laboratory tests.

The SPT procedures and equipment used in Perris Dam were previously described in Section 4.4.2. According to field and laboratory classifications, approximately 36 percent of SPT blow counts within this deeper alluvium were obtained from non-plastic silty sand (SM), about 23 percent low-plasticity clayey sand (SC), about 15 percent low-plasticity silty clayey sand (SC-SM, SM-SC), about 13 percent low-plasticity silt (ML), about 8 percent poorly graded sand with silt (SP-SM), and about 4 percent low-plasticity clay (CL).

Relationships between SPT N_{60} values and effective vertical overburden stresses were deduced from the field SPT N-values for five density bins using nonlinear least squares regression. Figure 4-13 shows SPT N_{60} values versus effective vertical overburden stresses, and correlations developed by nonlinear least squares regression to develop C_N relationships for five different density bins. Density bins were selected through iterations until the overburden correction factor exponent m used to calculate $N_{1,60}$ for binning, and the regressed overburden correction factor exponent m for each bin, converged. Overall fit of the resulting regressed N_{60} vs. σ'_v relationships is consistently good, with R^2 values ranging from 0.83 to 0.95 for the five data bins employed. Representative $N_{1,60}$ values of the five final density bins range from 19.6 to 61.9 blows/ft., while overburden correction factor exponents m range from 0.40 to 0.30. This deep alluvium is denser than the shallower overlying alluvium stratum analyzed previously in Section 4.4, and this led to higher $N_{1,60}$ values and smaller m values, as would be expected.

Fines contents of the samples associated with these SPT N-values range from 10 percent to 58 percent, with a median fines content of 31 percent. Fines contents affect measured SPT N_{60} values. To further investigate this, SPT N_{60} values were corrected to $N_{60,CS}$ to take fines content into account, and then these fines-corrected $N_{60,CS}$ values were regressed over the range of effective vertical overburden stresses. Figure 4-14 shows $N_{60,CS}$ vs. σ'_v relationships for five different density bins. Representative $N_{1,60,CS}$ values range from 23.7 to 70.9 blows/ft., while m values range from 0.40 to 0.30. Making fines corrections prior to regressing C_N relationships did not lead to very significant changes in m values; the changes were found to be relatively minor.

The SPT data includes a number of SPT performed in relatively plastic soils, as plasticity index of samples tested varied from 0 to 15 percent. SPT N-values associated with

more plastic, clayey material (CL and SC) were next excluded (deleted) from the data set, and the regressions to develop C_N relationships were performed again. As a result of this “scalping” of data for clayey soils, the percentage of non-plastic silty sand in the data set increased to 50 percent, with the remaining 50 percent being low-plasticity silt (ML), low plasticity silty clayey sand (SC-SM) and poorly graded sand with silt (SP-SM). Plasticity index values for the remaining soils varied from 0 to 7, and these remaining data were judged to better represent the types of soils predominantly represented in current liquefaction triggering field case histories databases. Another set of nonlinear regressions was performed based on these remaining 172 N_{60} and $N_{60,CS}$ values. Figures 4-15 and 4-16 show the regressed C_N relationships that resulted once the SPT data for CL and SC soils had been deleted. Figure 4-15 shows the regressed C_N relationships for N_{60} values, and Figure 4-16 shows similar relationships for regressions performed by first making fines corrections based on Cetin et al. (2004), and then regressing these data. For both figures, R^2 values were again high, and regressed overburden correction factor exponents m ranged from 0.30 to 0.43.

4.6 Perris Dam, Right Reach

Geologic deposition on the right reach of the Perris Dam is not as consistent as the geologic deposition on the left reach of the dam. Shallow slope wash deposits eroded off the right abutment beneath the right side of Perris Dam, and stream channel deposits incised through these slope wash deposits. From the end of the right abutment, the amount of stream channel deposits become more prominent, and relatively continuous geologic units were encountered perpendicular to the dam axis in the upstream-downstream direction underneath the crest towards the toe. Figure 4-17 shows typical section through the right reach of Perris Dam and its foundation.

As shown in Figure 4-18, SPT were performed along the toe, along a bench road approximately mid-way up the slope face, and along the crest on the Right Reach of the Perris Dam. Equipment and procedures, including hammer energy calibration, for the SPT investigations at Perris Dam were previously described in Section 4.4.2. A total of 52 SPT blow counts were collected between Stations 17+50 and 52+50 in the upper alluvium of the Right Reach. Effective vertical overburden stresses for these SPT ranged from 0.2 tsf to 7.8 tsf. SPT data from the upper foundation strata at the right reach of the dam, and corollary laboratory tests results performed on SPT samples, are presented in Table B-4 of Appendix B. According to field and laboratory classifications, about 48 percent of SPT blow counts were obtained from non-plastic silty sand (SM), about 35 percent poorly graded sand with silt (SP-SM), about 7 percent low-plasticity silt (ML) and about 6 percent low-plasticity clayey sand (SC).

Figure 4-19 shows collected SPT N_{60} values versus effective vertical overburden stresses for four different density bins. Density bins were selected through iterations until the overburden correction factor exponent m used to calculate $N_{1,60}$ for binning, and the regressed overburden correction factor exponent m converged. Correlations between N_{60} and σ'_v were developed using nonlinear least squares regression for these four density bins, and this provided good fit of N_{60} vs. σ'_v relationships as demonstrated by R^2 values ranging from 0.85

to 0.94. Representative $N_{1,60}$ values of the four density bins range from 17.6 to 68.2 blows/ft., while overburden correction factor exponents m range from 0.38 to 0.28..

Fines contents of samples ranged from 25 percent to 51 percent, with a median fines content of 29 percent. SPT N_{60} values were corrected to $N_{60,CS}$ to investigate the effects of fines contents on penetration resistance, and then the fines-adjusted $N_{60,CS}$ values were regressed over the range of effective vertical overburden stresses. Figure 4-20 shows $N_{60,CS}$ - σ'_v relationships for four different density bins. Representative $N_{1,60,CS}$ values range from 21.2 to 77.2 for the four bins, while m values range from 0.38 to 0.28. Fines contents correction did not significantly change the regressed m values because fines contents associated with the SPT N values were relatively consistent within each density bin.

The amounts of clayey, relatively more plastic soils, were found to be much less in the upper foundation soils of the right reach compared to the left reach of the dam. Only 6 percent of the SPT were performed in low-plasticity clayey sand (SC), and virtually none in CL materials. The majority of these SPT were performed in silty sands of low plasticity (to non-plastic) classified as SM. Consequently, when the SPT dataset was scalped to exclude clayey soils (CL and SC), little change in the regressed C_N relationships resulted. Figure 4-21 shows a plot of N_{60} versus effective vertical overburden pressure for the scalped dataset, and the resulting regressed C_N relationships. Similar regressions of the scalped dataset were performed with fines-adjusted “equivalent clean sand” $N_{1,60,CS}$ values, and Figure 4-22 shows $N_{1,60,CS}$ data versus effective vertical overburden stresses along with the results of the nonlinear regressions for C_N relationships. Representative $N_{1,60,CS}$ of density bins range from 20.4 to 77.2 blows/ft., while associated overburden correction factor exponents m range from 0.40 to 0.28. R^2 values continue to be high, ranging from 0.84 to 0.92.

4.7 Sunset Reservoir, North Basin

Sunset Reservoir is located in the Sunset District of San Francisco and it is divided into two basins, north and south, separated by an earthen berm. The north and west sides of the North Basin are comprised of a compacted earth fill embankment founded on surficial soil deposits overlying the rock of the Franciscan complex. Surficial soil deposits were classified as Pleistocene and more recent in age, and include native dune sands and silty sands. The upper dune sands are predominately clean, poorly graded, fine to medium sand (SP) of varying thickness (OCC, 2004), and they overlie loose to medium dense low plasticity silty sand (SM) of about 10 to 20 feet in thickness. The focus of this study is limited to the northwest of the reservoir where the majority of the SPT boreholes are located. Geologic deposition is judged to have been relatively consistent within foundation materials underneath this very limited section of the reservoir.

Figure 4-23 shows a cross section through this northwest section of the reservoir, and the foundation stratigraphy developed based on the boring data.

Figure 4-24 shows plan view of the Sunset Reservoir North Basin and boring locations along the embankment. A total of seven boreholes were performed on the northwest corner of the reservoir. The results of boreholes EB-4, EB-5, AB-4, AB-5, AB-6, BV-6, S-2 are shown

on Cross Section A (Figure 4-23). Field investigations were performed in four phases. In 1998, borings EB-4 and EB-5 were drilled by the rotary wash method. During second phase, in 2000, borings BV-2 and BV-6 were drilled by rotary wash. Later phases included borings AB-6 and S-2, which were drilled by mud rotary drilling in 2002, and AB-4 and AB-5, which were drilled by hollow stem auger in 2003. Hammer energy calibration was made during SPT sampling of 2003 investigation in another boring AB-1 on the dam site. Average energy transfer ratio was determined as 72 percent. However, there are differences in equipment and procedures used to perform SPT since field investigations were carried out in phases. For instances, SPT were performed with standard split-spoon penetrometer (2 inch O.D. and 1.375 inch I.D), except in borings B-4 and EB-5, which had spaces for internal liners. Samplers were generally driven by 140 lb. automatic trip hammers falling 30 inches, except borings BV-2 and BV-6, which required different energy corrections. Consequently, it is necessary to apply different SPT correction factor to standardize the test results. SPT N-values collected from Cross Section A, and necessary SPT correction factors based on hammer energy ratio, borehole diameters, sampler types and configuration, and rod length, are presented in Table B-5 in Appendix B.

SPT were performed in foundation deposits underneath the northwest side of the reservoir. Although geologic deposition was relatively consistent within this limited section, dune sand and silty sand of varying thickness showed some variation in density from loose to medium dense. SPT data were divided into consistent density bins, as delineated by relatively consistent $N_{1,60,CS}$ for each density bin. The influence of effective vertical overburden pressure on SPT can then be assessed from the field SPT data for each of the density bins. Density bins were selected iteratively until the overburden correction factor exponent m used to calculate $N_{1,60,CS}$ for binning coincided with the final regressed overburden correction factor exponents m .

Figure 4-27 shows SPT N_{60} values versus effective vertical overburden stresses for the foundation soils of Sunset Reservoir, North Basin, and correlations between N_{60} and σ'_v developed using nonlinear least squares regression for three density bins. Representative SPT $N_{1,60}$ values for the three density bins range from 10.5 to 40.0 blows/ft., while overburden correction factor exponents m range from 0.43 to 0.31. Overall “fit” is not nearly as good as with the cases previously described, and R^2 values for the three bins are in the range of $R^2 = 0.44$ to 0.56 .

Because the dataset includes clean sands as well as silty sands, fines content ranged from 0 to 48 percent, with an average of about 10 percent. The regressed correlations of Figure 4-27 neglect the effects of fine contents on penetration resistance, and so the exercise was repeated using fines-adjusted $N_{60,CS}$ values, and the results are presented in Figure 4-28. The fines-adjusted regression produces slightly better correlations between $N_{60,CS}$ and σ'_v , with R^2 values of 0.58 to 0.78, but the m values are largely unchanged.

Finally, the regression was performed again, this time after first excluding SPT data for all CL and SC materials. This exercise was performed twice, once with N_{60} values, and then with $N_{60,CS}$ values. The results are presented in Figures 4-29 and 4-30, and they are largely similar to the results presented previously in Figures 4-27 and 4-28.

4.8 Lopez Dam

Lopez Dam is a 155-foot high zoned earthfill dam, located in San Luis Obispo County, California. It has a crest width of 40 feet and a crest length of 1,120 feet. The dam section includes a central compacted clay core and underlying foundation cutoff trench, filter drain zones upstream and downstream of the core, a semi-pervious compacted sandy gravel upstream shell, and a compacted random fill downstream shell. The downstream and upstream shells are founded on alluvium, and the geologic evidence suggests that it is unlikely that there are any significant variations between the foundation materials beneath the upstream and downstream shells of the dam. The alluvial materials underneath the core of the dam were removed as part of excavation down to the bedrock for the foundation cutoff.

Figure 4-31 shows a cross-section through the right side of the dam, and Figure 4-32 presents a plan view showing SPT boring locations. A geologic and geotechnical investigation report on Lopez Dam prepared by GEI in 1994 concluded “existing alluvium in the valleys is possibly the result of two generations of deposition. The older alluvium appears as broad, generally flat terraces, either old stream bed or colluvium and forms slightly higher deposits bordering one or both sides of the young alluvium. Younger alluvium exists in the present stream channel and confined to the central stream valley. Both the young and old alluviums have very similar material and textural characteristics.”

Based on the core trench excavation and recent field investigations, the thickness of the foundation alluvium ranged from 22 feet near the right abutment to 110 feet near the (central) maximum section of the dam. The thickness of alluvium deposits is relatively uniform in the center of the dam and is about 100 to 120 feet. Alluvium materials included silt and clay with sand; sandy silt and sandy clay with various amount of gravel; narrowly to broadly graded sand with silt and clay and various amounts of gravel; and sandy gravel with silt and clay (GEI, 1995). According to the GEI investigation (1995), foundation alluvium beneath the downstream shells of the dam is fairly uniform although there are some variations in blow count with depth. Based on the SPT N-values, material descriptions and cross boring correlations, GEI (1995) divided the alluvium into five distinct layers described as Layers A through E.

In addition to the GEI investigation reported by GEI (1995), several additional site investigations had been conducted at this dam site. The first investigation was conducted for dam design in the 1960's. A second site investigation concentrating on the alluvium was conducted in 1980, and another limited site investigation was carried out in 1991. However, either the penetration testing procedures of those investigations are not appropriate or the location and the number of the boreholes are not adequate to accurately analyze the effect of overburden pressure on penetration resistance. That's why the results of those investigations were not included in this thesis.

GEI Consultants performed additional field and laboratory investigation programs at Lopez Dam in 1994 to further investigate the foundation alluvium. A total of eight borings were drilled to perform SPT along the downstream berm, downstream road, and downstream

toe of the dam. The locations of more recent field investigation are presented in Figure 4-32. Borings were generally advanced using 2-3/4 inch diameter, continuous-flight, hollow-stem augers powered by a Mobile B-61 truck-mounted drill rig. Once the foundation alluvium or the groundwater table was reached, the augers were removed and the drilling method was changed to rotary wash (GEI, 1995) in order to perform SPT suitable for liquefaction-related investigations. SPT were performed in the alluvium using AW rods and a split spoon sampler with an inside diameter of 1-3/8 inches. The sampler was driven with a standard 140-pound safety hammer falling 30 inches for each hammer blow. To determine energy transfer ratio of the hammer system, the safety hammer used to perform SPT was calibrated during the drilling of one of the borings on the site. According to hammer energy calibration performed on the site, the average hammer energy transfer ratio was approximately 52 percent. A summary of the equipment and the procedures used for standard penetration testing of the foundation alluvium is provided in Table B-6.

Among the five distinct alluvial strata, Layers A and B are relatively continuous, lying beneath the downstream berm towards the downstream toe and with geological characteristics that were judged to be relatively continuous in the direction perpendicular to the dam axis. These layers were characterized as fairly uniform in the horizontal direction beneath downstream side of the dam. Consequently, the effect of effective vertical overburden stresses can be deduced from available SPT data.

A total of 274 SPT were performed in the alluvium at approximately 2-foot intervals. SPT N-values which were obtained from gravely soils or affected by the presence of the gravel were screened out of the dataset (deleted), and 85 remaining SPT blow counts, which were performed in alluvium Layers A and B, were collected from the boreholes along the downstream berm, downstream road, and downstream toe of the dam. According to field and laboratory classifications, about 30 percent of these SPT blow counts were obtained from well graded sand with silt (SW-SM), about 26 percent non-plastic silty sand (SM) and about 29 percent clayey sand (SC) and well graded sand with clay (SW-SC). Fines contents of samples ranged from 5 percent to 60 percent. In processing these data, SPT associated with clayey samples and samples with high fines contents were excluded out of the dataset. The remaining dataset is then relatively consistent, and consists of 52 percent of well-graded sand with silt (SW-SM) and 38 percent of silty sand (SM), with the remainder being poorly graded sand (SP) or poorly graded sand with silt (SP-SM). Summaries of the SPT N-values, and corollary laboratory index tests performed on SPT samples, are presented in the Appendix B.

The remaining SPT data were iteratively separated into three bins, using the same approaches as described in the previous Sections of this these, in order to develop C_N relationships by means of nonlinear least squares regression. This exercise was performed twice, once with N_{60} values and then again with fines-adjusted $N_{60,CS}$ values. The results of these two sets of regressions are presented in Figures 4-33 and 4-34, respectively. Regressed “fit” for the denser fractions of these alluvial deposits was good, with R^2 values of between 0.77 to 0.88, but for the looser fractions R^2 values were far lower (on the order of 0.34 to 0.43).

4.9 Development of Overburden Correction Factors for Clean Sands and for Silty Soils Based on Field and Laboratory Data

4.9.1 Clean Sands

Chapter 3 presented a re-evaluation of the large scale laboratory calibration chamber test data of Marcuson and Bieganousky (1977) for three clean sands, and developed C_N relationships for clean sands based on these data.

In this current chapter, site-specific overburden correction factors (C_N relationships) were developed for clean alluvial sandy soils in the upper foundation strata beneath Duncan Dam. This provided an opportunity to compare correlations between standard penetration resistance and effective vertical overburden pressure developed based on laboratory and field data. Figure 4-5 compared overburden correction factor exponents (m) which were developed from laboratory data for 3 different clean sands (at different densities) and actual field SPT performed in clean sandy soils at Duncan Dam. Agreement between the two data sets was found to be good. Although reliable overburden correction factor exponents developed for field clean sands are few, these data support the usefulness of the C_N relationships developed based on the large scale laboratory calibration chamber test data. Equation 4.3 describes relationship between overburden stress exponent m and $N_{1,60}$ for clean sand that was developed based on these data.

4.9.2 Silty Soils

There is no similar dataset available for laboratory-based assessment of suitable C_N relationships for silty soils. Accordingly, the main focus of this chapter has been to develop such relationships based on field data comprised of SPT data obtained within foundation soil strata from beneath large dams, wherein (1) geological variability of the silty foundation strata was judged to be at least consistently variable from upstream to downstream over a useful lateral distance, and (2) the SPT were obtained at differing effective overburden stresses due to the differing effective overburden pressures from the overlying slope dam embankments.

Prior to this, it has been common to assume that the same C_N relationships can be used for both clean sands (SW and SP) and for silty soils (SM, SP-SM, SW-SM, and ML). Figure 4-35 shows a summary of the C_N exponent m -values developed in this chapter for silty soil cases (solid dots), and compares these with the clean sand values (open circles and open diamonds). As shown in this figure, it appears that C_N exponents (m values) for silty soils are systematically lower than for cleaner sandy soils. Figure 4-35 also presents regressed equations for C_N suitable for (1) clean sands, and (2) silty soils. These equations are

$$C_N = \frac{N_1}{N} = \left(\frac{1}{\sigma'_v} \right)^m \quad (\text{Equation 4-3})$$

where

$$m = 0.31 + 0.57 \cdot e^{(-0.078 \cdot N_{1,60})} \quad (\text{Equation 4- 4a})$$

for clean sands (SW, SP) and

$$m = 0.27 + 0.23 \cdot e^{(-0.040 \cdot N_{1,60})} \quad (\text{Equation 4-4b})$$

for silty soils (SM, SP-SM, SW-SM, and ML).

As an alternative, similar C_N relationships can be developed based on the datasets for clean sands and silty soils, but with fines-adjusted $N_{60,CS}$ values, as shown in Figure 4-36. Equations for the two C_N relationships (one for clean sands, and one for silty soils) are shown in the figure. In this figure, it can be seen that adjusting the N_{60} -values for fines effects (in this case based on Cetin et al, 2004) to develop $N_{60,CS}$ values serves to narrow the differences between the clean sand values and the values for silty soils, but does not fully eliminate these differences.

Based on this, Figure 4-37 presents a single overall (regressed) C_N relationship for both clean sands and silty soils. There are still some systematic differences between the apparent C_N behaviors of these two materials, but this single overall relationship may provide values accurate enough to be useful for many engineering purposes.

When greater precision is required, either the relationships of Figure 4-35 and Figure 4-36 may be used, or site-specific (material specific) C_N relationships can be developed.

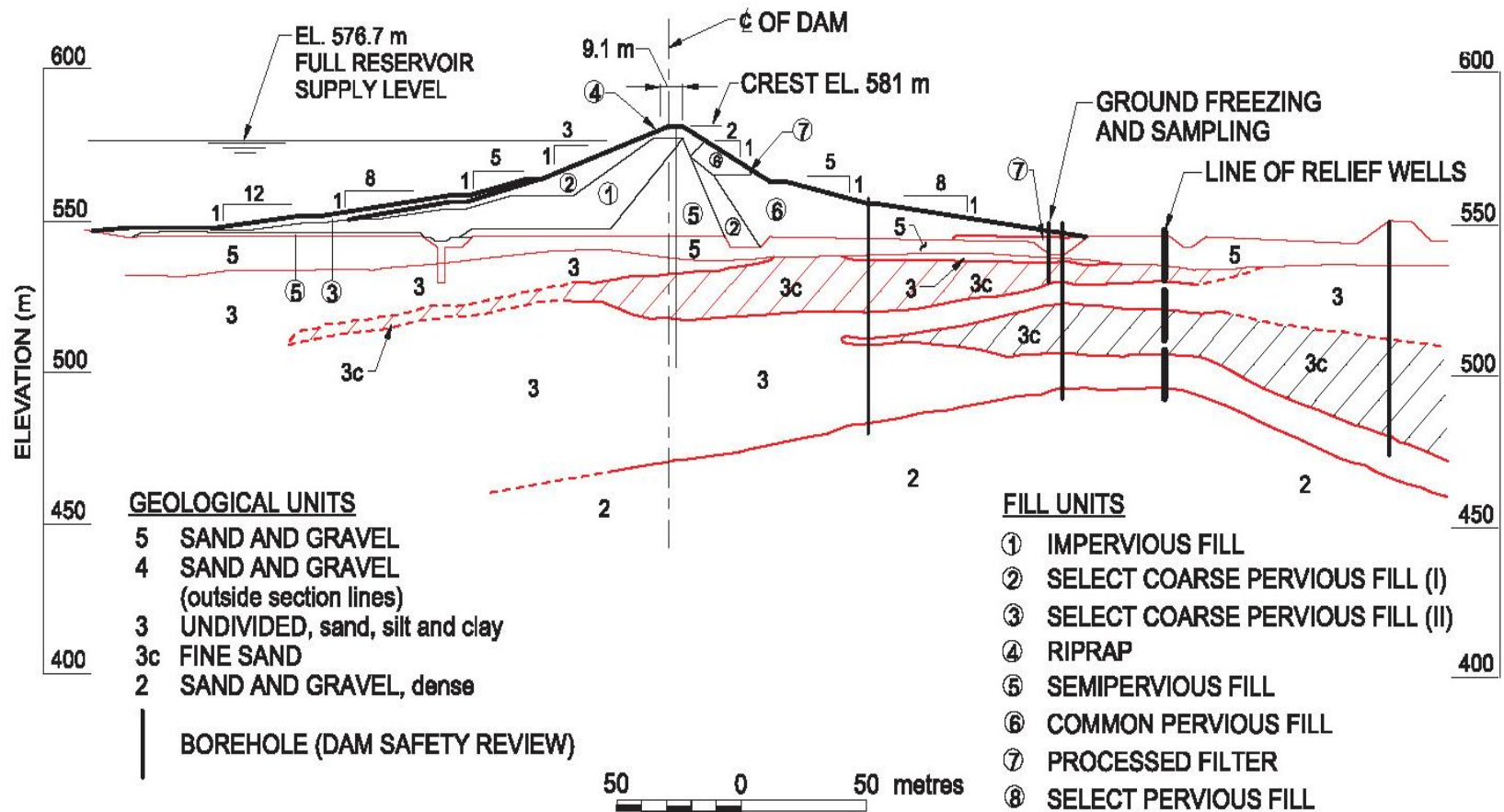


Figure 4-1: Typical Cross Section of Duncan Dam (from Olson, 2006)

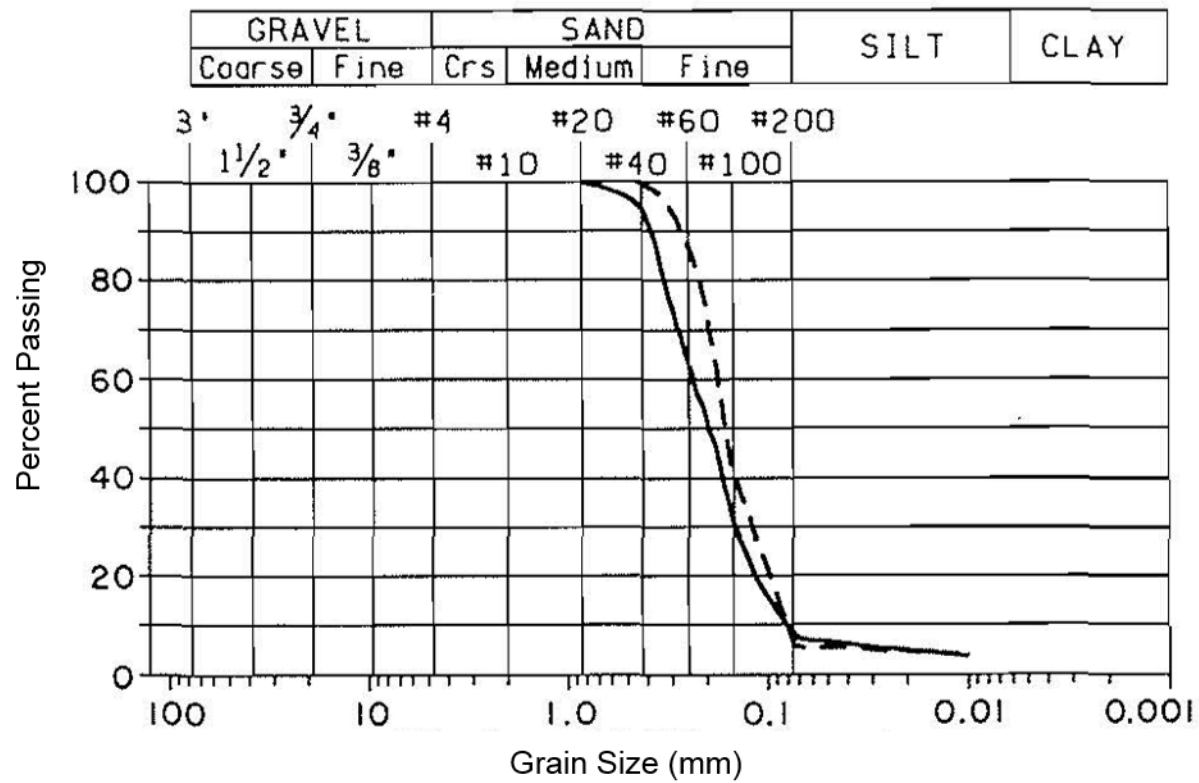
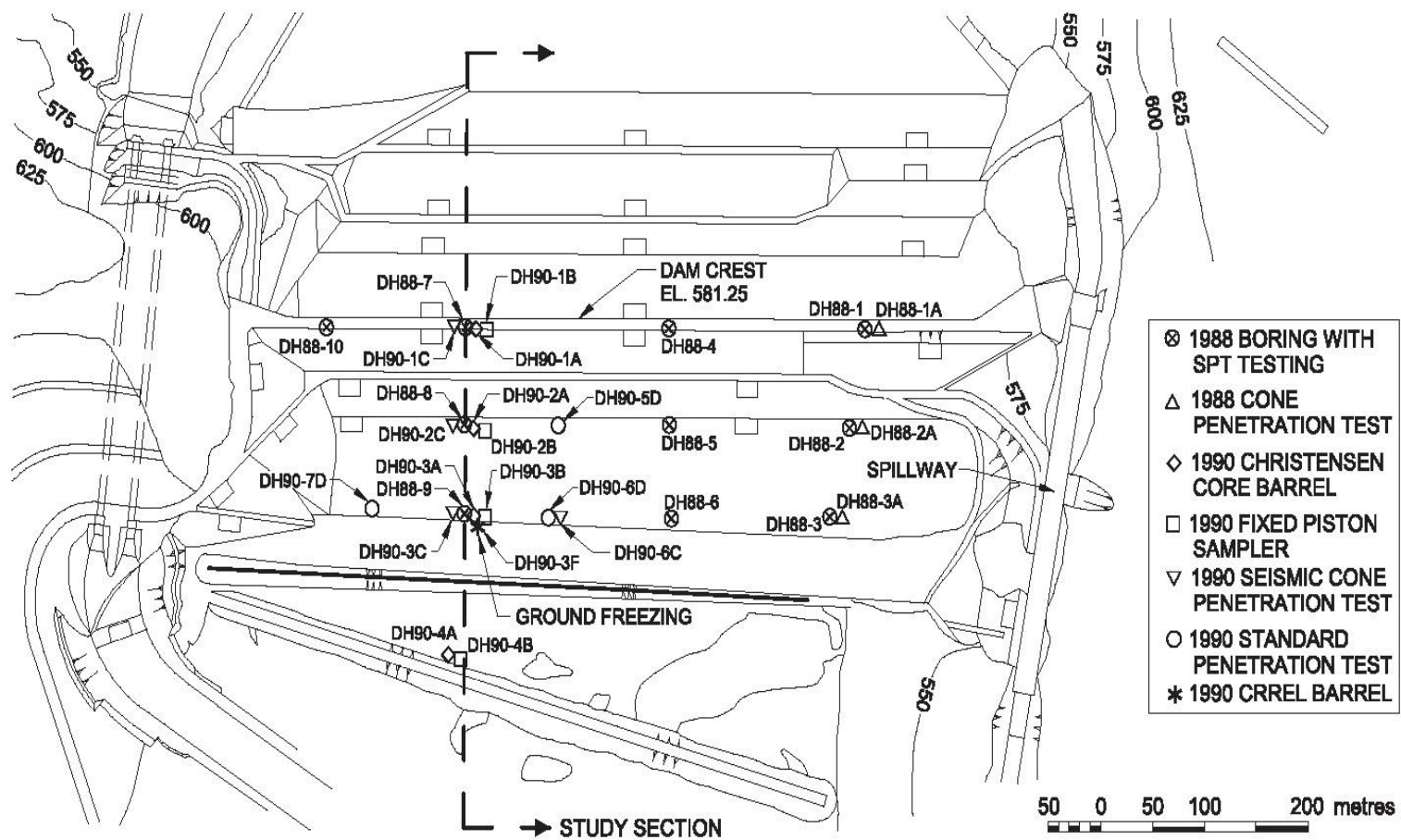


Figure 4-2: Grain Size Distribution Curve of Sandy Unit 3c (after Plewes et. al. 1994)



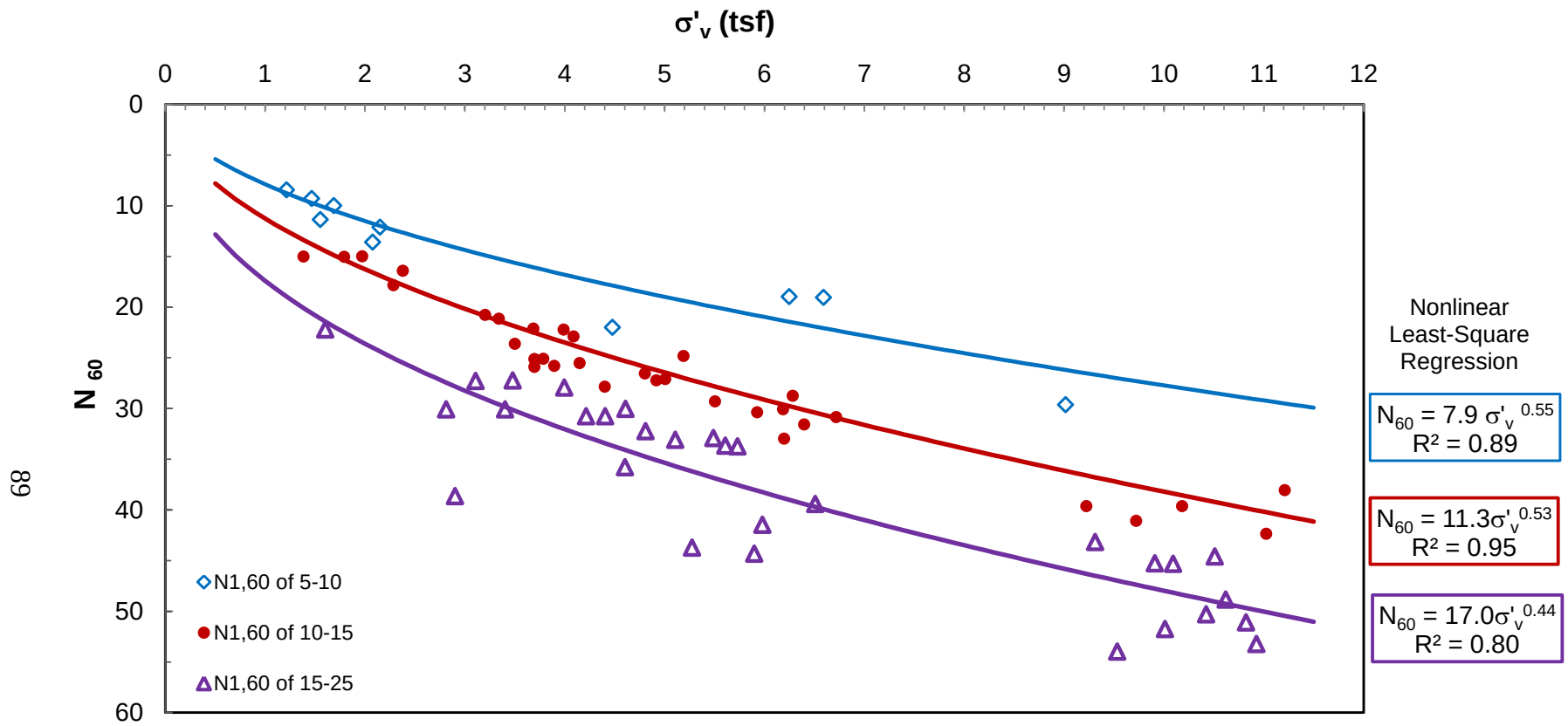


Figure 4-4: Density Bins of SPT data and Results of Nonlinear Regression for Duncan Dam
(Based on Original Data from Pillai and Stewart, 1994)

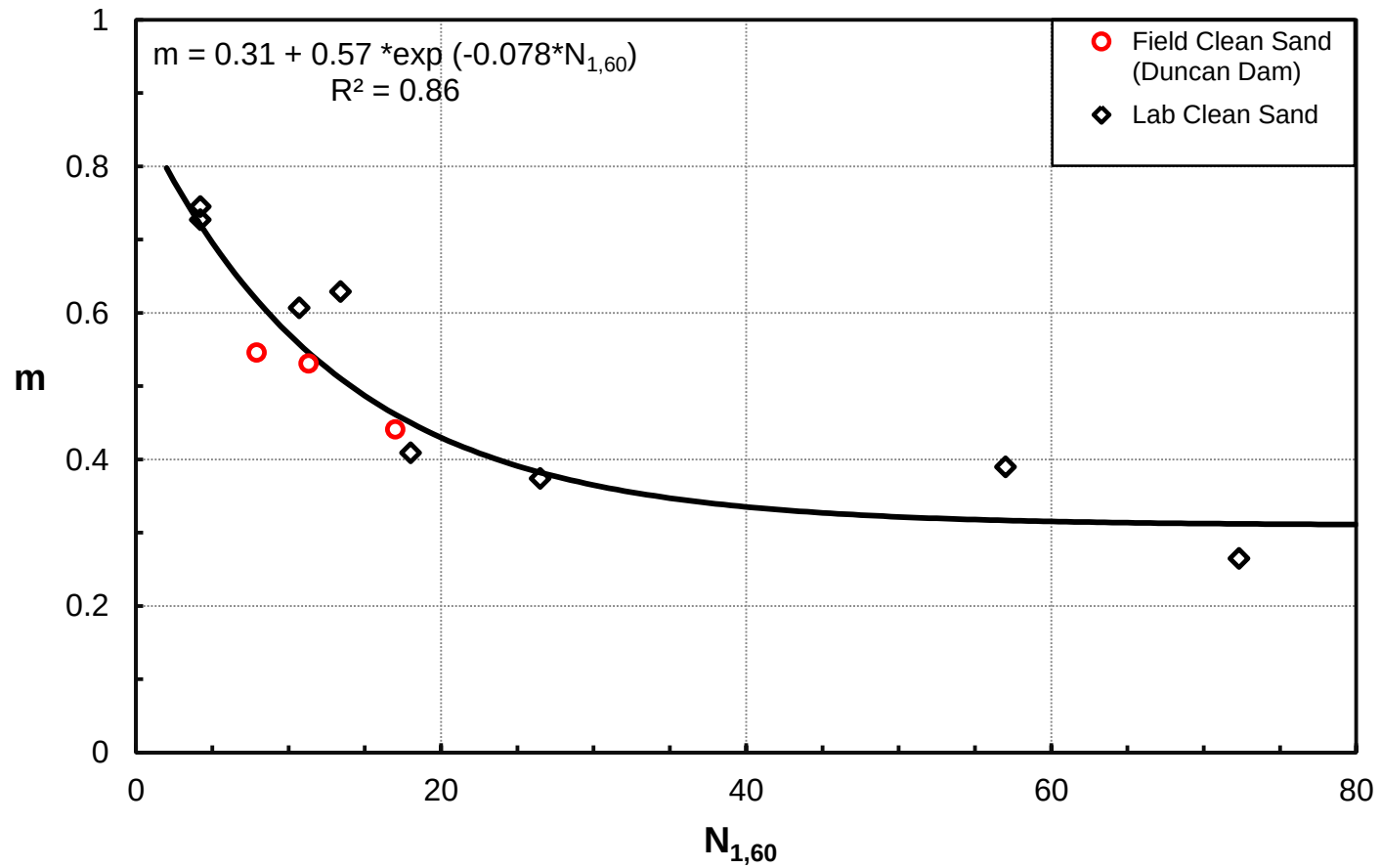


Figure 4-5: Comparison of Field-Based Overburden Correction Factor Exponents m from Nonlinear Regression of Duncan Dam Data (Pillai&Stewart, 1994) and Lab-Based Exponent m from Nonlinear Regression on SPT Calibration Chamber Test Data (Marcuson & Bieganousky, 1977a,b) along with the Relationships Proposed For Clean Sand

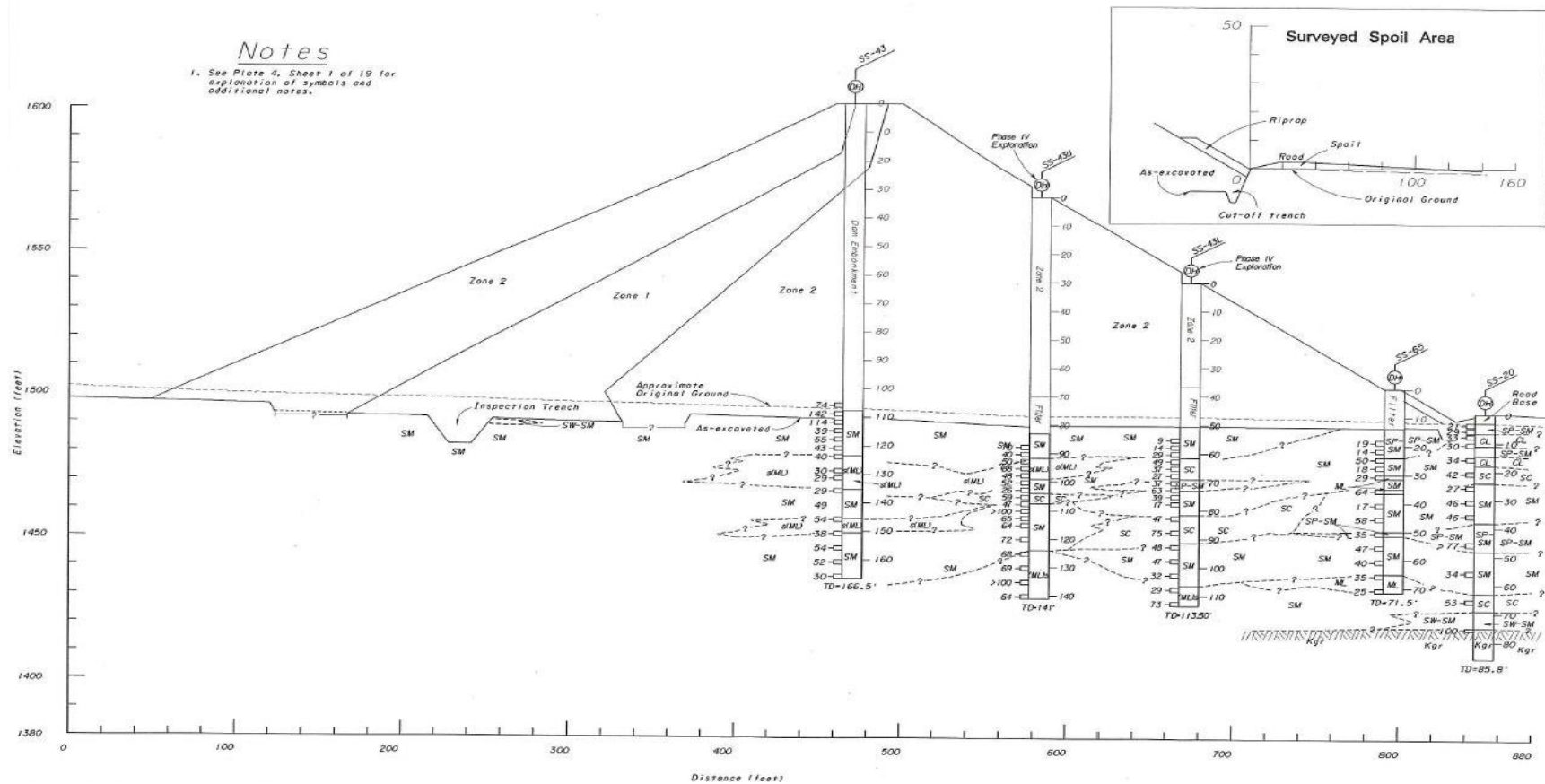


Figure 4-6: Cross-Section at the Left Reach of Perris Dam (from CDWR, 2004)



Figure 4-7: Boring Locations between Stations 90+00 to 110+00, Left Reach of Perris Dam (from ICB, 2011)

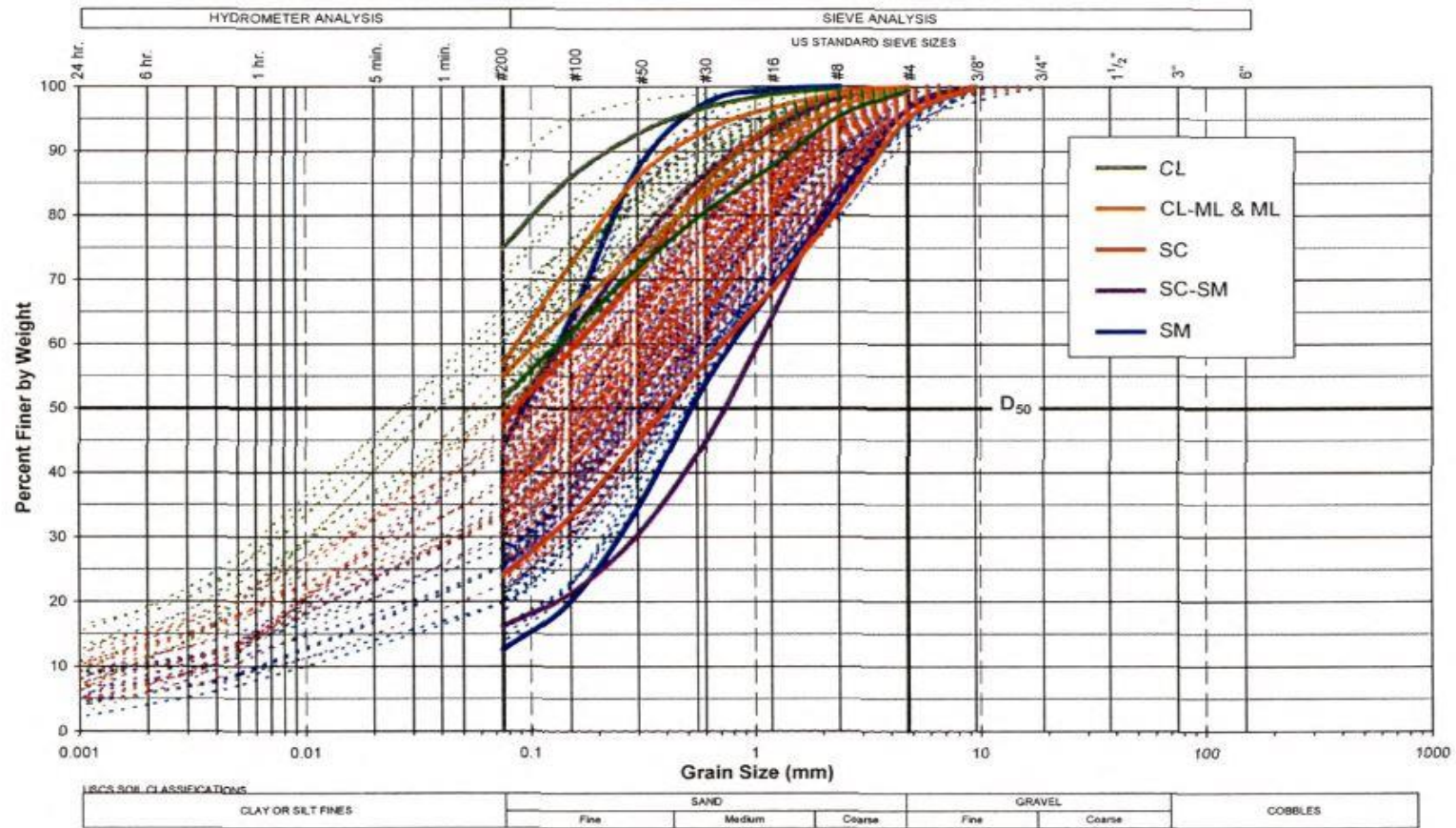


Figure 4-8: Soil Gradation Curves from Perris Dam Foundation SPT Samples, Left Reach (from CDWR, 2005)

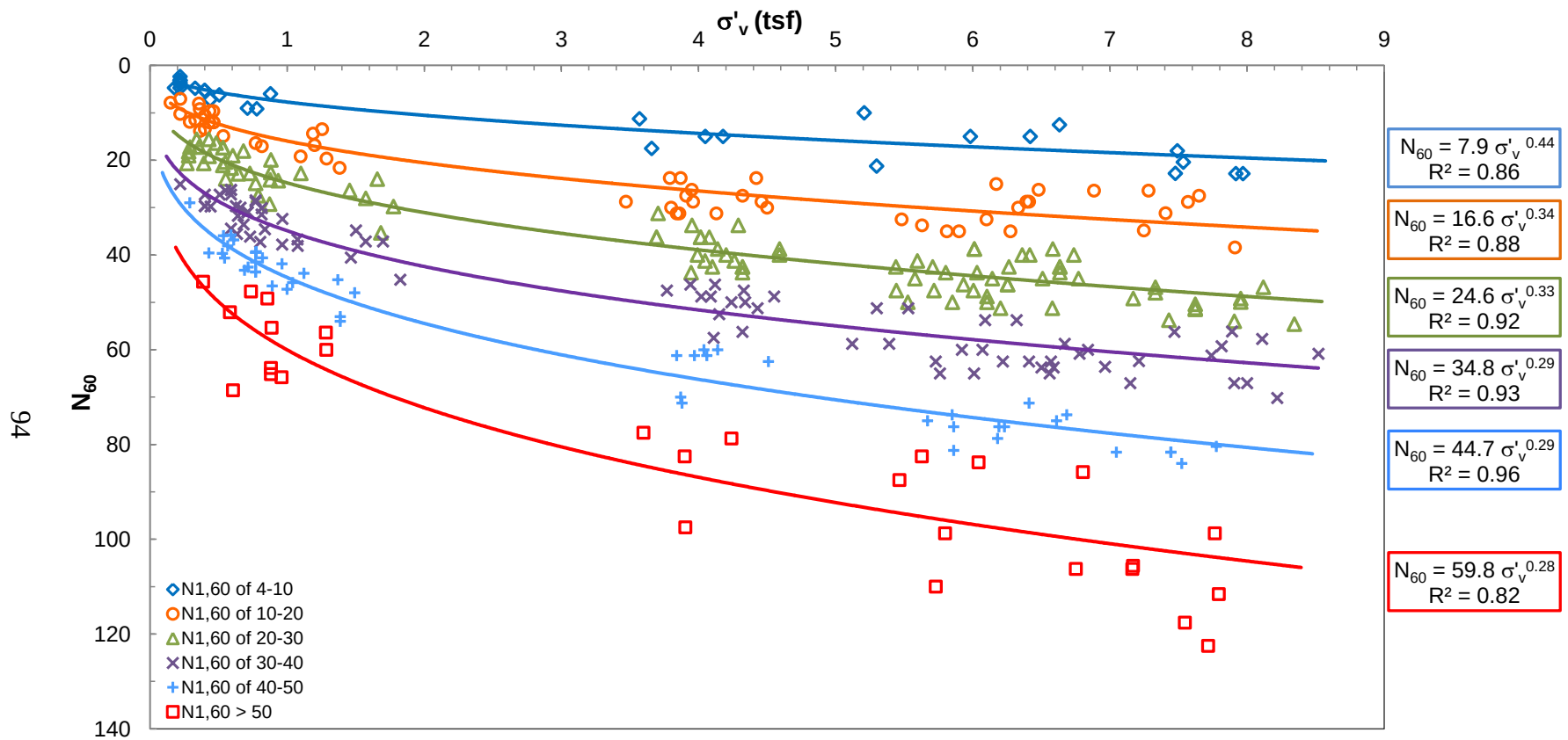


Figure 4-9: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Left Reach Shallow Alluvium
(Based on Original Data from CDWR, 2005)

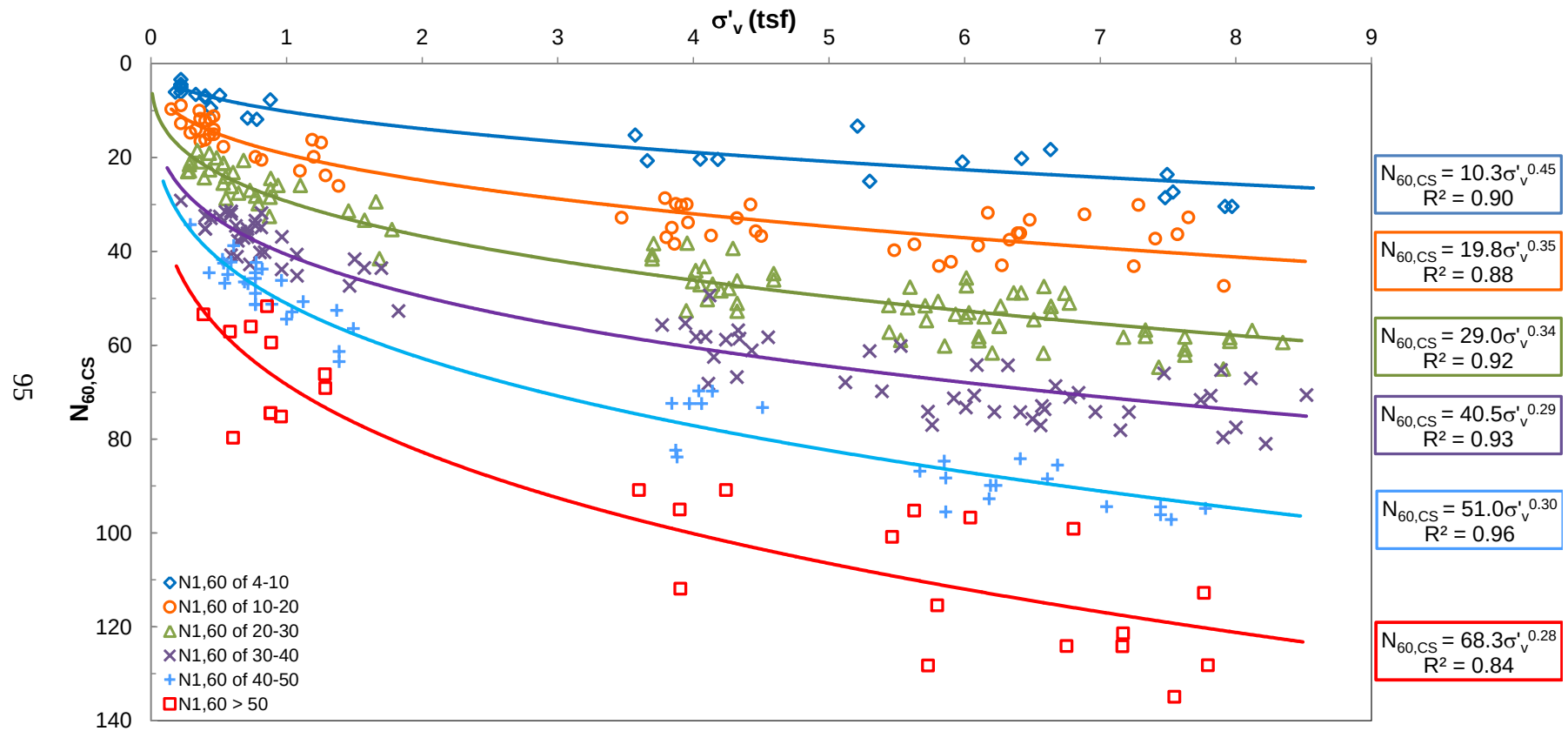


Figure 4-10: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Left Reach Shallow Alluvium
(Based on Original Data from CDWR, 2005)

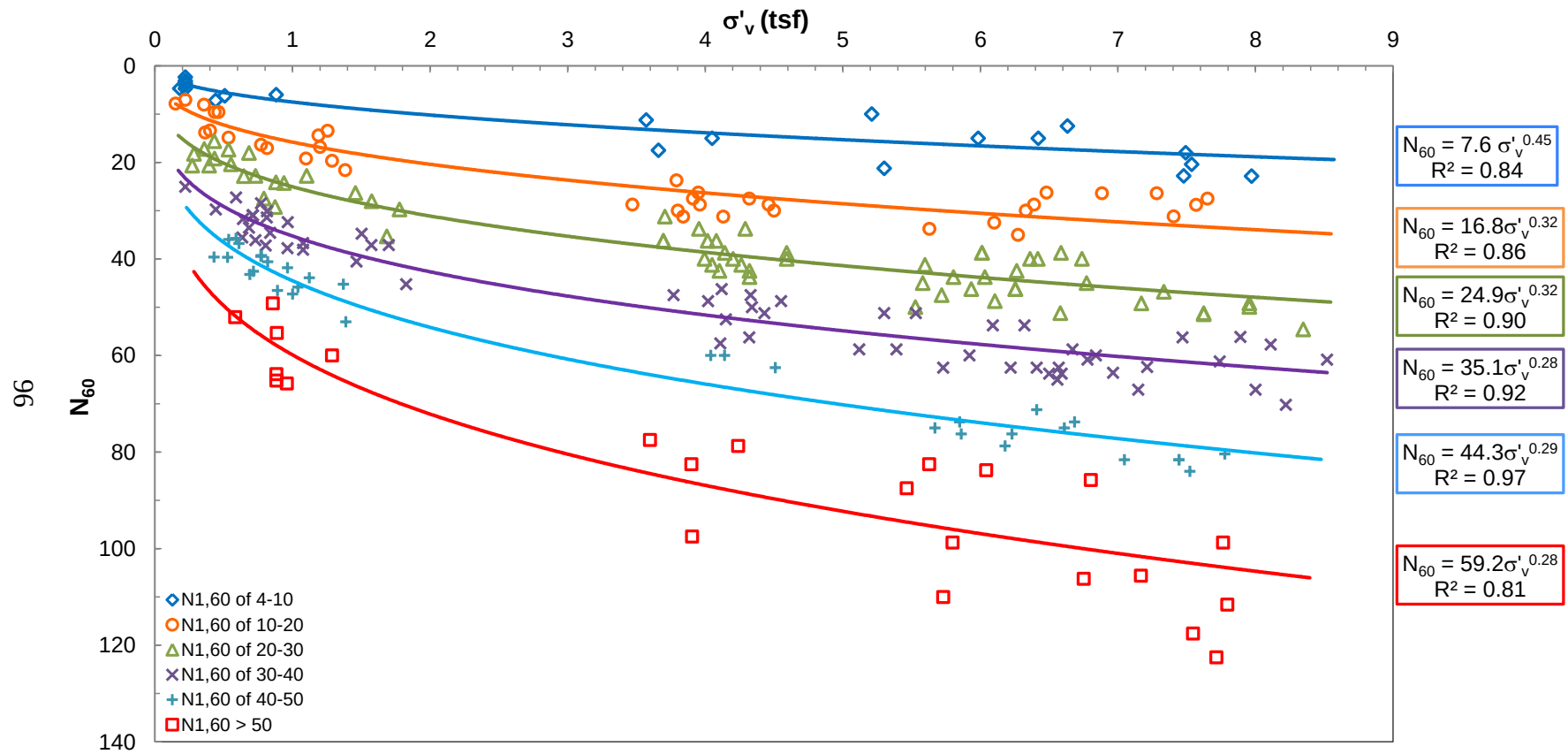


Figure 4-11: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Left Reach Shallow Alluvium Excluding CL&SC Samples (Based on Original Data from CDWR, 2005)

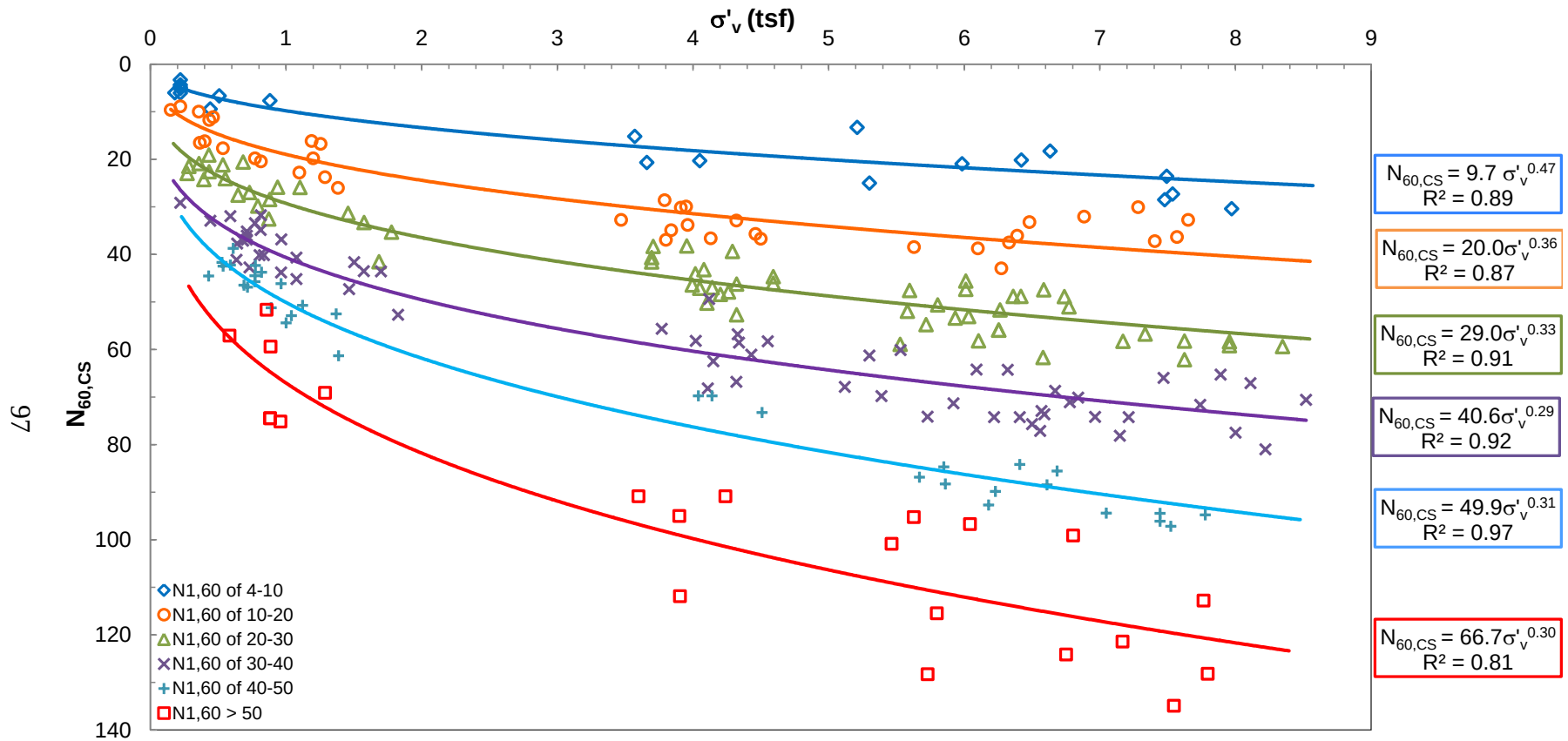


Figure 4-12: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Left Reach Shallow Alluvium Excluding CL&SC Samples (Based on Original Data from CDWR, 2005)

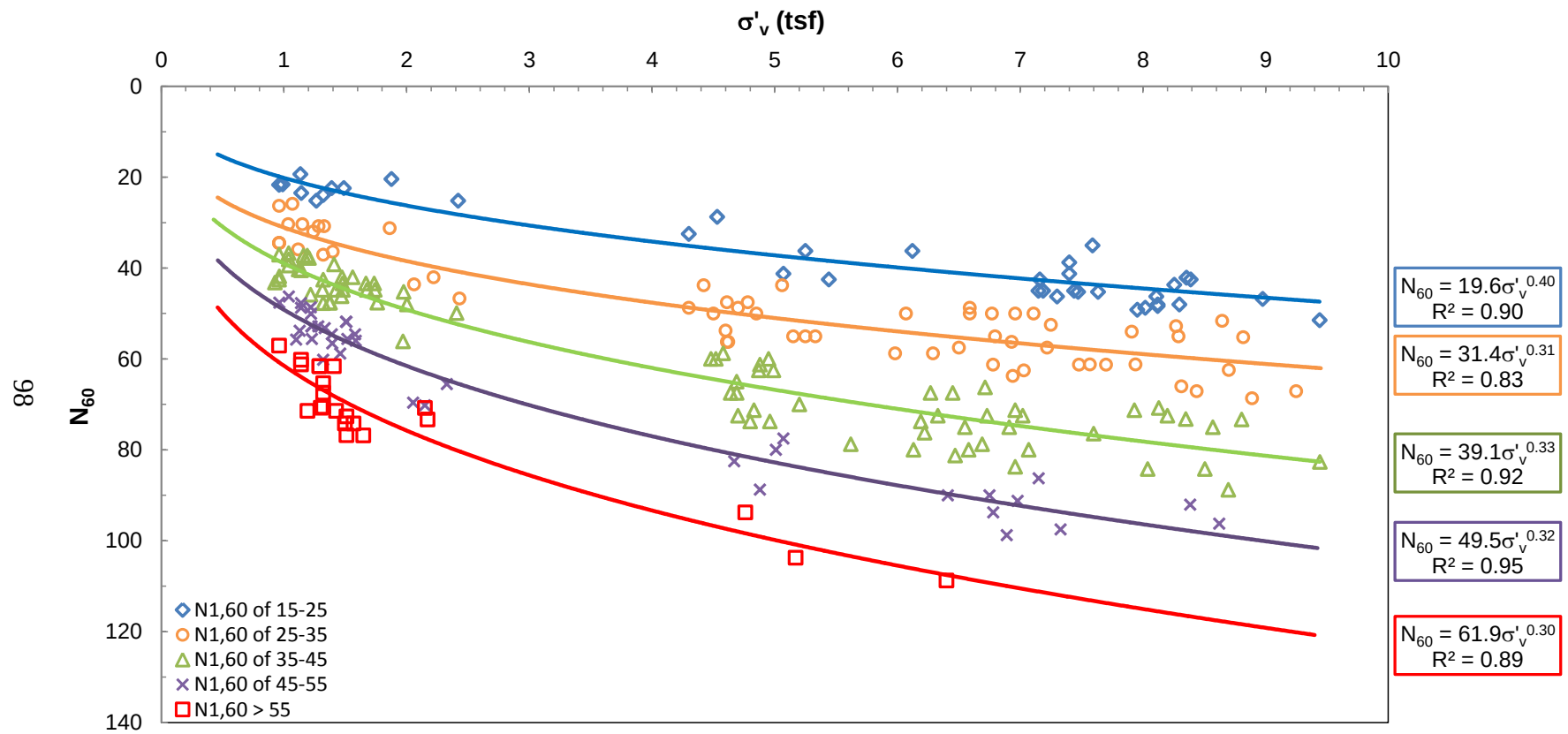


Figure 4-13: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Left Reach Deep Alluvium
(Based on Original Data from CDWR, 2005)

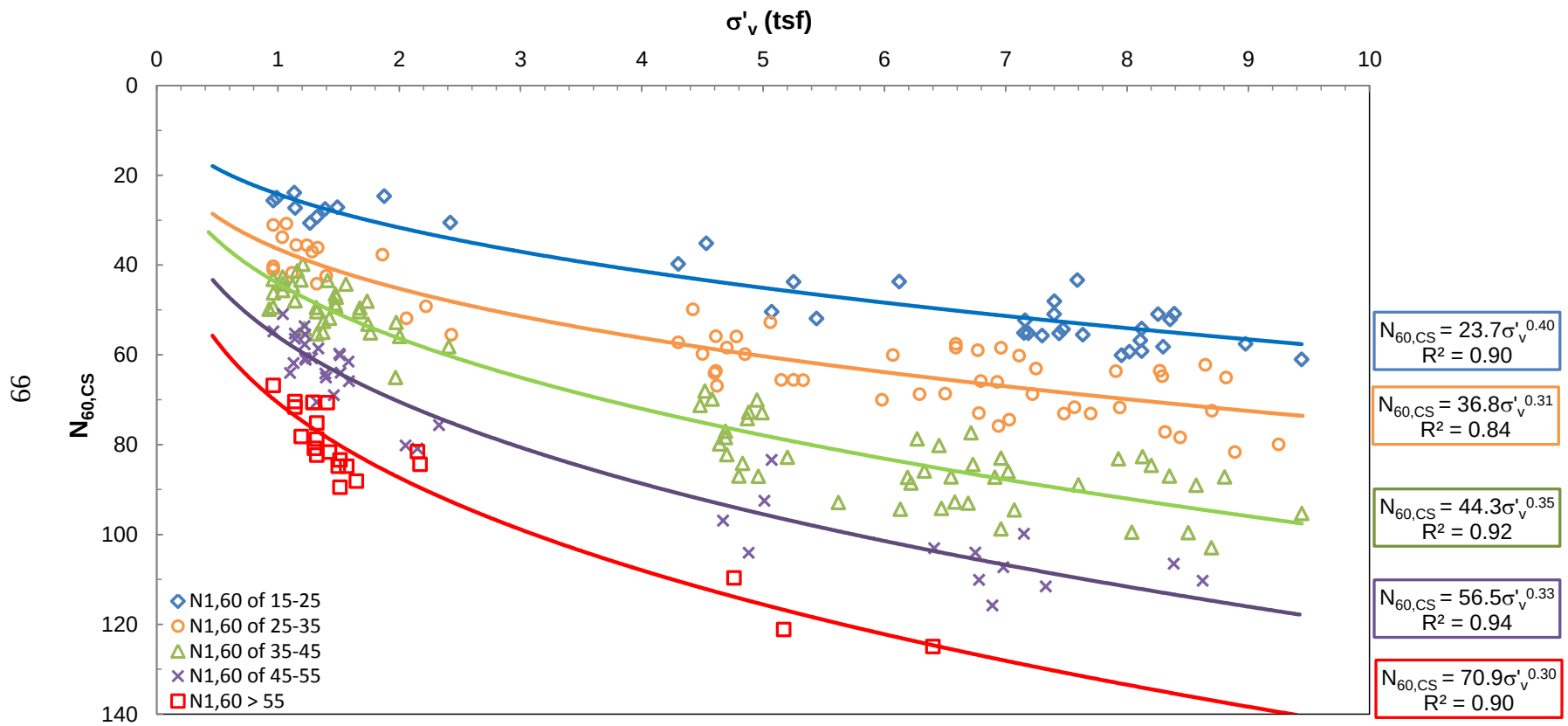


Figure 4-14: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Left Reach Deep Alluvium
(Based on Original Data from CDWR, 2005)

