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Evaluation of Soil Compaction Measuring Devices

FINAL REPORT

Prepared by

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EXECUTIVE SUMMARY

Title	**Soil Compaction Measuring Device Study**
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Report Period	Final - March 2005
Sponsoring Agencies	Consolidated Edison, KeySpan Energy, PECO Energy Company, Public Service Electric & Gas, Washington Gas, Environmental Protection Agency EPA, Federal Highway Administration, and FERC Funding Program
Objective	The objectives of this research program are: - Evaluate and rank soil compaction measuring devices which are available in the market for use in compaction control of utility trenches, bellholes, and keyholes. - Correlate the output of the devices with the measurements of the Nuclear Density Gauge (NDG). - Recommend modifications of selected devices to enhance their performance and gain their acceptability as a replacement of the NDG.
Approach	The compaction measuring devices were categorized as either in-process Quality Control (QC) devices or after-compaction Quality Assurance (QA) devices. The QC devices were: - The Soil Compaction Supervisor (SCS) - The Utility Dynamic Cone Penetrometer (Utility DCP) - The Humboldt Geogauge - The Clegg Hammers (10-Kg and 20-kg devices)

	The post-compaction devices were used in testing the entire depth of the compacted section. These devices were: - The Standard Dynamic Cone Penetrometer (Standard DCP) - The Panda The measurements of these devices were correlated to the density and moisture measurements of the NDG and the sand-cone tests. Measurements were performed in 3 ft by 3 ft bellholes, 2-ft wide trenches, and 18-inch diameter keyholes. These test sections varied in depth from 14 to 36 inches. Fifteen sets of tests were performed in these sections to evaluate the devices with various backfill types, lift heights, compactor types, soil relative compactions, and moisture contents.
Conclusions	The compaction measuring devices were strength or stiffness measuring devices which monitor the change of soil response due to the application of impact or vibrating force on the soil. All the devices, however, provided a measure of soil densification and they could be used satisfactorily to replace the NDG when they are properly correlated to soil relative compaction. The correlations between the readings of the devices and soil densities were carried out at optimum moisture contents. If the target moisture is not found, the soil must be dried or wetted to achieve the proper moisture content. Maximum compaction may not be achieved if the compaction tool, soil/lift height, and soil moisture are not according to specifications. A comparative performance of the devices is discussed in detail in the 'Conclusions' Chapter of the report and it is summarized in Tables 1 through 3. The conclusions from evaluation criteria of the QC devices are: - Soil moisture measurements of the Nuclear Density Gauge (NDG) were higher than the ones obtained from oven dried tests. The measurements were also higher near the sidewalls of the cuts. Due to the effect of the side boundaries of the cuts, the NDG is not suitable for compaction measurements in small bellholes and keyholes.

	Although the device could be calibrated to minimize the sidewall effects, the need to calibrate the device at each soil lift makes it impractical in these applications. - The Utility-DCP and the 10-kg Clegg Hammer had the highest overall performance of the QC devices. - The SCS performed well in confined bellholes and keyholes. However, the sensor lost the compaction signal at depths higher than 30 inches. The device also lacks a numerical display of compaction to enable calibrating the output to soil relative compaction. - The performance of the 20-kg Clegg Hammer was similar to the 10-kg device. However, it was heavier and less sensitive to small changes in relative compaction. - The measurements of the Geogauge were affected by the side boundaries of the cut and had a weak correlation in sand backfills and stone base layers. The recommended modifications of the selected devices are listed in the ‘Conclusions’ Chapter and they are related to increasing their durability, improving their data display and download capabilities and adding stand-alone or integrated moisture measurement capabilities.

Table 1 – List of the Acceptance Values for each Device [1]

Soil Type	NDG	SCS	Utility DCP	Geogauge	Clegg Hammer 10-Kg	Clegg Hammer 20-Kg	DCP	PANDA
Sand	Reference Value	Good	6	30	6	5	1.1 blow/inch	Pre-calibrated
Silty-Clay	Reference Value	Fair (soil must be w/in moisture range	22	45	8	6	5 blow/inch	Pre-calibrated
Granular & Stone-Base	Reference Value	Good	11	No correlation	14	9	2 blow/inch	Pre-calibrated

(1) Acceptance values of the device which compare to 90%-Modified Relative Compaction from NDG

Table 2 – List of the Operation Characteristics of the Devices

Features	NDG	SCS	Utility DCP	Geogauge	Clegg Hammer 10-Kg	Clegg Hammer 20-Kg	DCP	PANDA
Measurement	Wet & Dry Soil Density, Soil Moisture	Max. Attainable Compaction	Penetration (blow count)	Soil Stiffness & Young's Modules	Clegg Impact Value (IV)	Clegg Impact Value (IV)	Penetration (blow count)	Tip Resistance and Penetration
Moisture Readings	Yes , higher than oven-dried	No	No	No	No	No	No	No
Calibration of Device	Requires field calibration	Pre-set System	No	calibration plate	Factory calibrated	Factory calibrated	No	Factory calibrated
Portability [(1)]	Good	Good	Good	Good	Medium	Poor	Medium	Medium
Durability [(2)]	Good	Box - Good Sensors – Fair	Good	Good	Poor	Poor	Good	Good
Standard Procedure	ASTM D-2922 ASTM D-3017	None	None	ASTM 6758	ASTM D-5874	ASTM D-5874	ASTM D-6951	(French Standard)
Operator skill	Licensed Technician	Worker	Worker	Worker	Worker	Worker	Worker	Technician
Ease of use-Training	Medium –Requires Training	Easy –Minimal training	Easy –Minimal training	Easy-Minimal training	Easy –Minimal training	Easy –Minimal training	Easy-Require data plotting	Medium-Extensive training
Initial Cost	About $6,200	About $1,650	About $300	About $5,300	About $2,400	About 2,400	About $900	About $7,500

[(1)] Portability: Weight and ease of mobility on site
[(2)] Durability: The device ability to withstand daily use without damage or breakdown

Table 3 – List of the Application Characteristics of the Devices

Features	NDG	SCS	Utility DCP	Geogauge	Clegg Hammer 10-Kg	Clegg Hammer 20-Kg	DCP	PANDA
QC(each layer) QA (full depth) Application	QC	QC [continuous during compaction]	QC	QC	QC	QC	QA [Full depth]	QA [Full depth]
Data Storage	Stores Data	Stores Data	Manual recording	Stores Data	Manual display	Manual display	Manual recording	Stores in memory
Trench Boundary (1)	Readings affected by sidewall	No effect	No effect	Readings affected by sidewall	No effect	No effect	No effect	No effect
Keyhole Application	No	Yes	Yes (hard to read markers)	No	Yes	Questionable (heavy)	Yes	Yes
Depth of Readings	up to 12 inches	Up to 12 inches/lift (30" Full Excavation)	Up to 8 inches	9 inches per Manufact. Data [not confirmed in tests]	About 8 inches	About 10 inches	Full depth (up to 3 ft)	Full depth (has extension rods)
Surface Readings	Not recommended in soils	N/A	Unreliable for top 2-3 inches in sand	Sensitive to surface stiffness	Sensitive to surface stiffness	Sensitive to surface stiffness	Not recommended for top 6 inches in sand	Not recommended for top 6 inches in sand
Output Consistency(2)	Good	Good	Fair	Fair	Medium	Medium	N/A	N/A

(1) Trench boundary were evaluated based on effect of distance from trench or bellhole sidewalls

(2) Output Consistency = Repeatability of the results at the same testing conditions.

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INTRODUCTION

Many of the available soil compaction measuring devices, other than the Nuclear Density Gauge (NDG), do not provide direct readout of soil density or soil moisture values which are the two main parameters to control soil compaction performance. Most of theses devices are strength or stiffness measuring devices which monitor the change of in-place engineering properties due to the application of impact or vibrating force on the soil. Their output, however, provide a measure of soil densification and they can be used satisfactorily in compaction control when they are calibrated to soil relative compaction and moisture content.

In order to establish the relationship between the readings of these devices and soil relative compaction, there is a need to evaluate the sensitivity of the measured strength and stiffness parameters to the changes of soil types, moisture contents, and compaction efforts.

A comprehensive experimental program was performed in order to correlate the readings of these devices to soil densities and moisture conditions. The experiments focused on evaluating the devices during the compaction of trenches and utility cuts in roads and highways. The backfills commonly used in these applications were the native silty-clay soil excavated from the cut, granular soils, and stone base materials.

The compaction measuring devices were categorized into two types. These types are Quality Control (QC) measuring devices which are used in layer-by-layer measurements during compaction, and Quality Assurance (QA) devices that are used in measuring the post-compaction profile of the whole section. The QC devices were the Soil Compaction Supervisor (SCS), the Utility Dynamic Cone Penetrometer (Utility DCP), the 10-Kg and 20-Kg Clegg Hammers, and the Geogauge. The post-compaction QA devices were the Dynamic Cone Penetrometer (DCP) and the Panda meter. The measurements of these devices were correlated to the density and moisture measurements of the Nuclear Density Gauge (NDG) and the Sand Cone tests.

A description of the experimental program is shown in the first chapter of the report. This chapter presents the laboratory and field testing programs performed for the evaluation of the devices.

The results of the testing program are presented in the second chapter of the report. The chapter includes a description of each of the devices and its correlation to relative compaction and moisture content.

The results were utilized to establish the criteria for selecting the most applicable devices for use in compaction control of trenches and bellholes. The Conclusions chapter of the report presents the summary of the recommended modifications of the selected devices to enhance their performance and gain their acceptability as a replacement of the NDG.

EXPERIMENTAL PROGRAM

A comprehensive experimental program was performed in order to correlate the readings of the soil compaction-measuring devices to soil densities and moisture contents. The scope of the testing program focused on the following:

- Testing the types of soils commonly used as a backfill materials in the restoration of utility cuts; namely, sand backfill, silty-clay native soils, and stone-base.
- Evaluating the devices in standard bellhole sections, 2-ft wide trenches, and 18-inch diameter keyholes. Most of these sections were tested with 3 ft deep backfills.

Most of the test sections were constructed in the outdoor pavement testing facility at GTI. Some of the bellhole sections were constructed in the indoor soils lab.

A description of the experimental program is shown in Table 4. The table shows the geometry of the test sections, backfill types, and compaction properties.

Soil Properties

The compaction properties of the backfill materials were determined at the GTI Soils Lab. Figures 1 and 2 show the sieve-analysis and compaction testing equipment at the lab. Sieve analysis tests were performed on the soils according to ASTM D422 specifications. Soil moisture-density relationships were determined in Standard Proctor tests according to AASHTO specifications T99 and Modified Proctor tests according to AASHTO T180.

Two types of sand backfill were used in the tests. IL-Sand was a local uniform sand type FA-6 according to Illinois DOT specifications [*1*], with about 3 percent passing the No. 200 sieve. The second sand type, NJ-Sand, was a uniform backfill obtained from the New Jersey restoration site. The silty-clay soil had 50 percent fines passing sieve No. 200 and a medium plasticity index of 12. Stone-base soil was a well graded CA-6 aggregate material according to Illinois DOT specifications. The grain size distribution of the backfill is shown in Figure 3.

Table 5 shows the compaction properties of the soils based on the AASHTO Standard T180 for modified proctor tests.

Table 4 – Properties of the Test Sections in the Testing Program

Test Set	Section	Soil Type	Compactor Type	No. of lifts	lift thickness (inch)	Avg. Relative compact. (%)	Avg. w/c (%)	Notes
Sand_1	3x4-ft bellhole	IL-Sand	Vibrating Plate	6	6	92	5.5	Measured each lift at 90% relative compaction
Sand_2	3x4-ft bellhole	IL-Sand	Vibrating Plate	2	12	93-95	4.5-6	- Thicker layers - Measured at each pass
Sand_3	2x2-ft bellhole	IL-Sand	Vibrating Plate	1	14	94	variable	Tests at variable moisture contents 2-12%
Sand_4	3x4-ft bellhole	IL-Sand	Vibrating Plate	2	8 and 24	95	5	Variable layer thickness
Sand_5	3x4-ft bellhole	IL-Sand	Vibrating Plate	1	10	93	5	Boundary effects
Sand_6	18-inch keyhole	IL-Sand	Pneumatic Jumping Jack	6	6	91	6.5	Keyhole test, sand backfill
NJ-Sand	2-ft wide trench	NJ-Sand	Vibrating Plate	6	6	88	8	- New Jersey Backfill - Measure at each pass
Clay_1	2-ft wide trench	Silty-clay soil	Rammer	5	6	variable	12-14	Measured at each compactor pass
Clay_2	2x2-ft bellhole	Silty-clay soil	Rammer	1	14	85	variable	Tests at variable moisture contents 5-14%
Clay_3	18-inch keyhole	Silty-sand Native soil	Pneumatic Jumping Jack	6	6	90	14	Keyhole test, native soil

Table 4 – Properties of the Test Sections in the Testing Program [Continued]

Test	Section	Soil Type	Compactor Type	No. of layers	Layer thickness (inch)	Avg. Relative compaction (%)	Avg. w/c (%)	Notes
Stone-1	2x2-ft bellhole	Stone base CA-6	Vibrating Plate	1	14	78-80	variable	Tests at variable moisture contents 2-8%
Stone_2	3x4-ft bellhole	Stone base CA-6	Pneumatic Jumping Jack	5	6	94	12	Keyhole test, stone-base
Stone_3	2-ft wide trench	Stone base CA-6	Vibrating Plate	5	6	92-98	16	- Variable Relative Compaction - Measured at each pass
Outdoor bellholes	3x3-ft bellholes	Variable soils	Rammer	variable	variable	variable	variable	9 outdoor Bellholes with various backfills and densities
NJ Site	-Trench - 4x4 ft bellhole	NJ-Sand	Rammer	variable				- NJ Field section - Trench and bellhole - Performed forensic tests

Figure 1 - Performing soil gradation tests in the GTI Soils Lab

Figure 2 – The soil compaction testing equipment at GTI

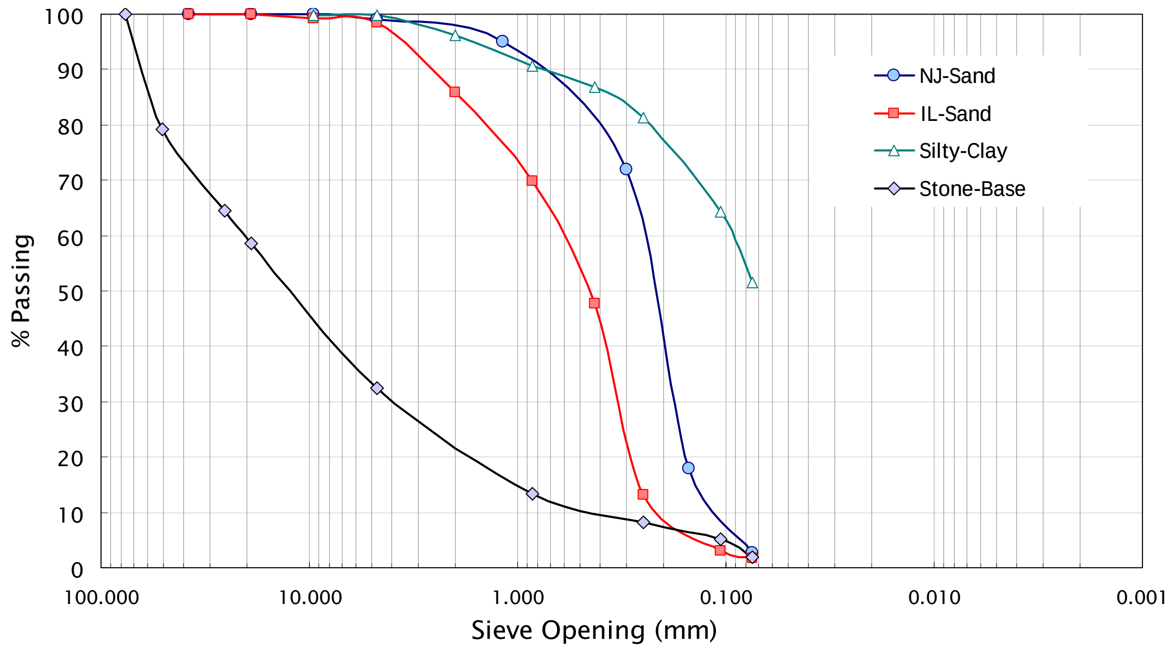

Figure 3 - Grain size distribution of the backfill materials

Compaction Measuring Devices

Table 6 shows a list of the compaction measuring devices used in the testing program and Table 7 shows a list of the manufacturers of the devices. A description of the devices is presented in detail in the following chapters of the report.

Table 5 – Modified Proctor Compaction Properties of backfill materials

Soil Type	Maximum Dry Density (pcf)	Optimum Moisture Content (%)
IL-Sand	119	5
NJ-Sand	102	9
Silty-Clay	123.7	13
Stone-Base soil	142.9	7.8

Table 6 - The Compaction Measuring Devices

	Device	
1	Nuclear Density Gauge [NDG] [Troxler Model 3440]	
2	Sand-Cone Density Apparatus	
3	Soil Compaction Supervisor [SCS]	
4	Dynamic Cone Penetrometer [Utility DCP]	
5	Dynamic Cone Penetrometer [Standard DCP]	
6	Geogauge	
7	Clegg Hammers [10-kg & 20-kg Hammers]	
8	PANDA	

Table 7 - A list of the devices' manufacturers

	Device	Distributor/Manufacturer
1	Nuclear Density Gauge – [Troxler Model 3440]	Troxler Electronic Laboratories Contact: Michael Dixon 1430 Brook Dr. Downers Grove, IL 60515 Phone: 630-261-9304
2	Sand-Cone Density Apparatus	Humboldt Mfg. Co. 7300 West Agatite Ave. Norridge, IL 60706 Phone: 800-544-7220
3	Soil Compaction Supervisor [SCS]	MBW Incorporated Contact: Frank Multerer P.O. Box 440 Slinger, WI 53086 Phone: 800-678-5237
4	Dynamic Cone Penetrometer [Utility DCP]	SGS Manufacturing Contact: Sandy Golgart 4391 Westgrove Dr. Addison, TX 75001 Phone: 800-526-0747
5	Dynamic Cone Penetrometer [Standard DCP]	Kessler Instruments, Inc. 160 Hicks St. Westbury, NY 11590 Phone: 516-334-4063
6	Geogauge	Humboldt Mfg. Co. 7300 West Agatite Ave. Norridge, IL 60706 Phone: 800-544-7220
7	Clegg Hammer [10-kg & 20-kg Hammers]	Lafayette Instruments Contact: Paul Williams P.O. Box 5729 Lafayette, IN 47903 Phone: 765-423-1505
8	PANDA	Sol Solution Contact: www.sol-solution.com 115 Old Short Hills Rd., Apt. 306 West Orange, NJ 07052 Phone: 973-243-7237

Test Sections

1. Bellhole Section Sand-1

Section Sand-1 consisted of a bellhole 3 ft wide, 4 ft long, and 3 ft deep. The bellhole contained a 4-inch plastic pipe at the bottom of the section. An earth pressure cell was placed at the top of the pipe to monitor the load transmitted from the compactor at various backfill heights. Figure 4 shows the instrumented section with the pressure cell, strain gauge on the PE pipe, and the Soil Compaction Supervisor (SCS) the bottom of the bellhole.

The bellhole was backfilled with soil type IL-Sand in 6-inch lifts as shown in the schematic diagram in Figure 5. The soil was compacted at the optimum moisture content using a vibrating plate (Figure 6). Compaction measurements were taken at each layer when the soil passed the 90 percent modified relative compaction. Table 8 shows the compaction properties of each layer.

Figure 4 - Bellhole test section Sand-1

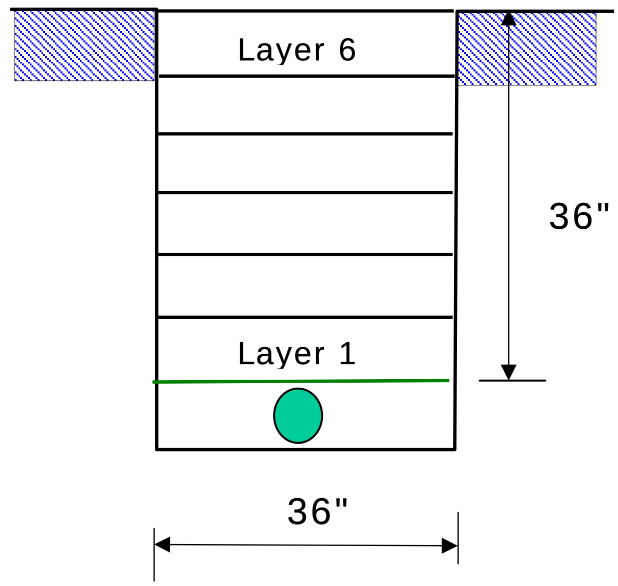

Figure 5 - Cross-section of the bellhole test section Sand-1

Figure 6 – Compaction of sand using vibrating plate in the bellhole

Table 8 – Layers' Properties in the Bellhole Sand-1

Layer	Layer height (after compaction)	Relative Compaction (% Modified)	Devices Used
1	5.5	89	After compacting each layer: NDG SCS Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction: Sand-cone (top layer) Standard DCP PANDA
2	6	92	
3	5	92.1	
4	5.5	91	
5	5.5	92.7	
6	5.7	93	

2. Bellhole Section Sand-2

Section Sand-2 was tested using the same type of backfill, IL-Sand. The backfill was excavated using a vacuum truck (Figure 7) and it was backfilled in two 12- inch thick layers. Figure 8 shows the cross section of the bellhole.

In this test, compaction measurements were taken after each compactor pass in order to evaluate the devices at various levels of compaction. Table 9 shows the compaction devices and backfill properties of the section.

Figure 7 – Vacuum excavation of the compacted backfill

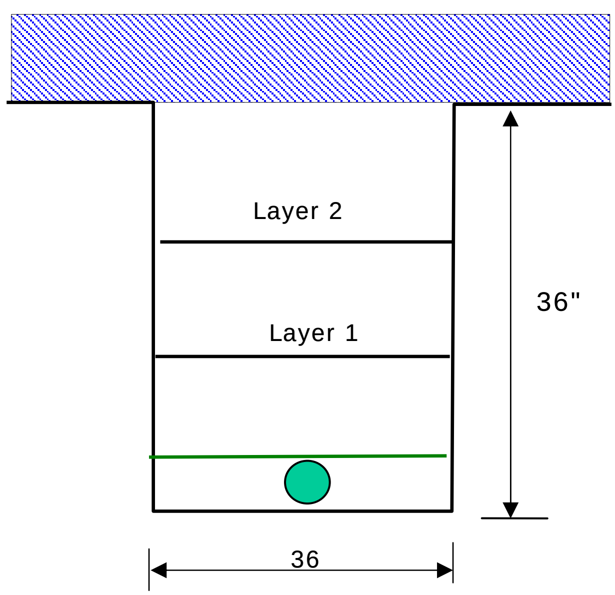

Figure 8 - Cross-section of the bellhole test section Sand-2

Table 9 – Properties of Bellhole Sand-2

Layer	Layer height (after compaction)	No. of compactor passes	Relative Compaction (% Modified)	Devices Used
1	12	7	89	After compacting each layer NDG SCS Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer) Standard DCP PANDA
2	13	8	92	

3. Bellhole Section Sand-3

The tests in this set were performed in order to evaluate the devices at various soil moisture contents. Several tests were performed with IL-Sand backfill compacted at various moisture contents ranging from 2 to 12 percents. A membrane moisture-barrier was placed in the bellhole before backfilling to keep the moisture content of the backfill constant during the tests.

The compaction was performed so as to maintain a constant soil dry density at each test. Accordingly, the changes in the measurements were due to moisture changes at the same relative compaction.

Soil moisture contents were determined using the NDG and lab-oven tests. Several types of commercially available Agriculture Moisture Gauges were also used and correlated to lab moisture results. Figure 9 shows the Agriculture Gauges. Table 10 shows the backfill properties and the compaction measuring devices used in these tests.

Figure 9 – The agriculture moisture gauges

Table 10 - Testing Program in the Bellhole Sand-3

Test	Layer height (after compaction)	Moisture content (%)	Relative Compaction (% Modified)	Devices Used
1	14	2.2	94.7	After compacting each layer NDG Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer)
2	14	4.2	94.3	
3	14	6.1	94.7	
4	13	10.7	95.7	
5	14	12.4	96	

4. Bellhole Section Sand-4

This test section consisted of one 8-inch thick layer of IL-Sand compacted atop a 26-inch thick loose sand layer. Figure 10 shows a cross section of the bellhole and Table 11 shows its compaction properties.

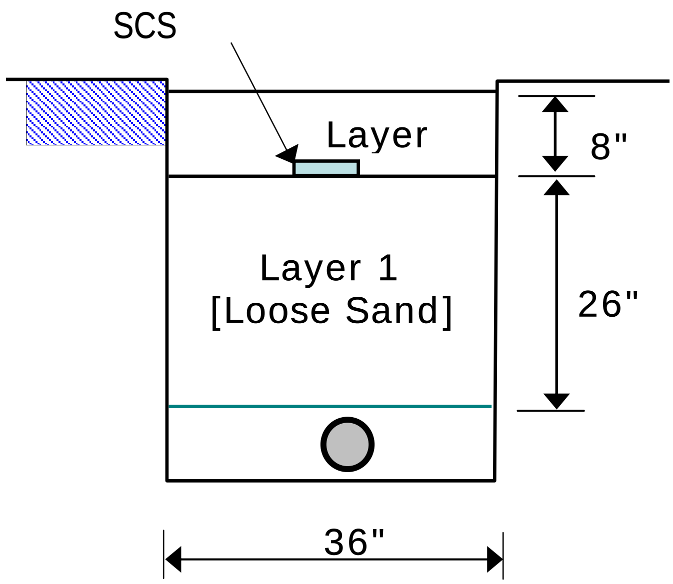

Figure 10 - Cross-section of the bellhole test section Sand-4

Table 11 – Compaction Properties of Bellhole Sand-4

Layer	Layer height (after compaction)	No. of compactor passes	Relative Comp. (% Modified)	Devices Used
1	8	2	93	After compacting of layer NDG SCS Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer) Standard DCP PANDA
2	26	-	88	

5. Bellhole Section Sand-5

These tests were performed in order to determine the depth of measurements of the devices. In these tests, a steel plate was placed in half of the bellhole section as shown in Figure 11. Soil was added in 3 to 4-inch lifts above the plate. Measurements were taken in both halves of the bellhole (i.e. with and without the plate) after the addition of each lift. Table 12 shows the properties of the test section.

Figure 11 – Testing the devices with and without the rigid plate in the bellhole

Table 12 – Test Properties of Bellhole Sand-5

Soil Ht. above plate	Moisture content (%)	Relative Comp. (%)	Devices Used
0	3.8	85	After compacting each layer NDG Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Sand-cone test
3	4	88	
5	4.1	92.5	
9	4.2	92.5	
12	3.5	94	
18	3.9	93.9	

6. Keyhole Section Sand-6

Section Sand-6 consisted of an 18-inch diameter keyhole. The keyhole was 25 inches deep and was backfilled in 5 layers of sand compacted at the optimum moisture content using a Pneumatic Jumping Jack. Figure 12 shows the compaction of the backfill. Figures 13 to 15 show the compaction measurements using several devices.

Measurements were taken after the compaction of each layer when the soil passed the 90 percent modified relative compaction. Table 13 shows the compaction properties of each layer.

Figure 12 – Compaction of the keyhole section

Figure 13 – Compaction measurements in the keyhole using the NDG

Figure 14 –Compaction measurements using the Clegg Hammer

Figure 15 – Post- compaction measurements using the PANDA

Table 13 – Backfill Properties in Keyhole Sand-6

Layer	Layer height (after compaction)	Relative Comp.* (% Modified)	Moisture content (%)	Devices Used
1	6	70	5.5	After compacting each layer NDG SCS Utility DCP Clegg 10-kg, 20-Kg Geogauge Lab moisture tests Post compaction Standard DCP PANDA
2	6	77	5.6	
3	6	82	6	
4	6	83	6.5	
5	6	91	6.5	

* Low relative compaction is due to boundary effects of keyhole on NDG.

7. Trench Section NJ-Sand

These tests were performed in a 2-ft wide and 3-ft deep trench section. The section was backfilled with NJ-sand and was compacted in 5 layers averaging 7 inches thick. Figure 16 shows compaction measurements using the sand-cone test and Table 14 shows the compaction properties of the layers in the trench.

After completion of the test, the section was re-excavated and forensic measurements were performed in the section. The analysis consisted of measuring the moisture and density of the top two soil layers to evaluate the effect of compaction of the top layer on the lower one. Figure 17 shows the DCP tests during the forensic analysis.

