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PERFORMANCE OF DRILLED DISPLACEMENT PILES IN THE MIDWESTERN UNITED STATES

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Drilled displacement (DD) piles often develop significantly larger unit shaft resistance values than other drilled or augered pile systems in coarse grained materials. Minimal vibration and limited spoil development are also associated with DD pile installation and these factors are frequently additional financial and/or environmental benefits of the system. The application of DD piles in North America dates to the mid-1990s and their use in the Midwestern United States has been significant, particularly in the past 10 years.

The authors have collected an extensive database of DD pile performance in the United States. The alluvial and glacial deposits of the Midwestern U.S. provide conditions where drilled displacement piles perform very efficiently when compared to coastal and residual geologies.

This paper presents a summary of the authors' experience regarding installation and performance of DD piles in the Midwestern U.S. Information presented includes summary presentations of DD performance across a range of site conditions as well as a discussion of the relationship of DD performance and installation effort in the Midwest as compared to other geologic settings in the U.S.

INTRODUCTION

According to the US census Bureau, the Midwestern United States comprises the twelve states shown in Figure 1. While the basal geology of these states varies significantly, they share some common features resulting from geologic processes that have occurred over the past two million (+-) years. Figure 2 shows the estimated extent of glacial coverage during (at least) four major episodes of freezing and melting of ice caps, with accompanying rise and fall of ocean levels. It can be seen that the extent of the earliest of these episodes, (indicated by the dashed line) covered most of the Midwest. Those areas of the Midwest that were not covered by ice were strongly influenced by runoff during melting, and Figure 3 shows the major river systems that have developed during the 10,000 (+-) years since the last major glacial period.

Many Geo-practitioners, when first exposed to the concept of cast-in-place displacement piles, think in terms of their application in the Coastal Plain along the Atlantic Seaboard, the Southeastern United States and particularly in Florida. While these areas can offer a good environment for application of the system, the glacial outwash and alluvial deposits of the Midwestern United States provide very favorable condition for the application of drilled displacement piles.

INSTALLATION EQUIPMENT/PROCESSES

Full lateral displacement, cast in-situ piles were developed in Europe during the 1980s and were introduced into the United States in the early 1990s. Several proprietary systems are currently available, and they vary in terms of tooling configuration and casting materials and procedures. The Deep Foundation Institute has adopted "Drilled Displacement Piles" as the umbrella term for these systems.

The projects described in this paper were executed by Berkel & Co. Contractors, Inc (Berkel) which uses the term "Auger, Pressure-Grouted Displacement Piles (APGD)" for their system. The displacement tool for this system is shown in Figure 4. Currently, tools ranging from 0.31 meter (12 in) to 0.46 meter (18 in) in diameter are available. The auger section is typically about 0.9 meter (3 feet) in length, but may vary depending upon application. The installation platform (Figure 4) includes a vertical mast with an attached turntable capable of producing 25 meter-tons (180,000 ft-lbs) of torque, and a system of cabling that allows a downward force (crowd) of 356 kN (40 tons) to be placed on the tools. Piles are cast with fluid grout introduced with over-pressure. A complete description of the system can be found in NeSmith, 2002.

In some cases, thick layers of dense sand in the outwash or alluvial deposits make it impractical to install full lateral displacement piles, yet it might be desirable to improve loose zones and limit stress relief in the dense zones to the extent possible, or to simply limit the volume of spoil. The use of an intermediate or "partial" displacement system has been used to address this situation. Viggiani (1993) analytically described the combinations of tooling configuration, rotational speed, and rate of tool travel whereby net displacement could be achieved with continuous flight auger systems.

The practical application of the concept is achieved by “cork-screwing” the tooling into the ground where possible, which results in the material in the pile area being displaced laterally by the stem. In dense soils, material is transported upward by the flighting, but the quantity of material transported is limited to only that necessary to advance the tool. An example of the tooling for intermediate displacement piles is shown on Figure 4. The tooling is mounted on the same fixed-mast installation platform described for full lateral displacement piles. The basic concepts of intermediate displacement piles are shown in Figure 5.

EXAMPLE PROJECTS

Five example projects from various locations across the Midwest are presented below. Three projects included full DD piles installed in alluvial sands. One project included full DD piles installed in alluvial silts with underlying sand. One project included intermediate DD piles installed in dense alluvial sand.

Piles were tested in general accordance with the “Quick Loading Option” of ASTM D 1143-07 with load increments of about 10 percent of the required ultimate load. IBC 2006 allows for the evaluation of pile load tests with any of the following methods:

1. Davisson Offset Limit
2. Brinch-Hansen 90% Criterion
3. Butler Hoy Criterion
4. Other methods approved by the building official

Piles were evaluated by all of the methods above, including a method proposed by NeSmith (2002) whereby ultimate load is defined as the lesser of the following:

- The load at which the slope of the hyperbolic model of the pile head load-displacement relationship becomes 0.02 inches/ton
- The load at which the pile head deflection is equal to 6 per cent of the pile diameter

It is noted that while the Davisson Offset Limit method is listed as an acceptable process for evaluating ultimate load for pile foundations in IBC 2006, the method was originally developed for driven piles and is not appropriate for cast-in-place foundations (NeSmith and Siegel, 2009). Davisson (1993) recommends a modifier of between 2 and 6 when calculating the offset for evaluating a cast-in-place pile, as research on drilled piers has shown that toe deflections of 2 to 5 percent of the diameter are required to reach ultimate load, compared to less than 1% for driven piles.

Ultimate loads presented below were estimated using the NeSmith, 2002 method. The load test results from Hankinson ND are presented along with the derived ultimate loads from all of the IBC 2006 methods for comparison. The Modified Davisson Limit was evaluated using a modifier of 4.5, based on the authors’ previous experience. The range of ultimate loads for these examples are considered typical of the authors’ experience.

Hankinson ND

Geologic Setting

From Gerber and NeSmith, (2008) the project area is located in south eastern North Dakota, near the outer edge of the Glacial Lake Agassiz basin. The region generally consists of a thick mantle of shore deposits that generally consist of unconsolidated, relatively fine-grained sand deposits. These deposits apparently were deposited nearer the shoreline and they are succinctly different than the heavy clay deposits in the Red River valley.

Underlying the unconsolidated granular deposits, there is glacial till commonly at 75 to 100 feet deep. The glacial till may have been deposited during several glacial advances and can consist of clayey and sandy deposits. Groundwater is commonly observed in the upper four feet of the soil profile.

Subsurface Conditions
Unconsolidated granular soils were observed to depths on the order of 70 to 80 feet. SPT tests in the upper 25 feet were generally in the range of 2 to 8 blows per foot. CPT sounding tip resistances ranged between 20 and 50 tsf. SPT results between 25 and 75 feet were generally between 9 and 15 blows per foot, with qc values ranging between 75 and 100 tsf. Once the borings penetrated the unconsolidated granular soils, they encountered a glacial till with clayey and granular strata. N values generally reached refusal conditions after penetrating the upper 10 to 15 feet of this material.

Groundwater was observed at shallow depths, generally between one-half and two feet deep. Laboratory tests were generally limited to water content tests with select particle size tests. Water contents ranged between 20 and 30 percent. Fines contents on select samples of the granular soil ranged between approximately 25 and 50 percent.

Test Pile Program
Three axial compression load tests were performed on 18-in diameter piles. Two piles were extended to 50 ft and one was extended to 40 ft. The tests were performed with a single loading sequence in 10 or 15 ton increments to a maximum load of approximately 250% of the design compressive load. Results of one 50 ft deep pile and the 40 ft pile are shown in Figures 7 and 8. Ultimate Loads were evaluated to be as follows:
18-in diameter – 50 ft length: 357 tons
18-in diameter – 40-ft length: 313 tons

Council Bluffs IA
Subsurface Conditions
The facility is located adjacent to the Missouri River, approximately 5 miles south of Council Bluffs, Iowa. Approximately 15 ft of (primarily) granular fill was present above the alluvial deposits in the area of the proposed addition. The upper alluvium was fine grained, and of low consistency, but there was a rapid transition to dense to very dense sand between 25 ft and 30 ft The occurrence of a dense sand layer in the upper alluvial profile is a common feature in the Council Bluffs area, and has been noted at other locations in the Midwest. At this site, the dense sand layer was approximately 7 ft thick and was underlain by loose to medium silty sand, which became denser with depth. A second prominent dense sand zone occurred in the range of 45 ft to 50 ft (see Figure 9). It was expected that an ultimate load well in excess of the required 200 tons would be developed for piles that extended into this layer.