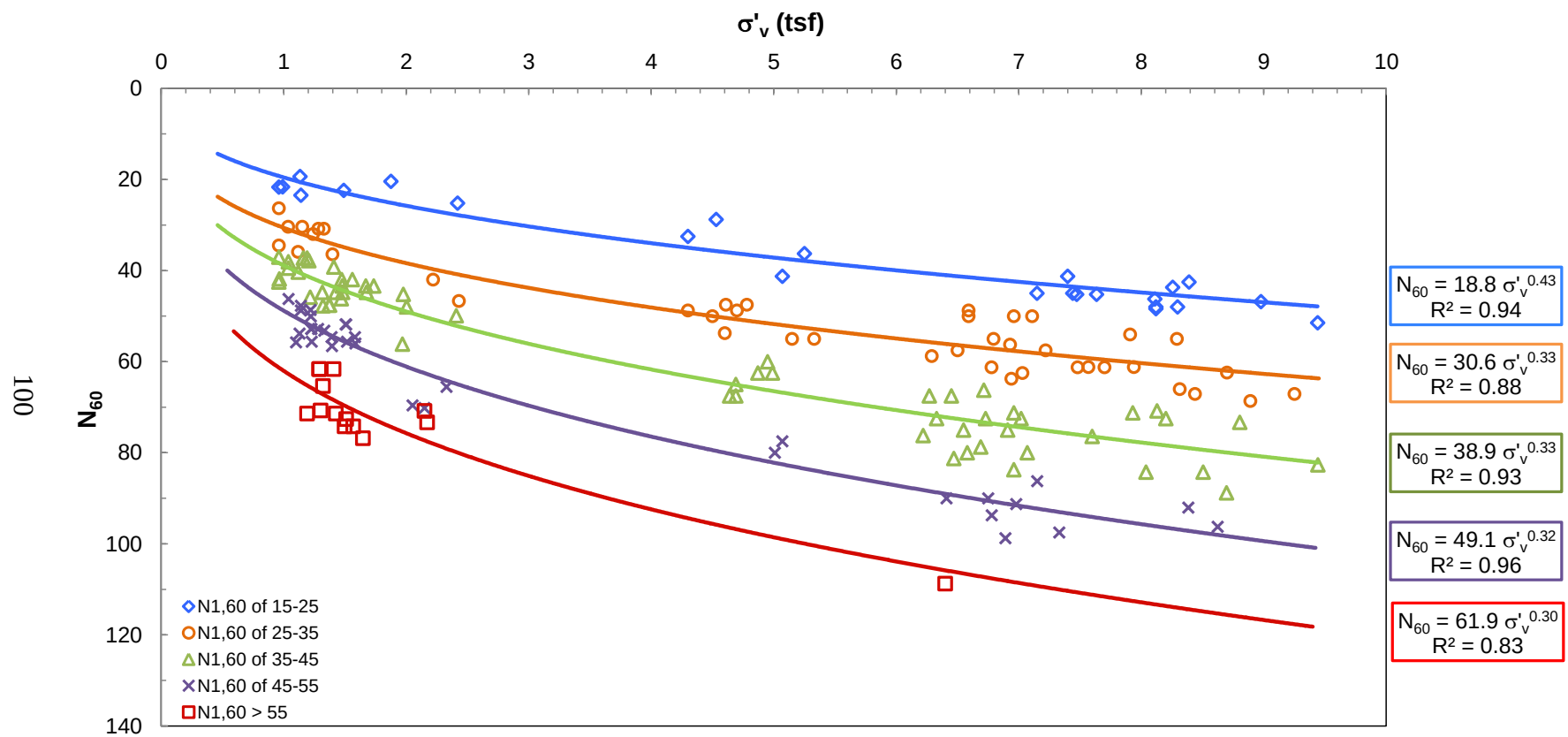


Figure 4-15: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Left Reach Deep Alluvium Excluding CL&SC Samples (Based on Original Data from CDWR, 2005)

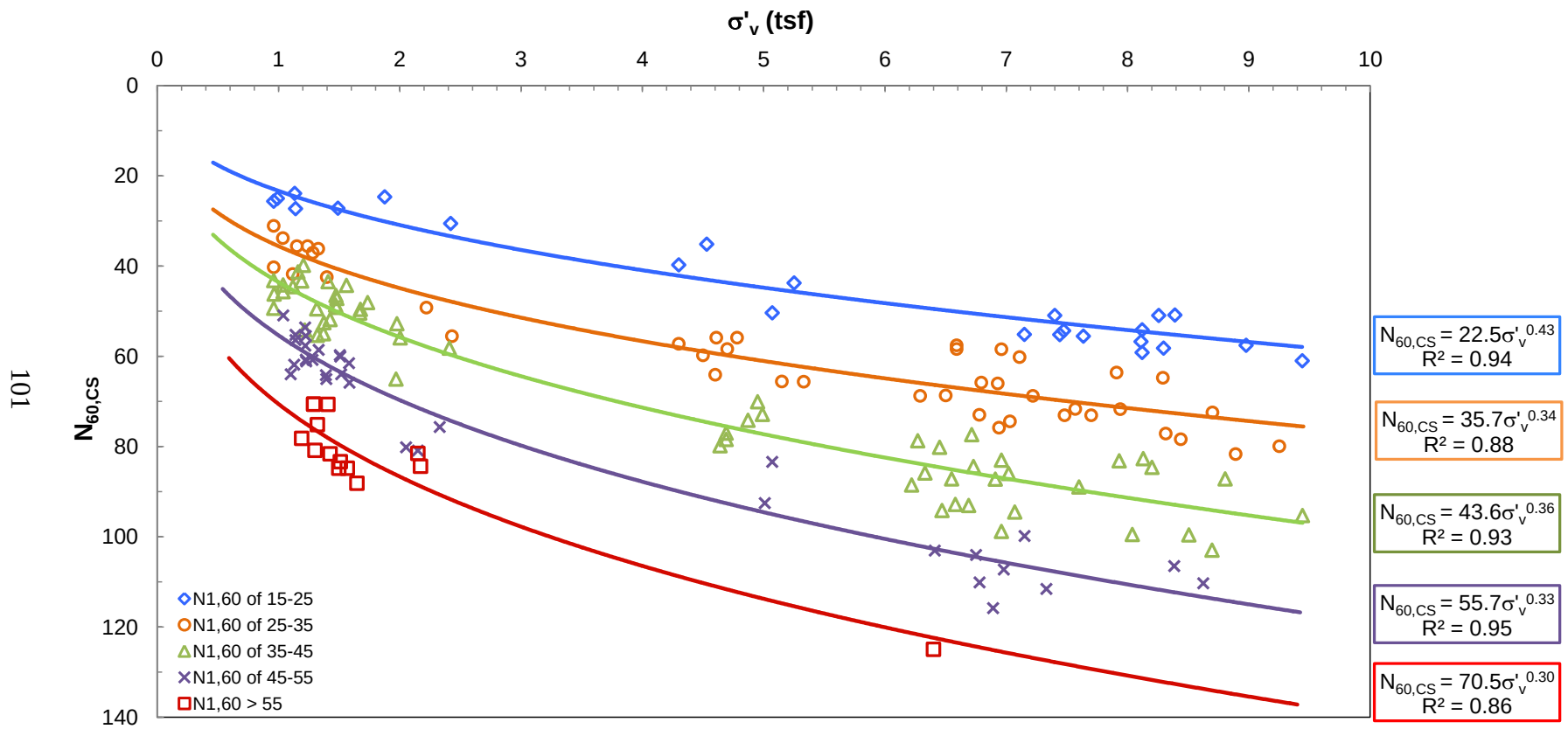


Figure 4-16: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Left Reach Deep Alluvium Excluding CL&SC Samples (Based on Original Data from CDWR, 2005)

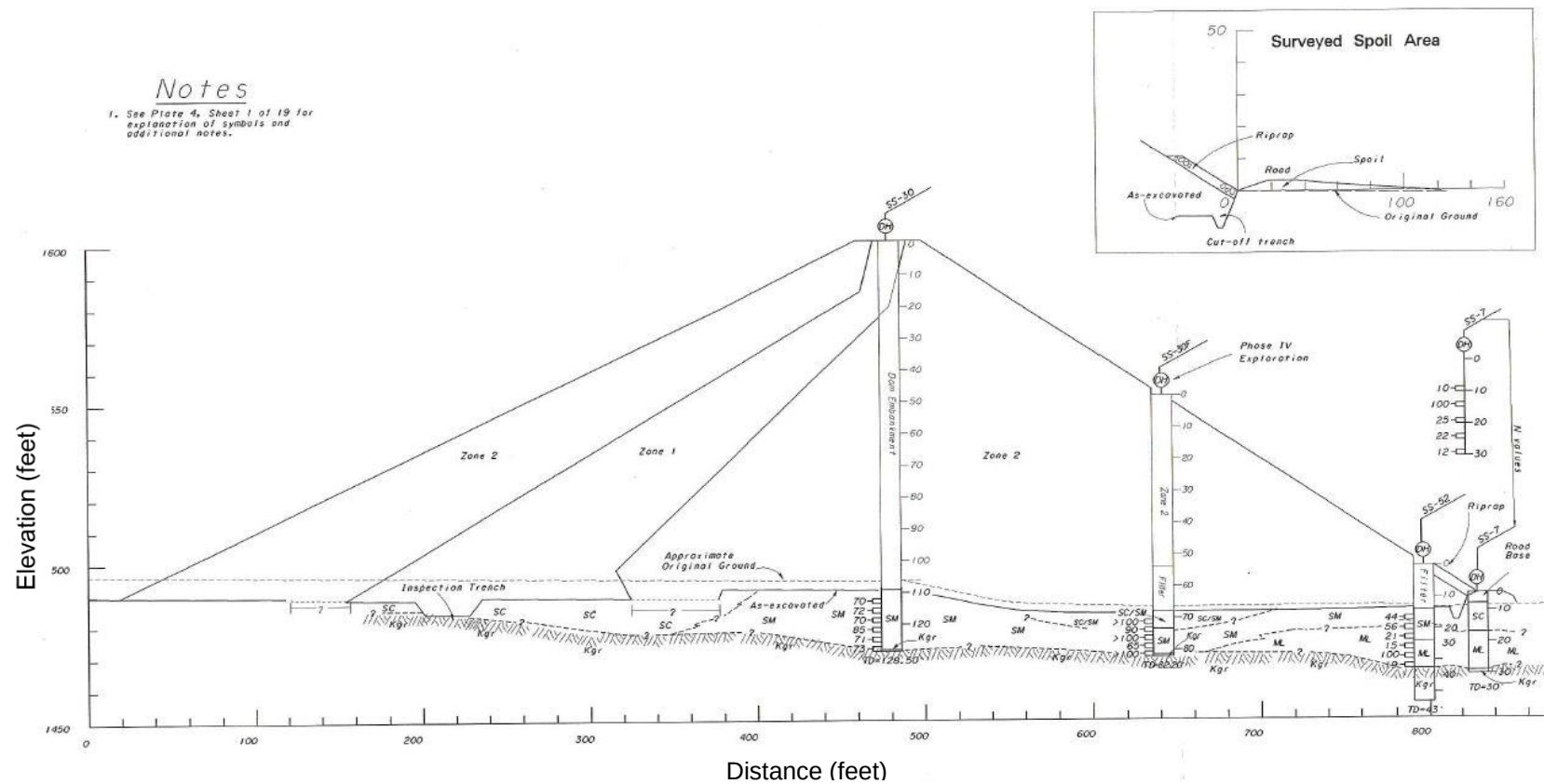


Figure 4-17: Typical Cross Section at the Right Reach of Perris Dam (from CDWR, 2005)

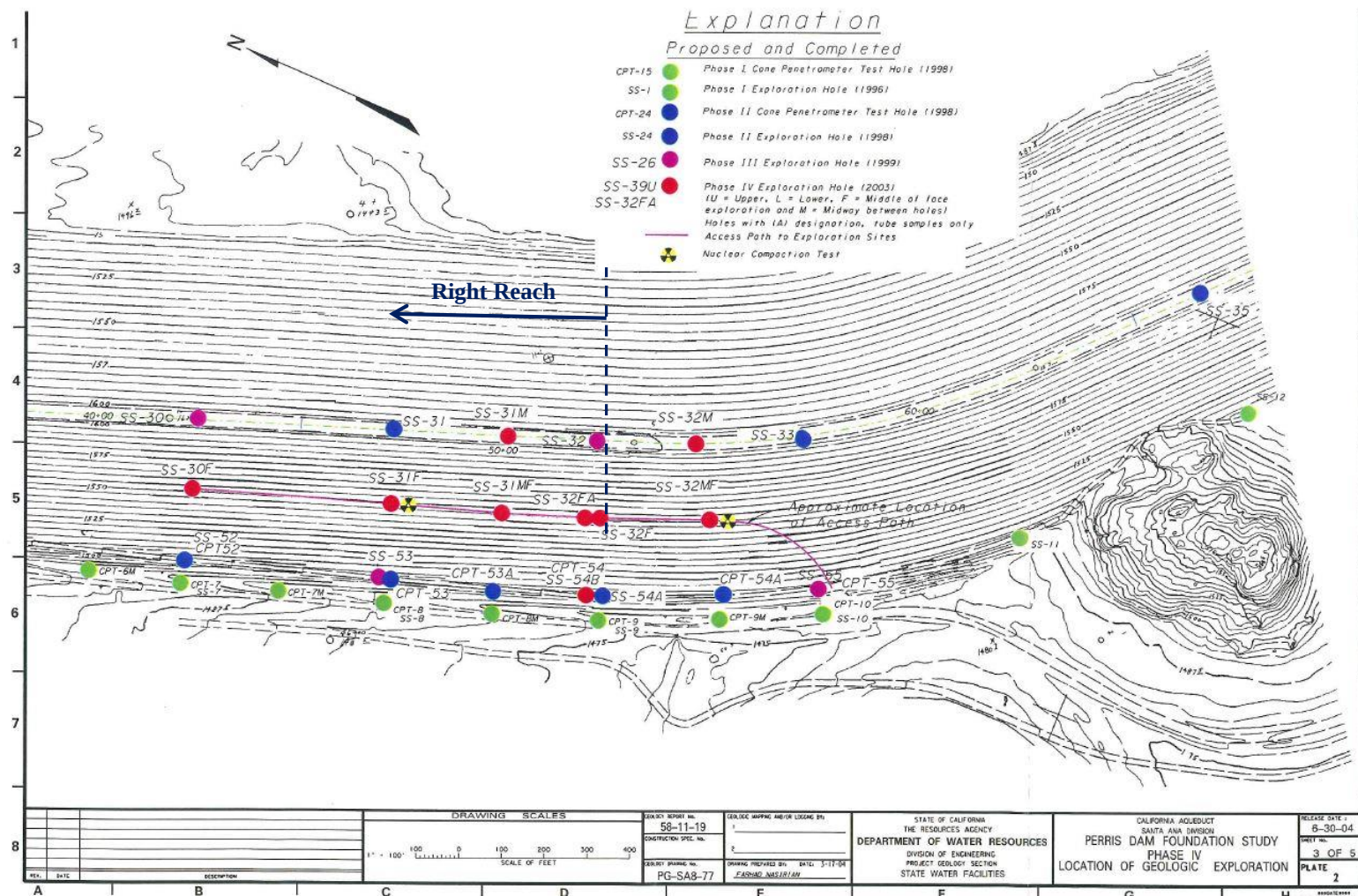


Figure 4-18: Plan View of Site Investigation at the Right Reach of the Perris Dam (from CDWR, 2004)

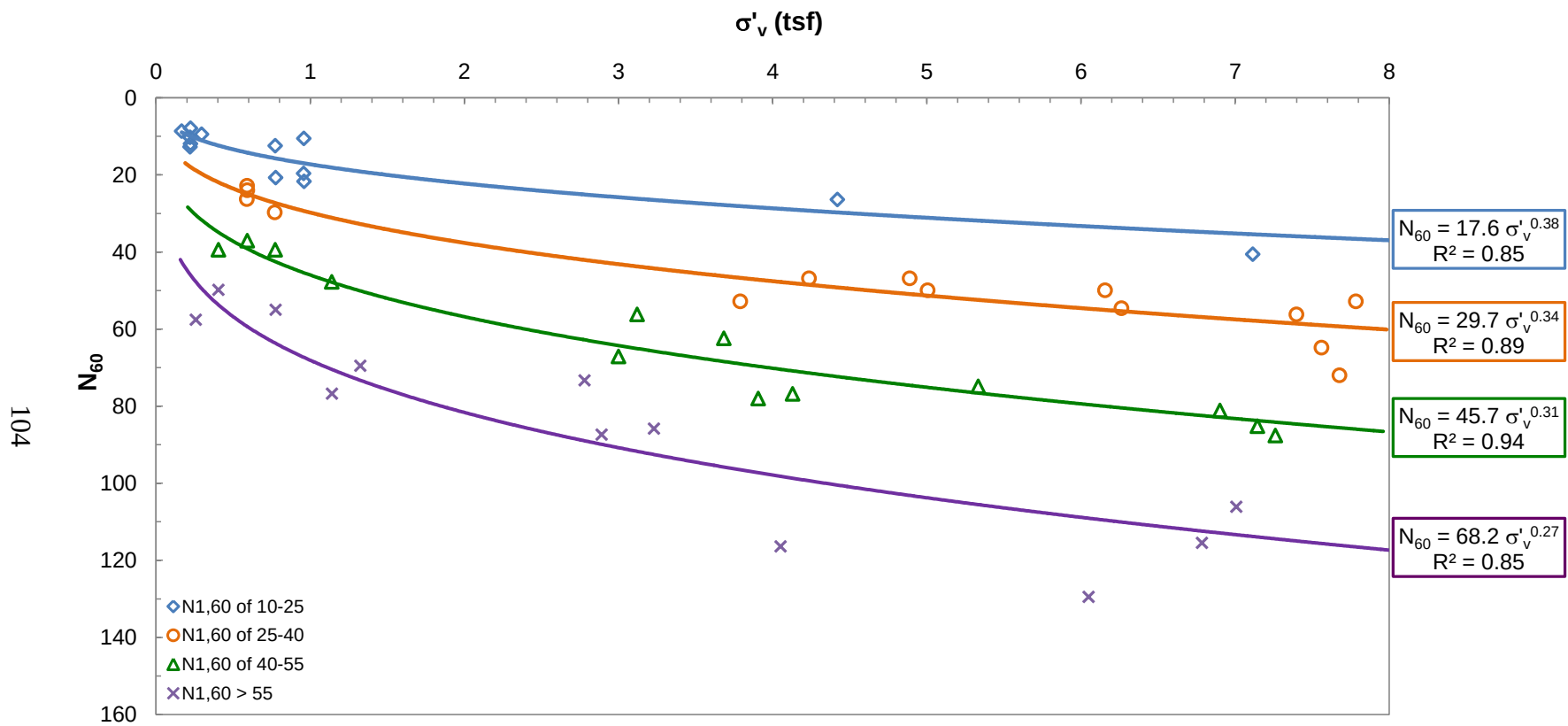


Figure 4-19: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Right Reach
 (Based on Original Data from CDWR, 2005)

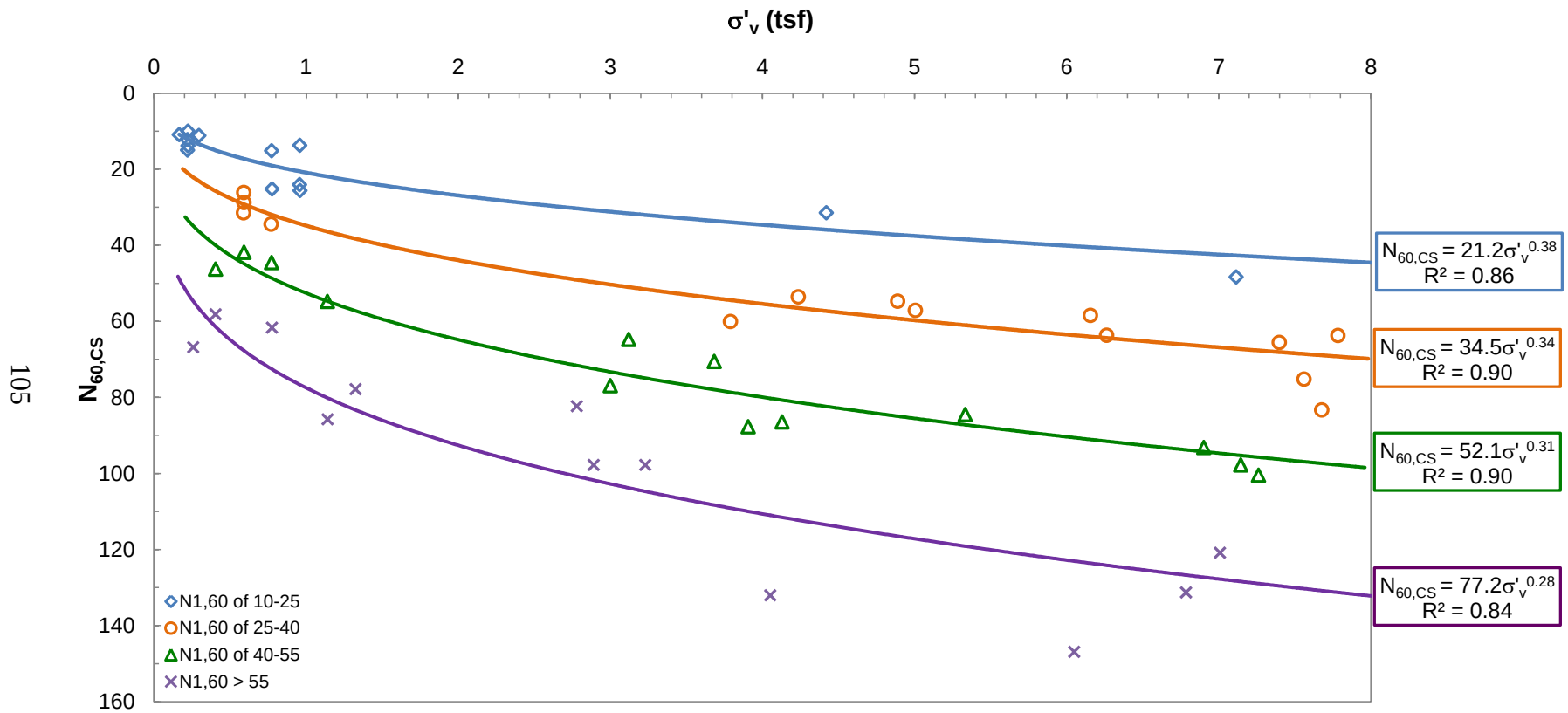


Figure 4-20: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Right Reach
(Based on Original Data from CDWR, 2005)

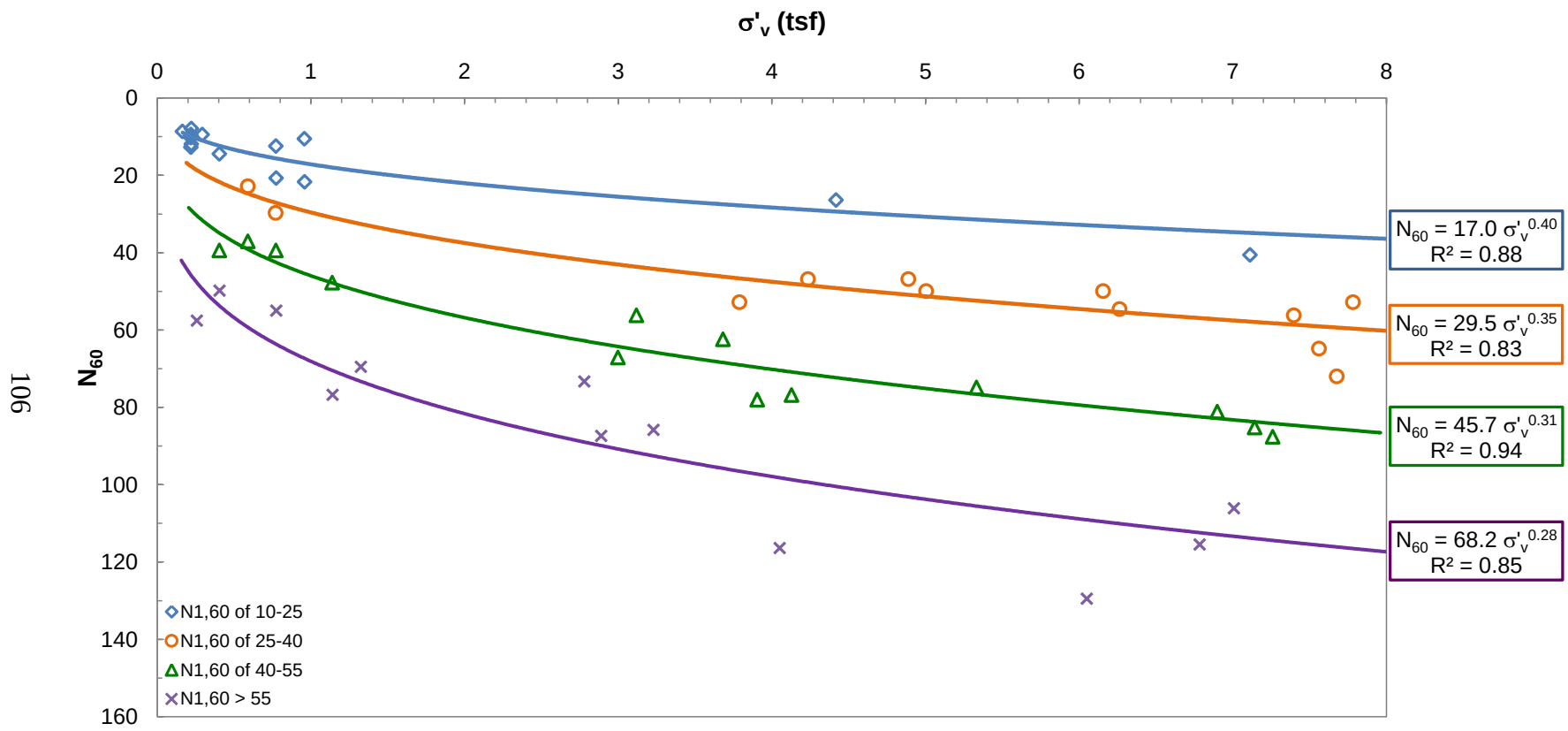


Figure 4-21: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Perris Dam, Right Reach Excluding CL & SC Samples (Based on Original Data from CDWR, 2005)

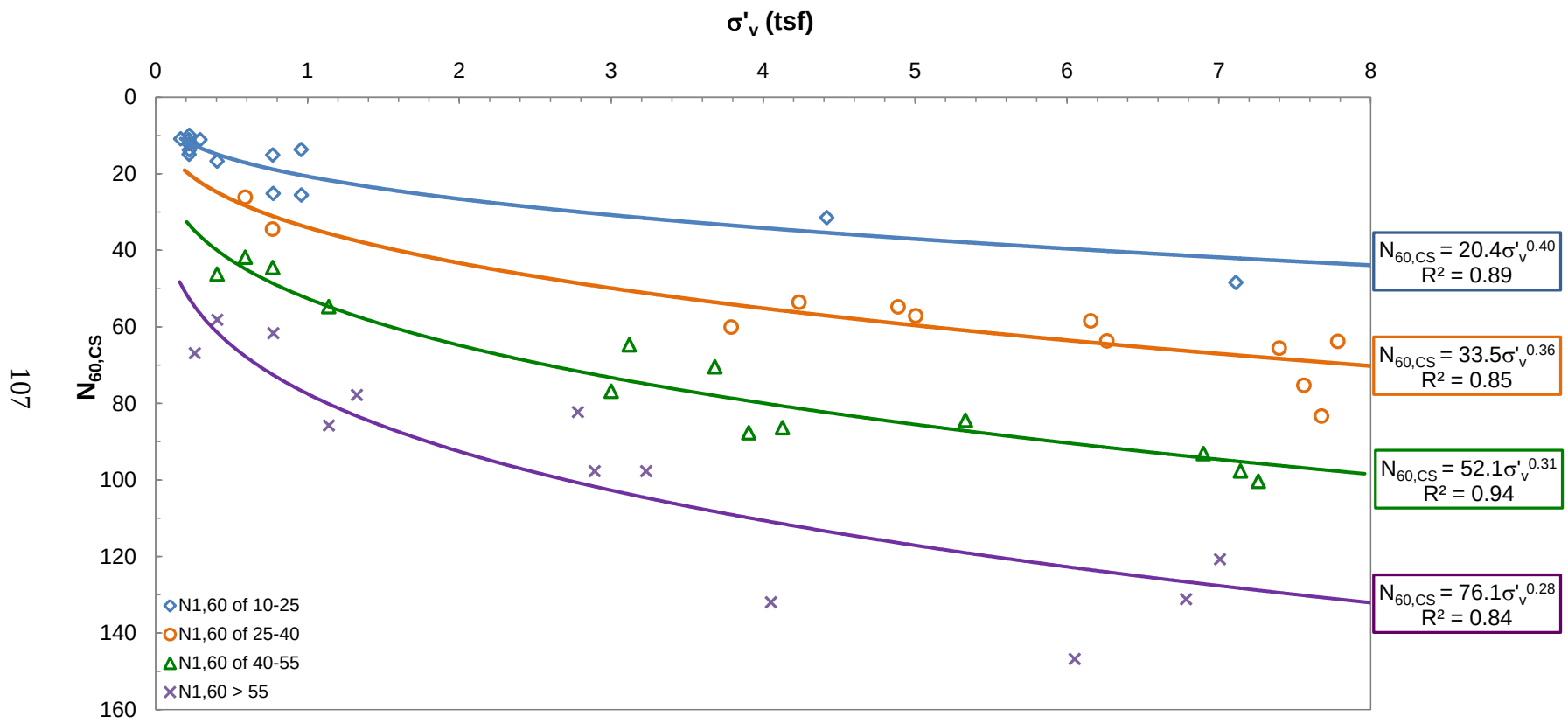


Figure 4-22: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Perris Dam, Right Reach Excluding CL & SC Samples (Based on Original Data from CDWR, 2005)

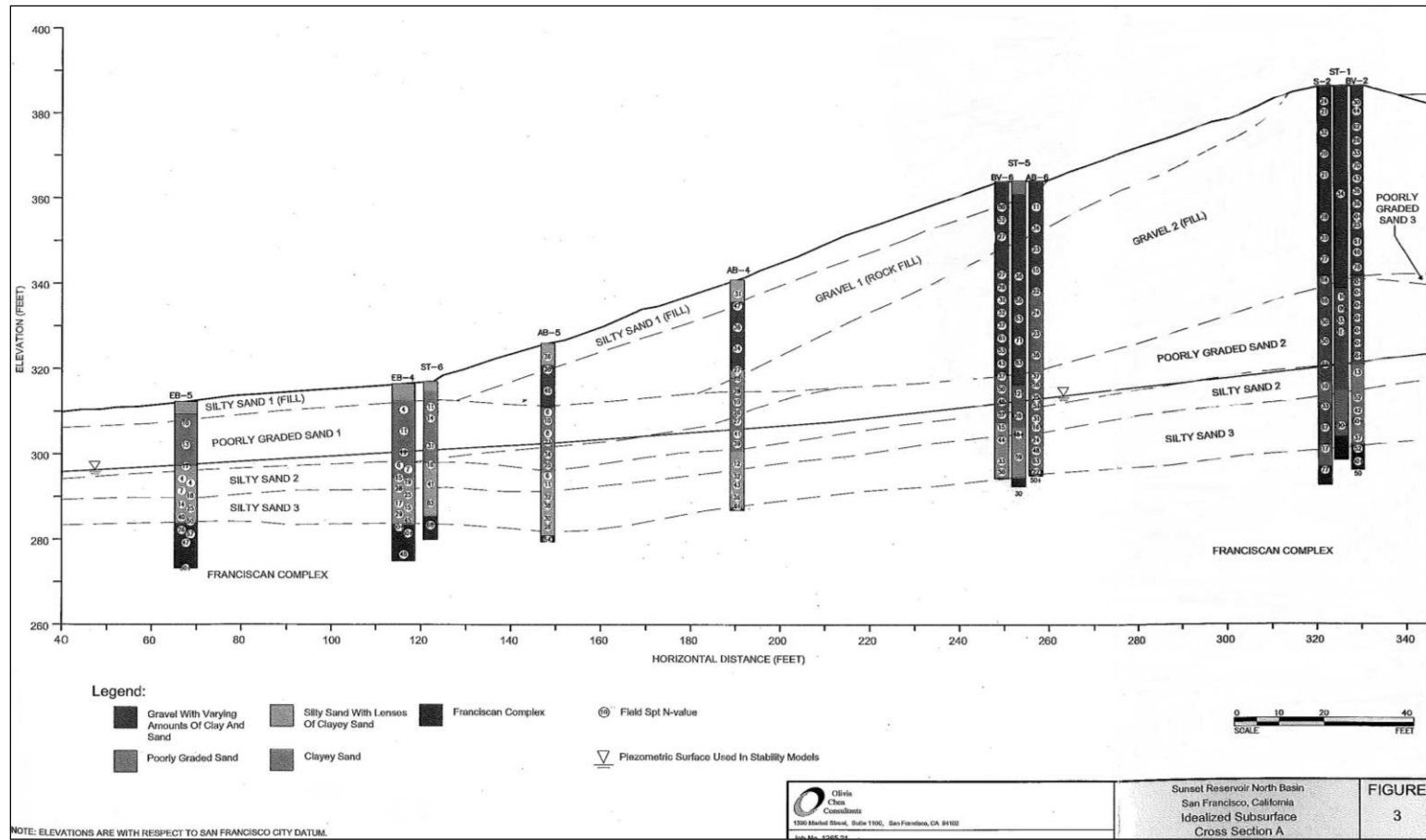


Figure 4-23: Cross Section A at Northwest End of Sunset Reservoir North Basin (from OCC, 2004)

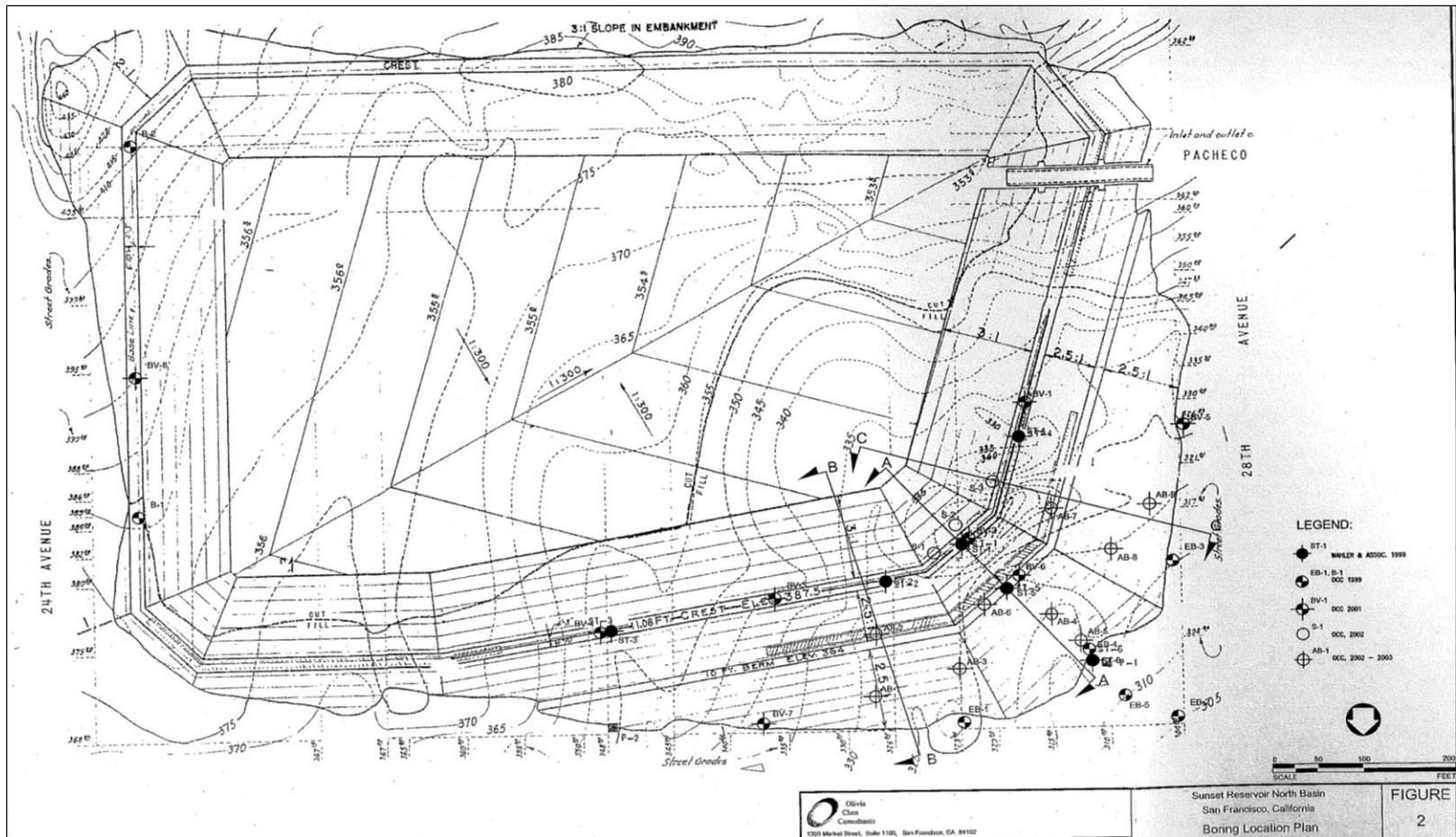


Figure 4-24: Plan of Sunset Reservoir North Basin Showing Boring Locations (from OCC, 2004)

Particle Size Distribution Report

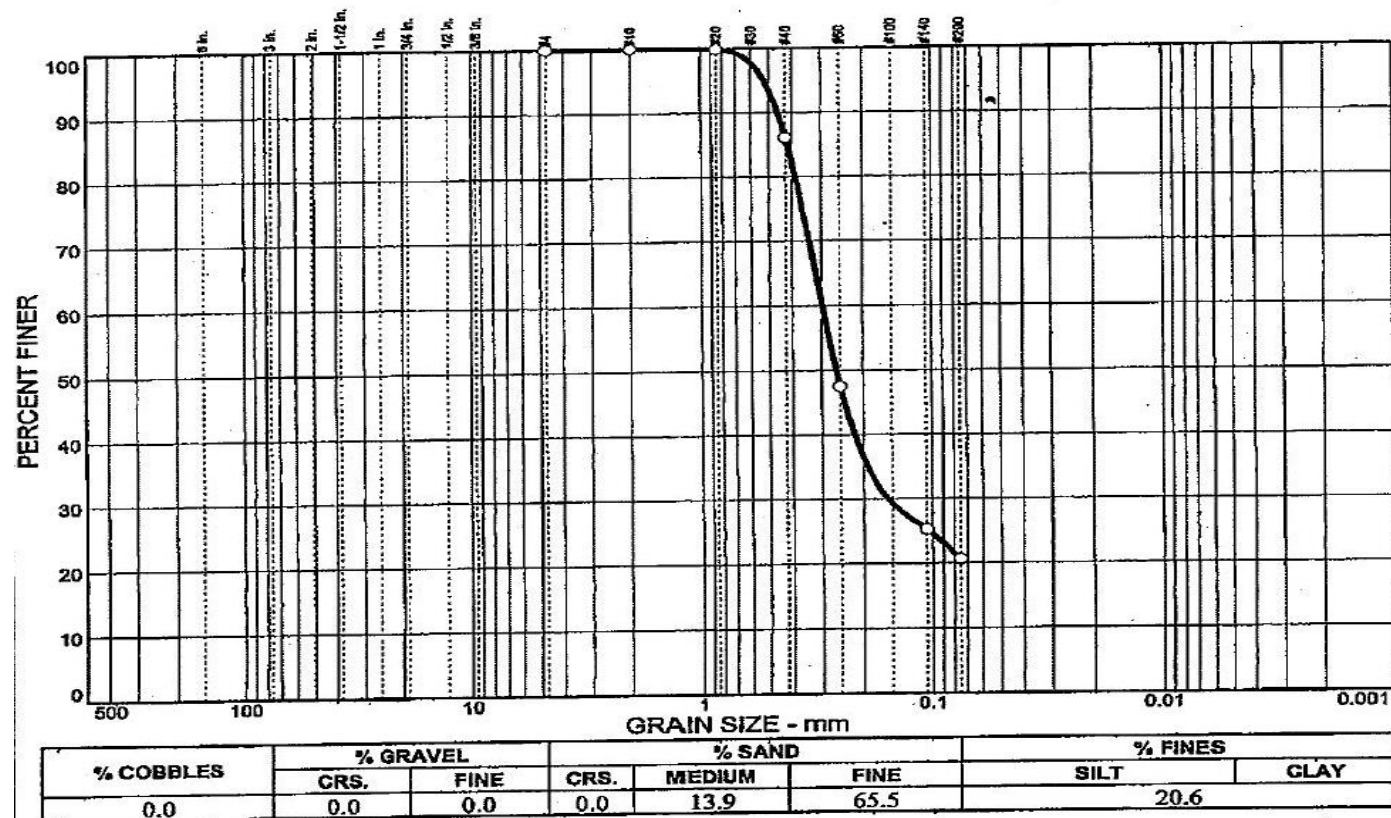


Figure 4-25: Sample Grain Size Distribution Curve of Silty Sand (SM) at Sunset Reservoir North Basin
(From OCC, 2004)

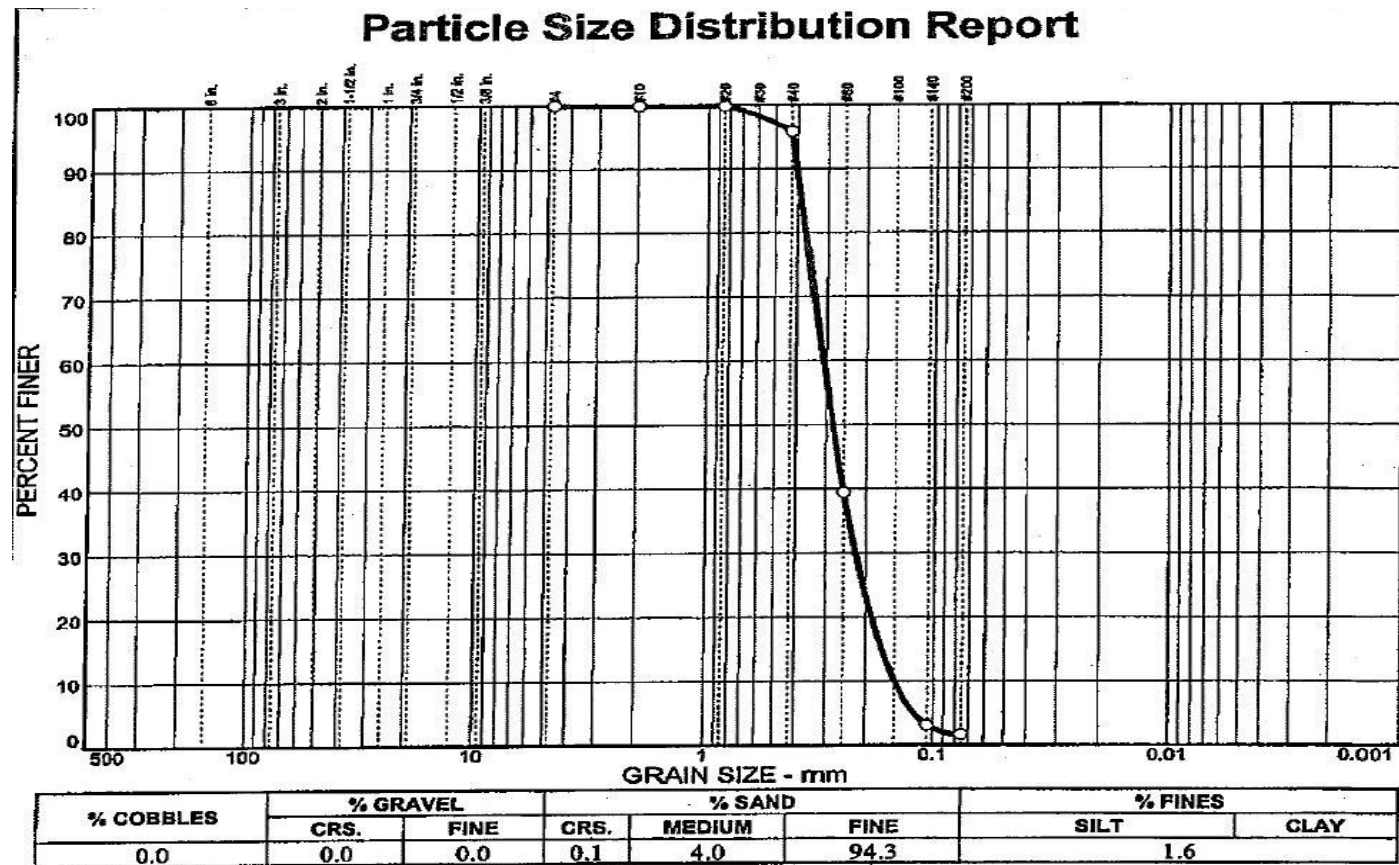


Figure 4-26: Sample Grain Size Distribution Curve of Poorly Graded Sand (SP) at Sunset Reservoir North Basin
(From OCC, 2004)

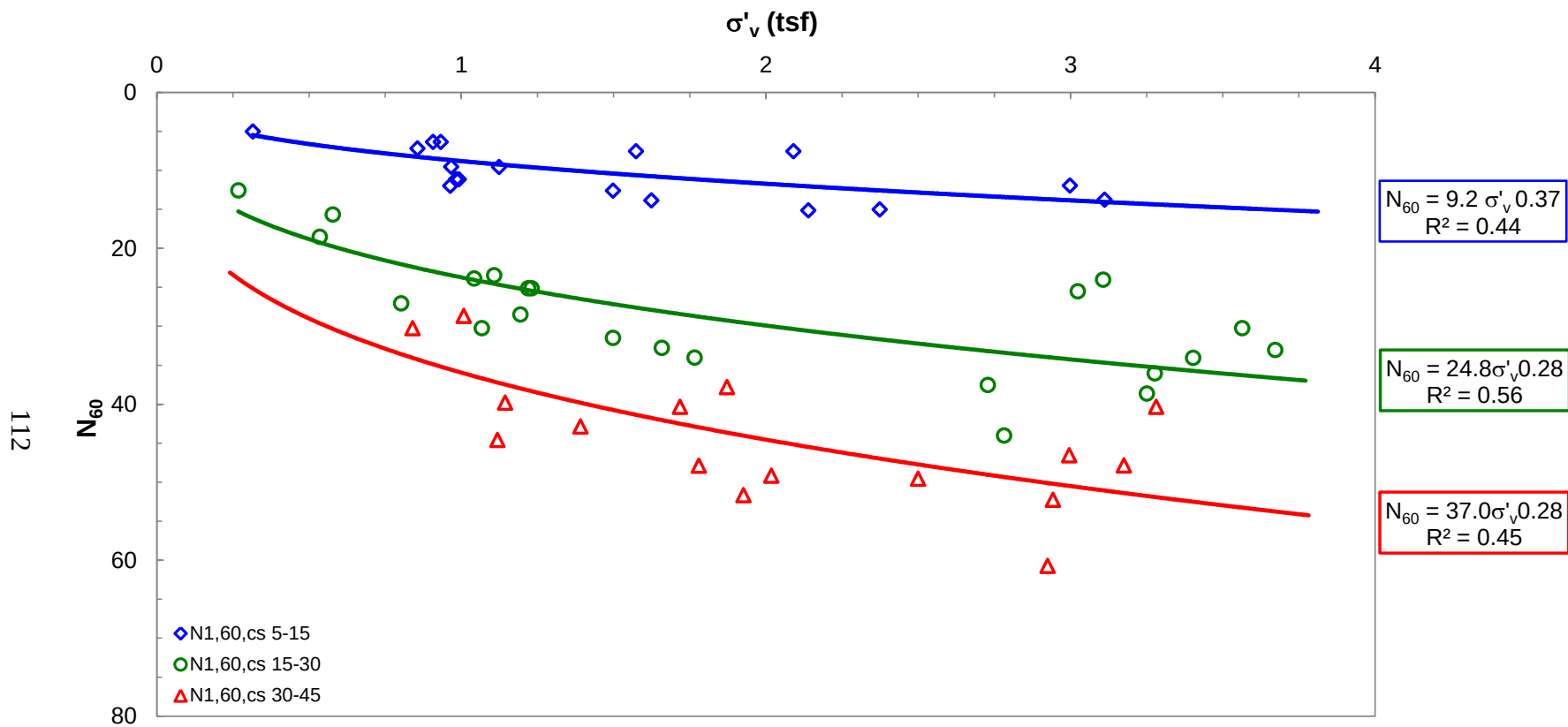


Figure 4-27: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Sunset Reservoir North Basin
(Data from OCC, 2004)

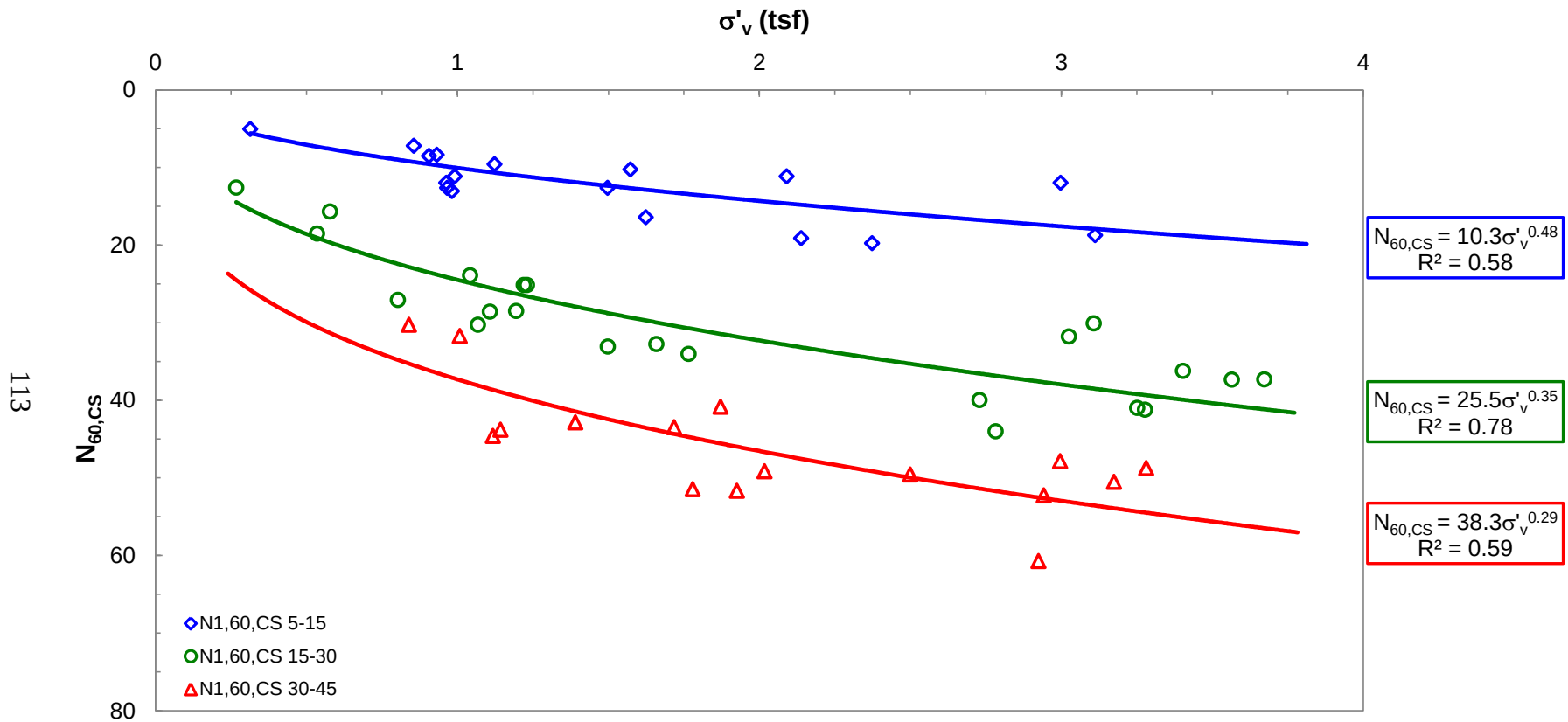


Figure 4-28: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Sunset Reservoir North Basin
(Data from OCC, 2004)

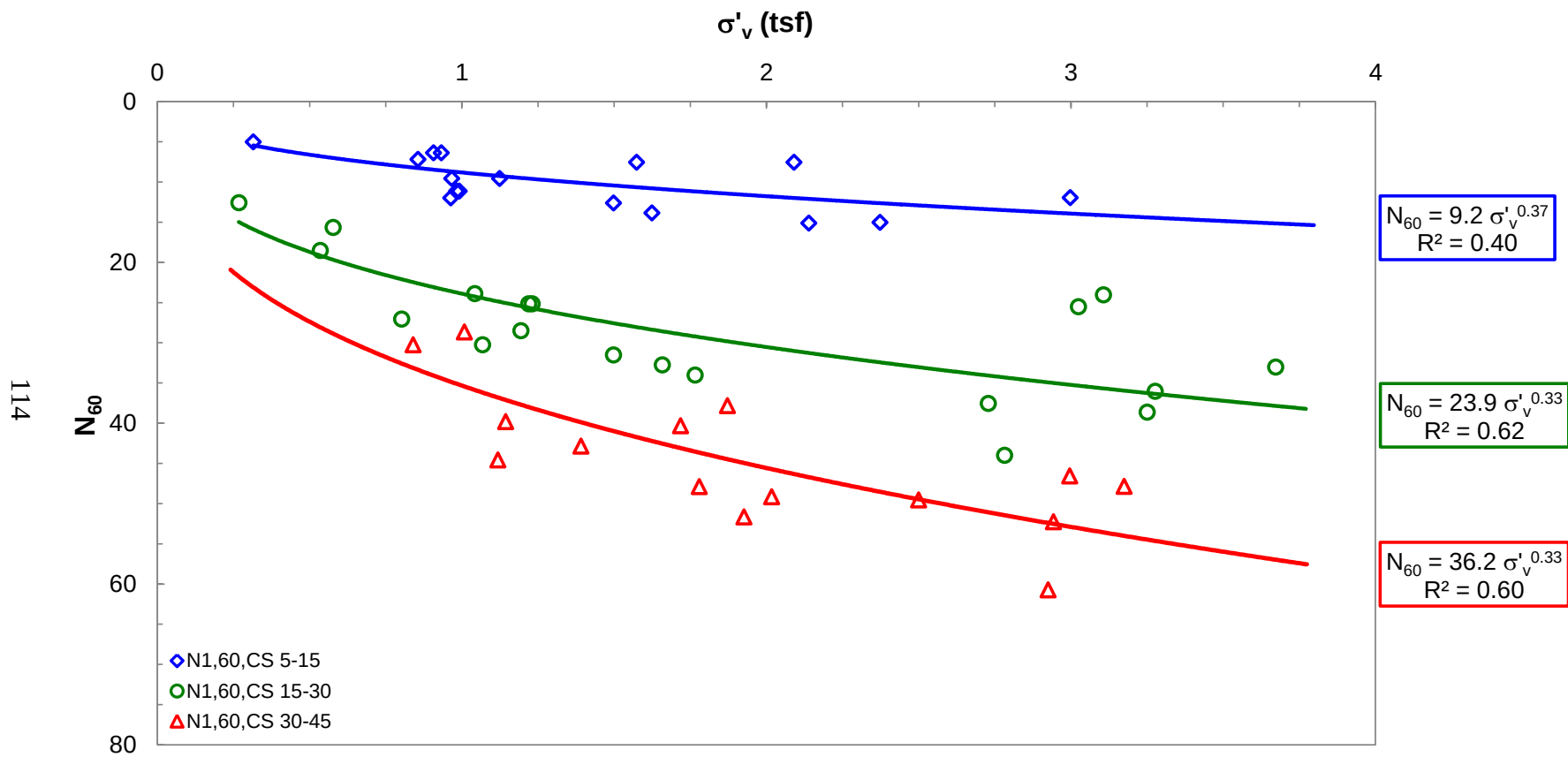


Figure 4-29: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Sunset Reservoir North Basin excluding CL & SC Samples (Data from OCC, 2004)

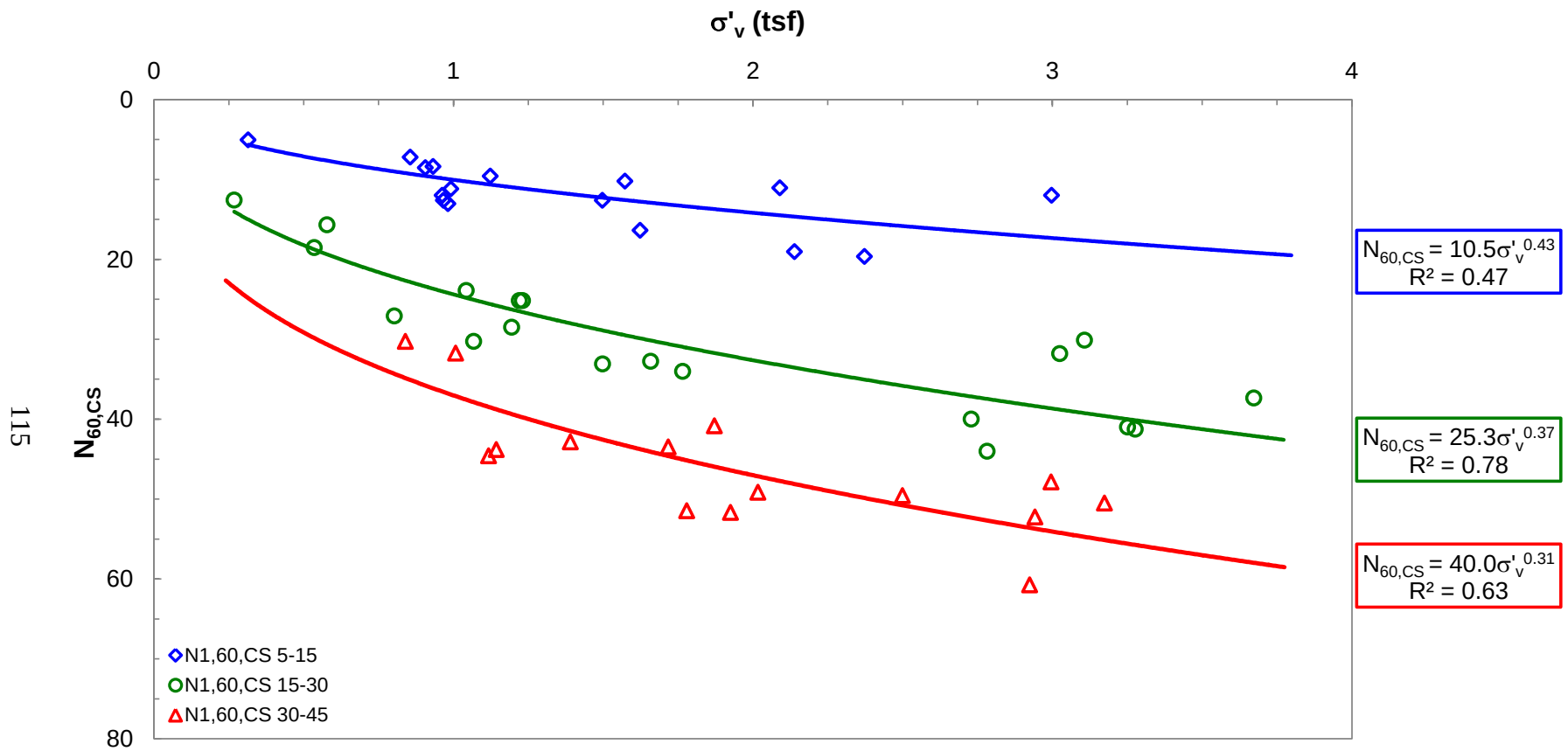


Figure 4-30: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Sunset Reservoir North Basin Excluding CL & SC Samples (Data from OCC, 2004)

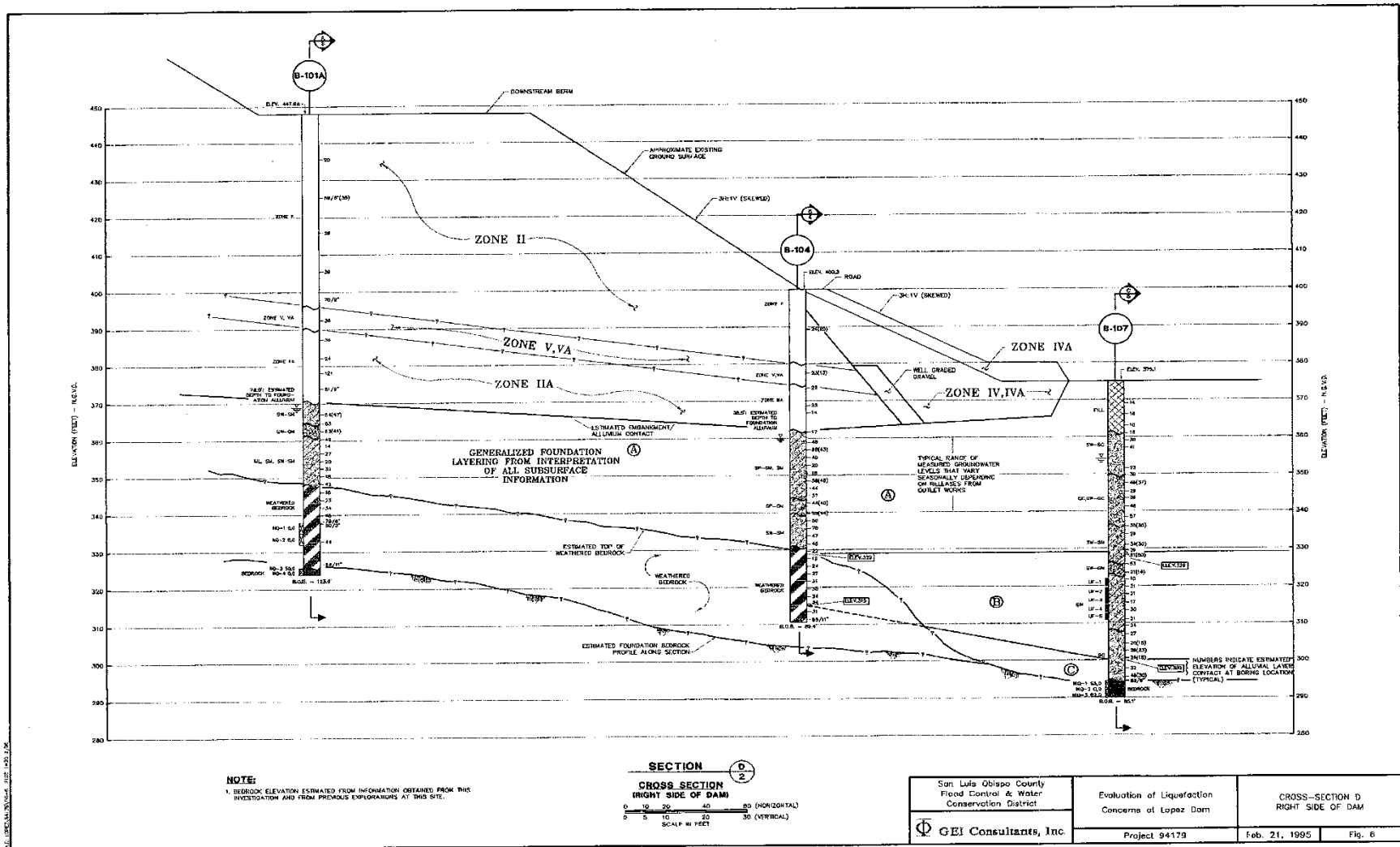


Figure 4-31: Lopez Dam, Cross Section D, Right Side of Dam (from GEI, 1995)

Figure 4-32: Plan View of Lopez Dam Showing Locations of Borings (from GEI, 1995)

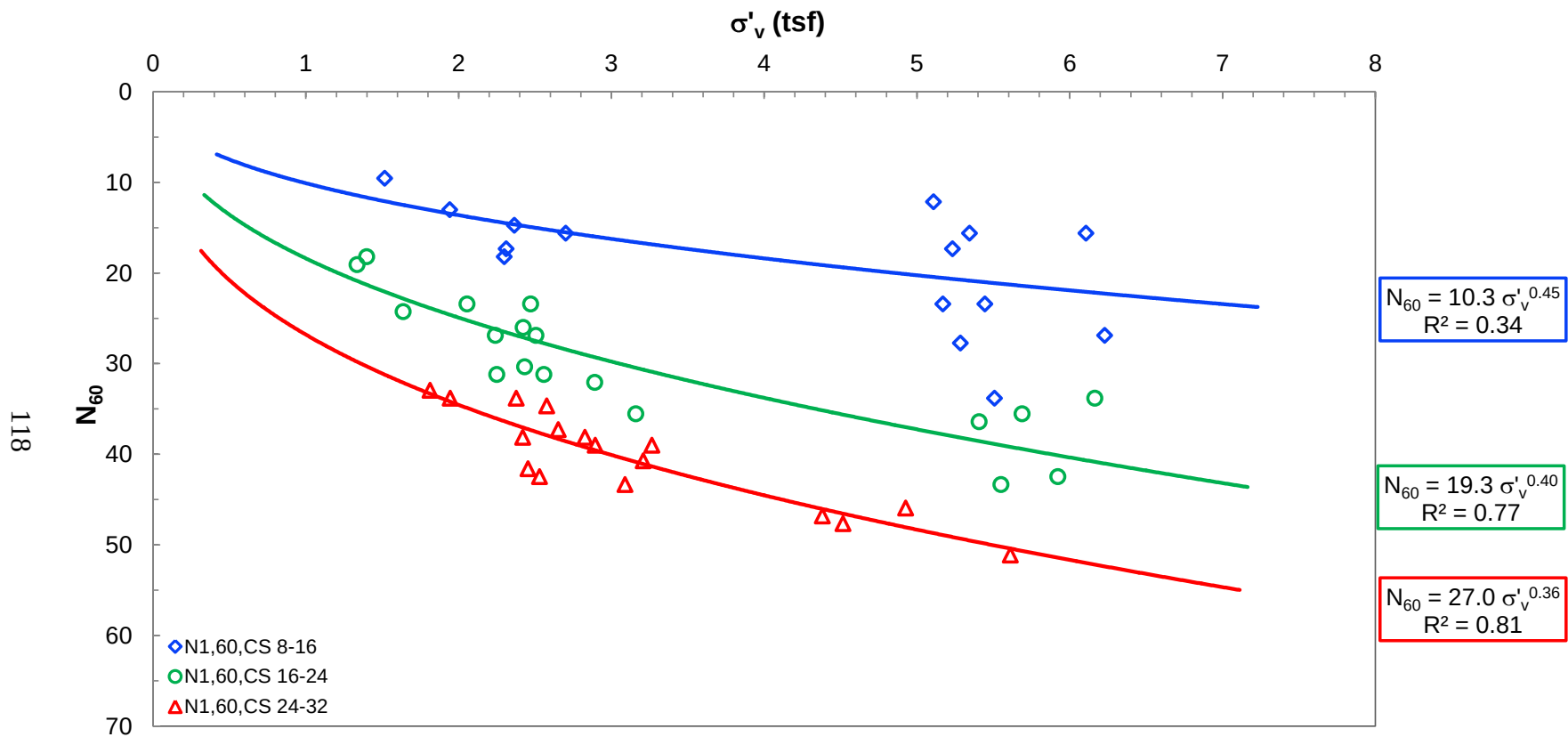


Figure 4-33: Density Bins of SPT N_{60} and Results of Nonlinear Regression for Lopez Dam Excluding CL & SC Samples (Data from GEI, 1995)

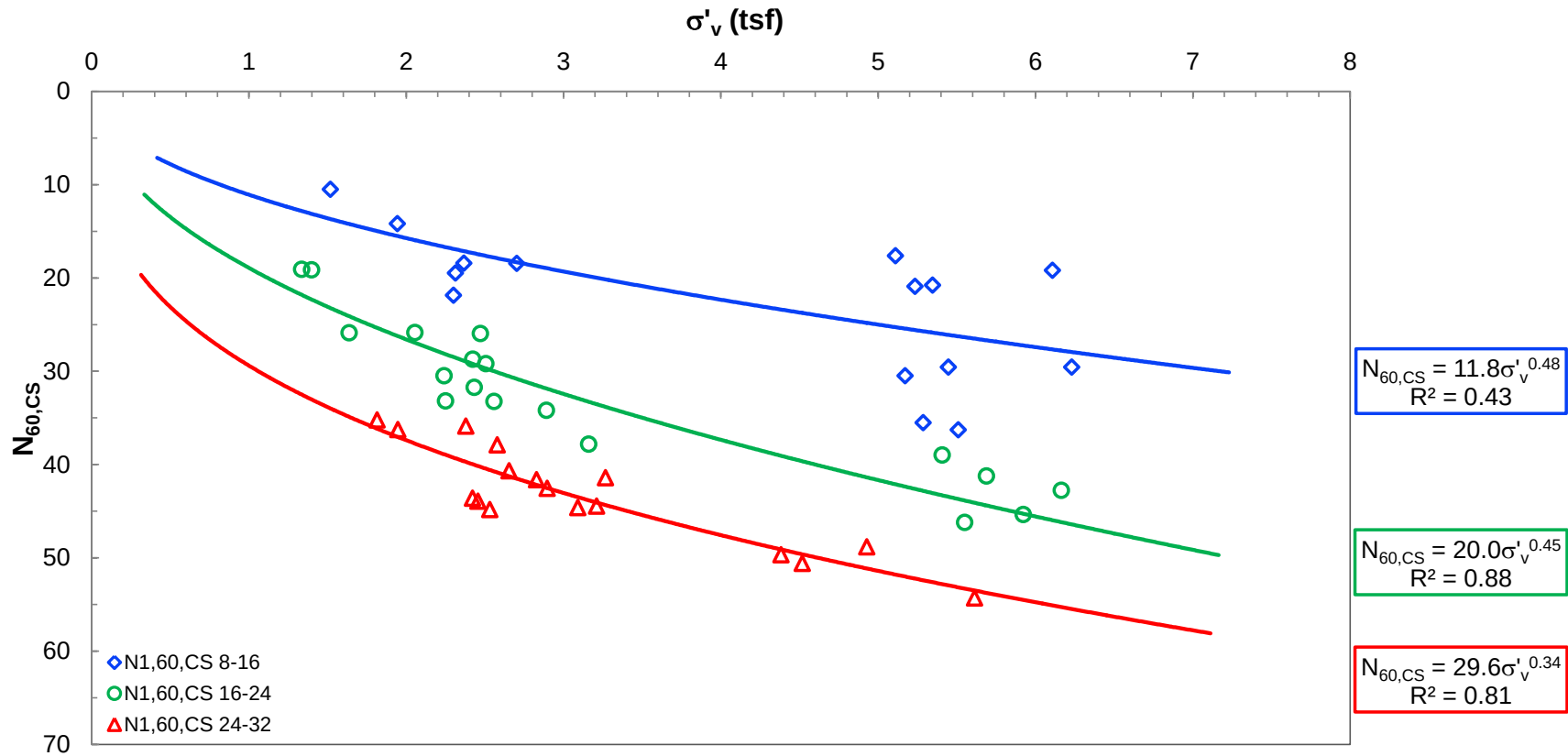


Figure 4-34: Density Bins of SPT $N_{60,CS}$ and Results of Nonlinear Regression for Lopez Dam Excluding CL & SC Samples (Data from GEI, 1995)