Table 14 – Backfill Properties in Trench NJ-Sand

Layer	Layer height (after compaction)	Relative Compaction (% Modified)	Moisture content (%)	Devices Used
1	6.5	90	6	After compacting each layer NDG SCS Utility DCP Clegg 10-kg, 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer) Standard DCP PANDA
2	7.5	93	8.4	
3	8	90.6	8.5	
4	6	91.9	9	
5	8	93	10	

Figure 16 – Sand-cone test on the NJ-Sand trench

Figure 17 – Utility DCP test on the soil during forensic study

8. Trench Section Silty Clay-1

The trench section was 2 ft wide and 3 ft deep. The section was backfilled using the silty-clay soil. The soil was initially dried in the oven and water was added to achieve the optimum moisture content. A concrete mixer was used to mix the soil to uniform moisture content (Figure 18).

The soil was compacted using a rammer compactor. The compaction control procedure consisted of using the devices after each single pass of the compactor over the backfill material. This approach enabled evaluating the devices at various soil compaction efforts and soil densities. The measurements were used in correlating sensitivity of the measurements to the increase in the number of passes. Table 15 shows the compaction properties in the trench layers. Figure 19 shows the trench and the compaction measuring devices.

Table 15 – Compaction Properties of the Silty Clay-1 trench section

Layer	Layer height	No. of passes (To reach 95% Relative Density)	Devices Used
1	8	5	After compacting each layer NDG Utility DCP Clegg 10-kg Clegg 20-Kg SCS Geogauge Lab moisture tests Post compaction Sand-cone (top layer) Standard DCP PANDA
2	6	6	
3	7	5	
4	6	7	
5	6	7	

Figure 18 – Soil mixing procedure for uniform moisture content

Figure 19 – Using the Utility DCP in the silty-clay trench

9. Bellhole Section Silty Clay-2

This section is similar to the bellhole section Sand-3. In this section, the backfill was silty-clay soil compacted at various soil moisture contents. The tests were performed at various moisture contents ranging from 4 to 15 percents. Compaction was performed so as to maintain a constant soil dry density at each layer. Table 16 shows the compaction properties of this test.

Table 16 – Compaction Properties of Bellhole Silty Clay-2

Test	Layer height (after compaction)	Moisture content (%)	Relative Comp. (% Modified)	Devices Used
1	14	3.8	88	After compacting the layer NDG Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer)
2	14	6.6	80.5	
3	14	12.3	82	
4	14	15.8	80	

10. Keyhole Section Silty Clay

This section is similar to the test section Keyhole Sand-6 with the silty-clay as a backfill. The top layer of the test section (layer 5) was a stone-base layer. Table 17 shows the compaction properties of the section.

Table 17 – Compaction Properties of Keyhole Silty Clay-3

Layer	Layer height (after compaction)	Relative Compaction (% Modified)	Moisture content (%)	Devices Used
1	6	82.5	15.6	After compacting each layer NDG SCS Utility DCP Clegg 10-kg, 20-Kg Geogauge Lab moisture tests Post compaction Standard DCP PANDA
2	6	85.6	18	
3	6	85.9	18.8	
4	6	95.4	18.4	
5	6	79	31.1	

11. Bellhole Section Stone Base -1

This section is similar to bellhole section Sand-3 and Bellhole section Silty Clay-2 with the stone base soil as a backfill. These three sections were used to evaluate the devices in the three types of soils at various moisture contents.

In this section, the number of compaction passes was kept identical in each test. However, measurements of the NDG showed that relative compaction also varied in each test. Table 18 shows the compaction properties of this test section.

Table 18 – Compaction Properties of Bellhole Stone Base-1

Test	Layer height (after compaction)	Moisture content (%)	Relative Compaction (% Modified)	Devices Used
1	14	2.6	82	After compacting each layer NDG Utility DCP Clegg 10-kg Clegg 20-Kg Geogauge Lab moisture tests Post compaction Sand-cone (top layer)
2	14	3.8	88	
3	14	6.7	94.6	
4	14	8	91.6	

12. Bellhole Section Stone Base-2

This bellhole section was 3 ft by 4 ft and it was backfilled in 6 layers using the stone-base backfill. The backfill was compacted at the optimum moisture content using a vibrating plate. Figure 20 shows a cross-section of the bellhole. Measurements were taken at each layer when the soil passed the 90 percent modified relative compaction. Table 19 shows the compaction properties of each layer.

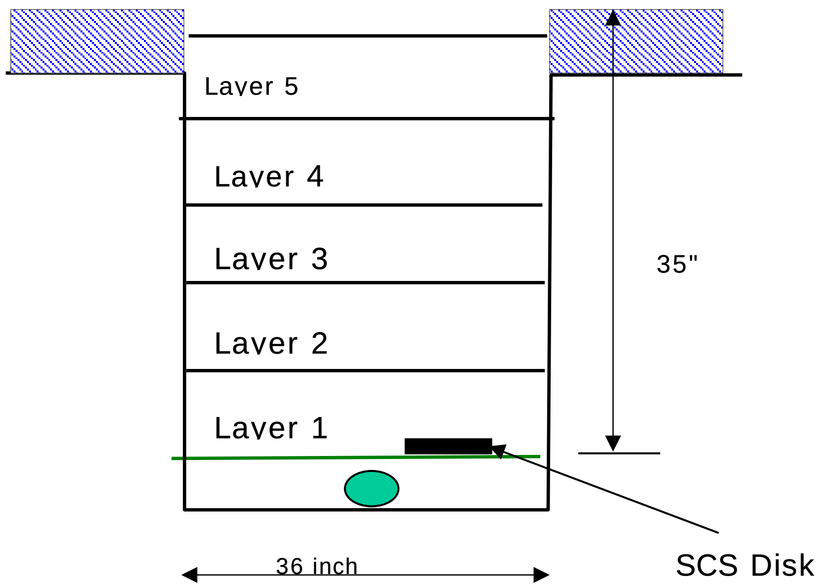

Figure 20 – Cross section of the Stone-Base bellhole

Table 19 – Compaction Properties of Bellhole Stone Base-2

Layer	Layer height (after compaction)	Relative Compaction (% Modified)	Moisture content (%)	Devices Used
1	6.5	92.7	8.3	<u>After compacting each layer</u> NDG SCS Utility DCP Clegg 10-kg, 20-Kg Geogauge Lab moisture tests <u>Post compaction</u> Sand-cone (last layer) Standard DCP PANDA
2	6	93	8.6	
3	6	92.4	7.9	
4	6	96	7.8	
5	6	95.5	7.3	

13. Trench Section Stone Base-3

This trench section was 2 ft wide and 3 ft deep and was backfilled using stone-base backfill.

The soil was compacted using a vibrating plate compactor. The compaction control procedure consisted of using the devices after each pass of compactor over the backfill material. This procedure enabled correlating the sensitivity of the measurements to the increase the number of passes. Table 20 shows the compaction properties in the trench layers.

Table 20 – Compaction Properties of the Trench Stone Base-3

Layer	Layer height	Relative Compaction (%)	Moisture Content (%)	Devices Used
1	9	92.2	5	After compacting each layer NDG Utility DCP Clegg 10-kg Clegg 20-Kg SCS Geogauge Lab moisture tests Post compaction Sand-cone (top layer) Standard DCP PANDA
2	8	88.7	4.1	
3	8	92	3.3	
4	5	91	4.1	
5	5	98	4.6	

14. Outdoor Bellhole Sections

The outdoor test sections consisted of 7 bellholes 3 ft by 3 ft. The bellholes had different depths ranging from 24 inches to 36 inches and they were backfilled using various types of soils.

Compaction in the bellholes was performed using a rammer compactor. The soil was compacted using various compaction efforts and layer thickness in order to obtain a wide range of relative compactions. Table 21 shows the backfill material and compaction properties of the bellholes. The compaction measurements at each layer were taken using the NDG, the Utility DCP, and the Clegg Hammers.

Soil moisture was monitored using the Agriculture-Moisture Gauges and was measured in the lab according to ASTM D-2216. Sand-cone tests were performed at the top layer of each section (except the stone section). Figure 21 shows the compaction measurements using the NDG in one of the bellholes in the field.

Figure 21 – Density measurements of the outdoor bellholes using the NDG

Table 21 - Testing Program in the Outdoor Bellhole Sections

Section	Backfill Material	Depth (inch) – No. of layers	Relative Compaction %	Devices Used
1	Loose Clay	24 - 3 layers	80%	At each Layer NDG Utility DCP Clegg 10-kg Clegg 20-kg Lab moisture tests Ag-Moisture device Post compaction Sand-cone (Top layer only)
2	Dense Clay	24 - 4 layers	95%	
3	Loose Sand	32 – 4 layers	85%	
4	Dense Sand	32 – 7 layers	95%	
5	4" sand on Pipe + Dense Clay	32 – 6 layers	95%	
6	Dense Clay + 10" Stone Base	32 – 4 layers	92%	
7	Stone	24 – 3 layers	-	

15. The New Jersey Test Site

The New Jersey field experiment was a part of the research project "Restoration of Utility Cuts [RUC]", which was performed by the National Research Council of Canada (NRCC) and the US Army Corps Cold Regions Research Lab (CRREL). In this field experiment, several bellholes and trenches were constructed in Route 19 near Clifton, NJ. The restoration of the cuts provided the opportunity to evaluate several compaction-measuring devices in the field.

The sections consisted of two bellholes with average dimensions of 3 ft by 4 ft (Figure 22) and three 20-inch wide trenches. The sections were constructed along one lane of the road and the length of the trenches extended along the width of the traffic lane (Figure 23). The NJ-Sand backfill was used in the bellholes and the two trenches. The third trench was backfilled using the native soil.

Figure 22- Compaction measurement of the bellhole using the Clegg Hammer

Figure 23- Compaction of the 20-inch wide trench in the NJ site

Four measuring devices were used to monitor the soil compaction at each layer in both the bellholes and trenches. These devices were the Utility Dynamic Cone Penetrometer (DCP), the Clegg-hammers (both the 10-kg Hammer and the 20-kg Hammer), and the Soil Compaction Supervisor (SCS). A summary of the device measurements in the three sections is shown in Table 22.

The NJ DOT personnel took density measurements using the NDG. Soil moisture-density relationship tests (proctor tests) of the sand backfill were also performed prior to compaction in order to define the maximum soil density required for compaction control.

Table 22 - Summary of the Measurement in the New Jersey Site

Section	Backfill Type	No. of layers	Measurements of compaction devices				
			NDG	DCP	Clegg [10-kg]	Clegg [20-kg]	SCS
Instrumented Bellhole	Select sand	6	✓	✓	✓	✓	-
Instrumented Trench	Select Sand	6	✓	✓	✓	✓	-
Regular Trench	Native soil (Silty sand to sandy soil)	4	✓	-	-	-	-

RESULTS AND ANALYSIS

Introduction

This chapter presents the results of the testing program. The analysis of the results focused on:

- Evaluating and ranking the soil compaction measuring devices for use in compaction control of utility trenches, bellholes, and keyholes.
- Correlating the output of the devices with the measurements of the Nuclear Density Gauge (NDG).
- Recommending modifications of selected devices to enhance their performance and gain their acceptability as a replacement of the NDG.

The compaction measuring devices were categorized into two types. These types are:

- Quality Control (QC) measuring devices which are used in layer-by-layer measurements during compaction
- Quality Assurance (QA) devices that are used in measuring the post-compaction profile of the entire section.

The QC devices evaluated in the testing program were the Soil Compaction Supervisor (SCS), the Utility Dynamic Cone Penetrometer (Utility DCP), the Humboldt Geogauge, and the Clegg Hammers. The post-compaction QA devices were the Standard Dynamic Cone Penetrometer (Standard DCP) and the Panda.

A description of the devices is presented in this chapter, followed by the correlation results of their output with soil densities and moisture contents. The results were utilized to select the most applicable device(s) for use in compaction control of trenches and bellholes of utility cuts.

The Nuclear Density Gauge (NDG)

Description

The Nuclear Density Gauge (NDG) operates by producing small doses of backscattered gamma waves. The radiation reflected from the soil is detected at the base of the gauge and converted to soil density when the gauge is calibrated to the specific soil (Figure 24). The gauge also determines the moisture content by detecting the hydrogen (water) in a 2-ft sphere around the gauge.

The NDG is an easily portable device and its operation is simple once it is calibrated to the soils in the field. The specifications for the calibration and use of the gauge for moisture and density measurements of soil and asphalt surfaces are listed in several ASTM procedures [2-*4*].

The accuracy of the gauge in the field depends on its successful calibration in similar soil conditions. The use of the gauge requires training and operation by a licensed technician and it is governed by regulations for its use and storage. Although the gauge is widely used in compaction control of embankments, base soils, and backfills, the strict conditions with regard to its use and disposal have prompted the search for other alternatives for monitoring compaction performance.

Relative Compaction and Moisture Measurements

The NDG was used as a Quality Control (QC) device for monitoring compaction properties of each soil layer. Tests were performed on various types of soils in trenches and bellholes. Figure 25 shows a view of the NDG in the bellhole. The NDG results were correlated with the results of the Sand-Cone and the other compaction measuring devices.

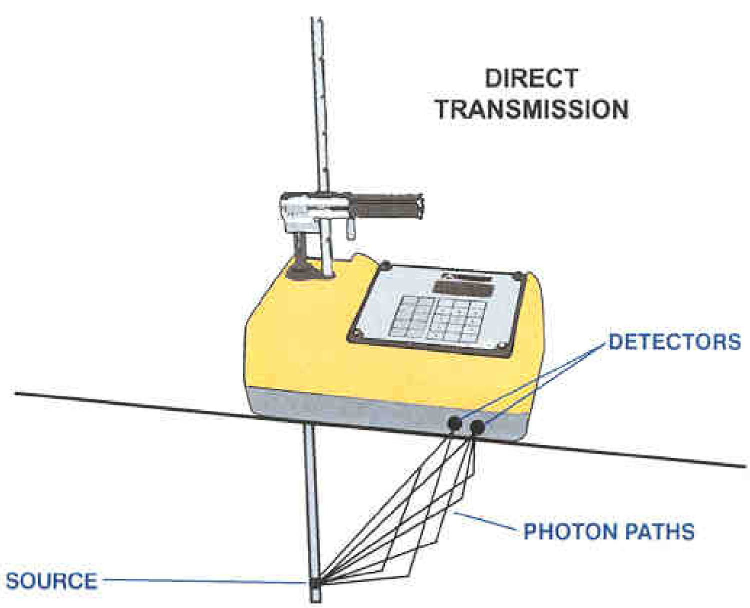

Figure 24 – NDG measurement of soil density by direct transmission
(From Troxler NDG Users Manual)

Figure 25 – NDG measurements in a bellhole using the NDG

Measurements of soil moistures using the NDG are usually higher than the readings obtained from the lab-oven tests. Figure 26 shows the results of both tests in various types of soils. The correlation between both results depends primarily on the type of soil.

Furthermore, the amount of hydrogen in the gypsum, lime, and fly ash particles may affect the moisture readings and results in higher moisture content. Offset factors obtained from the calibration tests should be used in the measurement of moisture in these materials.

The results of soil dry density (γ_{dry}) are calculated from the measurements of wet soil density (γ_{wet}) and moisture content (*w*) according to the following equation:

$$\gamma_{dry} = \gamma_{wet} / (1 + w)$$

Accordingly, high readings of soil moistures result in lower values of soil dry densities. Figure 27 shows the results of soil dry densities from the NDG and the Sand-Cone tests. The figure shows lower NDG readings for sand and silty-clay soils. The high results of stone-base soils are largely due to the difficulty in obtaining accurate densities from Sand-Cone tests in stone-base soil.

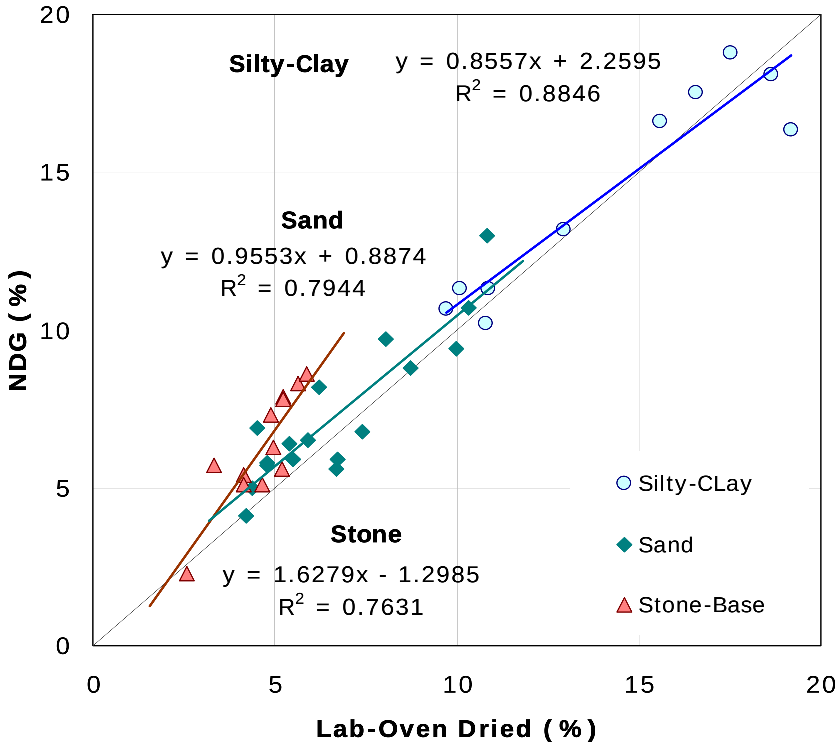

Figure 26 – Measurements of soil moisture using the NDG and lab-oven tests

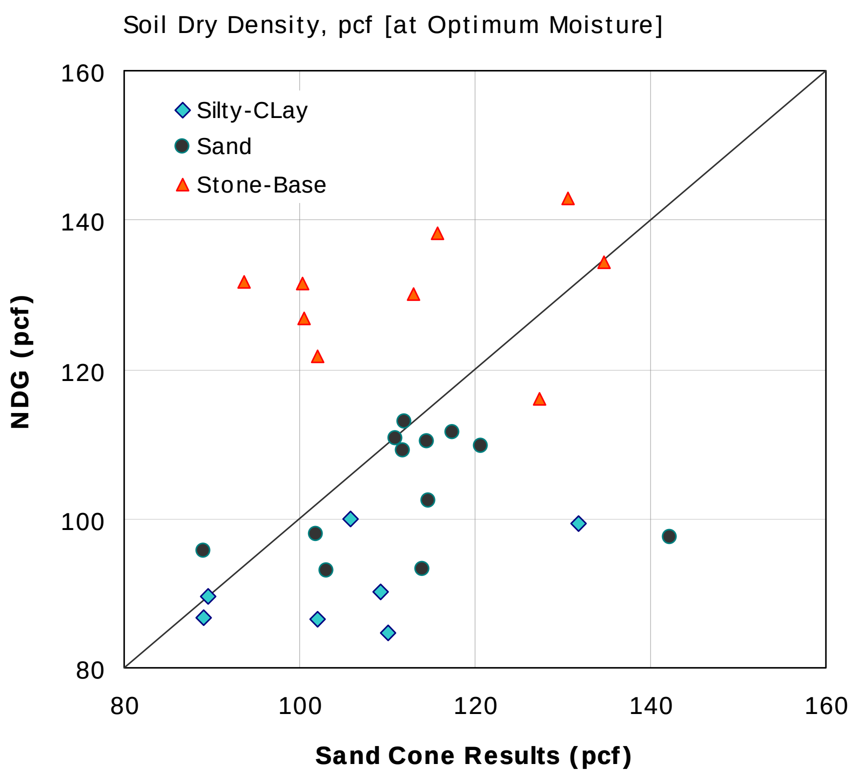

Figure 27 – Soil dry density from NDG and Sand-Cone tests

Effect of Gauge Probe Depth

Soil moisture measurements were not affected by the probe length of the NDG. However, soil densities varied with the increase of probe length. Figure 28 shows the NDG readings with various probe depths in four tests with various moisture contents. The readings were consistent with the oven-dried results and they were not affected by the depth of probe.

Measurements of soil dry density in sand, however, show that the NDG readings increased with the length of the probe (Figure 29). This increase can be due to the compaction process in sand which may result in looser sand at the top of the lift than at the bottom.

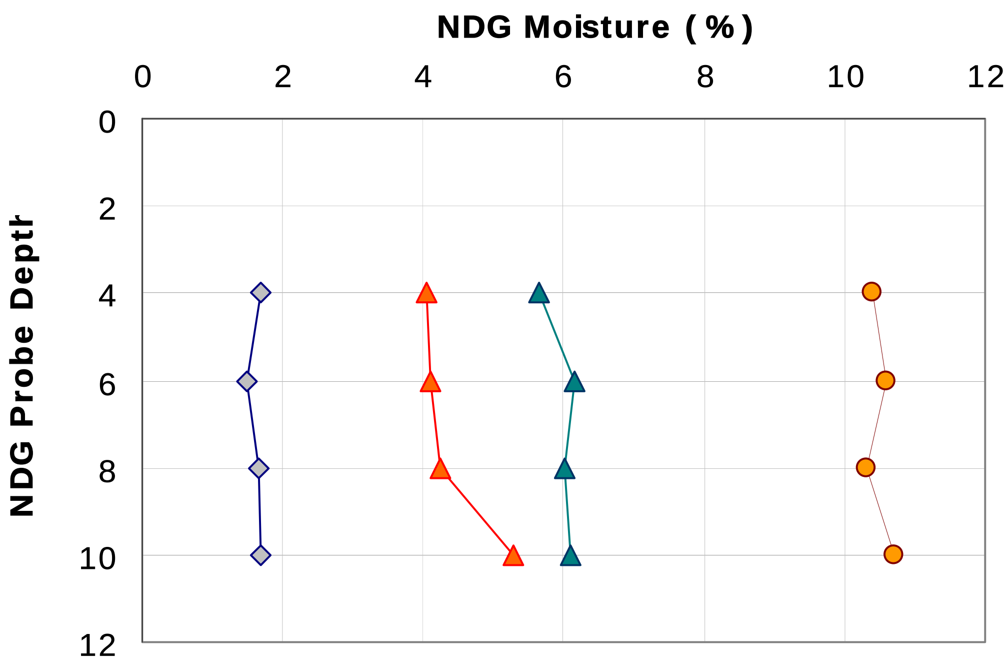

Figure 28 – Moisture readings at various probe depth in four tests

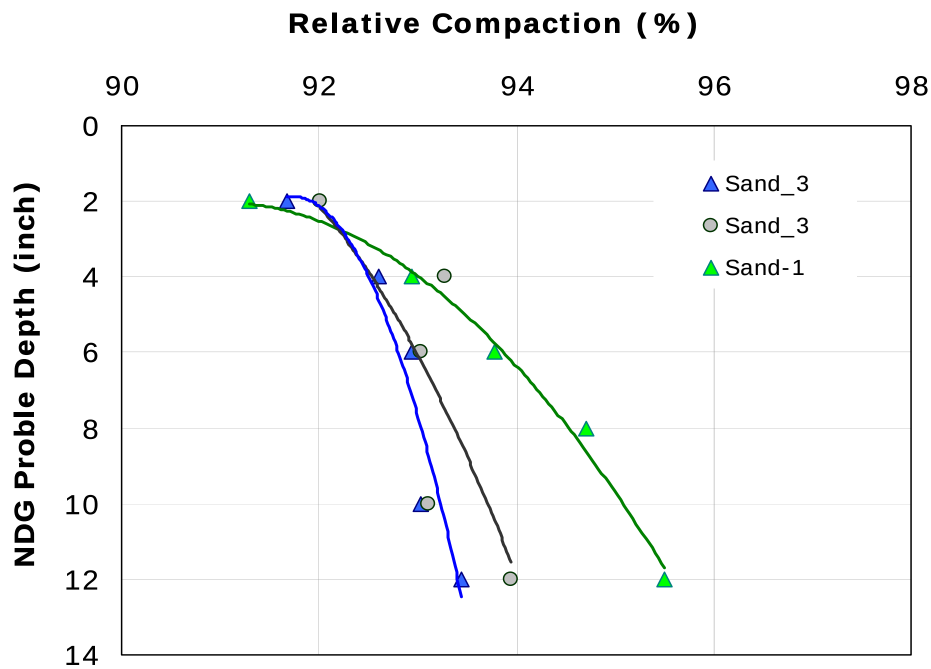

Figure 29 – Change of density measurements at various probe depths

Effect of Cut Boundaries on the Measurements

The trench and bellhole side wall boundaries affect the results of the NDG. The gauge usually reads higher moisture values due to the scatter of the rays back from the side walls. The NDG manual recommends using an offset if the gauge is used inside a trench and within 2 ft from a vertical side wall. The offset however does not adjust density measurements if rod length is more than 4 inches long [5].

In order to evaluate the effect of trench wall boundaries on the NDG results, measurements were taken at the center and near the vertical wall of the trenches in uniformly compacted sand. The readings were repeated at various layers in order to investigate the effect of trench height. Figure 30 shows a schematic of the locations of the measurements.

The results of the moisture measurements in the sand near the side wall of the trench are shown in Figure 31. The figure shows an increase of about 50 percent in moisture reading, and consequently lower relative compaction, near the wall boundary at depth 2 ft from the surface. The results show that the effect is negligible at a distance of about one foot from the wall.

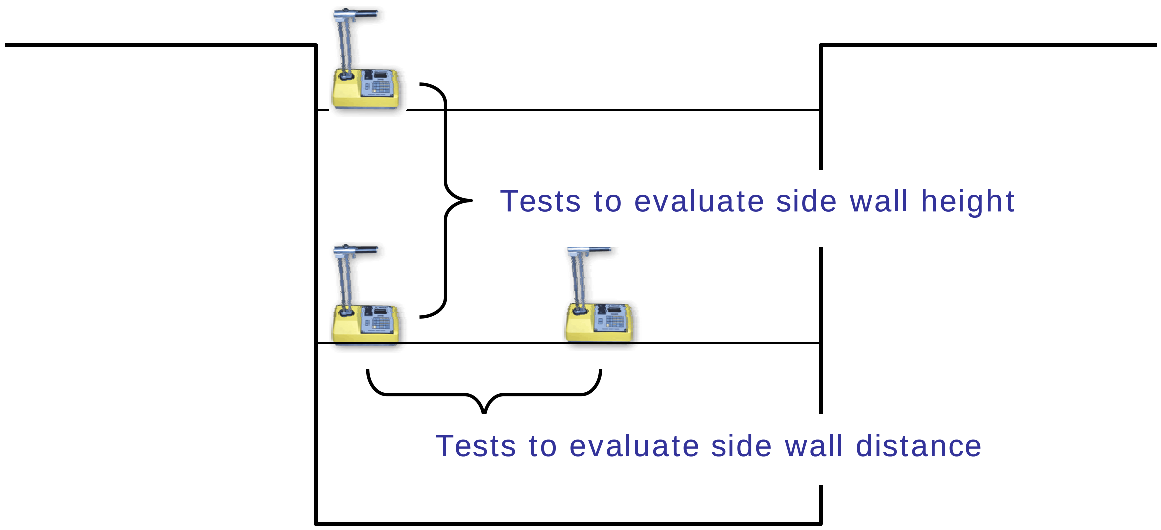

Figure 30 – Schematic of NDG measurements to evaluate effect of boundary

The effect of the side wall varies with the height of the trench. Measurements near the side wall at various trench heights are shown in Figure 32. The results show that the effect of side boundaries is reduced at shallower depths.

Figure 33 shows the measurements of soil moistures using the NDG and the lab-oven method in 18-inch diameter keyholes. The measurements, from the NDG are significantly higher than the ones obtained from the lab-oven tests.

Due to the effect of wall boundaries on the results of the NDG, the device is not suitable for compaction measurements in small bellholes and keyhole sections. The need to calibrate the device at each soil lift makes it unpractical to perform the tests.