Test Pile Program
One axial compression load test was performed on a 16-in diameter pile installed to 50 ft. The test was performed with a single loading sequence in 11 ton increments to a maximum load of over 300% of the design compressive load. The results of this test are shown on Figure 10. The Ultimate Load was evaluated to be 355 tons.

Des Moines IA
Subsurface Conditions
The site lies within both the outwash plain of the Des Moines Glacial Lobe and the floodplain of the Racoon River. Surficial materials included asphalt, concrete, pavement, crushed rock and sand. Fill of sand, clay and rubble was encountered to 1.5 ft to 10 ft below the ground surface. The fine-grained alluvium and glacial till consisted of lean to fat clay and silty clay and was observed to depths from 8 ft to 44 ft.

Coarse grained alluvium was typically very loose to medium dense with no significant density trends with depth or location across the site. It was encountered just below the ground surface, below the cohesive alluvium and above and below the till. The lower boundary was observed from 64 ft to 85 ft depth. Sedimentary bedrock underlay the alluvial sands and was predominantly weathered sandstone with frequently interbedded clay shale layers. Figure 11 is a composite plot of SPT results from borings across the site.

Test Pile Program
Test piles were installed from a working surface at least 15 ft below the original site grade, eliminating penetration through any rubble fill. Three 18-in diameter test piles were installed, two to depths of 34 ft to 35 ft (about 50 ft below the original ground surface) with the pile toe in medium dense to dense sand. One pile was installed to a depth of about 50 ft (about 65 ft from the original site grade) with the pile toe about 2 ft into weathered sandstone. Plots of applied load and pile head displacement are presented in Figures 12 and 13 along with hyperbolic estimates of the load-displacement relationship Ultimate Loads were evaluated to be as follows:
18-in diameter – 50.5 ft length: 415 tons
18-in diameter – 34.5-ft length: 370 tons

South Sioux City NE

Subsurface Condition

Variable fill materials (rubble to silt and lean clay) were encountered below the gravel and asphalt surface to a depth of about 6 ft. Stiff alluvial clays and silts were typically encountered to depths of 13 ft to 23.5 ft below the site grade, however were not encountered in some locations at all (including B-7 within the area of interest for this project).

Coarse-grained alluvial soils ranged from fine to coarse sand with some gravel. The sand were generally medium dense with some dense zones however in the two borings (B-7 and B-8) within the area of interest for this project; the sands were typically dense throughout the profile. Figure 14 includes SPT results from B-7 and B-8. Due to the density condition indicated, **intermediate DD piles** were installed to support the proposed structures in this area of the project site.

Test Pile Program

Two test piles, 14-in diameter and 20-in diameter, were installed to address a range of load conditions. Piles were installed from the ground surface to about 60 ft depth below the site grade. A plot of applied load and pile head displacement is presented in Figure 15 along with a hyperbolic estimate of the load-displacement relationship. The ultimate load of the 20-in diameter pile was evaluated to be 545 tons.

Cohasset MN

Subsurface Information

From NeSmith and Burton (2008) a composite plot of SPT results is shown on Figure 16. Subsurface materials consisted primarily of variable amounts of granular fill overlying predominantly low plasticity alluvial silts. Often, high plasticity clay was encountered immediately below the fill above the silts. In some cases, alluvial silty sands were encountered within the silt profile. Cleaner alluvial sands were typically encountered below the silts, in some cases within the expected pile installation depths.

Load Test Program

Four 16-in diameter test piles were installed to various depths across the site. Test pile T-1 (55 ft) was expected to terminate with the lower pile shaft and toe in sand and was installed to provide a working compressive load of 80 tons. Test piles T-2 (55 ft), T-3 (60 ft) and T-4 (70 ft) were installed with the pile shaft entirely in silt and with the toe in silt or just in silty sand to provide to 60 ton to 70 ton design compressive loads.

Load tests results for T-1 (lower shaft and toe in sand) and T-4 (shaft and toe in silt) are included in this paper. Plots of applied load and pile head displacement are presented in Figures 17 and 18 along with hyperbolic estimates of the load-displacement relationship. Ultimate Loads were evaluated to be as follows:

T-1 16-in diameter – 55 ft length: 225 tons

T-4 16-in diameter – 70-ft length: 205 tons

EVALUATION OF DD PILE PERFORMANCE

Figure 20 is a summary of the authors' database of DD pile performance. The plot is of the calculated Installation Effort (IE) measured during pile installation compared to the ultimate load of the pile. IE is a measure of the energy expended by the drilling platform as the drilling tool is advanced (NeSmith, 2006a and 2006b).

The piles installed in the medium to dense silty sands at the Hankinson ND site (**circles** on Fig. 20) provided high ultimate loads for the effort required to install the piles compared to the database as a whole; thus the results plot just about 1 standard deviation above the mean of the authors' database. In the cleaner sands at the Des Moines IA site (**diamonds** on Fig. 20), the piles produced even higher loads for the effort required for installation; plotting over two standard deviations above the mean of the data. It is noted that the intermediate DD piles from the South Sioux City NE site discussed above plot on about the same line as these piles from Des Monies IA.

The authors' database was originally comprised of projects performed predominantly in the coastal plain of the Atlantic seaboard and gulf coast of the Southeastern United States. In a number of these areas, the coarse grained materials are rounder and more uniform than the angular and varied coarse grained sands and gravels often found in alluvial plains in the Midwest. As more projects have been performed in this area, it has become apparent that the grain and depositional characteristics of this geology lend themselves to providing higher ultimate loads at lower required IE than a number of the coastal geologies in North America.

Also presented on Figure 20 are the four piles installed at Cohasset MN (**triangles** on Fig. 20). They are presented to illustrate the change in IE vs. ultimate load for piles installed in varying soils; in this case, piles installed fully in low plasticity silts compared to a pile installed with the lower shaft and toe in clean sand underlying the silt. The piles installed fully in silt plot well below the mean of the data; the pile of the pile with toe embedded just at the transition from silt to sand plots slightly closer to the mean; and the pile with the lower shaft and toe well into the underlying sand plot within 1 standard deviation of the mean of the data.

SUMMARY

Drilled full and intermediate displacement piles are becoming more commonly installed in a variety of conditions in the Midwestern U.S. Both full and intermediate displacement piles are proving to be very efficient in providing high resistances in these geologies. This appears to be due to soil grain and depositional characteristics that appear to be very favorable for the densification that results from displacement pile installation. As such, displacement piles may be considered as a potential foundation system across a range of site conditions commonly encountered in this region.

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Figure 1 – Midwestern United States