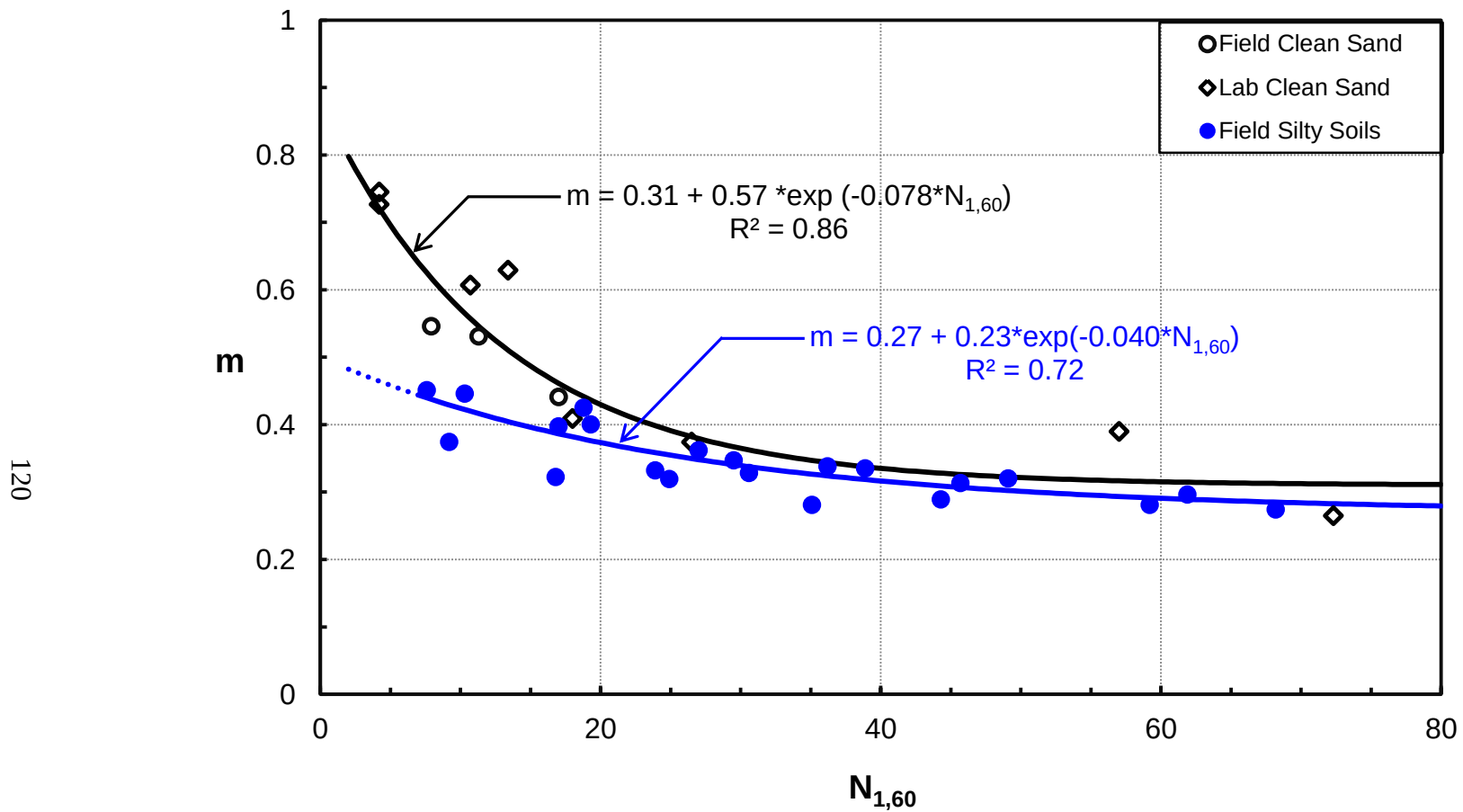


Figure 4-35: Comparison Plot of C_N Power Exponents (m) for Clean Sands and for Silty Soils as a Function of $N_{1,60}$

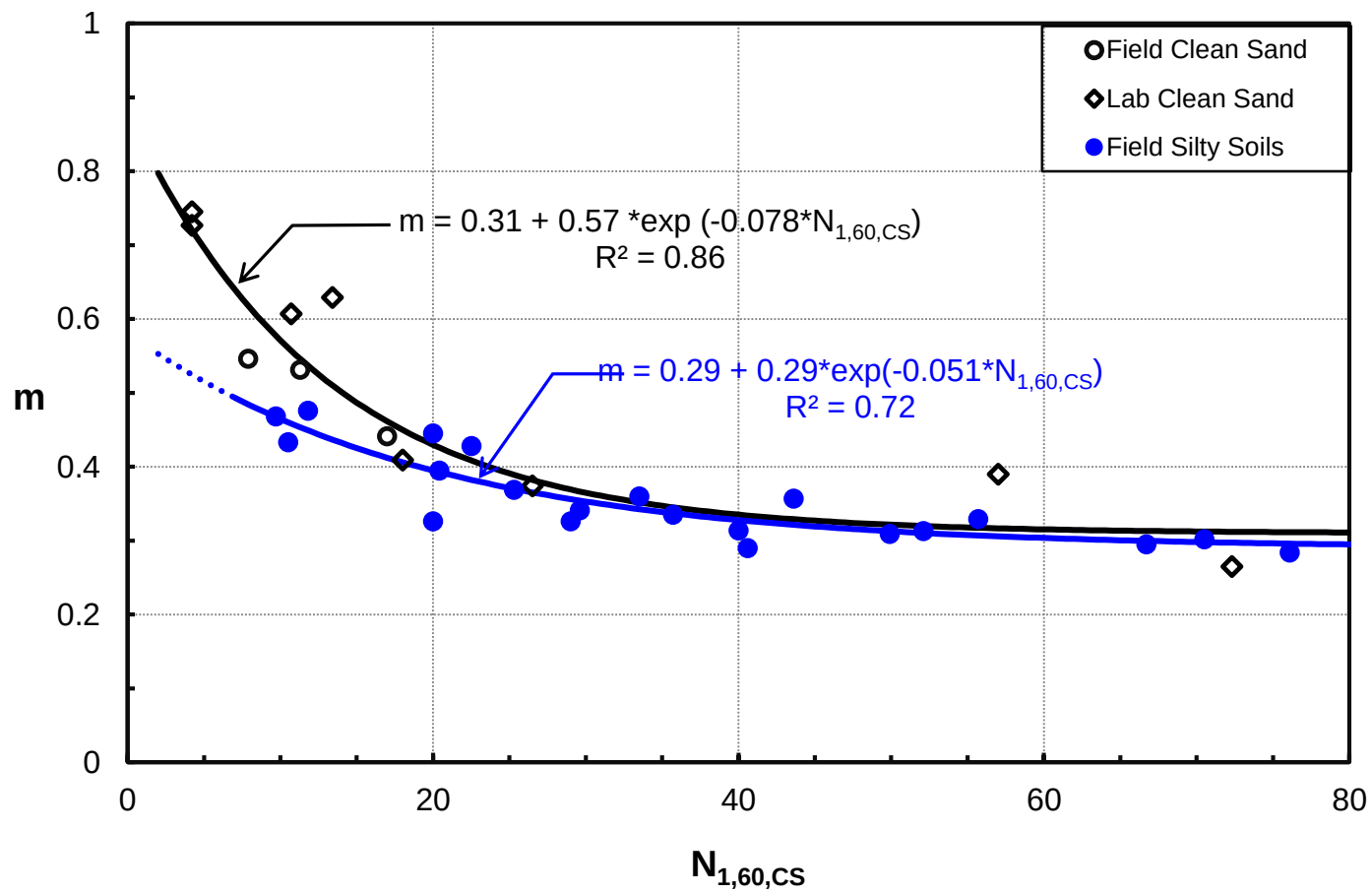


Figure 4-36: Comparison Plot of C_N Power Exponents (m) for Clean Sands and for Silty Soils as a Function of $N_{1,60,CS}$

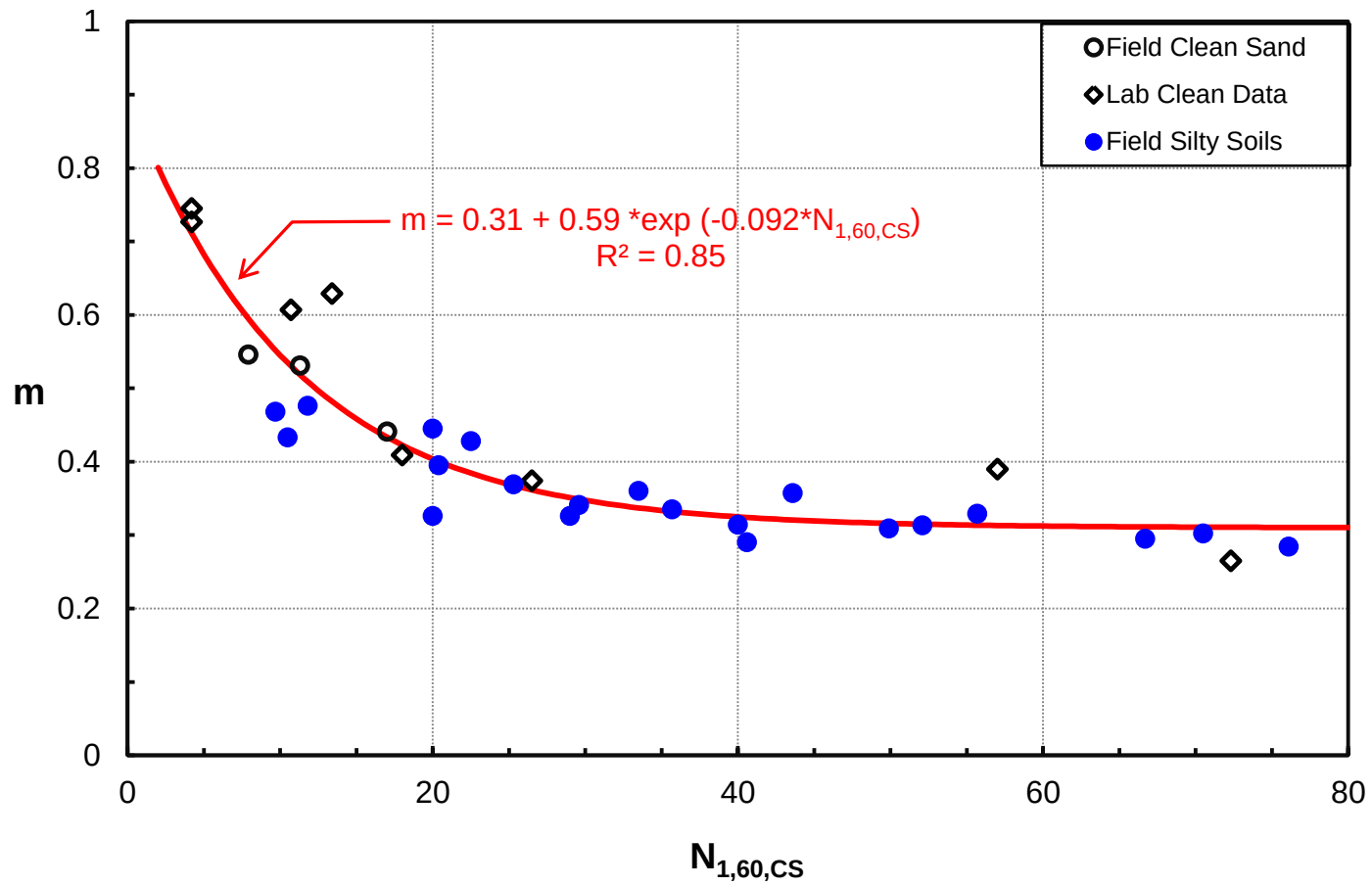


Figure 4-37: Overall Composite Relationship Between C_N Power Exponents (m) for both Clean Sands and for Silty Soils as a Function of $N_{1,60,CS}$

CHAPTER 5

ROD LENGTH CORRECTION FACTOR FOR SPT

5.1. Introduction

An additional factor affecting the results of Standard Penetration Tests is rod length, measured from the point of hammer impact to the forward tip of the split spoon penetrometer. There is currently debate within the profession as to just how much influence this has on SPT results, and how best to make appropriate corrections for these effects.

Figure 5-1 shows an example of early equipment used by Kovacs and Salomone (1982) to measure hammer energy during SPT tests. It was the advent of systems for measurement of hammer energy, coupled with the corollary development of dynamic analysis methods for analysis of the data produced by such measurement systems, which has led to our current state of knowledge on this issue.

Early energy measurements of the hammer energy actually delivered to the rods during SPT driving showed that when the length of the drill string (rods plus sampler) from the point of hammer impact to the bottom edge of the sampler is “short”, the energy delivered is reduced due to interference of the returning tensile wave reflecting back up from the base of the drill string before the entire hammer-induced compression wave is delivered into the rods. This gives rise to a rod length correction factor C_R .

Rod length correction (C_R) is significant only for relatively short drill string lengths of approximately 40 to 45 feet or less, and so it is an issue mainly for SPT performed at depths of less than approximately 35 to 40 feet. It is an especially important potential factor in the development of seismically-induced soil liquefaction triggering relationships, because most of the triggering and non-triggering field performance case histories employed in developing these types of empirical relationships involve soils at relatively shallow depths so that the field investigation teams can reliably ascertain whether or not the soil stratum of interest liquefied during the seismic event in question.

Although the issue of rod length correction has been studied since the mid-1970, there are currently significant differences of opinion as to the nature and scale of rod length correction factors that are appropriate. As a result, further work is warranted to resolve this. The approach that will be taken here will involve (1) review of prior analytical and experimental field studies of this issue, and then (2) acquisition and use of a suitable suite of actual field data with which to help resolve the current differences of opinion

5.2 The Force-Squared (F^2) Method - Schmertmann and Palacios (1979)

Beginning in the 1970's, Prof. Schmertmann and his students developed the first systems for measuring the compressive and tensile force waves in the drill rods produced

during SPT driving. Load cells on the drill rods began to be developed that could provide measurements of the dynamic compressive and tensile forces passing through the rods, and these provided the first means of measuring the actual energy transferred into the rod by the hammer. This, in turn, revealed the extent to which energy transfer efficiency varies depending on hammer type and other system details, and among these other details was the effect of rod length. It is not possible to freely “select” rod length; the lengths of the rods for each SPT performed in the field are a function of the depth of each test. Accordingly, if rod length affects energy transfer (or input) into the system, then corrections would need to be made to “standardize” the tests.

Figure 5-2, from the pioneering work of Schmertmann and Palacios (1979), illustrates the basic wave travel mechanisms in the rods due to the first hammer impact. Once the steel hammer strikes the top of the steel rod, hammer energy begins to be transferred into the rod string and a first compressive wave travels down the rods with a wave propagation velocity of $c \approx 16,800$ ft/sec in steel. The front end of this rapidly travelling compressive wave begins to reach the base (or cutting shoe edge) of the sampler at time $t \approx L/c$, where L is defined as total length of the rod string (including the length of sampler), and it begins to initiate the penetration of the sampler into the soil. Part of the energy of this wave is expended in causing penetration, and some additional energy dissipates into the soil as radiation damping. Part of the energy that reaches the base of the rods and sampler is reflected back up the rods as a tension wave (or as a compressive wave if soil resistance is high enough) depending on the soil resistance. The reflected tension wave travels up in the rod towards the hammer, and the front edge of this reflected wave begins to reach the top of the rod at time $t \approx 2L/c$ after the initiation of hammer impact. The arrival of this reflected tension wave often causes a physical separation between the hammer and the rod, and this tensile wave is then reflected back again down the rod as a compression wave. The hammer often falls a small distance and re-contacts the top of the rods at some point in time as this is occurring, providing a secondary hammer blow or “re-tap”.

According to the work energy theorem, energy transferred from the hammer to the drill rod can be calculated by integrating the product of force and velocity over a given time interval. This establishes what is called the Force and Velocity (F-V) Method, as given in Equation 5.1 below. Force can be measured using strain gages attached to the rod, and velocity can be obtained from the integration of acceleration.

Because accelerometers in the 1970’s and early 1980’s had technical limitations (limited peak acceleration capacity and limited high frequency resolution), it was difficult to fully accurately measure the very high accelerations due to the impact of the steel hammer on the steel rod. As a result, Schmertmann and Palacios (1979) developed an alternative workable method in which they related the velocity to force, as in Equation 5.2(a), by assuming that force and velocity are linearly proportional, in which case force times the inverse of impedance (c/EA) is equal to velocity, where E is the elastic modulus of steel and A is the area of the rod. This proportionality assumption is generally (or approximately) valid as long as time (t) after impact is less than $2L/c$, at which time the first incident tension wave begins to reach back up to the top load cell, as illustrated in Figure 5-3, and this proportionality does not hold anymore. Substituting velocity with force, the energy

transferred into the rod can then be obtained integrating the square of the force over the time, which is known as the Force-Squared (F^2) Method as given in Equation 5.2(b).

(1) Force-Velocity (F-V) Method:

$$E(t) = \int^t F(t) \cdot V(t) dt \quad \text{Equation 5.1}$$

(2) Force-Squared (F^2) Method:

$$V(t) = \frac{c}{EA} F(t) \quad \text{Equation 5.2(a)}$$

so that

$$E(t) = \frac{c}{EA} \int^t F^2 dt \quad \text{Equation 5.2(b)}$$

After developing a workable theory of wave propagation using the Force-Squared Method, Schmertmann and Palacios (1979) used this as a basis for development of systems and procedures to measure the force time histories of the stress waves, velocities, and energy transfer that occur during SPT sampling. As illustrated schematically in Figure 5-3, they used two dynamic load cells, specially designed to screw into the SPT rods, one located as close as possible to the top of the rod and another one located 5ft above the tip of the sampler to delay interaction of the incident and reflected waves enough to permit their analytical separation. In the end, they only used the force time histories recorded by the load cell at the top to obtain the energy delivered into the rods, and so the use of a second load cell section near the base of the rods was soon discontinued.

Figures 5-4(a) and 5-4(b) shows two force recordings of Palacios (1977); for a short and long rod, respectively. Each figure shows force measured in the instrumented rod sections as a function of time. These two figures, together, illustrate the main issue that gives rise to the need for “short rod” corrections.

Figure 5-4(a) shows force vs. depth for an SPT hammer blow with the sampler at a depth of 11 feet. Figure 5-4(b) shows force vs. time for an SPT hammer blow with the sampler at a depth of 44 feet. Looking at the records for the “Top” load cell (at the top of the rods, near the point of hammer impact), it can be seen that during the initial stages of time after initiation of hammer impact, both load cell readings reached a maximum compressive force of approximately 7,500 kg, demonstrating that each received essentially similar impact. Examining the lower figure (Figure 5-4(b)), it can be seen that compression continued to be “input” into the top of the rod for a duration of approximately 6 milliseconds. Next, examining the upper figure (Figure 5-4(a)), it can be seen that the returning (reflected) tensile wave from the base of the rods begins to arrive at a time of about 1.9 milliseconds, representing a travel time of $t \approx 2L/c$ as expected. When the tensile wave begins to arrive at the load cell location, it immediately begins to reduce the measured compression, and even reverses the still arriving compression from the hammer impact so that net tension is

measured at times of between about 1.9 to 3.8 milliseconds. After that, the tensile wave reflects back downwards and interferes with the still arriving compression from the hammer blow only as a positive augmentation of the compression relative to the compression measured at the same times in the (lower) Figure 5-4(b).

Comparison between Figures 5-4(a) and 5-4(b) shows clearly the principal effects of “short rods” on the energy measured as being input into the top of the rods. In Figure 5-4(b) the rods are long enough that the reflected tensile wave does not begin to arrive at the top of the rod until approximately $t = 6$ milliseconds (a higher $t = L/c$), so that nearly the full amount (and duration) of initial dynamic force from the first hammer blow passes downwards through the instrumented “Top” load cell location at the top of the rods before the returning tensile wave begins to interfere. As a result, the first compression wave pulse lasted longer in the lower figure, while the duration of initial compression wave pulse was reduced by the earlier return of the reflected tensile wave in the upper figure. As both the Force-Velocity Method (Equation 5.1), and the Force-Squared Method (Equation 5.2(b)) involve integration of compressive force over time (and over time when force and velocity are acting in the same downwards direction), the early return of the tensile wave reduces the accumulation of energy measured as having been “input” or driven into the top of the rods for the shorter rod (shallower) test shown in Figure 5-4(a).

There is a potentially significant limitation to the F^2 method, inasmuch as the proportionality assumption of Equation 5.2(a) is valid only as long as time (t) after impact is less than approximately $2L/c$, at which time the first incident tension wave begins to reach back up to the top load cell. It was not possible for Palacios and Schmertmann to make accurate measurements of acceleration at the high frequencies and high acceleration levels involved in the striking of steel rods with a heavy steel hammer, so they were unable to obtain the acceleration time histories needed for integration to develop actual velocity time histories. As a result, they could not perform calculations based upon the full Force-Velocity Method (Equation 5.1), and had to settle for the Force-Squared Method. That, in turn, meant that they were not able to account for the reversal (reflection) of tensile waves that returned to the top of the drill rod and then reflected back downward through the drill rods as a second (and then a third, etc.) compressive force wave. They were also unable to measure, and account for, additional energy input into the rods by secondary hammer impacts (or “re-taps”). It was the opinion of Schmertmann and Palacios that the additional energy successfully driven into the rod by these successive (lesser) compressive waves was not very significant. Subsequent researchers have challenged this assertion, and the controversy raised by this issue will be addressed in further detail in Sections 5.4 through 5.6. As a practical matter, limitations in accelerometer technology available at the time caused Schmertmann and Palacios to employ the F^2 Method, and that in turn caused them to essentially truncate their assessment of energy input into the rods at a time of $t \approx 2L/c$ after initiation of hammer impact.

Schmertmann and Palacios determined that shorter rods would more quickly provide a returning tensile wave to the top of the rods, and would thus limit the time period during which work energy could be input as part of the first hammer impact pulse. And it was only this first impact pulse that they counted as a source of energy being input into the rods.

The instrumentation system used to measure compressive force in this dynamic situation imposed additional limits on the ability of Palacios to measure compressive and tensile forces at the load cell location near the top of the rods. An oscilloscope was used to record the very rapid (dynamic) transient load passing through the load cell, and the maximum duration over which these could be recorded was 10 milliseconds. Palacios and Schmertmann were able to view longer durations visually, but were not able to record accurately the pulses beyond 10 milliseconds.

Figure 5-5 shows measured hammer energies calculated by Schmertmann and Palacios (by the Force-Squared Method) for 57 SPT performed at various depths within a set of six borings. The measured energies are plotted vs. SPT depth, and so they are correlated with rod length which would generally increase with increased depth, but in increments as rod lengths tend to increase in increments of 10 feet (though sometimes a shortened 3 foot or 5 foot rod will be used at the top to provide a convenient height of exposed rod for applying the hammer impacts). The dashed curve at the right of Figure 5-5 shows their calculated theoretical maximum hammer efficiency that could be achieved for any given rod length. At significant depth, this theoretical maximum is equal to the hammer weight of 140 lbs x 30 inches of drop height = 4,200 inch-pounds, but at shallower depths the returning tensile wave reduces the amount of work energy that can be input before the compressive force is reversed.

The actual (field) measured energies are shown in Figure 5-5 by the solid dots in the middle of the figure. These tend to have energies of approximately 45% to 65%, demonstrating that the theoretical free fall energy of a 140-pound hammer falling 30 inches is not usually achieved with a rope and cathead system due to friction with the falling rope and hammer. Examining the actual measured data more closely, it can be seen that there is a trend towards lower measured energies at shallower depths (shorter rods), but also that the short rod effects do not appear to be quite as significant as their theoretical calculation would have predicted.

The dashed line in Figure 5-5 represents their theoretical limiting condition due to short rods and early tensile wave return, and it predicts a reduction in delivered hammer energy of slightly more than 30% at a rod length of 10 feet, with the short rod effect asymptotically being reduced to a negligible value at a depth of approximately 40 to 50 feet.

5.3 Early Short Rod Corrections Based on the Force-Squared Method (1985 - 2001)

The energy measurements performed by Schmertmann and Palacios were quickly supplemented by others (e.g. Kovacs and Salomone, 1982), and nearly all of these early efforts used the Force-Squared Method to calculate energy input into the top of the rod. Based on these early data, a number of recommendations were made as to how to apply “short rod corrections” to SPT, and these are shown in Figure 5-6. Seed et al. (1984) proposed a 25% reduction in assumed hammer energy ($C_R = 0.75$) for rods shorter than 10 feet, and no reduction ($C_R = 1.0$) for rods longer than 10 feet. Skempton (1986) also

proposed a maximum correction of 25% ($C_R = 0.75$) at short rod lengths of 10 feet and less, but then tapered his correction factors with a step-function down to a null correction ($C_R = 1.0$) at rod lengths of 35 feet and greater; corresponding fairly well with the original “theoretical” rod length at which short rod effects would become nearly negligible according to the original calculations of Schmertmann and Palacios (see Figure 5-5). Youd et al. (2001) further smoothed the transition of this step-function, while retaining the maximum value of 25% reduction at very short rod lengths, and also retaining a rod length of approximately 35 feet as the length at which short rod effects would be expected to become negligible.

5.4 Further Advances and the Force-Velocity (F-V) Method

In early 1990s, as accelerometer technology improved, Sy and Campanella (1991) were able to begin to more accurately measure the acceleration due to the impact of a steel hammer on the steel rod during SPT driving. The resulting acceleration time histories could then be integrated to develop velocity time histories, and that made it possible to employ the more fundamentally sound Force-Velocity (F-V) Method to assess the energy input into the drill rod by the SPT hammer. That, in turn, meant that the effects of subsequent compressive wave pulses passing back down the drill rod after the first tensile wave reflection reached the top of the rod could now be measured and assessed.

Sy and Campanella performed field SPT with safety hammers, and they recorded acceleration and force time histories during an SPT hammer blow event at two different depths using piezoelectric load cells and piezoelectric accelerometers. Figures 5-7 and 5-8 show the measured force time histories, and the velocity time histories obtained by integration of measured acceleration time histories, and they determined energy using both the Force Velocity (F-V) and Force Square (F^2) Methods for two hammer blows; one on short rods (at SPT test depth of 1.5m) and one on longer rods (at a depth of 9.1m), respectively. For the short rod case (Figure 5-7), the duration of first compressive force input pulse is short as the returning tensile wave truncates it at a time of approximately 2.2 milliseconds after initial hammer contact. In the longer rod case, because of longer wave travel path, the returning tensile wave does not truncate the initial compressive input force event, and this initial compressive event continues to a time of approximately 5 milliseconds. Although the duration of their recordings was not long enough (limited to 20ms in the actual measurements, and to 10ms on the figures) to fully capture all of the subsequent impacts during an SPT blow, they recorded subsequent wave reflections up and down the rods up to 20ms. They were thus among the first to begin to successfully track energy at times longer than $2L/c$ after initiation of hammer impact, which could now begin to be accurately quantified using the F-V method.

As mentioned before, the F^2 Method assumes that force and velocity are proportional, in which case force times the inverse of impedance (c/EA) is equal to velocity, where E is the elastic modulus of steel and A is the area of the rod. This proportionality assumption is valid as long as time (t) after impact is less than $2L/c$, at which time the first incident tension wave begins to reach back up to the top of the rods. As a result, it was not possible to quantify

energy transfer after time = $2L/c$ by the F^2 method. Consequently, it was not possible to accurately quantify energy transferred into the rod due the secondary pulses (due to both reflections, and secondary hammer impacts) after $2L/c$. The F-V Method is superior to the F^2 Method since it can accurately quantify energy transfer after $t = 2L/c$, so long as acceleration measurements can be made with sufficient accuracy.

It should also be noted that proportionality between force and velocity may break down even before $t = 2L/c$. If there is any source of impedance difference, e.g. loose joints, abrupt changes in cross-sectional area (such as also occurs at joints, and at the sampler), etc. along the drill string (rods and joints and sampler), then these will cause reflections of energy that break up the otherwise more monolithic main pulses and further damage the assumption of proportionality during the initial time period up to $t = 2L/c$. For instance, loose joints in the rod can break up the main initial compressive wave pulse and cause tensile reflections, and if the F^2 Method is used, energy will be underestimated for this particular case. Similarly, if there are any heavy joints, or if cross-sectional area of the steel increases at “couplers” used to join rod sections, then these produce partial compressive reflections, again breaking up the otherwise more monolithic initial compressive pulse passing down through the rods at times of less than $2L/c$; in which case energy can be slightly overestimated if the F^2 Method is used. The F-V Method, on the other hand, does not require proportionality and it would lead to accurate characterization of energy transfer for these cases so long as suitably accurate acceleration data can be obtained. With improving accelerometers, it was now also beginning to be possible to track these effects (loose joints, and impedance changes at joints, etc.), and to do so at times exceeding $2L/c$ after initiation of hammer impact. It now became increasingly common practice to continue to characterize energy input into the rods (and reflected back out, and then back in, etc.) until the point of maximum successful energy transfer had occurred.

Taking advantage of the rapidly improving accelerometer technology of the time (piezo-electric accelerometers and piezo-resistive accelerometers), Morgano and Liang (1992) investigated the issue of rod length effects on energy transfer during SPT driving using both numerical simulation and field hammer energy measurements, and now based on the F-V Method. Figure 5-9 shows the results of their numerical simulation of an SPT blow in terms of calculated force, calculated velocity and calculated energy transfer for a situation with short rods (a combination of rod length = 10 ft, and a hammer with 80 percent efficiency). This is a poor quality figure in terms of image quality, but it represents a significant advance, and it is explanatory as to how energy pulses during one single SPT blow can contribute to the total delivered energy.

In the top section of this figure, the heavy solid lines show (theoretical) calculated compressive force at the top of the rods, and the lighter dashed lines show calculated downward velocity. Energy transfer into the rods occurs when compressive force and velocity both act in a downward direction, and as a result of reflections, etc., there are four episodes when such positive energy transfer occurs. The initial return of the reflected main tensile wave begins to reach the top of the rods at a time of $t = 2L/c$ of approximately 5 ms in this figure, but overall episodes of energy transfer into the rods continue up to a time of

approximately 50 ms (approximately 10 times longer the $2L/c$ “cut-off”), and the secondary reflected pulses carry significant additional energy into the rods and sampler.

Based on these types of theoretical analyses, performed using the same type of wave equation analyses employed for characterization of pile driving, Morgano and Liang (1992) performed numerical simulations for four different rod lengths, and for varying (theoretical) penetration resistances, and concluded that “transferred energy is dependent on rod length and this relationship is more critical when lower soil resistances are present”.

Their complimentary field experiments involved force and velocity measurements and calculation of energy based on the F-V Method using a pile driving analyzer (PDA) system. The integration of the product of force and velocity was carried out up to approximately 50ms beyond the point of initial hammer contact initiation. Consequently, measured transferred energy included the contribution of subsequent (secondary) reflected and refracted pulses, as well as secondary “re-taps” by the hammer. Figure 5-10 shows field energy measurements of Morgano and Liang (1992) for different rod lengths, during SPT driving with an automatic hammer striking with approximately 91% of theoretical SPT hammer energy. This was a limited field data set, but it can be observed that actual transferred energy is rod length dependent for rod lengths of less than about 40 to 50 ft. It should also be noted that this rod length effect manifests itself despite fully measuring and calculating energy transfer through all “secondary” pulses and reflections.

The work of Morgano and Liang (1992) was important in assessing systematically the effects of rod length in SPT energy transfer using the F-V Method, and to times extending beyond $2L/c$. However their field experimentation was limited to only one borehole. There have been additional field studies performed using the full F-V Method to measure hammer energies delivered to the rods during SPT driving (e.g.: Davidson et al., 1999; Butler, 1997; and Sancio and Bray, 2005), that indicated similar effects of rod length on transferred energy. Sancio and Bray (2005) noted, as had Morgano and Liang, that rod length effects appeared to be somewhat more significant for soils with lower penetration resistances. These field measurements/studies produced varied results with regard to the apparent effects of rod length. Rod length was clearly seen to be an issue when data for mechanical (automatic) hammers was considered, but the picture was significantly less clear when data from manual hammers was considered.

A good example is the large data set developed by Davidson et al. (1999), who measured hammer energy delivered to SPT rods in an extensive field testing program performed for the Florida Department of Transportation. A total of 58 different SPT hammers were used, and the energies measured were calculated by the F-V method. Hammer types included both automatic hammers and manually operated safety hammers. A total of 44 safety hammers, and 14 automatic hammers, were used. A variety of rod types were used, as the drill rigs in this program were “volunteered” by their owners/operators. For this reason (the volunteering), it was also not always possible to perform extensive testing with any single hammer and rig. At least one SPT boring was performed with each rig.

The resulting data are presented in Figure 5-11. As expected, energy delivered was found to be significantly higher with automatic hammers than with the manually operated safety hammers, and the consistency of delivery of energy with each individual hammer was also found to be much higher with the automatic hammers. A clear trend of decreasing energy delivered with decreasing rod length can be seen for the automatic hammer data, but no significant trend can be seen for the (manual) safety hammer data. It appears that any trend is obscured by the large (and readily apparent) operator-induced variability of energy delivered by the manually operated safety hammers.

More recently, Valiquette et al. (2010) collected energy, force and velocity (EFV) hammer energy measurements from field calibrations of twenty-eight SPT hammers, including 20 automatic hammer and 8 manual hammers, owned by the North Carolina Department of Transportation (NCDOT) and by private consultants. They found the (operator-dependent) manual hammers to be intrinsically variable, and that it was difficult to accurately discern short rod effects for the 8 hammer energy calibration borings (and the instrumented SPT performed within them) performed using the manual hammers. A majority of their data set (20 calibration borings) consisted of measurements made on automatic hammers, however, and these data indicated that rods shorter than approximately 40ft caused reduction of transferred energy into the rod as shown in Figures 5-12 and 5-13.

Morgano and Liang (1992) and Valiquette et al. (2010) both proposed rod length correction factors (C_R) based on their calculations and observations to correct measured field N-values, and these are both shown in Figure 5-13 (figure by Valiquette et al). The heavy solid line in Figure 5-13 shows the recommendations of Valiquette et al. (2010) based on their measured field data (and the F-V Method), and the dashed line (with longer dashes) shows the recommendations of Morgano and Liang based on their more limited field data (and the F-V Method). The other dashed line (with shorter dashes) in this figure shows the earlier theoretical C_R correction of Schmertmann and Palacios (1979) based on the F^2 Method which required truncation of energy characterization at time $t = 2L/c$. It can be seen that the two investigation teams using modern piezoelectric accelerometers and the full F-V method agree well with each other, and that their recommendations indicate that short rod effects are only slightly less pronounced than those originally predicted by Schmertmann and Palacios based on the F^2 Method. Thus, it would appear that continuing to characterize energy transfer beyond time $t = 2L/c$ in order to capture the effects of secondary pulses and reflections only moderately reduces the overall effects of short rods on energy transfer during SPT driving.

Figure 5-14 again presents the recommended C_R relationships of Morgano and Liang (1992) and Valiquette et al. (2010), this time with the earlier recommended C_R relationships from Figure 5-6 (which had been based on the F^2 Method). It can be clearly seen that the use of the full F-V Method reduces short rod effects.

Another important study was performed by Howie et al. (2003), who studied the details of instrumentation and of processing of data regarding wave travel during SPT hammer blows. They developed two instrumented rod sections of their own design, and also employed an instrumented rod section produced by GRL (which is the largely the current de

facto industry standard). Their “custom” sections had accelerometers capable of measuring higher peak accelerations, and of providing data at higher sampling frequencies. They used the available PDI SPT Energy Monitor by GRL to analyze their data, and also developed their own wave equation analysis software that was able to take advantage of the higher capacity (and higher frequency) measurement and sampling capabilities of their own two instrumented rod sections.

This allowed them to examine the details of hammer interactions with rod systems, revealing in more detail some of the aspects of wave reflections at joints, and issues associated with the instrumented rod sections themselves. They characterized “typical” patterns of initial compression waves for different hammer types, studied reflections due to rod joint details (including loose joints), and examined the effects of accelerometer details (including peak acceleration capacity, frequency capacity, and stiffness including both of fixity of the accelerometer to the instrumented rod section as well as stiffness of the accelerometer itself). They also studied the effects of differences in analysis methods, including various data smoothing and sampling strategies, etc., intrinsic to the analysis process.

They performed only a limited number of actual SPT hammer blows, mainly in a laboratory setting, but their work and findings were very important in helping to better characterize and explain many of these “details” and nuances intrinsic in the measurement (and analysis) of SPT hammer energies. Important findings for the purposes of these current studies included the following:

1. Although it was possible to improve sampling accuracy and the ability to study wave reflections from rod joints, etc., by employing higher capability accelerometers and by optimizing data acquisition and analysis methods to take advantage of this, the current standard instrumentation and analysis systems produced by GRL generally provide similar overall results, and similar overall energy measurements when analyzed correctly with the GRL software, though limitations in accelerometer capacity and sampling frequency can produce slightly lesser overall calculated energies with the GRL system in some cases.
2. Hammer impact details are more important than had been previously recognized. When a hammer strikes the top of the rods, waves reflect back and forth from top to bottom within the hammer while the hammer is still transferring energy to the rods. Safety hammers, being longer than the short actual hammer in automatic hammers, thus have clearly different characteristics in terms of the high-frequency staccato nature of energy driven into the rods than do automatic hammers, and it tends to take longer for safety hammers to transfer the full compressive force from the initial blow.
3. Wave reflections on the rods themselves can also be significant. Reflections can occur wherever rod geometry changes abruptly, and so are affected by differences between the top “anvil” rod section (that is actually struck by the hammer) and the “regular” rods below. Reflections also occur at rod joints, and when joints are loose these can produce increasingly significant tensile reflections that break up an otherwise more monolithic initial compressive wave passing down the rod string. These types of wave reflections obviate the assumptions

of the F^2 Method, but are captured correctly by the Force-Velocity Method so long as suitable acceleration data can be continuously obtained.

4. As with previous investigators, they found that continuing to calculate energy driven into the rods after the initial return of the main tensile wave (after $t \approx 2L/c$) can result in tracking of the full energy transfer. This can produce a larger overall transferred energy into the rods, especially for relatively short rods, but it does not always significantly increase the overall calculated energy transferred. Tensile reflections, correctly tracked and analyzed by the Force-Velocity Method, can draw energy out of the rods as well, and they recommended that energy of a hammer blow successfully transferred to the rods be defined as the maximum energy transferred at any point in time. This maximum energy transferred (ENTHRU) may occur prior to the end of the hammer impact and waves reflection event sequence.

Figures 5-15(a) through (c) present illustrations of analyses of three hammer blows (with different rod lengths) performed by Howie et al. These are sub-elements of larger figures in the report by Howie et al. (2003), and were Figures 6.1(b), 6.2(b) and 6.3(b) in that report.

Figure 5-15(a) shows force, scaled velocity, and energy records calculated by both the Force-Squared and the Force-Velocity Methods for an automatic hammer and an SPT test depth = 10 ft. In this figure, the initial tensile wave return begins to arrive at the instrumented rod location at a time of approximately 2.2 ms, at which time energy transfer into the rod is terminated (and even slightly reversed) as shown by the green line at the top of the figure. The green line shows energy transferred to the rods based on the Force-Velocity Method, and the red line shows energy transferred based on the Force-Squared Method. For this case (with very short rods, and few joints) the proportionality assumption of the Force-Squared Method is largely valid up until time = $2L/c$, and so the red and green lines are essentially the same. Energy is not calculated by the Force-Squared Method after $2L/c$ because the proportionality assumption required is no longer appropriate. Examining the green line showing energy transferred based on the Force-Velocity Method more closely, it can be observed that the initial compressive force from the initial hammer blow transfers energy up until $t \approx 2L/c$, after which a small bit of energy is lost and then energy transfer is largely null for a while, then two additional “events” occur and additional energy is transferred to the rods. Howie et al. (2003) infer that these two additional events represent secondary impacts of the hammer because of proportionality between the resulting increases in measured force and velocity, but for other situations (e.g. longer rods, and less rebound of the initial blow) similar (though usually smaller) additional energy transfer events can also occur due to wave reflections, etc.

Figure 5-15(b) shows force, scaled velocity, and energy records calculated by both the Force-Squared and the Force-Velocity Methods for a safety hammer and an SPT test depth = 35 ft. With this longer rod length, it can be seen that nearly the full initial compressive blow/force successfully transfers energy into the rods before the initial tensile wave returns at $t \approx 2L/c \approx 5.1$ ms. At that time, the returning tensile wave produces a significant loss of energy (see the green line at the top of the figure showing energy based on the full Force-Velocity Method). A bit later (at approximately $t = 7$ ms) energy begins to be

re-introduced. This second introduction of energy is not due to a secondary hammer blow, but is instead the result of wave reflections back down the rods. It is interesting to note that in this case the re-introduced energy nearly offsets the initial energy loss, but does not overtake it and produce equal or higher net energy after this part of the sequence. Further perturbations continue, and energy eventually rises to approximately the level calculated earlier at approximately $2L/c$, but does not rise significantly past that earlier energy transfer. It should be noted that this is specific to this combination of rods and hammer, and that subsequent perturbations over the entire event sequence can produce either a net increase, or a net decrease, over the energy transferred at $2L/c$. Accordingly, as discussed previously, it is maximum energy transferred at any point in time that is taken as the measure of energy imparted by the hammer blow.

Figure 5-15(c) shows force, scaled velocity, and energy records calculated by both the Force-Squared and the Force-Velocity Methods for an automatic hammer and an SPT test depth = 80 ft. For this situation, with much longer rods, full initial energy transfer is accomplished before the tensile wave return at $2L/c$, and subsequent perturbations (reflections, etc.) produce little overall net change in energy transferred. The time of maximum energy transfer occurred at the end of the initial hammer pulse, and this is not subsequently exceeded. Instead, net energy actually decreases later in the record. Similarly interesting is the observation that energy calculated by the Force-Squared Method (the red line at the top of this figure) is greater (up until $2L/c$) than that calculated by the Force-Velocity Method. This is likely due mainly to wave reflections from the more numerous joints on the longer rod string. These reflections serve to break up the otherwise more monolithic main pulses, and may also help to partially explain why the maximum energy was transferred earlier in the record rather than at the end.

The studies by Howie et al. (2003) helped to advance understanding of many of the issues and details affecting energy transfer, and energy measurement, during SPT driving. Howie et al. performed most of their SPT hammer blows in a laboratory setting, and did not extend their study to extensive field testing. That was not a lapse on their part; their focus had been on details of measurement and calculation, and a controlled laboratory setting was ideal for that purpose. But it meant that they did not develop a large field data set as well.

5.5 Another School of Thought

Although the evolution traced through the afore-mentioned theoretical, analytical and physical measurement studies have jointly led to the types of short rod correction relationships expressed in Figures 5-5, 5-6 and 5-14, new controversy has recently arisen and a new school of thought has emerged. This view posits that properly accounting for secondary energy pulses (reflected and refracted pulses, plus secondary hammer re-strikes) produces a total sum of energy successfully transferred to the rods such that no “short rod” correction is warranted.

This alternate view was spurred in part by recent work by Daniel et al. (2005) who developed a system for measuring, using electrical contact elements, when the hammer was actually in contact with the anvil, and when it was separated from the anvil. They measured

energy delivery using the full F-V Method, but further informed themselves as to the durations of actual hammer contact and were thus able to clearly discern secondary hammer “re-taps” as the hammer separated from the top anvil and then re-established contact as waves of energy reverberated up and down the rod string and within the hammer as well. Their data set was a relatively small one, but they concluded that the total energy eventually delivered from the hammer to the rod string was approximately equal to the inertial energy potential of the hammer dropping with known initial impact velocity (which they also measured), and that full energy delivery occurred within approximately 50 to 60 ms, during which time full penetration of the sampler was effectively completed as well. They found that re-taps delivered significant additional energy, and suggested that short rod corrections are inappropriate and unnecessary when all of the energy is accounted for by F-V integration until the end of the energy transfer events occur.

Theirs was principally a laboratory study, and they produced relatively little field data to support this position. But their paper drew additional support, and supporting field data, in discussions by Decourt (2006) and by Danziger, Danziger and Cavalcante (2006). The data presented by these two sets of discussers was also sparse, and had been developed by measurements on manual hammers with significant operator-induced variances in energy delivery.

ASTM has recently revised the Specification for SPT hammer energy measurement, and this revised specification recognizes that short rod effects may be less significant than had earlier been postulated based on early energy measurements developed using the F^2 Method. The new specification now requires the use of the F-V Method for hammer energy measurements. In addition, this recently revised ASTM standard takes aim at SPT-based empirical liquefaction triggering correlations and states rather firmly that this new finding (the reduced correction for short rod effects) renders all principal liquefaction triggering correlations inaccurate. The ASTM Specification D4633-10 states: “The correction for short rods of less than 30ft was based on the theoretical wave mechanics under the assumption that the hammer energy input was terminated by the reflective tensile wave and the remaining energy could not be predicted. The factors never agreed with actual field measurements.” and goes on to state that “Liquefaction evaluation methods such as NCEER 2001 that advocate short rod correction factors based on the theoretical calculation are not correct.” This has generated significant controversy, and it is this controversy that will be addressed by our current studies.

5.6 Assessment of Rod Length Effects Based on Field Energy Measurements Using the F-V Method, and Integrated Over the Full Duration of Interest

To further study the effects of rod length on hammer energy transfer, this current study was conducted using field hammer energy measurements obtained during SPT performed for purposes of “calibration” of automatic hammers. Automatic hammers were selected because this would eliminate operator variability that might otherwise obscure the effects of rod length on energy transfer.

Data were provided by the California Department of Water Resources, from both the Division of Safety of Dams and from the Levees Evaluation Division. A total of 24 SPT borings were selected as conforming to the data and instrumentation quality standards set for this study. Because the SPT were being performed specifically for purposes of hammer calibration, workmanship and oversight were good. Energy measurements were made (and analyzed) by four different organizations or consultants, each with a good reputation in this field. The rod instrumentation systems employed were all GRL systems, and employed two mounted strain gauges and two bolted piezoresistive accelerometers. The data acquired for each hammer blow was processed and analyzed using the GRL Pile Driving Analyzer (PDA) system and software. Integration of the product of force and velocity by PDA continued until energy transferred to the rod reached a maximum value; there was no “truncation” of secondary pulses. The maximum energy value (EMX) was calculated by the Force-Velocity Method as

$$EMX = \int_a^b F(t).V(t)dt \quad \text{Equation 5.3}$$

where a corresponds to the start of energy transfer and b corresponds to the time at which energy transferred to the rod reaches a maximum value.

The energy transfer ratio (ETR), which relates EMX to the maximum theoretical potential energy, was calculated as

$$ETR = \frac{EMX}{350 \text{ lb-ft}} \quad \text{Equation 5.4}$$

Only well instrumented automatic hammer calibrations were included, in order to eliminate hammer inconsistency as a variable. The use of two strain gauges and two piezoresistive accelerometers enabled the quality control of force and velocity measurements. Only SPT performed using rods of A type (AWJ) and N type (NW, NWJ) were considered. Another criteria establishing the dataset were good workmanship, e.g. tightening of rod joints, etc., supervised by engineering firms and agencies with a good understanding of SPT details and procedures, and of the importance of the data. A total of twenty-four automatic hammer calibration borings which had met these criteria were evaluated. Eight of these were performed on dam sites throughout the State of California, and sixteen of the calibrations were performed for levee projects. The calibration borings for the levee projects were not necessarily performed on levees; instead they were performed to calibrate the automatic hammers in preparation for subsequent work on levee sites throughout California’s large Central Valley. Geology and geography were varied at the sites where these 24 SPT hammer calibration borings were performed.

For each automatic hammer, the SPT driving energies were measured within the calibration borehole over a range of depths. The resulting measured energies from individual hammer blows at each SPT depth were averaged to produce the “representative” energy transfer for that SPT test. Within the borehole, the resulting representative energies transferred were then “normalized” relative to the apparent maximum (and relatively constant) level of energy transfer accomplished at significant depth, as illustrated for an example boring in Figure 5-16.

Energy transfer ratios (ETR) calculated at different depths were plotted vs. the total rod length, which is the distance between the bottom of the split spoon sampler and the instruments located 6'' below the top of the rods. For the example shown in Figure 5-16, it can be seen that ETR increases with increasing rod length and reaches an asymptotic energy transfer ratio at depth where rod length does not matter anymore. This is typical of the data set for the other borings as well. In Figure 5.16, the energy transfer ratio was measured as 69.5 percent with a (short) total rod length of 8 feet and reached to asymptotic ETR of 81.5 percent represented by the dashed line for rod lengths longer than approximately 35 to 40 feet.

Similar evaluations were performed for all of the twenty-four hammer calibration borings. Summaries of the data, and of the processing and normalization, for each of the 24 borings are presented in Appendix C. The asymptotic energy transfer ratios achieved at significant depth ranged from 65.5 percent to 92.2 percent during these calibrations, reflecting the higher energies imparted by automatic hammers. It was consistently observed that energy transfer ratios reduced with shorter rod lengths, though the degree of this reduction varied among the borings.

In the end, energy transfer ratios based on the Force-Velocity method were obtained for total of 8879 hammer blows, from 300 SPT performed within 24 different boreholes.

To examine and quantify apparent reduction in hammer energy transfer with shorter rod length, energy transfer ratios measured within same borehole were divided by the asymptotic energy transfer ratio of the hammer used in that particular borehole. This produces the apparent rod length correction factor (C_R) corresponding to each individual SPT depth (and rod length). Because measured N-value and hammer energy (expressed as energy transfer ratio, or ETR) are inversely correlated, the ratio of the ETR at any depth to the asymptotic ETR at great depth should give the necessary rod length correction factors (C_R) at each depth for that particular hammer.

The open dots on Figure 5-17 represent the rod length correction factors thus obtained for all 300 SPT from the twenty-four boreholes, and the solid line represents the rod length correction relationship (C_R vs. rod length) developed by straightforward regression of the data. Because asymptotic ETR values were chosen as representative of transferred energy ratio at depth, C_R at any individual location (or rod length) may sometimes be either bigger or smaller than 1 depending on whether energy transfer ratio (ETR) exceeds the representative asymptotic energy transfer ratio for that hammer and borehole. However, it is noted that the average of C_R at significant depth is approximately 1.0, and that no additional normalization was required to force this value to 1.0 when the data from the 24 individual borings were compiled together.

As shown in Figure 5-17, energy transfer ratio (ETR) and thus C_R , decrease at shallow depths with decreasing rod length. Based on these data, the proposed rod length correction relationship for automatic hammers would be

$$C_R = 1 - 0.36 e^{(-0.085 \cdot L)}$$

Equation 5.5

where L is the rod length from point of hammer impact at the top of the rod string to the base of the split spoon sampler.

Effects of soil type and character were considered. It was not possible to discern any clear effects of soil type (e.g. clays vs. cohesionless soils) on the relationship between C_R and rod length.

There was, however, an observable effect of penetration resistance (N -value) on this relationship, and this is shown in Figure 5-18. The energy measurements and resulting ETR values (and local C_R values) obtained were grouped into four different bins based on the N_{60} values measured for each SPT, and curves were developed for each bin. Bins were set for energy corrected but non-overburden corrected N_{60} -values of values of $N_{60} = 1$ -10 bpf, 10-20 bpf, 20-30 bpf and larger than 30bpf. Each bin was analyzed and regressed separately, and the results are shown by the dashed lines in Figure 5-18. The solid (red) line in Figure 5-18 is the overall regressed relationship (independent of N_{60}) from Figure 5-17. It is clear that the effects of short rods on transferred energy into the rod is more significant for looser soils with lower penetration resistance, as had been postulated by previous researchers. It is clear that there is a slight trend in which the significance of C_R diminishes with increasing N -values, but this is only a slight trend and it does not appear to be overly significant at the N -values of common interest ($N_{1,60} \leq 40$ blows/ft).

A similar trend was observed between N and ETR by Morgano and Liang (1992) and also by Sancio and Bray (2005), though Morgano and Liang had a limited data set and the data set of Sancio and Bray was obtained with rope and cathead hammers which served to partially obscure this subtle relationship due to unavoidable operator-related variability (which was why Sancio and Bray measured energy for each SPT performed throughout their field study targeting acquisition of data for post-earthquake liquefaction investigations in Adapazari, Turkey).

This trend has also been postulated by a number of investigators based on wave equation mechanics. When the initial compressive wave from a hammer blow reaches the base of the sampler, if it encounters soils of low resistance (low N -value) a strong tensile wave reflects back up the rods. If the initial compressive wave encounters essentially “rigid” resistance (e.g. hard rock) then a compressive wave reflects back up the rod. Theoretically, there would be a “stiff” resistance between these two extremes (neither low resistance nor fully rigid resistance) at which a minimal reflection would occur. The low to moderate ranges of resistance (N -values) of principal interest for most geotechnical applications ($N_{1,60} \leq 40$ to 50 bpf) do not rise to the level that would produce such minimal reflections and thus C_R is a moderately a function of N_{60} , and does not reach a value of $C_R = 1.0$, over the range of N -values of principal interest for most projects.

Figure 5-19 shows the regressed relationship from Figure 5-15, along with (a) the relationship recommended by the 2001 NCEER Workshop (Youd et al., 2001), and (b) the relationship proposed by Valiquette et al. (2010). Valiquette et al. developed a similar

database, employing SPT hammer energy measurements from automatic hammers from 20 SPT borings, and developed almost exactly the same relationship between C_R and rod length. Figure 5-20 repeats Figure 5-19, but this time adds the relationship proposed by Morgano and Liang (1992). Morgano and Liang had only a very limited data set, and did not employ an automatic hammer, but they exercised very careful control of their rope and cathead hammer system, and obtained very similar results. This relationship agrees reasonably well with the other two.

Thus it appears that, at least for automatic hammers the relationships of Figure 5-17 represent suitable correction factors (C_R) for “short rod effects”.

These could be further refined based on penetration resistance to develop relationships of C_R vs. N_{60} or $N_{1,60}$, but given that the primary range of interest is generally $N_{1,60}$ values of between about 5 to 35 blows/ft, it does not appear that the relatively limited additional improvement this would produce is warranted as it would also increase the complexity of the data processing and would require an iterative loop in processing of SPT data. There is ample additional support for a moderate N-value dependence here, both from other data sets as well as from theoretical considerations, and engineers and researchers might be invited to employ an N-value dependent C_R correlation (e.g. Figure 5-17) when special precision is sought for interpretation of SPT at very shallow depths.

The relationships of Figure 5-17 represent a reduction in the magnitude of the short rod correction relative to the earlier relationship recommended by Youd et al. (2001), but they do not represent a “null” correction. That is compatible with the observations and recommendations of nearly everyone cited thus far as having contributed to the evolving state of knowledge. Many had noted that carrying forward the full integration of energy by the Force-Velocity method would likely reduce the significance of the short rod corrections somewhat (relative to earlier corrections based on the Force-Squared Method with truncation of energy at $t = 2L/c$). But the same researchers and experts all also noted that short rod corrections continue to be present, even with the full F-V Method integration.

The question that remains is then: What sort of relationship should be employed for non-automatic hammers? Field data sets employing rope and cathead hammer systems have shown far greater scatter in terms of energy delivered to the rods as a function of rod length than was evidenced when only automatic hammer data were examined. The underlying question is then whether (a) the scatter intrinsic in unavoidable operator variability simply serves to obscure and partially “mask” short rod effects from non-automatic hammers, or (b) there is a fundamental difference in the mechanics of safety hammers that further reduces the effects of short rods on the energy delivered at shallow depths.

To this end, it is noted that the major data sets that developed data by the (correct) fully integrated F-V Method, without cut-off or truncation, and which considered both automatic hammer data and also non-automatic hammer data, all tended to observe more pronounced (or at least clearer) short rod effects for the automatic hammer data. The exception is the limited data set of Morgano and Liang (1992), but it must be recognized that they were performing research-level work with unusually good manual hammer control.

There are some fundamental differences between the hammer impacts from automatic hammers and those developed by safety hammers. One of these is overall magnitude of energy delivered. Because automatic hammers have less frictional resistance, they develop higher impact energy. In some cases, when operated to too high a rate, the mechanical internal lifting system can actually “hurl” the hammer block upwards too far and energies of slightly greater than 100% of the theoretical free fall energy (350 ft-lbs) can be achieved. A second difference was well-studied by Howie et al (2003), who noted that the quality and characteristics of the hammer blows are different as well, in ways that are subtle but clear when analyzing well-measured force and velocity wave traces. Automatic (mechanical) hammers tend to have a short, squat hammer block while safety hammers are of greater length (usually several feet) so that (a) internal hammer reverberations are generally more rapidly transmitted from base to top and back again within an automatic hammer, and (b) it takes a bit longer for transfer of full energy from the initial contact episode with a safety hammer.

None of these differences would suggest that there should be any significant systematic reduction in the magnitude of short rod effects on hammer energy delivery, and so it is suggested that the reduced ability to clearly see short rod effects in non-automatic hammer measurements is instead primarily the result of unavoidable operator variability in actual hammer blow energy introduced by the use of a rope and cathead system under most field conditions. Practice appears to be migrating towards increased use of mechanical hammers, expressly to avoid that variability, and so it is likely that rope and cathead systems will be used less frequently in the years ahead.

But it is still necessary to have an approximate relationship for short rod corrections of non-mechanical SPT hammer data because (1) non-mechanical hammers will continue to be used, and (2) field performance data from numerous previous studies (including previous post-earthquake investigations) were developed with non-mechanical hammers.

Another factor sowing confusion has been the historical sequence of development of knowledge and understanding of SPT hammer energy delivery issues. Initially, it was necessary to employ the Force-Squared method as an approximation, due to the lack of suitable instrumentation capability with regard to accurate measurement of accelerations during a hammer impact event. That resulted in energy measurements that tended to underestimate energy delivery, especially for short rod conditions wherein the first returning tensile wave arrived before full energy transmission from the first impact pulse had been consummated. As instrumentation improved, and the fully correct Force-Velocity method became feasible, it was widely recognized that the significance of short rod effects would likely be found to be reduced somewhat. But that did not mean that these would become null effects.

Nearly all of the major investigators cited thus far in this chapter have opined that although the F-V method is the correct approach, and although this method can calculate additional energy transfer that may occur after the initial $t = 2L/c$ cut-off intrinsic in the earlier F^2 method, they all continue to observe non-zero short rod effects in their field data

sets. This includes the data sets of Butler (1997) and of Davidson et al. (1999) who between them compiled a significant number of data for various hammer types, rod types, etc. Both employed the full F-V method, without truncation. Butler observed less clear, but often non-zero, rod length effects on hammer energies, as with the data set developed by Valiquette et al. (2010). The very large data set of Davidson et al., in particular, showed a short rod effect that was more clear and apparent for their mechanical hammer data, but noted a nearly null overall relationship for short rod effects for their far more scattered non-mechanical data.

Howie et al. (2003) made strong comments as to the importance of performing the full F-V integration, and noted that this would likely result in reduction of the apparent short rod effects that had previously been based largely on F^2 calculations. Howie et al did not, however, state that short rod effects could be expected to become null, nor even nearly so. Instead, they stated “Past researchers have observed that there is an increase in energy input with increasing depth, even when the F-V approach is used. The rate of increase, if any, does not appear to be as great as was indicated by the K_2 factor originally developed by Schmertmann for the F^2 approach.” And they go on to recommend that the K_2 factors of the previous ASTM Standard be abandoned.

But they do not recommend null correction for short rod effects. Indeed, they present only two actual field borings with SPT data, as theirs was primarily a laboratory and analytical/instrumentation study, and these are presented in Figure 5-21(a) and (b). Both of these sets of SPT were performed using non-mechanical safety hammers, and both sets were processed/analyzed using both the F^2 and the F-V method. In both figures, it is clear that the full F-V integration calculates higher overall energy delivery, and lesser short rod effects. In Figure 5-21(a) short rod effects are either unclear or not very pronounced when the full F-V method is used. In Figure 5-21(b), short rod effects are very clear, and correspond closely to the type and magnitude of those shown for automatic hammer data in Figures 5-17 through 5-19. The red and blue dashed lines in Figure 5-21(b) have been added to their original figure to highlight the apparent short rod effects for this F-V processed data.

As noted above, despite the increasing use of mechanical hammers, it is still necessary to have short rod corrections for non-mechanical hammers because (a) they continue to be widely used, and (b) important previous (historical) data sets were developed using non-mechanical hammer SPT data.

In forward engineering for current projects, it would be unconservative to systematically underestimate short rod effects at shallow depths.

Our recommendation is that the mechanical hammer data, and relationships, shown in Figures 5-17 and 5-18 appear to present the clearest view of short rod effects, with minimal confusion from hammer variability. Although operator-induced hammer variability clouds the issue for non-mechanical SPT hammer data, it appear that the best approach at this juncture is to use the C_R corrections developed for mechanical hammers, and to apply these to non-mechanical hammers as well. These represent short rod corrections of somewhat lesser magnitude than previous C_R relationships, but they do not represent null corrections.

For rod lengths of about 10 feet (representing SPT depths of typically about 4 to 6 feet with typical hammer, rod and sampler set-ups) the maximum amount of correction is a factor of $C_R \approx 0.86$ (a 14% adjustment of N-value for short rod effects) and the significance of C_R diminishes with increasing depth.

There is ample room for additional research to further study short rod effects for non-mechanical hammer systems, and it should be noted that extraordinarily good control of rope and cathead hammer energy delivery may be required in order to fully resolve this issue. An alternative would be to use safety hammers, but with a specially fabricated mechanically consistent hammer drop system, so that operator variability could be eliminated from the overall mix while still evaluating safety hammer blows.

5.7 An Additional Note About Hammer Calibration Practice

Last but not least, there is a lack of standardization in SPT hammer energy calibration practice. The recently revised ASTM Specification D4633-10 regarding SPT hammer energy measurement addresses the practice of periodic “calibration” of automatic hammers so that their energy delivery in the field can be taken as “known”. A minimum of 5 SPT at five depths are recommended, and a minimum of at least three SPT at three depths are required.

There is, however, no specification and no established standard of practice with regard to the ranges of depths over which hammer energy measurements are to be made when “pre-calibrating” an automatic hammer in this way. As a result, practice varies considerably, with some operators performing only a limited number of SPT at relatively shallow depths, some operators performing SPT to greater depths (but averaging the shallower SPT hammer energy measurements in with the deeper measurements), and some operators measuring and using the data only from SPT performed at sufficient depth as to eliminate short rod effects.

These approaches can result in significant differences in the “apparent” calibrated energies of the hammers, and that can have a potentially significant effect on the interpreted SPT values at all depths during subsequent field work for actual engineering projects.

As an example, consider the hammer calibration data presented for one hammer in Figure 5-22. If the energy calibration had been performed from shallow depths up until a maximum depth where the rod length reached up to 30 feet, the average energy transfer ratio of the hammer would have been calculated as 74 percent. If the energy measurements for all depths (all rod lengths) performed to the full depth of the borehole were averaged together, then the calibrated hammer energy would have been taken as $ER = 72.4\%$. But if only SPT performed with rod lengths of greater than 30 feet were averaged together, then the calibrated energy would have been taken as $ER = 78.3\%$. Considering the actual asymptotic energy ratio delivered at greater depths (where short rod effects have ceased to be significant), the actual hammer energy being delivered is 78.9% of the theoretical free fall energy ($ER = 78.9\%$).

It is this “deeper” value, largely independent of short rod effects, that is the most correct value, and it is this deeper value that should be used as a basis for interpretation of subsequent SPT performed with this hammer (with short rod corrections then being applied as appropriate). To use the “calibrated” energy measurements biased by short rod effects as the hammer energy, and then to make additional corrections for short rod effects would be redundant. Even more important, the use of the shallower energy measurement data causes the overall hammer energy to be underestimated, and produces a conservative bias for all subsequent SPT performed using this calibration result.

Figures 5-23 and 5-24 show two additional “hammer calibration” SPT borings, with the energy ratios based on (1) SPT measurements for rod lengths of 30 feet or less, (2) energy measurements for SPT with rod lengths of 30 to 50 feet, and (3) asymptotic energy delivery at greater depths again clearly delineated.

Both of the first two scenarios led to underestimated transferred energy, thus error in hammer calibrations. For many engineering projects, automatic hammers are periodically re-calibrated (e.g. every 6 months, or similar) and any error in hammer calibration will lead an embedded error for different projects where these erroneous calibration results are used. Consequently, hammer energy calibration should be carried out beyond the depth where rod length does not matter anymore.

Table 5-1 shows the hammer energy calibration data of this study processed by three different approaches: (1) energies measured for rod lengths of less than 30 feet are averaged, (2) energies measured for rod lengths of 30 to 50 feet are averaged, and (3) energies are evaluated at greater depths where measured energies are effectively constant over depth. These three evaluation procedures were applied to each individual SPT hammer calibration boring from Appendix C, and the results by each of these three methods were then averaged for all borings in this study as shown in Table 5-1.

As shown in Table 5-1, if the SPT hammer calibration boring is performed only to shallow depths (e.g. rod lengths less than 30 feet), then hammer energy would be significantly underestimated. But if only SPT performed at depths sufficient that rod lengths are 30 feet long and greater, then essentially negligible underestimation of hammer energy occurs. Accordingly, it is recommended that hammer energy calibrations be performed using only SPT data for rod lengths of 30 feet and greater, and that a minimum of 5 SPT be performed at depths sufficient to meet these criteria.

5.8 Summary and Recommendations

There has been an ongoing evolution of understanding of short rod effects over the past several decades. This has been largely due to a parallel development of improving instrumentation and analytical capabilities for making measurements of hammer energy successfully transferred from the hammer to the rods during SPT driving. Early instrumentation systems lacked accelerometers capable of accurately measuring the high accelerations, and the high frequencies, involved with the steel on steel hammer/rod anvil

impacts. This inability to accurately measure accelerations led to the need to employ the Force Squared (F^2) method for calculation of measured energies transferred to the rods. The F^2 method requires assumption of linear proportionality between force and velocity. This renders the F^2 method somewhat approximate, and it limits the use of the method to the time prior to the first return of the initial tensile reflection from the base back to the top of the rods. As a result, it is not possible to measure additional energy that may be transferred to the rods after this “cut-off”, and secondary hammer strikes as well as reflections back down the rods cannot be measured and accounted for.

As modern accelerometers have improved, we are now able to make the necessary acceleration measurements, and can now employ the full-integration Force-Velocity (F-V) method for calculation of energy entering the rods. This captures the correct physics, and requires no proportionality assumption. It also permits measurement and analysis of wave reflections and secondary hammer impacts until the entire energy transfer event has been completed. Accounting for energy transfer after the initial tensile wave return often leads to higher overall calculated successful energy transfer from the hammer to the rods.

Early short rod correction factors were based on data obtained and processed using the F^2 method, and these overestimated the importance of short rod effects. Later data, now using the F-V method clearly shows reduced short rod effects, but there is controversy regarding the extent to which these effects are diminished, and how best to account for them in interpreting SPT data.

Based on these current investigations, using automatic hammers, it is clear that although short rod effect are reduced somewhat by the use of the (correct) F-V method, they are still potentially significant. The relationship developed by these current studies shows short rod effects to be approximately 60% as significant at shallow depths as had been observed based on the F^2 method. These effects are also found to be moderately a function of penetration resistance, with the significance of short rod effects diminishing somewhat as penetration resistance increases. These observations are supported by other investigators. Recommended new relationships for short rod correction factors (C_R) for use in processing of SPT data have been developed and presented.

An additional issue is the increasing use of “calibrated” automatic hammers to provide known hammer energies for field investigation SPT. There are not standards or specifications regarding the depths (or rod lengths) to be used when using instrumentation to measure (and “calibrate” energy for a specific hammer. It is relatively common practice to perform at least several of the calibration SPT at relatively shallow depths where short rod length effects can affect the measured energy transferred. This has been demonstrated to potentially conservatively bias the “calibration” of the hammer with respect to subsequent (non-instrumented) field investigation SPT using the calibrated hammer. Recommendations have been developed and presented as to the appropriate ranges of depths (and rod lengths) suitable for hammer calibration in order to avoid this systematically conservative error.