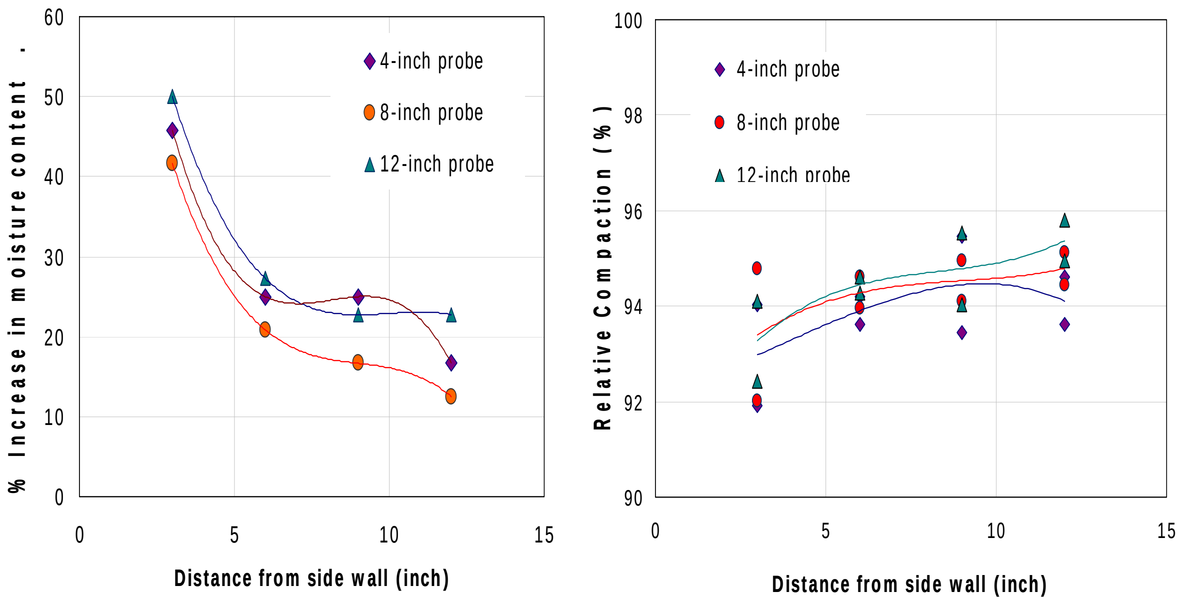

Figure 31 – Effect of distance from sidewall on the NDG measurements

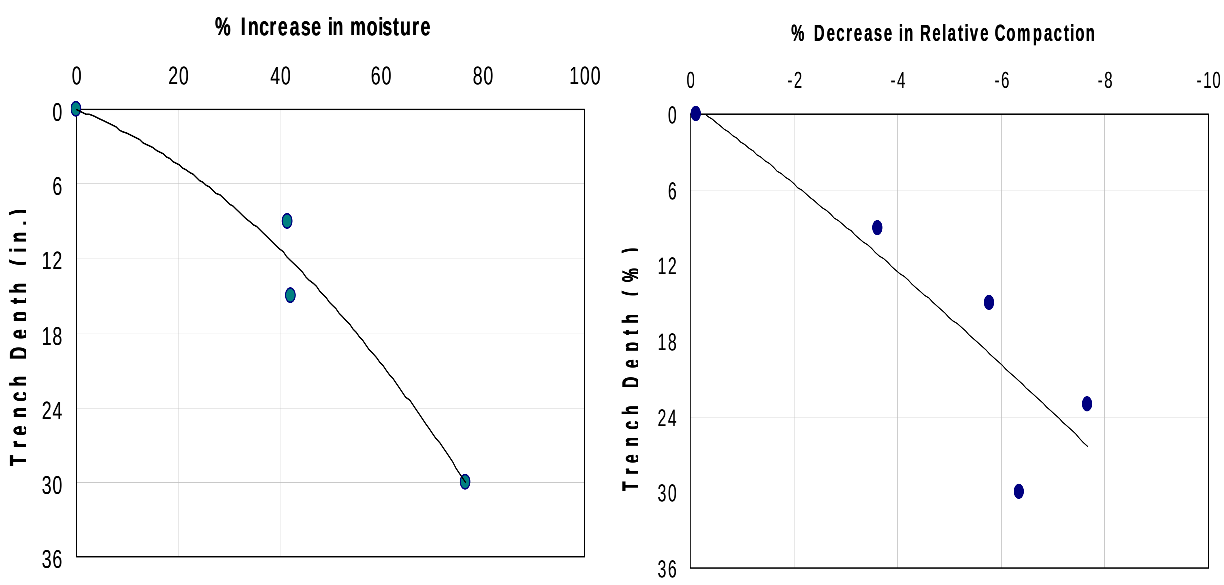

Figure 32 – Effect of sidewall height of the NDG measurements

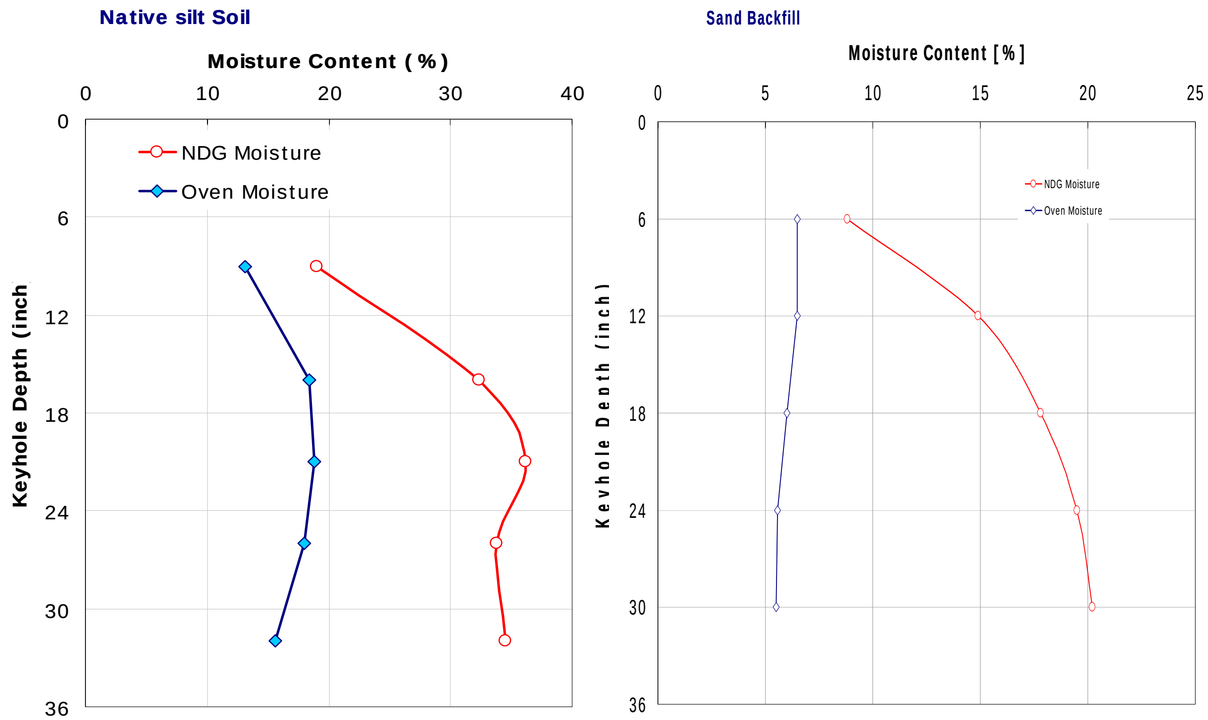

Figure 33 – Measurements of soil moisture in keyhole sections

Sand-Cone Apparatus

The sand-cone apparatus is used to determine the wet soil density in the field. The method consists of hand excavating a hole in the site and the wet mass of the excavated soil is determined. The apparatus is then used to fill the hole with free flowing sand of known density. The weight of the sand is used to determine the volume of the hole. The in-place wet density is determined by dividing the wet mass of the removed material over the volume of the hole. The water content of the soil removed from the hole is determined in the lab and the dry unit weight of soil can also be calculated. Figure 34 shows the Sand-Cone Apparatus used in the testing program.

The apparatus is simple and the procedure is listed in the ASTM Standard D-1556 [6]. However, the apparatus requires periodic calibration and the accuracy of the results depends on the experience of the operator. Furthermore, the calculation of soil dry density requires the determination of soil moisture using the lab-oven drying method.

Figure 34 – Use of the sand-cone apparatus in the stone-base trench

In order to run the test successfully, the soil should have sufficient cohesion to maintain stable sides along the excavated hole. Accordingly, the method may not be suitable for saturated or highly plastic soil that would deform or compress during excavation.

In the testing program, the sand-cone device was used to evaluate the measurements of the NDG tests. Typical results of the correlation between the NDG measurements and the results of the sand-cone tests were shown in Figure 27.

The Soil Compaction Supervisor (SCS)

Description

The Soil Compaction Supervisor (formerly, Soil Compaction Meter, SCM) consists of a sensor placed at the bottom of the hole and a readout box. The sensor produces a voltage in response to the waves transmitted through the soil from the compactor (Figure 35). The measured voltage value is primarily dependent on soil stiffness. The voltage signal levels off and the device produces a red signal when soil reaches its maximum achievable compaction, indicating to stop compaction. Figure 36 shows a view of the SCS used in the testing program.

The device is portable, economical, and easy to operate. The maximum achievable compaction, as indicated by the SCS, does not necessarily equal the target relative compaction. Further modifications with respect to storing and downloading the data may enhance its use as a QC tool during compaction.

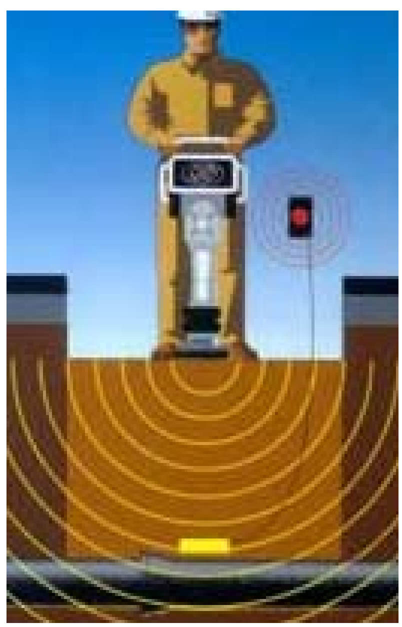

Figure 35 –The SCS measures the waves transmitted during compaction (From the SCS manual)

Soil Compaction Measurements

A previous study was conducted by the Gas Research Institute (GRI) to evaluate the performance of the SCM [*7*]. The study had a broad test matrix that included various soil types (clay, sand and silty sand), compaction tools, meter settings, lift heights, and moisture contents. It was concluded that the meter performed satisfactorily for the free-draining soils with the use of the vibratory plate. On the other hand, the application with cohesive soils required further research due to difficulty in achieving the targeted density.

The current testing program evaluated the output of the SCS in various soil types and moistures. The output was monitored after the completion of each pass of the compactor over the soil layers.

The device stores the status of each compacted soil layer in a file. The output lists the type of compactor and its duration. The device did not always successfully define the correct compactor. The procedure times out if compaction is suspended for more than 10 minutes for power savings. The output, however, is useful as an internal control record of the compaction process. Table 23 shows a typical output from the device

Figure 36 – The SCS sensor with the disk at the bottom of the trench

Table 23 – Sample Output File from the SCS Device

MBW-Soil Compaction
Supervisor

Soil :	Clay [from Pipe Farm]
Test	Clay_01
Operator:	DV
Date:	10/29-11/4

Start Date	Start Time	Length Minutes	Length Seconds	Job Number	Lift Number	Machine Type	Completion Status
29-Oct-02	1:11:08 PM	56	6	1	2	Percussion	Completed Normally at 02:07:14 PM
30-Oct-02	10:31:23 AM	10	58	1	3	Unknown Device	Inactivity Timeout at 10:42:21 AM
30-Oct-02	10:47:02 AM	28	5	1	4	Percussion	Completed Normally at 11:15:07 AM
31-Oct-02	12:49:01 PM	10	58	1	5	Unknown Device	Inactivity Timeout at 12:59:59 PM
31-Oct-02	1:05:00 PM	46	12	1	6	Percussion	Completed Normally at 01:51:12 PM
1-Nov-02	10:50:04 AM	71	52	1	7	Percussion	Completed Normally at 12:01:56 PM
1-Nov-02	10:50:04 AM	71	52	1	8	Percussion	Completed Normally at 12:01:56 PM
4-Nov-02	9:18:50 AM	55	43	1	9	Unknown Device	Inactivity Timeout at 10:14:33 AM
4-Nov-02	10:15:05 AM	4	22	1	10	Unknown Device	Lost Sensor at 10:19:27 AM

Figure 37 shows the NDG relative compaction readings after each compactor pass in the silty-clay trench. The arrows in the figure show the pass where the SCS indicated a completion of compaction (red signal). The arrows show that the device could successfully indicate the maximum achievable density for most of the layers. The device however did not produce signals at the last soil layer number 6.

As previously stated, the red output signal does not necessarily indicate that relative compaction reached 90 percent of the modified proctor. In order to correlate the device output signal to relative compaction, the results of the SCS device are plotted against soil relative compaction in Figures 38, 39, and 40 for sand, silty-clay, and stone-base soils, respectively. In these figures, the red markers indicate the instances where the device produced a red signal. The results show that most of the output signals in sand and stone-base soils corresponded to 90 percent, or more, relative compaction. The red light “Stop” condition did not correlate to an absolute 90% passing relative compaction in the silty-clay soil. The results in the figures also show that the device did not produce output signals, in most of the tests, when soil height was more than 30 inches above the sensor.

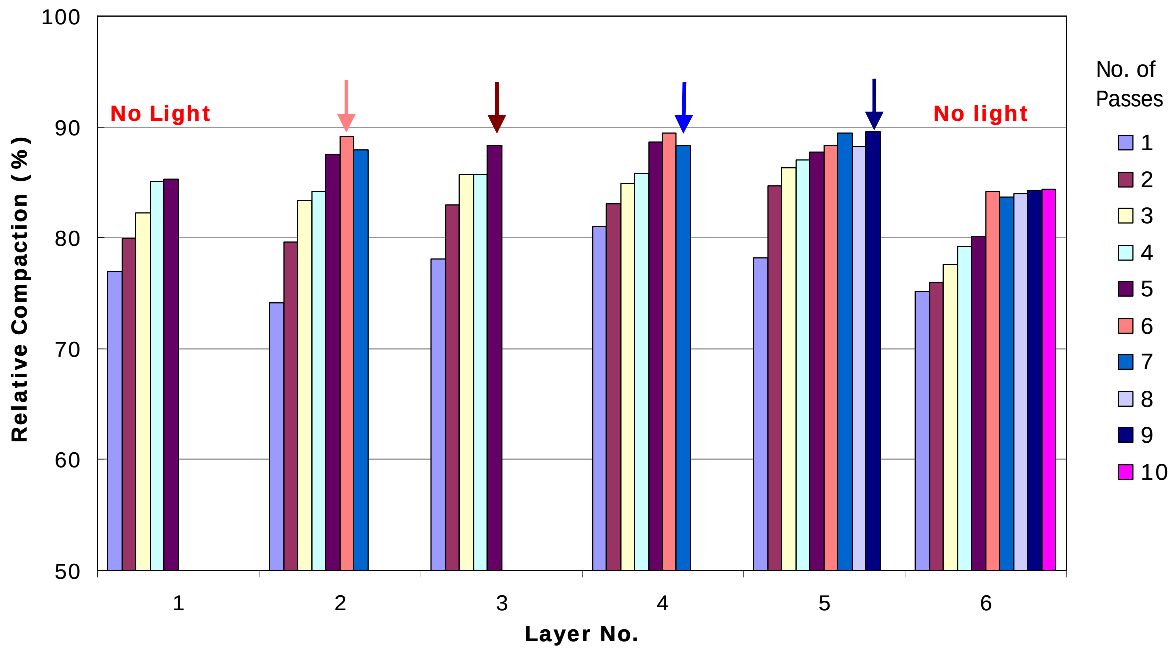

Figure 37 - Relative compaction at each layer in the silty-clay trench

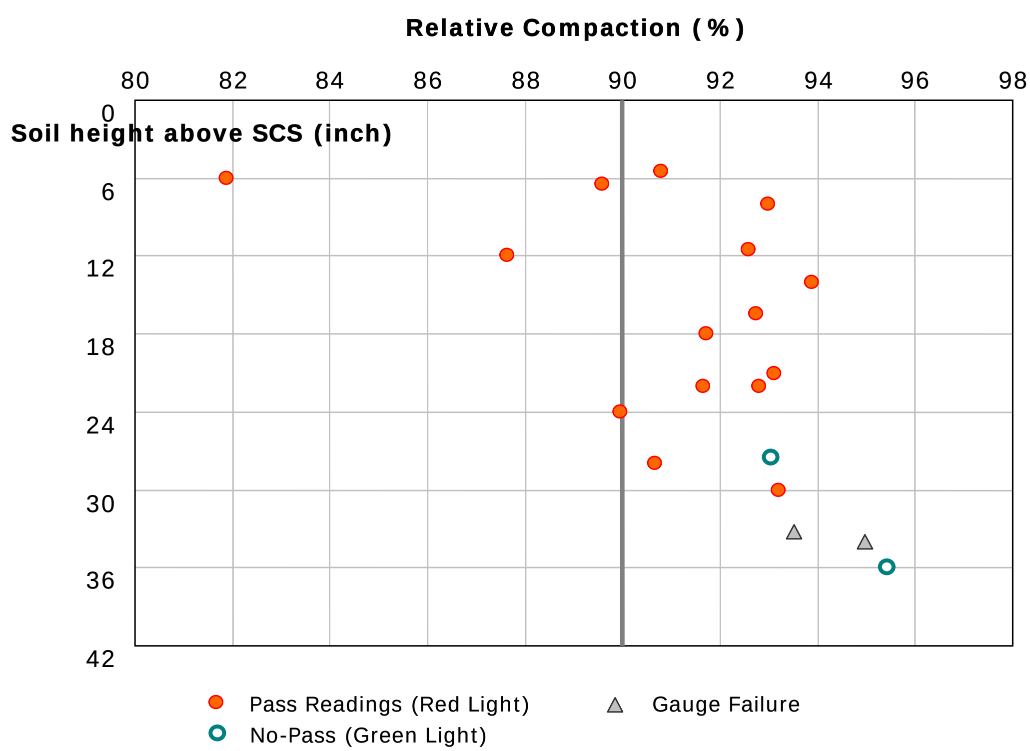

Figure 38 – Comparison between SCS output and relative compaction at various depths

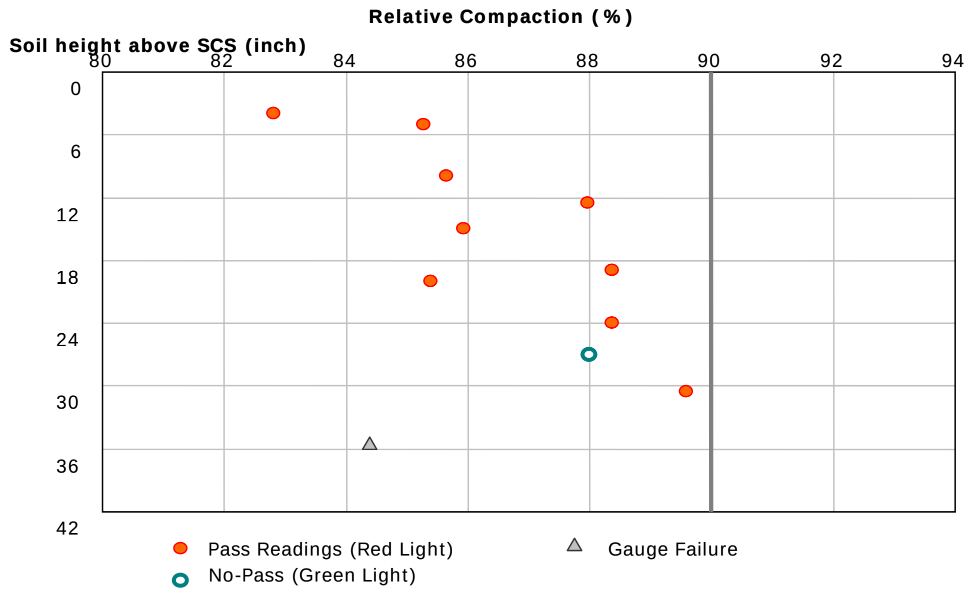

Figure 39 – Comparison between SCS output and relative compaction in silty-clay

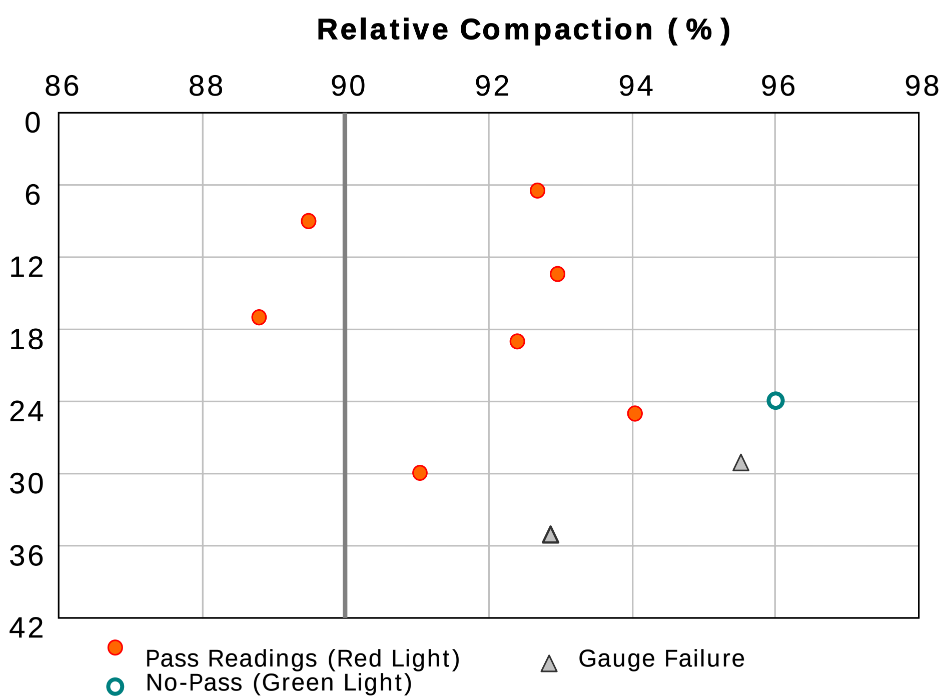

Figure 40 – Comparison between SCS output and relative compaction in stone-base

The Utility Dynamic Cone Penetrometer (Utility-DCP)

Description

The device is a smaller version of the Standard Dynamic Cone Penetrometer (presented later in the report) and it was developed for use by the utility companies for evaluating the compaction of backfill in trenches and bellholes. The Utility-DCP has a drop weight of 5 lb, in comparison to the 17.6 lb of the Standard DCP. The light weight of the device facilitates its use for the QC evaluation of compaction at each soil layer. Several standards for restoration practices currently utilize the Utility DCP for compaction control.

The utility cone is a pass/fail gauge. The evaluation criterion is a pre-determined number of blows, which is required to drive the cone a fixed distance of 3-¼ inches above the cone. The number of blow is usually calibrated for the various soil types.

Several utilities performed calibration tests in order to correlate cone results with measurements of field densities from the sand-cone and NDG devices [*8-13*]. This previous work resulted in various correlations for various soil types.

Soil Compaction Measurements

Figure 41 shows the Utility-DCP device in the test sections. In sand, the number of blows was counted between the middle and upper markers of the cone (a distance of 3-¼ inches). Previous tests have utilized the full count of blows between the cone and the upper marker in order to establish the blow count. However, the count between the middle and upper markers provided more consistent counts as the top few inches of sand were usually disturbed during compaction.

In clay and stone backfills, the number of blows was counted when the cone penetrates the distance between the top of the cone and the middle marker (located at 3-¼ inches above the cone).

The measurements of the Utility-DCP were compared to soil relative compaction at the optimum moisture content. The results are shown in Figures 42 for the sand. The results in the figure show the NDG measurements and the corresponding number of blows at the same location. The figure is used to determine the compaction acceptance criteria of the Utility-DCP based on the 90 percent relative compaction.

Figure 41 – Use of the Utility-DCP in bellhole and trench backfills

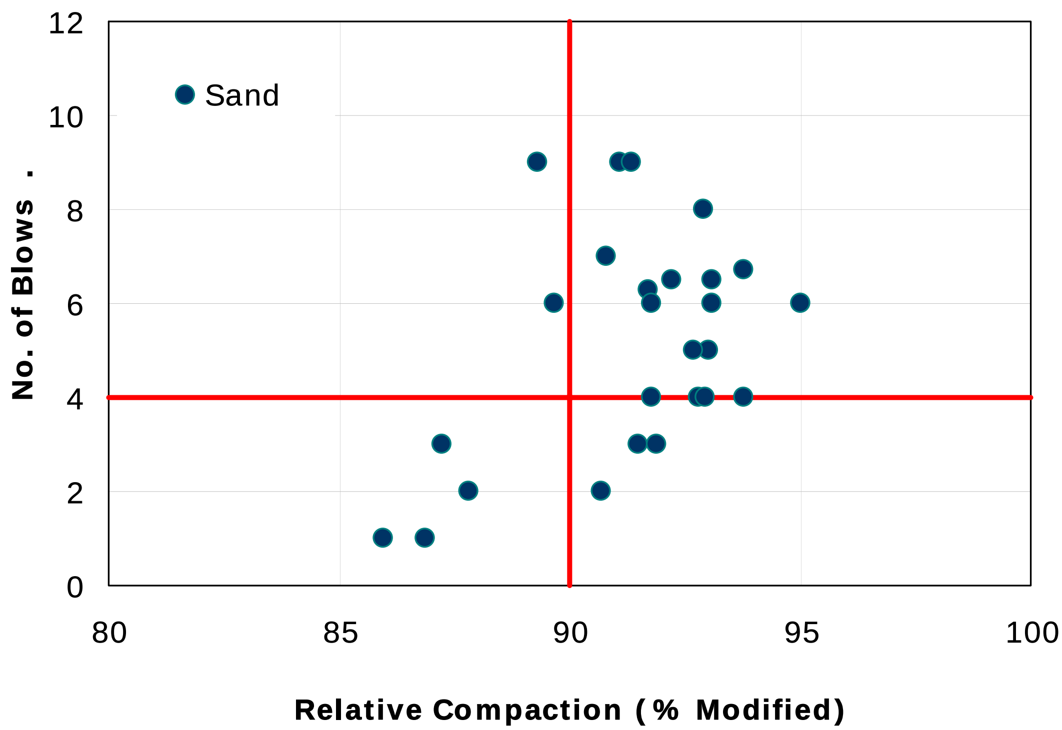

Figure 42 – Correlation of Utility-DCP with relative compaction in sand

The vertical line in Figure 42 is the 90 percent modified proctor relative compaction threshold that must be achieved for the lift to “Pass” according to the NDG results and the readings to the right of the line present the “Pass” compaction readings. The horizontal line in the figure represents the pass-fail value for the Utility-DCP readings. Accordingly, the top-right square of the figure presents the data where both devices had a “Pass” criteria and the bottom left square is where both the NDG and the Utility-DCP agreed on a “Fail” compaction criteria. This procedure was adopted from the previous work performed on the Utility-DCP [9-*13*].

The horizontal line which defined the “pass-fail” value for of the Utility-DCP was selected so that minimum number of readings (less than 5 percent) would fall in the top-left quarter of the figure. The results show that numbers of blows of 4 to 6 corresponded to the modified proctor relative compaction of 90 percent or higher. This relationship was based on the measurements of soils at their optimum moisture contents.

Similarly, the results of the testing program in silty-clay and stone-base soils are shown in Figures 43 and 44, respectively. A relationship between the DCP readings and soil relative compaction in both types of soils were calculated from the figures. Table 24 shows the correlation values of the Utility-DCP to the relative compaction measurements from the NDG.

Effect of Soil Moisture on the Results

The acceptance values in Table 24 were developed for soils compacted at the optimum moisture contents. These values change with the change of soil moisture content. Figures 45, 46, and 47 show the changes of cone readings at various moisture contents when soil relative density was kept constant within 2 percent. The results in the figures show that the number of blows increases with the increase in moisture content up to an optimum value.