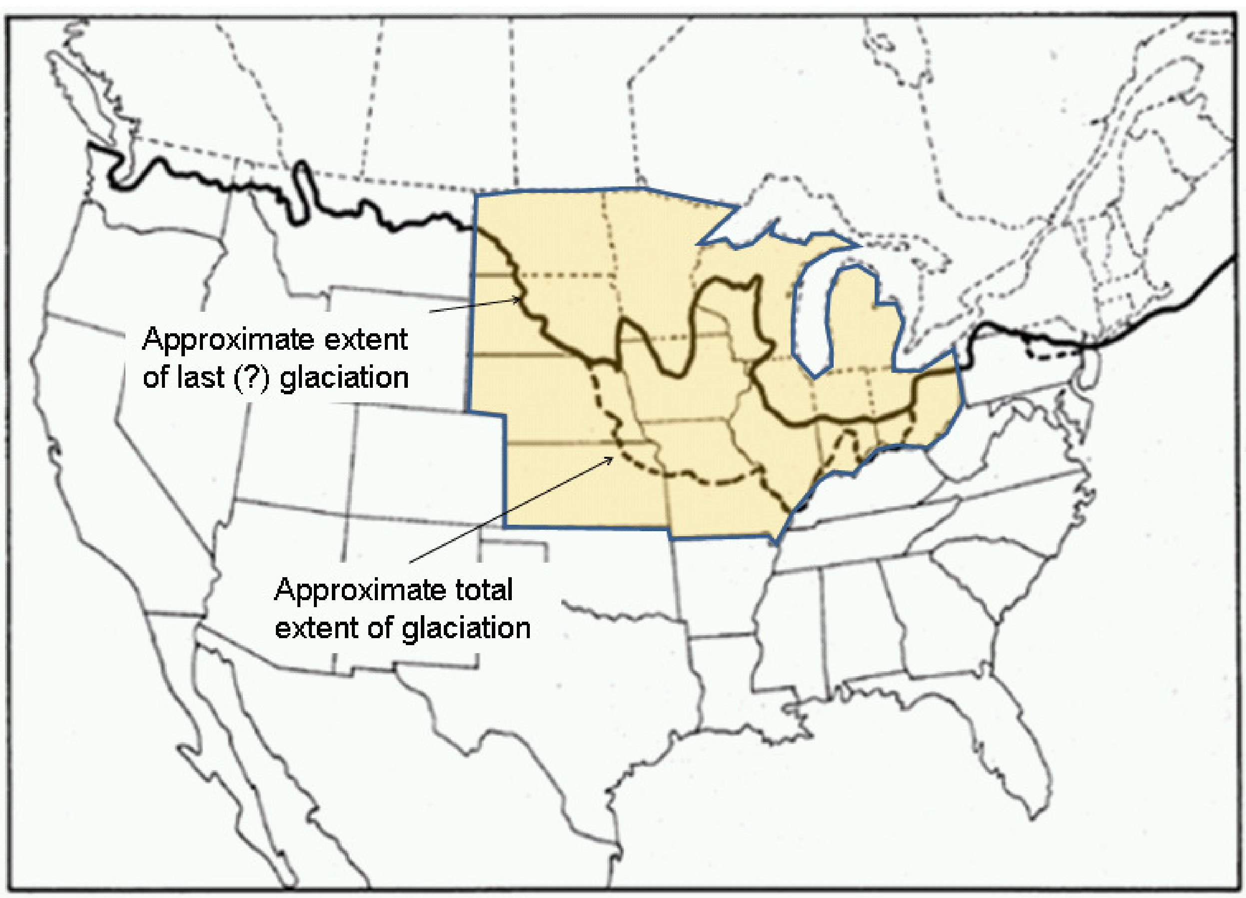
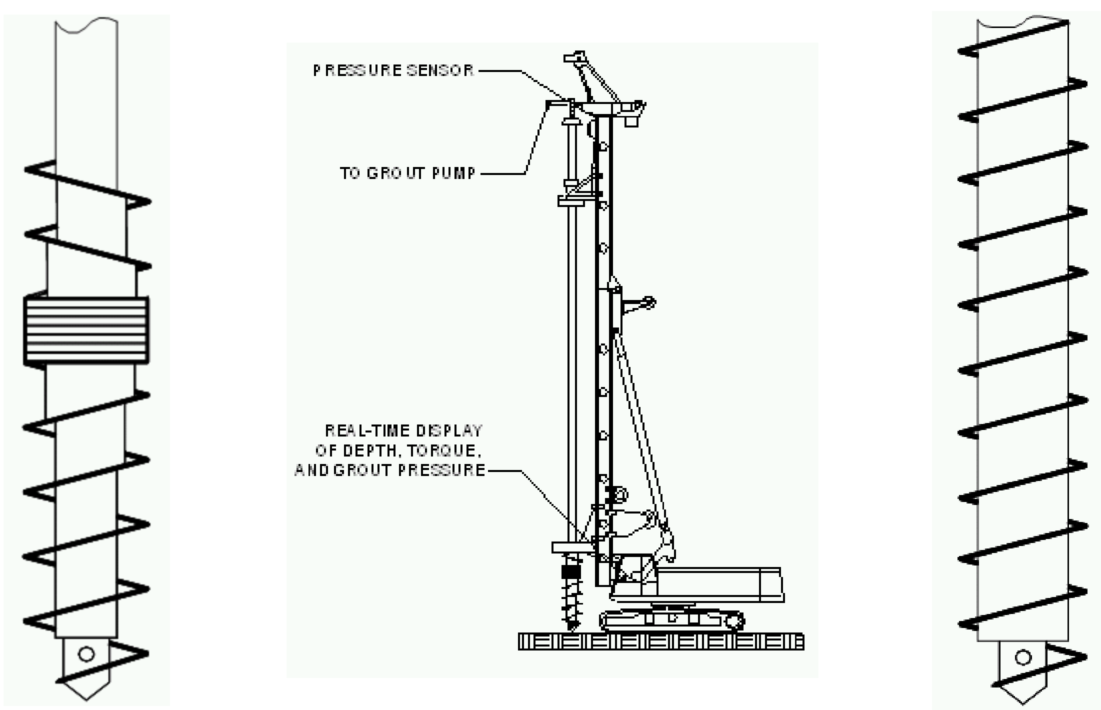


Figure 2 – Glacial Extents in the U.S.

Figure 3 – Major U.S. Rivers



(a) **(b)** **(c)**

Figure 4 – Schematic of (a) Drilled Displacement Pile Tool, (b) Drilling Platform and (c) Intermediate Displacement Tool

The volume of soil <u>removed</u> by the auger (V_r) during a time interval (Δt) drilling is given by:

$V_r = \pi/4\ (d^2 - d_0^2 * nl - v)\ \Delta t$

The volume of soil <u>displaced</u> by the tooling (V_d) during the same time interval (Δt) drilling is given by:

$V_d = \pi d_0^2/4 * (v\ \Delta t)$

If v = nl, Vr =0 and the auger penetrates as a screw.

Where

v= rate of penetration of the auger

n= rotational speed of the auger

l= pitch of the auger

d_0= OD of stem

d= diameter of flighting

In order to get a net compression effect, the displaced volume must exceed the removed volume

$V_d > V_r$ and thus

$v > nl(1 - d_0^2/d^2)$ **the larger this ratio, the more effective the displacement**