Table 5-1: Comparison of Hammer Energy Calibrations Performed for Rod Lengths of
(1) Between 0 to 30 feet, (2) Between 30 to 50 feet, and (3) with Constant
Energy at Depth

Boring #	Total Rod Length 0-30ft		Total Rod Length 30-50ft		Constant at Depth	
	ETR	Ratio	ETR	Ratio	ETR	Ratio
C1	80.7	0.92	88.0	1.00	88.0	1.00
C2	72.9	0.90	80.8	1.00	80.8	1.00
C3	76.3	0.91	80.6	0.96	84.3	1.00
C4	66.9	0.88	68.8	0.91	75.6	1.00
C5	69.1	0.87	77.0	0.97	79.0	1.00
C6	65.8	0.96	66.7	0.98	68.3	1.00
C7	86.6	0.96	91.2	1.01	90.3	1.00
C8	74.3	0.91	82.4	1.01	81.5	1.00
C9	75.1	0.93	80.0	0.99	80.5	1.00
C10	85.4	0.96	88.6	1.00	88.8	1.00
C11	81.6	0.93	90.6	N/A*	88.0	1.00
C12	77.2	0.88	85.9	0.98	87.3	1.00
C13	77.8	0.94	82.2	0.99	82.8	1.00
C14	67.5	0.96	68.0	0.96	70.5	1.00
C15	72.4	0.92	78.3	0.99	78.9	1.00
C16	70.2	0.93	74.8	0.99	75.3	1.00
C17	70.4	0.90	77.9	1.00	78.0	1.00
C18	87.9	0.95	90.3	0.98	92.2	1.00
C19	70.9	0.96	73.4	0.99	73.9	1.00
C20	77.0	0.89	83.3	0.96	86.7	1.00
C21	68.0	0.90	76.4	1.01	75.6	1.00
C22	58.0	0.89	64.3	0.98	65.5	1.00
C23	81.8	0.91	89.3	1.00	89.6	1.00
C24	81.5	0.89	91.1	0.99	92.1	1.00
Averages	=	0.92		0.99		1.00

*Only 1 Data Point for Rod Length between 30 to 50 feet.

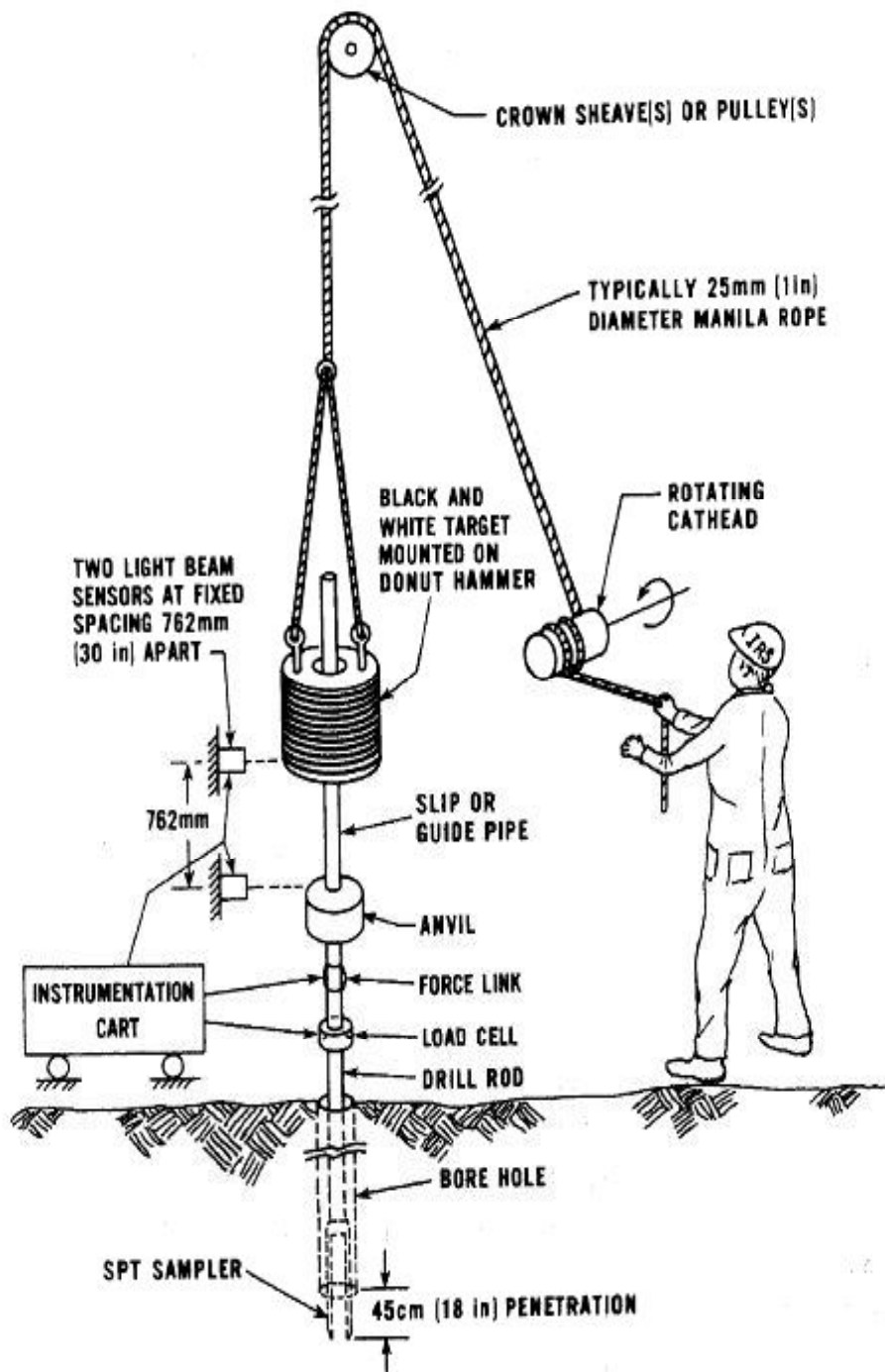


Figure 5-1: Sketch of One Possible SPT Set-Up with Donut Hammer and an Early Experimental Setup for Hammer Energy Measurements Using Load Cells and Laser Sensors (From Kovacs and Salomone, 1982)

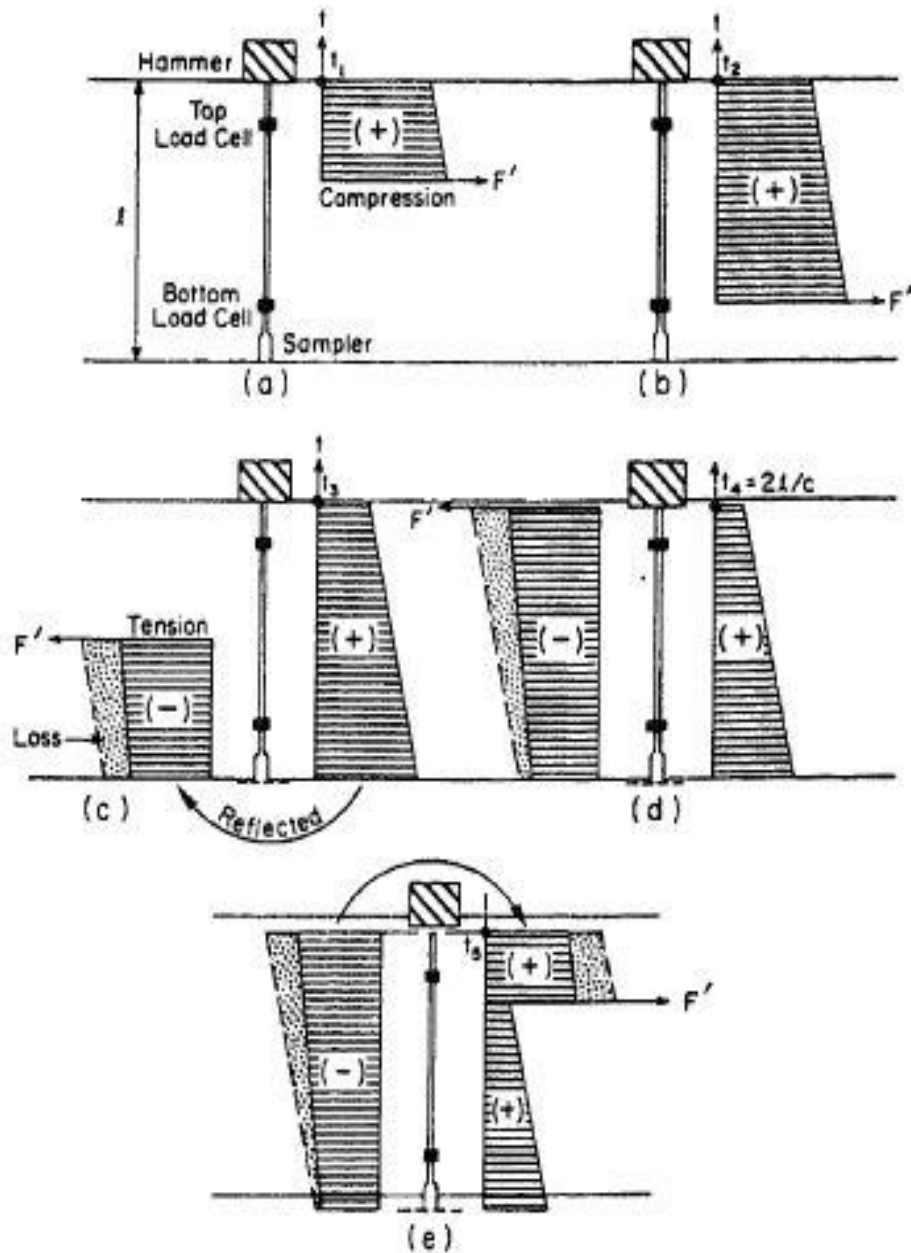


Fig 5-2: Schematic Illustration of Travel Mechanism of First Compression Wave Due to First Hammer Impact in SPT (From Schmertmann and Palacios, 1979)

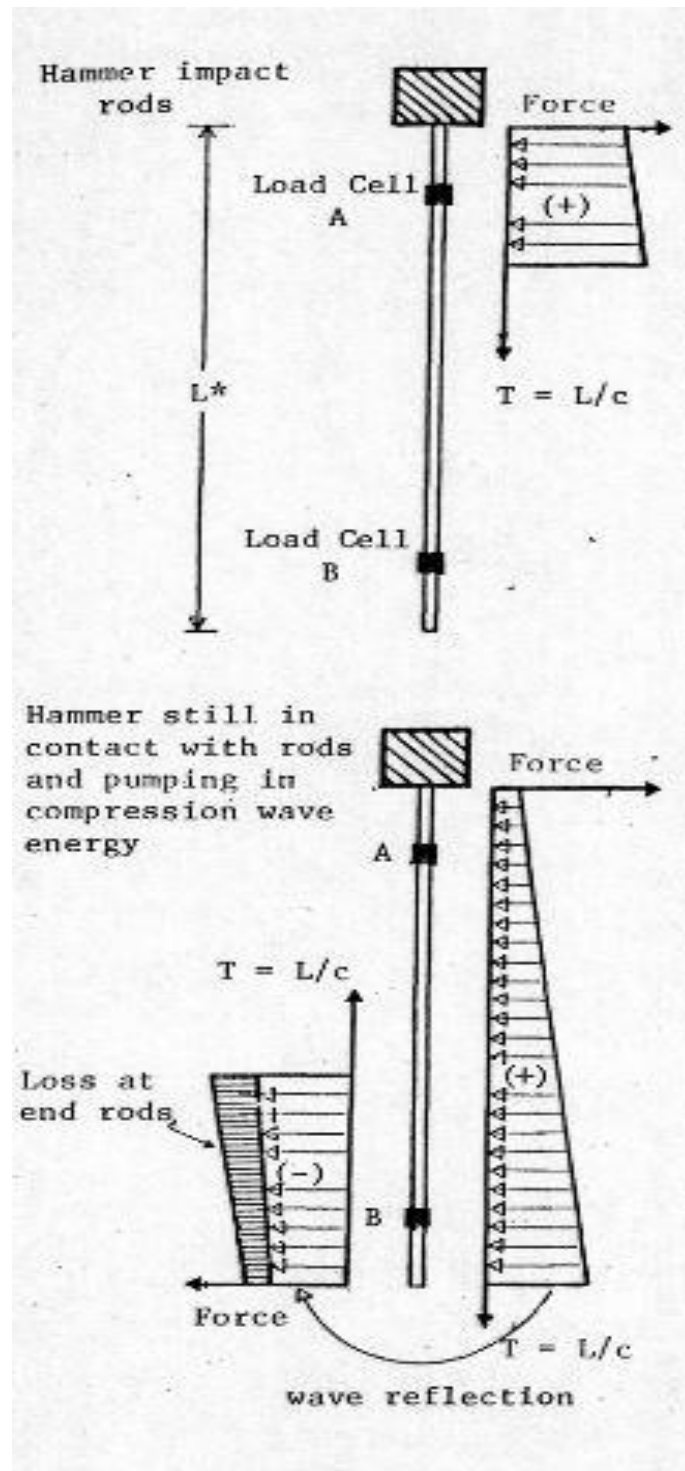


Figure 5-3: Schematic Illustration of Wave Travel After the Initial Hammer Impact During an SPT Blow (From Palacios, 1977)

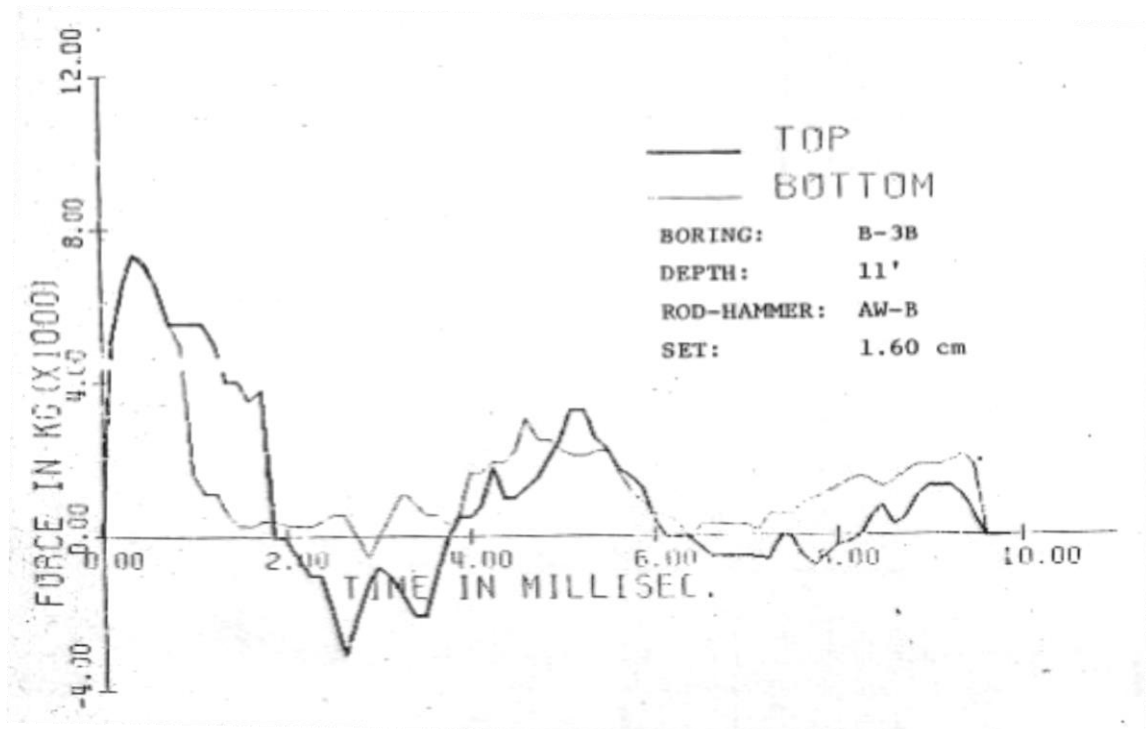


Figure 5-4(a): Force Measurement vs. Time for an SPT Performed at a Depth of 11 ft. with a Rope and Cathead System and a Safety Hammer (From Palacios, 1977)

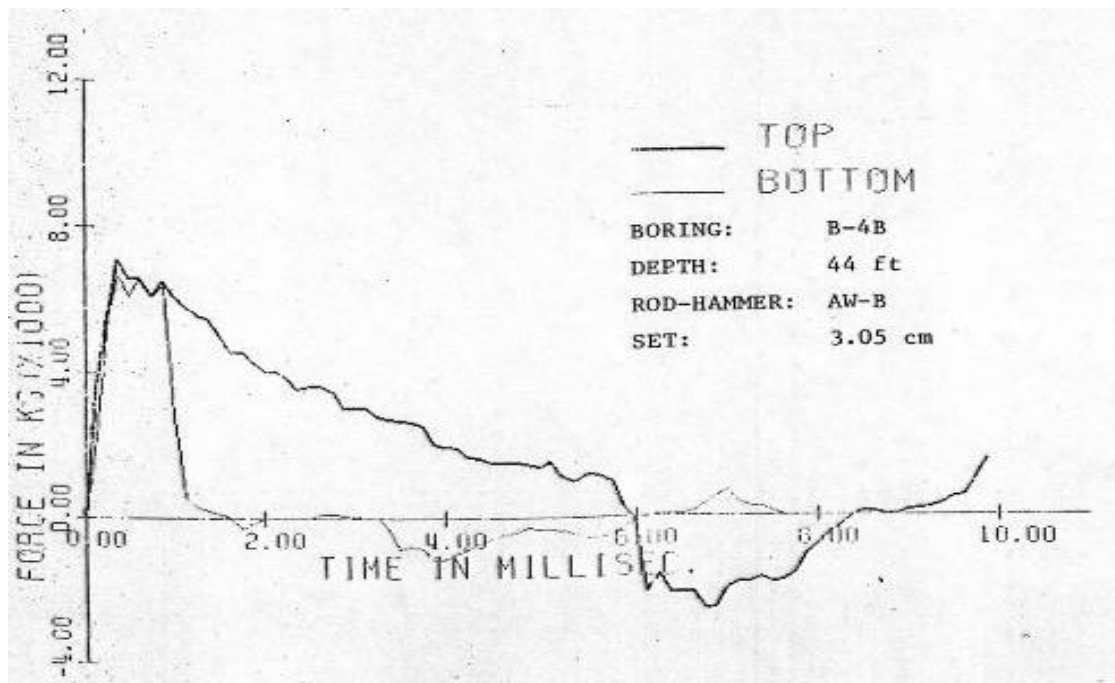


Figure 5-4(b): Force Measurement vs. Time for an SPT Performed at a Depth of 44 ft. with a Rope and Cathead System and a Safety Hammer (From Palacios, 1977)

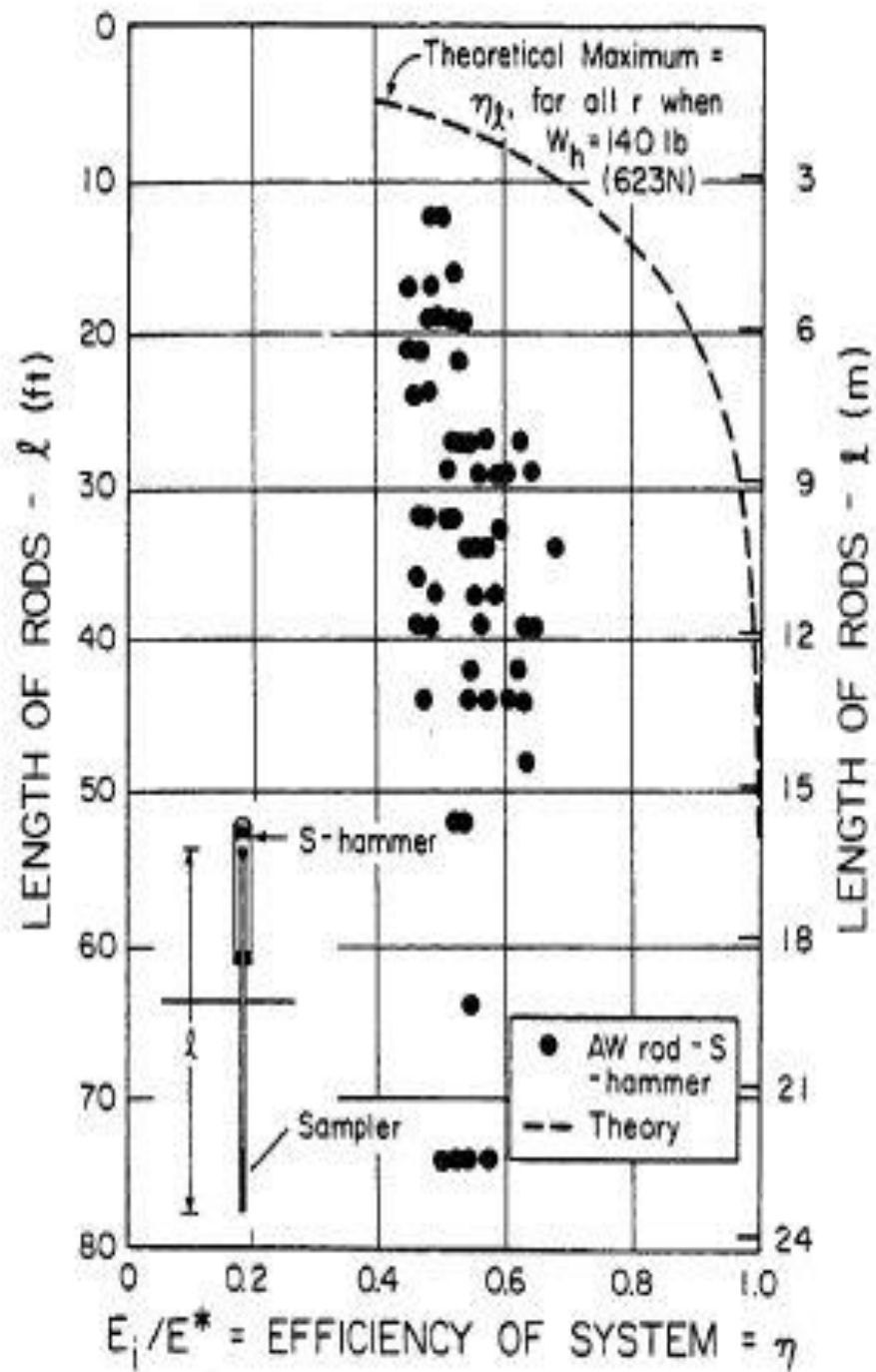


Figure 5-5: Variation of Energy Transfer Ratio with Rod Length for Safety Hammer
(From Schmertmann and Palacios, 1979)

Force Squared (F²) Method

$$E = \frac{c}{EA} \int_{t_1}^{t_2} [F(t)]^2 dt$$

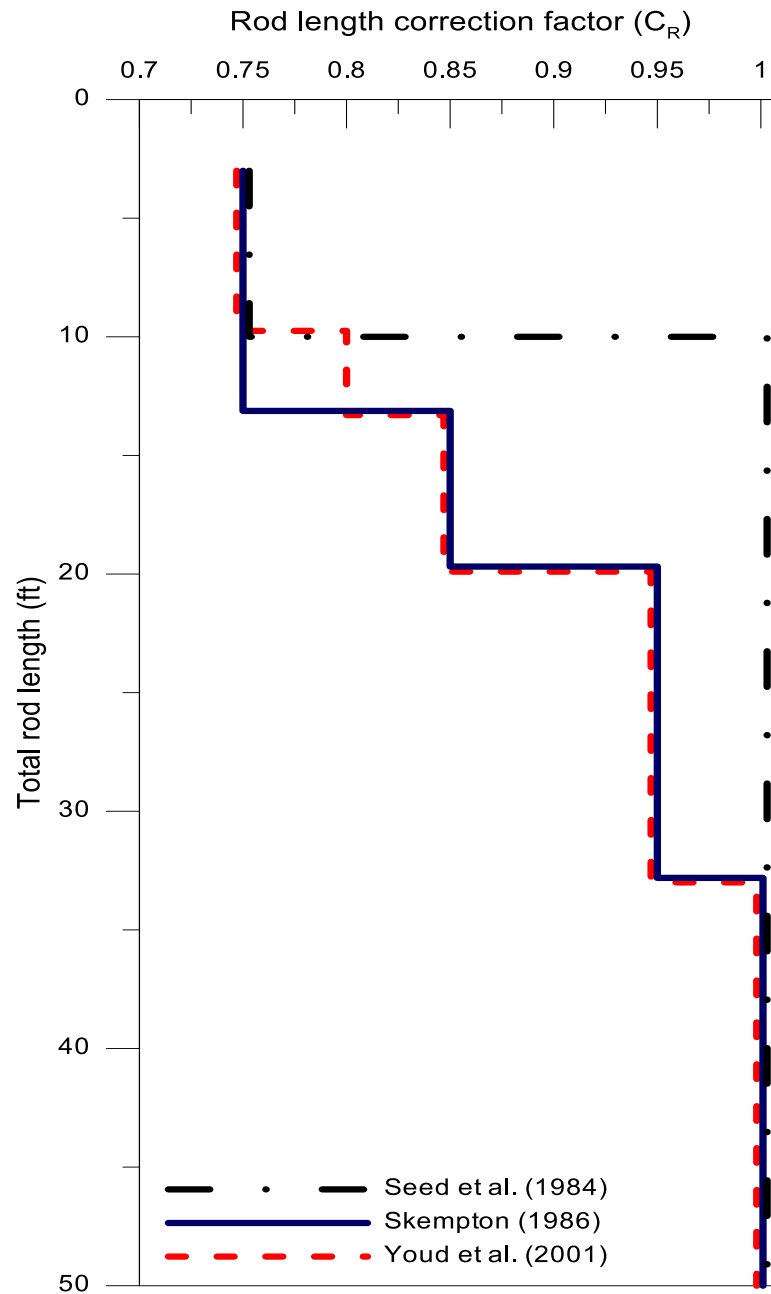


Figure 5-6: Rod Length Correction Factors Developed Based on Hammer Energy Measurements Using the F² Method

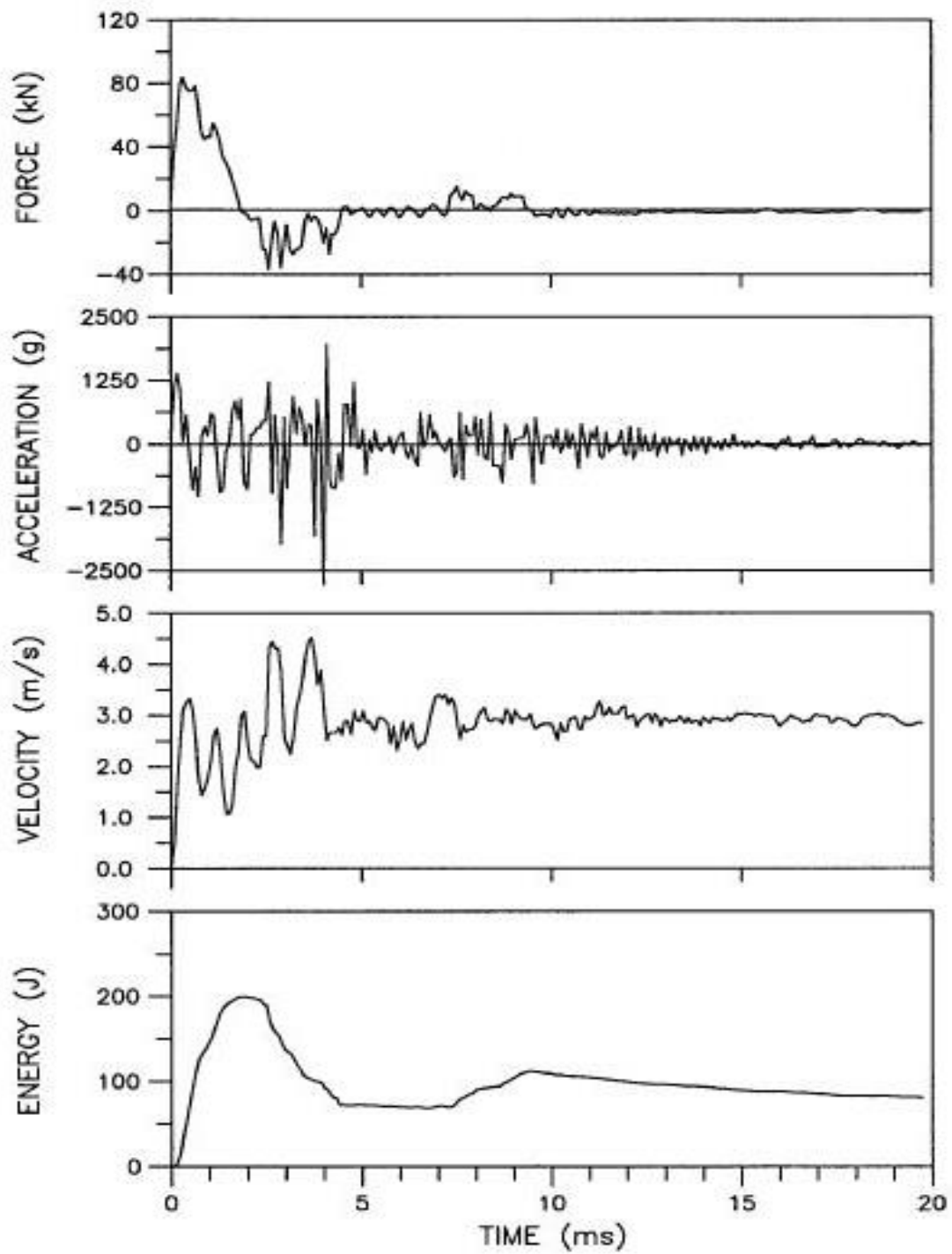


Figure 5-7: Force, Acceleration, Velocity and Energy Time Histories during a SPT Blow at 1.5m Depth (From Sy, 1993)

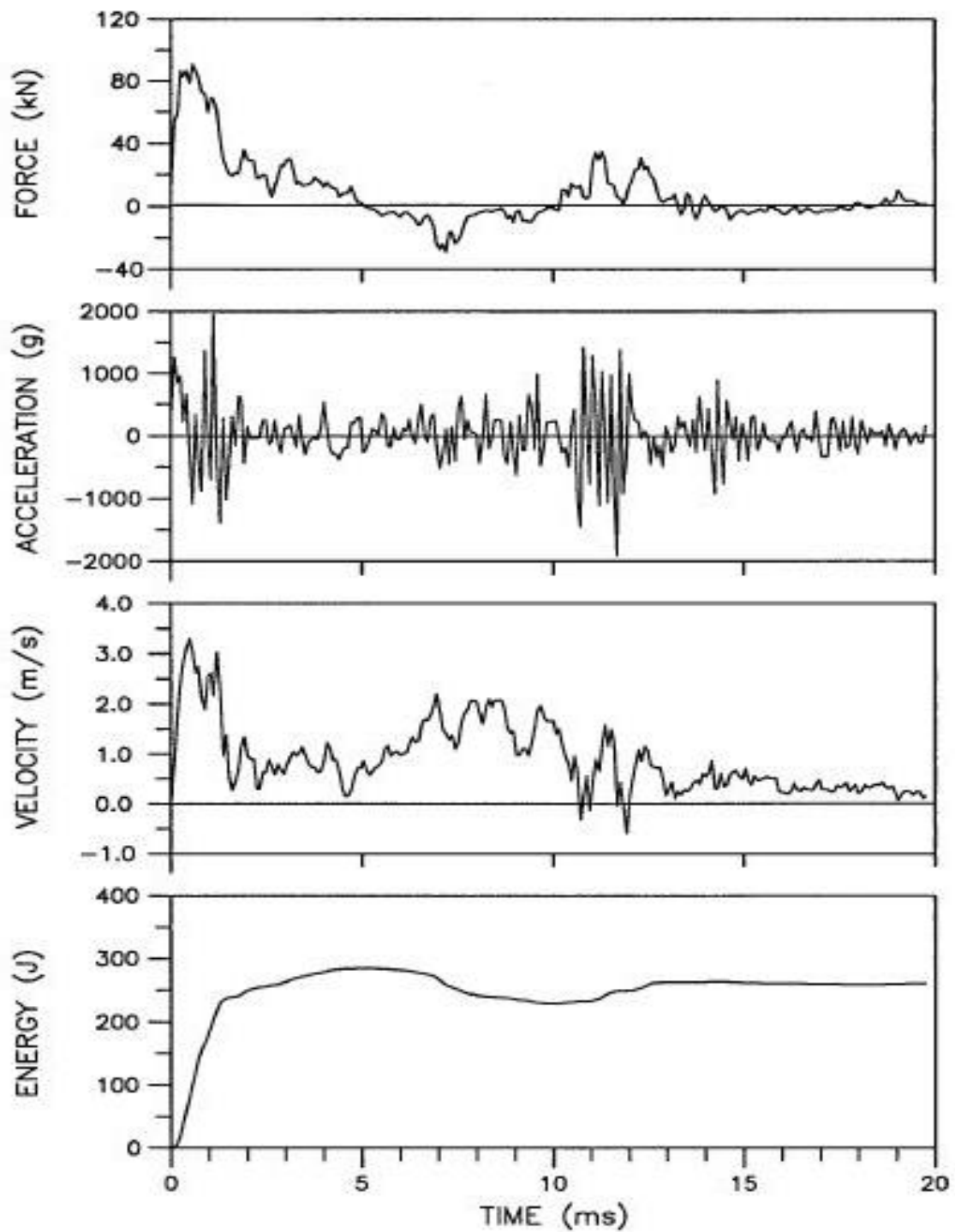


Figure 5-8: Force, Acceleration, Velocity and Energy Time Histories during a SPT Blow at 9.1m Depth (From Sy, 1993)

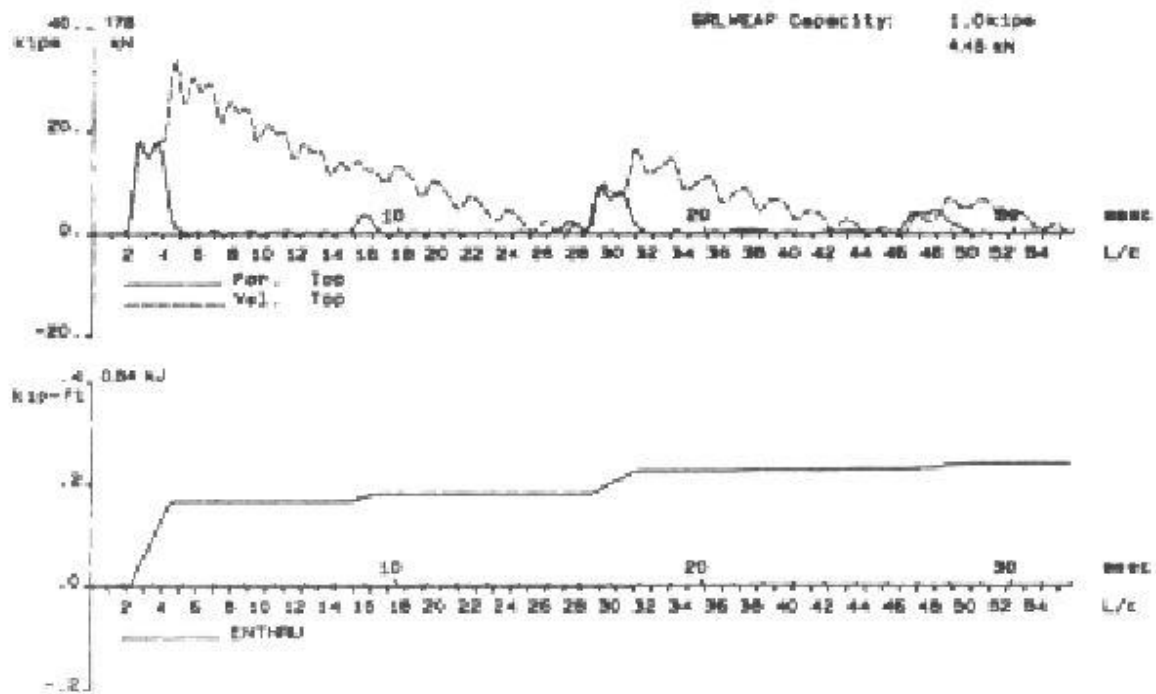


Figure 5-9: Numerical Simulation of Force and Velocity during a SPT Blow for Rod Length of 10 feet (from Morgano and Liang, 1992)

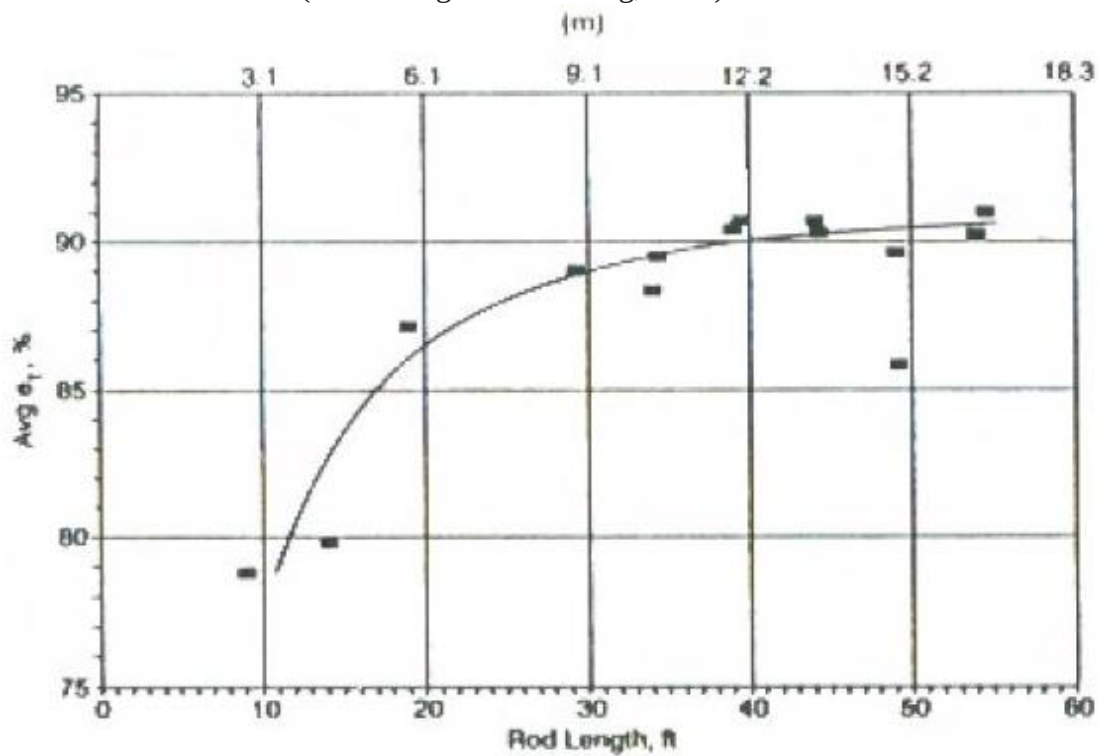


Figure 5-10: Field Hammer Energy Measurements vs. Rod Length (From Morgano and Liang, 1992)

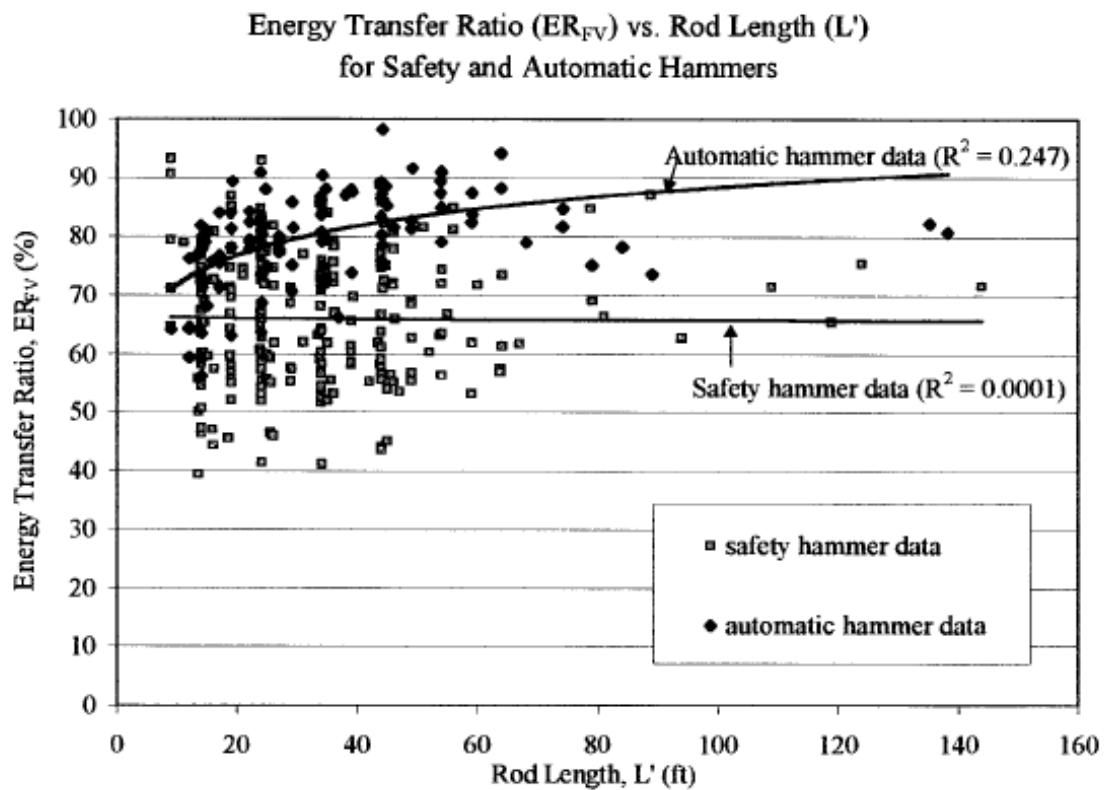


Figure 5-11: Summary of Data from Davidson et al. (1999) Showing Measured Hammer Energy Delivered to the Rods (by the F-V Method) vs Rod Length

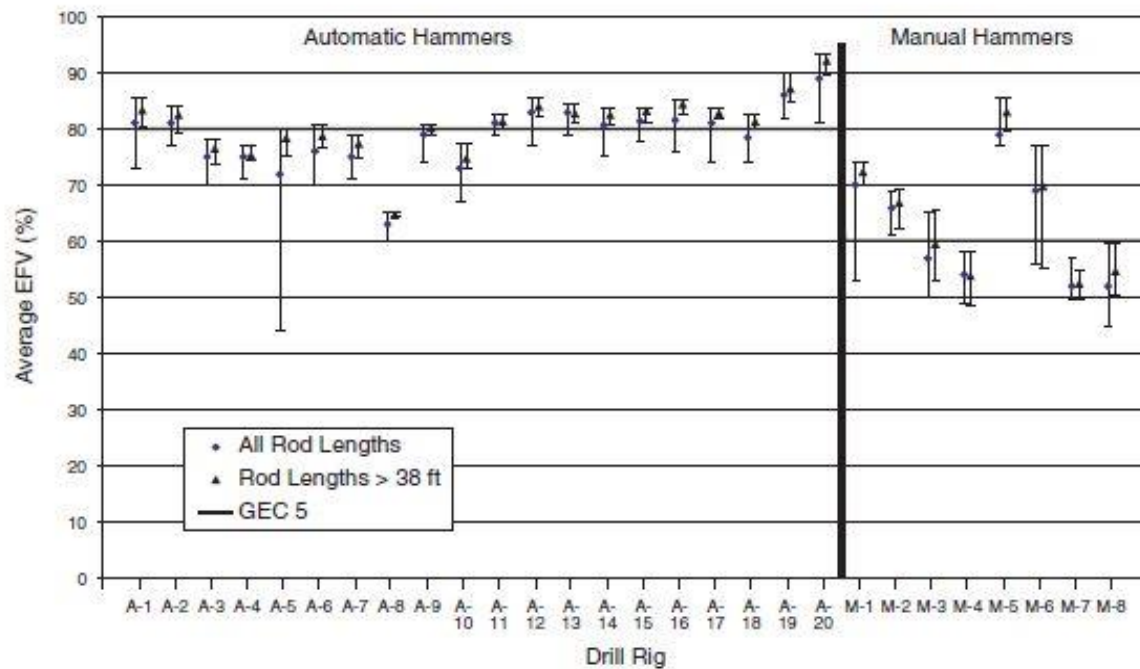


Figure 5-12: Overview of Rod Length Data Set Assembled by Valiquette et al. (2010) Showing Comparison Between Average Energy Transfer Ratio over All Rod Lengths versus Average Energy Transfer Ratio for Rod Lengths of Greater Than 38ft

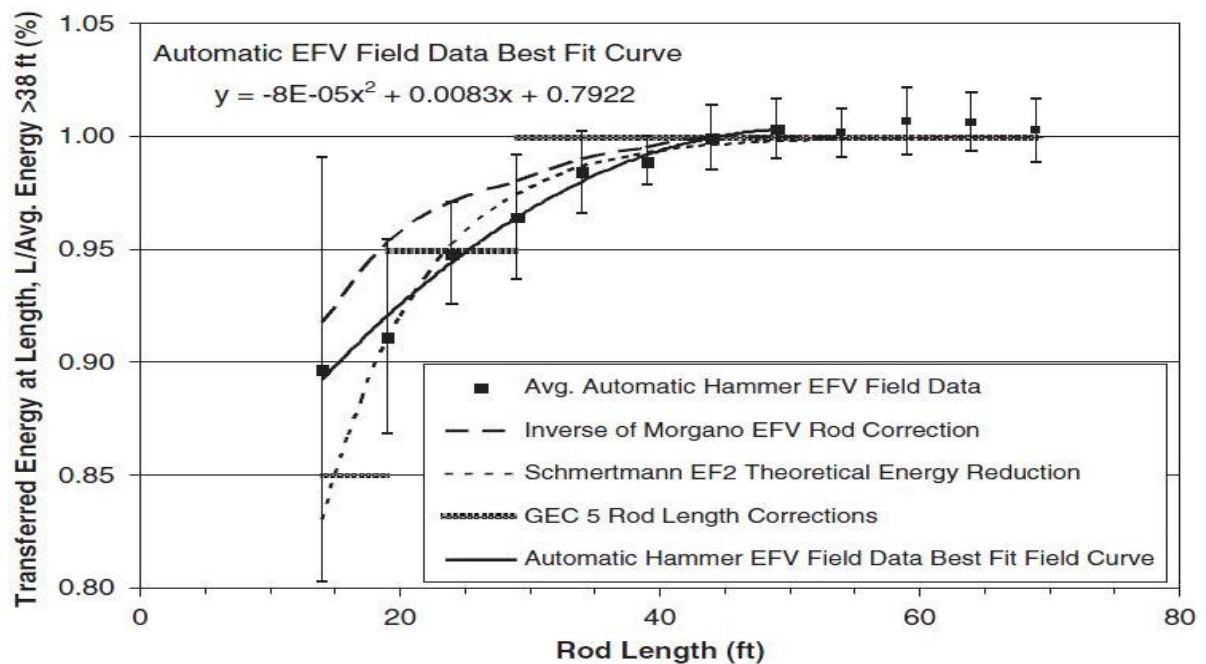


Figure 5-13: SPT Rod Length Correction Factor Proposed By Valiquette et al. (2010) For Automatic Hammers

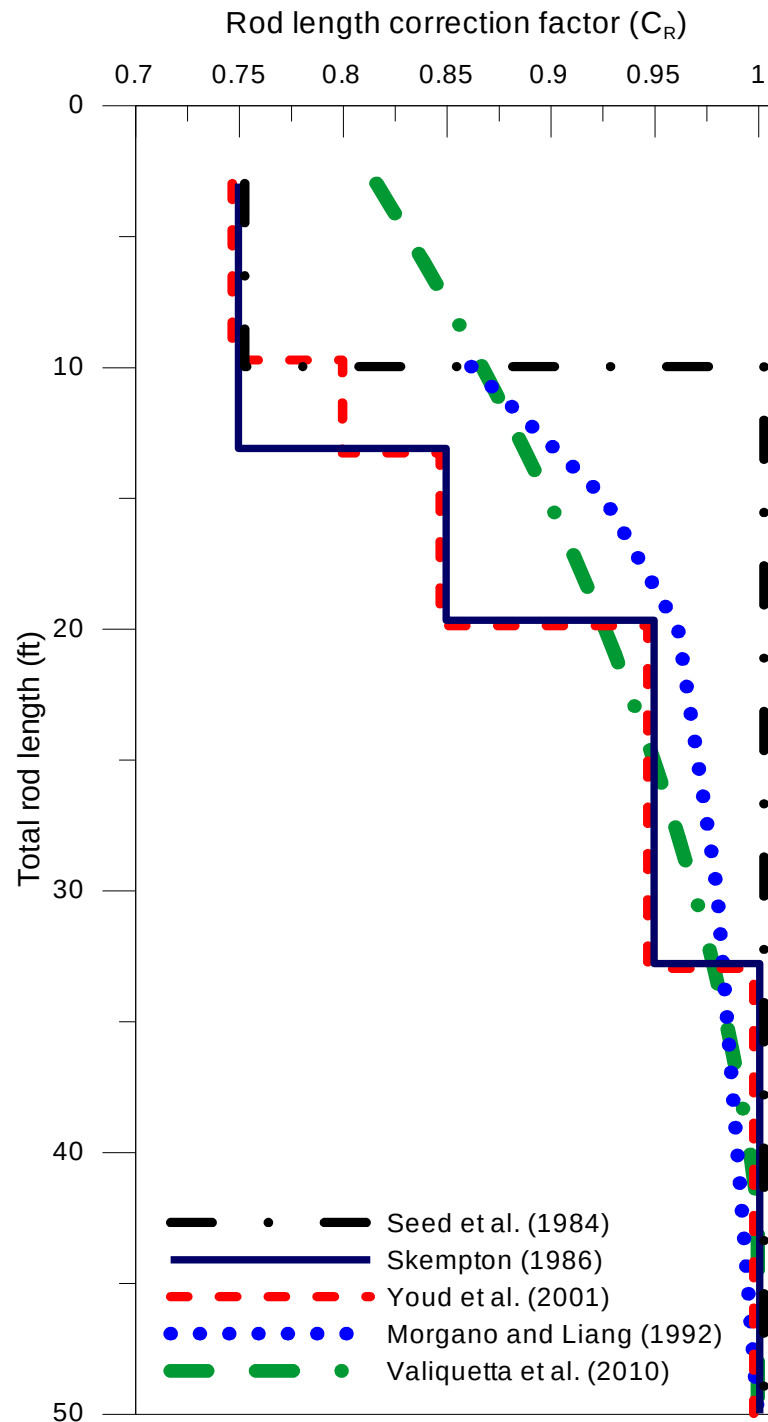


Figure 5-14: Comparison of Different SPT Rod Length Correction Relationships (C_R) Based on F^2 and FV Measurements

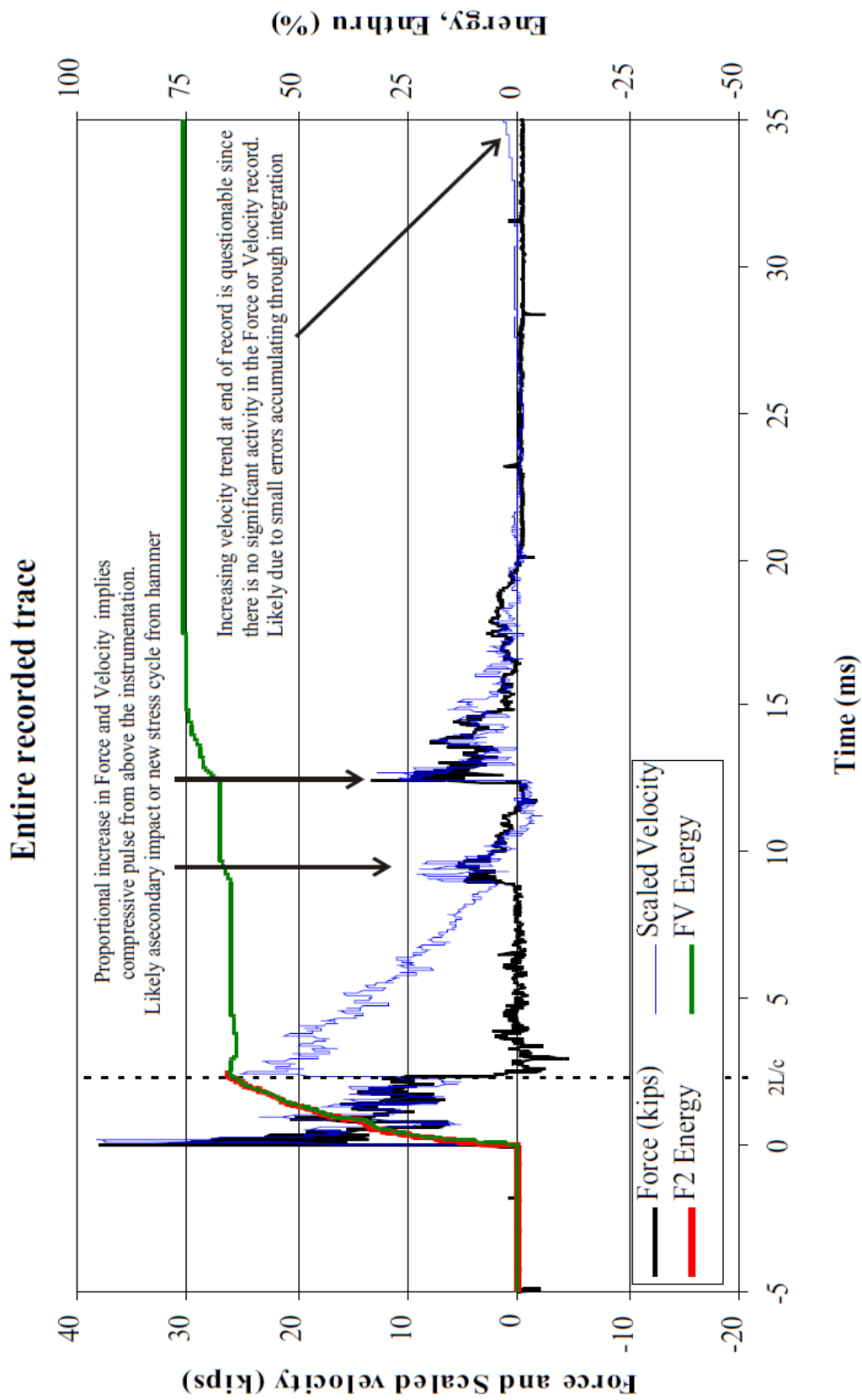


Figure 5-15(a) : Force, Scaled Velocity, and Energy Records Calculated by both the Force-Squared and the Force-Velocity Methods for an Automatic Hammer with Rod Length = 10 ft. (Howie, et al, 2003)

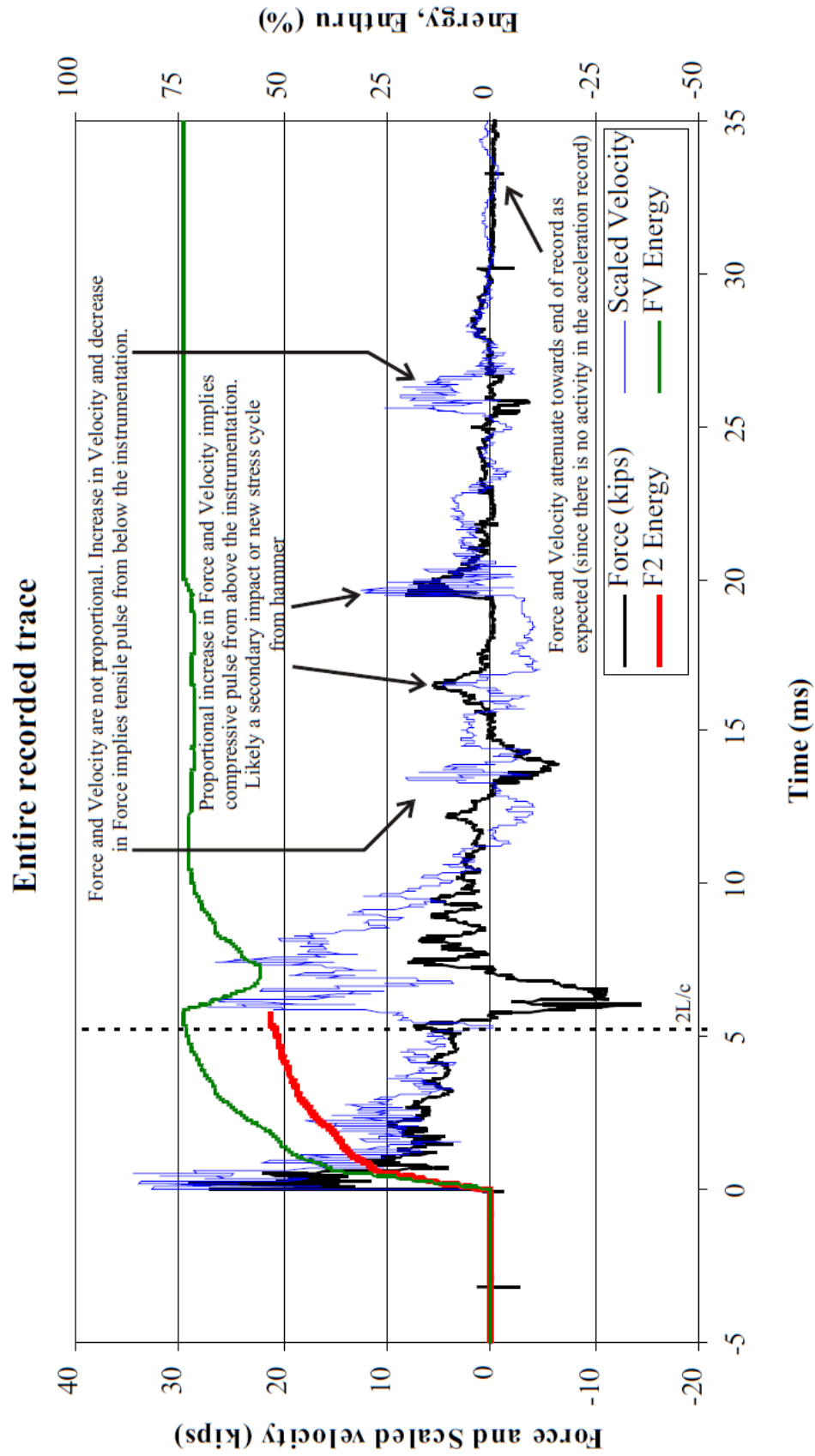


Figure 5-15(b) : Force, Scaled Velocity, and Energy Records Calculated by both the Force-Squared and the Force-Velocity Methods for a Safety Hammer with Rod Length = 35 ft. (Howie, et al, 2003)

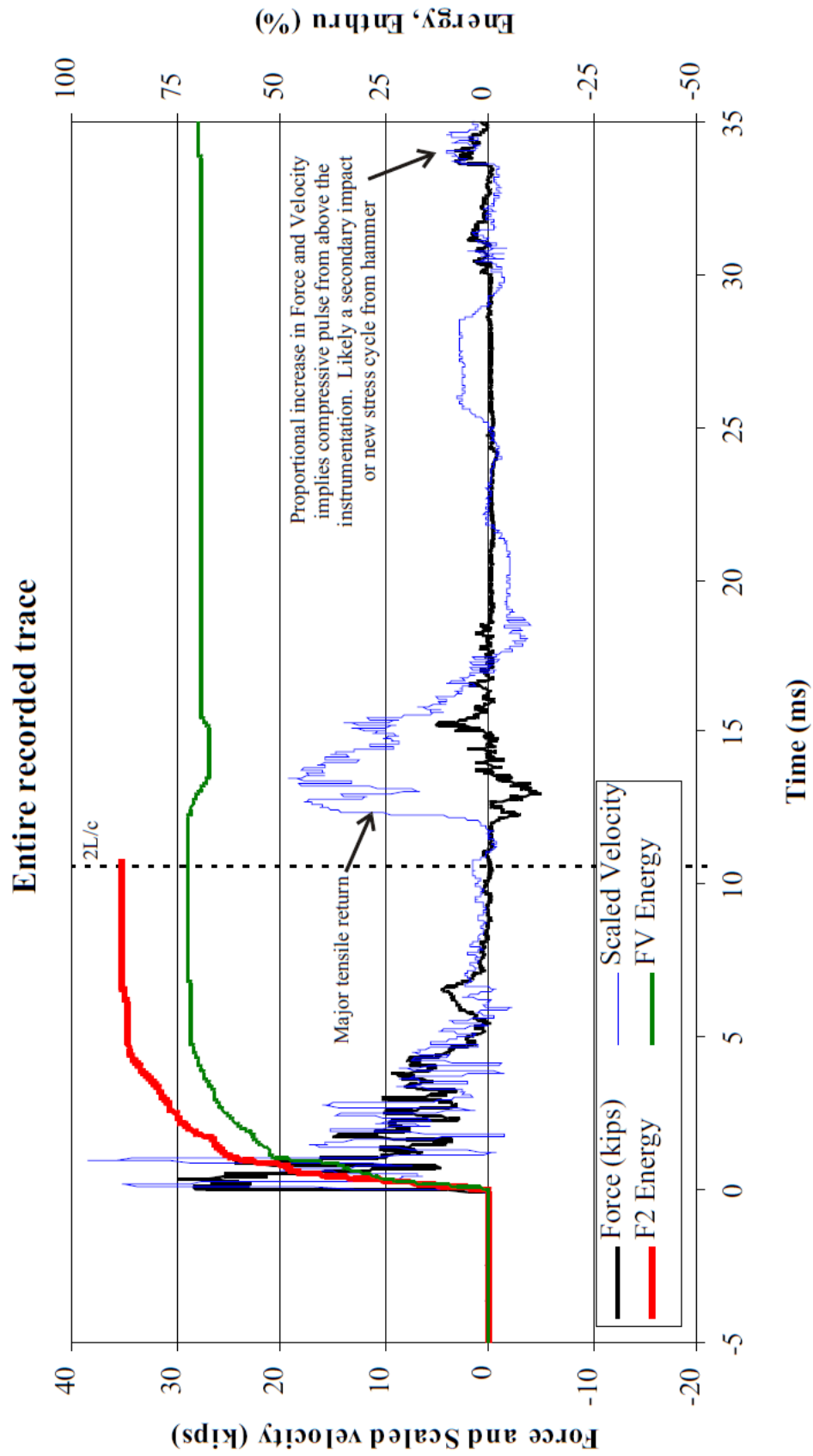


Figure 5-15(c) : Force, Scaled Velocity, and Energy Records Calculated by both the Force-Squared and the Force-Velocity Methods for an Automatic Hammer with Rod Length = 85 ft. (Howie, et al, 2003)

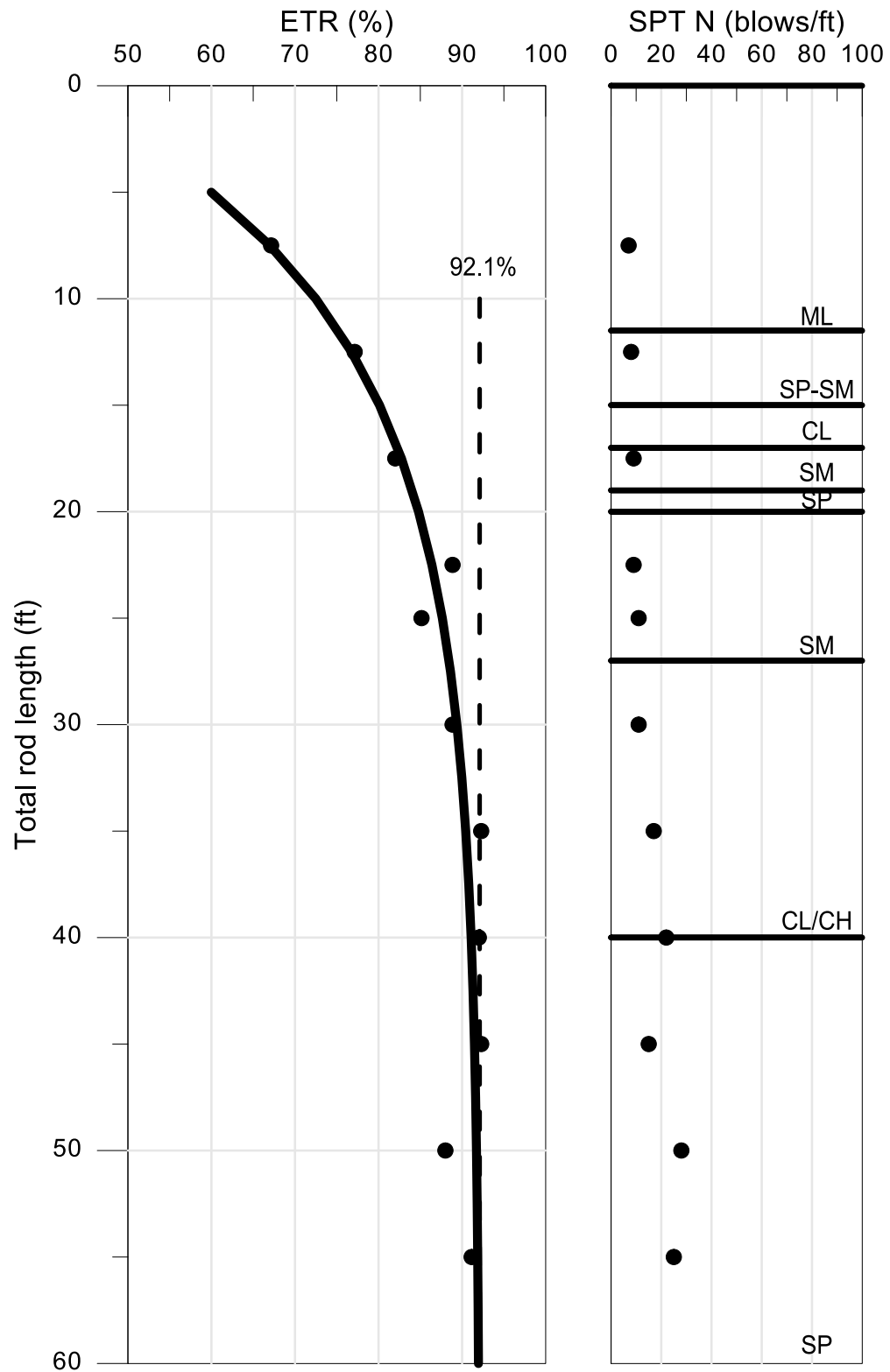


Figure 5-16: Example of Hammer Energy Measurements and Soil Stratigraphy

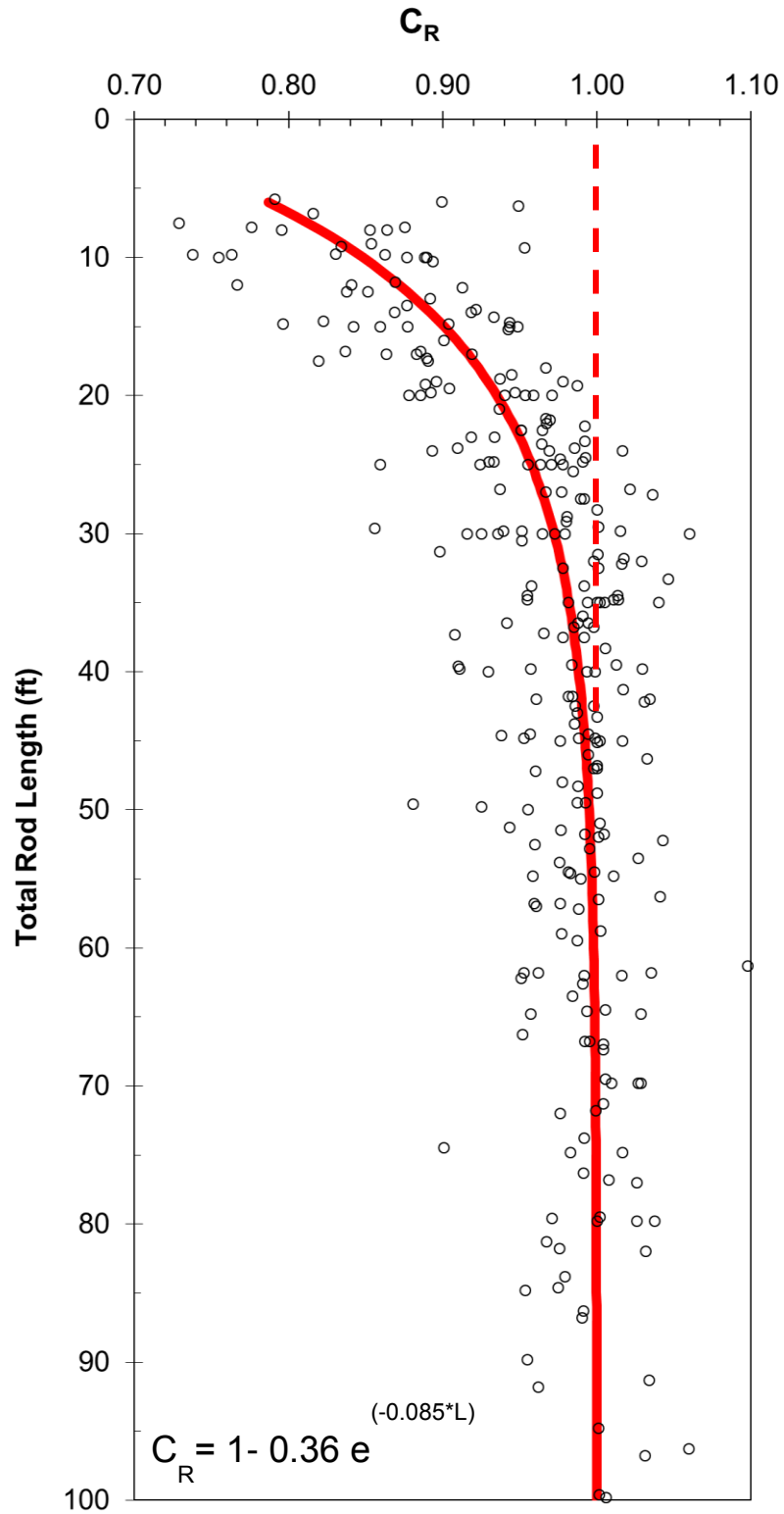


Figure 5-17: Proposed SPT Rod Length Correction Relationship (C_R)