Table 24 – Utility-DCP Results Corresponding to 90% Relative Compaction Based on the NDG Measurements

	sand	Silty-clay	Stone-base
No. of blows	6	22	11

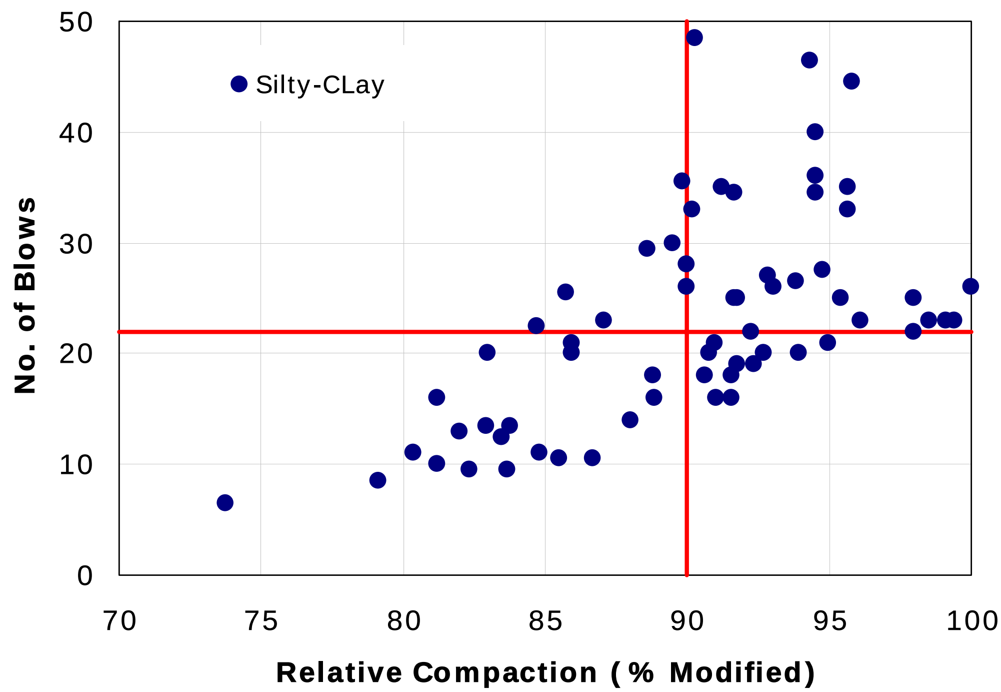

Figure 43 – Correlation of Utility-DCP with relative compaction in silty-clay

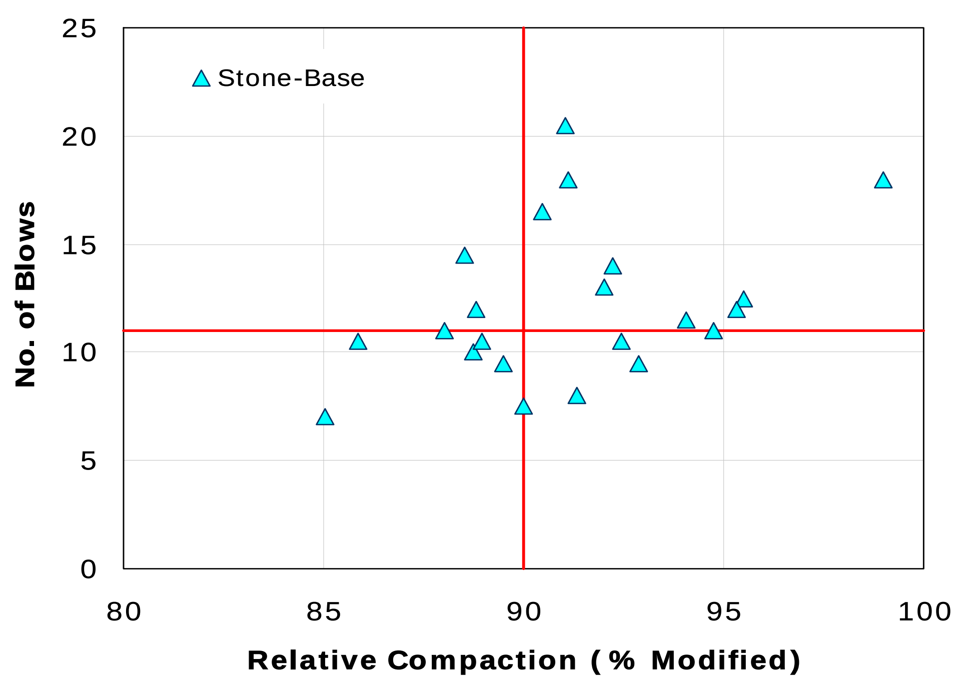

Figure 44 – Correlation of Utility-DCP with relative compaction in stone-base

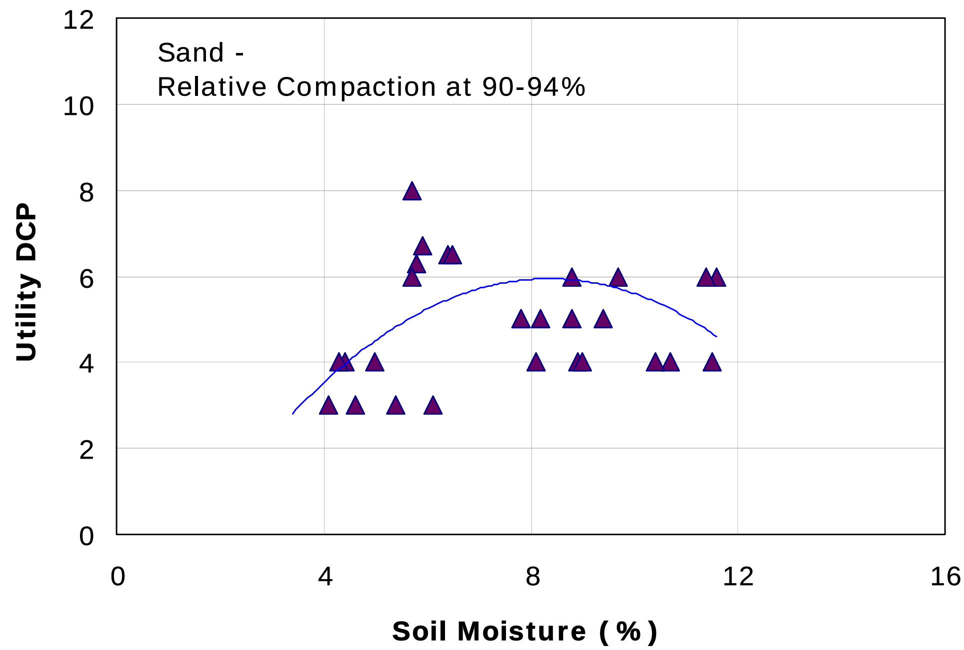

Figure 45 – Change of number of blows with moisture content in sand

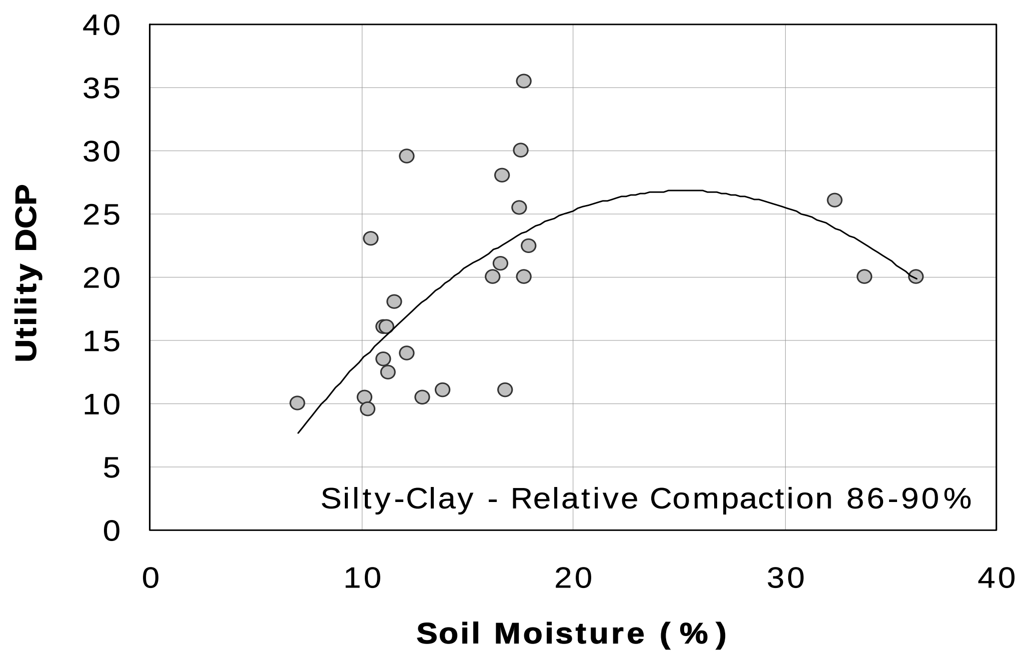

Figure 46 – Change of number of blows with moisture content in silty-clay

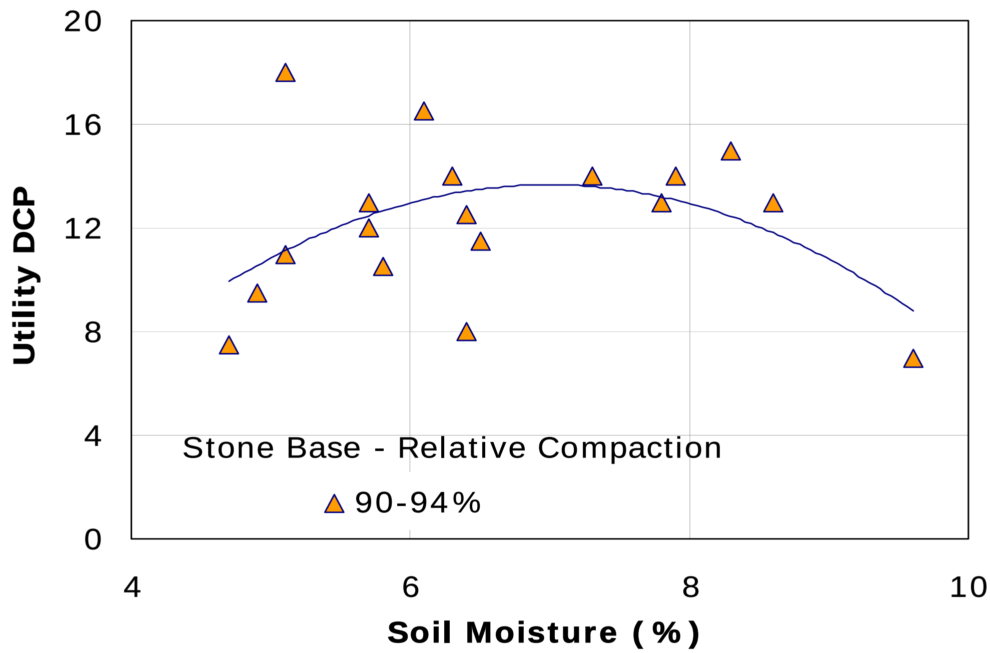

Figure 47 – Change of number of blows with moisture content in stone-base soil

The Geogauge

Description

The Humboldt Geogauge (formerly, Soil Stiffness Gauge) applies very small displacements to the soil surface at steady-state frequencies under the gauge base. At low frequencies, the force and the resulting surface velocity reading is determined and it is converted to in-situ soil stiffness [*15*]. Figure 48 shows the gauge used in the testing program. ASTM standard D-6758 determines the soil stiffness and modulus using this method [*16*].

Previous tests were preformed to evaluate the performance of the Geogauge in compaction control [*17-19*]. The results showed that the Geogauge could be used in measuring strength gain of stabilized materials and compaction effort. However, boundary effects had a detrimental impact on the data collected. The research work has also showed that no reliable relationship could be drawn between the stiffness measured from the Geogauge and the dry density measured from the nuclear density gauge. However, the manufacturers claim that when converted to density values using correlation charts, these measurements are within 5% of measurements made with a nuclear density gauge.

Most research agrees that proper seating of the Geogauge is essential to collecting reliable data. Placing a pat of moist sand over the backfill section increases the potential to collect consistent data.

Soil Compaction Measurements

The testing program focused on the use of the Geogauge in trenches and bellholes. Figure 49 shows the use of the gauge in compaction measurements in a trench backfill.

The relationship between the Geogauge Stiffness values and soil relative compaction are shown in Figure 50 through 52 for the sand, silty-clay soil, and stone-base backfill, respectively. The results were plotted for the tests performed at the optimum moisture content and they show weak correlations between the stiffness readings and soil relative compaction in the sand and stone-base backfills. A relatively better correlation value (R^2 =0.48) was obtained in the silty-clay soil.

Figure 48 - The Humboldt Geogauge used in the testing program

Figure 49 - Use of the Geogauge to evaluate compaction in trench backfill

Similar to the procedure used for the Utility-DCP, figures 50 through 52 were used to establish the 'pass-fail' criteria of the gauge with the 90 percent modified proctor compaction. The results of the correlations are shown in Table 25. No correlations were established for the stone-base backfill due to the scattered results and insufficient number of data points.

Table 25 – Geogauge Results Corresponding to 90% Relative Compaction from the NDG Measurements

	sand	Silty-clay	Stone-base
Geogauge Stiffness (Kips/in.)	30	45	No correlation

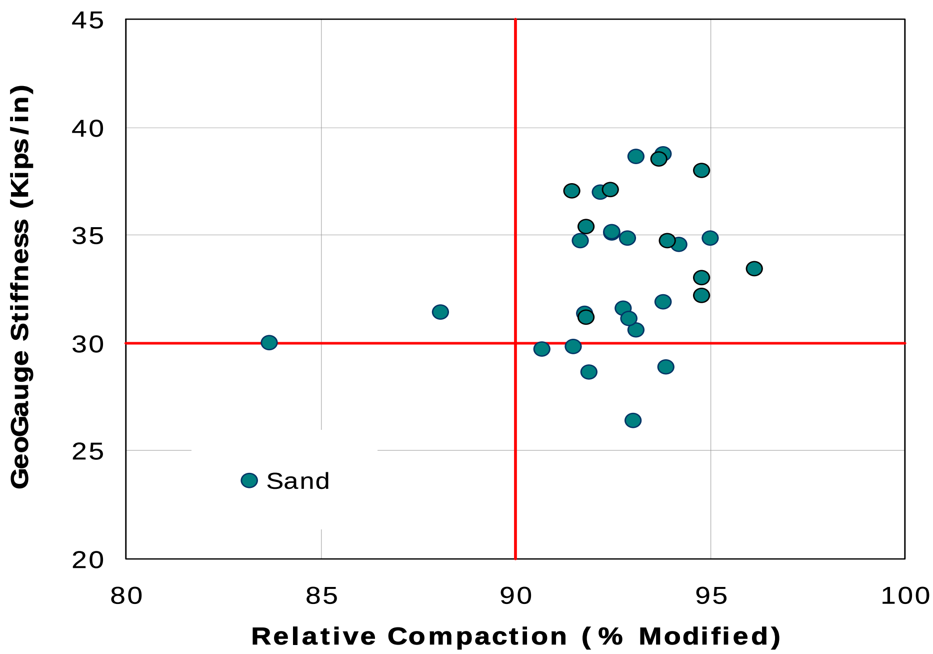

Figure 50 – Relationship between Geogauge Stiffness and relative compaction in sand

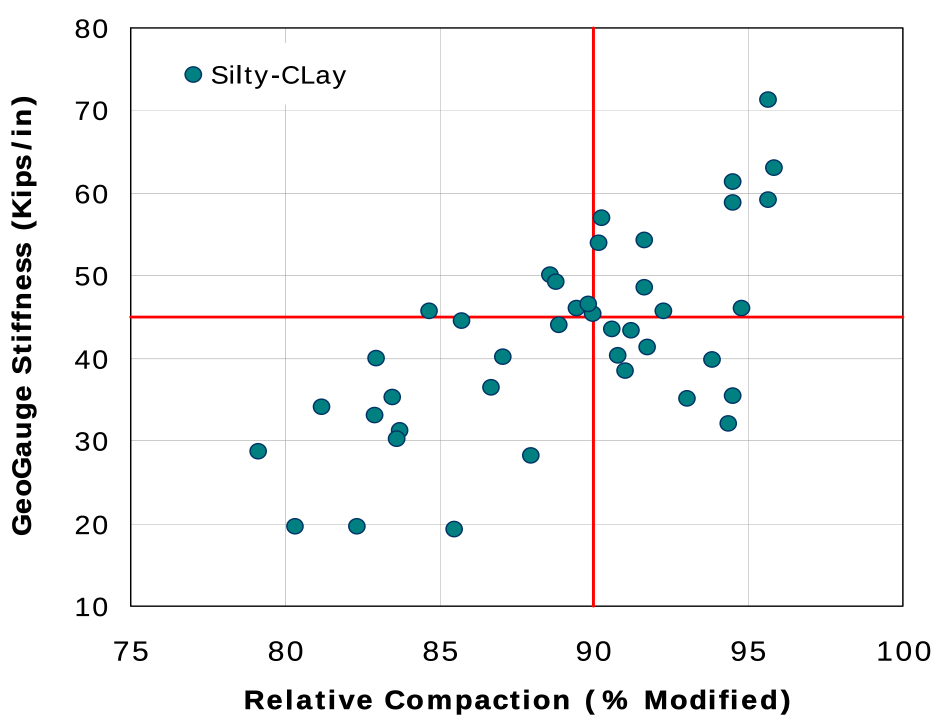

Figure 51 – Relationship between Geogauge Stiffness and relative compaction in silty-clay backfill

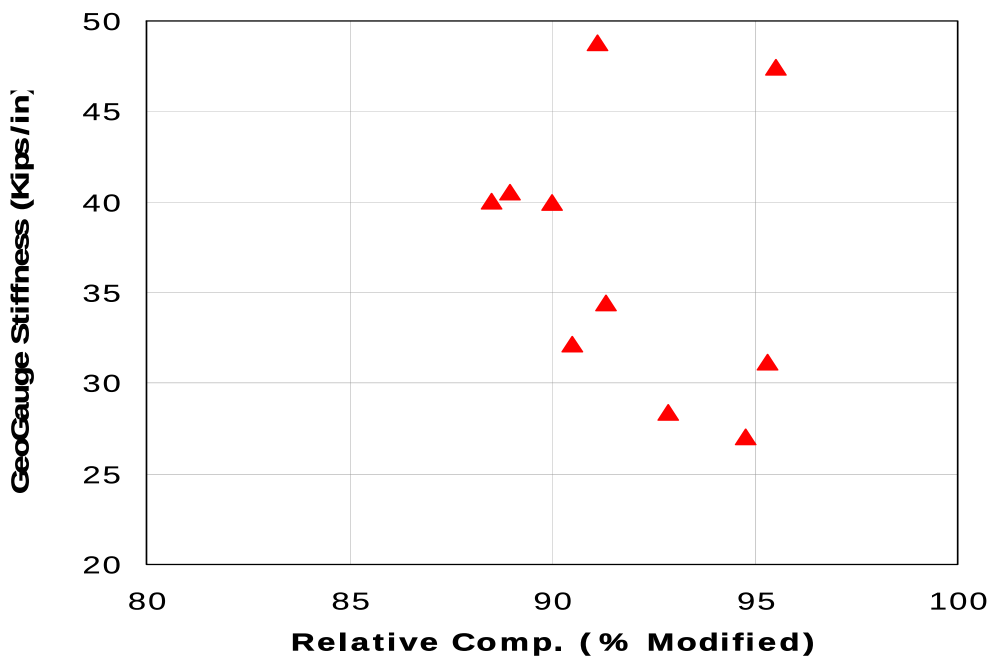

Figure 52 – Relationship between Geogauge Stiffness and relative compaction in stone-base backfill

Effect of Soil Moisture on the Readings

The measurements of the device were taken in backfills compacted at various moisture contents. In these tests, compaction was performed so as to keep the relative compaction constant (within ±2 percent) and vary only soil moisture content. The measurements are plotted in Figures 53 through 55 for the sand, silty-clay, and base soils, respectively.

The figures show that soil stiffness measurements increased with the increase of moisture content up to an optimum moisture value. The optimum moisture value at maximum stiffness did not necessarily correspond to the optimum moisture content at maximum density in the Modified Proctor test.

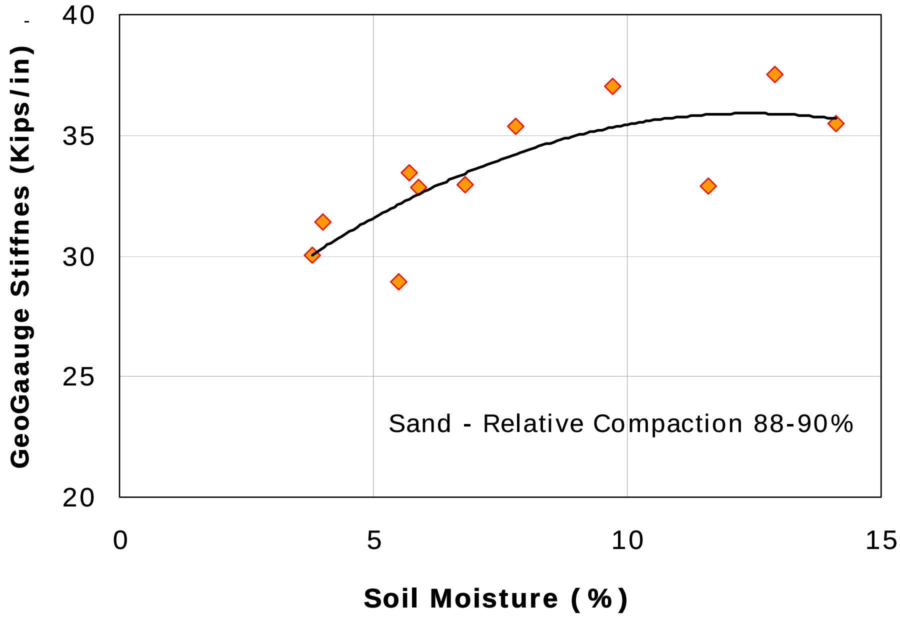

Figure 53 – Change of Geogauge stiffness with moisture in sand

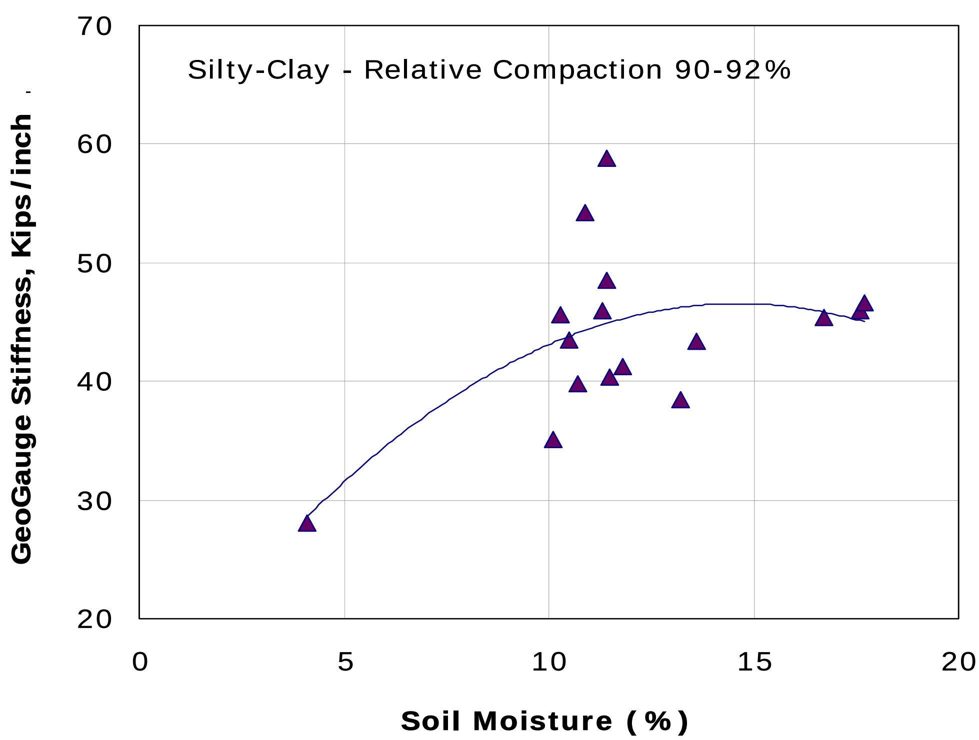

Figure 54 – Change of Geogauge stiffness with moisture in silty-clay

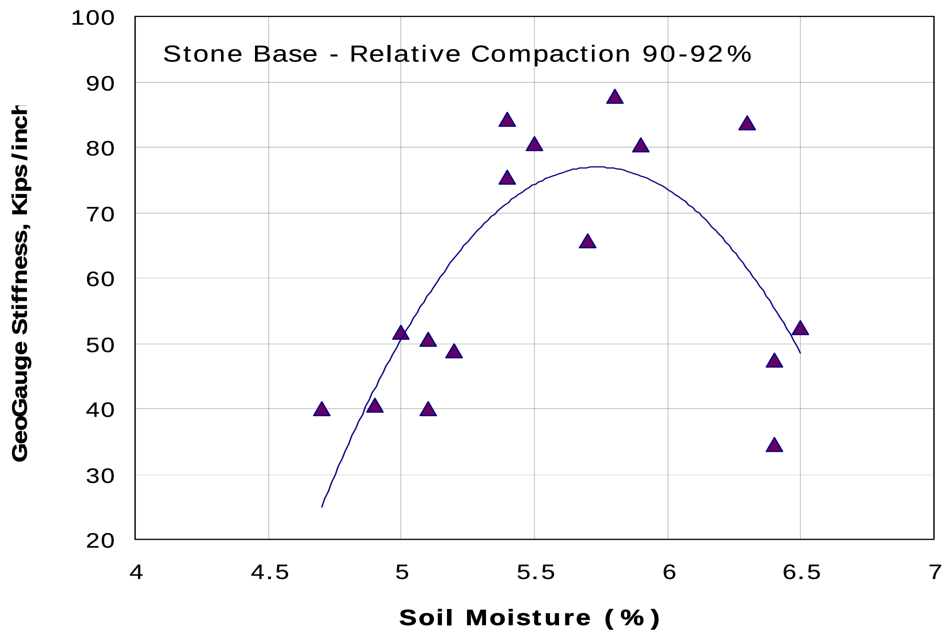

Figure 55 – Change of Geogauge stiffness with moisture in stone backfill

The Clegg Hammer

Description

The Clegg Hammer (formerly, Clegg Impact Soil Tester) consists of a compaction hammer operating within a vertical guide tube. When the hammer strikes the soil surface, a precision accelerometer mounted on the hammer feeds its output to a 'hand-held' digital readout unit. The unit registers the deceleration in units of Impact Value (IV). The IV relates to soil strength and correlates with CBR test results. The ASTM standard D-5874 covers the determination of the Impact Value (IV) of the soil. Figure 56 shows the 10-Kg Clegg Hammer used in the testing program.

The use of the Clegg Hammer in soil compaction measurements was evaluated in previous studies [*20-24*]. A previous study by the New York State Electric and Gas Company (NYSEG) consisted of excavating twelve bellholes [*23*]. The bellholes were backfilled using three different backfills in three lifts per hole. The compaction effort was altered for each hole in order to assure the achievement of acceptable and unacceptable backfill densities. Nuclear Density Gauge (NDG) readings and Clegg Impact Values (IV) were taken in order to determine the target IV values.

In another study, a correlation between the dry density and Impact Values were plotted for various ratios of number of passes per layer to the mean layer thickness [*24*]. The study concluded that the IV value was potentially useful and convenient indicator of the degree of compaction for granular materials. On the other hand, the use of the Clegg Hammer to estimate dry density values required very carefully-determined calibrations for each material under consideration.

The previous studies also addressed the issue of whether the Clegg IV is a measure of the stiffness or strength of a compacted material. It was concluded that in weak or poorly compacted materials, the IV is most likely to be predominately a measure of strength due to the large penetration of the drop weight. On the other hand, with strong or well compacted materials, with small penetration in soil, the IV is most likely to be predominantly a measure of stiffness.

Figure 56- View of the 10-Kg Clegg Hammer used in the testing program

Soil Compaction Measurements

Figure 57 shows compaction measurements using the 10-Kg Clegg Hammer in a trench. Figures 58 through 60 show the relationships between the 10-Kg Clegg IV and relative compactions of sand, silty-clay, and stone, respectively. Similarly, The results of the 20—Kg Clegg Hammer are show in Figure 61 through 63 for the three types of backfill.

The performance of the 20-Kg device is similar to the 10-Kg one. The impact values from both devices had weak correlations in sand and stone-base soil and better correlation is silty-clay soil. From these figures, the IV values, which correspond to the 90 percent relative compaction, are shown in Table 26.

Similar to the other stiffness gauges, the Clegg IV values increased with the increase in the moisture content up to a maximum value and then decreased at higher moisture contents. The maximum moisture content values did not necessarily equal the optimum moisture values obtained from Modified Proctor tests. Figures 64 through 66 show the changes of 10-Kg Clegg IV values at various moisture contents.