Equations from Viggiani, BAP II, 1993, p446

Figure 5 – Basic Concepts for Intermediate Displacement Piles

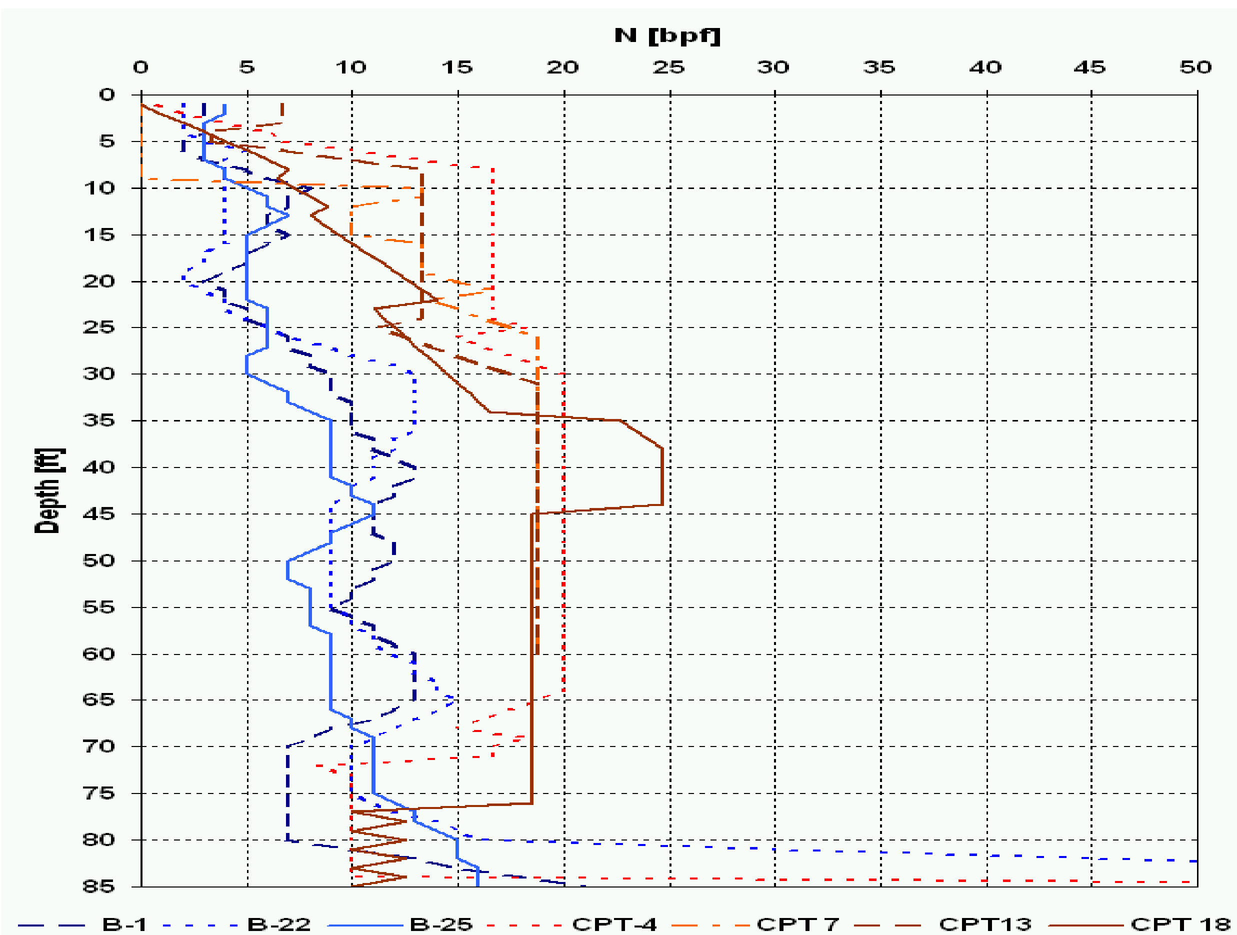


Figure 6 – Composite Plot of In Situ Tests
Hankinson ND

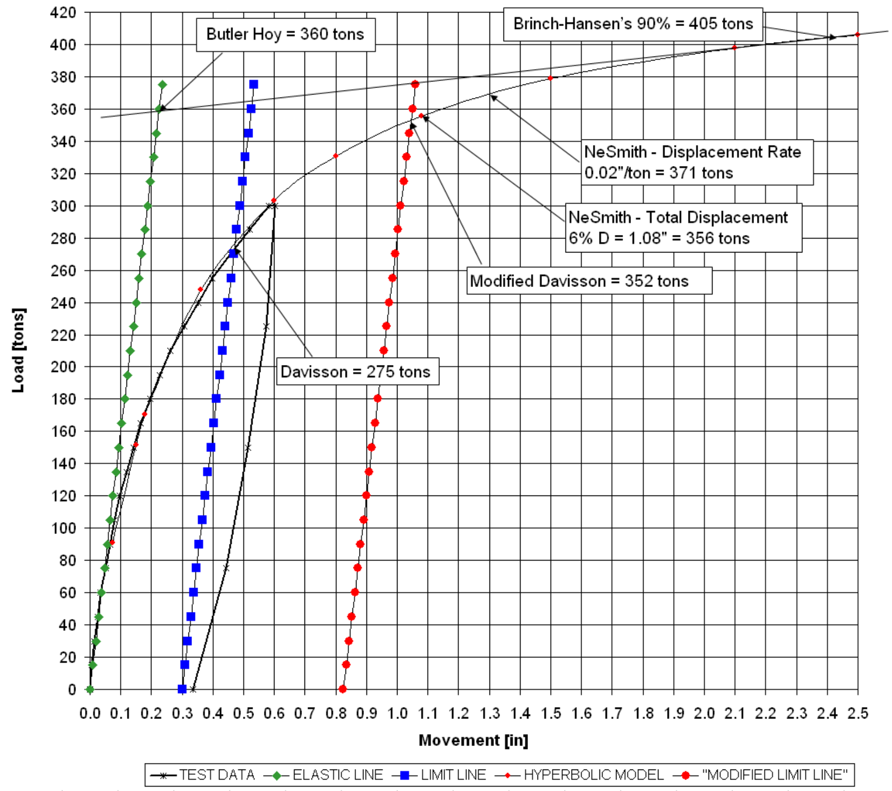


Figure 7 – Applied Loads vs. Pile Head Displacement with Ultimate Load Evaluations

Hankinson ND – 18-in Dia – 50 ft Length Drilled Displacement

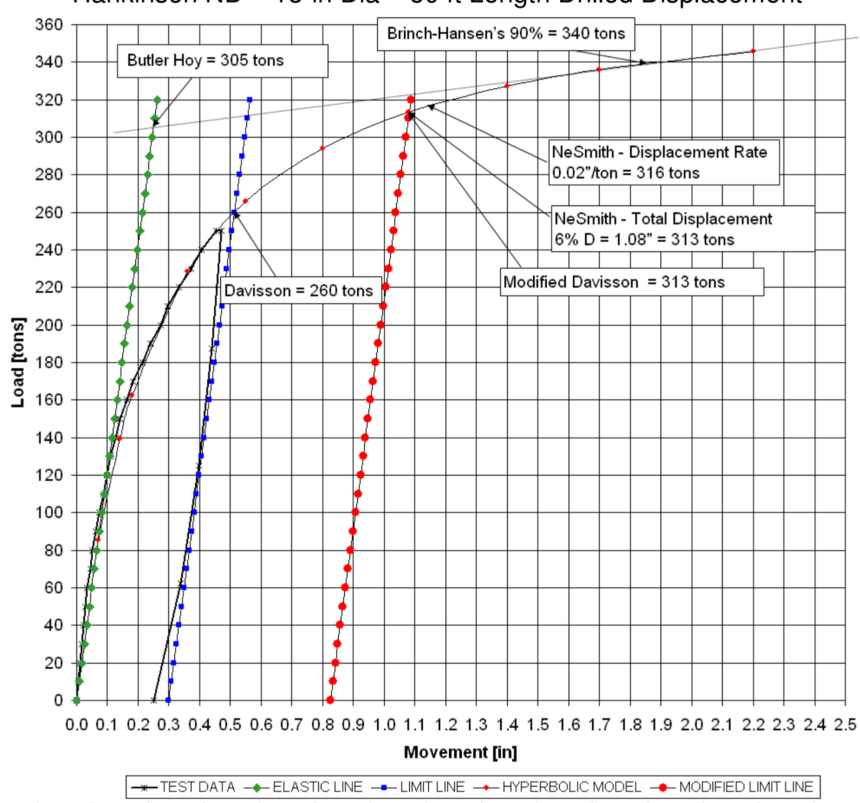


Figure 8 – Applied Load vs. Pile Head Displacement with Ultimate Load Evaluations