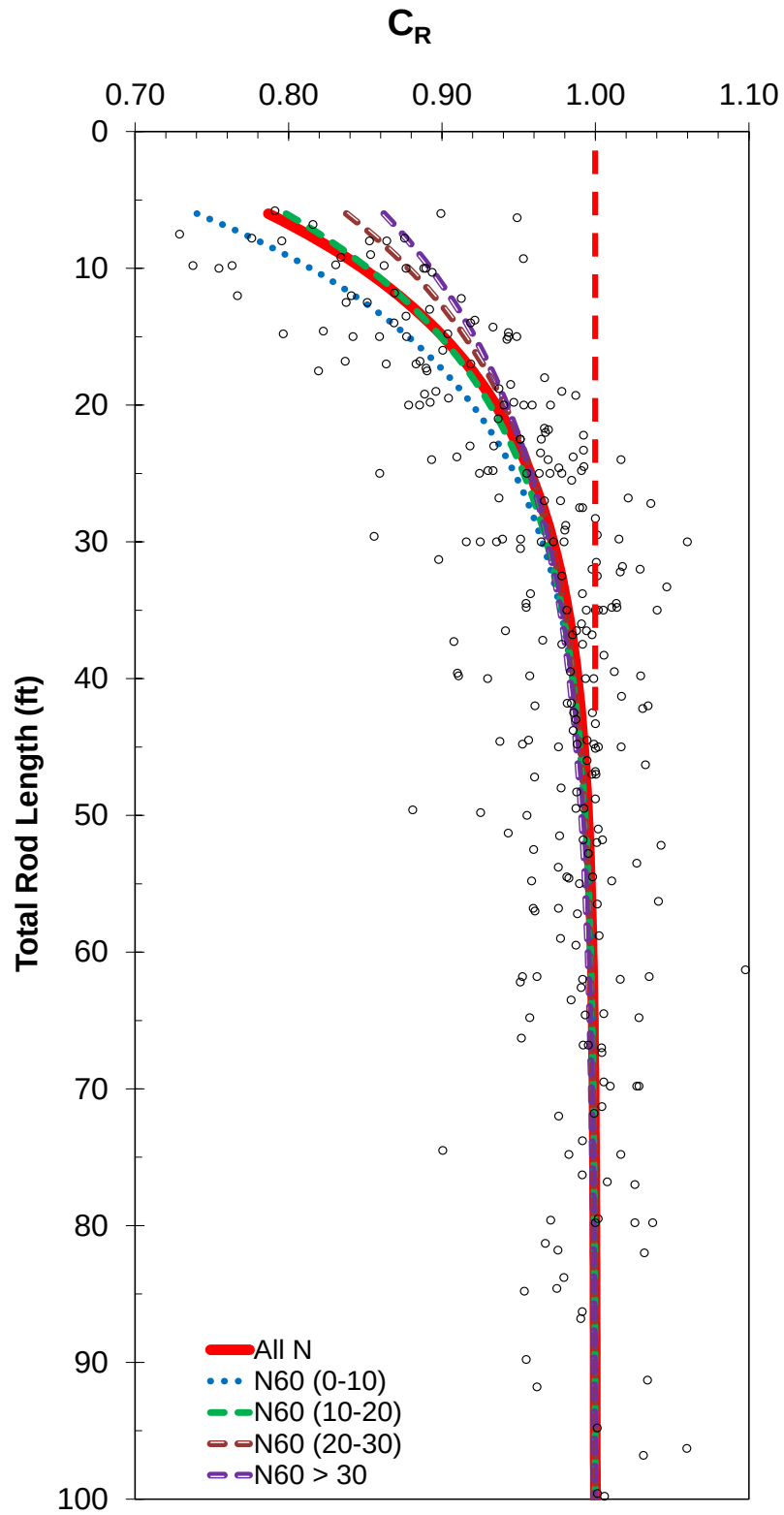


Figure 5-18: Proposed Rod Length Correction Relationships for Different N_{60} Bins

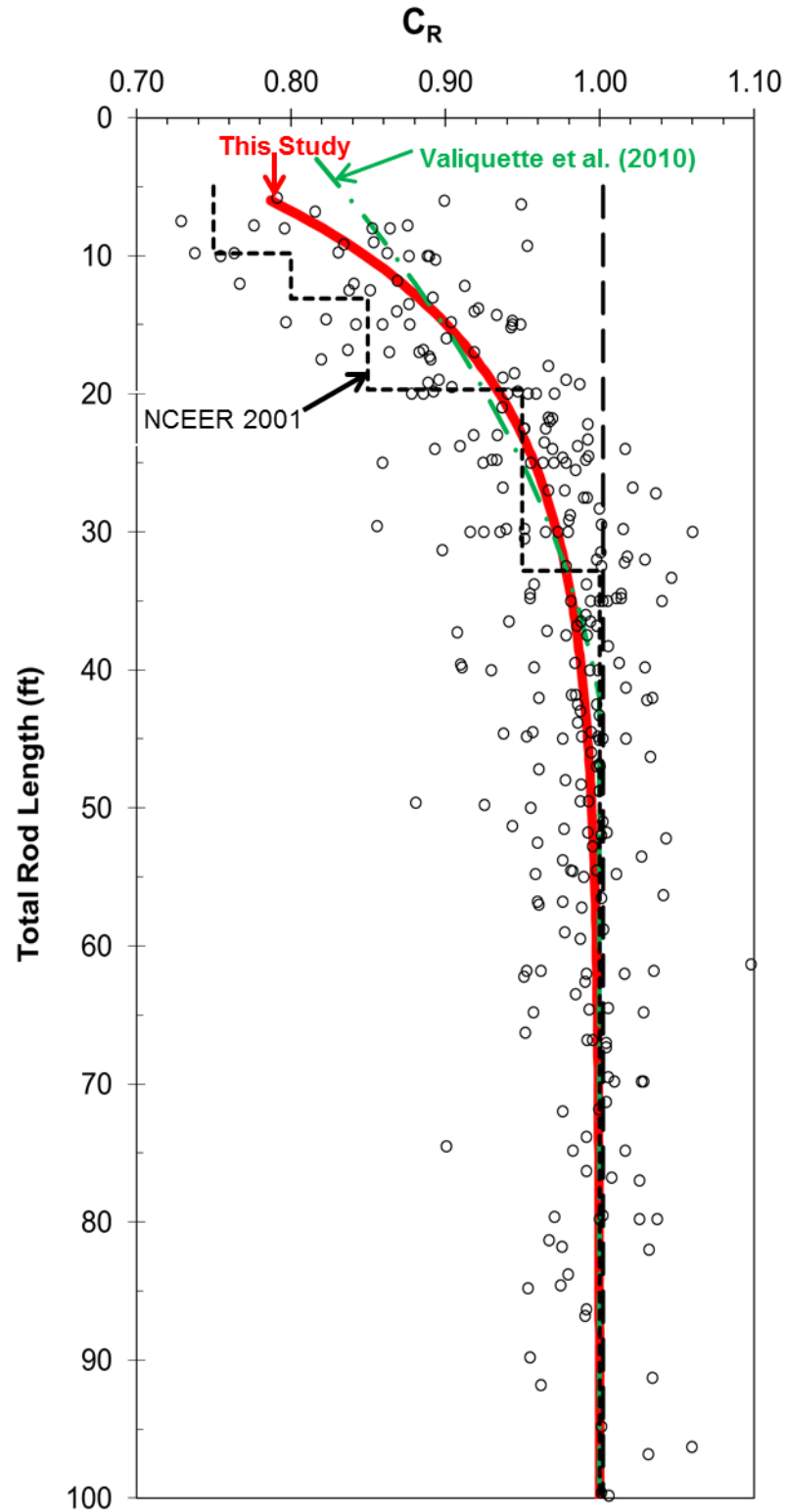


Figure 5-19: Comparison of Proposed Rod Length Correction (C_R) Relationship with Those of NCEER (2001), and Valiquette (2010)

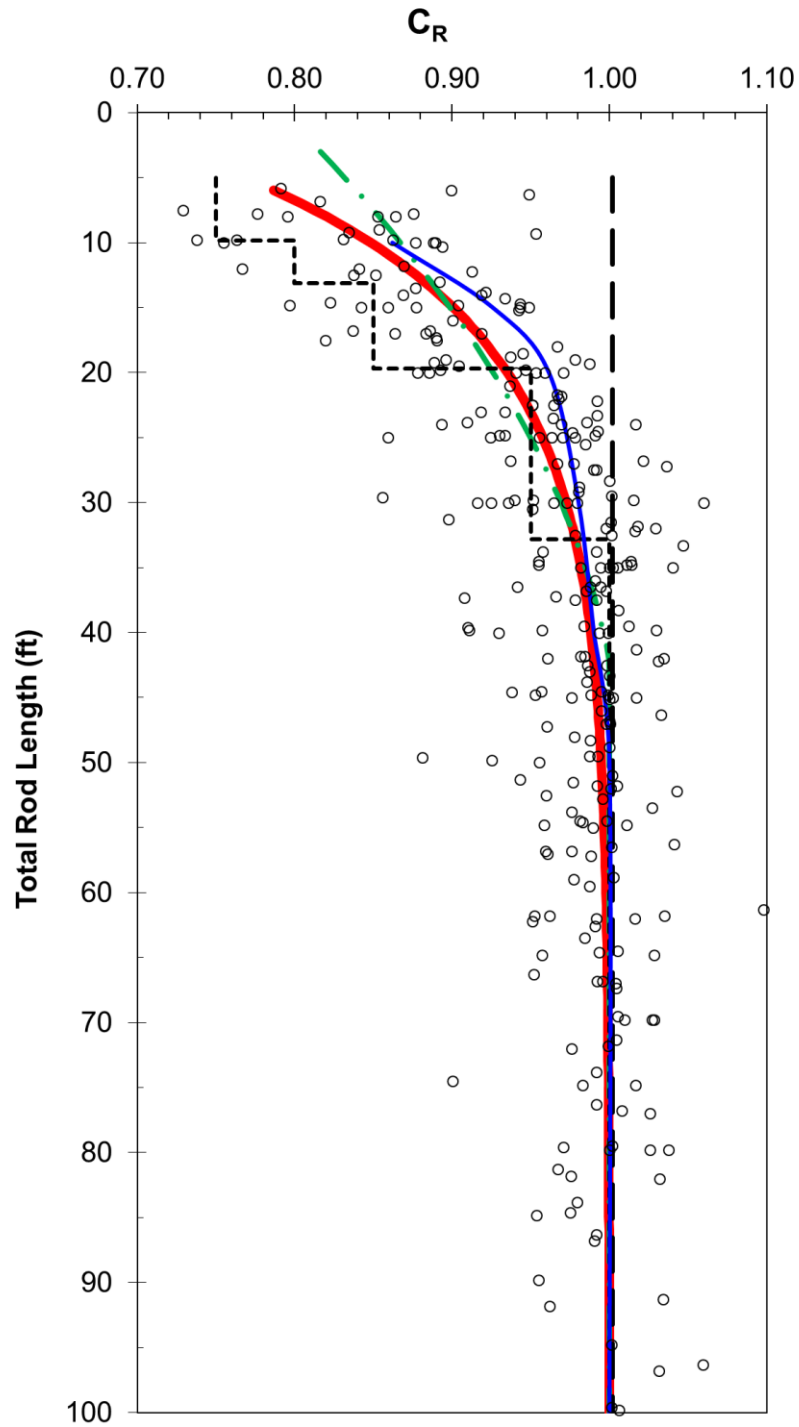


Figure 5-20: Comparison of Proposed Rod Length Correction (C_R) Relationship with NCEER (2001), Valiquette (2010), and Morgano and Liang (1992)

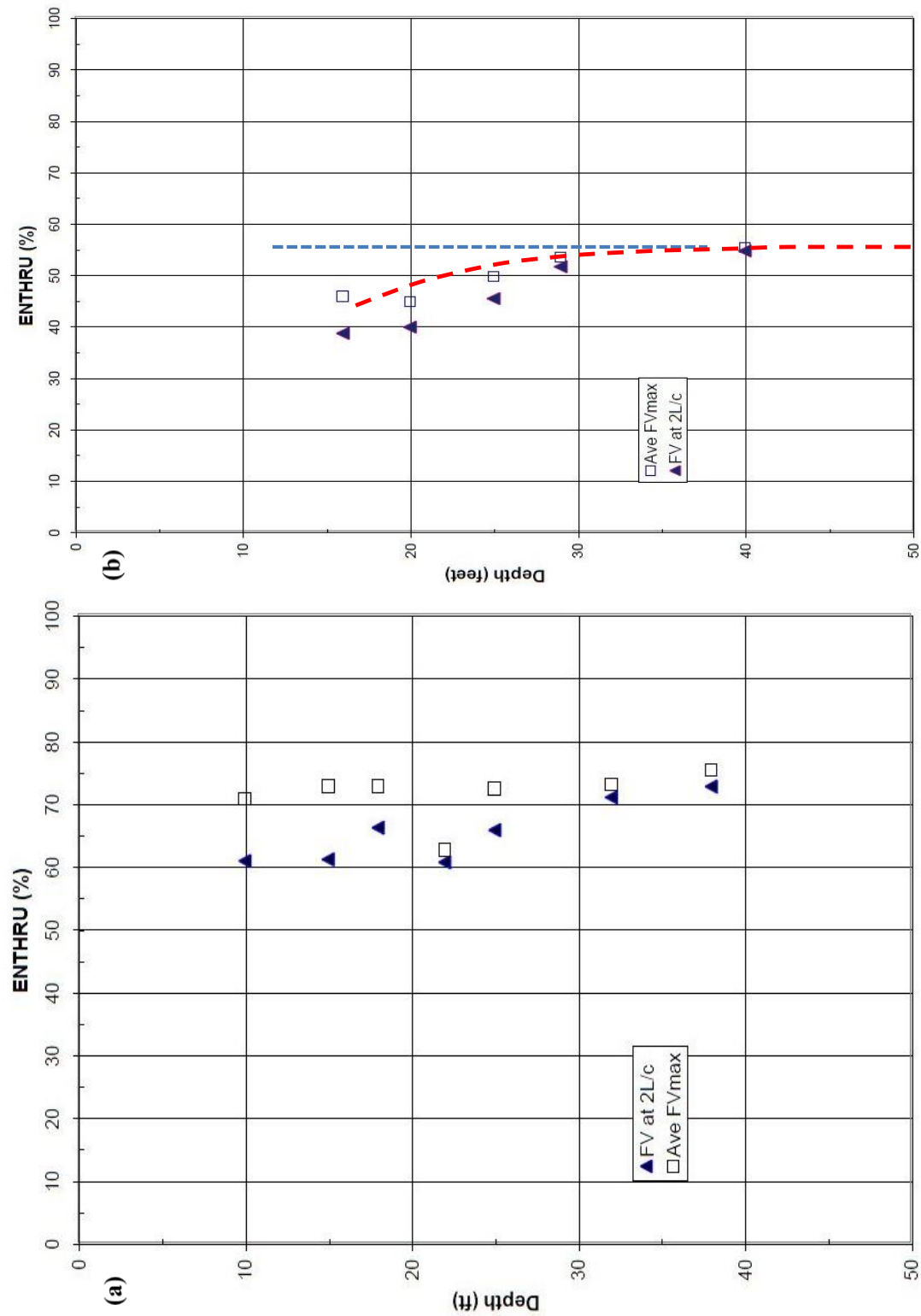


Figure 5-21: SPT Energy Measured by Howie et al (2003) Based on the FV Method vs. Test Depth for Foundex Safety Hammer and USACE Safety Hammer (from Howie et al., 2003)

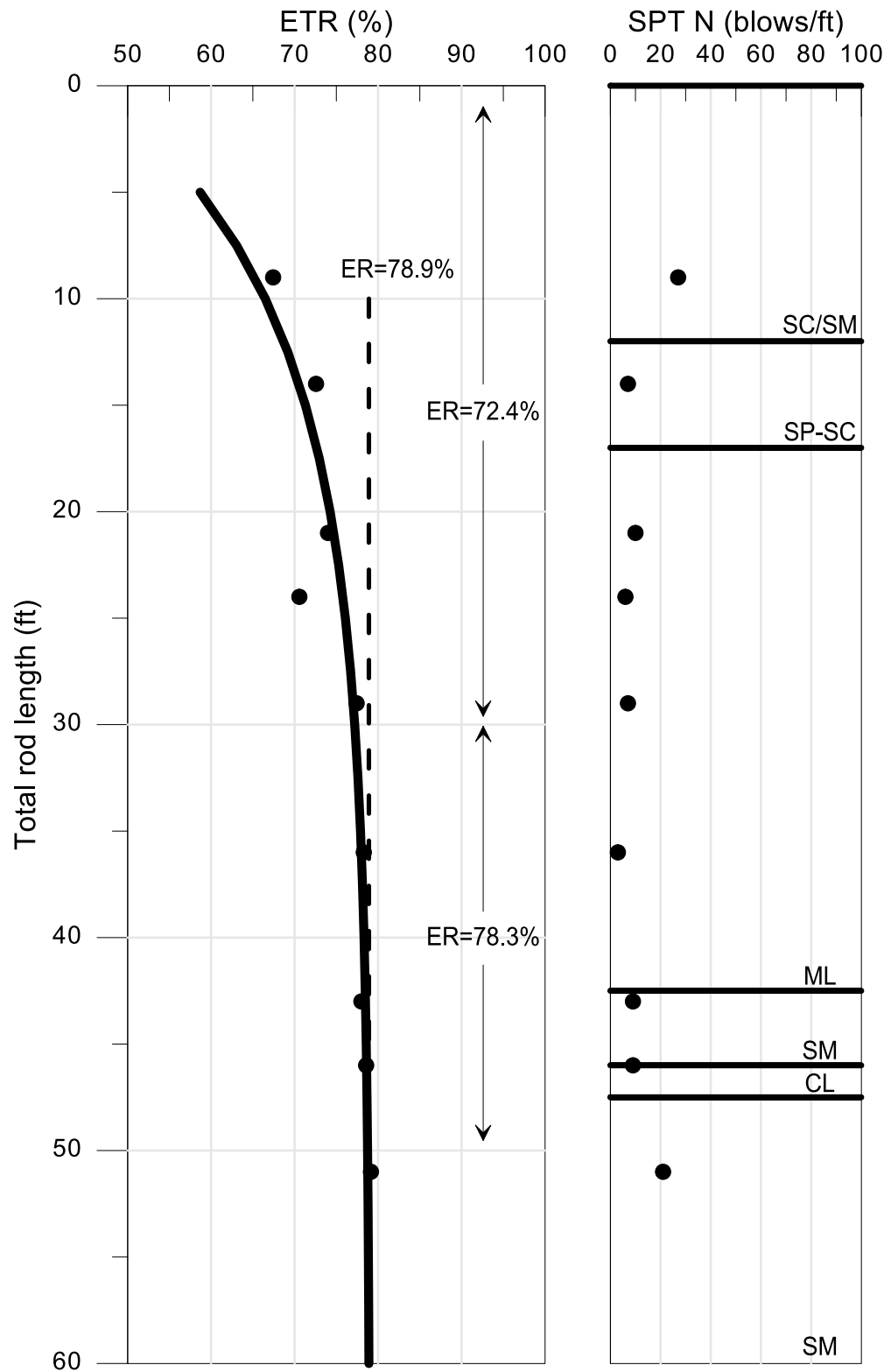


Figure 5-22: Measured Energy Transfer Ratio (ETR) and Stratigraphy for Boring C15

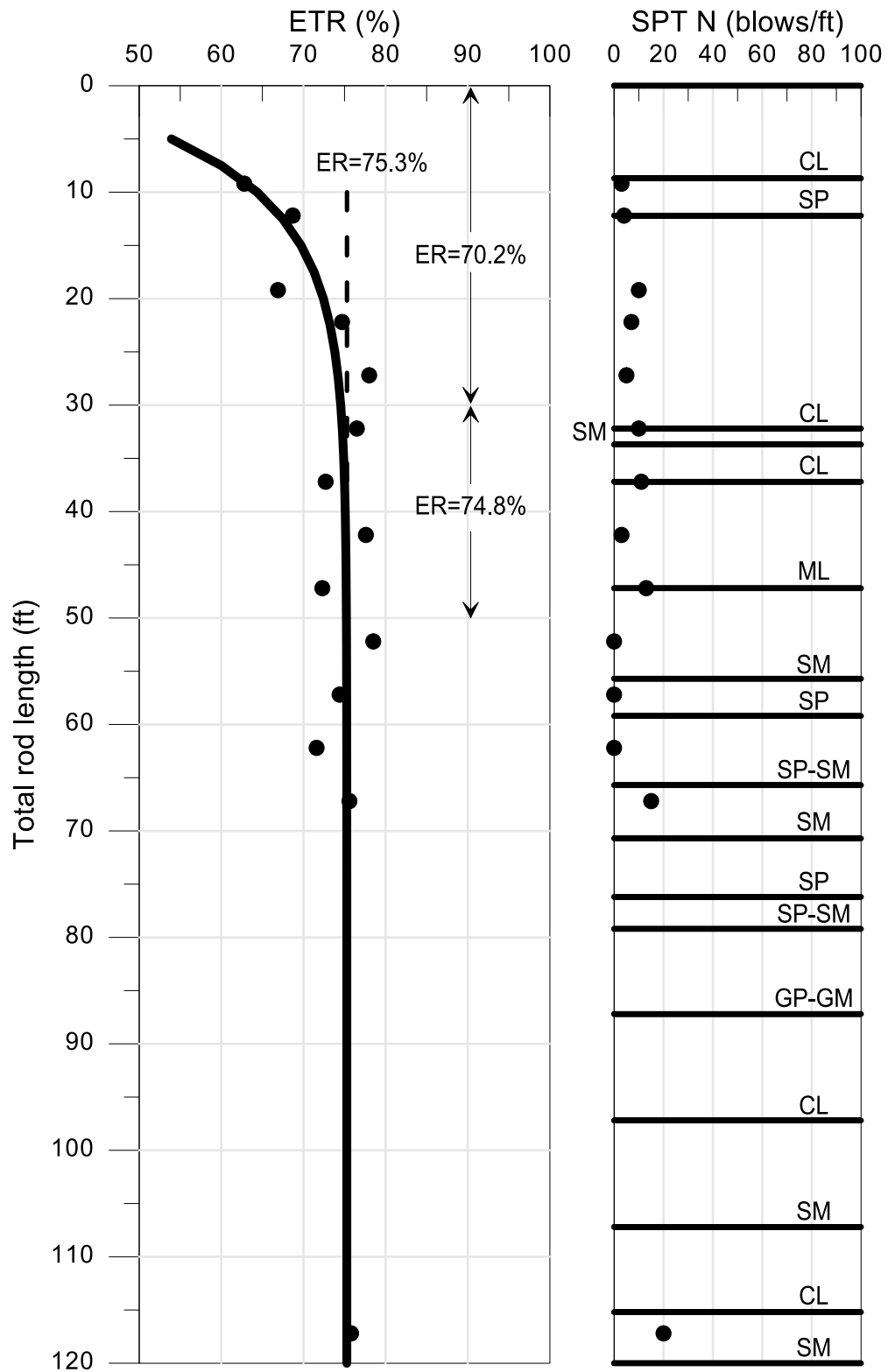


Figure 5-23: Measured Energy Transfer Ratio (ETR) and Stratigraphy for Boring C16

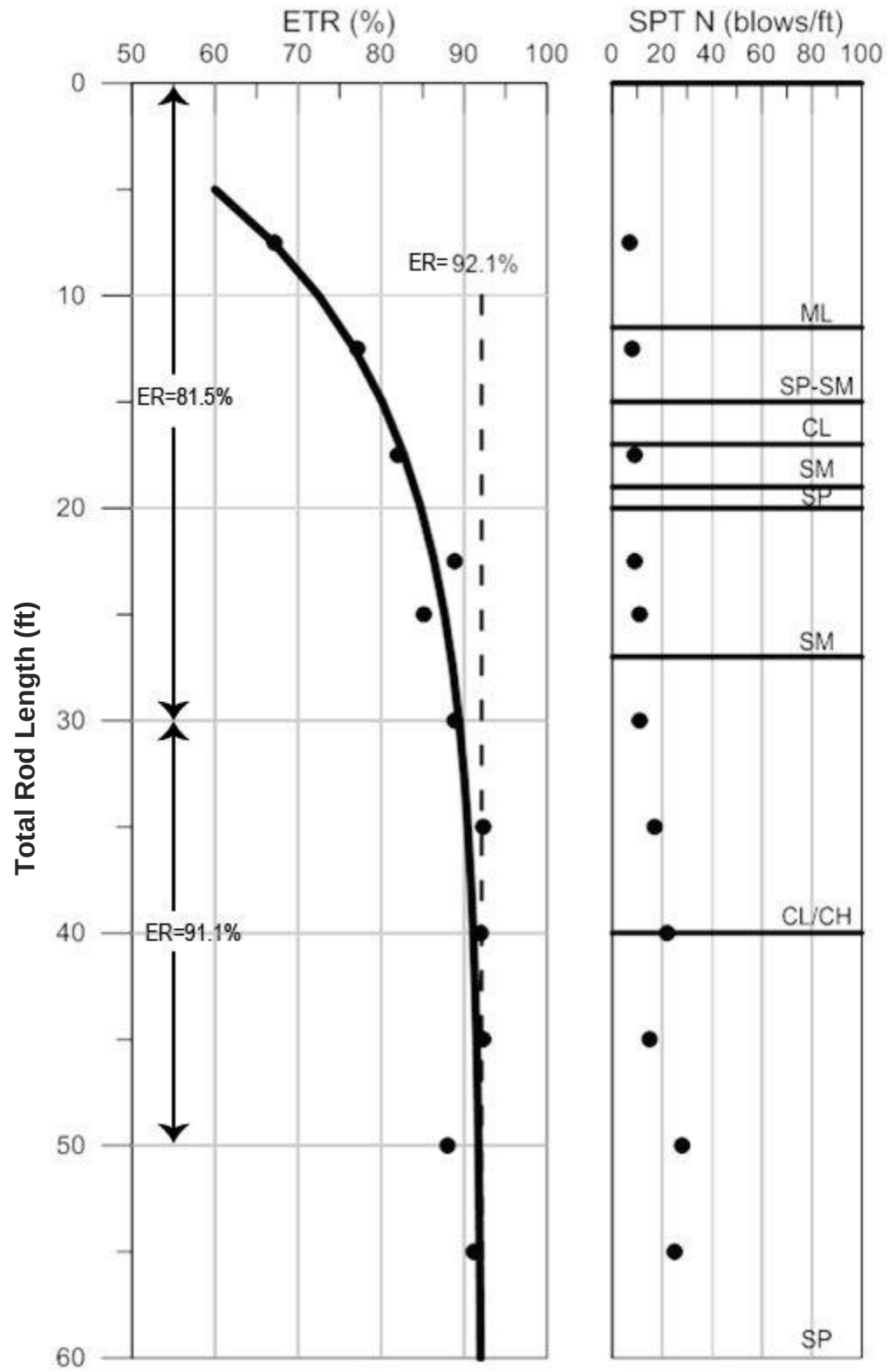


Figure 5-24: Measured Energy Transfer Ratio (ETR) and Stratigraphy for Boring C24

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Overview of Principal Findings

This research addresses two issues associated with the use and interpretation of the Standard Penetration Test (SPT). The first of these is normalization of measured penetration resistance (N-values) for the influence of variations in effective overburden stress, and the second is the effects of “short rods” on the SPT hammer energy successfully delivered to the rods and sampler during SPT driving. These will be addressed in turn.

6.1.1 Normalization for Effective Overburden Stress

6.1.1(a) Clean Sandy Soils

Effective overburden stress corrections are generally fairly well developed for clean sandy soils (SW and SP) with low fines contents. A great deal of engineering, in terms of empirical correlations for material property assessment as well as empirical correlations for behavioral predictions and design, makes use of these types of “ C_N ” corrections, or normalizations. These C_N relationships are, in turn, largely based on an important, but relatively limited, set of large scale laboratory calibration chamber test data for four clean sands developed by Marcuson and Bieganski (1977a,b).

Attempts to broaden the basis for these C_N relationships by means of actual field data have provided corollary support, but the field data are rendered somewhat less quantifiably reliable by questions as to whether the in situ soils actually have fully similar density, fabric, stress history, lateral effective stress (K_0), etc. over their depth even for cases wherein gradation appears to be relatively consistent over depth.

There are several potentially significant limitations as to our current knowledge and uncertainty with regard to C_N relationships for clean sandy soils. The first of these is simply the small suite of soils for which the quantifiably useful large-scale laboratory data set is available. Given the importance of these types of relationships, it is perhaps a bit surprising that no one has performed additional large-scale laboratory tests of this type to expand this data set to include additional sandy soils of different character and gradation.

A second important limitation is the lack of data regarding C_N at relatively shallow depths (for effective overburden stresses of less than 1 ton/ft², or less than 1 atmosphere). It should be possible to garner additional field data at these relatively shallow depths to help to better define C_N behavior over this range of stresses (and depths). This is an important range of stresses and depths for shallow foundation design, and empirical SPT-based correlations are important here. It is also an important range for empirical SPT-based liquefaction triggering correlations, because these correlations are based on observed field performance

(liquefaction or non-liquefaction) during earthquakes, and it is increasingly difficult to be certain as to whether or not liquefaction occurred (or was “triggered”) as depth increases and surface manifestations become increasingly difficult to discern and interpret. It should be noted that liquefaction triggering correlations are developed based mainly on relatively shallow field performance case histories, but that these are then routinely extrapolated to engineering predictions of field behavior at greater depths. Questions as to consistency of density, gradation, in situ stress history and OCR, etc. would all be pertinent for SPT performed at relatively shallow depths. But at relatively shallow depths it should be easier to find and test both natural deposits and fills wherein reasonably good uniformity of these key conditions could be relatively well assured. Given the importance of SPT-based empirical correlations, it is surprising that this type of effort has not yet been made. Part of the reason for this omission is likely the history of evolution of understanding of C_N . As early efforts were focused on extending shallow SPT (and correlations) to greater depths, there was never any significant (similar) effort focused on extending SPT (and correlations) upwards to shallower depths and to smaller overburden stresses.

A third important shortcoming has been the lack of large-scale laboratory data, and the lack of reliable field data, for development of C_N relationships for “silty” soils; soils with fines contents of greater than about 12%, and with predominantly low to moderately plasticity silt fines (SW-SM, SP-SM, SM, and ML materials). These are an important class of soils both for shallow foundation design as well as for soil liquefaction engineering, and one of the key efforts of this current work has been to attempt to better define C_N -type behavior for these types of materials, as discussed below in Section 6.1.1(b).

Overall, it appears that the profession now has reasonably workable C_N relationships for use in normalization of SPT for effective overburden stress effects for relatively clean sandy soils (e.g. Figures 3-10 and 3-15), and there appears to be growing understanding that these relationships may be limited due to the relative paucity of data employed to date in development of these relationships, and that site-specific (material-specific) C_N relationships may differ from the “representative” relationships currently available.

6.1.1(b) Silty Soils

Silty soils are an important class of materials both for shallow foundation design and also for soil liquefaction engineering, and empirical SPT-based correlations are important in both of these areas. These materials include soils with fines contents of greater than about 12%, and with predominantly low to moderately plasticity silt fines (SW-SM, SP-SM, SM, and ML materials). There is an absolute lack of available laboratory calibration test data for development of C_N relationships for normalization of these types of soils for effects of varying effective overburden stress. As a result, current engineering practice is generally to employ the same C_N relationships developed for clean sands, and to hope that these are appropriate.

The lack of available laboratory large-scale laboratory calibration chamber test data for silty soils is further exacerbated by the difficulty of finding field sites wherein in situ deposits of silty soils can usefully be subjected to SPT testing for purposes of development of

C_N -type relationships. Silty soils are generally deposited in transitional depositional environments and conditions, and are notoriously variable as a result. This makes it extremely difficult to find, and test, deposits with any assured consistency of density, gradation, plasticity, stress history (and OCR), etc. over either depth or laterally within a typical “silty” deposit.

The approach taken herein was to locate 30 dam foundation units comprised of silty soils wherein the engineering geologists and engineers had judged that there was “relatively” good consistency of soil attributes. This does not mean that these important soil properties were fully consistent either laterally or over depth, but rather that they were at least relatively consistently inconsistent over the lateral and vertical ranges tested. Beginning with slightly more than 30 candidate sites, the list of sites to study in detail was culled to the most promising four dam sites, and in the end six silty foundation soil units were studied.

Based upon SPT performed within these silty dam foundations units, at varying effective overburden stresses (with the varying effective overburden stresses being provided largely by the overlying trapezoidal-shaped dam embankments), new C_N relationships for silty soils were developed. These C_N relationships differed somewhat from C_N relationships for clean sands (see Figures 4-35 through 4-37), but it was found that when suitable fines corrections were applied (e.g. the types of fines corrections employed in empirical SPT-based soil liquefaction triggering correlations) then the differences narrowed considerably and it would be possible to use the same C_N relationships for a range of materials spanning from clean sands through silty sands and sandy silts of low to moderate plasticity (see Figure 4-37).

There are significant limitations to these new relationships, including (1) the natural variability of the soil units within which the data were developed and analyzed, and (2) lack of well-defined data at relatively shallow depths (and thus at low effective overburden stresses). Nonetheless, the general similarity between C_N -type behavior of clean sands and silty soils is promising, and these new relationships appear to provide a basis for continuing to move forward with empirical SPT-based relationships for this important class of materials.

There is ample room for further work on this topic, and it would be especially useful to perform high-quality, large-scale laboratory calibration chamber tests (with SPT) in which soil conditions could be known with better specificity.

6.2 Correction of SPT for Short Rod Effects

Chapter 5 addressed the second issue: short rod effects on measured SPT N-values. When the drill rod length, measured from the point of hammer contact at the top of the drill rods down to the tip of the advancing sampler, is less than about 35 to 45 feet the initial tensile reflection wave returning from the base of the rods begins to reach the top of the rods before the full compressive force has been successfully transferred from the hammer to the rods. This reduces the energy transferred from the hammer to the rods, and it has been

common practice to adjust the penetration resistance measured (N-value) to account for the lesser driving energy imparted by the hammer.

Subsequent tensile and compressive reflecting waves passing up and down within both the rods and the hammer, and potential secondary hammer impacts as the hammer may briefly separate from the top of the rods, further complicate the situation. First noted in the 1970's, understanding of these issues, and of the corrections needed to account for them in the use and interpretation of SPT data, have advanced considerably over the several decades that followed. Significant advances have been made over this period in instrumentation capabilities, especially with regard to development of accelerometers capable of accurately measuring the high accelerations and high frequencies on the rods associated with the metal to metal hammer to anvil contacts, and corollary advances in wave equation-based analyses of these dynamic systems, have also been made.

Early "short rod" corrections widely used in engineering practice were based on simplified analytical assumptions that were necessary in the late 1970's and the early 1980's before improved accelerometers were capable of making the accurate acceleration measurements needed from more refined, and more fundamentally correct solutions. The early solutions were not able to track energy transfer after the initial return of the first reflected tensile wave, but more modern instrumentation and analyses are now able to accomplish that. As a result, it is now apparent that early solutions overestimated to some extent the significance of short rod effects. These advances have led to new controversy, however, as to the actual magnitudes of short rod effects, and the corrections appropriate for them.

To help resolve this controversy, a set of field data was gathered for twenty-four instrumented SPT borings performed for purposes of calibration of automatic (mechanical) hammers. Based on these data, a new set of recommended short rod correction factors were developed (see Figures 5-17 and 5-18). These corrections are recognized to be moderately a function of penetration resistance, with the magnitude of the "short rod" effect diminishing as penetration resistance increases (Figure 5-18), but this is a relatively minor effect and it is recommended that the relationship of Figure 5-17 (which is independent of penetration resistance) is suitable for most common practice.

These relationships are well established based on the automatic hammers used, and they are well-supported by a similar data set (also using automatic hammers) developed by Valiquette et al. (2010). Data sets developed using manual hammers (with rope and cathead systems for raising and dropping the hammer) show less clear trends, and so it may be expected that debate will continue. It is suggested here that short rod effects are best measured and evaluated using automatic hammers, because that eliminates the otherwise significant operator variability in hammer energy intrinsic in the rope and cathead type of system, and that large variability in actual energy delivered serves to obscure the more subtle short rod issue. There are alternate points of view on this issue, however, and it must be expected that debate, and further studies, will continue.

Another interesting issue, and one of increasing importance, involves the increasingly common practice of periodically performing well-instrumented SPT with automatic hammers for purposes of calibrating hammer energy. This periodic calibration is performed so that the hammer energy delivered will be known, and the hammers are then used for production work in engineering investigations. There are no established standards as to the ranges of depths (and thus the approximate rod lengths) over which this type of calibration testing is to be performed. As a result, it is fairly common practice to perform this calibration testing at depths that are too shallow; where short rod effects cause the hammer energy to be underestimated relative to the actual hammer energy that would be delivered at greater depths. It would be better to perform the calibration testing at slightly greater depths, and thus to establish a suitable baseline independent of short rod effects, and then to apply short rod corrections as necessary when subsequently performing shallower SPT. To perform the “hammer calibration” SPT at depths that are too shallow results in systematic underestimation of actual hammer energy, and produces systematically conservative (biased low) N-values at all depths when the hammer is subsequently used for field engineering investigations. Recommendations are presented in Chapter 5 for avoiding this problem.

REFERENCES

ASTM (2008), D1586-08a: Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling, ASTM Standards.

ASTM (2010), ASTM D4633-10: Standard Test Method for Energy Measurement for Dynamic Penetrometers, ASTM Standards.

Bazaraa, A. R. S. S. (1967), Use of the Standard Penetration Test for Estimating Settlements of Shallow Foundations on Sand, Ph.D. Thesis, University of Illinois, Urbana.

Bieganousky, W. A., and Marcuson, W. F. (1976), Liquefaction Potential of Dams and Foundations, Report No. 1, Laboratory Standard Penetration Tests on Reid Bedford Model and Ottawa Sand, Research Report S-76-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, October.

Bieganousky, W. A., and Marcuson, W. F. (1977), Liquefaction Potential of Dams and Foundations, Report No. 2, Laboratory Standard Penetration Tests on Platte River Sand and Standard Concrete Sand, Research Report S-76-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, February.

Boulanger, R. W. (2002), Evaluating Liquefaction Resistance at High Overburden Stresses, 3rd U.S.-Japan Workshop on Advanced Research on Earthquake Engineering for Dams, San Diego, CA, June 22-23, 2002.

Boulanger, R. W. (2003), High Overburden Stress Effects in Liquefaction Analyses, Journal of the Geotechnical Eng. Div., ASCE Vol.129 (GT12), 1071-1082

Butler, J.J. (1997), Analysis of Energy Measurement Methods of SPT Driving Systems, M.S. Thesis in Civil Engineering, Utah State University, Logan, UT.

Campanella, R.G. and Sy, A. (1994), Recent Developments in Energy Calibration of Penetration Tests at UBC, Proceedings of XIII ICSMFE, 1994, New Delhi, India, pp. 151-156.

Castro, G. (1995), Empirical Methods in Liquefaction Evaluation, Primer Ciclo de Conferencias Internacionales, Leonardo Zeevaert, Mexico City, pp. 35-36.

CDWR (1975), Final Geologic Report on Perris Dam and Lake: Part I - Foundation Conditions, Grouting, and Instrumentation, Project Geology Report C-94, October 1975, California Dept. of Water Resources.

CDWR (1998), Perris Dam Foundation Study, Results of Phase I Geologic Investigations, Project Geology Section Report No. 58-11-15, May 1998, California Dept. of Water Resources.

CDWR (2000), Perris Dam Foundation Study Results of Phase III Geologic Investigations, Project Geology Section Report No. 58-11-17, April, California Dept. of Water Resources.

CDWR (2004), Perris Dam Foundation Study Results of Phase IV Geologic Investigation, Project Geology Section Report No. 58-11-19, June, California Dept. of Water Resources.

CDWR (2005), Perris Dam Foundation Study, Final Report, December, California Dept. of Water Resources.

CDWR (2009) Perris Dam Remediation Project; Dewatering, Excavation and Cement Deep Soil Mixing, Project Geology Report No. D-193, July, California Dept. of Water Resources.

CDWR (2011), Perris Dam ICB 2011 Package, California Dept. of Water Resources.

Clayton, C. R. I., Hababa, M. B., Simons, N.E. (1985), Dynamic Penetration Resistance and the Prediction of the Compressibility of a Fine-grained sand –a Laboratory Study, *Geotechnique*, Vol. 35, No. 1, pp. 19-31.

Cetin, K.O., Seed, R. B., Der Kiureghian, A., Tokimatsu, K., Harder, L. F., Kayen, R.E., and Moss, R. E. S. (2004), Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential, *Journal of Geotechnical and Geoenvironmental Eng.*, ASCE, Vol. 130, No. 12, pp. 1314-340.

Daniel, C.R., Howie, J.A., Jackson, R.S. and Walker, B. (2005), Review of Standard Penetration Test Short Rod Corrections, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 131, No. 4, pp.489-497.

Davidson, J. L., Maultsby, J. P., and Spoor, K. B. (1999), Standard Penetration Test Energy Calibrations, Report No. WPI 0510859, Florida Department of Transportation, Tallahassee, Fla., 1999.

Danziger, F.A.B., Danziger, B.R., and Cavalcante, E.H. (2006), Discussion to the Review of Standard Penetration Test Short Rod Corrections by Daniel, C.R., Howie, J.A., Jackson, R.S. and Walker, B. (2005), *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 132, No. 12, pp.1634-1640.

Decourt (2006), Discussion to the Review of Standard Penetration Test Short Rod Corrections by Daniel, C.R., Howie, J.A., Jackson, R.S. and Walker, B. (2005), *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 132, No. 12, pp.1633-1634.

GEI Consultants Inc. (1995), Analysis Parameters Report; Evaluation of Liquefaction Concerns at Lopez Dam, prepared for County of San Luis Obispo, Englewood, CO, March.

Ghionna, V., and Jamiolkowski, M. (1991), A Critical Appraisal of Calibration Chamber Testing of Sands, Proc., 1st International Symp. on Calibration Chamber Testing (ISOCCT1), Elsevier Pubs., Postdam, N.Y., pp.13-39.

Gibbs, H. J., and Holtz, W. G. (1957), Research on Determining the Density of Sands by Penetration Testing, Proc., 4th International Conference on Soil Mechanics and Foundation Engineering, London, Vol. 1, pp. 35-39.

Holden, J.C. (1991), History of the First Six CRB Calibration Chambers, Proc., 1st International Symp. on Calibration Chamber Testing (ISOCCT1), Elsevier Pubs., Postdam, N.Y.

Howie, J. A., Daniel, C. R., Jackson, R.S., and Walker, B. (2003), "Comparison of Energy Measurements Methods in the Standard Penetration Test", report prepared for the U.S. Bureau of Reclamation, Dept. of Civil Engineering, Univ. of British Columbia, Vancouver, B.C., Canada. February.

Kayen, R. E., Mitchell, J. K., Seed, R. B., Lodge, A., Nishio, S., and Coutinho, R. (1992), "Evaluation of SPT-, CPT-, and Shear Wave-Based Methods for Liquefaction Potential Assessment Using Loma Prieta Data", Proc., 4th Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, Vol. 1, pp. 177-204.

Liao, S. S. C., and Whitman, R. V. (1986), "Overburden Correction Factors for SPT in Sand, Journal of the Geotechnical Eng. Div., ASCE, Vol.112, No. GT3, pp. 373-377.

Little, T. E., Imrie, A. S. and Psutka, J. F. (1994), Geologic and Seismic Setting Pertinent to Dam Safety Review of Duncan Dam, Canadian Geotech. J., Vol. 31, pp. 919-926.

Mansur, C. I., and Kaufman R. I. (1958), Pile Tests, Low-Sill Structure, Old River, Louisiana, J. of Soil Mechanics and Foundation Engin., ASCE, Vol. 123, pp.715-48.

Marcuson, W. F. (1977), Liquefaction Potential of Dams and Foundations, Report No. 4, Determination of In Situ Density of Sands, Research Report S-76-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, August 1977.

Marcuson, W. F., and Bieganousky, W. A. (1977a), Laboratory Standard Penetration Tests on Fine Sands, Journal of the Geotechnical Eng. Div., ASCE Vol.103, Mo. GT6, pp. 565-88.

Marcuson, W. F., and Bieganousky, W. A. (1977b), SPT and Relative Density in Coarse Sands, Journal of the Geotechnical Eng. Div., ASCE, Vol.103, No. GT11, pp. 1295-1309.

Meyerhof, G. G. (1957), Discussion, Proc., 4th International Conference on Soil Mechanics and Foundation Engineering, London, Vol. 3, p.110.

Morgano, C.M. and Liang, R. (1992), Energy Transfer in SPT-Rod Length Effect, Proc., 4th Int. Conf. on the Application of Stress-Wave Theory to Piles, The Hague, The Netherlands, A.A. Balkema Publishers, pp. 121-127.

Moss, R. E. S. (2003), CPT-Based Probabilistic Assessment of Seismic Soil Liquefaction Initiation, Ph.D. Thesis, University of California, May 2003.

Moss, R. E. S., Seed, R. B., and Olsen, R. S. (2006), Normalizing the CPT for Overburden Stress, Journal of Geotechnical and Geoenvironmental Eng., Vol. 132, No. 3, pp. 378-387.

Narula S. C. and Wellington J. F. (1982), The Minimum Sum of Absolute Errors Regression: A State of the Art Survey”, International Statistical Review, Vol. 50, No. 3, pp. 317–326.

OCC (2004), Geotechnical Investigation; Embankment Stability Evaluation, Sunset Reservoir North Basin, San Francisco, California, Olivia Chen Consultants Project No. 1265.21, February, 2004.

Palacios, A. (1977), The Theory and Measurement of Energy Transfer During Standard Penetration Test Sampling, Ph.D. Thesis, University of Florida.

Peck, R. B., Hanson, W. E., and Thornburn, T. H. (1974), Foundation Engineering, Second Edition, John Wiley & Sons, Inc.

Philcox, K. T. (1962), Some Recent Developments in the Design of High Buildings in Hong Kong, The Structural Engineer, Vol. 40, No. 10, pp.303-323.

Pillai, V. S. and Byrne, P. M. (1994), Effect of Overburden Pressure on Liquefaction Resistance of Sand, Canadian Geotech. J., Vol. 31, pp. 53-60.

Pillai, V. S. and Stewart R. A. (1994), Evaluation of Liquefaction Potential of Foundation Soils at Duncan Dam, Canadian Geotech. J., Vol. 31, pp. 951-966.

Plewes, H. D., Pillai, V. S., Morgan, M. R. and Kilpatrick, B. L. (1994), In Situ Sampling, Density Measurements, and Testing of Foundation Soils at Duncan Dam, Canadian Geotech. J., Vol. 31, pp. 927-938.

Salgado, R., Mitchell, J. K., and Jamiolkowski, M. (1998), Calibration Chamber Size Effects on Penetration Resistance in Sand, Journal of Geotechnical and Geoenvironmental Eng., ASCE, Vol. 124, No. 9, pp. 878-888.

Sancio, R., and Bray, J. (2005), An Assessment of the Effect of Rod Length on SPT Energy Calculations Based on Measured Field Data, *Geotechnical Testing Journal*, Vol. 28, No.1, 2005, pp-22-30,

Schmertmann, J.H. and Palacios, A. (1979), Energy Dynamics of SPT, *Journal of the Geotechnical Eng. Div., ASCE*, Vol.105, No. GT8, pp. 909-926.

Seed, H. B. (1979), Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes, *Journal Geotechnical Eng. Div., ASCE*, Vol. 105, No. GT2, pp. 201-55.

Seed, H.B., Tokimatsu, K., Harder, L. F., and Chung, R. M. (1984), The influence of SPT Procedures on Soil Liquefaction Resistance Evaluations, Report No. UCB/EERC-84/15, Earthquake Eng. Research Center, Univ. of California, Berkeley, CA, October.

Seed, H.B., Tokimatsu, K., Harder, L.F. and Chung, R. (1985), Influence of SPT Procedures on Soil Liquefaction Resistance Evaluations, *Journal of the Geotechnical Eng. Div., ASCE*, Vol.111, No. GT12, pp. 1425-1445.

Seed, R.B., Cetin, K. O., Moss, R. E. S., Kammerer, A., Wu, J., Pestana, J., Riemer, M., Sancio, R. B., Bray, J. D., Kayen, R. E., and Faris, A. (2003), Recent Advances in Soil Liquefaction Engineering: a Unified and Consistent Framework, Keynote Presentation, 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Long Beach, CA.

Skempton, A. W. (1986), Standard Penetration Test Procedure and the Effects in Sands of Overburden Pressure, Relative Density, Particle Size, Aging, and Overconsolidation, *Géotechnique*, London, Vol.36, No.3, pp. 425-447.

Sy, A. and Campanella, R.G. (1991), Wave Equation Modeling of SPT, *Geotechnical Congress, ASCE Geotechnical Special Publication No. 27*, Vol. 1, pp. 225-240.

Sy, A. (1993), Energy Measurements and Correlations of the Standard Penetration Test (SPT) and the Becker Penetration Test (BPT), Ph.D. Thesis, University of British Columbia.

Teng, W.C. (1962), *Foundation Design*, Prentice-Hall Inc. Pubs., pp. 37-40.

Terzaghi, K. and Peck, R. B. (1948), *Soil Mechanics in Engineering Practice*, First Edition, New York; Wiley Pubs.

Terzaghi, K., Peck, R. B. and Mesri, G. (1996), *Soil Mechanics in Engineering Practice*, Third Edition, Wiley-Interscience, Pubs.

Tokimatsu, K., and Yoshimi, Y. (1983), Empirical Correlation of Soil Liquefaction Based on SPT N-Value and Fines Content, *Soil and Foundations*, Vol.23, No.4, pp. 56-74.

Tomlinson, M.J. (1969), *Foundation Design and Construction*, Second Edition, Pitman Publishing, pp. 102-104.

U.S. Department of the Interior, Bureau of Reclamation (1953), *Earth Laboratory Report No. EM-314, First Progress Report of Research on the Penetration Resistance Method of Subsurface Exploration*, 1952.

U.S. Department of the Interior, Bureau of Reclamation (1953), *Earth Laboratory Report No. EM-356, Second Progress Report of Research on the Penetration Resistance Method of Subsurface Exploration*, 1953.

Valiquette, M., Robinson, B., and Borden R. H. (2010), *Energy Efficiency and Rod Length Effect in Standard Penetration Test Hammers*, *Journal of the Transportation Research Board*, No. 2186, pp. 47-56.

Woodward-Clyde Consultants (1992), *Lopez Dam, Liquefaction Analysis*, prepared for County of San Luis Obispo, Oakland, California, February.

Youd, T. L., Idriss, I. M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W. D. L., Harder, L. F., Hynes, M. E., Ishihara, K., Koester, J.P., Liao, S. S. C., Marcuson, W. F., Martin, G. R., Mitchell, J. K., Moriwaki, Y., Power, M. S., Robertson, P. K., Seed, R. B., and Stokoe, 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*, *J. Geotechnical and Geoenvironmental Eng.*, Vol. 127, No. 10, pp. 817-833.

Zolkov, E., and Wiseman, G. (1965), *Engineering Properties of Dune and Beach Sands and the Influence of Stress History*, *Proc., Sixth International Conference on Soil mechanics and Foundation Engineering*, Canada, Vol. 1, pp. 134-138.

Appendix A:
Photographs of Equipment and Testing, and Details of
Densification Adjustments, for the WES Tests of
Marcuson and Bieganousky



Figure A-1: Stacked-Ring Chamber used in WES Study (from Bieganousky et al., 1976)

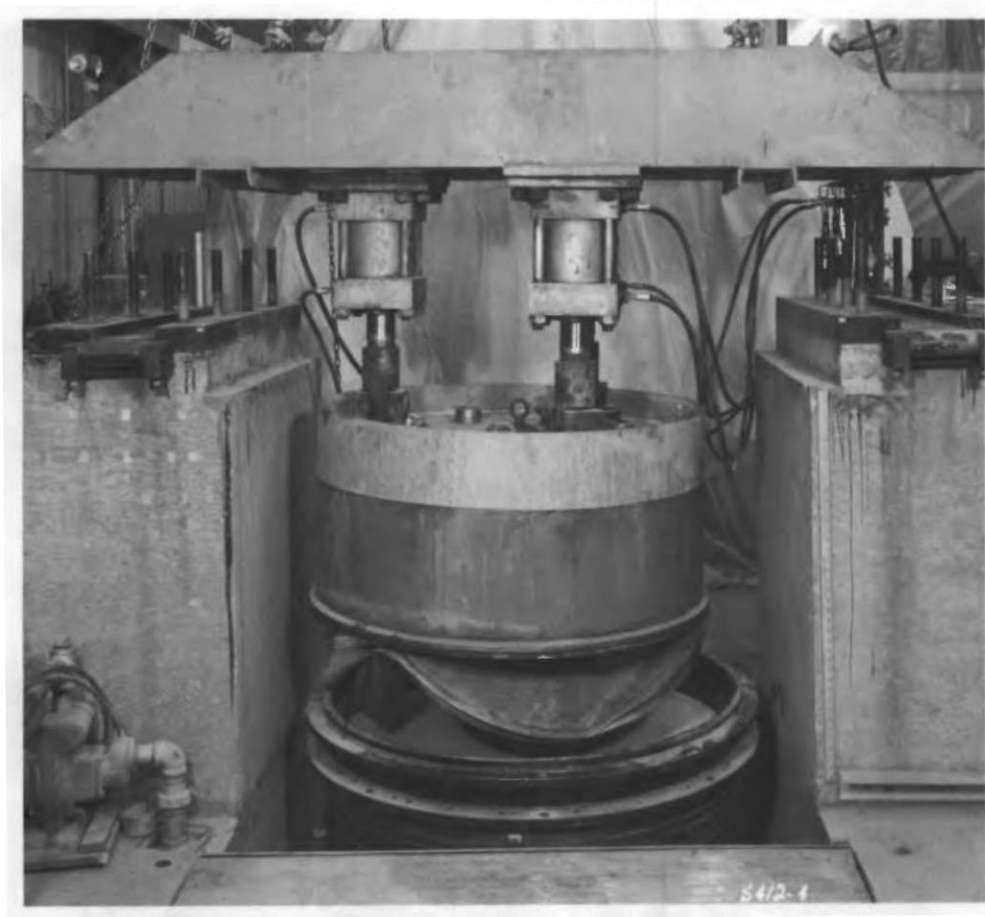


Figure A-2: Overburden Loader System Used in WES Study (from Bieganousky et al., 1976)

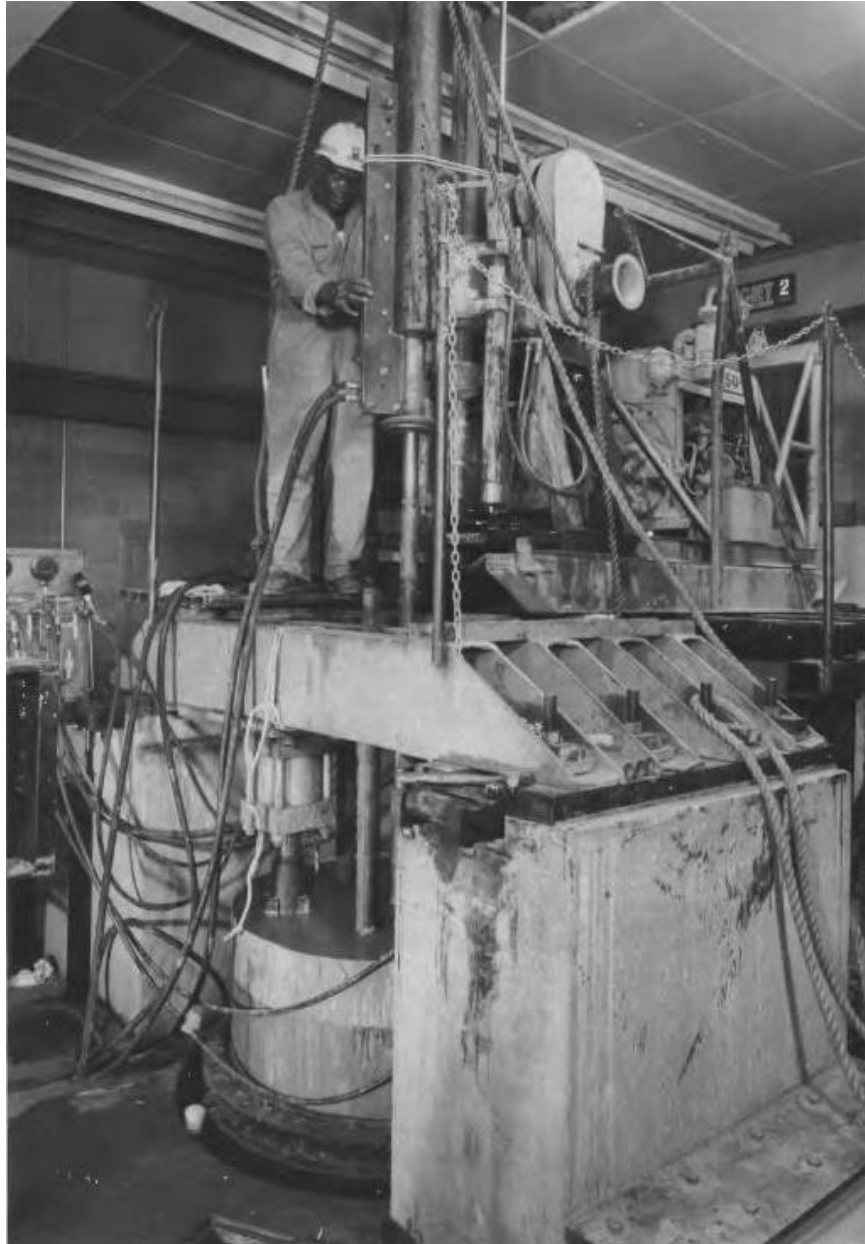


Figure A-3: Actual Photograph of Test Facility in Operation (from Bieganousky et al., 1976)



Figure A-4: Hydraulically Driven 140-lb Trip Hammer Used in WES Study (from Bieganousky et al., 1976)



Figure A-5: Rotating Rainer Used in WES Study (from Biegansky et al., 1976)



Figure A-6: Single-Hose Rainer Used in WES Study (from Bieganousky et al., 1976)



Figure A-7: Vibratory Compactor Used in WES Study (from Bieganousky et al., 1976)

Densification Adjustment for Reid Bedford Model Sand (RBMS)

For the first bin, relative density of specimen prepared using RBMS was 18.3 percent. The application of overburden pressure of 0.72, 2.88, 5.76tsf increased the relative density to 24.3, 27.8 and 29.5 percent, respectively. Relative density of 27.8 percent at 2.88tsf was selected as pivotal relative density for blow counts densification adjustment.

$N/D_R^2 = 16 + 17 * \sigma'_v$ (Skempton, 1986) where σ'_v is in tsf and D_R is in decimal:

- At 0.72 tsf (10psi) $N/D_R^2 = 28$,
From D_R of 24.3 percent to 27.8 percent;
 $\Delta N = 28 * (0.278^2 - 0.243^2) = +0.5$ blow counts
- At 5.76 tsf (40psi) $N/D_R^2 = 114$,
From D_R of 29.5 percent to 27.8 percent;
 $\Delta N = 114 * (0.278^2 - 0.295^2) = -1.1$ blow counts

For the second bin, relative density of specimen prepared using RBMS was 40.9 percent. The application of overburden pressure of 0.72, 2.88, 5.76tsf increased the relative density to 43.8, 45.3 and 46.1 percent, respectively. Relative density of 45.3 percent at 2.88tsf was selected as pivotal relative density for blow counts adjustment.

$N/D_R^2 = 16 + 17 * \sigma'_v$ (Skempton, 1986) where σ'_v is in tsf and D_R is in decimal:

- At 0.72 tsf (10psi) $N/D_R^2 = 28$,
From D_R of 43.8 percent to 45.3 percent;
 $\Delta N = 28 * (0.453^2 - 0.438^2) = +0.4$ blow counts
- At 5.76 tsf (80psi) $N/D_R^2 = 114$,
From D_R of 46.1 percent to 45.3 percent;
 $\Delta N = 114 * (0.453^2 - 0.461^2) = -0.8$ blow counts

For the third bin, data from three different specimens were collected. Relative densities of specimens were 73.2, 71.5 and 74.4 percent at 10 psi, 40 psi and 80 psi, respectively. So, relative density of 73.2 percent at 10 psi is selected as pivotal relative density for blow counts adjustment.

$N/D_R^2 = 16 + 17 * \sigma'_v$ (Skempton, 1986) where σ'_v is in tsf and D_R is in decimal:

- At 2.88 tsf (40psi) $N/D_R^2 = 65$,
From D_R of 71.5 percent to 73.2 percent;

$$\Delta N = 65 * (0.732^2 - 0.715^2) = +1.6 \text{ blow counts}$$

- At 5.76 tsf (80psi) $N/D_r^2 = 114$,
From D_R of 74.4 percent to 73.2 percent;
 $\Delta N = 114 * (0.732^2 - 0.744^2) = -2.0 \text{ blow counts}$

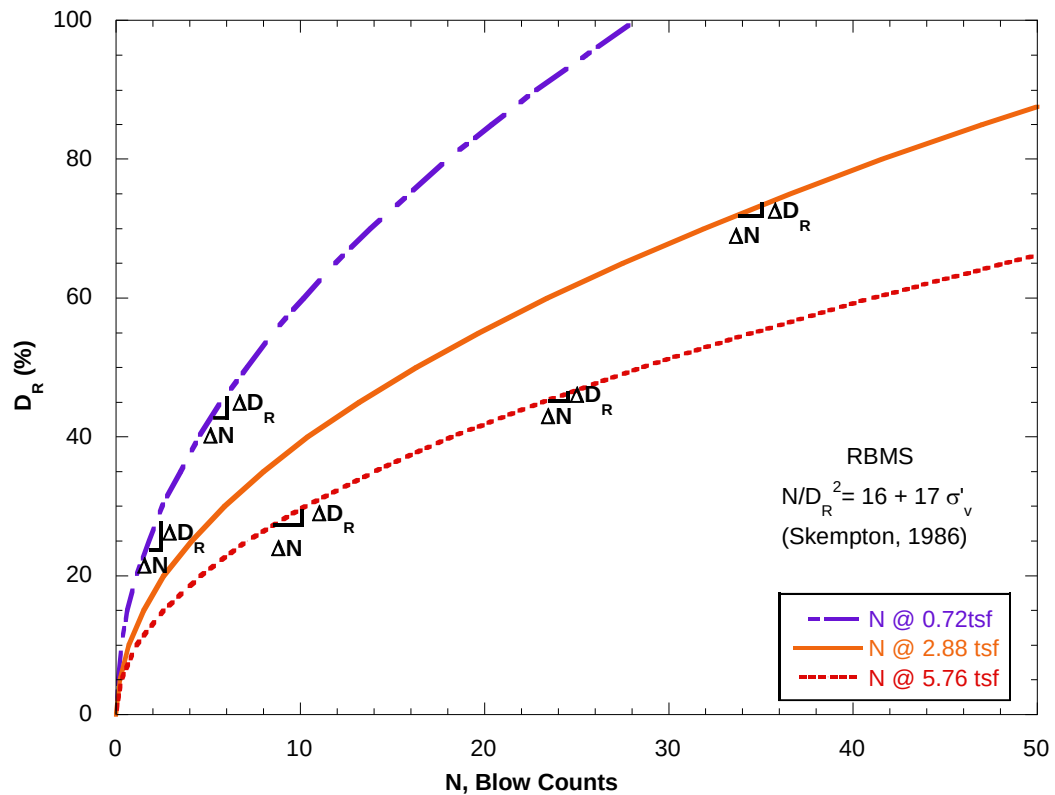


Figure A-8: Illustration of Densification Adjustments in SPT N Values for Reid Bedford Model Sand (RBMS)

Densification Adjustment for Platte River Sand (PRS)

For the first bin, scatter in N values corresponding to low relative density caused to unreasonable N values, thus unreasonable m value, if densification adjustment is applied. Consequently, densification adjustment is not applied to N values in the first bin, and m value for this particular bin is not included in the m coefficient data set regressed from adjusted N values. However, m value for this particular bin is kept in the coefficient m dataset regressed from unadjusted N values since it represents variability in the data.

For the second bin, relative densities of specimen prepared with PRS were 53.7, 56.2 and 58.1 percent at 10 psi, 40 psi and 80 psi, respectively. So, relative density of 56.2 percent at 40 psi is selected as pivotal relative density for blow counts adjustment.

$N/D_r^2 = 30 + 22 \sigma'_v$ (Skempton, 1986) where σ'_v is in tsf and D_r is in decimal:

- At 0.72 tsf (10psi) $N/D_r^2 = 46$,
From D_r of 53.7 percent to 56.2 percent;
 $\Delta N = 46 * (0.562^2 - 0.537^2) = +1.3$ blow counts
- At 5.76 tsf (80psi) $N/D_r^2 = 157$,
From D_r of 58.1 percent to 56.2 percent;
 $\Delta N = 157 * (0.562^2 - 0.581^2) = -3.4$ blow counts

For the third bin, there is no need for density adjustment. Because it was very dense, there was not noticeable densification in the specimen as applied effective stress level increased. Relative density of specimens, which SPT were performed on, was 91.4 percent for all of three effective stress levels. Consequently, density adjustment is not necessary for this bin.

Densification Adjustment for Standard Concrete Sand (SCS)

For the first bin, relative densities of specimen prepared with SCS were 20.1, 25.9 and 29.7 percent at 10 psi, 40 psi and 80 psi, respectively. So, relative density of 25.9 percent at 40 psi is selected as pivotal relative density for blow counts adjustment.

$N/D_r^2 = 21 + 24 \sigma'_v$ (Skempton, 1986) where σ'_v is in tons/ft² and D_R is in decimal:

- At 0.72 tsf (10psi) $N/D_R^2 = 38$,
From D_R of 20.1 percent to 25.9 percent;
 $\Delta N = 38 * (0.259^2 - 0.201^2) = +1$ blow counts
- At 5.76 tsf (80psi) $N/D_R^2 = 159$,
From D_R of 29.7 percent to 25.9 percent;
 $\Delta N = 159 * (0.259^2 - 0.297^2) = -3.4$ blow counts

For the second bin, relative densities of specimen prepared with SCS were 49.3, 50.5 and 51.7 percent at 10 psi, 40 psi and 80 psi, respectively. So, relative density of 50.5 percent at 40 psi is selected as pivotal relative density for blow counts adjustment.

$N/D_r^2 = 21 + 24 \sigma'_v$ (Skempton, 1986) where σ'_v is in tsf and D_R is in decimal:

- At 0.72 tsf (10psi) $N/D_R^2 = 38$,
From D_R of 49.3 percent to 50.5 percent;
 $\Delta N = 38 * (0.505^2 - 0.493^2) = +0.5$ blow counts
- At 5.76 tsf (80psi) $N/D_R^2 = 159$,
From D_R of 51.7 percent to 50.5 percent;
 $\Delta N = 159 * (0.505^2 - 0.517^2) = -2$ blow counts

For the third bin, relative density of specimen was 95.9 percent for all three applied stress level. Because it was dense, there was not noticeable densification, and hence no need for adjustment for the third bin.