Figure 57 – Use of the Clegg Hammer to evaluate compaction in trench backfill

Table 26 – Clegg Hammer results corresponding to 90% Relative Compaction [at optimum moisture content]

	Sand	Silty-clay	Stone-base
10-Kg Hammer (IV)	6	8	14
20-Kg Hammer (IV)	5	6	9

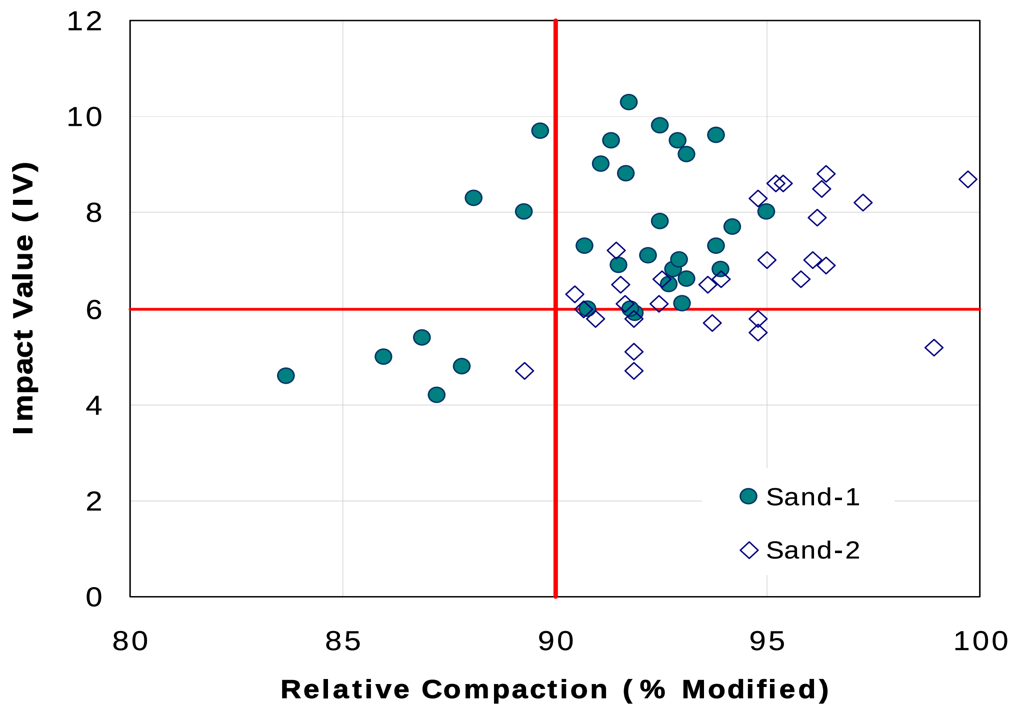

Figure 58 –The 10-Kg Clegg Hammer IV vs. relative compaction in sand

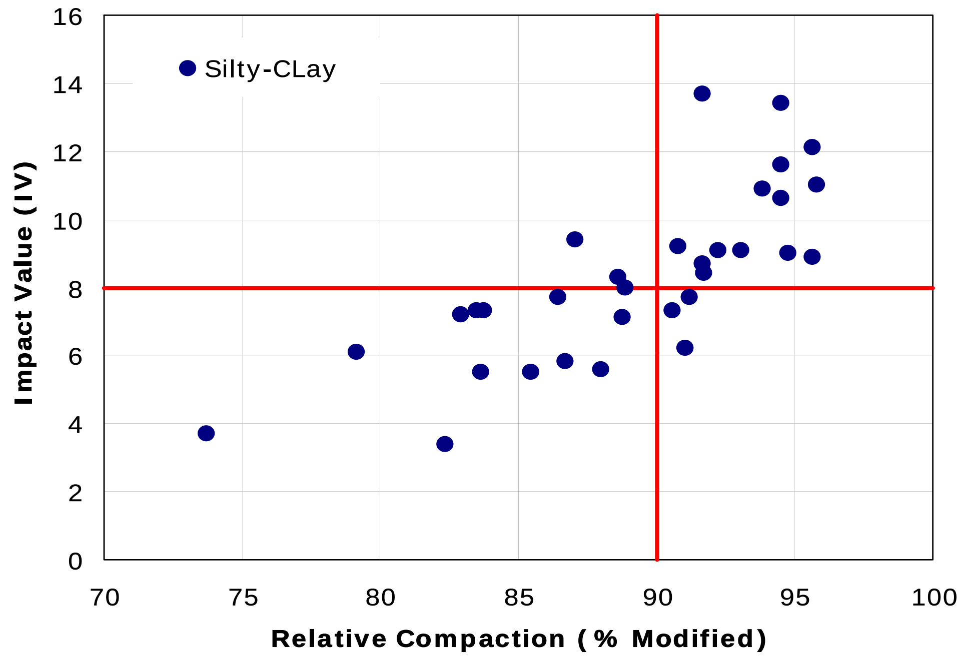

Figure 59 –The 10-Kg Clegg Hammer IV vs. relative compaction in silty-clay

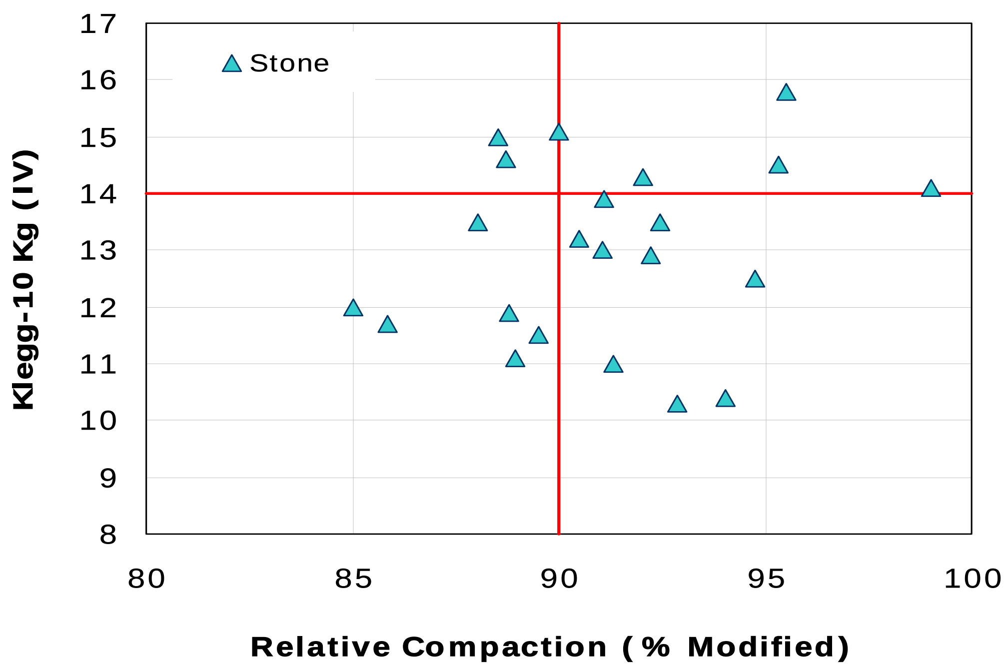

Figure 60 –The 10-Kg Clegg Hammer IV vs. relative compaction in stone

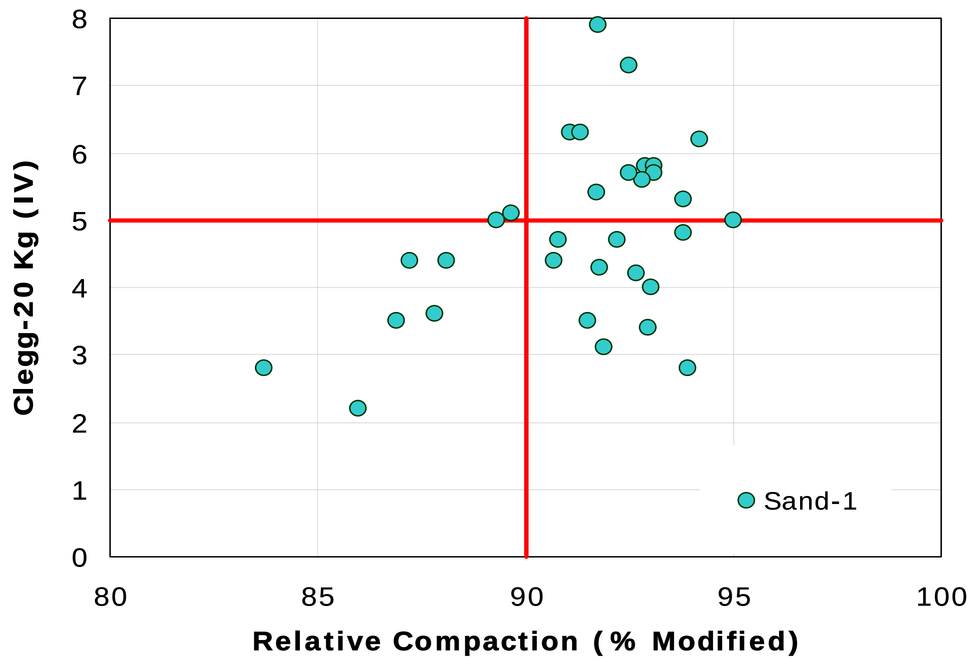

Figure 61 –The 20-Kg Clegg Hammer IV vs. relative compaction in sand

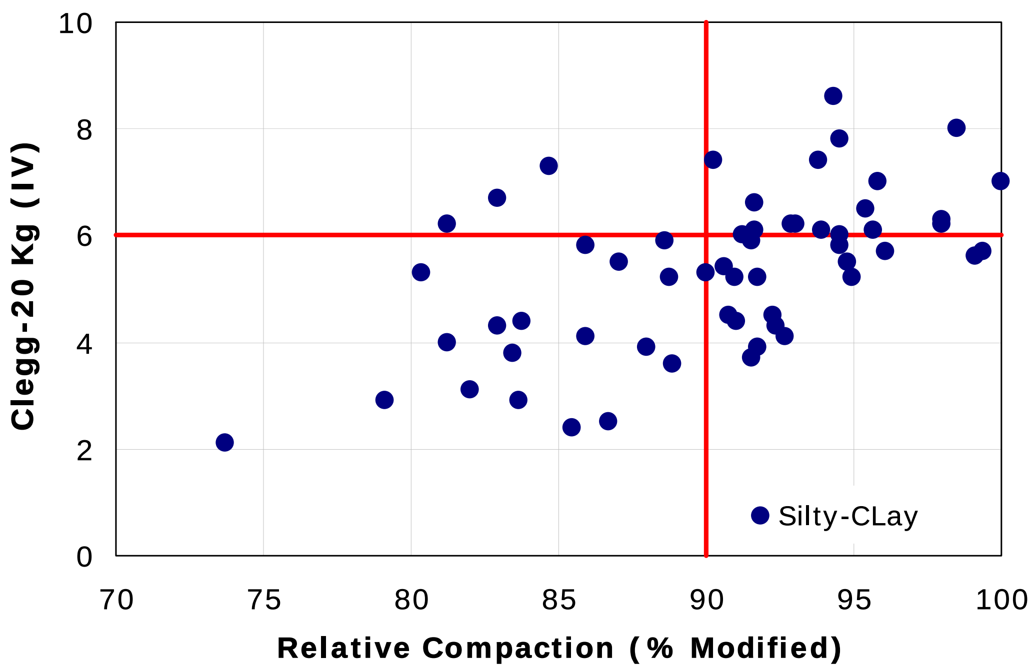

Figure 62 –The 20-Kg Clegg Hammer IV vs. relative compaction in silty-clay

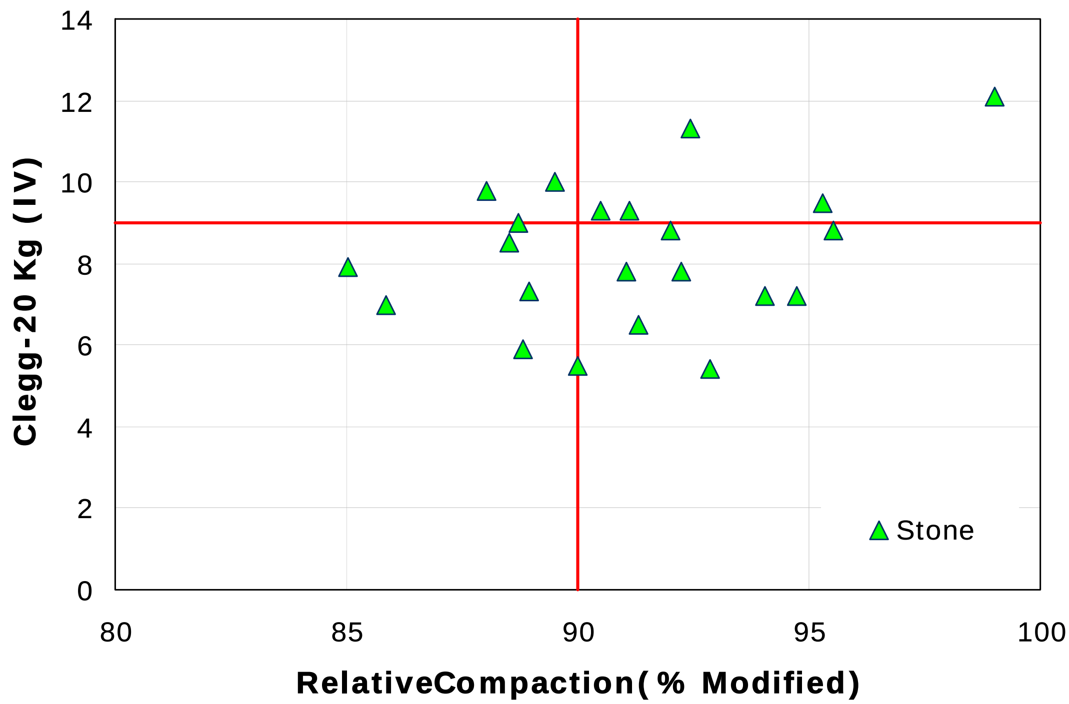

Figure 63 –The 20-Kg Clegg Hammer IV vs. relative compaction in stone

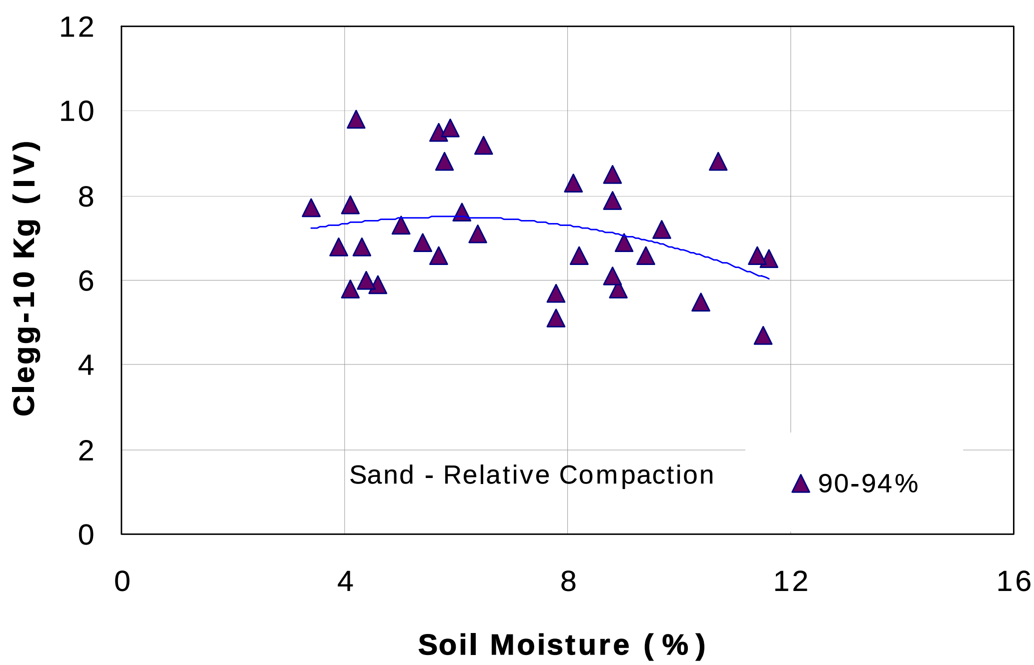

Figure 64 – Effect of change in moisture content on the IV results in sand

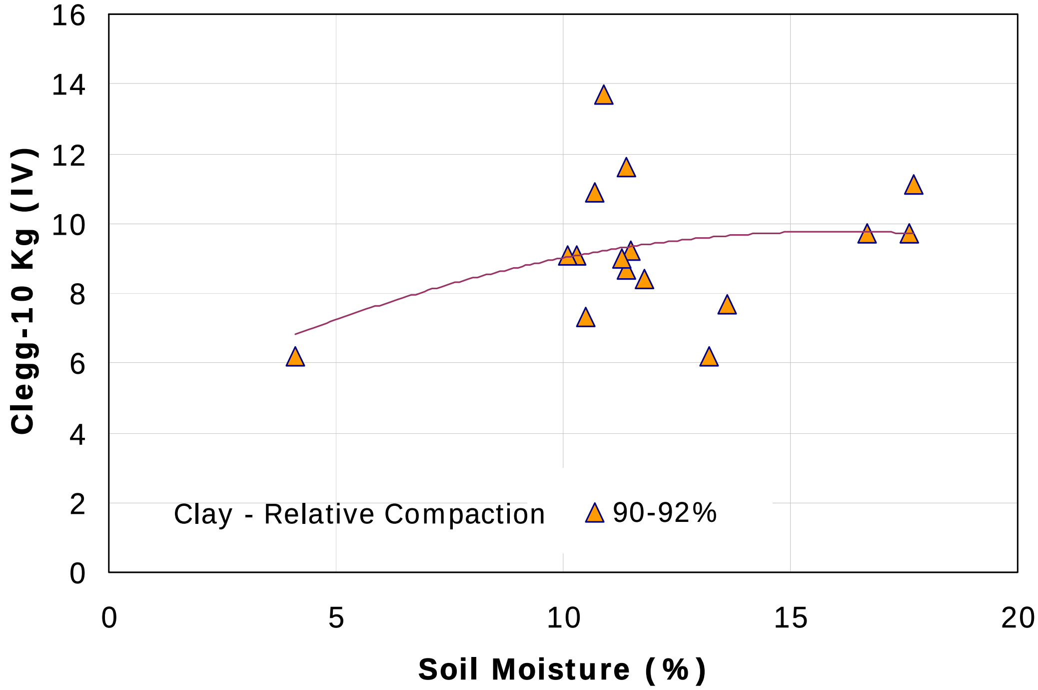

Figure 65 – Effect of change in moisture content on the IV results in clay

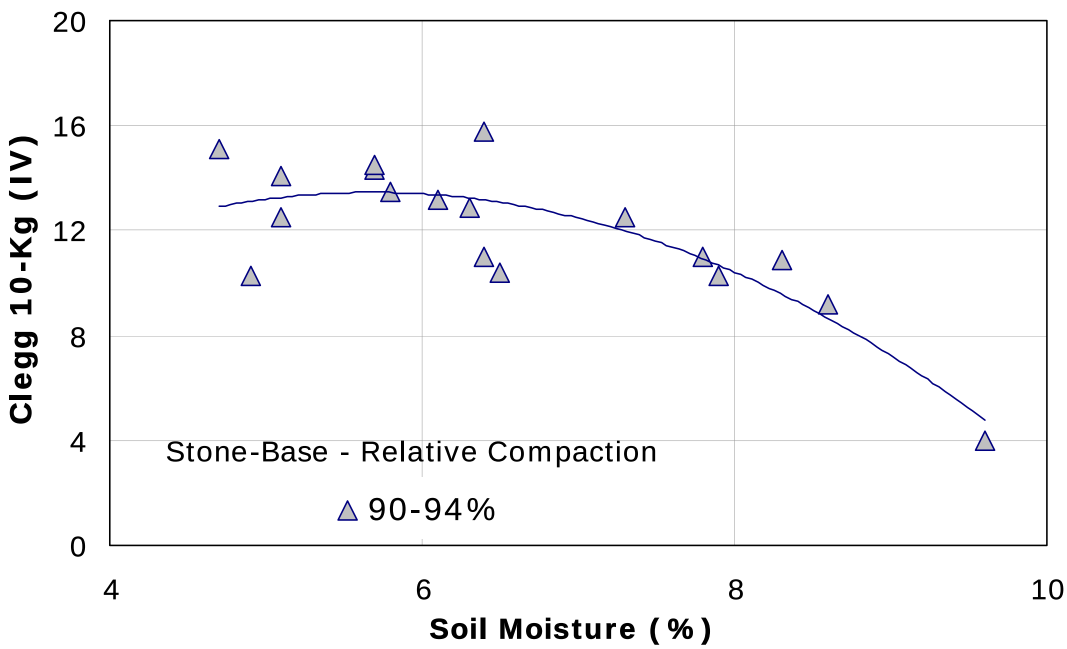

Figure 66 – Effect of change in moisture content on the IV results in stone

Effect of Sidewall Boundaries

Measurements at the center and the edge of bellholes using the Geogauge, Utility DCP, and Clegg hammers are shown in Figure 67. The results show that the readings from the Geogauge were sensitive to the location of the gauge with respect to the sidewall. At the same locations, the reading from the DCP and Clegg hammers were not influenced by the bellhole boundary.

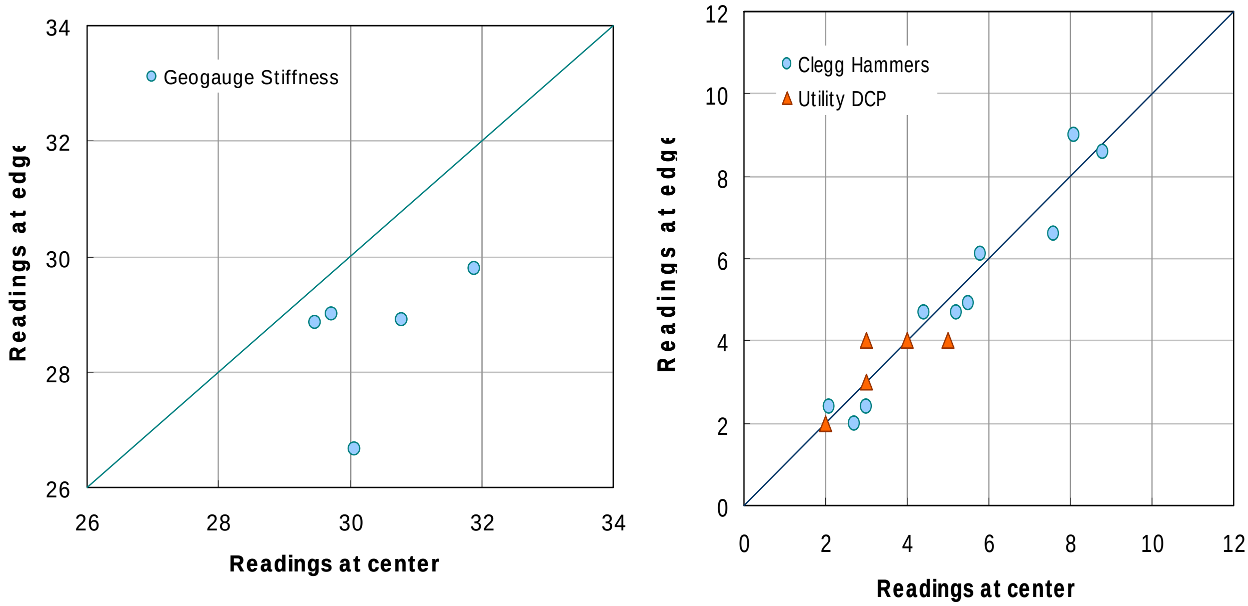

Figure 67 – Measurements at the center and edge of bellhole

The Standard Dynamic Cone Penetration (Standard-DCP)

Description

The Standard DCP evaluates soil densification by the amount of penetration of a standard cone. The device is composed of two connected rods with a replaceable cone at the end of the lower rod. The cone is driven into the soil by dropping a standard single or dual mass hammer weighting 17.6 pounds through the guided upper rod. The drop weight pushes the lower rod into the soil. Figure 68 shows a schematic of the Standard-DCP. The penetration of the cone into the soil is read on a vertical scale and recorded in the field. The device is identified as 'Standard' in this report in order to differentiate it from the smaller Utility DCP version. Figure 69 shows the Standard-DCP and the Utility DCP.

The Standard-DCP is relatively inexpensive, easy to transport and to operate, and is useful as a QA tool for evaluating post compaction as the weight of the hammer is sufficient to drive the cone to a distance of about 3 feet into the soil. However, the measurements usually require two people to operate, one to drop the hammer and the other to read the depth of penetration. The device has an ASTM standard specification (D 6951). The nature of cone penetration testing limits its use where large stones may affect the penetration reading.

The device is used by some highway agencies in the evaluation of granular base layers and the results can be correlated to useful highway design parameters such as the California Bearing Ratio (CBR), and soil resilient modulus [*26-31*].

Testing and Analysis Procedures

The penetration of the cone into the soil is read for each blow on a vertical scale. Figure 70 shows the use of the DCP after the compaction of a bellhole section. Test results are commonly expressed as Penetration Index, DPI (inch/blow), which is the depth of penetration for each drop of the hammer.

Data are recorded in a spreadsheet form as shown in Table 27. The data in the first two columns are recorded during the test. The third column is the negative values of the rod readings in the second column. The negative values are used only for the purpose of plotting the graph. The fourth column is the Penetration Index (DPI), which is calculated from column two by subtracting the previous DCP reading from the current one.

The results of the DPI versus the penetration depth are commonly plotted in a graph as shown in Figure 71-(a). Limited information can be obtained from these plots with regard to the quality of soil compaction. The plots, however, can be used to identify the boundaries of soil layers (when significant changes in DPI values occur) and as an indication of the relative densification of the layers.

The results of the DCP were correlated to several soil and pavement design parameters. The California Bearing Ratio (CBR) is probably the most common correlation. The US Army Corps of engineers has established two equations correlating DPI to CBR [*27*]. These equations are:

$$Log\ (CBR\ \%) = 2.46 - 1.12\ Log\ (DPI) \qquad \text{(for CBR greater than 10 percent)}$$

$$CBR\ \% = 1 / (0.017\ X\ DPI) \qquad \text{(for CBR less than 10 percent)}$$

A correlation was also established between soil dry density (γ_d) and DPI in the form [*28*]:

$$\gamma_d = 10^{1.5} \ x\ DPI^{-0.14} \ x\ (\sigma_v / P_a)^{0.5} \ x\ \gamma_w$$

where σ_v is effective vertical stress, P_a is reference stress, and γ_w is water unit weight. It was, however, recommended to use this relationship in conjunction with other density measuring devices.

The Minnesota Department of Transportation has conducted extensive work on the use of the DCP results. It currently specifies two different applications of the DCP testing in its pavement assessment procedure. One application involves using the DCP as a quality control device in backfill of edge drain trenches. The other application, which is of interest to our application, is its use as a QA in the compaction of granular base layers. In this application, the MD-DOT specified DPI limit values of $DPI < 0.75$ inch/blow for each 3-inch lift.

It should be noted that a higher values of DPI indicates a loose soil and the shape of the curve in figure 71-(a) is the reciprocal of the strength curves obtained from other devices such as the Panda system (as will be shown later). Accordingly another plot is suggested to better represent the changes of soil strength. The horizontal axis of the new plot is the inverse values of the DPI.

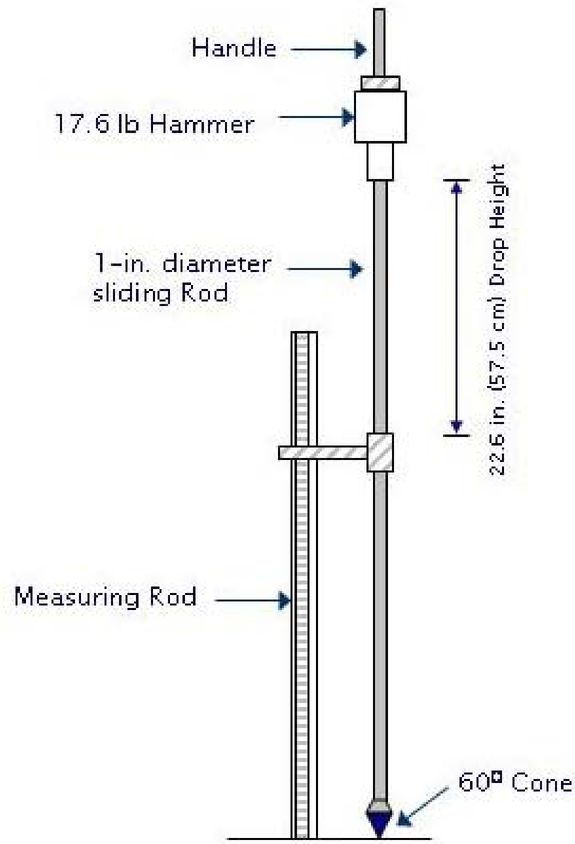

Figure 68 - The Standard Dynamic Cone Penetration Device (DCP)

Figure 69 – The Standard-DCP and the Utility-DCP

Figure 70 - The DCP test in the indoor bellhole section

Table 27 – Sample Data from the Standard-DCP

STANDARD DCP RESULTS				
Name:	DCP- Outdoor Keyhole, Native Soil			
Soil :	Native Soil Outside Lab			
Operator:	DV, AF			
Test-1	9/12/2003			
Blow Count	Rod Reading (in.)	Inverted Reading (in.)	Penetration Index (in./blow)	Blow Index (blow/in.)
0	0.9	-0.9	0	0
1	1.8	-1.8	0.9	1.1
2	2.4	-2.4	0.6	1.7
3	2.9	-2.9	0.5	2.0
4	3.2	-3.2	0.3	3.3
5	3.5	-3.5	0.3	3.3
6	3.8	-3.8	0.3	3.3
7	4.2	-4.2	0.4	2.5
8	4.5	-4.5	0.3	3.3
9	4.9	-4.9	0.4	2.5
10	5.3	-5.3	0.4	2.5
11	5.9	-5.9	0.6	1.7
12	6.4	-6.4	0.5	2.0
13	7.4	-7.4	1.0	1.0
14	8.1	-8.1	0.7	1.4
15	8.8	-8.8	0.7	1.4
16	9.6	-9.6	0.8	1.3
17	10.4	-10.4	0.8	1.3
18	11.2	-11.2	0.8	1.3
19	12.3	-12.3	1.1	0.9
20	13.2	-13.2	0.9	1.1
21	14.1	-14.1	0.9	1.1
22	15.1	-15.1	1.0	1.0
23	16.1	-16.1	1.0	1.0
24	17.0	-17.0	0.9	1.1
25	18.0	-18.0	1.0	1.0
26	18.8	-18.8	0.8	1.3
27	19.5	-19.5	0.7	1.4
28	20.3	-20.3	0.8	1.3
29	21.2	-21.2	0.9	1.1
30	22.1	-22.1	0.9	1.1
31	22.9	-22.9	0.8	1.3
32	23.5	-23.5	0.6	1.7
33	24.2	-24.2	0.7	1.4
34	24.9	-24.9	0.7	1.7
35	25.7	-25.7	0.8	0.3

The plot of 1/DPI versus depth is shown in Figure 71-(b). The parameter 1/DPI is defined here as the ‘Blow-Index’ (blow/inch) which is the number of blows for each unit depth of one inch.