Hankinson ND – 18-in Dia – 40 ft Length Drilled Displacement

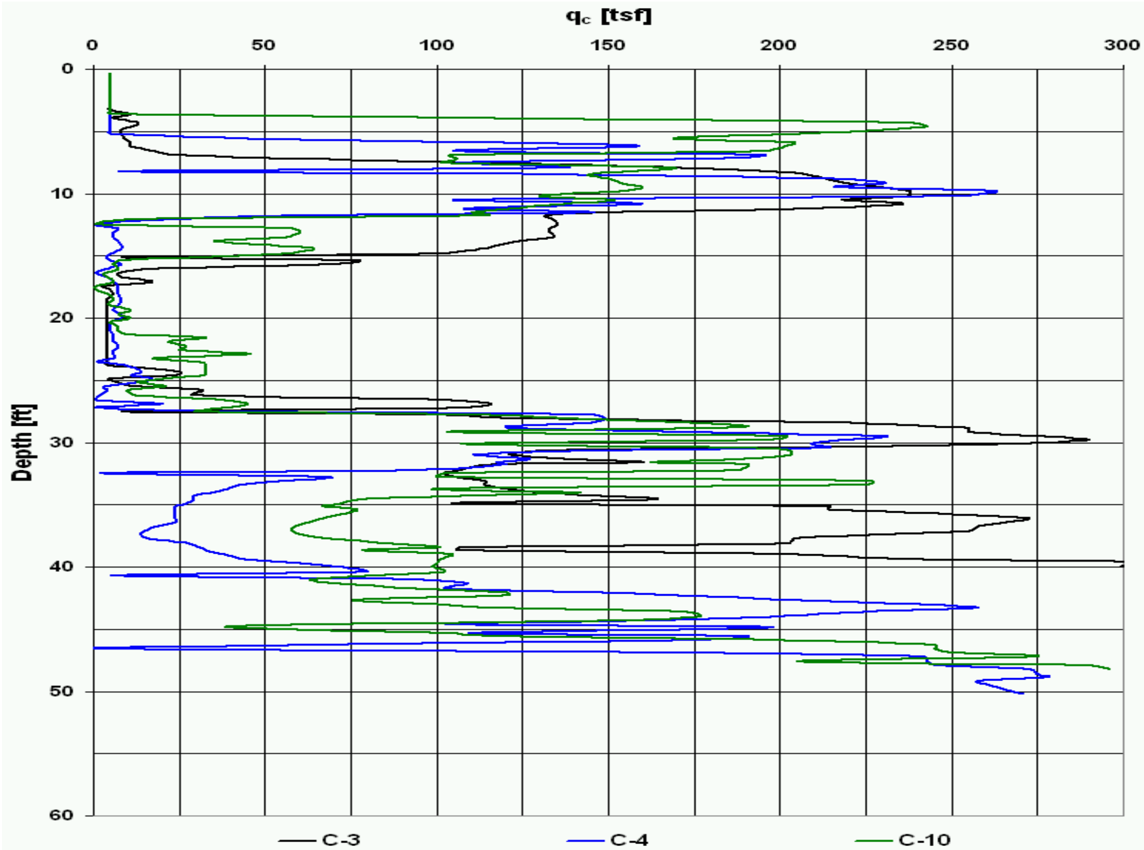


Figure 9 – Composite Plot of CPT Results
Council Bluffs IA

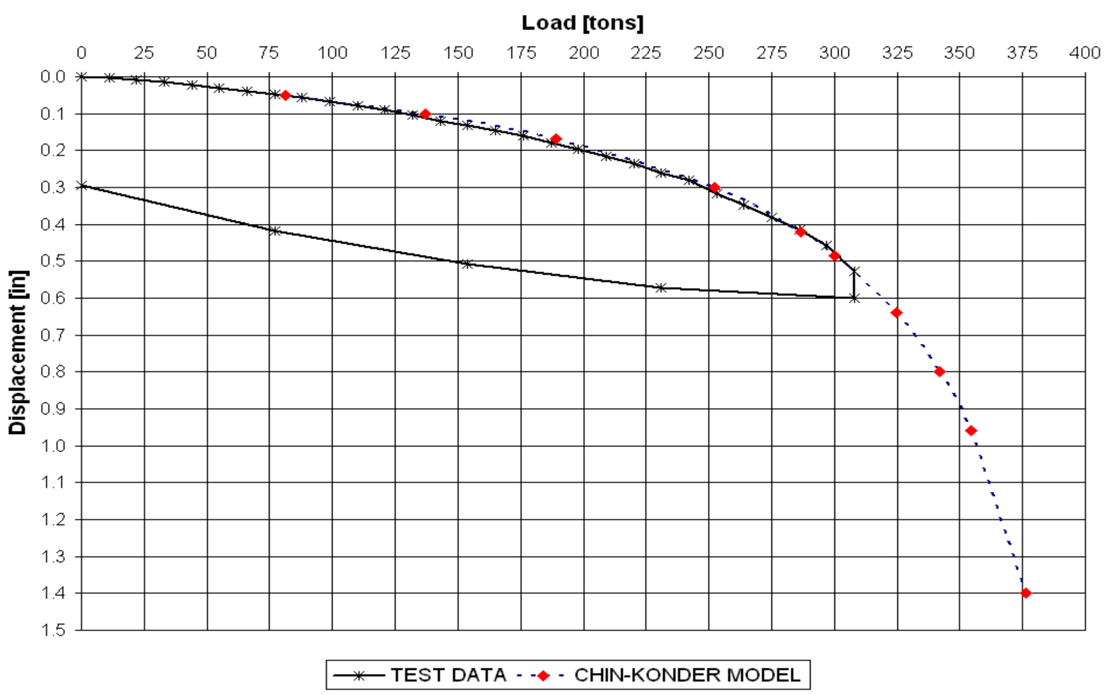


Figure 10 – Applied Load vs. Pile Head Displacement
Council Bluffs IA – 16-in Dia – 50 ft Length Drilled Displacement – Pile Toe in Sand