Appendix B:

Tables of Data for SPT Field Cases of Dam Foundation Soils

Table B-1: Summary Table of SPT at Duncan Dam
For Different Density Bins

Borehole	σ'_v (tsf)	N-value (Blows/ft)	C_E	N_{60}
1st Bin				
DH90-7D	7.0	27	0.72	19.0
DH90-6D	6.6	26	0.72	19.0
DH90-7D	1.3	12	0.72	8.4
DH90-7D	1.6	13	0.72	9.3
DH88-9	1.8	14	0.72	10.0
DH90-6D	2.3	17	0.72	12.1
DH90-6D	1.6	16	0.72	11.4
DH88-9	2.2	19	0.72	13.6
DH88-7	9.5	41	0.72	29.6
DH90-5D	4.7	31	0.72	22.0
2nd Bin				
DH88-9	2.1	21	0.72	15.0
DH88-9	2.5	23	0.72	16.4
DH88-9	1.9	21	0.72	15.0
DH90-5D	5.5	35	0.72	24.8
DH88-8	4.2	31	0.72	22.2
DH88-9	4.3	32	0.72	22.9
DH88-9	2.4	25	0.72	17.8
DH90-5D	3.5	30	0.72	21.2
DH88-9	3.4	29	0.72	20.8
DH90-5D	3.9	31	0.72	22.1
DH88-8	6.6	40	0.72	28.8
DH88-9	1.5	21	0.72	15.0
DH88-7	11.9	53	0.72	38.1
DH88-9	5.1	37	0.72	26.6
DH88-8	5.3	38	0.72	27.1
DH88-8	7.1	43	0.72	30.8
DH90-5D	6.5	42	0.72	30.1
DH88-8	5.2	38	0.72	27.2
DH88-9	3.7	33	0.72	23.6
DH90-5D	4.4	36	0.72	25.5
DH90-5D	5.8	41	0.72	29.3
DH90-5D	6.3	42	0.72	30.4
DH88-9	4.0	35	0.72	25.1
DH88-8	6.8	44	0.72	31.6
DH88-9	3.9	35	0.72	25.1

DH88-8	4.1	36	0.72	25.8
DH88-7	10.8	55	0.72	39.6
DH88-9	4.7	39	0.72	27.9
DH88-8	3.9	36	0.72	25.9
DH88-7	11.7	59	0.72	42.4
DH88-8	6.6	46	0.72	33.0
DH88-7	9.8	55	0.72	39.6
DH88-7	10.3	57	0.72	41.1
3rd Bin				
DH88-9	4.2	39	0.72	27.9
DH88-8	4.9	42	0.72	30.0
DH88-8	5.8	46	0.72	32.9
DH88-8	6.1	47	0.72	33.7
DH88-8	3.7	38	0.72	27.2
DH88-8	5.9	47	0.72	33.7
DH88-7	11.1	62	0.72	44.6
DH88-8	4.7	43	0.72	30.8
DH88-8	5.4	46	0.72	33.1
DH88-8	5.1	45	0.72	32.2
DH88-7	9.9	60	0.72	43.2
DH88-8	4.5	43	0.72	30.8
DH88-7	10.7	63	0.72	45.3
DH88-9	3.3	38	0.72	27.3
DH88-7	10.5	63	0.72	45.3
DH88-7	11.2	68	0.72	48.8
DH88-8	6.9	55	0.72	39.4
DH88-9	3.6	42	0.72	30.1
DH88-7	11.5	71	0.72	51.1
DH88-7	11.0	70	0.72	50.3
DH88-9	1.7	31	0.72	22.2
DH88-9	4.9	50	0.72	35.8
DH88-7	11.6	74	0.72	53.2
DH88-7	10.6	72	0.72	51.8
DH88-8	6.3	58	0.72	41.5
DH88-9	3.0	42	0.72	30.1
DH88-7	10.1	75	0.72	54.0
DH88-8	6.2	62	0.72	44.3
DH88-8	5.6	61	0.72	43.7
DH88-9	3.1	54	0.72	38.6

Table B-2: Summary Table of SPT at the Left Reach of Perris Dam, Shallow Alluvium For Different Density Bins

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
1 st Bin														
SS-17	91+30	6.0	SM-SP	SM	28	0	0.68	1.05	1.10	1.42	0.22	3	2.4	3.3
SS-44U	111+67	80	SM	SC-SM	23	0	1.25	1.00	1.00	1.33	5.21	8	10.0	13.3
SS-18	96+68	6.0	CL	SC	41	12	0.68	1.05	1.10	1.43	0.22	4	3.1	4.5
SS-21	111+63	6	SM-SP	SM	32	0	0.68	1.05	1.10	1.39	0.22	4	3.1	4.4
SS-43L	106+80	56.0	SM	SM	30	0	1.25	1.00	1.00	1.35	3.57	9	11.3	15.2
SS-21T	111+75	6	(ML)s	SM	31	0	1.20	1.00	1.00	1.35	0.22	3	3.6	4.8
SS-21T	111+75	24	SP-SM	SC-SM	24	7	1.20	1.00	1.00	1.29	0.88	5	6.0	7.7
SS-16	86+30	6	SM-SP	SM	29	0	0.68	1.05	1.10	1.31	0.22	5	3.9	5.1
SS-40ML	94+22	75.0	SP	SM	46	0	1.25	1.00	1.00	1.46	6.63	10	12.5	18.3
SS-41MU	99+25	102.0	s(ML)	SC-SM	30	5	1.25	1.00	1.00	1.35	6.42	12	15.0	20.2
SS-41MUA	99+33	96.0	ML	SC-SM	44	6	1.25	1.00	1.00	1.40	5.98	12	15.0	20.9
SS-21T	111+75	9	(ML)s	SC	38	8	1.20	1.00	1.00	1.36	0.33	4	4.8	6.5
SS-21	111+63	11	SC	SC	29	8	0.76	1.05	1.10	1.30	0.4	6	5.3	6.8
SS-17A	91+72	6.0	SM-SP		31	3	0.68	1.05	1.10	1.29	0.22	6	4.7	6.1
SS-17B	91+72	5.0	SM-SP		31	3	0.68	1.05	1.10	1.28	0.18	6	4.7	6.0
SS-19	101+70	11.0	SM	SC	35	10	0.76	1.05	1.10	1.36	0.40	6	5.3	7.2
SS-40M	94+20	129.0	ML	SM	29	0	1.20	1.00	1.00	1.31	7.49	15	18.0	23.6
SS-40ML	94+22	70.0	(CL)s	CL	50	8	1.25	1.00	1.00	1.36	4.18	12	15.0	20.4
SS-41ML	99+25	67.0	(ML)s		57	3	1.25	1.00	1.00	1.36	4.05	12	15.0	20.3
SS-42FF2	101+20	11.0	SP-SM	SW-SM	8	0	1.24	1.00	1.00	1.08	0.51	5	6.2	6.7
SS-42	101+70	136.0	SP-SM	SM	34	0	1.20	1.00	1.00	1.34	7.54	17	20.4	27.3
SS-21T	111+75	12	(ML)s		57	0	1.20	1.00	1.00	1.31	0.44	6	7.2	9.4
SS-41	96+72	141.0	SM	SC-SM	36	5	1.20	1.00	1.19	1.33	7.97	16	22.8	30.4
SS-41FF2	95+90	19.0	SM	SC	33	8	1.31	1.00	1.00	1.29	0.78	7	9.2	11.9
SS-41MFF1	98+50	16.0	SP-SM	SC	32	8	1.29	1.00	1.00	1.28	0.71	7	9.0	11.6
SS-41	96+72	131.0	s(ML)	SC	35	8	1.20	1.00	1.19	1.33	7.92	16	22.8	30.4
SS-42M	104+20	131.0	ML	SC-SM	27	6	1.20	1.00	1.00	1.25	7.48	19	22.8	28.5
SS-43L	106+80	58.0	SM	SM	20	0	1.25	1.00	1.00	1.18	3.66	14	17.5	20.7
SS-44U	111+67	82.5	SM	SM	20	0	1.25	1.00	1.00	1.18	5.3	17	21.3	25.0

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
2 nd Bin														
SS-17C	91+72	6.0	SM		31	3	0.68	1.05	1.10	1.25	0.22	9	7.1	8.9
SS-43FF2	105+90	6.0	SM	SC-SM	29	7	1.15	1.00	1.00	1.24	0.36	7	8.1	10.0
SS-64	101+80	20.0	SM		31	3	1.20	1.00	1.12	1.25	1.26	10	13.4	16.8
SS-17A	91+72	4.0	SM-SP		31	3	0.68	1.05	1.10	1.23	0.15	10	7.9	9.6
SS-40MU	94+22	105.0	SM	SC-SM	48	5	1.25	1.00	1.00	1.27	6.48	21	26.3	33.2
SS-41U	96+72	96.0	ML	CL	63	12	1.25	1.00	1.00	1.27	6.17	20	25.0	31.8
SS-42	101+70	125.0	SM	SM	18	0	1.20	1.00	1.00	1.14	7.28	22	26.4	30.1
SS-42FF1	101+20	6.0	SC		36	13	1.15	1.00	1.00	1.27	0.36	8	9.2	11.7
SS-42FF2	101+20	9.0	SM	SC-SM	28	6	1.20	1.00	1.00	1.22	0.43	8	9.6	11.7
SS-42M	104+20	118.0	SP-SM	SC-SM	28	4	1.20	1.00	1.00	1.21	6.88	22	26.4	32.1
SS-43FF2	105+90	9.0	SP-SM	SC-SM	20	5	1.20	1.00	1.00	1.16	0.46	8	9.6	11.1
SS-43M	109+30	118.0	(ML)s	SM	25	0	1.25	1.00	1.00	1.19	7.65	22	27.5	32.8
SS-63	96+77	22.0	SP	SM	16	0	1.20	1.00	1.00	1.12	1.19	12	14.4	16.2
SS-41M	99+22	130.0	SP-SM	SC-SM	44	4	1.20	1.00	1.00	1.26	7.57	24	28.8	36.3
SS-41ML	99+25	77.0	SC	SC	39	9	1.25	1.00	1.00	1.26	4.42	19	23.8	30.0
SS-16	86+30	11	CL	SC	20	10	0.76	1.05	1.10	1.15	0.4	12	10.5	12.1
SS-40M	94+20	132.0	ML	SM	27	3	1.20	1.00	1.00	1.19	7.41	26	31.2	37.2
SS-40MU	94+22	103.0	SM	SM	38	3	1.25	1.00	1.00	1.25	6.39	23	28.8	36.1
SS-40U	91+72	101.0	ML	SC	50	10	1.25	1.00	1.00	1.25	6.41	23	28.8	36.1
SS-41ML	99+25	62.0	SM	SC	42	13	1.25	1.00	1.00	1.26	3.87	19	23.8	29.9
SS-42ML	104+20	60.0	s(ML)	SM	28	0	1.25	1.00	1.00	1.20	3.79	19	23.8	28.6
SS-41MFF1	98+50	9.0	SM	SC	37	12	1.20	1.00	1.00	1.25	0.46	10	12.0	15.0
SS-41MU	99+25	99.0	ML	SC-SM	36	5	1.25	1.00	1.00	1.25	6.33	24	30.0	37.5
SS-42FF1	101+20	9.0	SM	SC	23	8	1.20	1.00	1.00	1.17	0.46	10	12.0	14.0
SS-42L	101+80	65.0	SM	SM	20	0	1.25	1.00	1.00	1.14	3.95	21	26.3	29.9
SS-42MFF	103+50	9.0	s(CL)	SC	36	8	1.20	1.00	1.00	1.25	0.43	10	12.0	15.0
SS-65	106+80	22.0	SP-SM	SM	25	0	1.20	1.00	1.00	1.18	1.20	14	16.8	19.8
SS-17D	91+72	6.0	CL		56	12	0.68	1.05	1.10	1.24	0.22	13	10.2	12.7

SS-40ML	94+22	63.0	SP-SM	SM	14	0	1.25	1.00	1.00	1.10	3.91	22	27.5	30.2
SS-40ML	94+22	78.0	s(CL)	SM	43	0	1.25	1.00	1.00	1.24	4.46	23	28.8	35.7
SS-41L	96+72	74.0	SM	SM	28	0	1.25	1.00	1.00	1.20	4.32	22	27.5	32.9
SS-42MFF	103+50	6.0	s(CL)	SC	31	8	1.15	1.00	1.00	1.22	0.33	10	11.5	14.0
SS-17	91+30	11.0	SM-SW		31	3	0.76	1.05	1.12	1.21	0.40	15	13.4	16.2
SS-17A	91+72	21.0	SM-SP		31	3	0.76	1.05	1.14	1.21	0.77	18	16.4	19.8
SS-18	96+68	8.0	CL		56	12	0.68	1.05	1.11	1.24	0.29	15	11.9	14.7
SS-40L	91+72	67.0	ML	SC-SM	26	4	1.25	1.00	1.00	1.18	3.96	23	28.8	33.8
SS-41L	96+72	79.0	SM	SM	33	0	1.25	1.00	1.00	1.22	4.50	24	30.0	36.7
SS-42M	104+20	126.0	SM	SC	37	9	1.20	1.00	1.00	1.24	7.25	29	34.8	43.1
SS-43FF2	105+90	11.0	SM	SC-SM	28	7	1.24	1.00	1.00	1.19	0.53	12	14.9	17.7
SS-43FF2	105+90	19.0	SM	SM	30	5	1.31	1.00	1.00	1.20	0.81	13	17.0	20.5
SS-43U	106+80	103.0	SM	SC-SM	28	5	1.25	1.00	1.00	1.19	6.10	26	32.5	38.7
SS-62	91+72	20.0	SM		31	3	1.20	1.00	1.17	1.21	1.29	14	19.7	23.8
SS-40M	94+20	146.0	SM	CL	51	16	1.20	1.00	1.00	1.23	7.91	32	38.4	47.3
SS-41FF2	95+90	6.0	SM		30	3	1.15	1.00	1.00	1.20	0.36	12	13.8	16.5
SS-41U	96+72	103.0	ML	SM	34	0	1.25	1.00	1.00	1.23	6.27	28	35.0	42.9
SS-42MU	104+20	91.0	SM	SM	21	2	1.25	1.00	1.00	1.14	5.63	27	33.8	38.5
SS-43ML	109+30	55.0	SC	SM	21	0	1.25	1.00	1.00	1.14	3.47	23	28.8	32.8
SS-43MU	109+30	88.0	SM	SC	33	12	1.25	1.00	1.00	1.22	5.48	26	32.5	39.7
SS-63	96+77	19.0	SP	SC-SM	28	7	1.20	1.00	1.00	1.19	1.10	16	19.2	22.8
SS-65	106+80	28.0	SM		31	3	1.20	1.00	1.00	1.20	1.38	18	21.6	26.0
SS-40ML	94+22	59.5	SC	SM	35		1.25	1.00	1.00	1.23	3.80	24	30.0	37.0
SS-41L	96+72	64.0	(CL)s	CL	65	14	1.25	1.00	1.00	1.23	3.86	25	31.3	38.4
SS-41L	96+72	69.0	SC	SM	26	0	1.25	1.00	1.00	1.17	4.13	25	31.3	36.6
SS-42MU	104+20	96.0	ML	SC	37	9	1.25	1.00	1.00	1.23	5.81	28	35.0	43.1
SS-42MU	104+20	98.0	ML	SC	31	8	1.25	1.00	1.00	1.21	5.90	28	35.0	42.2
SS-43ML	109+30	65.0	SM	SM	18	0	1.25	1.00	1.00	1.12	3.84	25	31.3	34.9

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
3 rd Bin														
SS-63	96+77	36.0	SC	CL	53	10	1.20	1.00	1.00	1.23	1.66	20	24.0	29.4
SS-42MFF	103+50	16.0	SM	SC-SM	22	6	1.29	1.00	1.00	1.14	0.68	14	18.1	20.6
SS-40MFF	93+46	9.0	SM/SC		40	3	1.20	1.00	1.00	1.22	0.43	13	15.6	19.1
SS-21	111+63	13	SC		37	0	0.76	1.05	1.14	1.22	0.48	18	16.4	20.0
SS-40L	91+72	59.0	ML	SC-SM	40	6	1.25	1.00	1.00	1.23	3.71	25	31.3	38.3
SS-40MFF	93+46	11.0	SM/SC		40	3	1.24	1.00	1.00	1.22	0.53	14	17.4	21.2
SS-41L	96+72	71.0	SM	SM	26	0	1.25	1.00	1.00	1.17	4.29	27	33.8	39.4
SS-41MFF1	98+50	11.0	SM	CL	51	10	1.24	1.00	1.00	1.22	0.53	14	17.4	21.2
SS-41U	96+72	108.0	ML	SM	41	0	1.25	1.00	1.00	1.22	6.58	31	38.8	47.5
SS-42FF1	101+20	21.0	SM	SC	41	10	1.33	1.00	1.00	1.22	0.88	15	20.0	24.4
SS-40MU	94+22	115.0	ML	SC-SM	37	7	1.25	1.00	1.00	1.22	6.74	32	40.0	48.9
SS-41MFF1	98+50	14.0	SM	CL	53	14	1.27	1.00	1.00	1.22	0.61	15	19.1	23.2
SS-41MUA	99+33	93.0	ML	CL-ML	51	7	1.25	1.00	1.00	1.22	6.01	31	38.8	47.4
SS-41U	96+72	111.0	ML	SC-SM	48	7	1.25	1.00	1.00	1.22	6.36	32	40.0	48.8
SS-43L	106+80	68.0	SC	SM	21	0	1.25	1.00	1.00	1.13	3.95	27	33.8	38.2
SS-43MFF	108+40	9.0	SM	SC	30	8	1.20	1.00	1.00	1.19	0.34	13	15.6	18.5
SS-43MU	109+30	101.0	SM	SC-SM	28	5	1.25	1.00	1.00	1.18	6.01	31	38.8	45.6
SS-65	106+80	19.0	SP-SM	SC-SM	22	4	1.20	1.00	1.00	1.14	1.10	19	22.8	25.9
SS-39U	86+67	108	(ML)s	SC-SM	44	7	1.25	1.00	1.00	1.22	6.42	32	40.0	48.8
SS-40ML	94+22	65.0	(CL)s	CL	64	12	1.25	1.00	1.00	1.22	4.02	29	36.3	44.1
SS-41FF2	95+90	21.0	SM	SC	30	8	1.33	1.00	1.00	1.18	0.88	17	22.6	26.8
SS-41L	96+72	66.0	CL	SC-SM	41	4	1.25	1.00	1.00	1.22	4.02	29	36.3	44.1
SS-64	101+80	26.0	SP-SM		31	3	1.20	1.00	1.22	1.19	1.46	18	26.4	31.4
SS-40MFF	93+46	6.0	SM/SC		40	3	1.15	1.00	1.00	1.21	0.36	15	17.3	20.9
SS-40MU	94+22	113.0	ML	SC	39	12	1.25	1.00	1.00	1.22	6.64	35	43.8	53.2
SS-40U	91+72	108.0	ML	SC	46	12	1.25	1.00	1.00	1.22	6.64	34	42.5	51.7
SS-41MFF2	98+44	9.0	SM/SC		30	3	1.20	1.00	1.00	1.18	0.55	17	20.4	24.1
SS-41MU	99+25	112.0	ML	SC	39	8	1.25	1.00	1.00	1.22	6.64	34	42.5	51.7
SS-41U	96+72	106.0	ML	CL-ML	52	4	1.25	1.00	1.00	1.22	6.26	34	42.5	51.7
SS-43L	106+80	61.0	SM	SM	24	0	1.25	1.00	1.00	1.15	3.70	29	36.3	41.6

SS-43ML	109+30	57.0	SM	SM	20	0	1.25	1.00	1.00	1.12	3.70	29	36.3	40.7
SS-43ML	109+30	67.0	SM	SM	31	0	1.25	1.00	1.00	1.19	4.08	29	36.3	43.2
SS-43MU	109+30	91.0	SM	SC-SM	25	4	1.25	1.00	1.00	1.15	5.60	33	41.3	47.6
SS-62	91+72	29.0	SM		31	3	1.20	1.00	1.23	1.19	1.58	19	28.0	33.3
SS-17	91+30	21.0	SM-SW		31	3	0.76	1.05	1.19	1.19	0.73	24	22.8	27.0
SS-17A	91+72	8.0	SC		36	13	0.68	1.05	1.15	1.21	0.29	21	17.2	20.8
SS-40	91+72	138.0	SC		36	13	1.20	1.00	1.30	1.22	8.12	30	46.8	56.9
SS-40U	91+72	110.0	SM	SC-SM	22	6	1.25	1.00	1.00	1.13	6.77	36	45.0	51.0
SS-41FF2	95+90	9.0	SM		30	3	1.20	1.00	1.00	1.18	0.43	16	19.2	22.6
SS-41FF2	95+90	11.0	s(CL)		60	12	1.24	1.00	1.00	1.21	0.53	17	21.1	25.5
SS-41L	96+72	76.0	SM	SM	25	0	1.25	1.00	1.00	1.15	4.59	31	38.8	44.7
SS-41L	96+72	81.0	SM	SM	25	0	1.25	1.00	1.00	1.15	4.59	32	40.0	46.1
SS-41MFF2	98+44	14.0	SM		30	3	1.27	1.00	1.00	1.18	0.88	19	24.1	28.5
SS-42FF2	101+20	24.0	SP-SM	SW-SM	11	2	1.35	1.00	1.00	1.07	0.94	18	24.3	25.9
SS-42L	101+80	73.0	ML	SC-SM	38	6	1.25	1.00	1.00	1.21	4.14	31	38.8	47.0
SS-42MU	104+20	101.0	ML	SC-SM	39	5	1.25	1.00	1.00	1.21	6.03	35	43.8	53.1
SS-62	91+72	34.0	SP-SM		31	3	1.20	1.00	1.24	1.19	1.78	20	29.8	35.3
SS-44U	111+67	90	SC	SC	35	0	1.25	1.00	1.00	1.21	5.71	34	42.5	51.6
SS-21	111+63	16	SC		37	0	0.76	1.05	1.18	1.21	0.59	23	21.7	26.2
SS-44U	111+67	85	SM	SC	38	0	1.25	1.00	1.00	1.21	5.44	34	42.5	51.5
SS-19	101+70	8.0	SM		31	3	0.68	1.05	1.16	1.18	0.28	22	18.2	21.5
SS-40U	91+72	98.0	SC	SC	33	13	1.25	1.00	1.00	1.20	6.14	36	45.0	54.0
SS-41FF2	95+90	14.0	SM		40	3	1.27	1.00	1.00	1.21	0.65	18	22.9	27.6
SS-41ML	99+25	72.0	(ML)s	SC-SM	45	6	1.25	1.00	1.00	1.21	4.20	32	40.0	48.4
SS-41MU	99+25	104.0	(ML)s	CL	50	12	1.25	1.00	1.00	1.21	6.51	36	45.0	54.6
SS-42	101+70	128.0	SM	SC	39	8	1.20	1.00	1.00	1.21	7.33	40	48.0	58.1
SS-42ML	104+20	67.0	SP-SM	SC-SM	27	5	1.25	1.00	1.00	1.16	3.99	32	40.0	46.5
SS-42U	101+80	94.0	SC/SM	SM	26	0	1.25	1.00	1.00	1.16	5.80	35	43.8	50.6
SS-43	106+80	127.0	s(ML)		57	3	1.20	1.00	1.30	1.21	7.33	30	46.8	56.7
SS-40	91+72	141.0	SM		31	3	1.20	1.00	1.30	1.19	7.96	32	49.9	59.2
SS-40M	94+20	138.0	SM/SC		31	3	1.20	1.00	1.00	1.19	7.96	41	49.2	58.4
SS-40MU	94+22	98.0	ML	SC-SM	42	7	1.25	1.00	1.00	1.21	6.25	37	46.3	55.9
SS-41MFF2	98+44	6.0	SM/SC		30	3	1.15	1.00	1.00	1.17	0.39	18	20.7	24.3
SS-41ML	99+25	69.0	(ML)s	SM	27	0	1.25	1.00	1.00	1.16	4.26	33	41.3	47.9

SS-41U	96+72	101.0	ML	SC-SM	37	6	1.25	1.00	1.00	1.21	6.25	37	46.3	55.9
SS-42FF2	101+20	19.0	SP-SM	SC	23	10	1.31	1.00	1.00	1.13	0.77	19	24.9	28.2
SS-42ML	104+20	70.0	ML	SM	24	0	1.25	1.00	1.00	1.14	4.05	33	41.3	47.1
SS-44U	111+67	92.5	SM	SC-SM	26	0	1.25	1.00	1.00	1.16	5.58	36	45.0	52.0
SS-39U	86+67	100.5	SM	SC-SM	26	4	1.25	1.00	1.00	1.15	5.93	37	46.3	53.4
SS-17	91+30	8.0	SC		36	13	0.68	1.05	1.16	1.20	0.28	23	19.0	22.9
SS-17	91+30	16.0	CL		56	12	0.76	1.05	1.20	1.20	0.55	25	23.9	28.7
SS-40L	91+72	77.0	SC	SC	34	9	1.25	1.00	1.00	1.20	4.32	34	42.5	51.0
SS-40ML	94+22	73.0	SP	SM	15	0	1.25	1.00	1.00	1.09	4.32	34	42.5	46.3
SS-41	96+72	136.0	SM/ML	CL	61	9	1.20	1.00	1.30	1.21	7.62	33	51.5	62.1
SS-42	101+70	131.0	SM	SC	44	13	1.20	1.00	1.00	1.21	7.62	42	50.4	60.9
SS-42L	101+80	78.0	ML		57	3	1.25	1.00	1.00	1.21	4.32	35	43.8	52.7
SS-42M	104+20	121.0	SP-SM		31	3	1.20	1.00	1.00	1.18	7.17	41	49.2	58.3
SS-42ML	104+20	72.0	SM		31	3	1.25	1.00	1.00	1.18	4.10	34	42.5	50.3
SS-42U	101+80	104.0	SM	SC	23	8	1.25	1.00	1.00	1.14	6.01	38	47.5	54.0
SS-43M	109+30	123.0	SP-SM	SM	23	0	1.25	1.00	1.00	1.14	7.62	41	51.3	58.2
SS-44U	111+67	95	SM	SC-SM	26	0	1.25	1.00	1.00	1.15	5.72	38	47.5	54.8
SS-44U	111+67	87.5	SC	SC	42	0	1.25	1.00	1.00	1.20	5.44	38	47.5	57.2
SS-41ML	99+25	64.0	SC		36	13	1.25	1.00	1.00	1.20	3.95	35	43.8	52.6
SS-41MUA	99+33	101.0	SM/SC	SC	31	11	1.25	1.00	1.00	1.18	6.10	40	50.0	59.0
SS-41U	96+72	98.0	ML	SC-SM	33	6	1.25	1.00	1.00	1.19	6.10	39	48.8	58.2
SS-39	86+67	141	SP		15	0	1.20	1.00	1.30	1.09	8.35	35	54.6	59.4
SS-40M	94+20	141.0	SM/SC	CL	54	12	1.20	1.00	1.00	1.20	7.91	45	54.0	65.0
SS-40MU	94+22	101.0	SC	SC	45	15	1.25	1.00	1.00	1.20	6.20	41	51.3	61.6
SS-40U	91+72	103.0	ML		57	3	1.25	1.00	1.00	1.20	6.58	41	51.3	61.7
SS-42MFF	103+50	19.0	SM		15	3	1.31	1.00	1.00	1.09	0.79	21	27.5	29.9
SS-42U	101+80	99.0	SC/SM	SC	35	9	1.25	1.00	1.00	1.20	5.85	40	50.0	60.2
SS-43FF2	105+90	21.0	SM		20	3	1.33	1.00	1.00	1.11	0.87	22	29.3	32.6
SS-43M	109+30	116.0	SC		36	13	1.25	1.00	1.00	1.20	7.43	43	53.8	64.7
SS-43MFF	108+40	6.0	SM		20	3	1.15	1.00	1.00	1.11	0.27	18	20.7	23.0
SS-43U	106+80	91.0	SM		31	3	1.25	1.00	1.00	1.18	5.53	40	50.0	58.9
SS-64	101+80	32.0	SM		31	3	1.20	1.00	1.28	1.18	1.68	23	35.3	41.6

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
4 th Bin														
SS-16	86+30	16	CL		58	0	0.76	1.05	1.22	1.20	0.59	27	26.3	31.5
SS-39	86+67	129	SM		29	0	1.20	1.00	1.30	1.16	7.89	36	56.2	65.3
SS-17A	91+72	16.0	CL		56	12	0.76	1.05	1.22	1.20	0.59	27	26.3	31.5
SS-19	101+70	21.0	SM-SP		31	3	0.76	1.05	1.23	1.17	0.77	29	28.5	33.4
SS-41ML	99+25	74.0	ML/CL		56	12	1.25	1.00	1.00	1.20	4.33	38	47.5	56.8
SS-42MU	104+20	88.0	SM		31	3	1.25	1.00	1.00	1.17	5.53	41	51.3	60.1
SS-43L	106+80	66.0	SC		36	13	1.25	1.00	1.00	1.20	3.94	37	46.3	55.3
SS-43L	106+80	71.0	SP-SM	SM	12	0	1.25	1.00	1.00	1.07	4.12	37	46.3	49.4
SS-65	106+80	31.0	ML		57	3	1.20	1.00	1.00	1.20	1.50	29	34.8	41.6
SS-21T	111+75	21	SC		37	0	1.20	1.00	1.00	1.20	0.77	24	28.8	34.5
SS-21T	111+75	15	SC		37	0	1.20	1.00	1.00	1.20	0.55	22	26.4	31.6
SS-39	86+67	135	SM		29	0	1.20	1.00	1.30	1.16	8.11	37	57.7	67.1
SS-17C	91+72	16.0	SM-SP		31	3	0.76	1.05	1.22	1.17	0.59	28	27.3	32.0
SS-40ML	94+22	80.0	SP		36	3	1.25	1.00	1.00	1.20	4.55	39	48.8	58.3
SS-41MFF1	98+50	19.0	SP-SM		10	3	1.31	1.00	1.00	1.06	0.81	23	30.1	31.8
SS-42L	101+80	60.0	SP-SM		31	3	1.25	1.00	1.00	1.17	3.77	38	47.5	55.7
SS-42MU	104+20	103.0	ML		57	3	1.25	1.00	1.00	1.19	6.09	43	53.8	64.2
SS-42U	101+80	109.0	ML		57	3	1.25	1.00	1.00	1.20	6.32	43	53.8	64.3
SS-43M	109+30	113.0	SM		31	3	1.25	1.00	1.00	1.17	7.47	45	56.3	66.0
SS-43MU	109+30	83.0	s(ML)		57	3	1.25	1.00	1.00	1.20	5.30	41	51.3	61.3
SS-62	91+72	32.0	SP-SM		31	3	1.20	1.00	1.29	1.17	1.70	24	37.2	43.6
SS-40	91+72	132.0	SC		36	13	1.20	1.00	1.30	1.19	7.81	38	59.3	70.7
SS-40ML	94+22	68.0	(CL)s		56	12	1.25	1.00	1.00	1.19	4.09	39	48.8	58.2
SS-42FF1	101+20	19.0	SM		20	3	1.31	1.00	1.00	1.11	0.81	24	31.4	34.9
SS-42MFF	103+50	11.0	s(CL)		60	12	1.24	1.00	1.00	1.19	0.51	22	27.3	32.5
SS-42ML	104+20	75.0	SM		31	3	1.25	1.00	1.00	1.17	4.34	40	50.0	58.6
SS-43FF3	105+90	24.0	SM		25	3	1.35	1.00	1.00	1.14	0.97	24	32.4	36.9
SS-43ML	109+30	70.0	(ML)s		57	3	1.25	1.00	1.00	1.19	4.02	39	48.8	58.2

SS-64	101+80	29.0	SP-SM		31	3	1.20	1.00	1.29	1.17	1.57	24	37.2	43.5
SS-39	86+67	146	SM		29	0	1.20	1.00	1.30	1.16	8.52	39	60.8	70.6
SS-21T	111+75	18	SC		37	0	1.20	1.00	1.00	1.19	0.66	25	30.0	35.8
SS-40L	91+72	74.0	SC	SC	32	11	1.25	1.00	1.00	1.18	4.24	40	50.0	58.8
SS-41FF2	95+90	16.0	SM		40	3	1.29	1.00	1.00	1.19	0.71	24	31.0	36.9
SS-41MFF2	98+44	11.0	SM/SC		30	3	1.24	1.00	1.00	1.16	0.71	25	31.0	36.1
SS-42ML	104+20	77.0	(ML)s		57	3	1.25	1.00	1.00	1.19	4.43	41	51.3	61.1
SS-43FF3	105+90	16.0	SM		25	3	1.29	1.00	1.00	1.14	0.71	24	31.0	35.2
SS-43MFF	108+40	16.0	SC		30	13	1.29	1.00	1.00	1.16	0.63	23	29.7	34.5
SS-40MU	94+22	110.0	SP-SM		31	3	1.25	1.00	1.00	1.17	6.67	47	58.8	68.7
SS-40U	91+72	113.0	SM		31	3	1.25	1.00	1.00	1.17	6.84	48	60.0	70.1
SS-43M	109+30	121.0	SM		31	3	1.25	1.00	1.00	1.17	7.74	49	61.3	71.6
SS-17A	91+72	11.0	SC		36	13	0.76	1.05	1.22	1.19	0.4	28	27.3	32.4
SS-40L	91+72	72.0	SC	SC-SM	37	7	1.25	1.00	1.00	1.19	4.15	42	52.5	62.5
SS-40MFF	93+46	14.0	SM/SC		40	3	1.27	1.00	1.00	1.19	0.64	25	31.8	37.7
SS-42MFF	103+50	21.0	SM		30	3	1.33	1.00	1.00	1.16	0.84	26	34.6	40.2
SS-43	106+80	115.0	SM		31	3	1.20	1.00	1.30	1.17	6.78	39	60.8	71.1
SS-43	106+80	124.0	s(ML)		57	3	1.20	1.00	1.30	1.19	7.21	40	62.4	74.2
SS-43FF3	105+90	26.0	SM		20	3	1.36	1.00	1.00	1.11	1.08	27	36.7	40.7
SS-62	91+72	26.0	SM		31	3	1.20	1.00	1.30	1.17	1.47	26	40.6	47.3
SS-40MU	94+22	108.0	SM		31	3	1.25	1.00	1.00	1.17	6.57	50	62.5	72.9
SS-41MUA	99+33	98.0	SM/SC	SC	33	10	1.25	1.00	1.00	1.18	6.07	48	60.0	70.7
SS-42FF2	101+20	16.0	SM/SC		20	3	1.29	1.00	1.00	1.11	0.68	26	33.5	37.1
SS-43MFF	108+40	11.0	SM		20	3	1.24	1.00	1.00	1.11	0.44	24	29.8	32.9
SS-43MU	109+30	86.0	s(ML)		57	3	1.25	1.00	1.00	1.19	5.39	47	58.8	69.8
SS-43U	106+80	98.0	s(ML)		57	3	1.25	1.00	1.00	1.19	5.92	48	60.0	71.3
SS-39U	86+67	110.5	ML		57	0	1.25	1.00	1.00	1.19	6.41	50	62.5	74.2
SS-44U	111+67	77.5	SM		29	0	1.25	1.00	1.00	1.16	5.12	47	58.8	67.9
SS-20	106+70	6.0	SM-SP		31	3	0.68	1.05	1.21	1.16	0.22	29	25.1	29.2
SS-20	106+70	11.0	CL		56	12	0.76	1.05	1.24	1.19	0.40	30	29.7	35.2
SS-40	91+72	135.0	SC		36	13	1.20	1.00	1.30	1.19	7.91	43	67.1	79.6
SS-41MFF1	98+50	24.0	SM		30	3	1.35	1.00	1.00	1.16	0.96	28	37.8	43.8

SS-41MFF1	98+50	26.0	SM		35	3	1.36	1.00	1.00	1.19	1.08	28	38.1	45.2
SS-42L	101+80	75.0	ML		57	3	1.25	1.00	1.00	1.19	4.32	45	56.3	66.8
SS-42M	104+20	115.0	SM		31	3	1.20	1.00	1.00	1.17	6.96	53	63.6	74.2
SS-39U	86+67	105.5	ML		57	0	1.25	1.00	1.00	1.19	6.22	50	62.5	74.2
SS-39	86+67	132	SM		29	0	1.20	1.00	1.30	1.16	8	43	67.1	77.5
SS-39U	86+67	113	ML		57	0	1.25	1.00	1.00	1.19	6.5	51	63.8	75.7
SS-39U	86+67	115.5	SM		29	0	1.25	1.00	1.00	1.16	6.59	51	63.8	73.6
SS-17C	91+72	11.0	SC		36	13	0.76	1.05	1.24	1.19	0.40	30	29.7	35.2
SS-40U	91+72	105.0	ML		57	3	1.25	1.00	1.00	1.19	6.56	52	65.0	77.1
SS-43ML	109+30	72.0	(ML)s		57	3	1.25	1.00	1.00	1.19	4.11	46	57.5	68.2
SS-43U	106+80	93.0	s(ML)		57	3	1.25	1.00	1.00	1.19	5.73	50	62.5	74.1
SS-64	101+80	35.0	SM		31	3	1.20	1.00	1.30	1.16	1.83	29	45.2	52.7
SS-20	106+70	16.0	CL		56	12	0.76	1.05	1.27	1.18	0.59	34	34.5	40.8
SS-40MFF	93+46	16.0	SM/SC		40	3	1.29	1.00	1.00	1.18	0.73	28	36.1	42.8
SS-43	106+80	121.0	SM		31	3	1.20	1.00	1.30	1.16	7.15	43	67.1	78.1
SS-43FF3	105+90	14.0	SM		30	3	1.27	1.00	1.00	1.16	0.63	28	35.6	41.1
SS-43MFF	108+40	21.0	SM		15	3	1.33	1.00	1.00	1.08	0.80	28	37.2	40.2
SS-43U	106+80	101.0	SM	SC	24	8	1.25	1.00	1.00	1.13	6.01	52	65.0	73.3
SS-39	86+67	138	SM		29	0	1.20	1.00	1.30	1.15	8.22	45	70.2	81.0
SS-39U	86+67	93	SC		37	0	1.25	1.00	1.00	1.18	5.76	52	65.0	77.0

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
5 th Bin														
SS-20	106+70	8.0	CL		56	12	0.68	1.05	1.23	1.18	0.29	33	29.0	34.3
SS-42L	101+80	68.0	SM		31	3	1.25	1.00	1.00	1.16	4.04	48	60.0	69.7
SS-42L	101+80	70.0	SM		31	3	1.25	1.00	1.00	1.16	4.14	48	60.0	69.8
SS-17D	91+72	16.0	ML		57	3	0.76	1.05	1.28	1.18	0.59	35	35.8	42.3
SS-41MFF2	98+44	21.0	SM/SC		30	3	1.33	1.00	1.00	1.16	1.12	33	43.9	50.7
SS-41ML	99+25	79.0	SC/SM	SC-SM	33	4	1.25	1.00	1.00	1.17	4.51	50	62.5	73.3
SS-42FF1	101+20	14.0	SP-SC		10	13	1.27	1.00	1.00	1.05	0.61	29	36.8	38.7
SS-42FF1	101+20	24.0	SM/SC		20	3	1.35	1.00	1.00	1.10	0.96	31	41.9	46.2
SS-43FF3	105+90	11.0	SM		35	3	1.24	1.00	1.00	1.18	0.54	29	36.0	42.5
SS-43FF3	105+90	19.0	SM		15	3	1.31	1.00	1.00	1.08	0.77	30	39.3	42.4
SS-64	101+80	23.0	SM		31	3	1.20	1.00	1.30	1.16	1.37	29	45.2	52.5
SS-16	86+30	21	SM-SW		25	0	0.76	1.05	1.30	1.13	0.77	38	39.4	44.5
SS-18	96+68	21.0	SM		31	3	0.76	1.05	1.30	1.16	0.77	38	39.4	45.7
SS-40L	91+72	69.0	SP	SC	47	8	1.25	1.00	1.00	1.18	4.06	49	61.3	72.4
SS-40MFF	93+46	19.0	SM		15	3	1.31	1.00	1.00	1.08	0.82	31	40.6	43.8
SS-42ML	104+20	65.0	SC		36	13	1.25	1.00	1.00	1.18	3.97	49	61.3	72.4
SS-43L	106+80	63.0	SC		36	13	1.25	1.00	1.00	1.18	3.84	49	61.3	72.4
SS-63	96+77	31.0	SC/SP	SC	34	9	1.20	1.00	1.00	1.18	1.49	40	48.0	56.4
SS-42MFF	103+50	14.0	s(CL)		60	12	1.27	1.00	1.00	1.18	0.57	30	38.1	44.9
SS-42U	101+80	111.0	ML		57	3	1.25	1.00	1.00	1.18	6.41	57	71.3	84.2
SS-21	111+63	21	SC		37	0	0.76	1.05	1.30	1.18	0.77	40	41.5	48.9
SS-41MFF2	98+44	19.0	SM		30	3	1.31	1.00	1.00	1.15	1.04	35	45.9	52.9
SS-41U	96+72	113.0	SM		31	3	1.25	1.00	1.00	1.16	6.69	59	73.8	85.5
SS-41MU	99+25	107.0	ML		57	3	1.25	1.00	1.00	1.18	6.61	60	75.0	88.5
SS-42FF1	101+20	11.0	SP-SM		10	3	1.24	1.00	1.00	1.05	0.53	32	39.7	41.7
SS-44U	111+67	97.5	SM		29	0	1.25	1.00	1.00	1.15	5.85	59	73.8	84.7
SS-17D	91+72	21.0	CL		56	12	0.76	1.05	1.30	1.18	0.77	42	43.6	51.3

SS-20	106+70	21.0	SC		36	13	0.76	1.05	1.30	1.18	0.77	42	43.6	51.3
SS-41FF2	95+90	24.0	SM/SC		30	3	1.35	1.00	1.00	1.15	1.00	35	47.3	54.4
SS-41M	99+22	141.0	SP		36	3	1.20	1.00	1.00	1.18	7.78	67	80.4	94.8
SS-42FF1	101+20	16.0	SM		20	3	1.29	1.00	1.00	1.10	0.72	33	42.6	46.9
SS-43MFF	108+40	14.0	SC		30	13	1.27	1.00	1.00	1.15	0.54	32	40.6	46.8
SS-40U	91+72	95.0	SC		36	13	1.25	1.00	1.00	1.18	6.19	61	76.3	89.9
SS-42U	101+80	106.0	ML		57	3	1.25	1.00	1.00	1.18	6.23	61	76.3	89.9
SS-43FF3	105+90	21.0	SM		20	3	1.33	1.00	1.00	1.10	0.89	35	46.6	51.2
SS-43MFF	108+40	19.0	SM		15	3	1.31	1.00	1.00	1.08	0.69	33	43.2	46.5
SS-43MU	109+30	93.0	SM		31	3	1.25	1.00	1.00	1.16	5.67	60	75.0	86.8
SS-41M	99+22	124.0	ML		57	3	1.20	1.00	1.00	1.18	7.44	68	81.6	96.1
SS-41M	99+22	127.0	SP-SM		31	3	1.20	1.00	1.00	1.16	7.44	68	81.6	94.4
SS-42U	101+80	96.0	SC/SM		31	3	1.25	1.00	1.00	1.16	5.86	61	76.3	88.3
SS-43FF3	105+90	9.0	SM		25	3	1.20	1.00	1.00	1.12	0.43	33	39.6	44.5
SS-62	91+72	23.0	SM		31	3	1.20	1.00	1.30	1.16	1.39	34	53.0	61.3
SS-63	96+77	28.0	SC		36	13	1.20	1.00	1.00	1.18	1.39	45	54.0	63.5
SS-40L	91+72	64.0	ML	SC	40	9	1.25	1.00	1.00	1.18	3.87	56	70.0	82.4
SS-40M	94+20	135.0	SM/SC		31	3	1.20	1.00	1.00	1.16	7.52	70	84.0	97.2
SS-42	101+70	121.0	SM		31	3	1.20	1.00	1.00	1.16	7.05	68	81.6	94.4
SS-42MU	104+20	106.0	ML		57	3	1.25	1.00	1.00	1.18	6.18	63	78.8	92.7
SS-42ML	104+20	62.0	SC		36	13	1.25	1.00	1.00	1.18	3.88	57	71.3	83.8
SS-39U	86+67	95.5	SC		37	0	1.25	1.00	1.00	1.18	5.86	65	81.3	95.5

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	C _F	σ' _v (tsf)	N	N ₆₀	N _{60,cs}
			Field	Lab										
6 th Bin														
SS-42FF2	101+20	21.0	SP-SM		10	3	1.33	1.00	1.00	1.05	0.86	37	49.2	51.7
SS-17C	91+72	21.0	CL		56	12	0.76	1.05	1.30	1.17	0.74	46	47.7	56.0
SS-43	106+80	118.0	SM		31	3	1.20	1.00	1.30	1.15	6.80	55	85.8	99.1
SS-43MU	109+30	96.0	SM		31	3	1.25	1.00	1.00	1.15	5.63	66	82.5	95.2
SS-63	96+77	25.0	SC		36	13	1.20	1.00	1.00	1.17	1.28	47	56.4	66.2
SS-43MU	109+30	98.0	SM		31	3	1.25	1.00	1.00	1.15	6.04	67	83.8	96.7
SS-43L	106+80	73.0	SP-SM		31	3	1.25	1.00	1.00	1.15	4.24	63	78.8	90.8
SS-40L	91+72	62.0	ML		62	3	1.25	1.00	1.00	1.17	3.60	62	77.5	90.9
SS-65	106+80	25.0	SM		31	3	1.20	1.00	1.00	1.15	1.29	50	60.0	69.1
SS-43MFF	108+40	24.0	SM		15	3	1.35	1.00	1.00	1.07	0.89	41	55.4	59.4
SS-43U	106+80	88.0	SM		31	3	1.25	1.00	1.00	1.15	5.46	70	87.5	100.8
SS-18	96+68	11.0	CL		56	12	0.76	1.05	1.30	1.17	0.39	44	45.6	53.4
SS-42FF2	101+20	14.0	SM/SC		20	3	1.27	1.00	1.00	1.10	0.58	41	52.1	57.1
SS-43ML	109+30	62.0	SM		31	3	1.25	1.00	1.00	1.15	3.90	66	82.5	95.0
SS-39U	86+67	118	SM		29	0	1.25	1.00	1.00	1.14	7.76	79	98.8	112.8
SS-42MU	104+20	93.0	ML		57	3	1.25	1.00	1.00	1.17	5.80	79	98.8	115.4
SS-40MFF	93+46	21.0	SM/SC		40	3	1.33	1.00	1.00	1.17	0.88	48	63.8	74.5
SS-41MFF2	98+44	16.0	SM		30	3	1.29	1.00	1.00	1.14	0.96	51	65.8	75.2
SS-39U	86+67	98	SC		37	0	1.25	1.00	1.00	1.17	7.16	85	106.3	124.2
SS-41MFF1	98+50	21.0	SM		30	3	1.33	1.00	1.00	1.14	0.88	49	65.2	74.4
SS-42	101+70	119.0	SM		31	3	1.20	1.00	1.00	1.15	7.17	88	105.6	121.4
SS-41MU	99+25	109.0	ML		57	3	1.25	1.00	1.00	1.17	6.75	85	106.3	124.1
SS-41M	99+22	136.0	SM		31	3	1.20	1.00	1.00	1.15	7.79	93	111.6	128.2
SS-42L	101+80	63.0	SM		31	3	1.25	1.00	1.00	1.15	3.90	78	97.5	111.9
SS-43U	106+80	96.0	s(ML)		57	3	1.25	1.00	1.00	1.17	5.73	88	110.0	128.3
SS-41M	99+22	133.0	SM		31	3	1.20	1.00	1.00	1.15	7.55	98	117.6	134.9
SS-43FF2	105+90	14.0	SC		40	13	1.27	1.00	1.00	1.16	0.61	54	68.6	79.7
SS-39U	86+67	103	ML		57	0	1.25	1.00	1.00	1.17	7.72	98	122.5	142.8

Table B-3: Summary Table of SPT at the Left Reach of Perris Dam, Deep Alluvium for All Density Bins

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
1 st Bin														
SS-65	106+80	41.0	SM	SC-SM	29	6	1.2	1	1	17	20.4	1.9	1.21	24.6
SS-42ML	104+20	80.0	SM	SC-SM	31	6	1.25	1	1	23	28.8	4.5	1.22	35.1
SS-40MU	94+22	135.0	SM	SC	33	9	1.25	1	1	28	35.0	7.6	1.24	43.3
SS-42MFF	103+50	29.0	SC/SM	SC-SM	38	6	1.38	1	1	14	19.3	1.1	1.24	23.9
SS-63	96+77	56.0	SM		31	3	1.2	1	1	21	25.2	2.4	1.21	30.5
SS-43FF3	105+90	39.0	SM	SC-SM	32	6	1.4	1	1	16	22.4	1.5	1.21	27.1
SS-44U	111+67	107.5	SM	SC	30	0	1.25	1	1	29	36.3	6.1	1.21	43.7
SS-41U	96+72	131.0	ML	SC	47	7	1.25	1	1	31	38.8	7.4	1.24	48.1
SS-43ML	109+30	77.0	ML	SC-SM	33	7	1.25	1	1	26	32.5	4.3	1.22	39.7
SS-42MFF	103+50	36.0	SM	SC	35	8	1.4	1	1	16	22.4	1.4	1.23	27.5
SS-41	96+72	161.0	s(ML)	CL	55	15	1.2	1	1.3	27	42.1	8.4	1.24	52.1
SS-41ML	99+25	99.0	SP-SM		31	3	1.25	1	1	29	36.3	5.3	1.21	43.7
SS-43M	109+30	138.0	SM	SC-SM	29	5	1.25	1	1	34	42.5	8.4	1.20	50.8
SS-40MU	94+22	130.0	ML	SC-SM	41	6	1.25	1	1	33	41.3	7.4	1.23	50.9
SS-21T	111+75	27	SP-SM		25	3	1.2	1	1	18	21.6	1.0	1.16	25.0
SS-41	96+72	151.0	SP	SM	25	0	1.2	1	1.3	28	43.7	8.3	1.17	51.0
SS-21	111+63	36	CL		58	12	0.76	1.05	1.2	25	23.9	1.3	1.22	29.2
SS-21	111+63	26	SM		29	3	0.76	1.05	1.18	23	21.7	1.0	1.18	25.6
SS-41MU	99+25	122.0	ML	CL	52	14	1.25	1	1	34	42.5	7.2	1.23	52.3
SS-43FF2	105+90	29.0	SM	SC-SM	26	7	1.38	1	1	17	23.5	1.1	1.16	27.3
SS-39	86+67	161	ML		57		1.2	1	1.3	30	46.8	9.0	1.23	57.6
SS-43	106+80	131.0	s(ML)		57	3	1.2	1	1.3	29	45.2	7.6	1.23	55.5
SS-43M	109+30	131.0	SM	SC-SM	35	5	1.25	1	1	37	46.3	8.1	1.23	56.8
SS-41MU	99+25	129.0	(ML)s	SM	35	0	1.25	1	1	36	45.0	7.4	1.23	55.2
SS-43	106+80	136.0	SM		31	3	1.2	1	1.3	29	45.2	7.5	1.20	54.3
SS-42FF2	101+20	34.0	SM	SC	38	9	1.4	1	1	18	25.2	1.3	1.22	30.6
SS-41U	96+72	126.0	ML	SC	48	9	1.25	1	1	36	45.0	7.2	1.23	55.1

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,CS}
			Field	Lab										
1 st Bin														
SS-39U	86+67	130.5	ML	SM	42		1.25	1	1	36	45.0	7.1	1.23	55.1
SS-41M	99+22	146.0	SM/ML	SC-SM	33	6	1.2	1	1	40	48.0	8.3	1.21	58.2
SS-40U	91+72	125.0	ML	SC	32	10	1.25	1	1	37	46.3	7.3	1.20	55.7
SS-42	101+70	151.0	SP-SM	SM	20	3	1.2	1	1	40	48.0	8.1	1.13	54.1
SS-41ML	99+25	94.0	(ML)s	SC-SM	48	6	1.25	1	1	33	41.3	5.1	1.22	50.4
SS-40	91+72	151.0	SW		36	3	1.2	1	1.3	31	48.4	8.1	1.22	59.2
SS-40L	91+72	106.5	ML/CL		58		1.25	1	1	34	42.5	5.4	1.22	51.9
SS-43M	109+30	128.0	SM	SC	34	8	1.25	1	1	39	48.8	8.0	1.22	59.3
SS-39	86+67	171	SM		29		1.2	1	1.3	33	51.5	9.4	1.18	61.0
SS-42	101+70	141.0	SC	SC	46	11	1.2	1	1	41	49.2	8.0	1.22	60.1

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,CS}
			Field	Lab										
2 nd Bin														
SS-42FF1	101+20	26.0	SM/SC	SC	32	13	1.36	1	1	19	25.8	1.1	1.19	30.8
SS-40M	94+20	151.0	SM	SC	45	14	1.2	1	1	43	51.6	8.6	1.21	62.2
SS-63	96+77	41.0	SP-SM	SC	42	10	1.2	1	1	26	31.2	1.9	1.21	37.7
SS-42L	101+80	95.0	ML	SC	47	8	1.25	1	1	35	43.8	5.1	1.21	52.7
SS-42U	101+80	116.0	ML	SC-SM	31	6	1.25	1	1	39	48.8	6.6	1.18	57.5
SS-40U	91+72	120.0	ML		57	3	1.25	1	1	40	50.0	7.1	1.20	60.2
SS-42	101+70	146.0	SM	SC	38	11	1.2	1	1	44	52.8	8.3	1.20	63.5
SS-44U	111+67	127.5	SM		29		1.25	1	1	40	50.0	7.0	1.17	58.4
SS-44U	111+67	122.5	SM	SC	31		1.25	1	1	40	50.0	6.8	1.18	59.0
SS-20	106+70	26.0	SM		31	3	0.76	1.05	1.22	27	26.3	1.0	1.18	31.1
SS-40L	91+72	79.0	SC	SC	24	16	1.25	1	1	35	43.8	4.4	1.14	49.8
SS-44U	111+67	117.5	SM		29		1.25	1	1	40	50.0	6.6	1.17	58.4
SS-40M	94+20	161.0	SP-SM	SC	31	13	1.2	1	1	46	55.2	8.8	1.18	65.1
SS-42M	104+20	146.0	SM		31	3	1.2	1	1	45	54.0	7.9	1.18	63.6
SS-41MU	99+25	124.0	ML	SC	48	9	1.25	1	1	42	52.5	7.3	1.20	63.1
SS-43M	109+30	136.0	SM		31	3	1.25	1	1	44	55.0	8.3	1.18	64.8
SS-44U	111+67	103.5	SC		37		1.25	1	1	40	50.0	6.1	1.20	60.0
SS-43FF3	105+90	34.0	SM		30	3	1.4	1	1	22	30.8	1.3	1.17	36.1
SS-41L	96+72	86.0	SM		31	3	1.25	1	1	38	47.5	4.8	1.18	55.9
SS-42MFF	103+50	34.0	SC/SM		35	3	1.4	1	1	22	30.8	1.3	1.20	37.0
SS-41ML	99+25	82.0	SP-SM		31	3	1.25	1	1	38	47.5	4.6	1.18	55.9
SS-41MFF1	98+50	29.0	SM		30	3	1.38	1	1	22	30.4	1.2	1.17	35.6
SS-41U	96+72	116.0	ML		57	3	1.25	1	1	44	55.0	6.8	1.20	65.8
SS-41ML	99+25	84.0	SP		36	3	1.25	1	1	39	48.8	4.7	1.20	58.4
SS-43ML	109+30	92.0	SC		36	13	1.25	1	1	40	50.0	4.9	1.20	59.8
SS-40U	91+72	115.0	SM		31	3	1.25	1	1	45	56.3	6.9	1.17	66.0
SS-43FF3	105+90	31.0	SM		20		1.39	1	1	23	32.0	1.2	1.11	35.6
SS-40MU	94+22	125.0	ML		57	3	1.25	1	1	46	57.5	7.2	1.20	68.7
SS-43MFF	108+40	29.0	SM		20		1.38	1	1	22	30.4	1.0	1.11	33.8
SS-43L	106+80	76.0	SM		31	3	1.25	1	1	39	48.8	4.3	1.17	57.2

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,CS}
			Field	Lab										
2 nd Bin														
SS-42L	101+80	80.0	ML		57	3	1.25	1	1	40	50.0	4.5	1.20	59.8
SS-39	86+67	151	SM		29		1.2	1	1.3	40	62.4	8.7	1.16	72.4
SS-42M	104+20	151.0	SM		31	3	1.2	1	1	51	61.2	7.9	1.17	71.7
SS-42U	101+80	114.0	ML		57	3	1.25	1	1	46	57.5	6.5	1.19	68.6
SS-39U	86+67	145.5	ML		57		1.25	1	1	49	61.3	7.7	1.19	73.1
SS-42M	104+20	136.0	SM		31	3	1.2	1	1	51	61.2	7.6	1.17	71.7
SS-40U	91+72	130.0	ML		57	3	1.25	1	1	49	61.3	7.5	1.19	73.1
SS-41L	96+72	101.0	(ML)s		57	3	1.25	1	1	44	55.0	5.3	1.19	65.6
SS-40L	91+72	101.5	SC		37		1.25	1	1	44	55.0	5.3	1.19	65.6
SS-43U	106+80	108.0	SM		31	3	1.25	1	1	47	58.8	6.3	1.17	68.8
SS-41L	96+72	96.0	(ML)s		57	3	1.25	1	1	44	55.0	5.2	1.19	65.6
SS-39	86+67	166	ML		57		1.2	1	1.3	43	67.1	9.3	1.19	79.9
SS-65	106+80	51.0	(SM)g		31	3	1.2	1	1	35	42.0	2.2	1.17	49.2
SS-42L	101+80	83.0	ML		57	3	1.25	1	1	43	53.8	4.6	1.19	64.1
SS-44U	111+67	101	SC		37		1.25	1	1	47	58.8	6.0	1.19	70.0
SS-41U	96+72	121.0	ML		57	3	1.25	1	1	49	61.3	6.8	1.19	73.0
SS-43FF3	105+90	36.0	SM		30	3	1.4	1	1	26	36.4	1.4	1.17	42.4
SS-41M	99+22	151.0	SM/ML		31	3	1.2	1	1	55	66.0	8.3	1.17	77.1
SS-40MU	94+22	120.0	ML		57	3	1.25	1	1	50	62.5	7.0	1.19	74.4
SS-40	91+72	146.0	SM		31	3	1.2	1	1.3	43	67.1	8.4	1.17	78.4
SS-17D	91+72	36.0	CL		56	12	0.76	1.05	1.29	36	37.1	1.3	1.19	44.2
SS-16	86+30	56	CL		58		0.76	1.05	1.3	42	43.6	2.1	1.19	51.9
SS-42FF2	101+20	29.0	SM		30	3	1.38	1	1	26	35.9	1.1	1.16	41.7
SS-17	91+30	26.0	SC		36	13	0.76	1.05	1.27	34	34.5	1.0	1.19	41.0
SS-17C	91+72	26.0	SM-SP		31	3	0.76	1.05	1.27	34	34.5	1.0	1.17	40.3
SS-18	96+68	26.0	CL		56	12	0.76	1.05	1.27	34	34.5	1.0	1.19	41.0
SS-39	86+67	156	ML		57		1.2	1	1.3	44	68.6	8.9	1.19	81.7
SS-40MU	94+22	118.0	ML		57	3	1.25	1	1	51	63.8	6.9	1.19	75.8
SS-16	86+30	66	ML		57		0.76	1.05	1.3	45	46.7	2.4	1.19	55.5
SS-42ML	104+20	82.0	SC		36	13	1.25	1	1	45	56.3	4.6	1.19	66.9
SS-40L	91+72	84.0	SC	SC	24	13	1.25	1	1	45	56.3	4.6	1.13	63.6

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
3 rd Bin														
SS-42FF1	101+20	36.0	SM		20	3	1.4	1	1	28	39.2	1.4	1.11	43.5
SS-40MFF	93+46	29.0	SM		30	3	1.38	1	1	27	37.3	1.2	1.16	43.3
SS-43MU	109+30	118.0	SM		31	3	1.25	1	1	53	66.3	6.7	1.17	77.4
SS-43L	106+80	93.0	SM		31	3	1.25	1	1	48	60.0	5.0	1.17	70.1
SS-42	101+70	156.0	SP-SM		31	3	1.2	1	1	59	70.8	8.1	1.17	82.7
SS-42FF1	101+20	29.0	SM		20	3	1.38	1	1	27	37.3	1.2	1.11	41.3
SS-41MFF2	98+44	24.0	SP-SM		10	3	1.35	1	1	28	37.8	1.2	1.05	39.8
SS-43L	106+80	83.0	SC		36	13	1.25	1	1	47	58.8	4.6	1.19	69.9
SS-40	91+72	161.0	ML		57	3	1.2	1	1.3	47	73.3	8.8	1.19	87.2
SS-43M	109+30	126.0	SM		31	3	1.25	1	1	57	71.3	7.9	1.17	83.2
SS-62	91+72	41.0	SM		31	3	1.2	1	1.3	29	45.2	2.0	1.17	52.8
SS-41MFF2	98+44	39.0	SM/SC		20	3	1.4	1	1	31	43.4	1.7	1.11	48.1
SS-43M	109+30	133.0	SM		31	3	1.25	1	1	58	72.5	8.2	1.17	84.6
SS-40MFF	93+46	39.0	SP-SM		10	3	1.4	1	1	30	42.0	1.6	1.05	44.3
SS-42MFF	103+50	26.0	SC		30	13	1.36	1	1	27	36.7	1.0	1.16	42.6
SS-41ML	99+25	89.0	SC		36	13	1.25	1	1	49	61.3	4.9	1.19	72.8
SS-41M	99+22	156.0	SC		36	13	1.2	1	1	61	73.2	8.3	1.19	87.0
SS-40L	91+72	82.0	SC	SC	25	16	1.25	1	1	48	60.0	4.5	1.13	68.1
SS-42MU	104+20	113.0	(ML)s		57	3	1.25	1	1	54	67.5	6.5	1.19	80.2
SS-43ML	109+30	82.0	SC		36	13	1.25	1	1	48	60.0	4.5	1.19	71.3
SS-41FF2	95+90	44.0	SM		30	3	1.4	1	1	31	43.4	1.7	1.16	50.4
SS-42ML	104+20	92.0	SM		31	3	1.25	1	1	50	62.5	5.0	1.17	72.9
SS-42MU	104+20	108.0	SM		31	3	1.25	1	1	54	67.5	6.3	1.17	78.7
SS-43M	109+30	143.0	SC		36	13	1.25	1	1	60	75.0	8.6	1.19	89.1
SS-42FF1	101+20	39.0	SM/SC		20	3	1.4	1	1	30	42.0	1.5	1.11	46.5
SS-42L	101+80	90.0	ML		57	3	1.25	1	1	50	62.5	4.9	1.19	74.2
SS-41MFF1	98+50	46.0	SC		40	13	1.4	1	1	32	44.8	1.7	1.19	53.2
SS-62	91+72	51.0	SM/SC		31	3	1.2	1	1.3	32	49.9	2.4	1.17	58.2
SS-42U	101+80	126.0	SM		31	3	1.25	1	1	57	71.3	7.0	1.17	83.0

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
3 rd Bin														
SS-17D	91+72	26.0	SM-SW		31	3	0.76	1.05	1.29	36	37.1	1.0	1.17	43.2
SS-41FF2	95+90	26.0	SM/SC		30	3	1.36	1	1	28	38.1	1.0	1.16	44.2
SS-41MFF2	98+44	36.0	SM/SC		20	3	1.4	1	1	32	44.8	1.7	1.11	49.6
SS-40U	91+72	118.0	ML		57	3	1.25	1	1	58	72.5	7.0	1.19	86.0
SS-42MFF	103+50	39.0	SM/SC		25	3	1.4	1	1	31	43.4	1.5	1.13	49.2
SS-63	96+77	46.0	SP-SM		31	3	1.2	1	1	40	48.0	2.0	1.16	55.9
SS-42MU	104+20	121.0	SM		31	3	1.25	1	1	58	72.5	6.7	1.16	84.4
SS-21	111+63	31	SC		37		0.76	1.05	1.3	39	40.5	1.1	1.19	48.0
SS-17	91+30	31.0	SC		36	13	0.76	1.05	1.3	39	40.5	1.1	1.19	48.0
SS-17C	91+72	36.0	SC		36	13	0.76	1.05	1.3	41	42.5	1.3	1.19	50.4
SS-43MFF	108+40	31.0	SM		20	3	1.39	1	1	29	40.3	1.1	1.11	44.6
SS-42FF2	101+20	26.0	SM		30	3	1.36	1	1	29	39.4	1.0	1.16	45.7
SS-42L	101+80	85.0	ML		57	3	1.25	1	1	52	65.0	4.7	1.18	77.0
SS-43	106+80	141.0	SM		31	3	1.2	1	1.3	49	76.4	7.6	1.16	88.9
SS-39	86+67	176	SM		29		1.2	1	1.3	53	82.7	9.4	1.15	95.3
SS-41FF2	95+90	39.0	SP-SM		10	3	1.4	1	1	32	44.8	1.5	1.05	47.2
SS-42MU	104+20	110.0	ML		57	3	1.25	1	1	58	72.5	6.3	1.18	85.9
SS-43FF3	105+90	46.0	SC		30	13	1.4	1	1	34	47.6	1.8	1.16	55.1
SS-42MU	104+20	126.0	SM		31	3	1.25	1	1	60	75.0	6.9	1.16	87.2
SS-43FF2	105+90	36.0	SM/SC		30	3	1.4	1	1	32	44.8	1.4	1.16	51.9
SS-42MU	104+20	116.0	SM		31	3	1.25	1	1	60	75.0	6.6	1.16	87.2
SS-43U	106+80	106.0	SC		36	13	1.25	1	1	59	73.8	6.2	1.18	87.3
SS-41L	96+72	84.0	SM		31	3	1.25	1	1	54	67.5	4.7	1.16	78.5
SS-40ML	94+22	98.0	SC		36	13	1.25	1	1	56	70.0	5.2	1.18	82.8
SS-40ML	94+22	83.0	SP		36	3	1.25	1	1	54	67.5	4.6	1.18	79.9
SS-40MFF	93+46	36.0	SP-SM		10	3	1.4	1	1	33	46.2	1.5	1.05	48.6
SS-42FF1	101+20	34.0	SM		20	3	1.4	1	1	32	44.8	1.3	1.10	49.5
SS-41	96+72	156.0	SP		36	3	1.2	1	1.3	54	84.2	8.5	1.18	99.6

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
3 rd Bin														
SS-43MU	109+30	108.0	SM		31	3	1.25	1	1	61	76.3	6.2	1.16	88.5
SS-41MU	99+25	119.0	s(ML)		57	3	1.25	1	1	64	80.0	7.1	1.18	94.5
SS-42U	101+80	119.0	ML		57	3	1.25	1	1	63	78.8	6.7	1.18	93.1
SS-43	106+80	146.0	s(ML)		57	3	1.2	1	1.3	54	84.2	8.0	1.18	99.5
SS-43FF2	105+90	24.0	SM		20	3	1.35	1	1	31	41.9	1.0	1.10	46.2
SS-40ML	94+22	88.0	SC		36	13	1.25	1	1	57	71.3	4.8	1.18	84.2
SS-43MFF	108+40	39.0	SM		20	3	1.4	1	1	34	47.6	1.4	1.10	52.5
SS-40MFF	93+46	34.0	SM		30	3	1.4	1	1	34	47.6	1.4	1.15	55.0
SS-43U	106+80	116.0	SM		31	3	1.25	1	1	64	80.0	6.6	1.16	92.8
SS-42MFF	103+50	31.0	SC/SM		35	3	1.39	1	1	33	45.9	1.2	1.18	54.2
SS-17A	91+72	26.0	SM-SP		31	3	0.76	1.05	1.3	41	42.5	1.0	1.16	49.3
SS-41L	96+72	91.0	SC		36	13	1.25	1	1	59	73.8	5.0	1.18	87.0
SS-40M	94+20	166.0	SM		31	3	1.2	1	1	74	88.8	8.7	1.16	103.0
SS-40L	91+72	87.0	SM/SC	SC	26	12	1.25	1	1	58	72.5	4.7	1.13	82.2
SS-20	106+70	36.0	SM		31	3	0.76	1.05	1.3	46	47.7	1.3	1.16	55.3
SS-43U	106+80	113.0	SM		31	3	1.25	1	1	65	81.3	6.5	1.16	94.2
SS-42ML	104+20	87.0	SC		36	13	1.25	1	1	59	73.8	4.8	1.18	87.0
SS-43MU	109+30	106.0	SC		36	13	1.25	1	1	64	80.0	6.1	1.18	94.4
SS-39U	86+67	125.5	s(ML)		57		1.25	1	1	67	83.8	7.0	1.18	98.8
SS-42MFF	103+50	24.0	SC		30	13	1.35	1	1	32	43.2	0.9	1.15	49.8
SS-40L	91+72	111.5	SC		37	13	1.25	1	1	63	78.8	5.6	1.18	92.9
SS-64	101+80	41.0	SM		31	3	1.2	1	1.3	36	56.2	2.0	1.16	65.1

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
4 th Bin														
SS-42U	101+80	131.0	SM		31	3	1.25	1	1	69	86.3	7.2	1.16	99.9
SS-43FF2	105+90	39.0	SM/SC		30	3	1.4	1	1	37	51.8	1.5	1.15	59.7
SS-17C	91+72	41.0	SM-SP		31	3	0.76	1.05	1.3	50	51.9	1.5	1.16	60.1
SS-40L	91+72	97.0	SP-SM	SM	15	0	1.25	1	1	62	77.5	5.1	1.08	83.4
SS-43FF2	105+90	31.0	SM		20	3	1.39	1	1	35	48.7	1.2	1.10	53.6
SS-40	91+72	156.0	SW-SM		31	3	1.2	1	1.3	59	92.0	8.4	1.16	106.5
SS-43FF2	105+90	26.0	SM/SC		20	3	1.36	1	1	34	46.2	1.0	1.10	51.0
SS-20	106+70	31.0	SM		31	3	0.76	1.05	1.3	46	47.7	1.1	1.16	55.3
SS-17A	91+72	31.0	SM-SP		31	3	0.76	1.05	1.3	47	48.8	1.1	1.16	56.4
SS-41MFF1	98+50	31.0	SM		30	3	1.39	1	1	36	50.0	1.2	1.15	57.6
SS-43FF3	105+90	41.0	SM		25	3	1.4	1	1	39	54.6	1.6	1.13	61.5
SS-40ML	94+22	93.0	SP-SM		31	3	1.25	1	1	64	80.0	5.0	1.16	92.5
SS-43U	106+80	121.0	SM		31	3	1.25	1	1	72	90.0	6.8	1.16	104.0
SS-41MU	99+25	117.0	s(ML)		57	3	1.25	1	1	73	91.3	7.0	1.18	107.3
SS-41FF2	95+90	41.0	SM/SC		40	3	1.4	1	1	40	56.0	1.6	1.18	65.9
SS-43MFF	108+40	26.0	SC		30	13	1.36	1	1	35	47.6	1.0	1.15	54.8
SS-43MFF	108+40	36.0	SM/SC		20	3	1.4	1	1	38	53.2	1.3	1.10	58.6
SS-41MFF2	98+44	31.0	SM		30	3	1.39	1	1	40	55.6	1.5	1.15	64.0
SS-40MFF	93+46	31.0	SM/SC		30	3	1.39	1	1	38	52.8	1.3	1.15	60.8
SS-44U	111+67	112.5	SM		29		1.25	1	1	72	90.0	6.4	1.15	103.1
SS-42FF2	101+20	36.0	SM		40	3	1.4	1	1	39	54.6	1.4	1.18	64.2
SS-41FF2	95+90	31.0	SP-SM		10	3	1.39	1	1	38	52.8	1.2	1.05	55.5
SS-42FF2	101+20	31.0	SM		30	3	1.39	1	1	38	52.8	1.2	1.15	60.8
SS-39U	86+67	140.5	SM		29		1.25	1	1	77	96.3	8.6	1.15	110.3
SS-64	101+80	51.0	SM		31	3	1.2	1	1.3	42	65.5	2.3	1.16	75.7
SS-43ML	109+30	87.0	SC		36	13	1.25	1	1	66	82.5	4.7	1.17	96.9
SS-42U	101+80	121.0	ML		57	3	1.25	1	1	75	93.8	6.8	1.17	110.1
SS-39U	86+67	135.5	SM		29		1.25	1	1	78	97.5	7.3	1.14	111.6