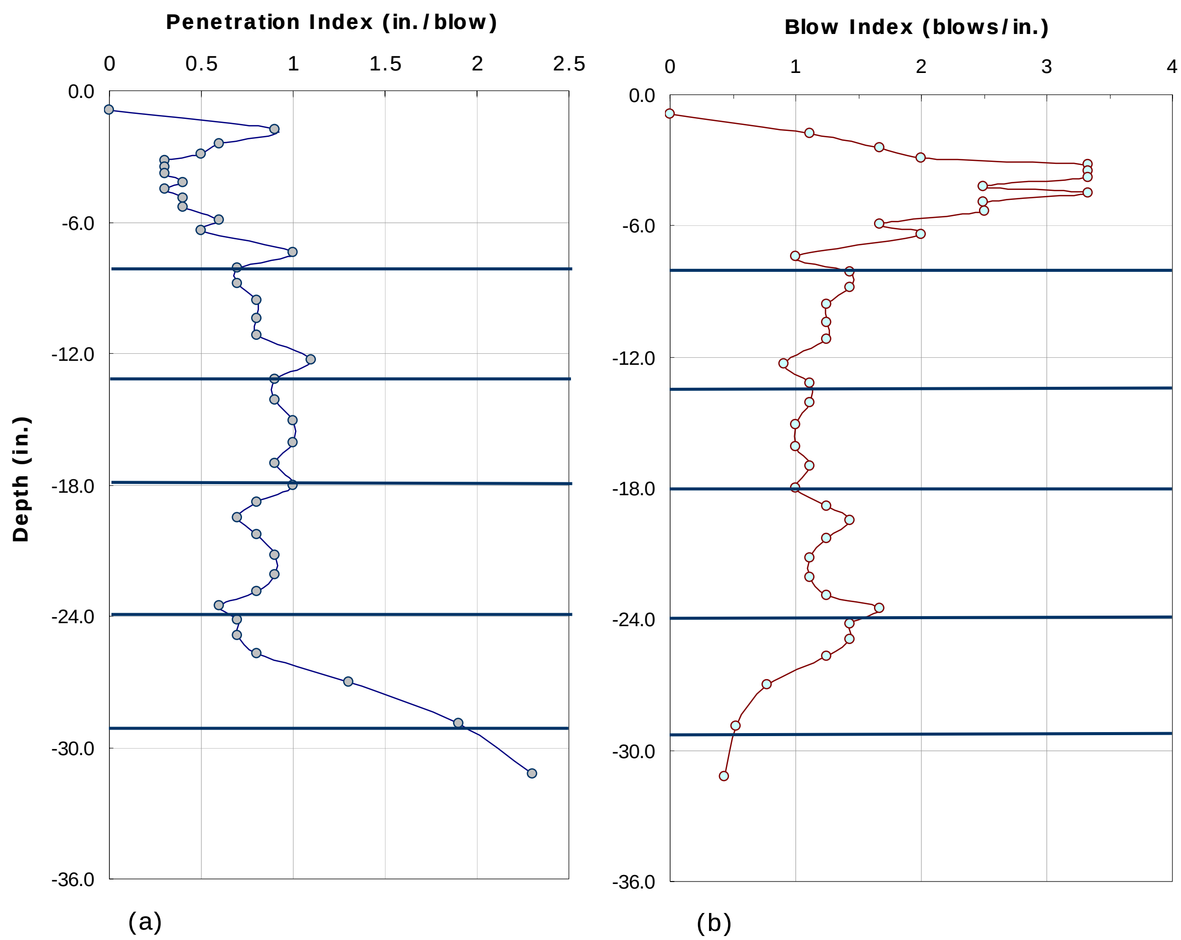

Figure 71 – Two forms for plotting the output from the DCP Tests

Results of the Testing Program

The DCP test was used as a post-compaction QA tool in order to determine the acceptance criteria of the Standard DCP with respect to relative compaction. Tests were performed on various types of soils after the completion of the compaction of the trenches and bellholes. Results were compared with the density measurements from the NDG tests.

The results of the Standard DCP tests are shown in Figures 71 through 79. The results are plotted using the Blow-Index values versus depth of the test section. The relative compaction of the soil layers using the 6-inch probe depth of the NDG are also plotted in the figures.

The DCP test does not give reliable readings in the top unconfined layer of sand as the cone tip usually penetrates few inches under its own weight before measurements are taken. For this reason, test results in sand in figures 72 through 76 show that the DCP measurements of the top 6-inch soil layers where low and did not relate to the NDG readings. In the consecutive soil layers, the Blow-Index results show the trend of soil densification with depth.