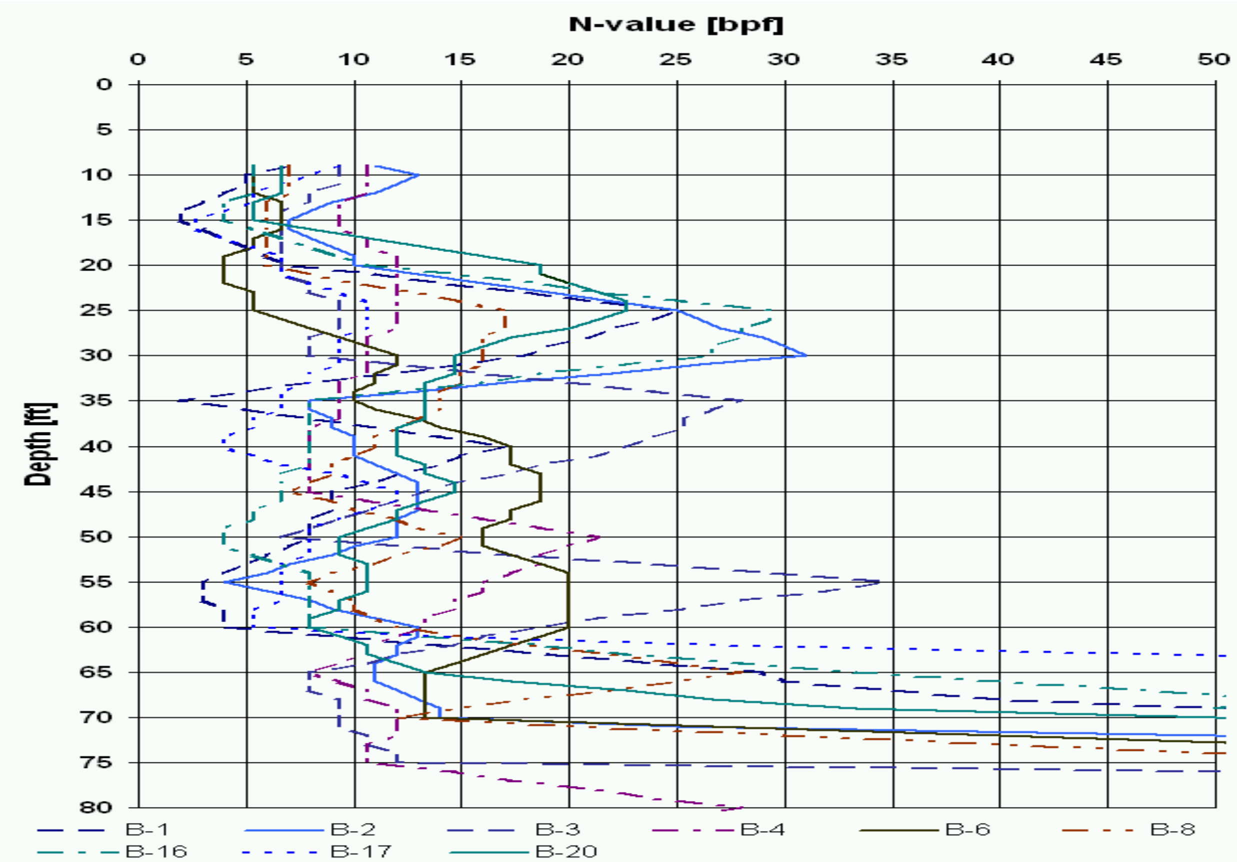


Figure 11 – Composite Plot of SPT Results
Des Moines IA

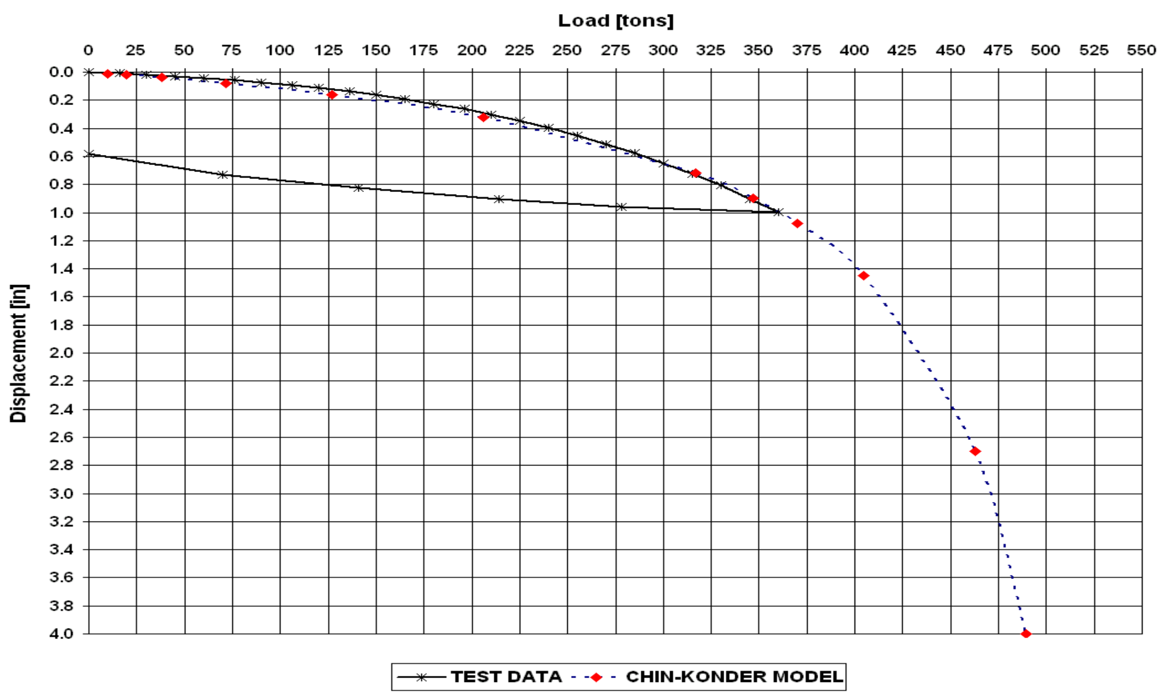


Figure 12 – Applied Load vs. Pile Head Displacement
Des Moines IA – 18-in Dia – 34.5 ft Length Drilled Displacement – Pile Toe in Sand

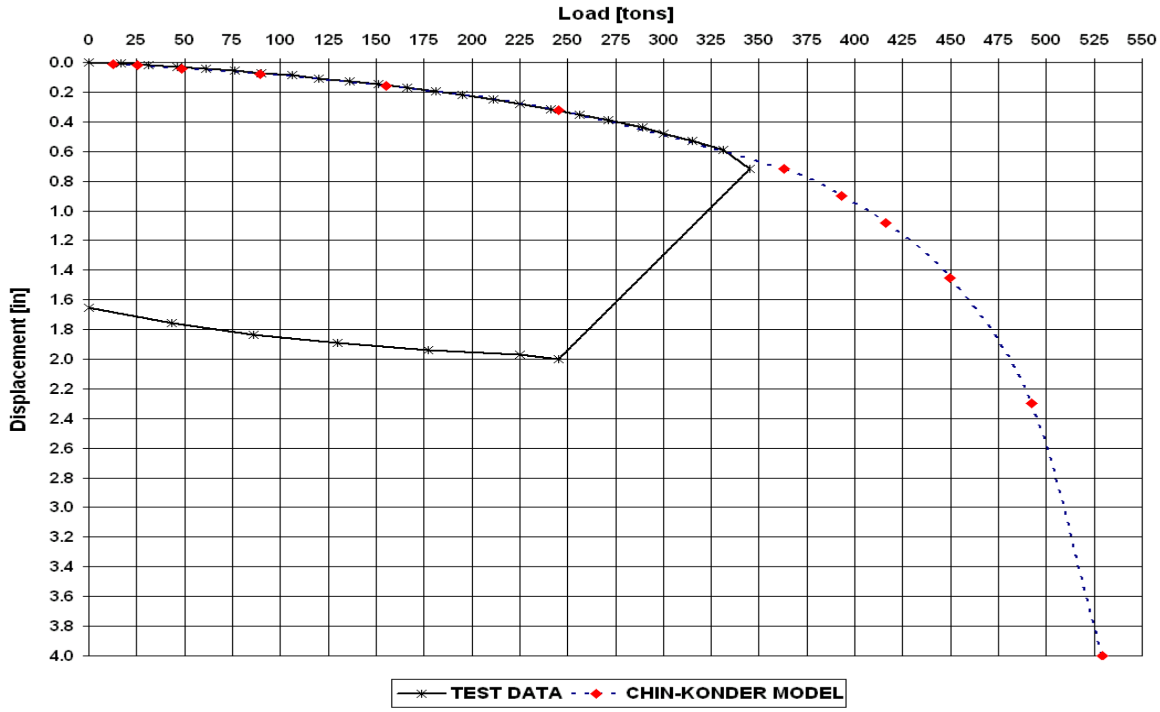


Figure 13 – Applied Load vs. Pile Head Displacement
Des Moines IA – 18-in Dia – 50.5 ft Length Drilled Displacement – Pile Toe in Weather Rock