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
4 th Bin														
SS-41MFF2	98+44	29.0	SM		30	3	1.38	1	1	41	56.6	1.4	1.15	65.0
SS-41FF2	95+90	29.0	SM/SC		30	3	1.38	1	1	39	53.8	1.1	1.15	61.8
SS-41MFF1	98+50	39.0	SC		40	13	1.4	1	1	42	58.8	1.5	1.17	69.0
SS-42FF1	101+20	31.0	SM/SC		20	3	1.39	1	1	40	55.6	1.2	1.10	61.1
SS-41U	96+72	118.0	ML		57	3	1.25	1	1	79	98.8	6.9	1.17	115.8
SS-40L	91+72	92.0	SM/SC	SC	40	13	1.25	1	1	71	88.8	4.9	1.17	104.1
SS-40MFF	93+46	26.0	SM		30	3	1.36	1	1	41	55.8	1.1	1.15	64.0
SS-64	101+80	46.0	SM		31	3	1.2	1	1.3	45	70.2	2.1	1.15	80.9
SS-18	96+68	36.0	CL		56	12	0.76	1.05	1.3	58	60.2	1.3	1.17	70.5
SS-65	106+80	46.0	SM		31	3	1.2	1	1	58	69.6	2.1	1.15	80.2

Borehole	Station	Depth (ft)	Classification		FC (%)	PI	C _E *C _R	C _B	C _S	N	N ₆₀	σ' _v (tsf)	C _F	N _{60,cs}
			Field	Lab										
5 th Bin														
SS-63	96+77	51.0	SM		31	3	1.2	1	1	59	70.8	2.1	1.15	81.5
SS-41FF2	95+90	36.0	SM		30	3	1.4	1	1	44	61.6	1.4	1.15	70.7
SS-43L	106+80	88.0	SC		36	13	1.25	1	1	75	93.8	4.8	1.17	109.7
SS-41MFF1	98+50	34.0	SM		30	3	1.4	1	1	44	61.6	1.3	1.15	70.6
SS-43FF2	105+90	34.0	SM/SC		30	3	1.4	1	1	44	61.6	1.3	1.15	70.6
SS-62	91+72	46.0	SM		31	3	1.2	1	1.3	47	73.3	2.2	1.15	84.4
SS-18	96+68	31.0	CL		56	12	0.76	1.05	1.3	58	60.2	1.1	1.17	70.4
SS-19	101+70	26.0	SC		36	13	0.76	1.05	1.3	55	57.1	1.0	1.17	66.8
SS-16	86+30	31	CL		58	12	0.76	1.05	1.3	59	61.2	1.1	1.17	71.6
SS-43MU	109+30	113.0	SM		31	3	1.25	1	1	87	108.8	6.4	1.15	124.9
SS-17	91+30	36.0	SM-SP		31	12	0.76	1.05	1.3	63	65.4	1.3	1.15	75.1
SS-42ML	104+20	97.0	SC		36	12	1.25	1	1	83	103.8	5.2	1.17	121.1
SS-16	86+30	36	CL		58	12	0.76	1.05	1.3	65	67.4	1.3	1.17	78.8
SS-17D	91+72	41.0	SM-SP		31	3	0.76	1.05	1.3	70	72.6	1.5	1.15	83.4
SS-41MFF1	98+50	36.0	SM		30	3	1.4	1	1	51	71.4	1.4	1.14	81.6
SS-41MFF2	98+44	34.0	SM		30	3	1.4	1	1	53	74.2	1.6	1.14	84.8
SS-17A	91+72	36.0	SC		36	13	0.76	1.05	1.3	68	70.5	1.3	1.17	82.3
SS-41MFF2	98+44	26.0	SM		30	3	1.36	1	1	52	70.7	1.3	1.14	80.8
SS-42FF2	101+20	39.0	SM/SC		30	3	1.4	1	1	53	74.2	1.5	1.14	84.8
SS-65	106+80	36.0	SM/SC		31	3	1.2	1	1	64	76.8	1.6	1.15	88.1
SS-17A	91+72	41.0	CL		56	12	0.76	1.05	1.3	74	76.8	1.5	1.17	89.5
SS-43MFF	108+40	34.0	SM/SC		20	3	1.4	1	1	51	71.4	1.2	1.09	78.2

Table B-4: Summary Table of SPT at the Right Reach of Perris Dam for Different Density Bins

Borehole	Station	Depth (ft)	Location	USCS Classification	FC %	$C_E * C_R$	C_B	C_S	N (bpf)	N_{60} (bpf)	σ'_v (tsf)	C_F	$N_{60,CS}$
1st Bin													
SS-7	42+30	26	Toe	ML	57	0.76	1.05	1.1	12	10.5	0.96	1.30	13.7
SS-7	42+30	6	Toe	SM-SP	38	0.68	1.05	1.1	10	7.9	0.22	1.27	10.0
SS-8	47+30	21	Toe	SM	29	0.76	1.05	1.11	14	12.4	0.77	1.22	15.1
SS-5	32+30	8	Toe	SM-SP	25	0.68	1.05	1.1	12	9.4	0.29	1.18	11.1
SS-6	37+30	4.5	Toe	SP-SM	46	0.68	1.05	1.1	11	8.6	0.17	1.26	10.9
SS-1	12+66	6	Toe	SM-SP	25	0.68	1.05	1.1	12	9.4	0.22	1.18	11.1
SS-26	22+66	81	Crest	SM	26	1.2	1	1	22	26.4	4.42	1.19	31.5
SS-8	47+30	6	Toe	SM	29	0.68	1.05	1.1	13	10.2	0.22	1.20	12.2
SS-10	56+55	11	Toe	SM-SP	25	0.76	1.05	1.13	16	14.4	0.40	1.16	16.7
SS-3	22+30	6	Toe	SM-SP	25	0.68	1.05	1.11	15	11.9	0.22	1.16	13.8
SS-9	52+30	6	Toe	SM	29	0.68	1.05	1.11	16	12.7	0.22	1.18	15.0
SS-2	17+66	26	Toe	SM	29	0.76	1.05	1.18	23	21.7	0.96	1.18	25.6
SS-29	37+70	122	Crest	SM	29	1.2	1	1.3	26	40.6	7.11	1.19	48.4
SS-7	42+30	21	Toe	ML	57	0.76	1.05	1.18	22	20.7	0.77	1.22	25.2

Borehole	Station	Depth (ft)	Location	USCS Classification	FC %	$C_E * C_R$	C_B	C_S	N (bpf)	N_{60} (bpf)	σ'_v (tsf)	C_F	$N_{60,CS}$
2nd Bin													
SS-2	17+66	16	Toe	SM	25	0.76	1.05	1.19	24	22.8	0.59	1.15	26.1
SS-32	52+30	135	Crest	ML	57	1.2	1	1	44	52.8	7.78	1.21	63.8
SS-28	32+51	104	Crest	SM	29	1.2	1	1.3	32	49.9	6.16	1.17	58.4
SS-27	27+65	88	Crest	SM	29	1.2	1	1.3	30	46.8	4.89	1.17	54.7
SS-26	22+66	76	Crest	SM/SP	25	1.2	1	1	39	46.8	4.24	1.14	53.5
SS-27	27+65	91	Crest	SP-SM	25	1.2	1	1.3	32	49.9	5.00	1.14	57.1
SS-31	47+44	126	Crest	SM	29	1.2	1	1.3	36	56.2	7.40	1.17	65.6
SS-2	17+66	21	Toe	SM	29	0.76	1.05	1.24	30	29.7	0.77	1.16	34.5
SS-28	32+51	107	Crest	SM	29	1.2	1	1.3	35	54.6	6.26	1.17	63.7
SS-26	22+66	64	Crest	SM/SP	25	1.2	1	1	44	52.8	3.79	1.14	60.1
SS-32	52+30	129	Crest	SM	29	1.2	1	1	54	64.8	7.56	1.16	75.2
SS-32	52+30	132	Crest	SM	29	1.2	1	1	60	72.0	7.68	1.16	83.3

Borehole	Station	Depth (ft)	Location	USCS Classification	FC %	$C_E * C_R$	C_B	C_S	N (bpf)	N_{60} (bpf)	σ'_v (tsf)	C_F	$N_{60,CS}$
3 rd Bin													
SS-22	17+66	59	Crest	SM	29	1.2	1	1.3	36	56.2	3.12	1.15	64.7
SS-9	52+30	21	Toe	SM-SP	25	0.76	1.05	1.3	38	39.4	0.77	1.13	44.5
SS-3	22+30	16	Toe	SM-SP	25	0.76	1.05	1.29	36	37.1	0.59	1.13	41.8
SS-26	22+66	61	Crest	SM/SP	25	1.2	1	1	52	62.4	3.68	1.13	70.5
SS-2	17+66	31	Toe	SM	29	0.76	1.05	1.3	46	47.7	1.14	1.15	54.8
SS-27	27+65	100	Crest	SP-SM	25	1.2	1	1.3	48	74.9	5.33	1.13	84.4
SS-29	37+70	116	Crest	SM	29	1.2	1	1.3	52	81.1	6.90	1.15	93.1
SS-8	47+30	11	Toe		35	0.76	1.05	1.3	38	39.4	0.40	1.17	46.3
SS-22	17+66	56	Crest	SM	29	1.2	1	1.3	43	67.1	3.00	1.15	76.9
SS-30	42+48	121	Crest	SM	29	1.2	1	1	71	85.2	7.14	1.15	97.7
SS-30	42+48	124	Crest	SM	29	1.2	1	1	73	87.6	7.26	1.15	100.4
SS-26	22+66	73	Crest	SM/SP	25	1.2	1	1	64	76.8	4.13	1.13	86.4
SS-26	22+66	67	Crest	SM/SP	25	1.2	1	1	65	78.0	3.91	1.12	87.7

Borehole	Station	Depth (ft)	Location	USCS Classification	FC %	$C_E \cdot C_R$	C_B	C_S	N (bpf)	N_{60} (bpf)	σ'_v (tsf)	C_F	$N_{60,CS}$
4 th Bin													
SS-22	17+66	50	Crest	SP-SM	25	1.2	1	1.3	47	73.3	2.78	1.12	82.3
SS-3	22+30	21	Toe	SM-SP	25	0.76	1.05	1.3	53	55.0	0.77	1.12	61.7
SS-9	52+30	11	Toe	SM-SC	37	0.76	1.05	1.3	48	49.8	0.40	1.17	58.2
SS-22	17+66	62	Crest	SM	29	1.2	1	1.3	55	85.8	3.23	1.14	97.7
SS-29	37+70	119	Crest	SM	29	1.2	1	1.3	68	106.1	7.01	1.14	120.7
SS-4	27+30	36	Toe	SM-SP	25	0.76	1.05	1.3	67	69.5	1.32	1.12	77.8
SS-22	17+66	53	Crest	SP-SM	25	1.2	1	1.3	56	87.4	2.89	1.12	97.7
SS-29	37+70	113	Crest	SM	29	1.2	1	1.3	74	115.4	6.78	1.14	131.2
SS-4	27+30	31	Toe	SM-SP	25	0.76	1.05	1.3	74	76.8	1.14	1.12	85.7
SS-26	22+66	71	Crest	SM	29	1.2	1	1	97	116.4	4.05	1.13	132.0
SS-28	32+51	101	Crest	SM	29	1.2	1	1.3	83	129.5	6.05	1.13	146.8
SS-6	37+30	7	Toe	ML	57	0.68	1.05	1.3	62	57.5	0.26	1.16	66.9
SS-4	27+30	11	Toe	SM-SP	25	0.76	1.05	1.3	83	86.1	0.40	1.11	95.7
SS-27	27+65	94	Crest	SM	29	1.2	1	1.3	106	165.4	5.11	1.13	186.7

Table B-5: Summary Table of SPT at Sunset Reservoir, North Basin for Different Density Bins (OCC, 2004)

Borehole	Soil Classification	Depth (ft)	σ'_{vo} (tsf)	Fines%		N (bpf)	C_E	C_R	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
				Field	Lab								
1 st Bin													
BV-2	SP-SC	67	3.00	0	0	13	0.92	1.00	1.00	1.00	12.0	1.00	12.0
AB-4	SM	41	2.09	40 to 45	40	6	1.20	1.00	1.05	1.00	7.6	1.47	11.1
AB-5	SP	16	0.86	0 to 5	0	6	1.20	0.95	1.05	1.00	7.2	1.00	7.2
AB-5	SM	31	1.57	65 to 70	29	6	1.20	1.00	1.05	1.00	7.6	1.35	10.2
EB-4	SP	6	0.32	0	0	4	1.33	0.75	1.05	1.20	5.0	1.00	5.0
EB-5	SM	19	0.93	0	27	4	1.33	0.95	1.05	1.20	6.4	1.31	8.4
EB-5	SM	18	0.91	0	29	4	1.33	0.95	1.05	1.20	6.4	1.34	8.5
AB-5	SP	21	1.12	0 to 5	0	8	1.20	0.95	1.05	1.00	9.6	1.00	9.6
AB-4	SP	28	1.50	0 to5	0	10	1.20	1.00	1.05	1.00	12.6	1.00	12.6
BV-6	SC	58	3.11	0	35	15	0.92	1.00	1.00	1.00	13.8	1.36	18.7
EB-4	SM	20	0.99	0	0	7	1.33	0.95	1.05	1.20	11.1	1.00	11.1
AB-5	SP	18	0.96	0 to 5	0	10	1.20	0.95	1.05	1.00	12.0	1.00	12.0
AB-5	SM	33	1.62	35 to 40	21.4	11	1.20	1.00	1.05	1.00	13.9	1.18	16.4
S-2	SM	71	2.37	20 to 25	34.8	10	1.43	1.00	1.05	1.00	15.0	1.32	19.7
EB-4	SM	19	0.97	0	35.1	6	1.33	0.95	1.05	1.20	9.6	1.32	12.6
AB-4	SM	43	2.14	30 to 35	30	12	1.20	1.00	1.05	1.00	15.1	1.26	19.1
EB-5	SM	21	0.98	0	20	7	1.33	0.95	1.05	1.20	11.1	1.17	13.0

Borehole	Soil Classification	Depth (ft)	σ'_{vo} (tsf)	Fines%		N (bpf)	C_E	C_R	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
				Field	Lab								
2 nd Bin													
AB-6	SM	58	3.11	25 to 30	No	16	1.43	1.00	1.05	1.00	24.0	1.25	30.1
S-2	SM	86	3.02	20 to 25	48.2	17	1.43	1.00	1.05	1.00	25.5	1.24	31.8
AB-6	SM	68	3.67	25 to 30	20	22	1.43	1.00	1.05	1.00	33.0	1.13	37.3
BV-2	SC	83	3.40	0	10	37	0.92	1.00	1.00	1.00	34.0	1.06	36.2
BV-6	SC	66	3.56	0	35	33	0.92	1.00	1.00	1.00	30.3	1.23	37.3
EB-4	SP	11	0.58	0	0	11	1.33	0.85	1.05	1.20	15.7	1.00	15.7
EB-5	SP	5	0.27	0	0	10	1.33	0.75	1.05	1.20	12.6	1.00	12.6
AB-5	SP	23	1.23	0 to 5	0	21	1.20	0.95	1.05	1.00	25.1	1.00	25.1
BV-2	SM	77	3.25	0	10	42	0.92	1.00	1.00	1.00	38.6	1.06	41.0
EB-4	SM	29	1.22	0	0	15	1.33	1.00	1.05	1.20	25.1	1.00	25.1
AB-6	SC/SM	61	3.28	20 to25	23.3	24	1.43	1.00	1.05	1.00	36.0	1.14	41.2
EB-4	SM	22	1.04	0	0	15	1.33	0.95	1.05	1.20	23.9	1.00	23.9
AB-6	SP	51	2.73	5 to 10	10.9	25	1.43	1.00	1.05	1.00	37.5	1.06	40.0
EB-5	SP	10	0.54	0	0	13	1.33	0.85	1.05	1.20	18.5	1.00	18.5
AB-4	SP	31	1.66	0 to5	0	26	1.20	1.00	1.05	1.00	32.8	1.00	32.8
AB-4	SP	33	1.77	0	0	27	1.20	1.00	1.05	1.00	34.0	1.00	34.0
EB-4	SM	28	1.19	0	0	17	1.33	1.00	1.05	1.20	28.5	1.00	28.5
BV-6	SP	52	2.78	0 to5	0	48	0.92	1.00	1.00	1.00	44.0	1.00	44.0
AB-5	SP-SM	28	1.50	35 to 40	8.6	25	1.20	1.00	1.05	1.00	31.5	1.05	33.1
EB-5	CL	25	1.11	0	75	14	1.33	1.00	1.05	1.20	23.5	1.22	28.6
EB-4	SM	23	1.07	0	0	19	1.33	0.95	1.05	1.20	30.2	1.00	30.2
EB-5	SP	15	0.80	0	0	17	1.33	0.95	1.05	1.20	27.1	1.00	27.1

Borehole	Soil Classification	Depth (ft)	σ'_{vo} (tsf)	Fines%		N (bpf)	C_E	C_R	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
				Field	Lab								
3 rd Bin													
BV-6	SC	61	3.28	0	35	44	0.92	1.00	1.00	1.00	40.3	1.21	48.7
AB-6	SP	56	3.00	5 to 10	5	31	1.43	1.00	1.05	1.00	46.5	1.03	47.9
BV-2	SM	74	3.17	0	10	52	0.92	1.00	1.00	1.00	47.8	1.06	50.5
AB-5	SM	41	1.87	0	14.2	30	1.20	1.00	1.05	1.00	37.8	1.08	40.8
BV-6	SP	55	2.94	0 to5	0	57	0.92	1.00	1.00	1.00	52.3	1.00	52.3
S-2	SP	76	2.50	0 to 5	0	33	1.43	1.00	1.05	1.00	49.5	1.00	49.5
EB-5	SM	22	1.01	0	19	18	1.33	0.95	1.05	1.20	28.7	1.11	31.7
EB-4	SP	16	0.84	0	0	19	1.33	0.95	1.05	1.20	30.2	1.00	30.2
AB-5	SM	36	1.72	0	14.2	32	1.20	1.00	1.05	1.00	40.3	1.08	43.5
AB-4	SP	38	2.02	0	0	39	1.20	1.00	1.05	1.00	49.1	1.00	49.1
BV-2	SP-SC	64	2.92	0	0	66	0.92	1.00	1.00	1.00	60.7	1.00	60.7
AB-5	SP	26	1.39	0 to 5	0	34	1.20	1.00	1.05	1.00	42.8	1.00	42.8
AB-4	SP	36	1.93	0	0	41	1.20	1.00	1.05	1.00	51.7	1.00	51.7
AB-5	SM	38	1.78	0	14.2	38	1.20	1.00	1.05	1.00	47.9	1.07	51.5
EB-4	SM	26	1.14	0	18.9	25	1.33	0.95	1.05	1.20	39.8	1.10	43.8
EB-4	SM	25	1.12	0	0	28	1.33	0.95	1.05	1.20	44.6	1.00	44.6

Table B-6: Summary Table of SPT at Lopez Dam, Alluvium A & B (Data from GEI,1995)

Borehole	Sample Depth (ft)	σ'_v (tsf)	USCS Classification	FC (%)	N (bpf)	C_E	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
1st Bin											
B101A	89.3	5.11	ML	90	14	0.87	1	1	12.1	1.45	17.6
B102	121.3	6.11	SM	20	18	0.87	1	1	15.6	1.23	19.2
B108A	31.3	1.52	SW	10	11	0.87	1	1	9.5	1.10	10.5
B101A	97.2	5.34	SM	30	18	0.87	1	1	15.6	1.33	20.8
B101A	93.5	5.23	SM	20	20	0.87	1	1	17.3	1.21	20.9
B108A	45.6	1.94	SW-SM	10	15	0.87	1	1	13.0	1.09	14.2
B104	49.4	2.70	SM	20	18	0.87	1	1	15.6	1.18	18.5
B102	125.4	6.23	SW, SM	12	31	0.87	1	1	26.9	1.10	29.6
B107	59.2	2.37	SM	15-40	17	0.87	1	1	14.7	1.25	18.4
B103	117.5	5.45	SM	30	27	0.87	1	1	23.4	1.26	29.6
B108A	58	2.31	SW-SM,SM	10,20	20	0.87	1	1	17.3	1.12	19.5
B101A	91.4	5.17	SM	40	27	0.87	1	1	23.4	1.30	30.5
B107	57	2.30	SM	25	21	0.87	1	1	18.2	1.20	21.9
B103	119.6	5.51	SW-SM	10	39	0.87	1	1	33.8	1.07	36.3
B101A	95.2	5.29	ML,SM,SW-SM	95,40,10	32	0.87	1	1	27.7	1.28	35.5

Borehole	Sample Depth (ft)	σ'_v (tsf)	USCS Classification	FC (%)	N (bpf)	C_E	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
2 nd Bin											
B108A	27.3	1.40	SW,SW-SM	5,10	21	0.87	1	1	18.2	1.05	19.1
B108A	25.2	1.34	SP-SW	5	22	0.87	1	1	19.1	1.00	19.1
B106	59	2.47	SM	15	27	0.87	1	1	23.4	1.11	26.0
B101A	99.3	5.41	SW-SM	10	42	0.87	1	1	36.4	1.07	39.0
B102	123.2	6.16	SM-ML	50	39	0.87	1	1	33.8	1.26	42.8
B103	125.6	5.69	SM,SW-SM	30-40,10	41	0.87	1	1	35.5	1.16	41.2
B106	45	2.05	SM	15	27	0.87	1	1	23.4	1.10	25.8
B107	63.9	2.51	SW-SM,SM,SW-SM	10,15,10-15	31	0.87	1	1	26.9	1.09	29.2
B107	61.1	2.42	SM,SM	20,10	30	0.87	1	1	26.0	1.10	28.7
B102	115.1	5.92	SW-SM	10	49	0.87	1	1	42.5	1.07	45.3
B102	102.6	5.55	SW-SM	10	50	0.87	1	1	43.3	1.06	46.2
B104	55.7	2.89	SW-SM	10	37	0.87	1	1	32.1	1.07	34.2
B108A	35.3	1.64	SW-SM	10	28	0.87	1	1	24.3	1.07	25.9
B108A	62	2.43	SW-SM	5-10	35	0.87	1	1	30.3	1.05	31.7
B107	55	2.24	SM	20	31	0.87	1	1	26.9	1.13	30.5
B108A	66.2	2.56	SW,SM	5,15	36	0.87	1	1	31.2	1.06	33.2
B106	82.1	3.16	SW-SM	10	41	0.87	1	1	35.5	1.06	37.8
B108A	55.9	2.25	SW-SM	10	36	0.87	1	1	31.2	1.06	33.2

Borehole	Sample Depth (ft)	σ'_v (tsf)	USCS Classification	FC (%)	N (bpf)	C_E	C_B	C_S	N_{60} (bpf)	C_F	$N_{60,CS}$ (bpf)
3rd Bin											
B101A	83.2	4.93	SW-SM	10	53	0.87	1	1	45.9	1.06	48.8
B104	68.3	3.27	SW-SM	10	45	0.87	1	1	39.0	1.06	41.4
B108A	60.2	2.38	SW-SM	10	39	0.87	1	1	33.8	1.06	35.9
B102	104.7	5.61	SW-SM	10	59	0.87	1	1	51.1	1.06	54.3
B103	81.8	4.38	SW-SM	10	54	0.87	1	1	46.8	1.06	49.7
B103	86.3	4.52	SW-SM	10	55	0.87	1	1	47.7	1.06	50.6
B104	45.2	2.58	SM	15	40	0.87	1	1	34.7	1.09	37.9
B104	53.6	2.83	SM	15	44	0.87	1	1	38.1	1.09	41.6
B104	62.4	3.09	SP	5	50	0.87	1	1	43.3	1.00	44.6
B104	66.4	3.21	SW-SM	15	47	0.87	1	1	40.7	1.09	44.5
B106	65.1	2.65	SM	15	43	0.87	1	1	37.3	1.09	40.7
B106	73.2	2.90	SM	15	45	0.87	1	1	39.0	1.09	42.6
B107	45.1	1.95	SW-SM	10-15	39	0.87	1	1	33.8	1.07	36.3
B108A	41.3	1.81	SW-SM	10-15	38	0.87	1	1	32.9	1.07	35.2
B104	41.1	2.46	SP-SM	10	48	0.87	1	1	41.6	1.06	43.9
B106	57.3	2.42	SM,SW-SM	35,15	44	0.87	1	1	38.1	1.14	43.6
B106	61	2.53	SW-SM	10	49	0.87	1	1	42.5	1.06	44.9

Appendix C:
Field SPT Hammer Calibration Borings Data

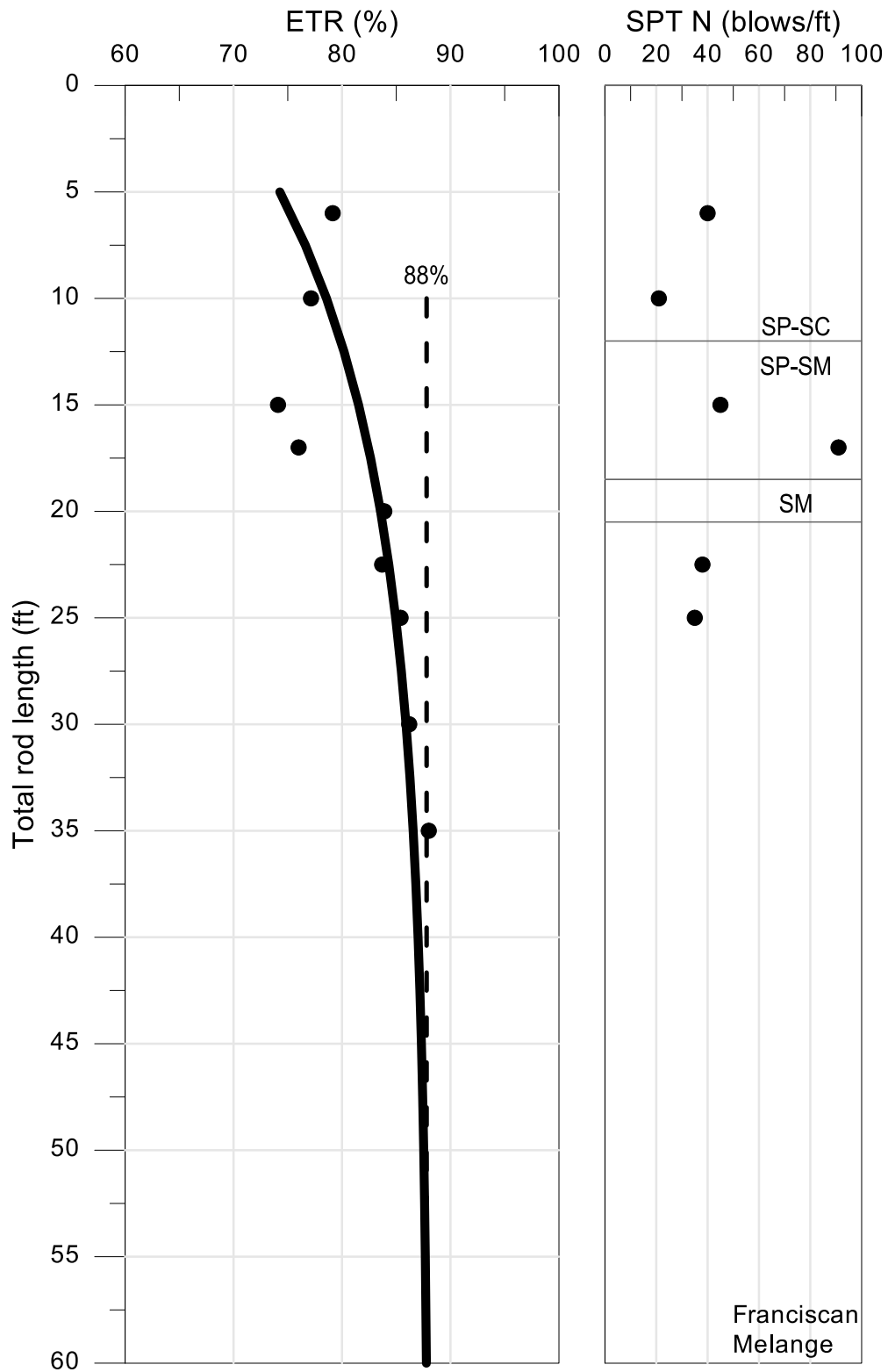


Figure C-1: ETR and Stratigraphy for Boring C1

Table C-1: Rod Lengths and Summary of Hammer Energy Measurements for C1

Hammer Type Automatic
Drill Rig Type Diedrich D-120
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	2	40	6	40	277	79.1	4	28.6
2	6	21	10	10	270	77.1	2.8	22.4
3	11	45	15	6	259	74.1	9.3	23.1
4	13	91	17	17	266	76.0	4.9	26.1
5	16		20	28	294	83.9	4.6	30.5
6	19	38	23	70	293	83.7	4.9	29.1
7	21	35	25	90	299	85.4	3.4	29.7
8	26		30	53	302	86.2	6	29.4
9	31		35	117	308	88.0	4.1	29.4

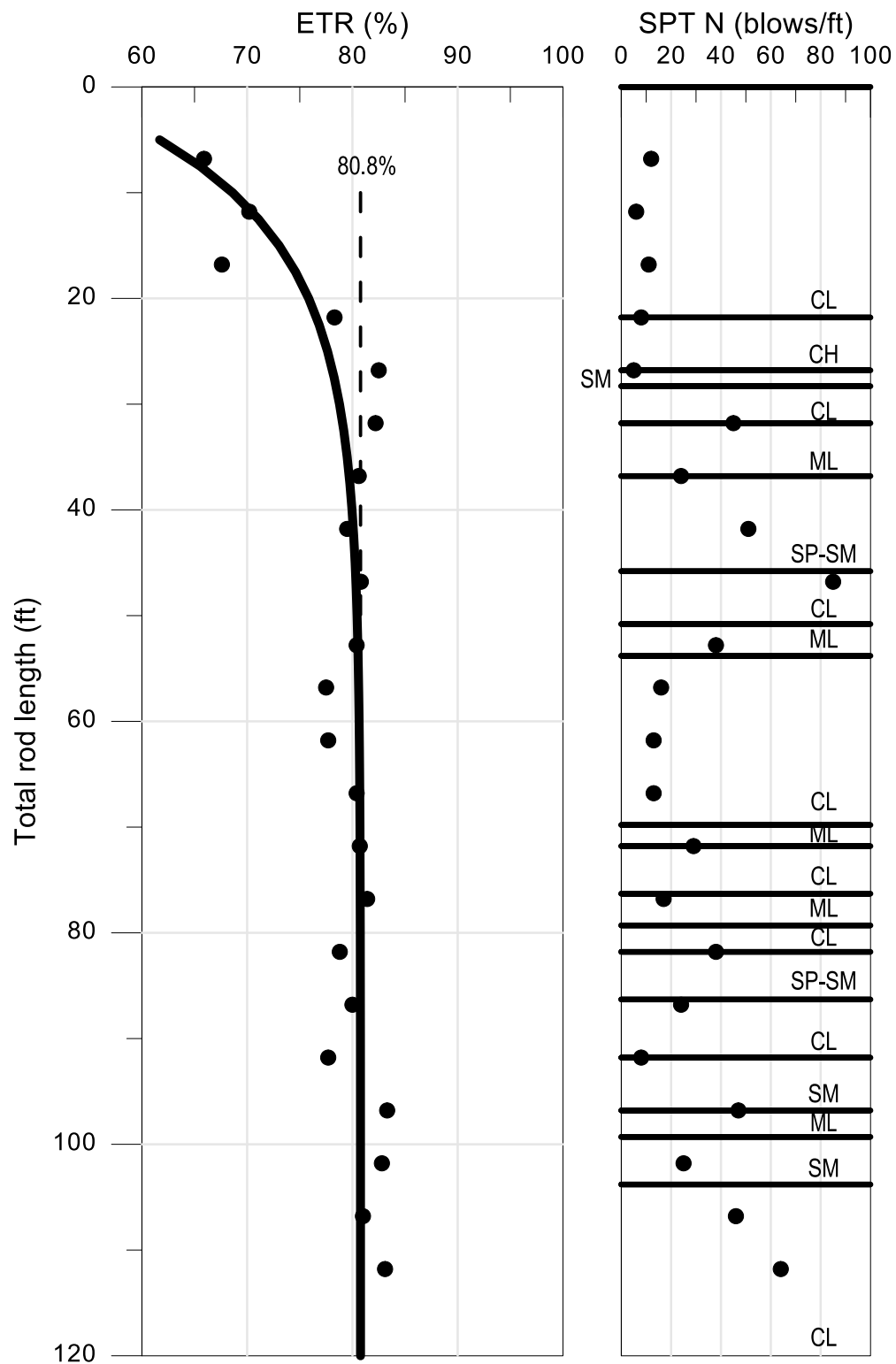


Figure C-2: ETR and Stratigraphy for Boring C2

Table C-2: Rod Lengths and Summary of Hammer Energy Measurements for C2

Hammer Type Automatic
Drill Rig Type Mobile B-80
Rod Type NW rod

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	0	12	6.8	18	231	65.9	2.0	34.5
2	5	6	11.8	8	246	70.2	2.8	43.8
3	10	11	16.8	12	237	67.6	2.7	34.7
4	15	8	21.8	9	274	78.3	0.9	51.9
5	20	5	26.8	7	289	82.5	2.8	49.4
6	25	45	31.8	53	288	82.2	1.6	52.7
7	30	24	36.8	32	282	80.6	1.0	48.3
8	35	51	41.8	69	278	79.5	1.8	49.3
9	40	85	46.8	98	283	80.8	1.2	49.1
10	45	38	52.8	49	281	80.4	0.9	52
11	50	16	56.8	22	271	77.5	14.3	58.3
12	55	13	61.8	13	272	77.7	10.8	60.8
13	60	13	66.8	22	281	80.4	1.0	55.2
14	65	29	71.8	41	282	80.7	1.6	52
15	70	17	76.8	22	285	81.4	0.9	50.8
16	75	38	81.8	55	276	78.8	1.0	49.3
17	80	24	86.8	30	280	80	1.0	48.7
18	85	8	91.8	11	272	77.7	9.4	57.1
19	90	47	96.8	66	292	83.3	1.5	49.7
20	95	25	101.8	37	290	82.8	1.3	52.7
21	100	46	106.8	60	284	81	1.3	53.4
22	105	64	111.8	78	291	83.1	1.4	50.6

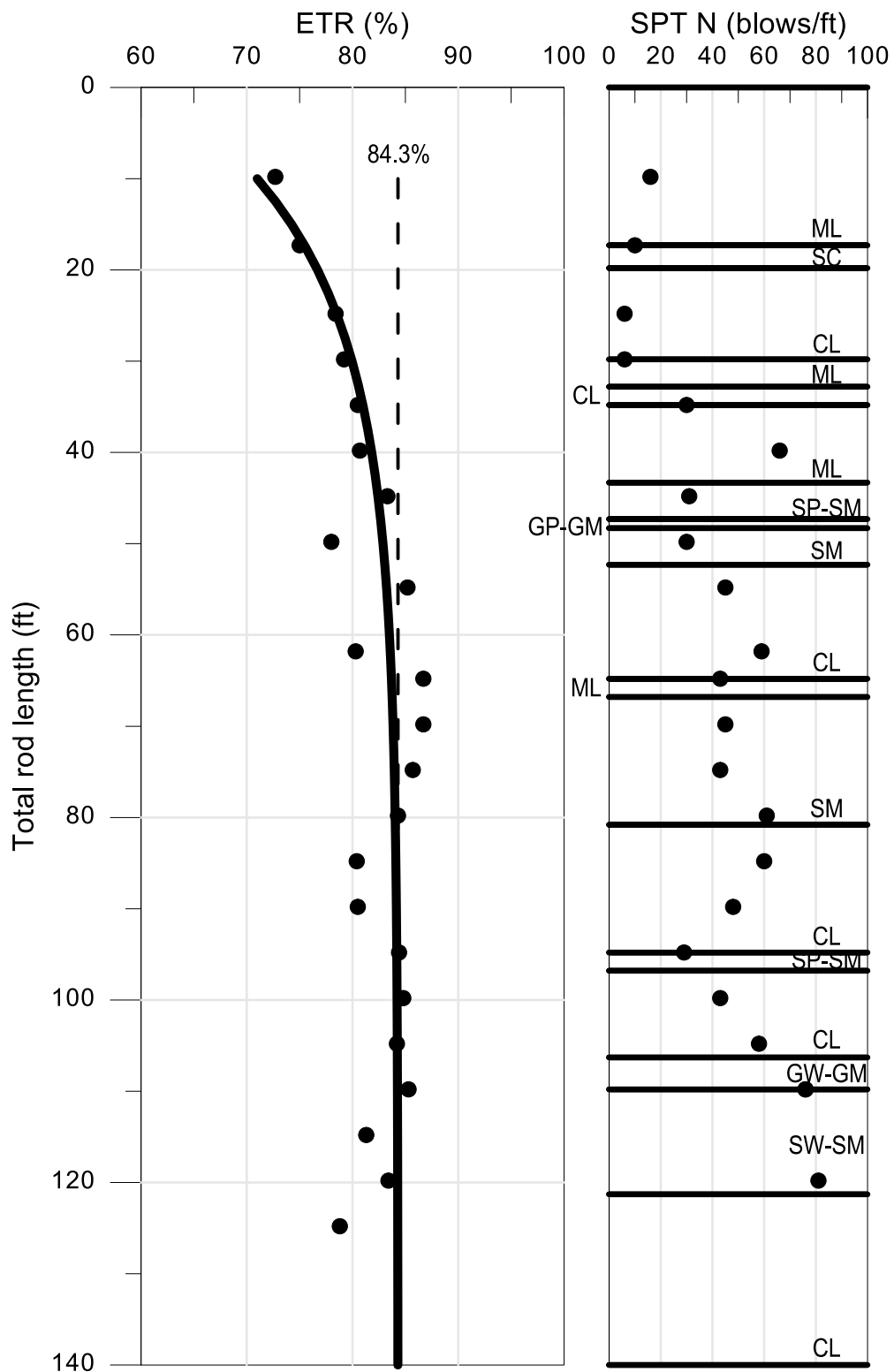


Figure C-3: ETR and Stratigraphy for Boring C3

Table C-3: Rod Lengths and Summary of Hammer Energy Measurements for C3**Hammer Type** Automatic**Drill Rig Type** Fraste Multi Drill XL**Rod Type** NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	16	9.8	20	254.5	72.7	2.7	44.4
2	12.5	10	17.3	17	262.5	75.0	1.1	40.0
4	20	6	24.8	6	274.4	78.4	2.7	39.7
5	25	6	29.8	10	277.2	79.2	2.5	39.3
6	30	30	34.8	36	281.8	80.5	1.9	37.3
7	35	66	39.8	92	282.5	80.7	5.2	45.3
8	40	31	44.8	47	291.6	83.3	1.3	42.4
9	45	30	49.8	40	273.0	78.0	2.7	34.4
10	50	45	54.8	62	298.2	85.2	1.5	43.8
11	57.5	59	61.8	88	281.1	80.3	1.4	39.3
12	60	43	64.8	62	303.5	86.7	1.7	44.5
13	65	45	69.8	60	303.5	86.7	1.6	44.8
14	70	43	74.8	58	300.0	85.7	2	45.9
15	75	61	79.8	77	295.1	84.3	1.3	45.2
16	80	60	84.8	93	281.4	80.4	1.8	45.0
17	85	48	89.8	67	281.8	80.5	1.5	45.1
18	90	29	94.8	45	295.4	84.4	1.1	45.9
19	95	43	99.8	64	296.8	84.8	1.3	44.4
20	100	58	104.8	78	294.7	84.2	1.3	43.6
21	105	76	109.8	73	298.6	85.3	1.1	45.5
22	110		114.8	50	284.6	81.3	3.4	45.3
23	115	81	119.8	94	291.9	83.4	0.9	45.2
24	120		124.8	24	275.8	78.8	8.3	41.6

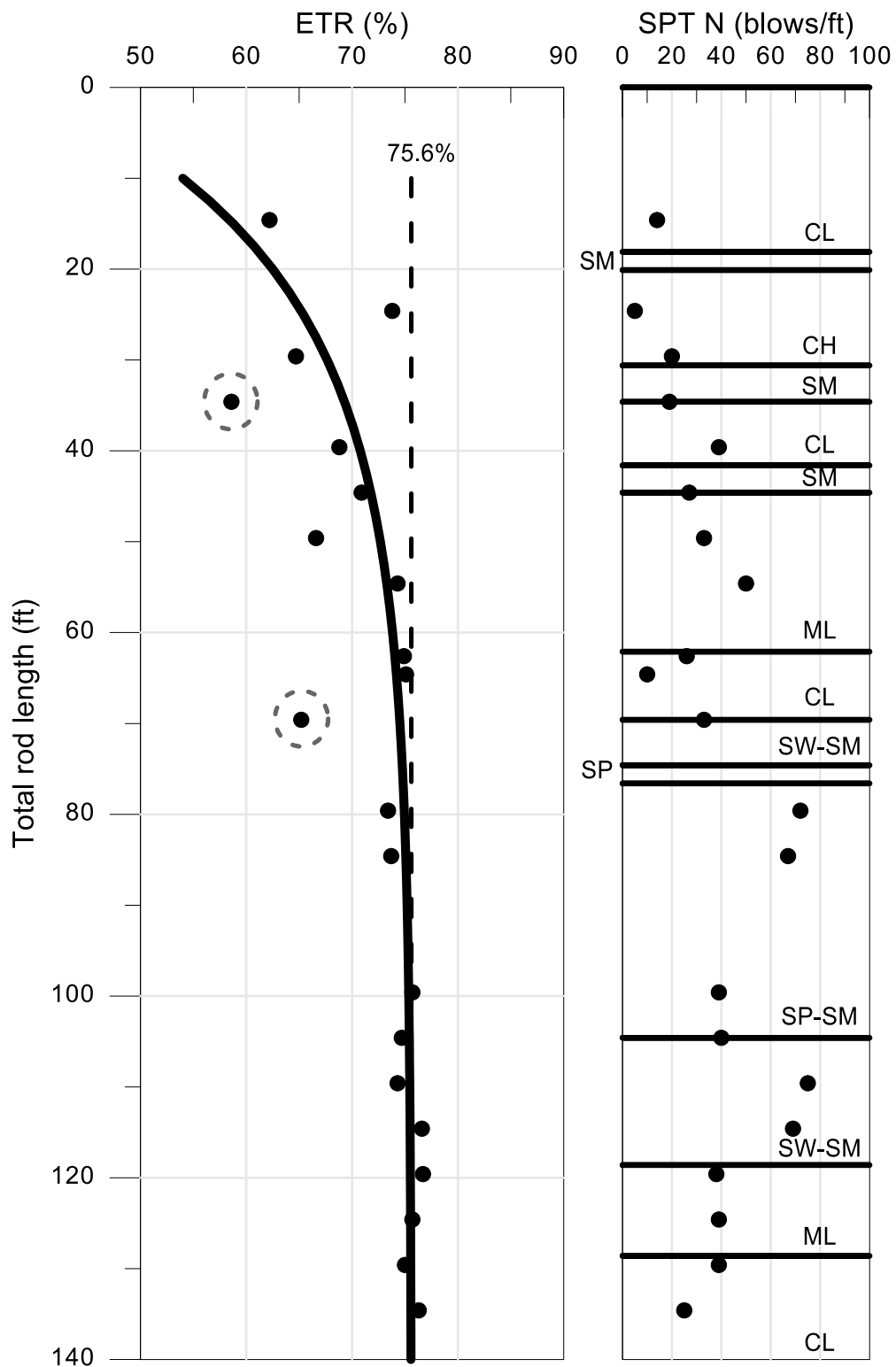


Figure C-4: ETR and Stratigraphy for Boring C4

Table C-4: Rod Lengths and Summary of Hammer Energy Measurements for C4

Hammer Type Automatic
Drill Rig Type Jeffco 15K
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
2	5	14	14.6	21	218	62.2	10.6	28.4
4	15	5	24.6	7	258	73.8	5.6	21.5
5	20	20	29.6	22	226	64.7	4.3	24.8
6	25	19	34.6	24	205	58.6	14.3	25.8
7	30	39	39.6	44	241	68.8	11.4	30.1
8	35	27	44.6	35	248	70.9	10.8	25.6
9	40	33	49.6	43	233	66.6	5.4	27.3
10	45	50	54.6	60	260	74.3	0.9	30.5
11	53	26	62.6	33	262	74.9	8.5	29.8
12	55	10	64.6	12	263	75.1	5.5	26.9
13	60	33	69.6	51	228	65.2	20	27.4
15	70	72	79.6	85	257	73.4	6.8	29.7
16	75	67	84.6	79	258	73.7	5.2	25.3
17	90	39	99.6	54	265	75.7	2	31.1
18	95	40	104.6	58	261	74.7	2.7	28.7
19	100	75	109.6	86	260	74.3	1.6	26.7
20	105	69	114.6	85	268	76.6	2.9	29.3
21	110	38	119.6	43	268	76.7	2.7	26.2
22	115	39	124.6	48	265	75.7	8.7	31.7
23	120	39	129.6	54	263	75	9.5	33.2
24	125	25	134.6	34	267	76.3	4.6	30.7

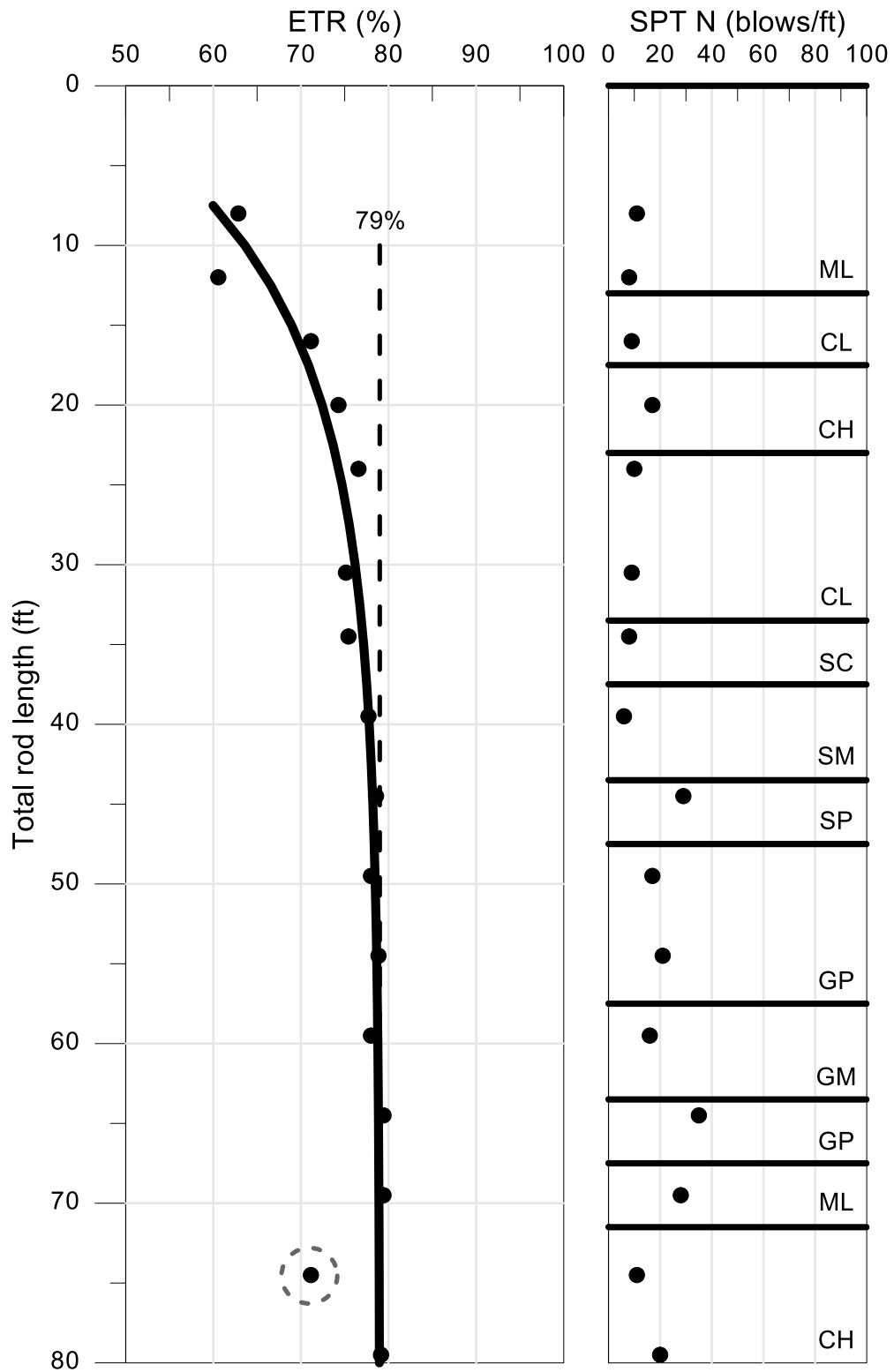


Figure C-5: ETR and Stratigraphy for Boring C5

Table C-5: Rod Lengths and Summary of Hammer Energy Measurements for C5

Hammer Type Automatic
Drill Rig Type CME75
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	3.5	11	8	14	220	62.9	-	30.0
2	7.5	8	12	9	212	60.6	-	34.0
3	11.5	9	16	12	249	71.1	-	25.0
4	15.5	17	20	21	260	74.3	-	26.0
5	19.5	10	24	13	268	76.6	-	25.0
6	26	9	30.5	13	263	75.1	-	24.0
7	30	8	34.5	12	264	75.4	-	25.0
8	35	6	39.5	7	272	77.7	-	22.0
9	40	29	44.5	33	275	78.6	-	30.0
10	45	17	49.5	22	273	78.0	-	27.0
11	50	21	54.5	27	276	78.9	-	28.0
12	55	16	59.5	24	273	78.0	-	27.0
13	60	35	64.5	35	278	79.4	-	31.0
14	65	28	69.5	38	278	79.4	-	32.0
15	70	11	74.5	13	249	71.1	-	30.0
16	75	20	79.5	25	277	79.1	-	33.0

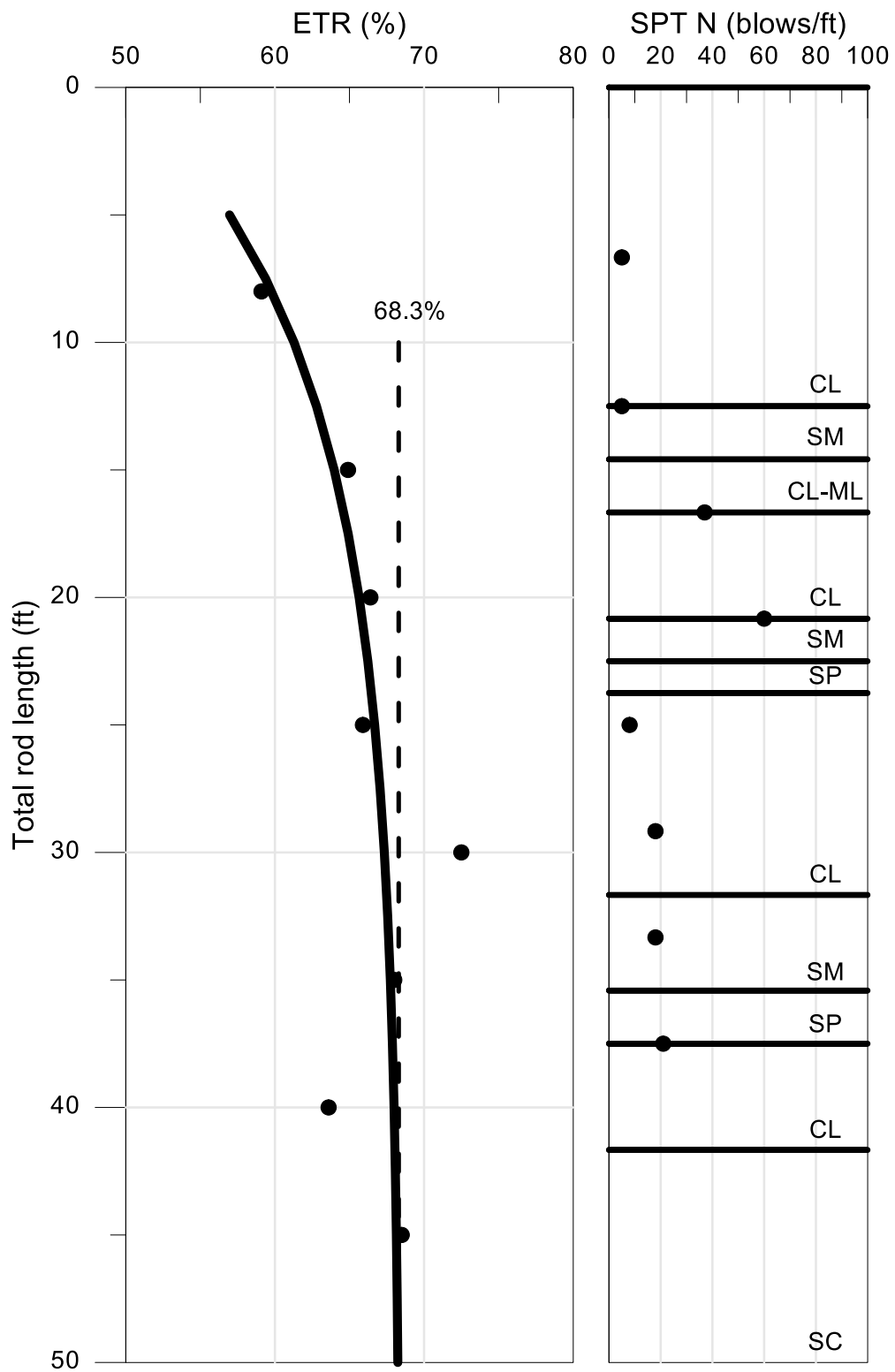


Figure C-6: ETR and Stratigraphy for Boring C6

Table C-6: Rod Lengths and Summary of Hammer Energy Measurements for C6

Hammer Type Automatic
Drill Rig Type Fraste MD XL
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	5	8	9	207	59.1	6.3	24.0
2	12	5	15	5	227	64.9	3.7	30.2
3	17	37	20	43	232	66.4	2.2	34.2
4	22	60	25	68	231	65.9	1.7	36.9
5	27	8	30	11	254	72.5	2.3	34.8
6	32	18	35	22	238	68.0	2	32.6
7	37	18	40	25	223	63.6	1.3	30.4
8	42	21	45	25	240	68.5	2.6	32.5

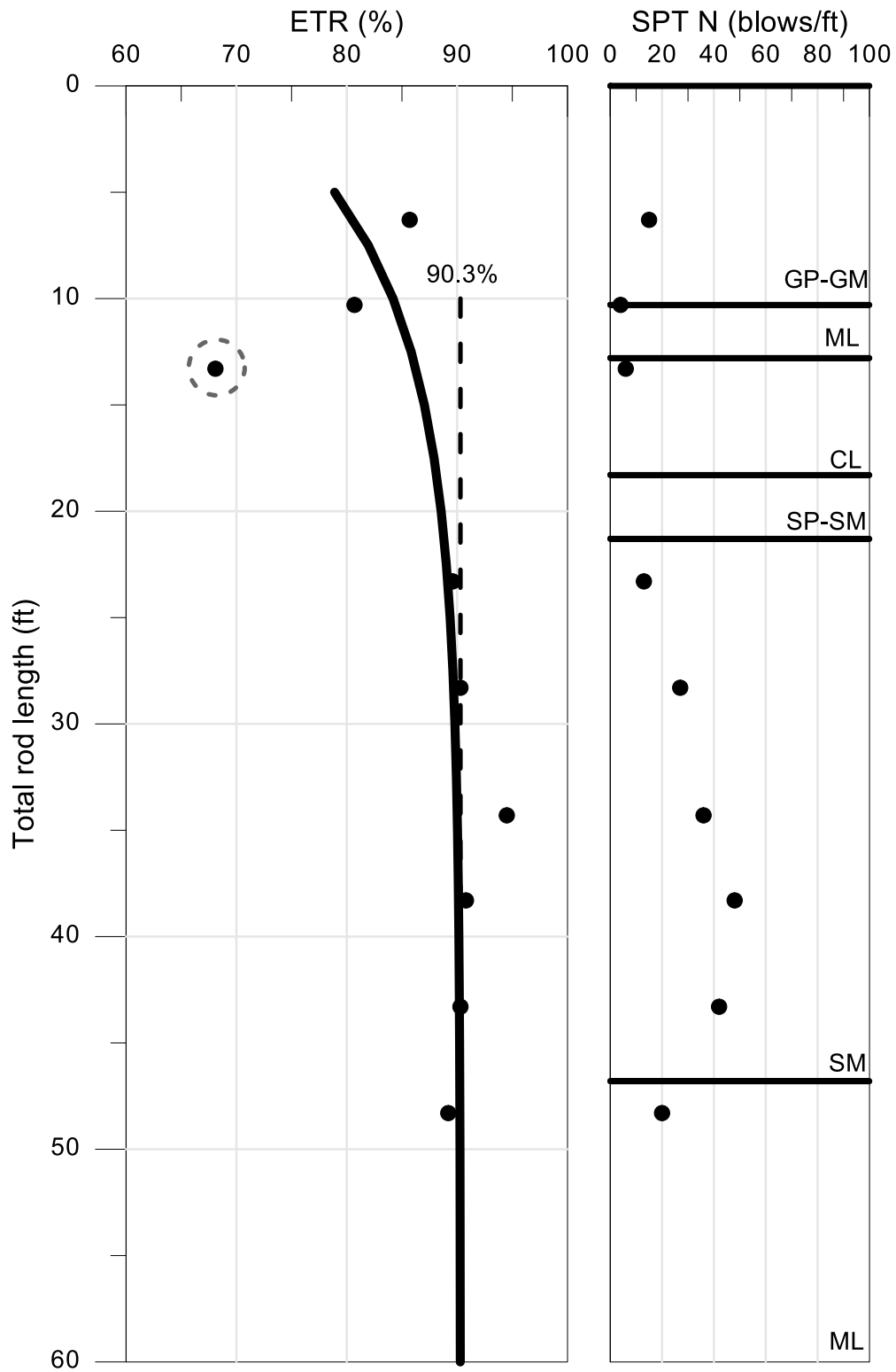


Figure C-7: ETR and Stratigraphy for Boring C7

Table C-7: Rod Lengths and Summary of Hammer Energy Measurements for C7

Hammer Type Automatic
Drill Rig Type CME 55
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	1	15	6.3	20	300	85.7	1.6	48.4
2	5	4	10.3	1	282	80.7	NA	44.1
3	8	6	13.3	1	238	68.1	NA	
4	18	13	23.3	2	314	89.6	6	42.7
5	23	27	28.3	37	316	90.3	1.8	45.5
6	29	36	34.3	47	331	94.5	1.5	46.6
7	33	48	38.3	60	318	90.8	1.5	42.8
8	38	42	43.3	49	316	90.3	1.9	43.8
9	43	20	48.3	12	312	89.2	1.7	45.1

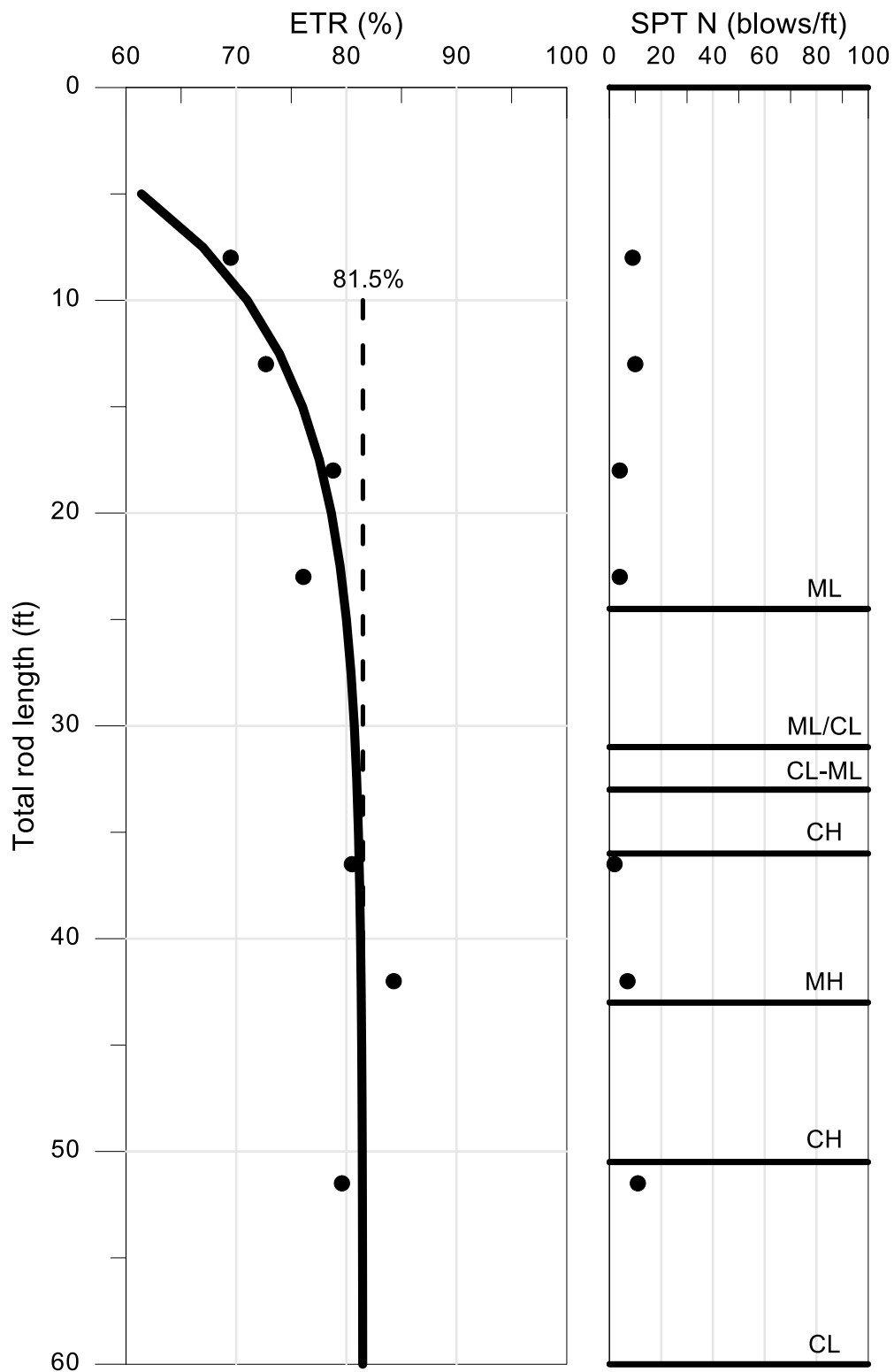


Figure C-8: ETR and Stratigraphy for Boring C8

Table C-8: Rod Lengths and Summary of Hammer Energy Measurements for C8

Hammer Type EMU Automatic
Drill Rig Type Mobile B-53
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	9	8	11	243	69.5	5.6	26.9
2	10	10	13	13	254	72.7	3	27.4
3	15	4	18	5	276	78.8	4.1	29.5
4	20	4	23	4	266	76.1	0.7	25.9
5	33.5	2	36.5	7	282	80.5	3.2	24.9
6	39	7	42	10	295	84.3	4.1	22.6
7	48.5	11	51.5	24	279	79.6	2.7	26.7

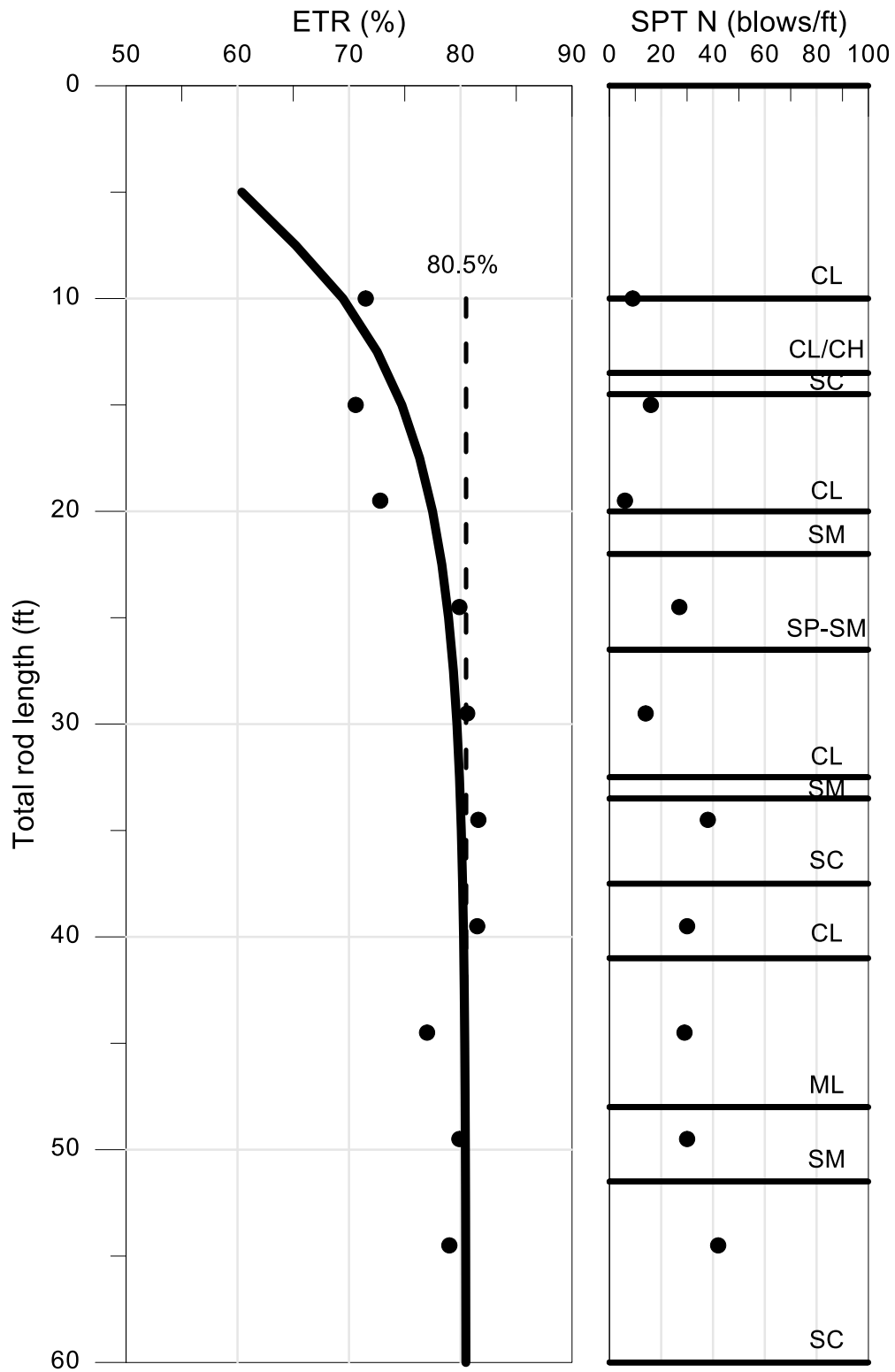


Figure C-9: ETR and Stratigraphy for Boring C9

Table C-9: Rod Lengths and Summary of Hammer Energy Measurements for C9

Hammer Type Automatic
Drill Rig Type CME
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	6	9	10	12	250	71.5	2.5	34.2
2	11	16	15	21	247	70.6	1.3	28.1
3	15.5	6	19.5	7	255	72.8	2.6	18.7
4	20.5	27	24.5	33	280	79.9	4.5	32.5
5	25.5	14	29.5	20	282	80.6	1	31.2
6	30.5	38	34.5	46	286	81.6	0.8	32.6
7	35.5	30	39.5	36	285	81.5	0.6	32.5
8	40.5	29	44.5	36	270	77.0	10	32.4
9	45.5	30	49.5	42	280	79.9	0.6	29.8
10	50.5	42	54.5	60	277	79.0	1	30.0