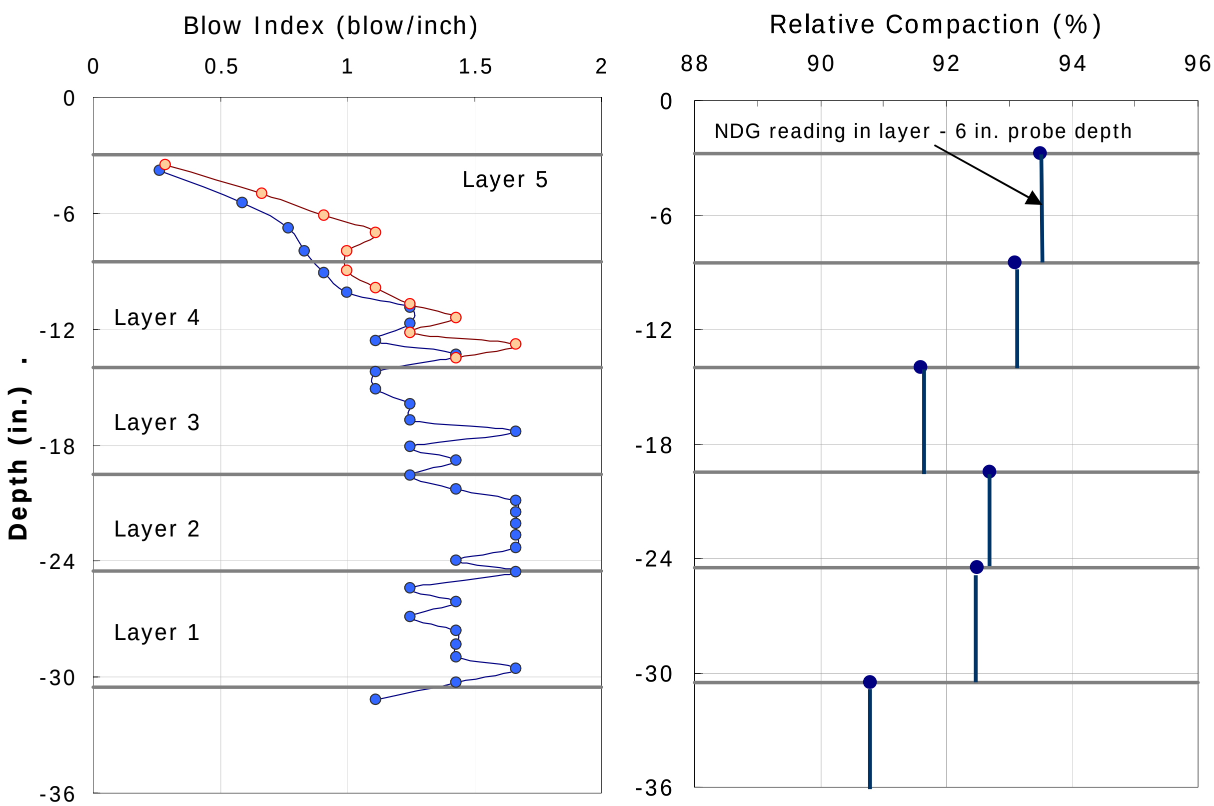

Figure 72 – Standard-DCP results of test [Sand-1] in bellhole

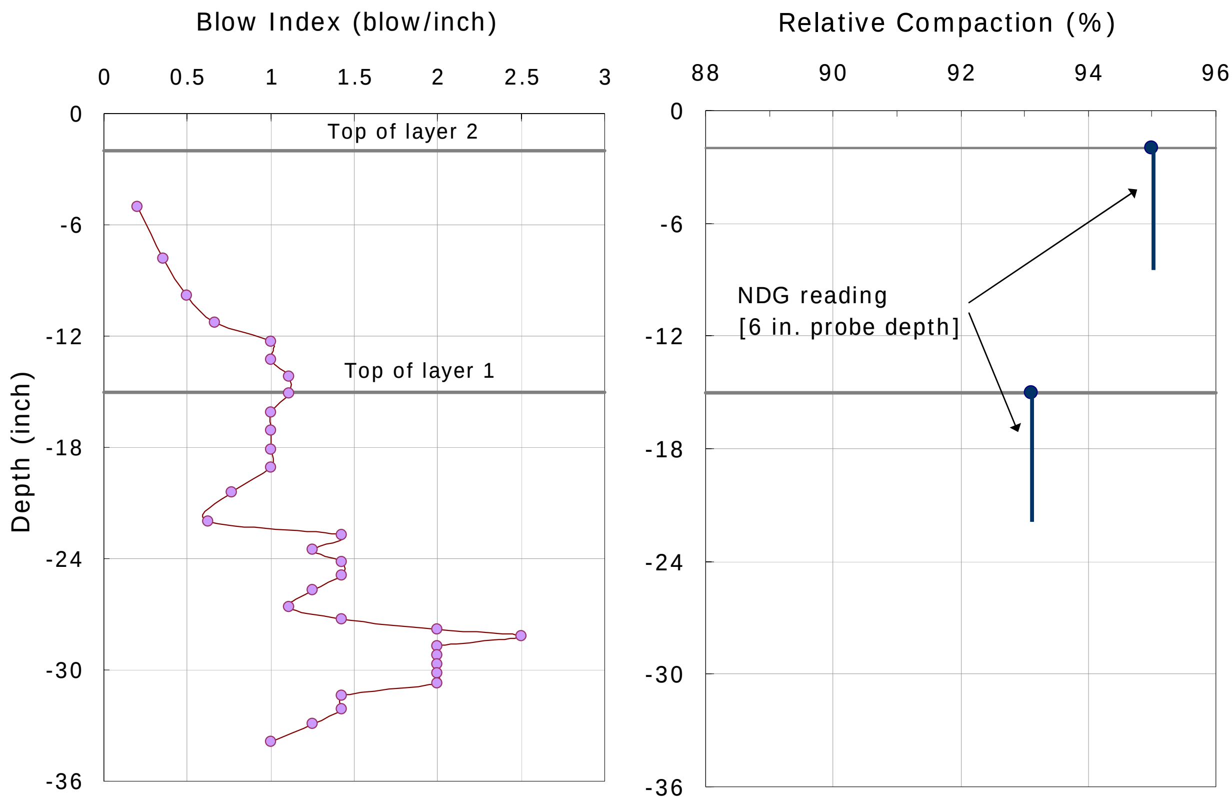

Figure 73 – Standard-DCP results of test Sand-2 in bellhole

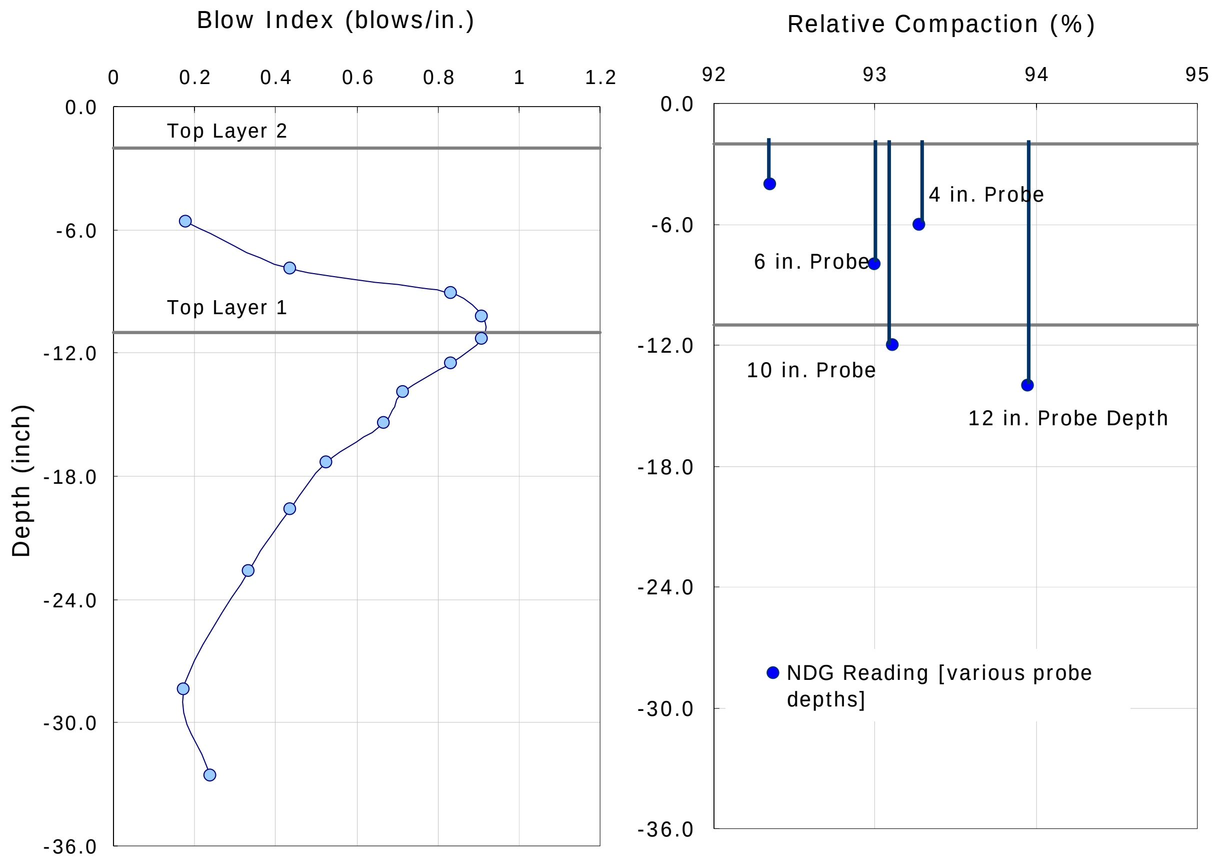

Figure 74 – Standard-DCP results of test Sand-4 in bellhole

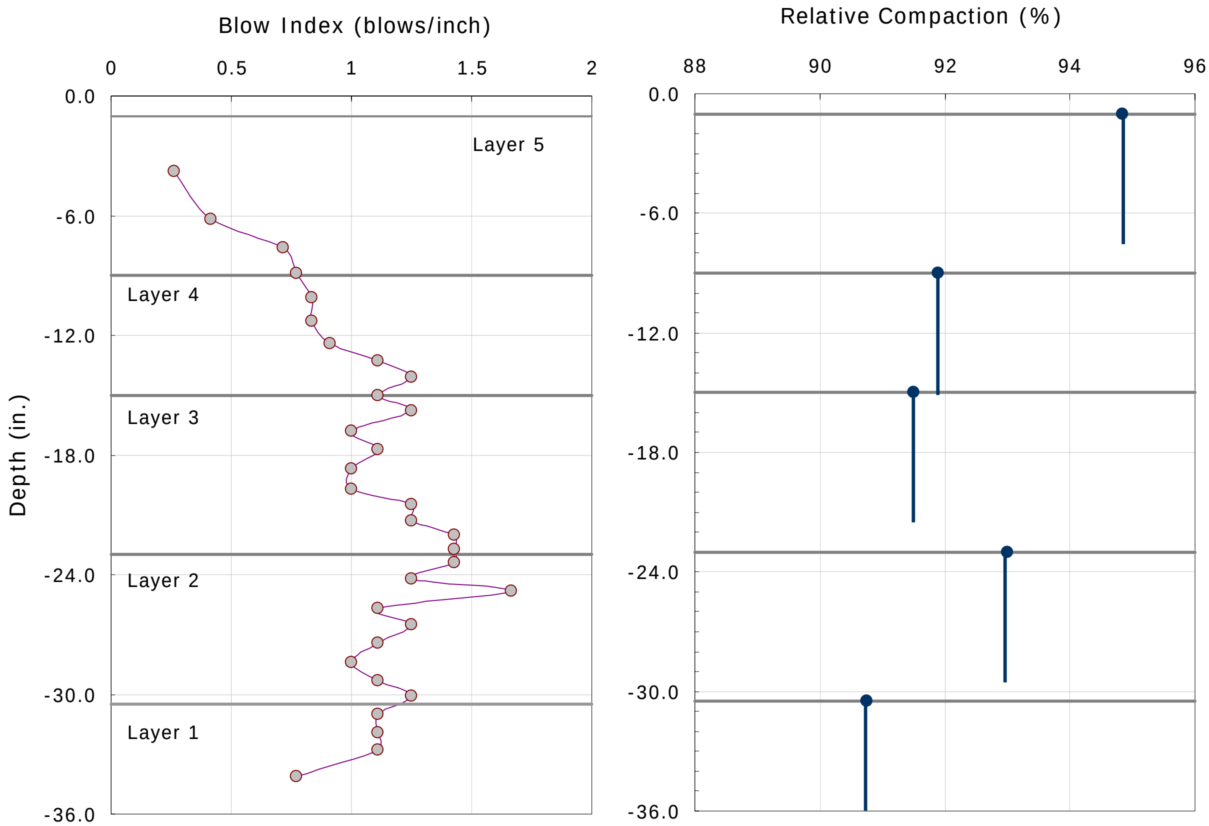

Figure 75 – Standard-DCP results of test NJ Sand in trench

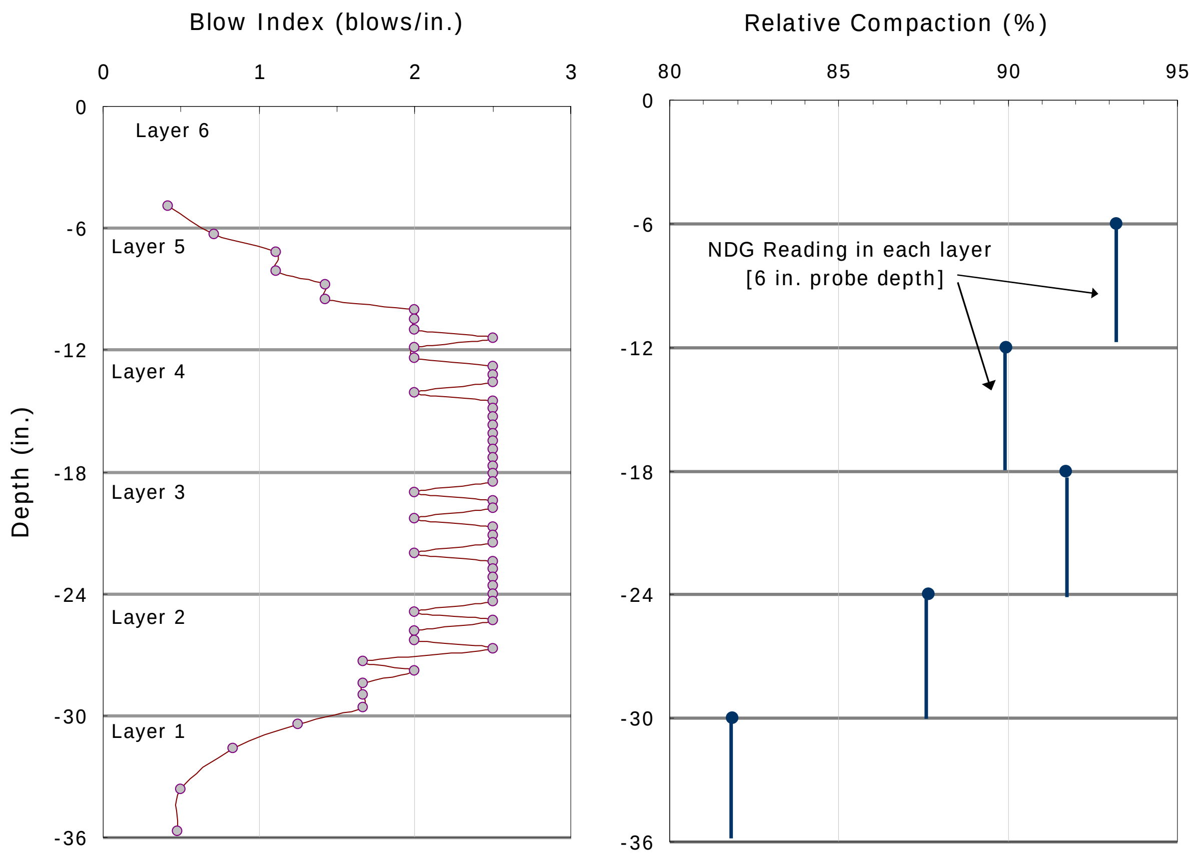

Figure 76 - Standard DCP results of test Sand-6 in keyhole

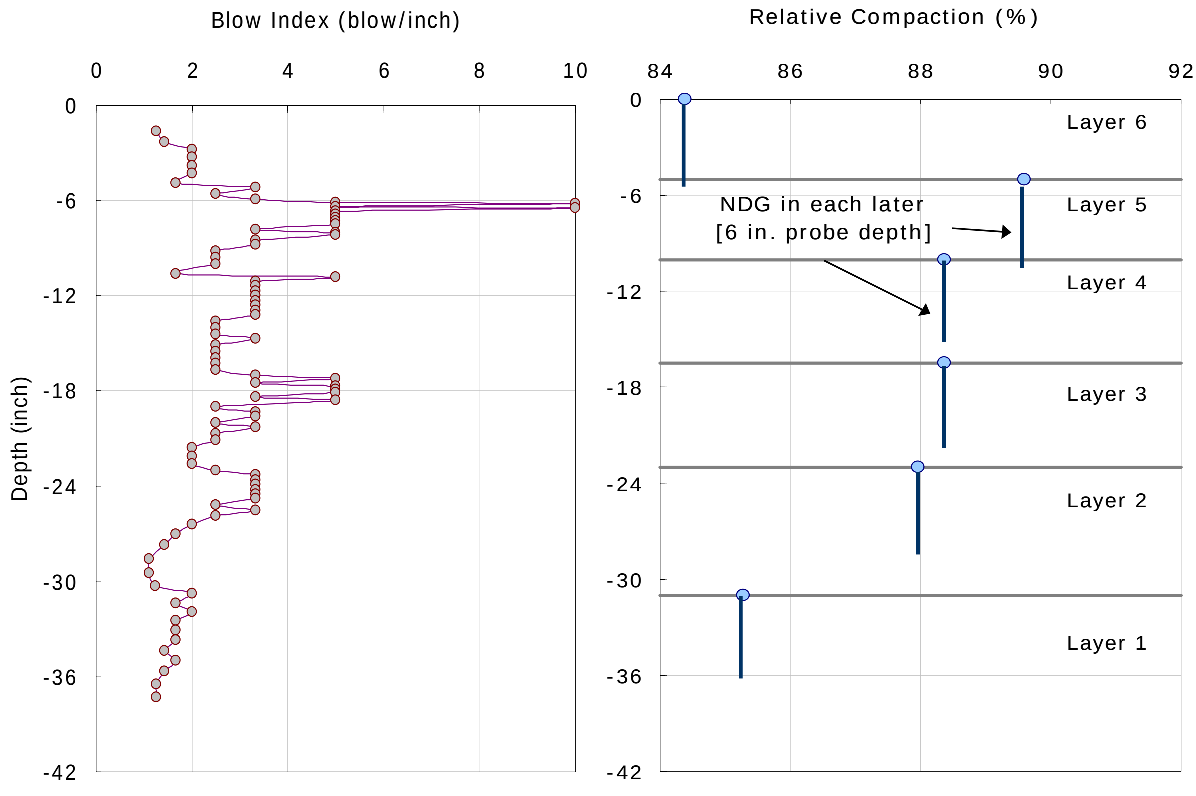

Figure 77 – Standard-DCP results of test Clay-1 in trench

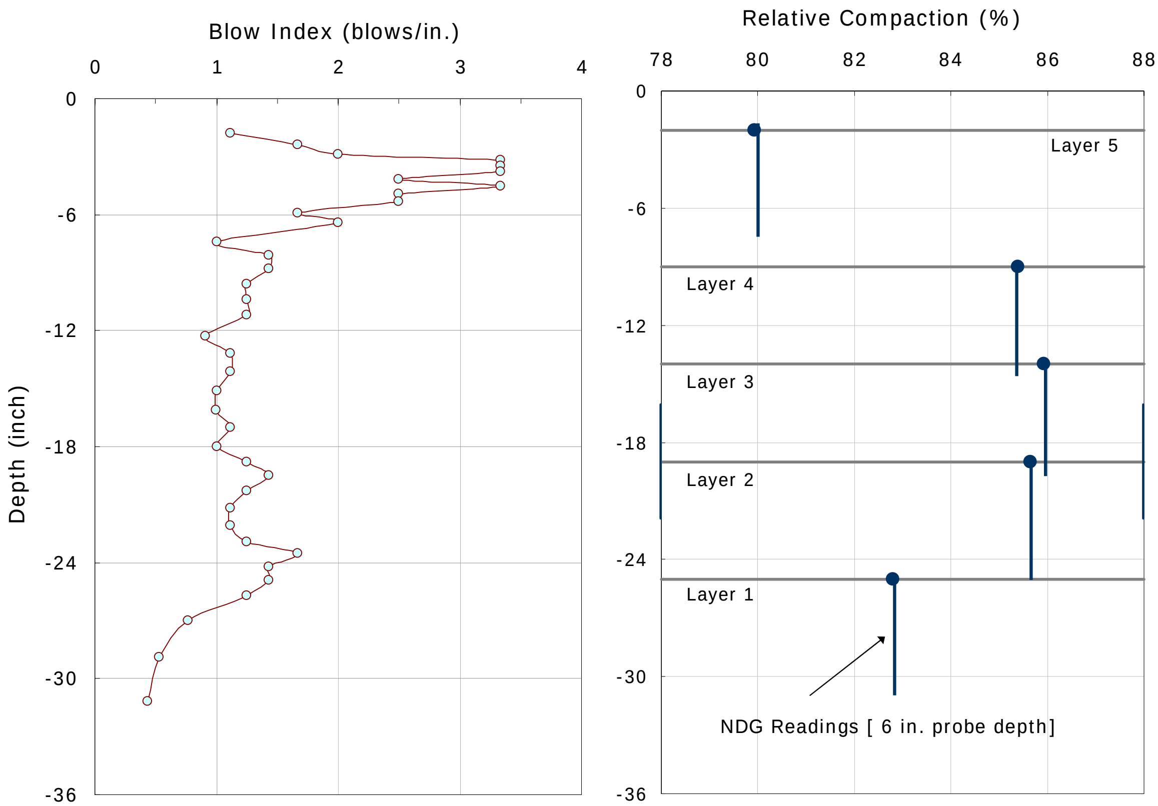

Figure 78 – Standard-DCP results of test Clay-3 in keyhole

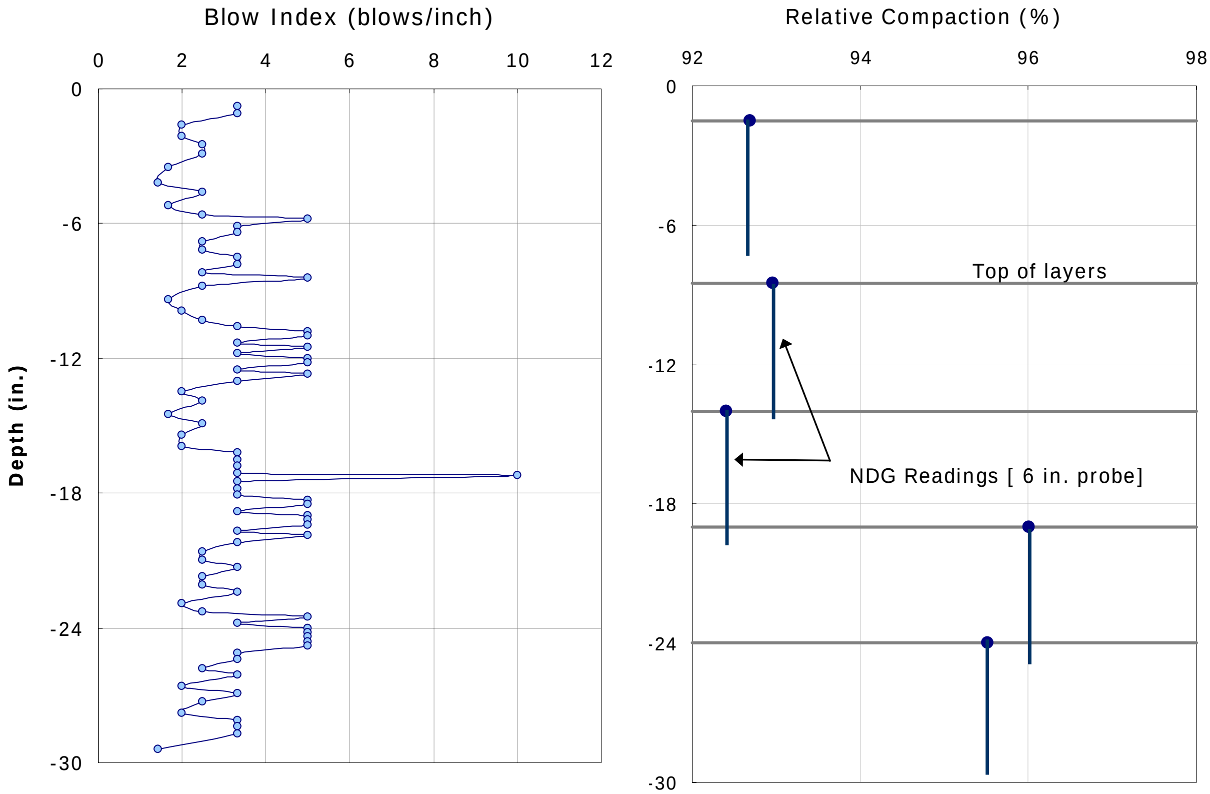

Figure 79- Standard DCP results of test Stone-2 in bellhole

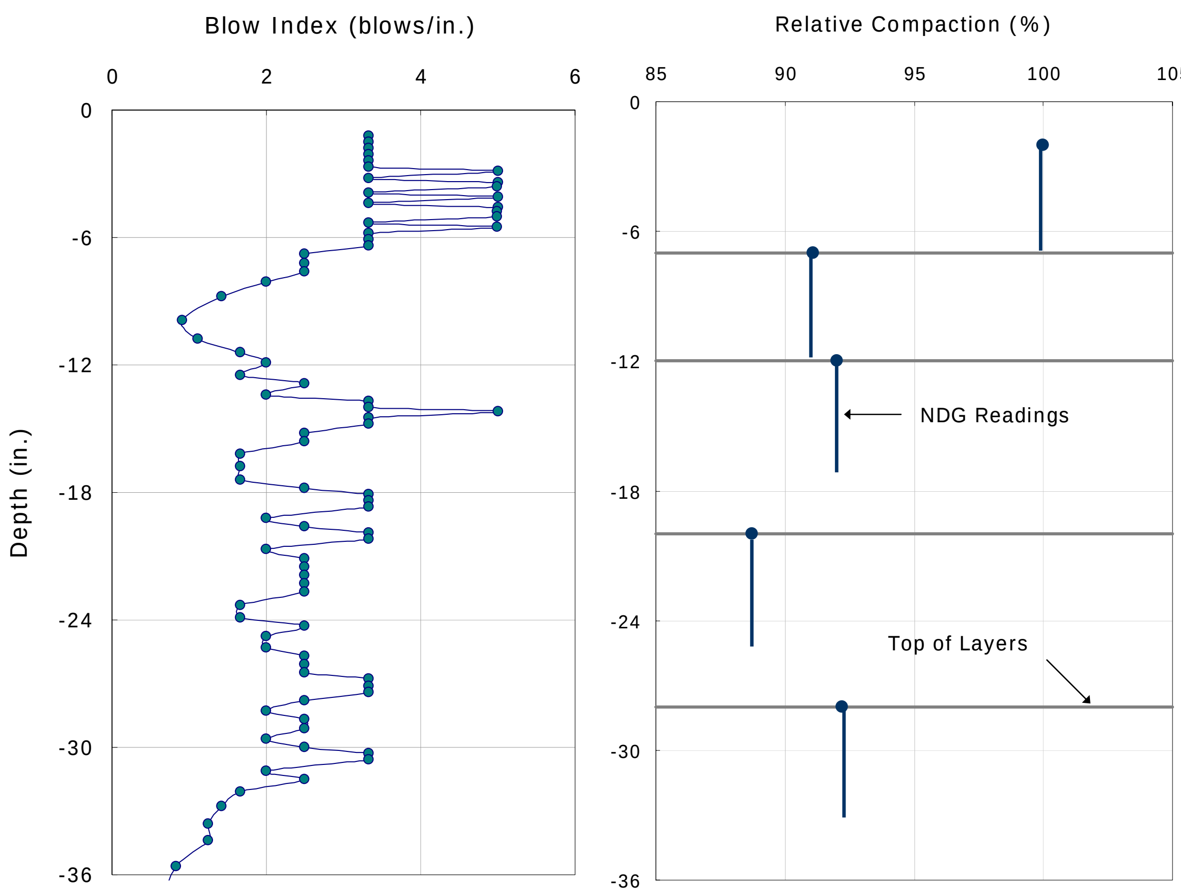

Figure 80 – Standard-DCP results of test Stone-3 in trench

The results in Figures 72 through 80 can be used to establish acceptance criteria of the relative compaction using the Standard DCP. Estimates of the Blow-Index values, which correspond to 90 percent modified relative compaction, are shown in table 28.

Table 28 – Standard-DCP results corresponding to 90% Relative Compaction

	sand	Silty-clay	Stone-base
Blow Index (blows/inch)	1.1	5	2

The PANDA

Description

The Panda is a dynamic cone penetrometer where a manual hammer is used to drive a standard cone into the soil. Figure 81 shows a schematic of the device. As the cone rod is driven into the soil, an accelerometer measures the impact velocity and a retractable tape measures the penetration depth.

The output data is recorded at each blow in an electronic box and the accompanied software reduces the data and compares it with established pre-calibrated curves for various standard soils. The device was developed in France and the calibrated curves were based on the French GTR soil classification system. Accompanying charts are provided to correlate soil types between the American (AASHTO and USCS) and the French standards. Data input and output are only presented in the SI units.

The device is used as a QA tool for post compaction and the output curves from the software program show the acceptance/refusal criteria for compaction control.

The field test can be performed by one person and it is operator-independent. The data reduction and interpretation program assumes user's knowledge of soil classification and compaction standards and requires technical training for the use of the PC software.

Testing and Analysis Procedures

Figure 82 shows the Panda testing in a typical bellhole test section. During the test, the measurements of penetration depth and cone resistance are recorded and stored in a file in the microprocessor box. Figure 83 shows a sample data output. The data is transferred to a PC and a software package is used in order to plot and interpret the data. The results are compared with a database of reference curves in order to establish the pass/fail lines of compaction control.

The use of the software requires data input from the user in order to establish soil type and compaction criteria [*32*]. These data input parameters are:

- Trench Geometry: The user inputs the number of compacted layers in the trench and each layer thickness.

- Soil Classification: The user selects the soil type in each layer. The selection list is based on the French soil classification system, GTR, shown in Figure 84. The French classification standard is correlated with the AASHTO and USCS classification systems in the user's manual. The user may utilize the conversion charts in Figure 85 for classifying the soil. The use of the table, however, requires the proper selection of soil type based on soil sieve analysis data and Atterberg Limits (soil Liquid Limit and Plasticity Index PI).

- Compaction Requirements: The user selects the compaction level that is required for each layer of the trench. The selection list of the available compaction levels is shown in Figure 86. It should be noted that the list does not explicitly include the commonly required compaction level of 90% Modified Proctor test.

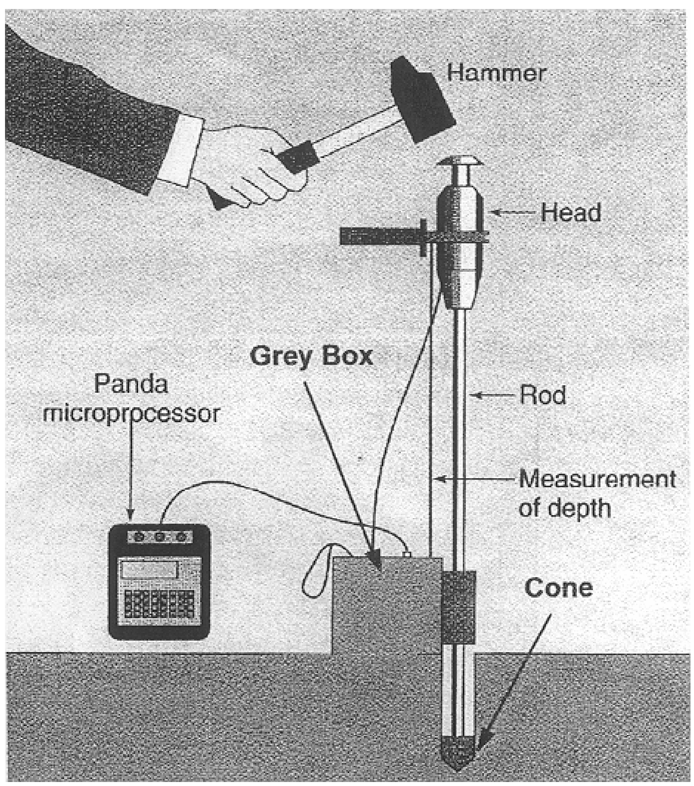

Figure 81 - Schematic of the components of the Panda system

Figure 82 - Panda testing in the indoor bellhole section

```
File name :      c:\pandaw\sand_3.pda

Site :   SAND2.2 Date :  12/03/02
                 Water table :   3.000    m

         Test  :  02       Cone area :       2        cm²
                           Origin :          0.000    m
                           Operator :        -
                           Remarks  :        -
```

Index	Depth (m)	Cone resistance
1	0.035	0.35
2	0.052	0.93
3	0.068	1.06
4	0.080	1.36
5	0.088	1.69
6	0.105	1.26
7	0.119	1.54
8	0.133	1.23
9	0.152	1.61
10	0.167	1.99
11	0.180	2.26
12	0.197	1.93
13	0.212	2.05
14	0.228	2.59
15	0.245	2.23
16	0.267	2.58
17	0.285	2.71
18	0.296	4.04
19	0.307	3.52
20	0.318	4.97
21	0.326	3.95
22	0.337	5.02
23	0.347	4.51
24	0.354	5.18
25	0.361	3.60
26	0.370	3.46
27	0.379	4.07
28	0.388	4.84
29	0.398	3.81
30	0.408	4.28
31	0.413	4.05
32	0.419	3.84
33	0.427	4.05
34	0.435	4.41
35	0.442	3.56

Figure 83 - Sample output file from the Panda field measurements

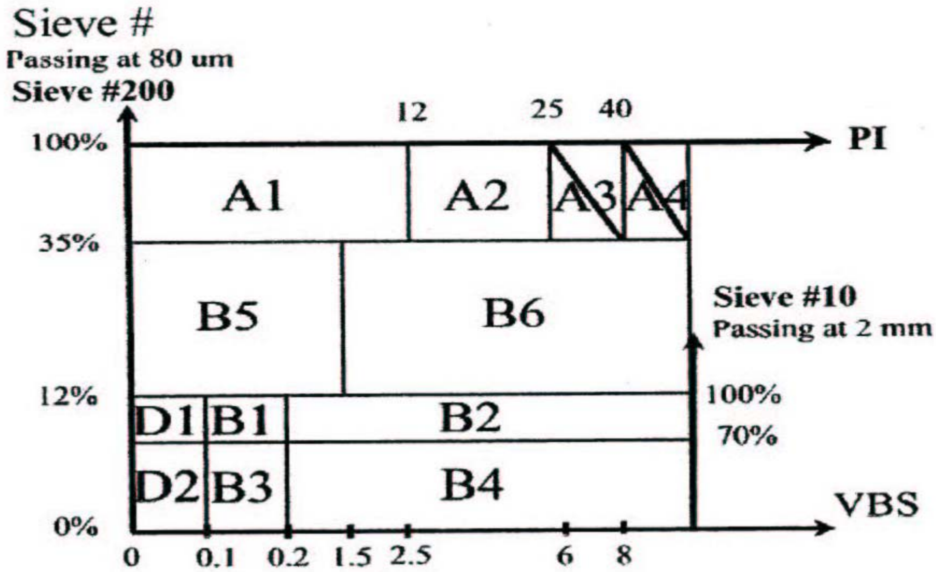

Figure 84 – Soil Classification System according to French Specifications

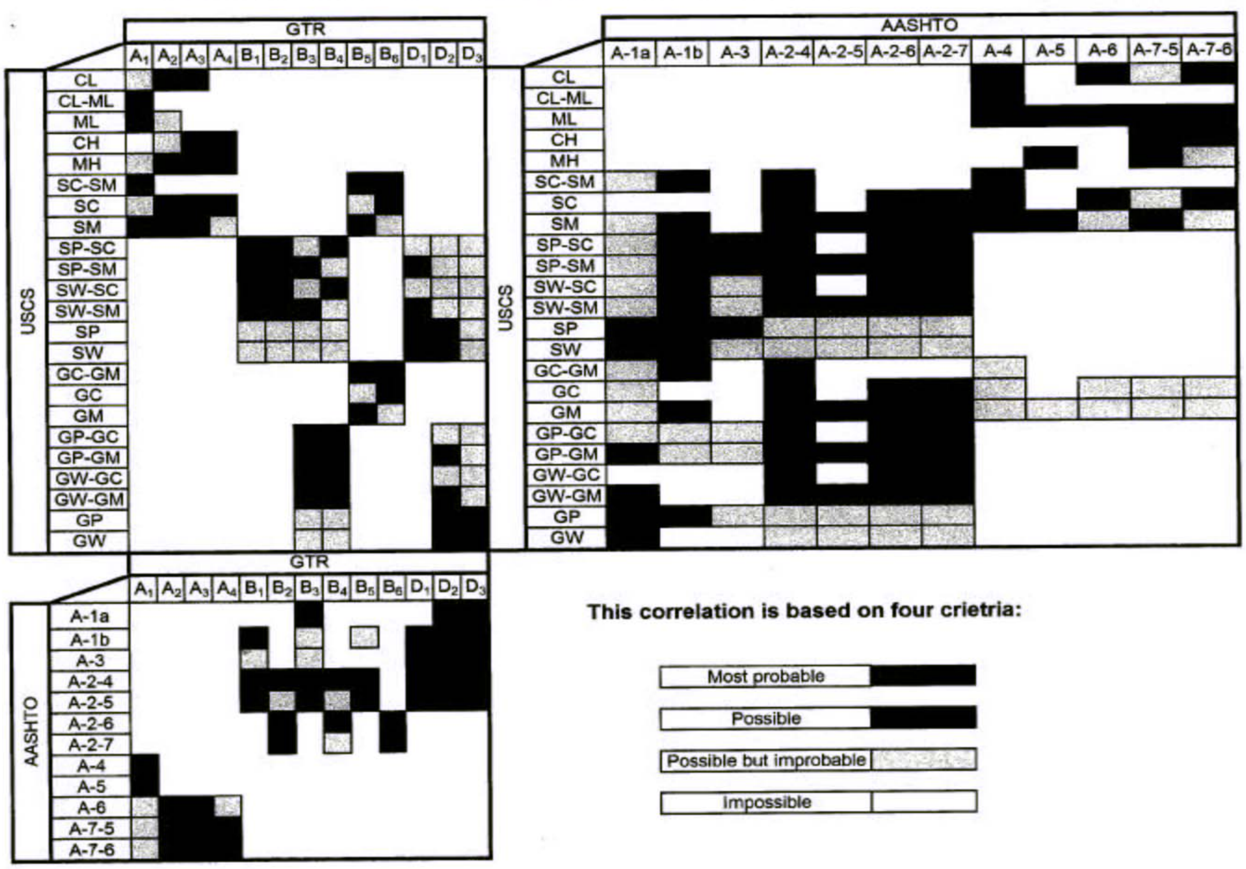

Figure 85 - Conversion charts between the GTR, AASHTO and USCS systems

Compaction Quality Level	Application Zone	Required Density (Top of the Layer)	Required Density (Bottom of the Layer)
q4	Inferior part of the road Base	95% of Standard Proctor Density	92% of Standard Proctor Density
q3	Superior part of the road base	98.5% of Standard Proctor Density	96% of Standard Proctor Density
q2	Road Structure	97% of Modified Proctor Density	95% of Standard Modified Proctor Density

Figure 86 - Compaction requirements for the Panda data entry

Results of the Testing Program

The Panda was tested in various types of soils as a QA device after the completion of the compaction of the trenches and bellholes and the results were compared with the relative compaction measurements from the NDG tests.

The results of the Panda tests correlate to the results of the Standard DCP since both devices measure soil response to dynamic penetration. As the cone rod is driven into the soil, the DCP measures cone displacement while the Panda correlates to its resistance. A comparison between the results of both devices is shown in Figures 87 and 88 for sand and silty-clay soils, respectively. The figures show a correlation between the results of both devices.

The results of the Panda and the corresponding NDG measurements for various types of soils are shown in Figures 89 through 95.

The output of the Panda program shows two limit lines for compaction criteria; one 'Acceptance' line and one 'Refusal' line. Only the 'Refusal' lines were considered and most of the tests were evaluated for a compaction quality level q3 of 96 percent Standard Proctor Density at the bottom of the layer. The results in Figure 91 were plotted against two levels of compaction; namely q3 and q4. The figure shows that the compaction did not pass q3 level in most of the section. NDG results, however, showed that the density was higher than 90 percent modified relative compaction.

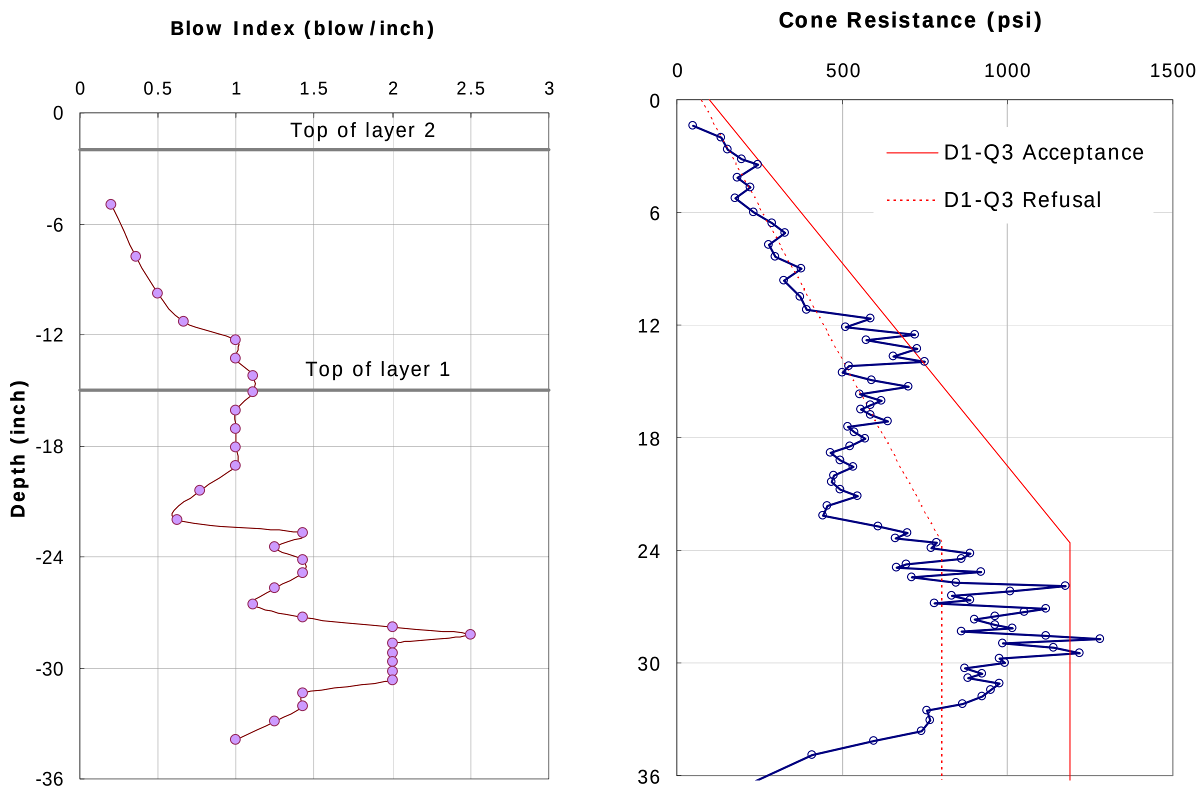

Figure 87 – Comparison of Standard DCP and Panda in Sand

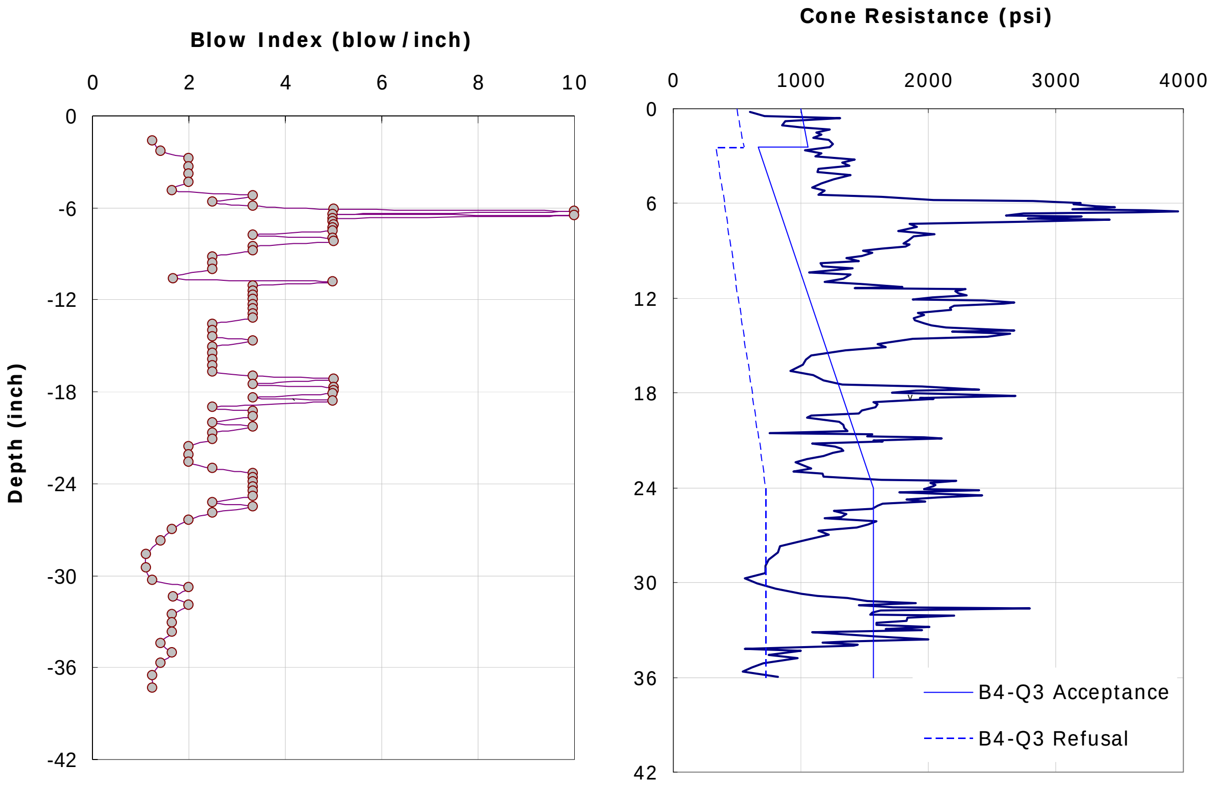

Figure 88 – Comparison between Standard DCP and Panda in Silty-Clay

The sand used in the tests shown in Figures 89 and 90 could be classified as soil type D1 or D2 and the results were plotted for both soil types and compaction quality level q3. The results show that the compaction acceptance criterion is sensitive to the selection of soil type.