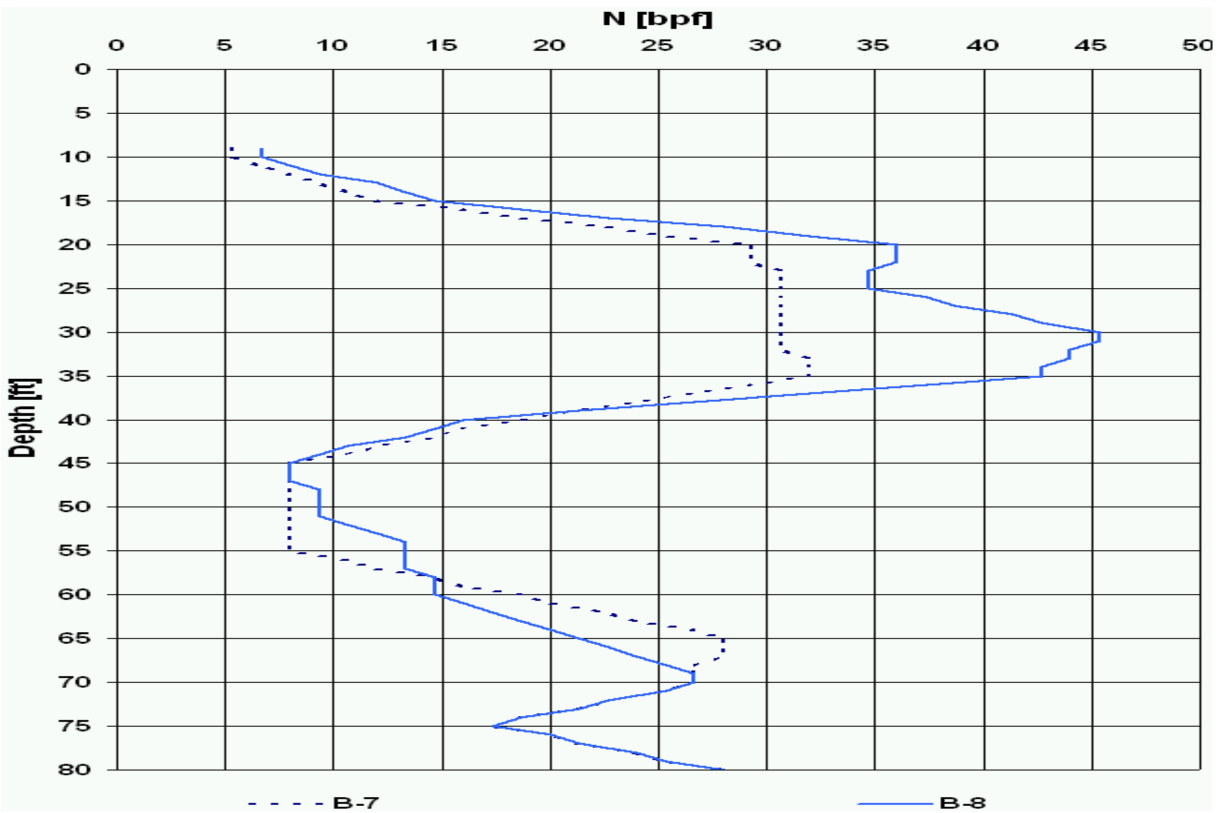


Figure 14 – Composite Plot of SPT Results
South Sioux City NE

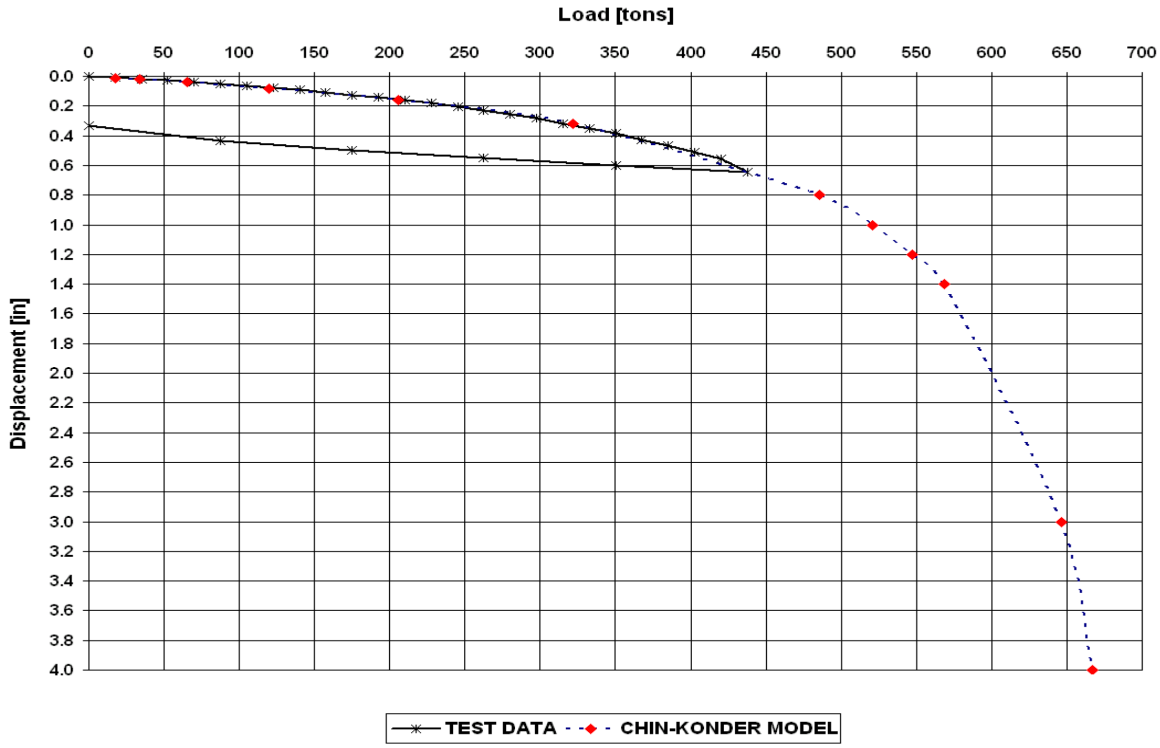


Figure 15 – Applied Load vs. Pile Head Displacement
South Sioux Cit NE – 20-in Dia – 60 ft Length Drilled Displacement

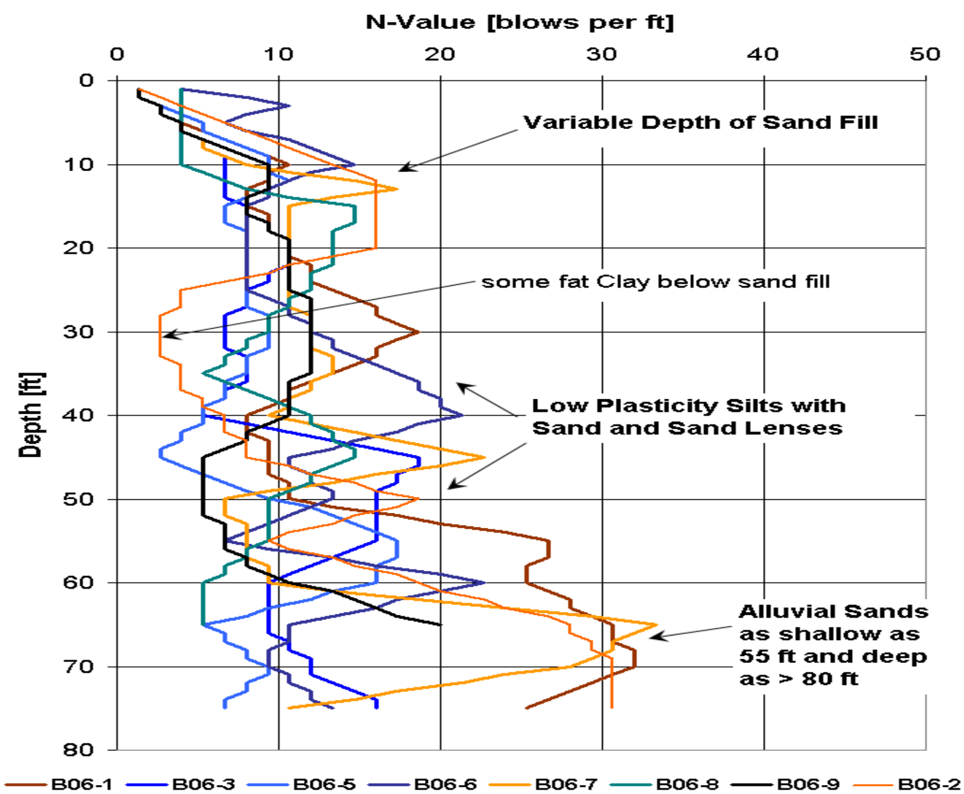


Figure 16 – Composite Plot of SPT Results
Cohasset MN

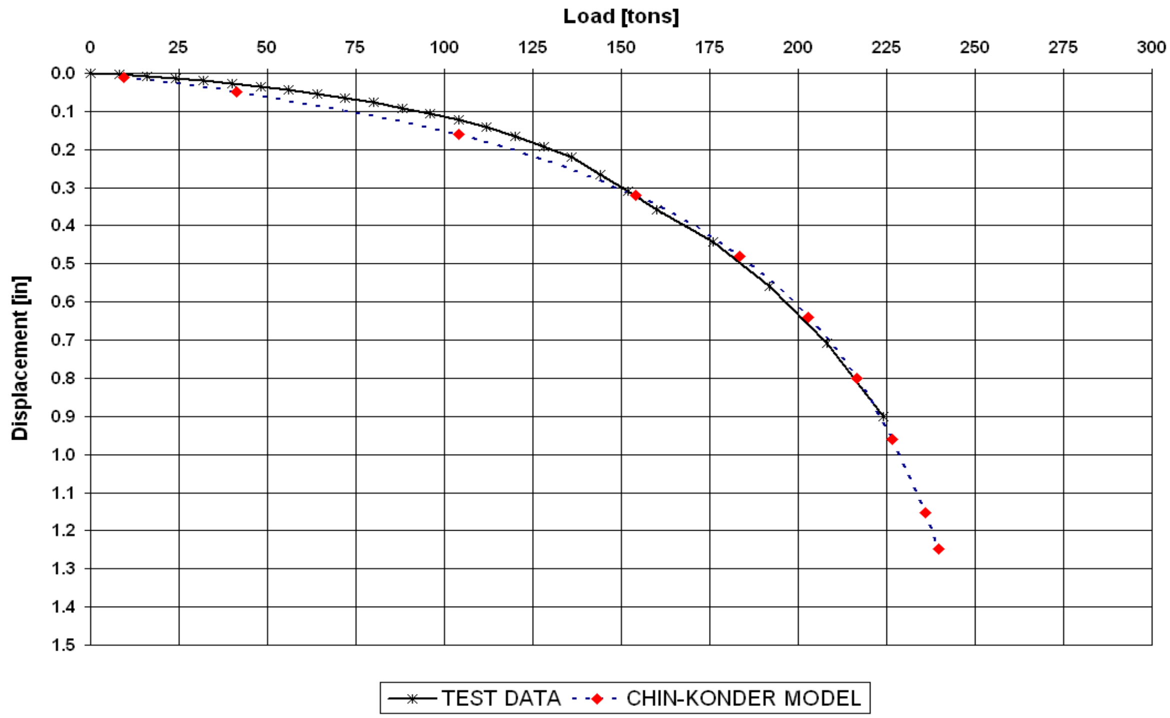


Figure 17 – Applied Load vs. Pile Head Displacement
Cohasset MN – 16-in Dia – 55 ft Length Drilled Displacement – Lower Pile Shaft and Toe in Sand