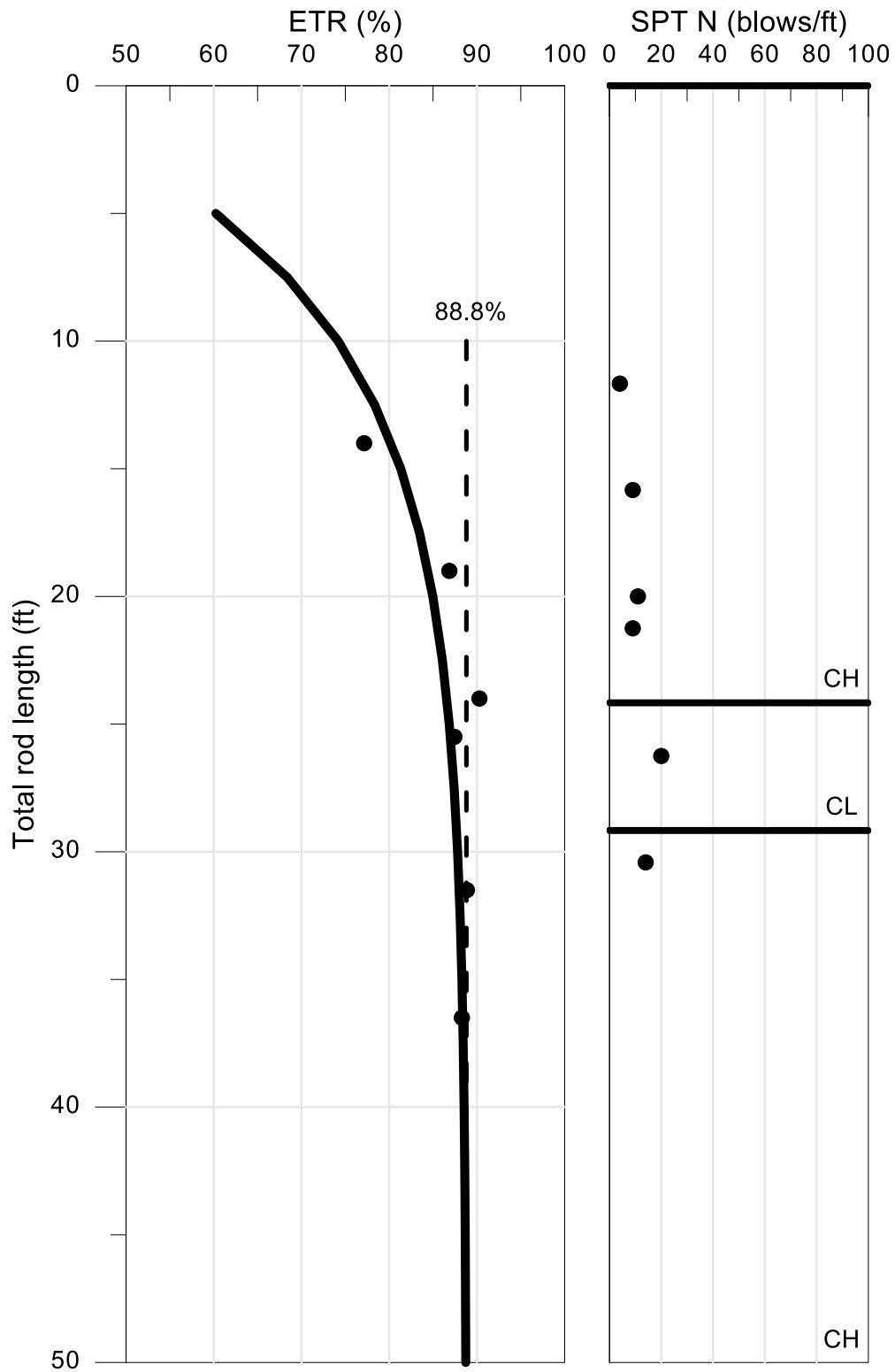


Figure C-10: ETR and Stratigraphy for Boring C10

Table C-10: Rod Lengths and Summary of Hammer Energy Measurements for C10

Hammer Type Automatic
Drill Rig Type CME 85
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	10	4	14	4	270	77.1	6	52.5
2	15	9	19	11	304	86.9	2	51.7
3	20	11	24	8	316	90.3	1	50.1
4	21.5	9	25.5	9	306	87.4	1	49.9
5	27.5	20	31.5	25	311	88.9	1	54.2
6	32.5	14	36.5	55	309	88.3	2	54.0

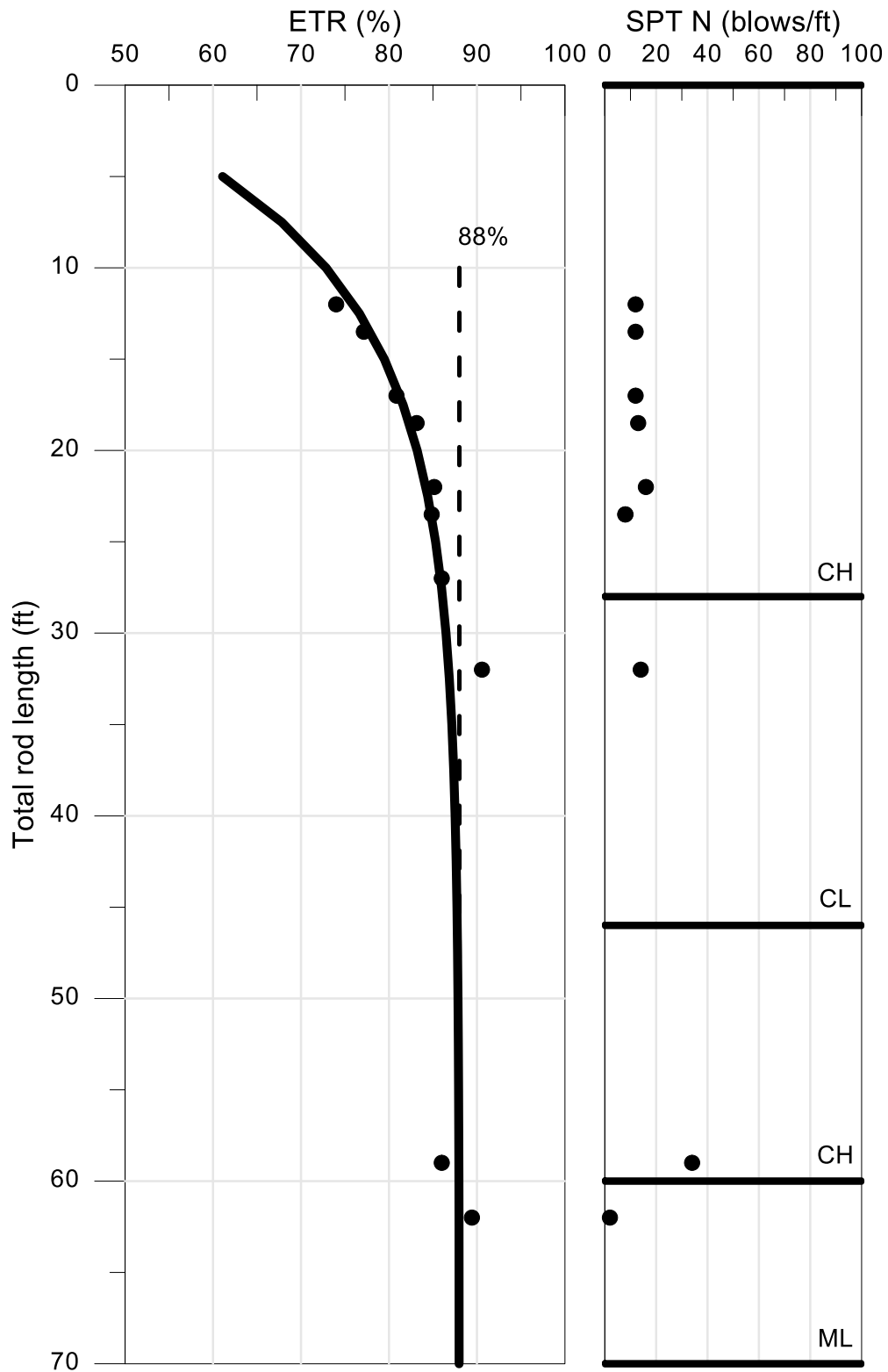


Figure C-11: ETR and Stratigraphy for Boring C11

Table C-11: Rod Lengths and Summary of Hammer Energy Measurements for C11

Hammer Type Automatic
Drill Rig Type CME 85
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	8	12	12	22	259	74.0	2	38.1
2	9.5	12	13.5	13	270	77.1	1	46.8
3	13	12	17	15	283	80.9	1	49.4
4	14.5	13	18.5	13	291	83.1	1	49.7
5	18	16	22	19	298	85.1	1	51.5
6	19.5	8	23.5	19	297	84.9	1	48.0
7	23	NA	27	19	301	86.0	1	46.9
8	28	14	32	19	317	90.6	2	51.5
9	55	34	59	40	301	86.0	1	51.7
10	58	2	62	3	313	89.4	2	47.9

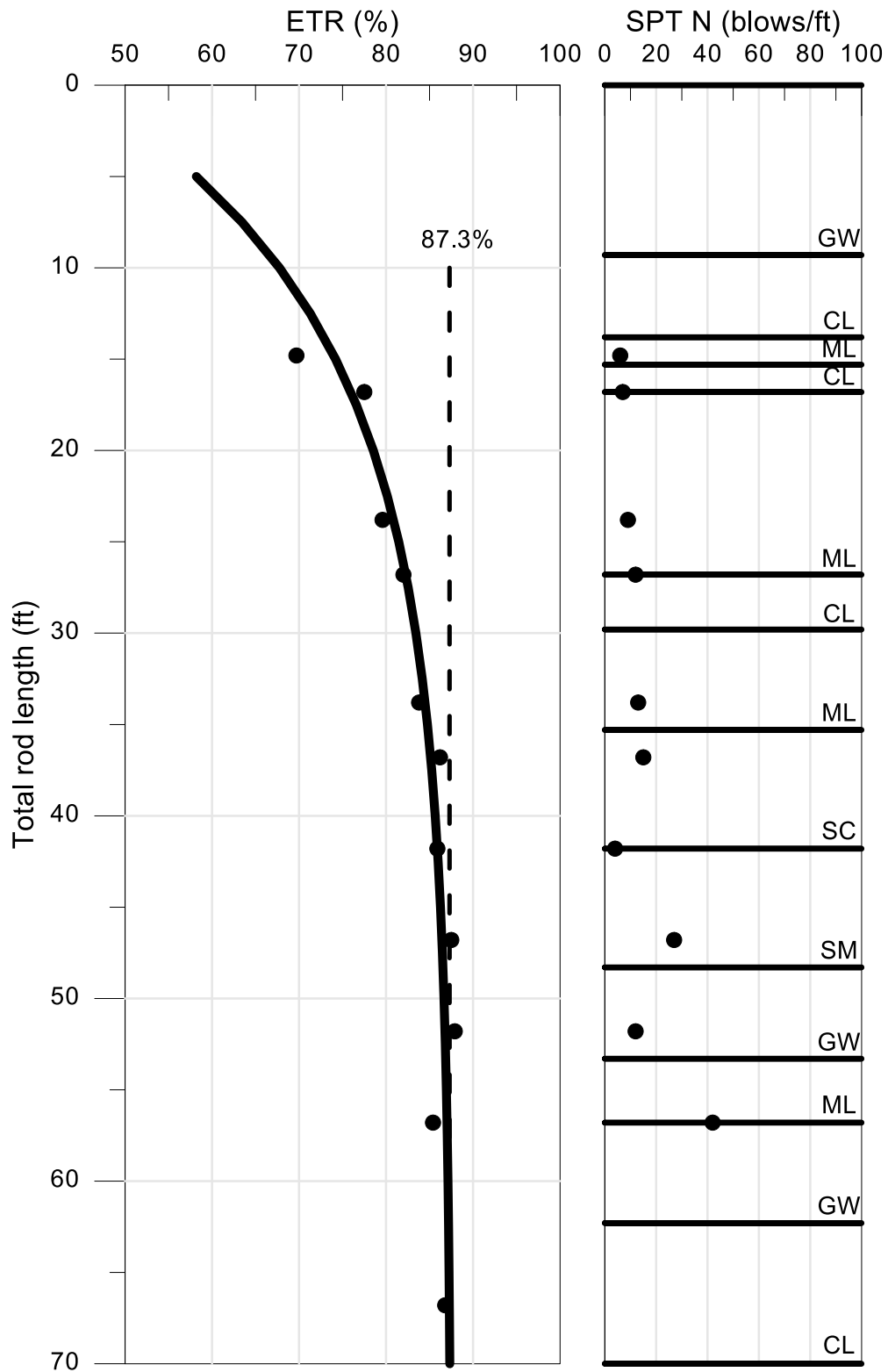


Figure C-12: ETR and Stratigraphy for Boring C12

Table C-12: Rod Lengths and Summary of Hammer Energy Measurements for C12

Hammer Type Automatic
Drill Rig Type Mobile B-80
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	7	6	14.8	11	244	69.7	2.3	50.1
2	10	7	16.8	11	271	77.5	2.7	53.0
3	17	9	23.8	12	279	79.6	3.7	50.4
4	20	12	26.8	15	287	82.0	0.9	48.1
5	27	13	33.8	19	293	83.8	1.3	52.3
6	30	15	36.8	21	302	86.2	1.8	56.5
7	35	4	41.8	6	301	85.9	1.4	54.4
8	40	27	46.8	30	306	87.5	1.6	53
9	45	12	51.8	17	308	87.9	1.4	57
10	50	42	56.8	58	299	85.4	1.3	53.9
12	60	NA	66.8	44	304	86.8	1.2	47.2

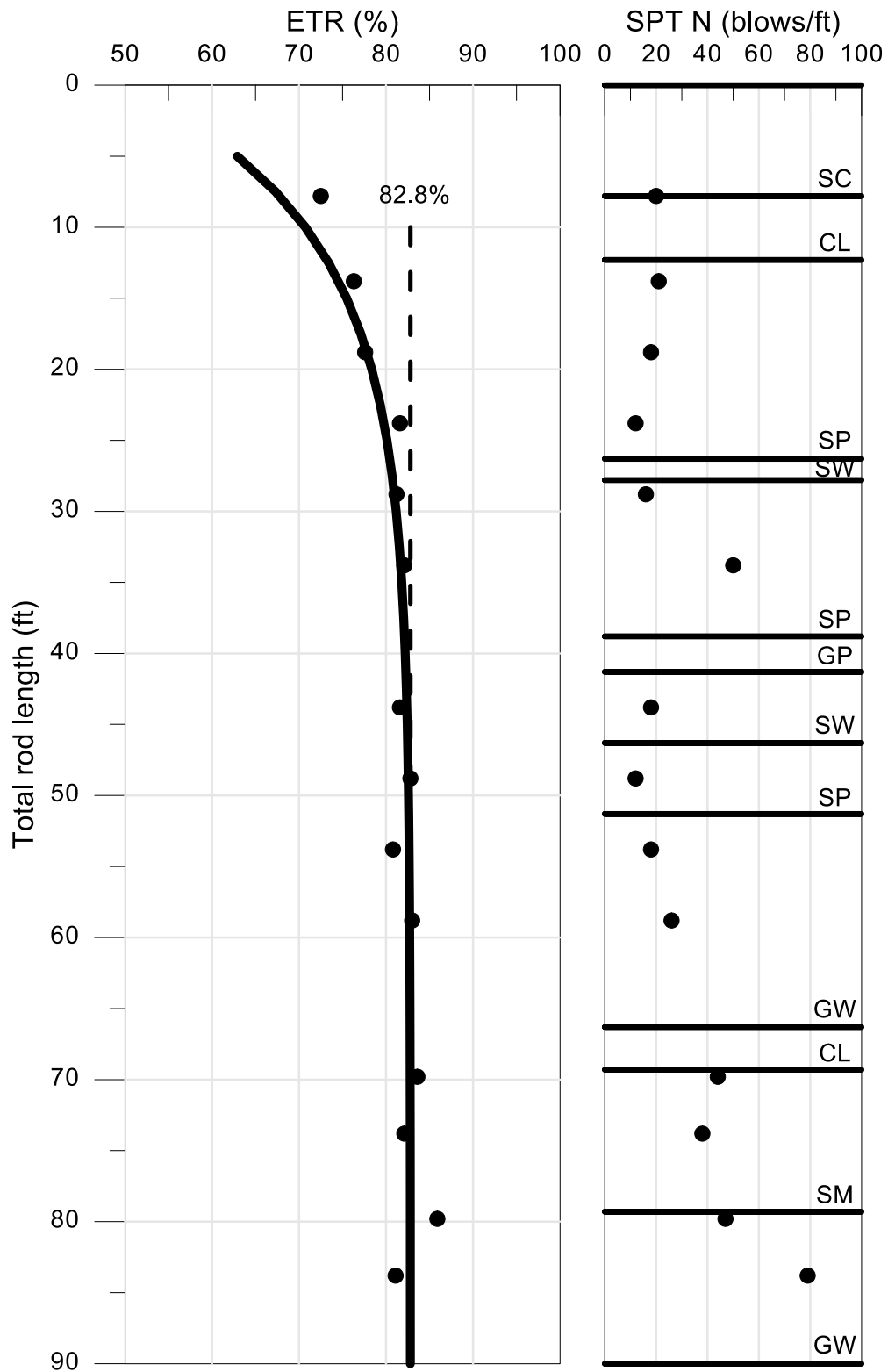


Figure C-13: ETR and Stratigraphy for Boring C13

Table C-13: Rod Lengths and Summary of Hammer Energy Measurements for C13

Hammer Type Automatic
Drill Rig Type CME 850
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	3	20	7.8	28	254	72.5	2.5	27
2	7	21	13.8	26	267	76.3	1.4	27.5
3	11.5	18	18.8	23	272	77.6	1.1	26.3
4	16.5	12	23.8	17	286	81.6	0.7	31.8
5	21.5	16	28.8	20	284	81.2	0.5	30.0
6	26.5	50	33.8	58	287	82.1	0.8	28.0
7	31.5	18	43.8	22	286	81.6	0.7	28.5
8	36.5	12	48.8	17	290	82.8	0.8	30.2
9	41.5	18	53.8	23	283	80.8	0.6	29.5
10	46.5	26	58.8	40	291	83.0	0.6	34.8
14	63	44	69.8	61	293	83.6	0.8	38.1
15	66.5	38	73.8	56	287	82.1	0.7	33.5
17	74	47	79.8	86	301	85.9	0.4	37.2
18	79	79	83.8	91	284	81.1	0.5	29.1

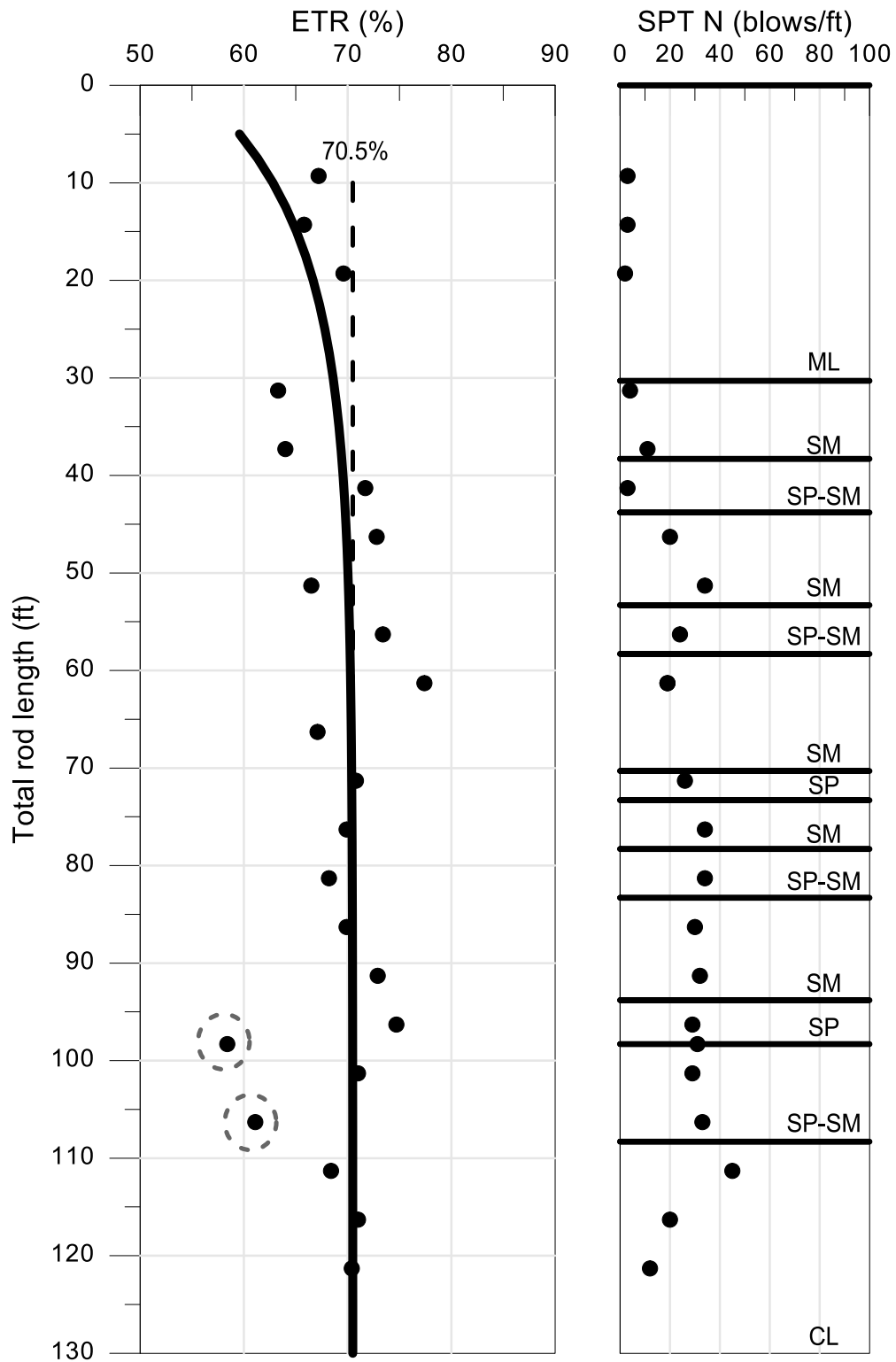


Figure C-14: ETR and Stratigraphy for Boring C14

Table C-14: Rod Lengths and Summary of Hammer Energy Measurements for C14**Hammer Type** Automatic**Drill Rig Type** CME 75**Rod Type** AWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	3	9.3	7	235	67.2	9	46.5
2	10	3	14.3	3	230	65.8	11.6	40.3
3	15	2	19.3	4	244	69.6	8.2	49.8
5	20	4	31.3	1	222	63.3	NA	
7	25	11	37.3	14	224	64.0	1.7	56.1
9	30	3	41.3	2	251	71.7	1	49.6
11	35	20	46.3	28	255	72.8	3.3	58.5
12	40	34	51.3	15	233	66.5	2.4	47.6
13	45	24	56.3	23	257	73.4	3.6	54.1
14	50	19	61.3	19	271	77.4	3.9	58.8
15	55	NA	66.3	16	235	67.1	3.4	57.1
16	60	26	71.3	34	248	70.8	1.7	49.8
17	65	34	76.3	48	245	69.9	3.6	49.8
18	70	34	81.3	47	239	68.2	2.3	49.6
19	75	30	86.3	44	245	69.9	2.3	55.4
20	80	32	91.3	49	255	72.9	2.2	54.9
21	85	29	96.3	47	261	74.7	3.5	53.7
22	86.5	31	98.3	37	204	58.4	2.1	50
23	90	29	101.3	54	249	71.0	5.4	54.3
24	95	33	106.3	40	214	61.1	1.2	49.1
25	100	45	111.3	66	239	68.4	2.2	46.1
26	105	20	116.3	44	249	71.0	2.2	49.8
27	110	12	121.3	20	246	70.4	2.4	49.4

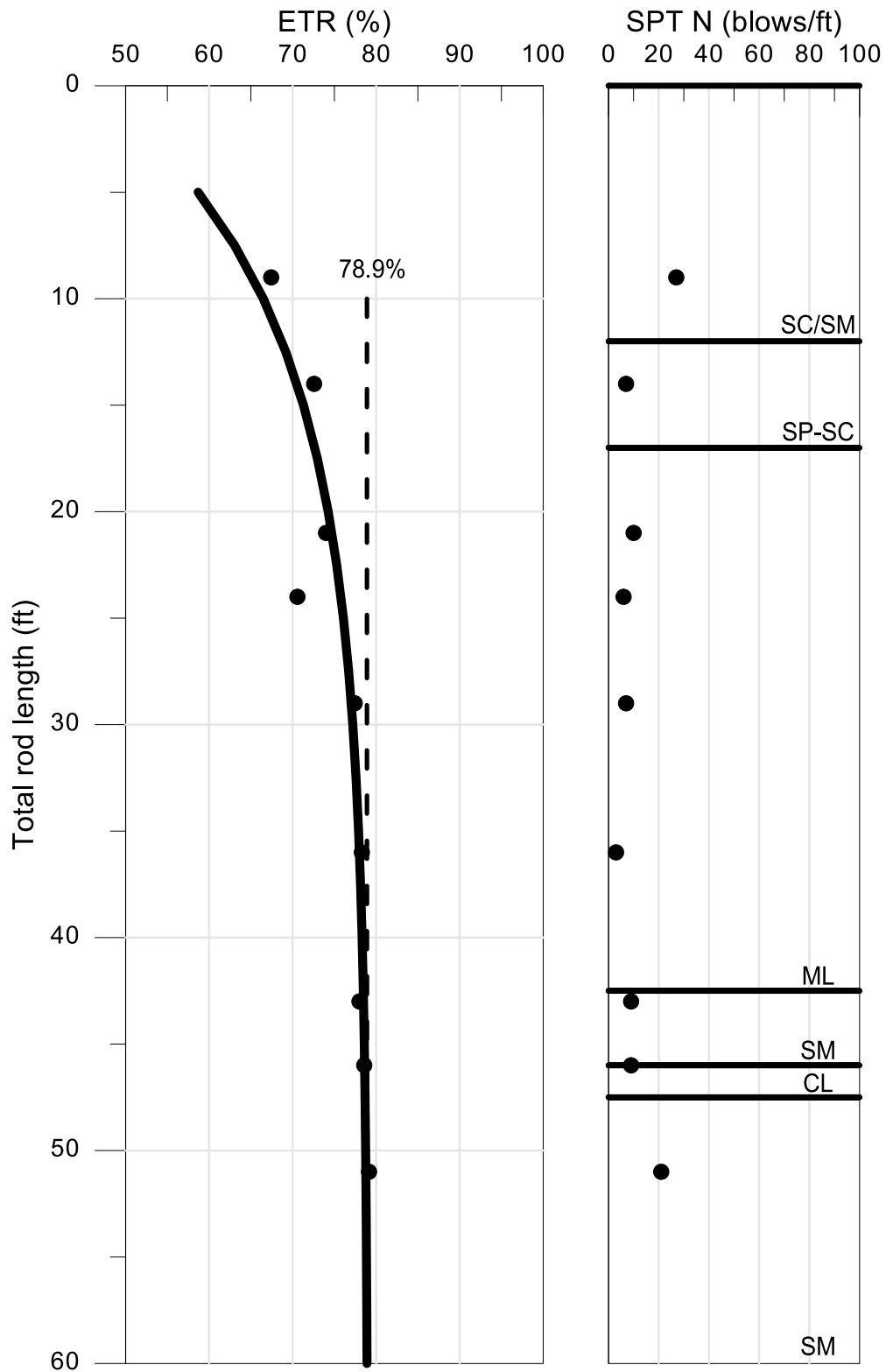


Figure C-15: ETR and Stratigraphy for Boring C15

Table C-15: Rod Lengths and Summary of Hammer Energy Measurements for C15

Hammer Type Automatic
Drill Rig Type Mobile B-53
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	27	9	23	236	67.4	2.6	34.5
2	10	7	14	24	254	72.6	1.4	34.5
3	17	10	21	5	259	74.0	2.9	31.4
4	20	6	24	7	247	70.6	1.7	22.7
5	25	7	29	11	271	77.4	1.1	30.9
6	32	3	36	8	274	78.3	0.6	29.3
7	39	9	43	9	273	78.0	0.9	29.5
8	42	9	46	13	275	78.6	0.6	31.4
9	47	21	51	17	277	79.1	1.1	34.7

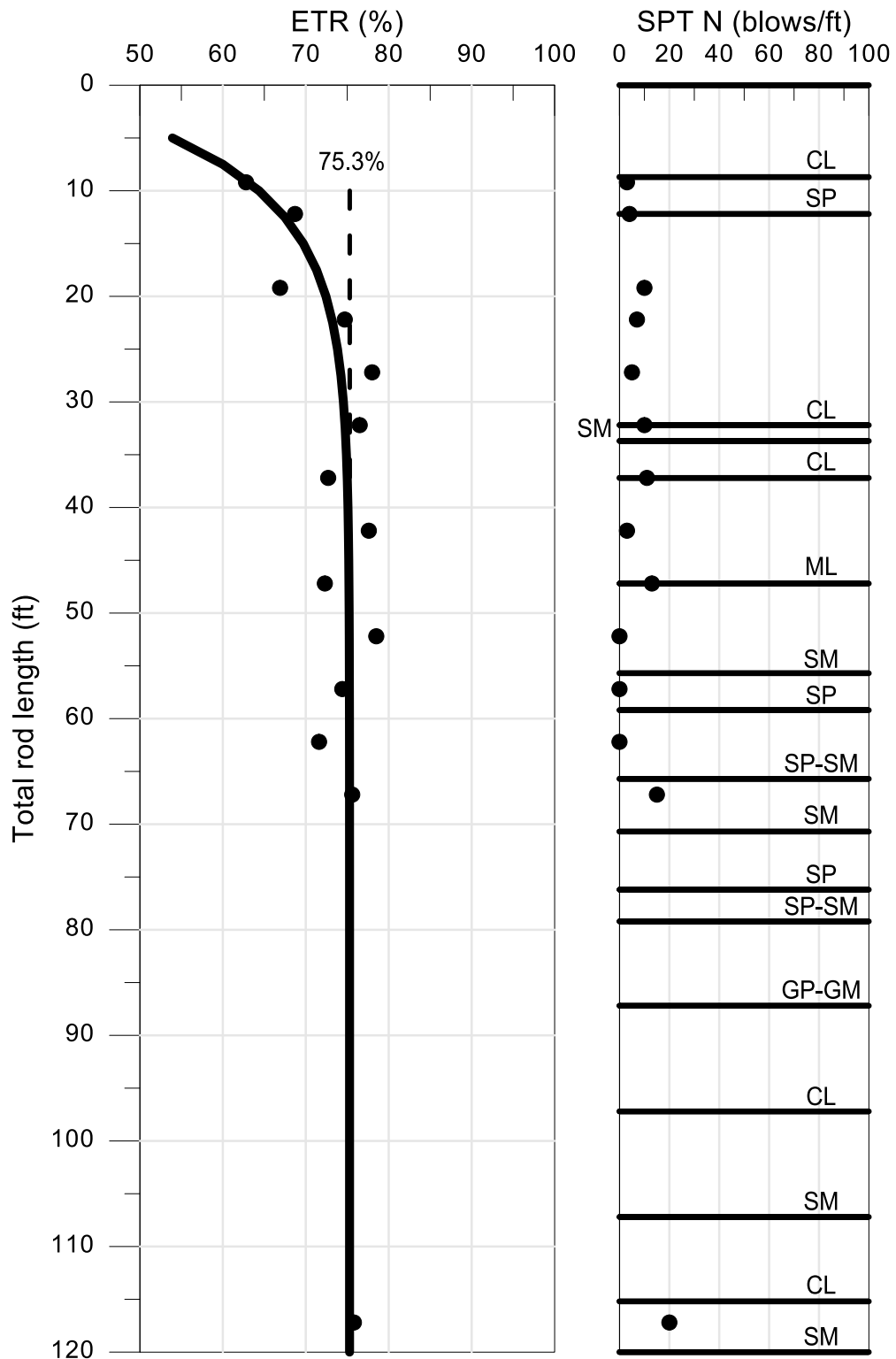


Figure C-16: ETR and Stratigraphy for Boring C16

Table C-16: Rod Lengths and Summary of Hammer Energy Measurements for C16

Hammer Type Automatic
Drill Rig Type Fraste MD XL
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	3	9.2	17	220	62.8	2.9	47.2
2	10	4	12.2	13	240	68.7	1.6	53.0
4	16.5	10	19.2	10	234	66.9	2.5	38.8
5	20	7	22.2	6	261	74.7	1.1	48.9
6	25	5	27.2	7	273	78.0	1.1	45.6
7	30	10	32.2	13	268	76.5	0.9	46.9
8	35	11	37.2	4	254	72.7	1	41.9
9	40	3	42.2	25	272	77.6	1.5	47.1
10	45	13	47.2	11	253	72.3	1	39.7
11	50	0	52.2	23	275	78.5	0.9	46.7
12	55	0	57.2	21	260	74.4	0.9	43.5
13	60	0	62.2	30	251	71.6	1.2	40
14	65	15	67.2	27	265	75.6	1.6	47.2
15	115	20	117.2	37	265	75.8	1.5	43.6

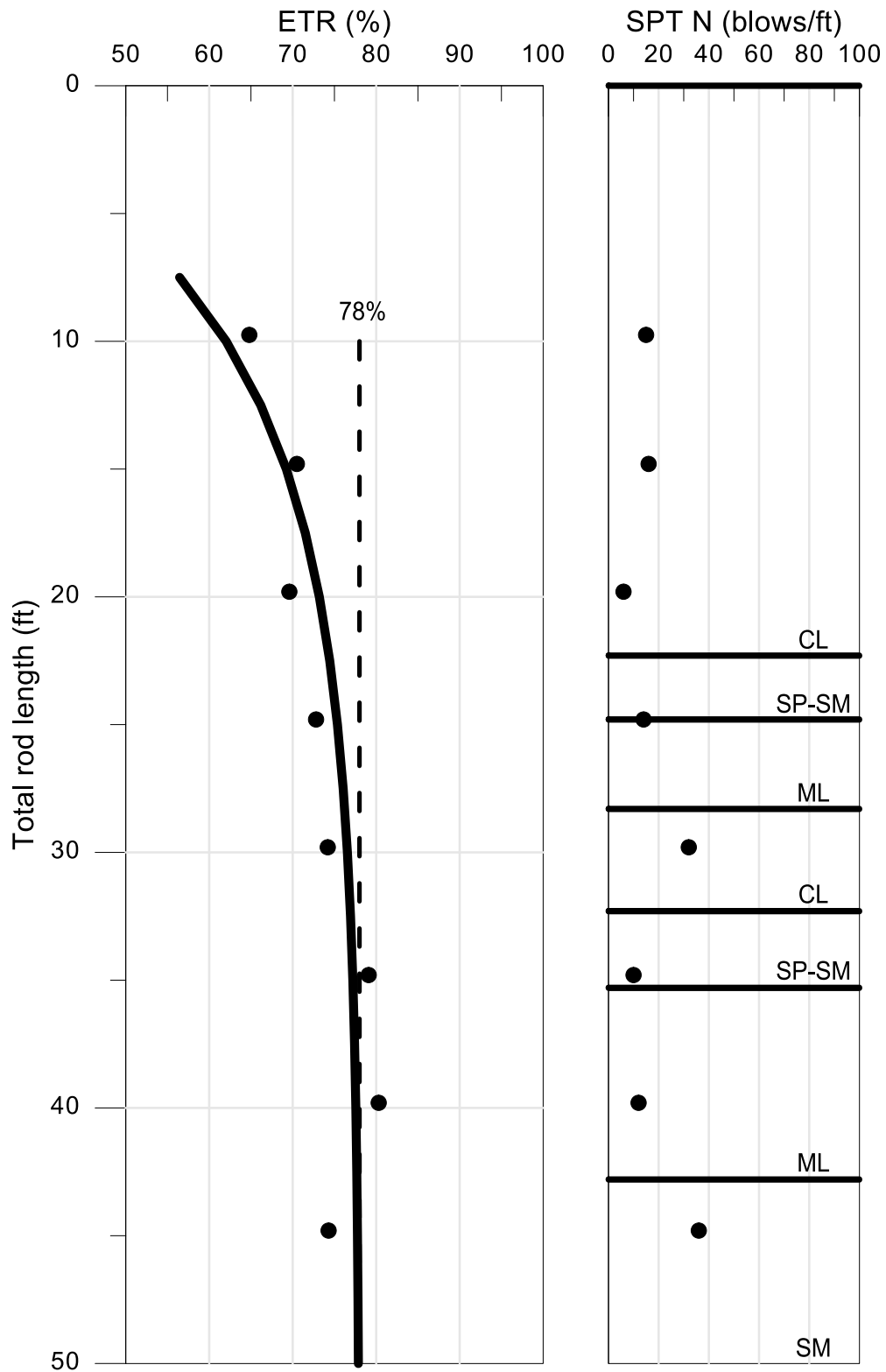


Figure C-17: ETR and Stratigraphy for Boring C17

Table C-17: Rod Lengths and Summary of Hammer Energy Measurements for C17

Hammer Type Automatic
Drill Rig Type Mobile B-53
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	5	15	9.8	17	227	64.8	3.9	40.1
2	10	16	14.8	22	247	70.5	4.7	42.7
3	14.5	6	19.8	8	244	69.6	1.3	38.1
4	20	14	24.8	14	255	72.8	6.2	44.3
5	25	32	29.8	34	260	74.2	1.5	42.9
6	30	10	34.8	11	277	79.1	2.2	42.1
7	35	12	39.8	15	281	80.3	2.4	46.1
8	40	36	44.8	36	260	74.3	1.8	50.4

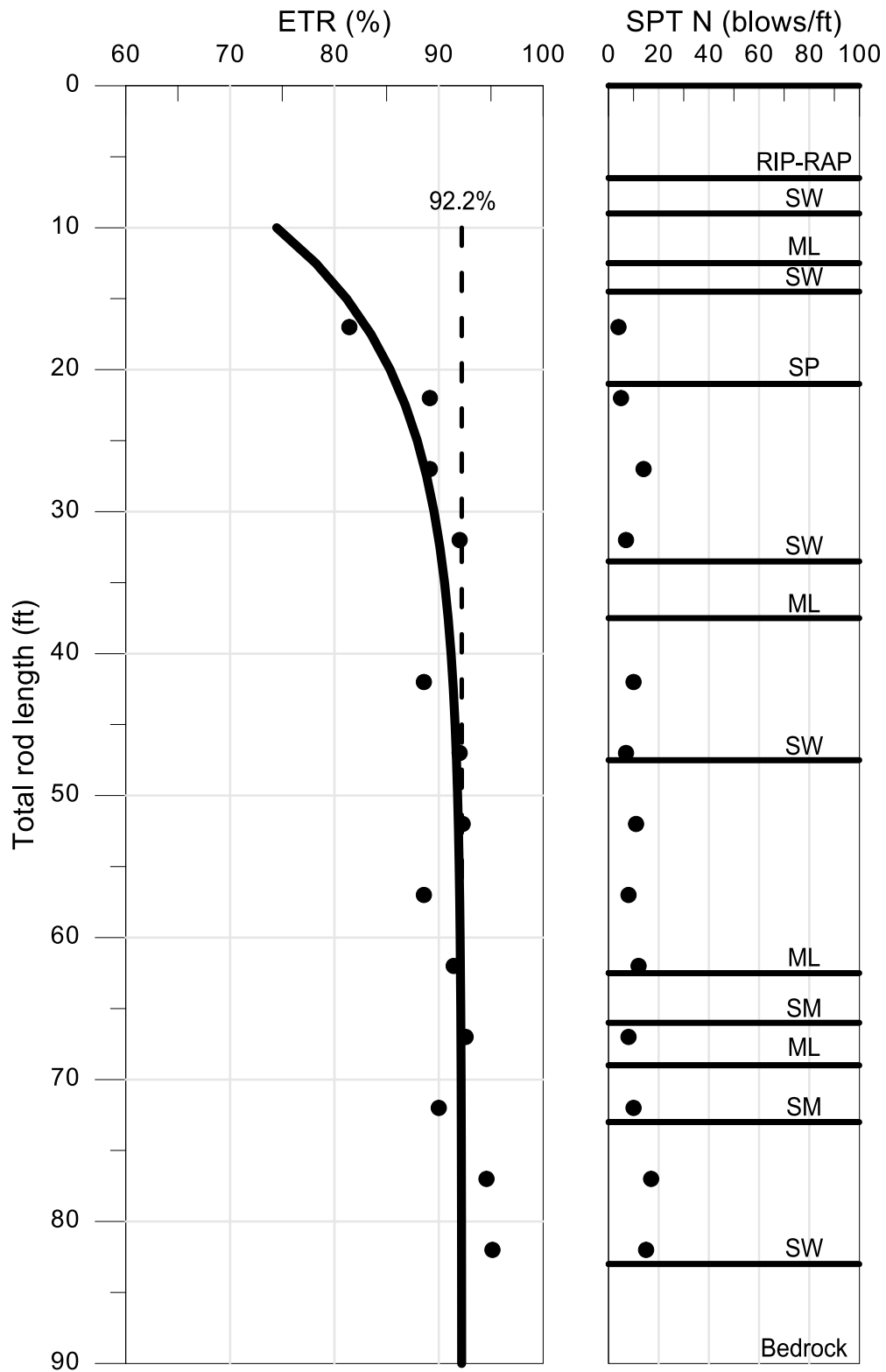


Figure C-18: ETR and Stratigraphy for Boring C18

Table C-18: Rod Lengths and Summary of Hammer Energy Measurements for C18

Hammer Type Automatic
Drill Rig Type CME-45
Rod Type NWJ

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	14	4	17.0	5	285	81.4	2.6	33.8
2	19	5	22.0	6	312	89.1	2.6	35.9
3	24	14	27.0	17	312	89.1	5.1	34.7
4	29	7	32.0	9	322	92.0	4.9	35.2
5	39	10	42.0	19	310	88.6	3.7	35.9
6	44	7	47.0	10	322	92.0	3.7	33.2
7	49	11	52.0	13	323	92.3	3.1	36.7
8	54	8	57.0	11	310	88.6	2.0	36.7
9	59	12	62.0	15	320	91.4	4.0	37.5
10	64	8	67.0	11	324	92.6	5.1	36.1
11	69	10	72.0	13	315	90.0	3.1	36.3
12	74	17	77.0	22	331	94.6	3.4	36.2
13	79	15	82.0	14	333	95.1	3.4	37.4

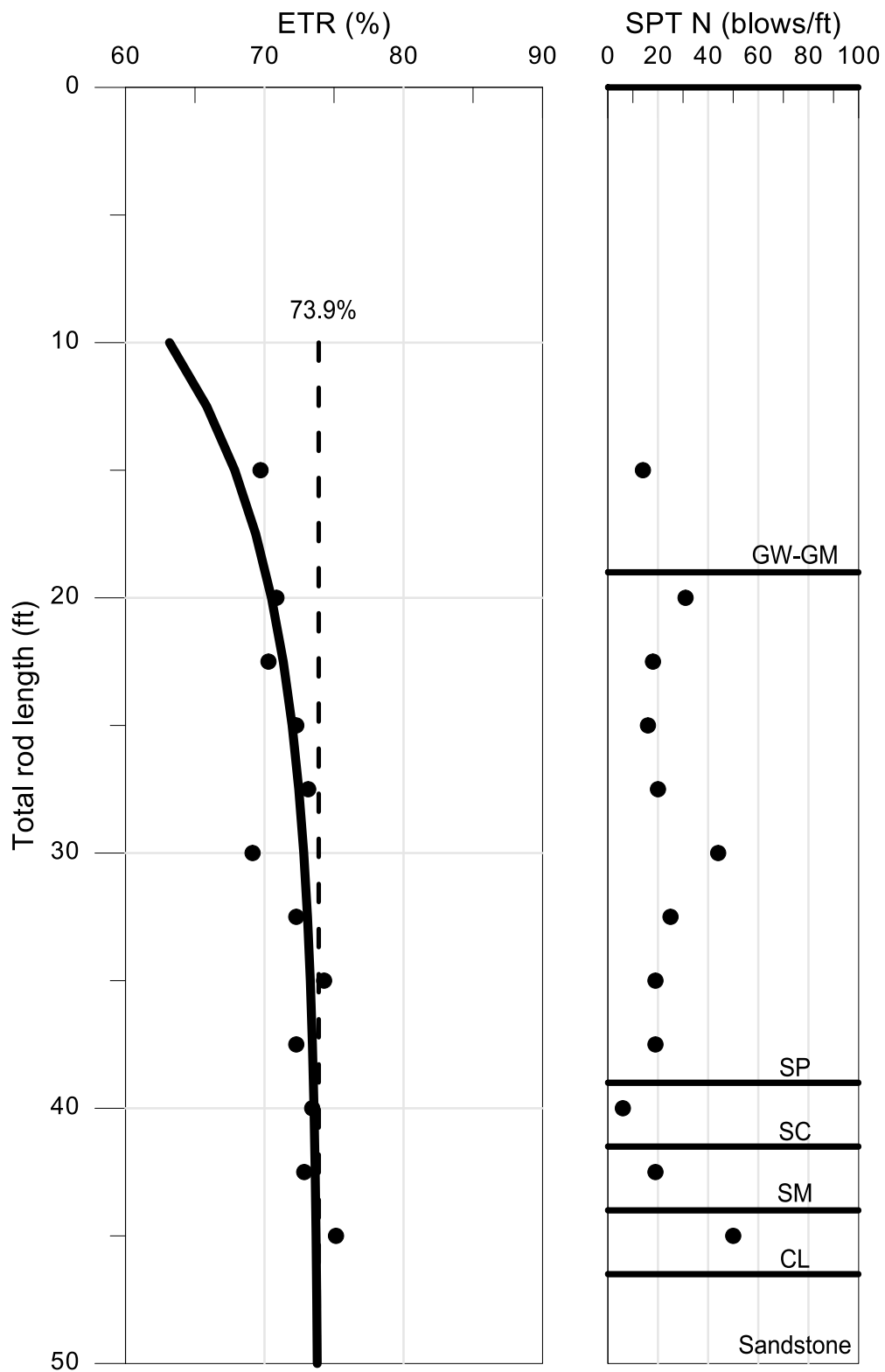


Figure C-19: ETR and Stratigraphy for Boring C19

Table C-19: Rod Lengths and Summary of Hammer Energy Measurements for C19

Hammer Type Automatic
Drill Rig Type CME 850
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	11	14	15.0	23	244	69.7	2.3	33.2
2	16	31	20.0	37	248	70.9	1.1	32.5
3	18.5	18	22.5	23	246	70.3	0.6	32.4
4	21	16	25.0	20	253	72.3	1.4	32.6
5	23.5	20	27.5	23	256	73.1	0.6	31.7
6	26	44	30.0	50	242	69.1	1.4	32.1
7	28.5	25	32.5	37	253	72.3	1.4	32
8	31	19	35.0	23	260	74.3	0.9	32.6
9	33.5	19	37.5	24	253	72.3	1.1	32.1
10	36	6	40.0	18	257	73.4	1.4	32.2
11	38.5	19	42.5	11	255	72.9	0.6	32.3
12	41	50	45.0	61	263	75.1	0.9	32.5

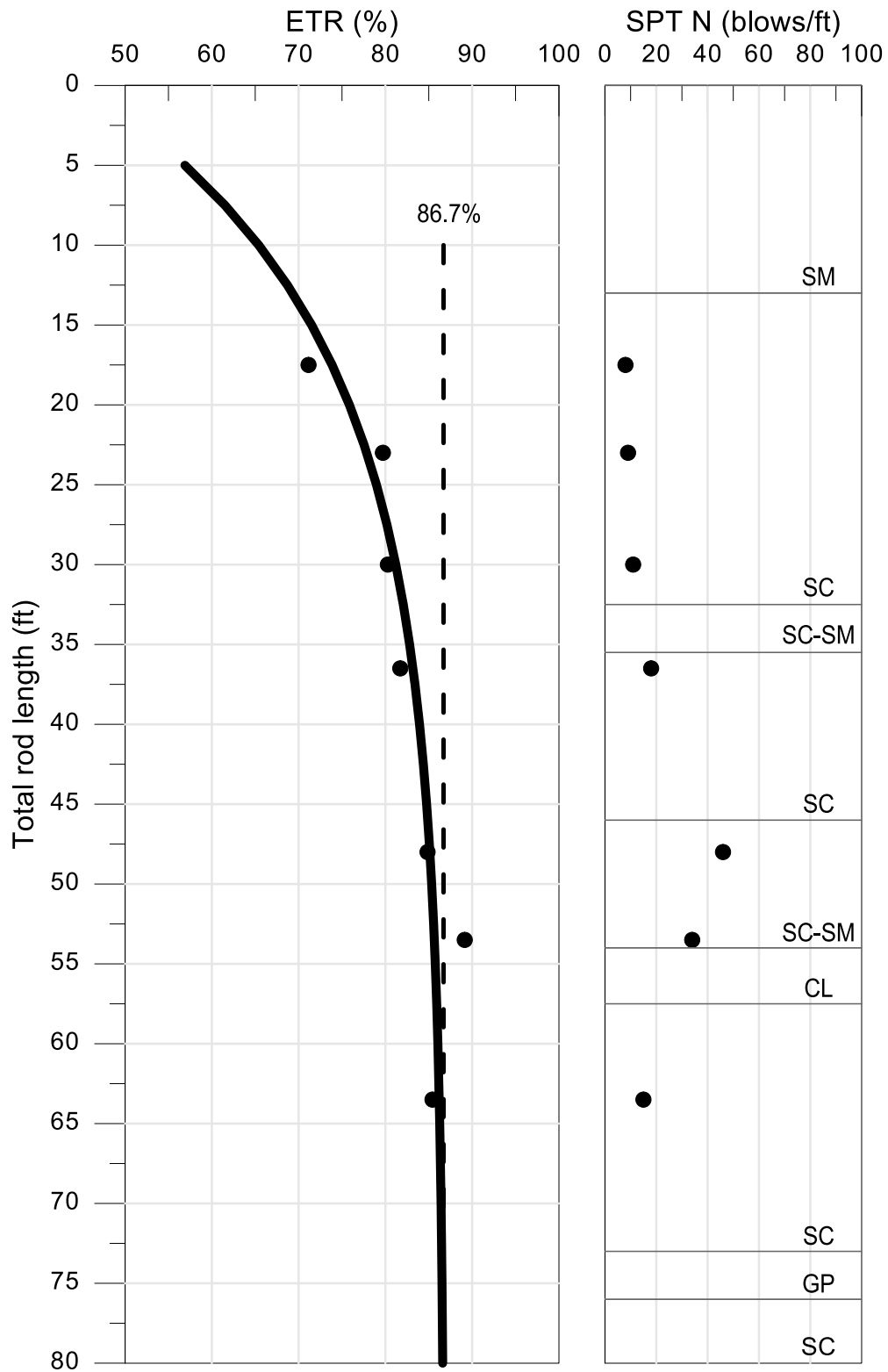


Figure C-20: ETR and Stratigraphy for Boring C20

Table C-20: Rod Lengths and Summary of Hammer Energy Measurements for C20

Hammer Type Automatic
Drill Rig Diedrich D128
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	14	8	17.5	12	249	71.1	2.9	35.2
3	19	9	23.0	14	279	79.7	2.6	35.8
4	26	11	30.0	15	281	80.3	2.6	36.1
6	33	18	36.5	17	286	81.7	2.0	35.9
7	44	46	48.0	67	297	84.9	2.9	34.9
9	50	34	53.5	42	312	89.1	3.4	36
10	60	15	63.5	24	299	85.4	5.4	35.7

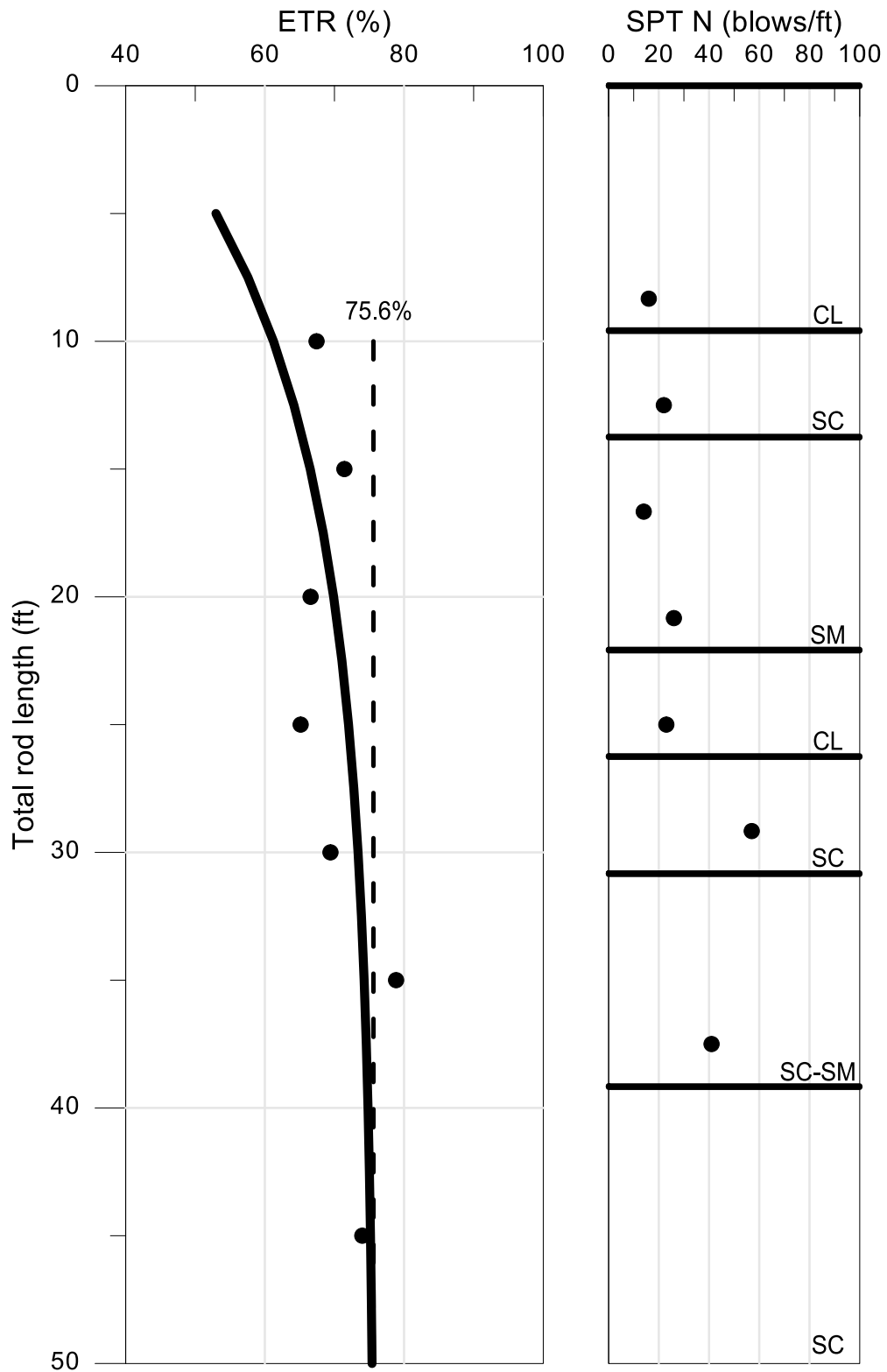


Figure C-21: ETR and Stratigraphy for Boring C21

Table C-21: Rod Lengths and Summary of Hammer Energy Measurements for C21

Hammer Type Automatic
Drill Rig Type CME750
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	6	16	10.0	16	236	67.4	6.3	44.8
2	11	22	15.0	22	250	71.4	1.1	47.2
3	16	14	20.0	14	233	66.6	0.6	36.3
4	21	26	25.0	26	228	65.1	1.1	38
5	26	23	30.0	23	243	69.4	0.9	39.9
6	31	57	35.0	57	276	78.9	1.4	43.8
7	41	41	45.0	41	259	74.0	1.4	35.5

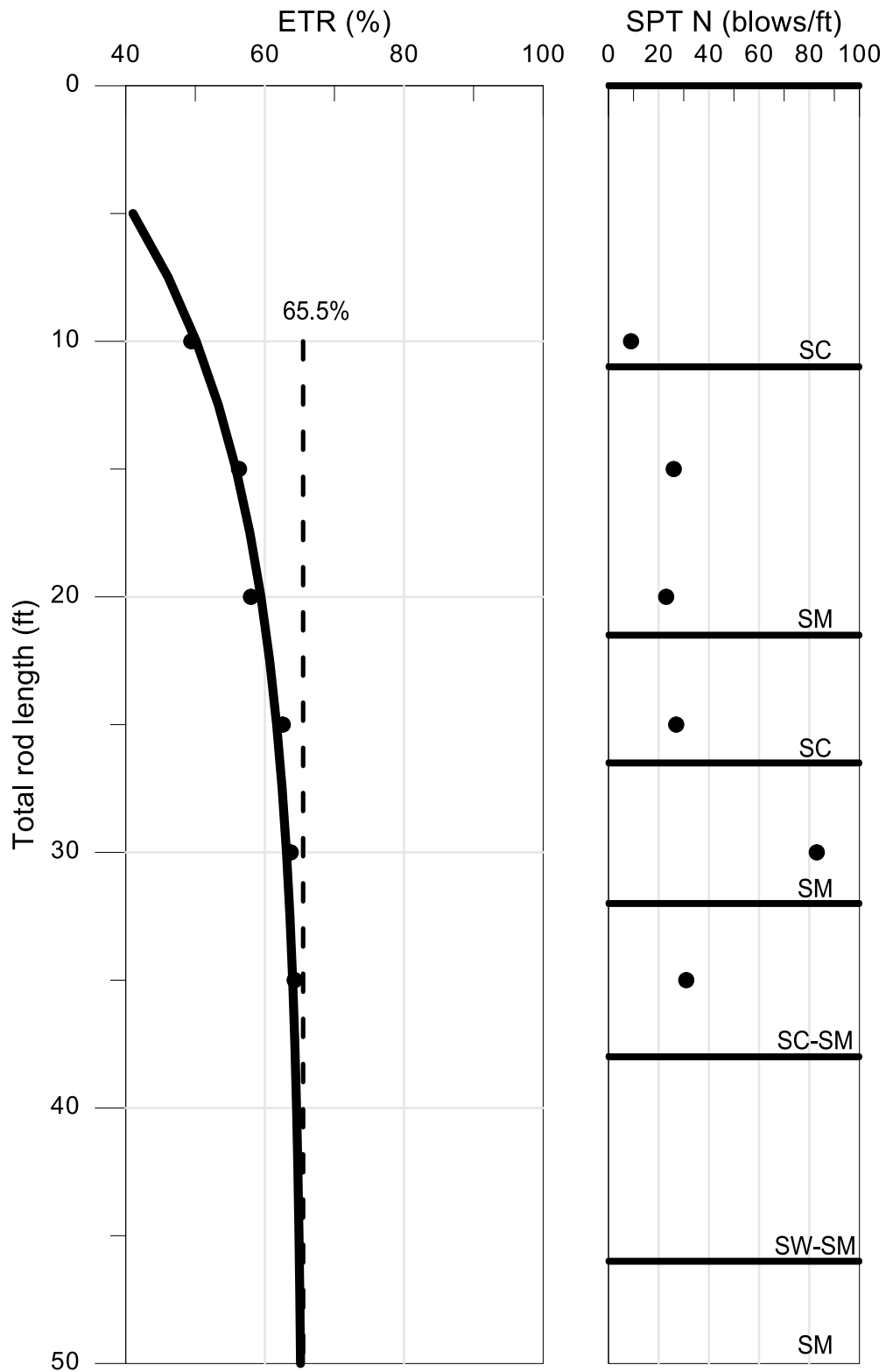


Figure C-22: ETR and Stratigraphy for Boring C22

Table C-22: Rod Lengths and Summary of Hammer Energy Measurements for C22

Hammer Type Automatic
Drill Rig Type CME95
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	6	9	10.0	9	173	49.4	2.3	25.7
2	11	26	15.0	26	197	56.3	3.7	36.8
3	16	23	20.0	23	203	58.0	3.1	40.4
4	21	27	25.0	27	219	62.6	6.0	38.7
5	26	83	30.0	83	223	63.7	4.9	35
6	31	31	35.0	31	225	64.3	4.9	47.2

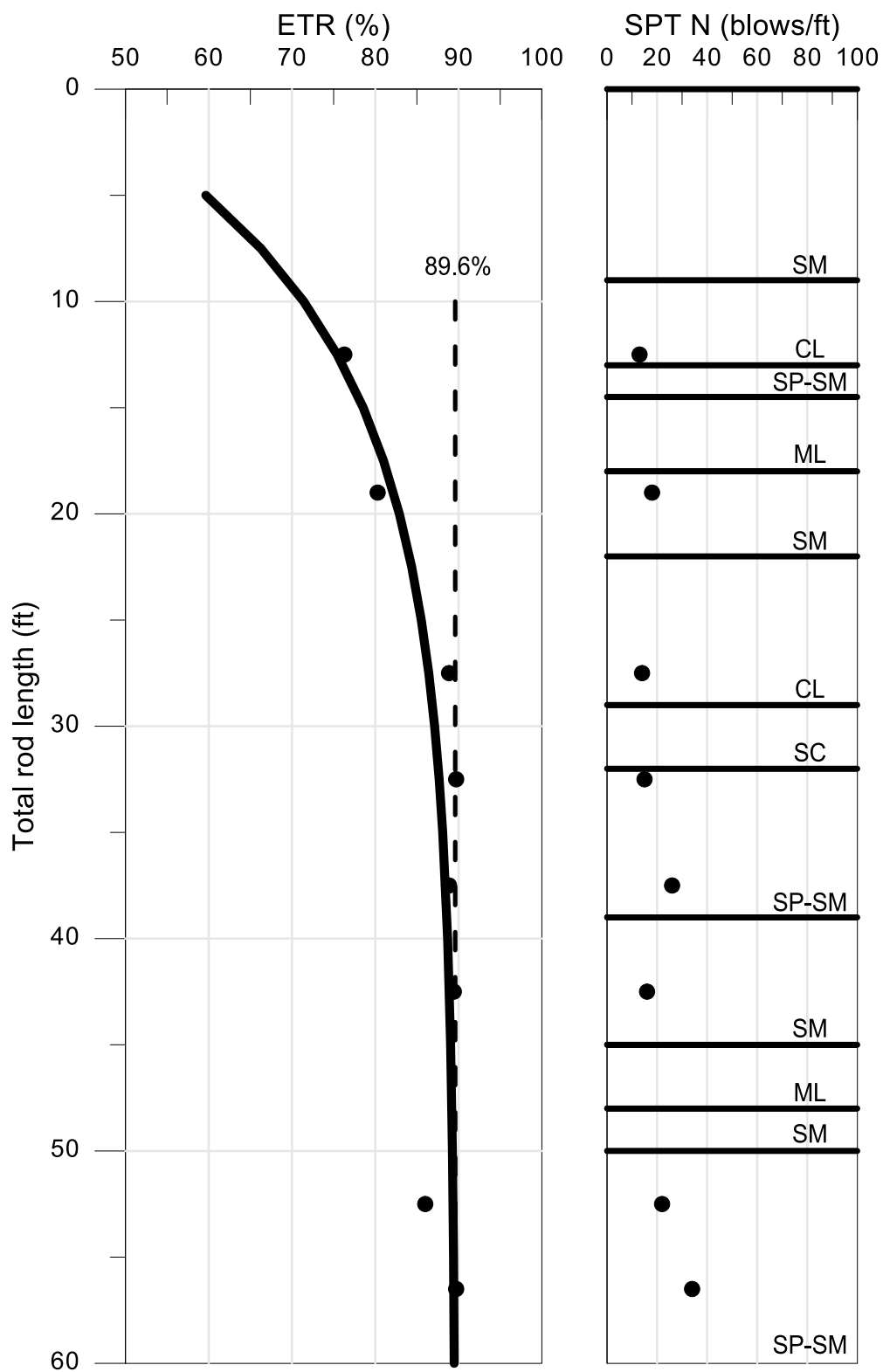


Figure C-23: ETR and Stratigraphy for Boring C23

Table C-23: Rod Lengths and Summary of Hammer Energy Measurements for C23

Hammer Type Automatic
Drill Rig Type CME750
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	8.5	13	12.5	18	267	76.3	2.3	58.9
2	15	18	19.0	45	281	80.3	2.6	49.6
3	23.5	14	27.5	17	311	88.9	0.9	57.1
4	28.5	15	32.5	24	314	89.7	0.6	56.7
5	33.5	26	37.5	31	311	88.9	0.9	54.7
6	38.5	16	42.5	43	313	89.4	1.1	55.7
7	48.5	22	52.5	36	301	86.0	0.9	53.2
8	52.5	34	56.5	39	314	89.7	1.1	54.6

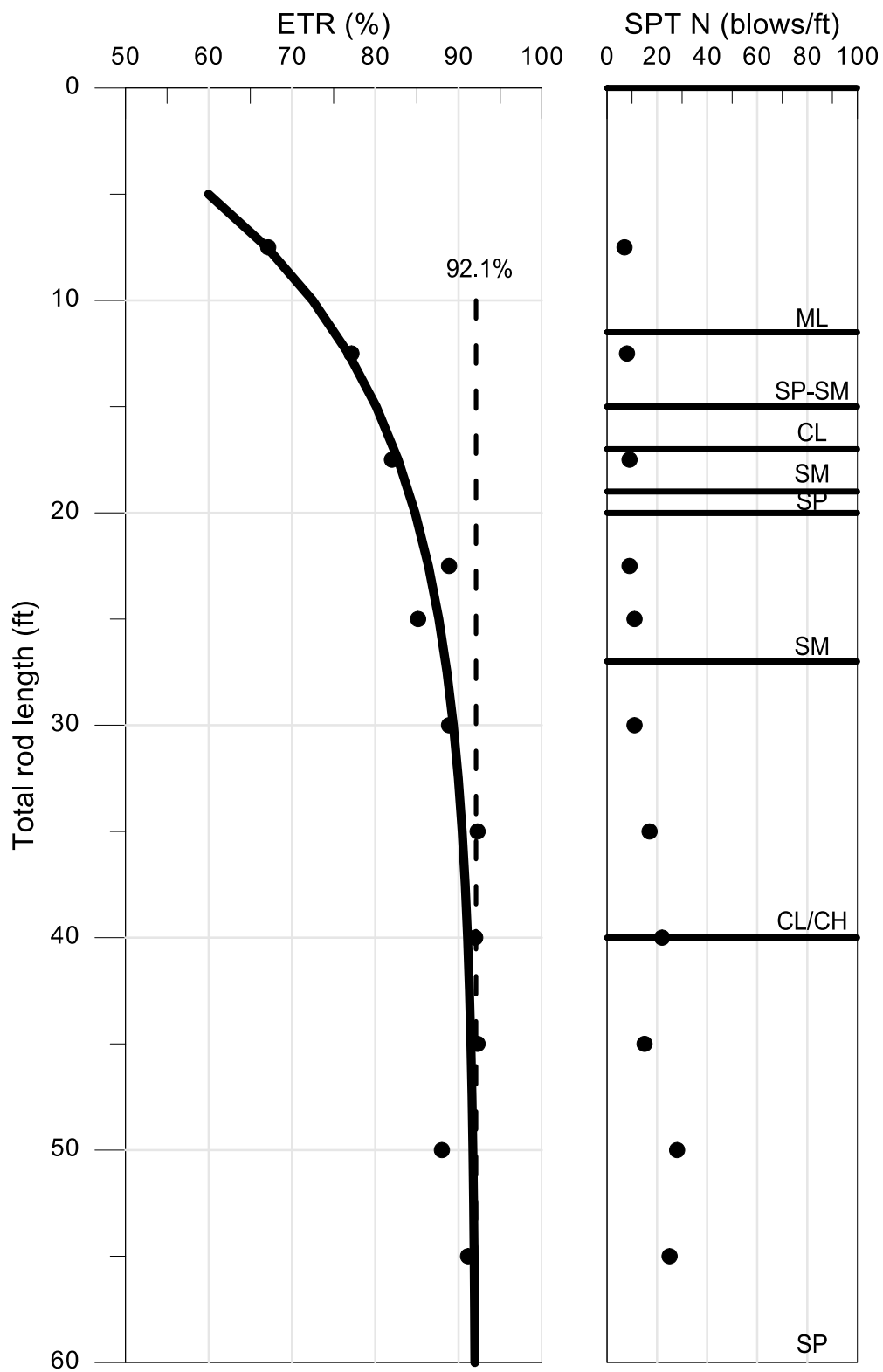


Figure C-24: ETR and Stratigraphy for Boring C24

Table C-24: Rod Lengths and Summary of Hammer Energy Measurements for C24

Hammer Type Automatic
Drill Rig Type CME750
Rod Type NW

Sample No	Depth (ft)	SPT-N (blows/ft)	Rod Length* (ft)	Number of Blows Analyzed	EMX (lb-ft)	ETR (%)	Standard Dev. (%)	BPM Blows/min
1	3.5	7	7.5	7	235	67.1	2.0	49.7
2	8.5	8	12.5	12	270	77.1	2.3	50.6
3	13.5	9	17.5	12	290	82.0	2.6	57.5
4	18.5	9	22.5	14	311	88.9	1.7	54.5
5	21	11	25.0	10	298	85.1	1.1	53
6	26	11	30.0	13	311	88.9	0.9	53.2
7	31	17	35.0	23	323	92.3	1.7	53.1
8	36	22	40.0	28	322	92.0	0.6	51.5
9	41	15	45.0	22	323	92.3	0.9	50.9
10	46	28	50.0	44	308	88.0	1.7	51.9
11	51	25	55.0	41	319	91.1	1.4	53.9