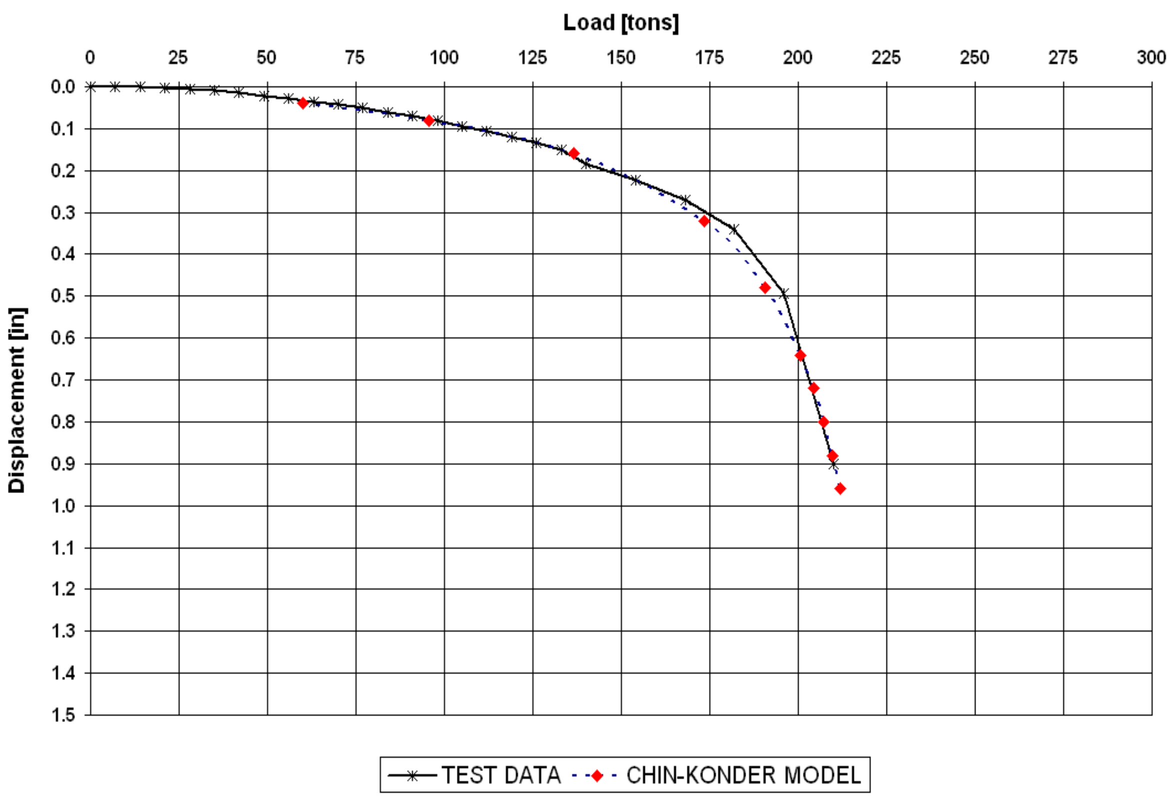


Figure 19 – Applied Load vs. Pile Head Displacement
Cohasset MN – 16-in Dia – 70 ft Length Drilled Displacement – Pile Toe in Silt

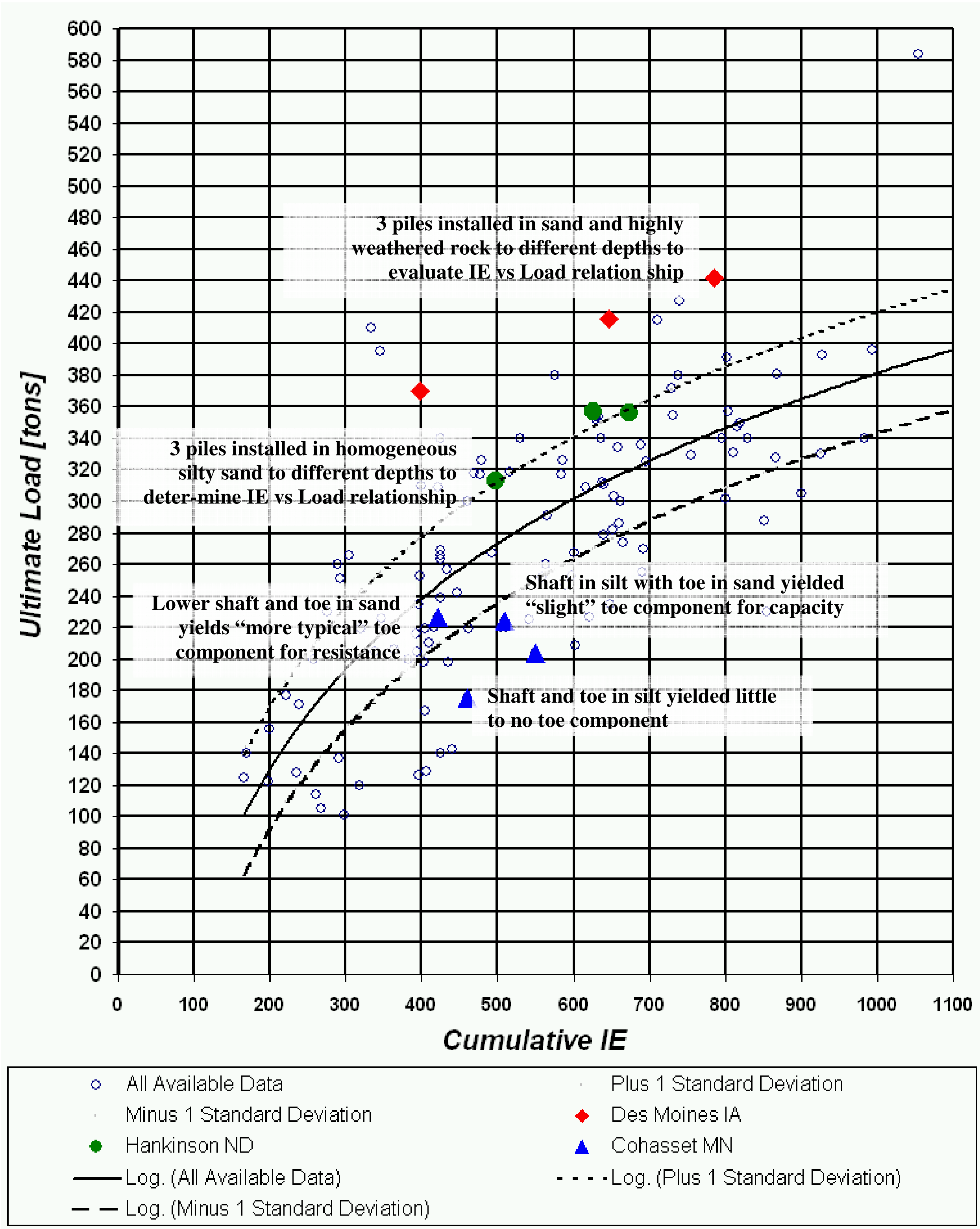


Figure 20 – Database of IE vs. Ultimate Load