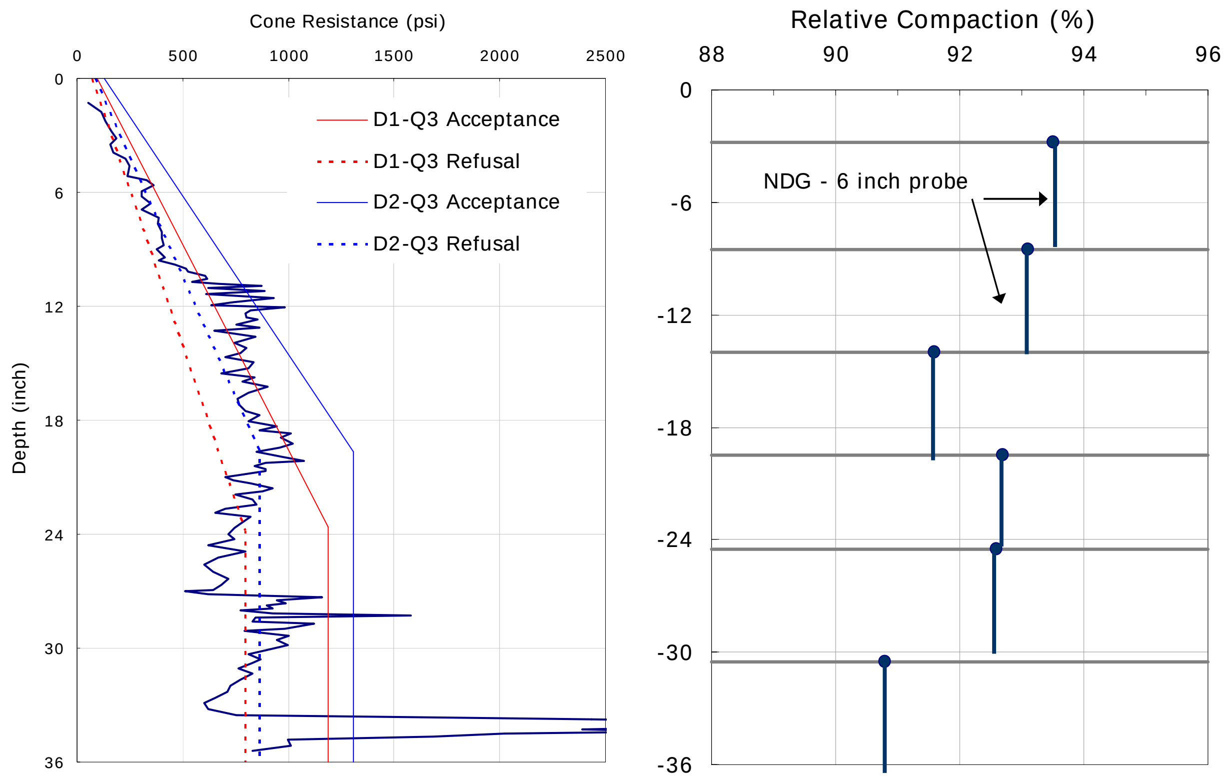

Figure 89 – Results of the Panda in test Sand-1

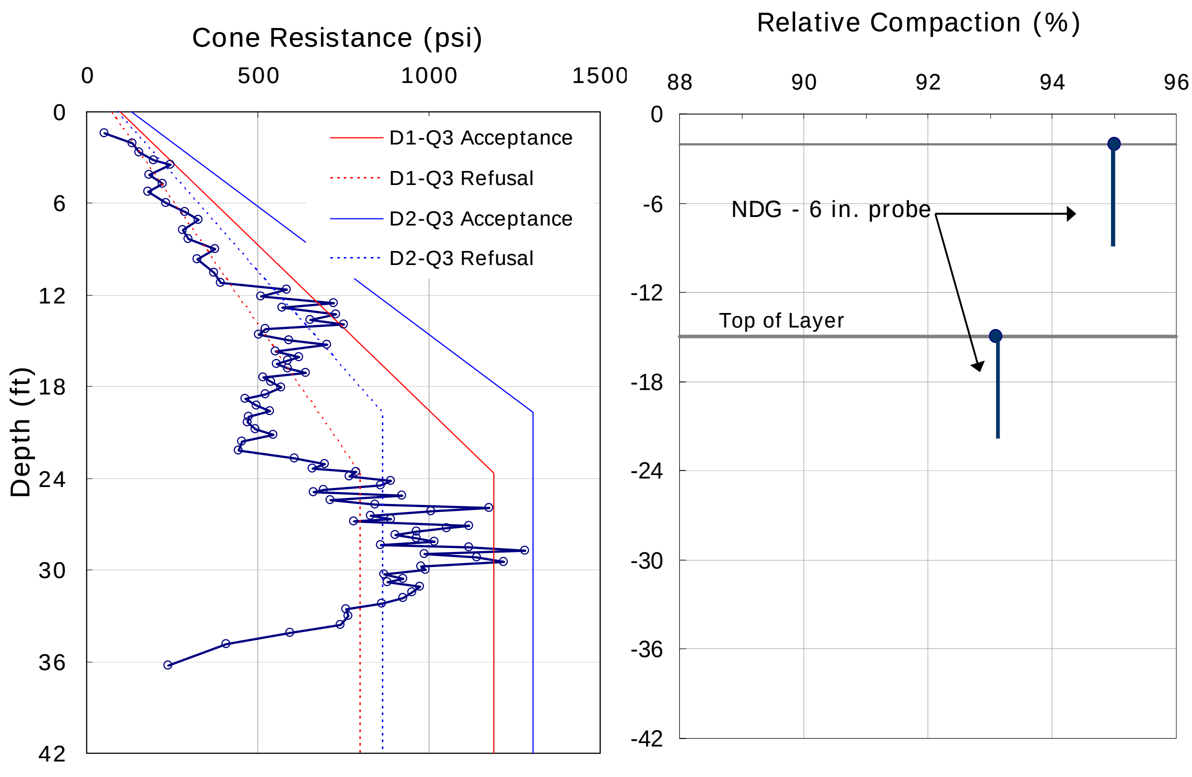

Figure 90 – Results of the Panda in test Sand-2

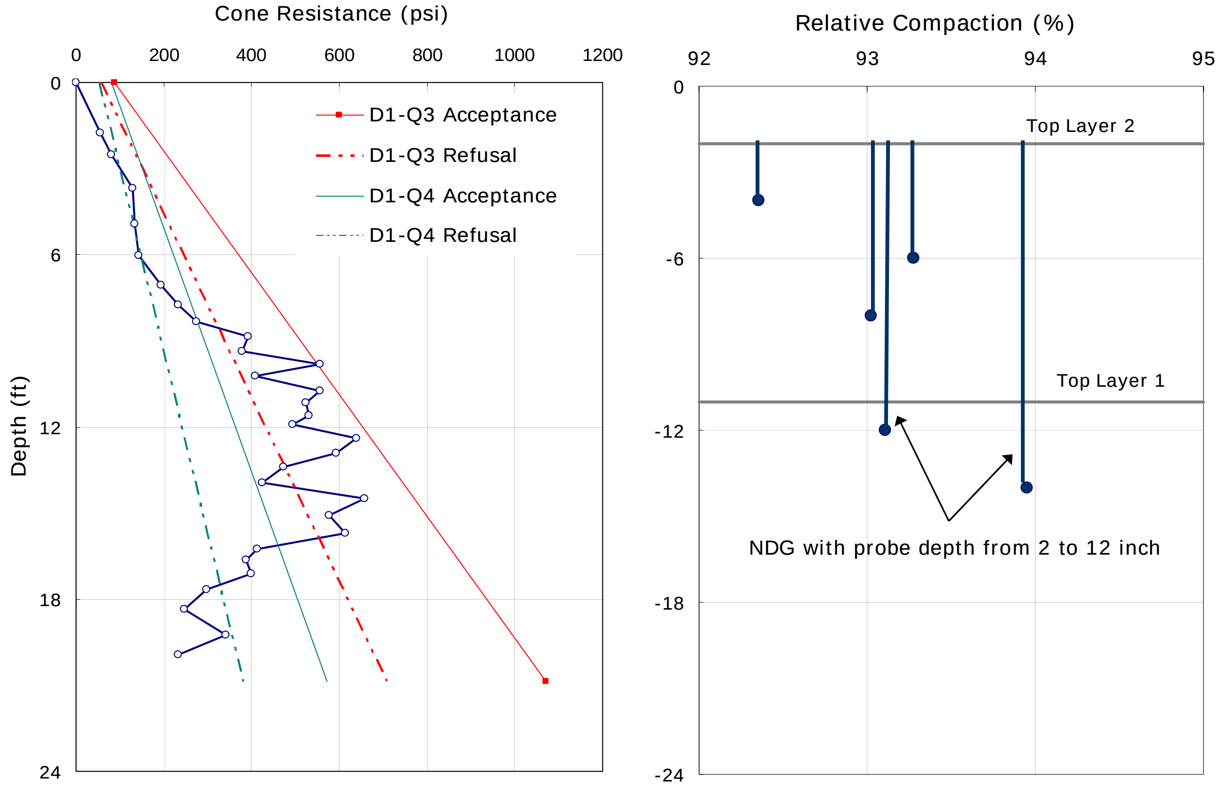

Figure 91 – Results of the Panda in test Sand-4

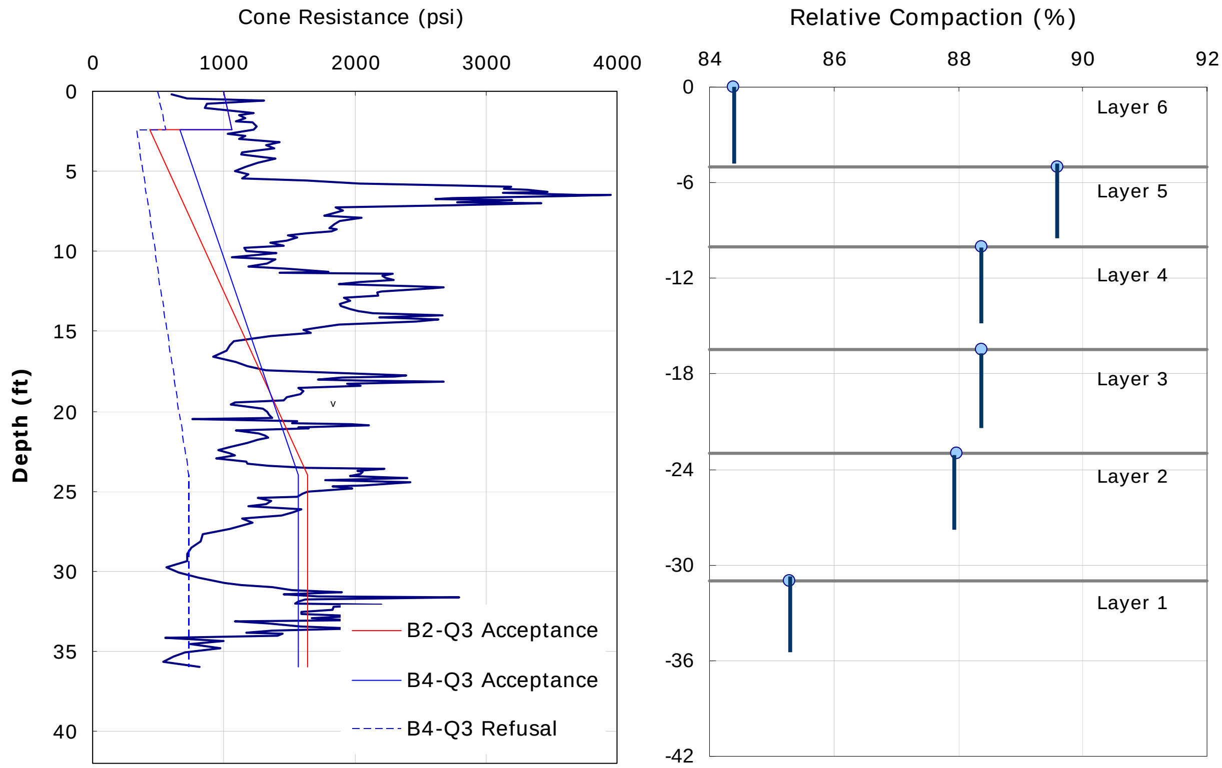

Figure 92 – Results of the Panda in test Clay-1

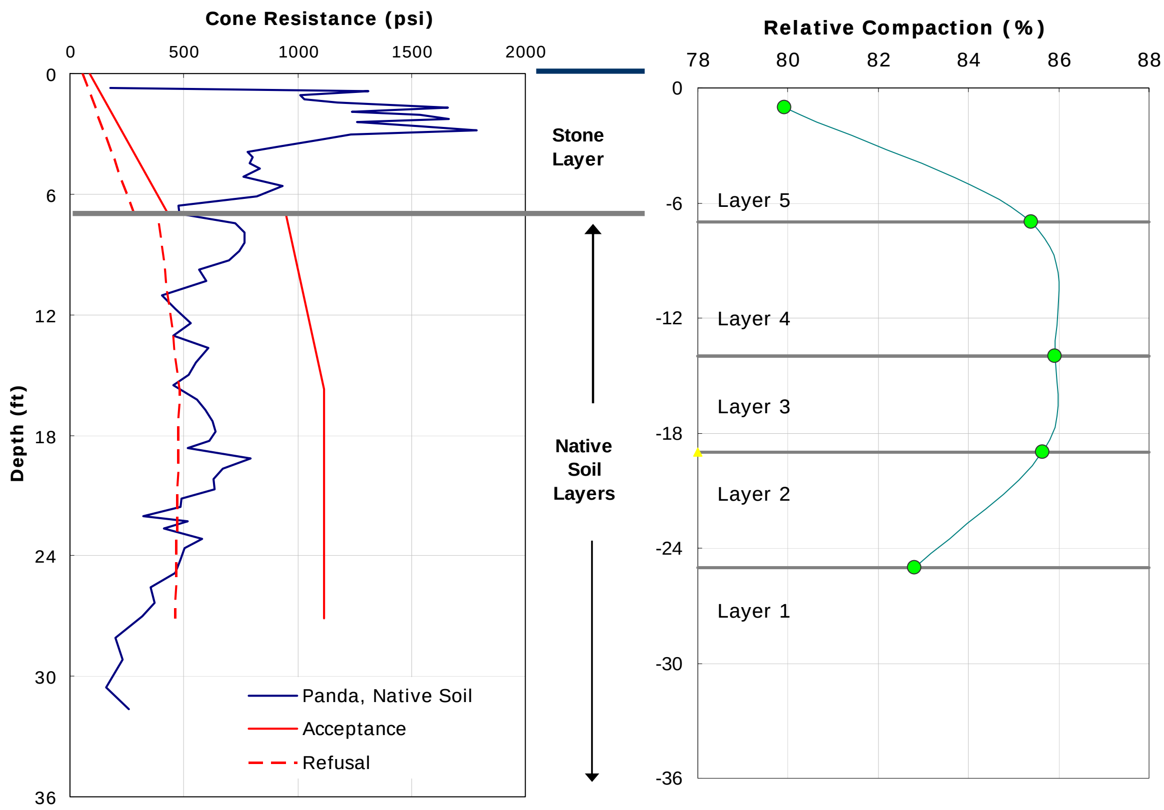

Figure 93 – Results of the Panda in test Clay-2

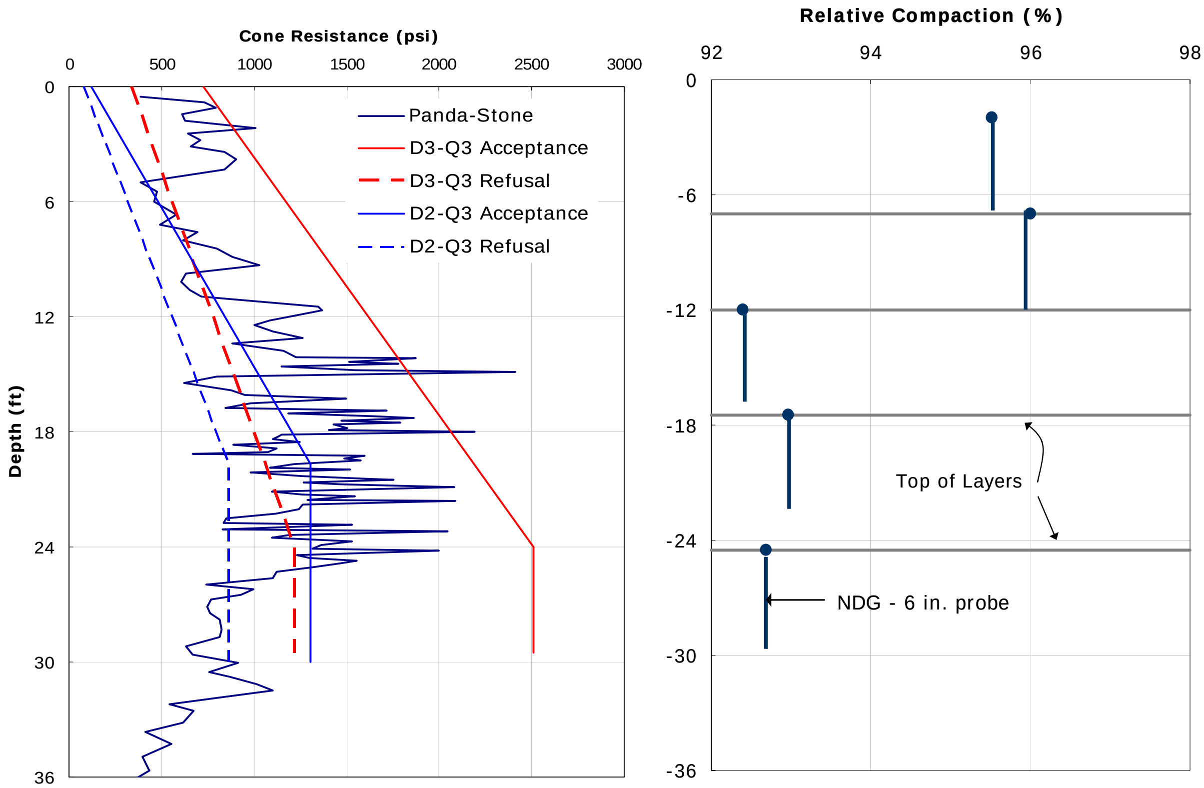

Figure 94 – Results of the Panda in test Stone-2

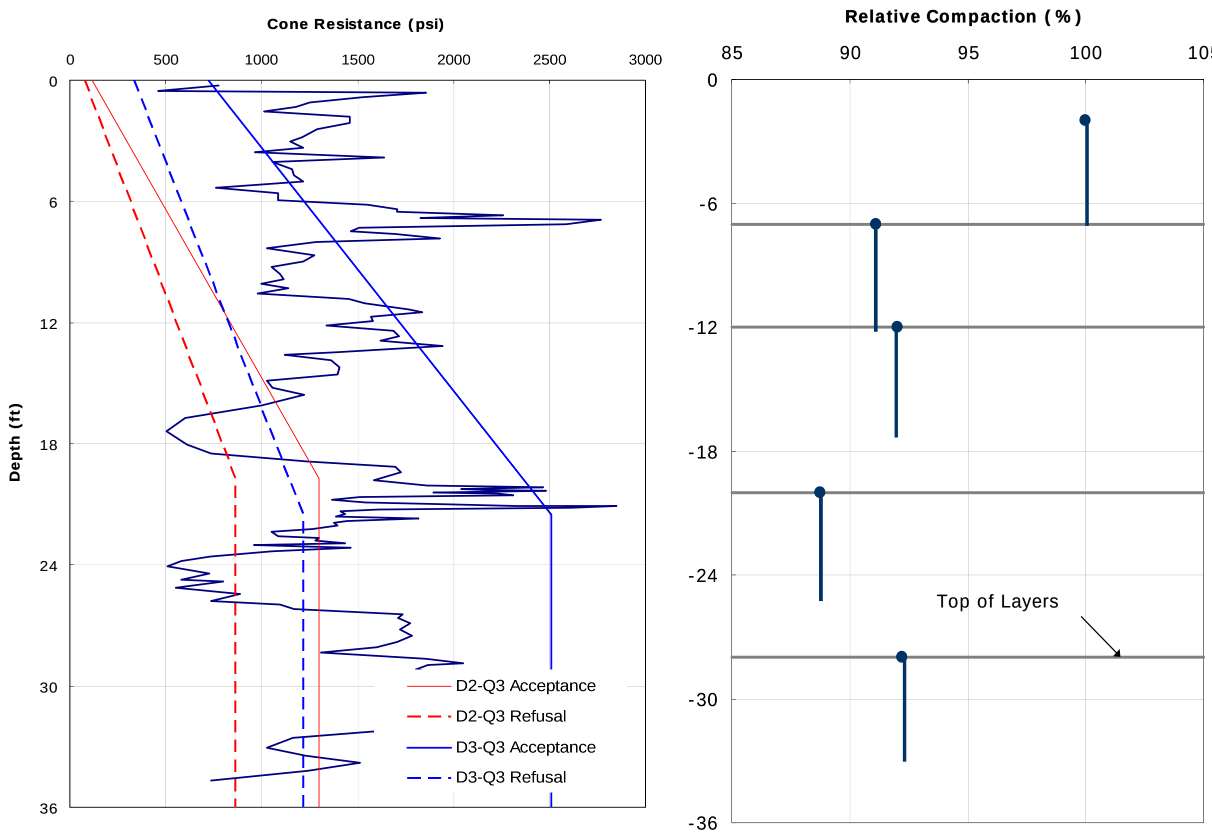

Figure 95 – Results of the Panda in test Stone-3

The Agriculture Moisture Gauges (Ag Gauges)

With the exception of the NDG, the soil compaction devices evaluated in this testing program do not provide measurements of soil moisture content. The Agriculture Moisture Gauges (Ag Gauges) were used in the testing program for the estimation of the moisture content in the field.

The Ag Gauges provided a better estimate of soil moisture than the ‘Hand-Ball” test since it worked for most soils and did not depend on the operator’s experience. The gauges are economical and available at various hardware stores.

Three different gauges were calibrated in the experimental program with various types of soils and moisture contents. The Ag gauges are shown in Figure 96. The results of the calibration are shown in Figure 97 for sand backfill. The results show that the half-range reading of the gauges is a good estimation of the sand’s optimum moisture content of 6 percent.

Figure 96 - The Agriculture Moisture Gauges

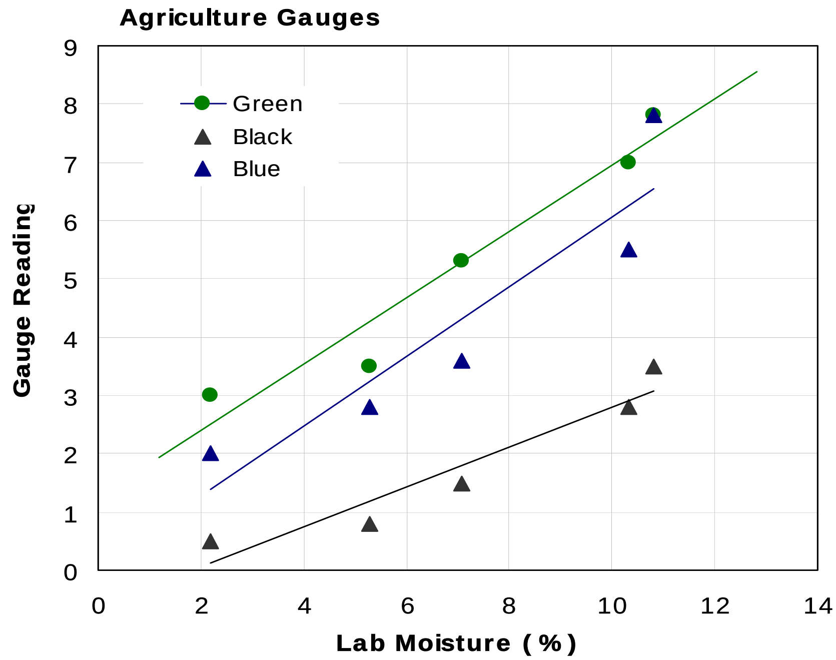

Figure 97 - Calibration of the Ag Gauges in sand backfill

Measurement of Earth Pressure

Earth pressure was monitored during the compaction of the soil layers in a bellhole in order to monitor the development of soil stresses at the top of the buried plastic pipe during compaction. Figure 98 shows a cross-section of the bellhole with the location of the pressure gauge. The process consisted of monitoring soil pressure at each lift during the passing of the vibratory plate compactor on the top of the pressure cell.

The earth pressure measurements at each lift are shown in Figures 99 through 103. The results show the static load at each layer before the application of the compaction and the increase in the pressure during the pass of the compactor. The peak values in the figures represent the maximum pressure applied when the compactor was directly over the top of the pressure cell.

The results show that soil pressure reached a value of about 5 psi when soil height is 6 inches above the pipe. The ratio between the static load (due to soil weight) and the dynamic load (due to thee compaction loads) are shown in Figure 104. The figure shows that the effect of compaction is negligible when the soil height is about 24 to 30 inches above the pressure cells.

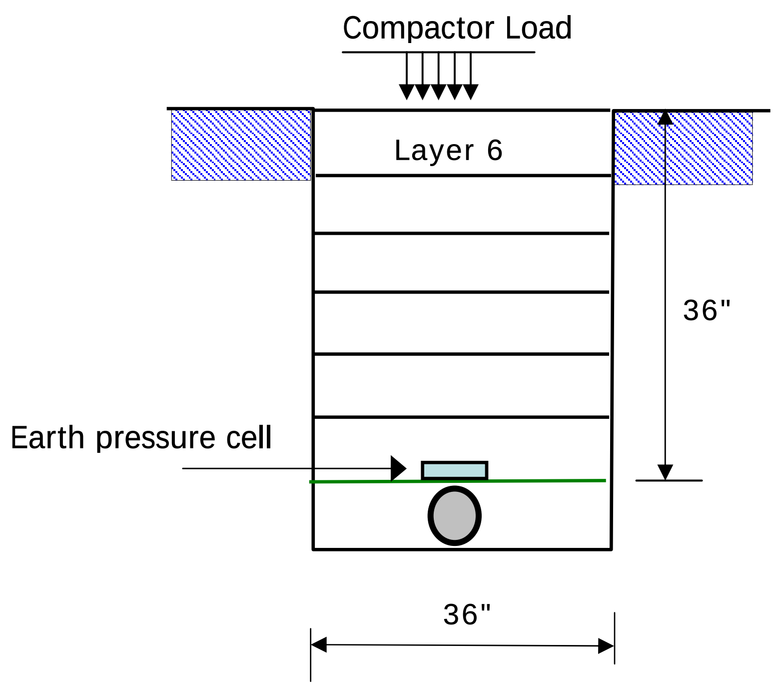

Figure 98– Schematic of the pressure cell in the bellhole

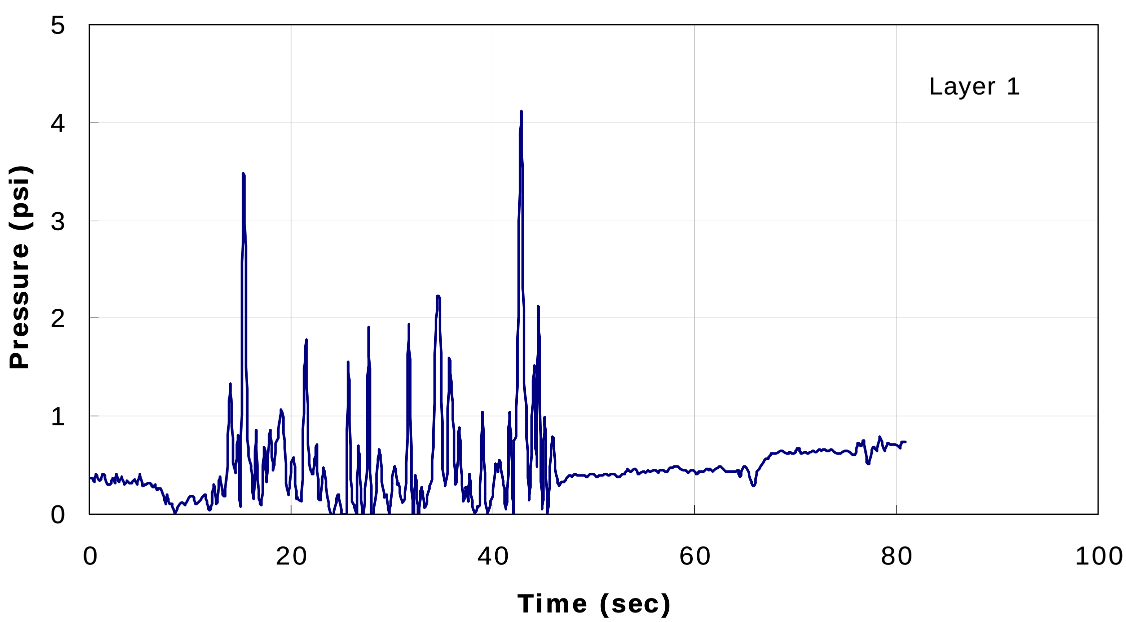

Figure 99 – Earth pressure in the first soil lift

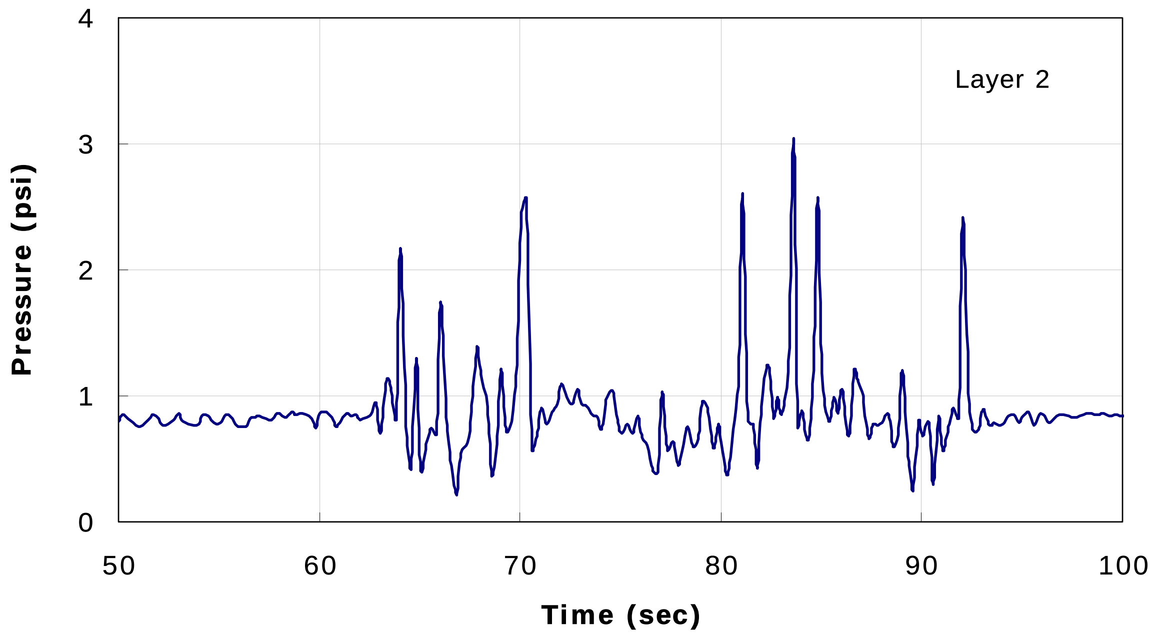

Figure 100 – Earth pressure in the second soil lift

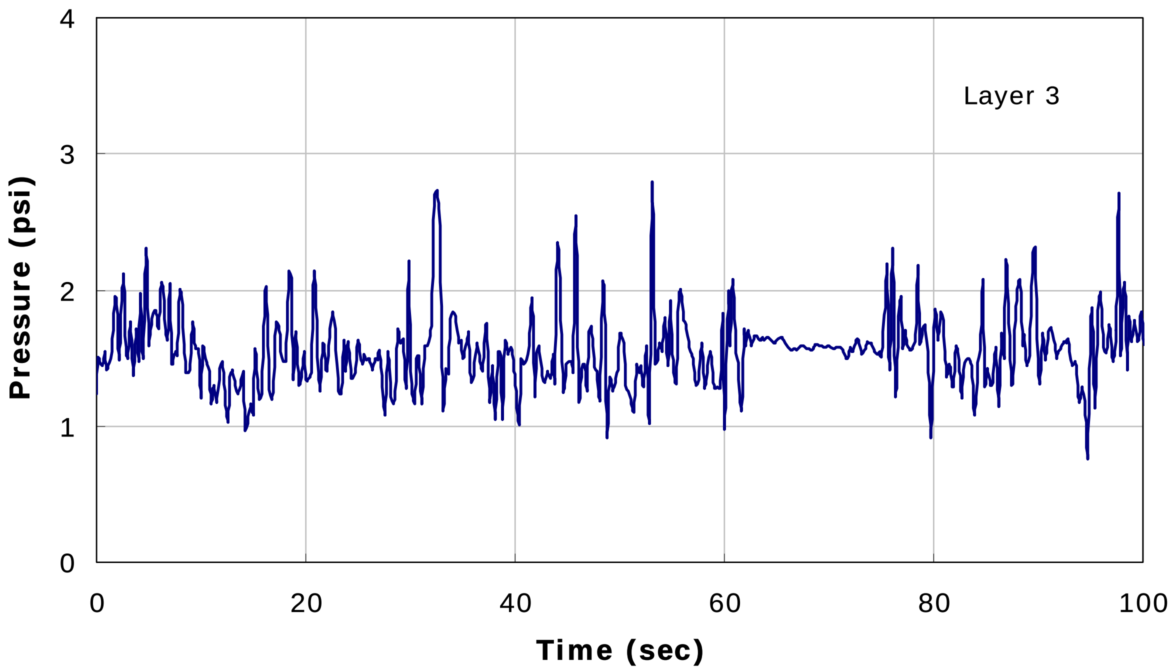

Figure 101 – Earth pressure in the third soil lift

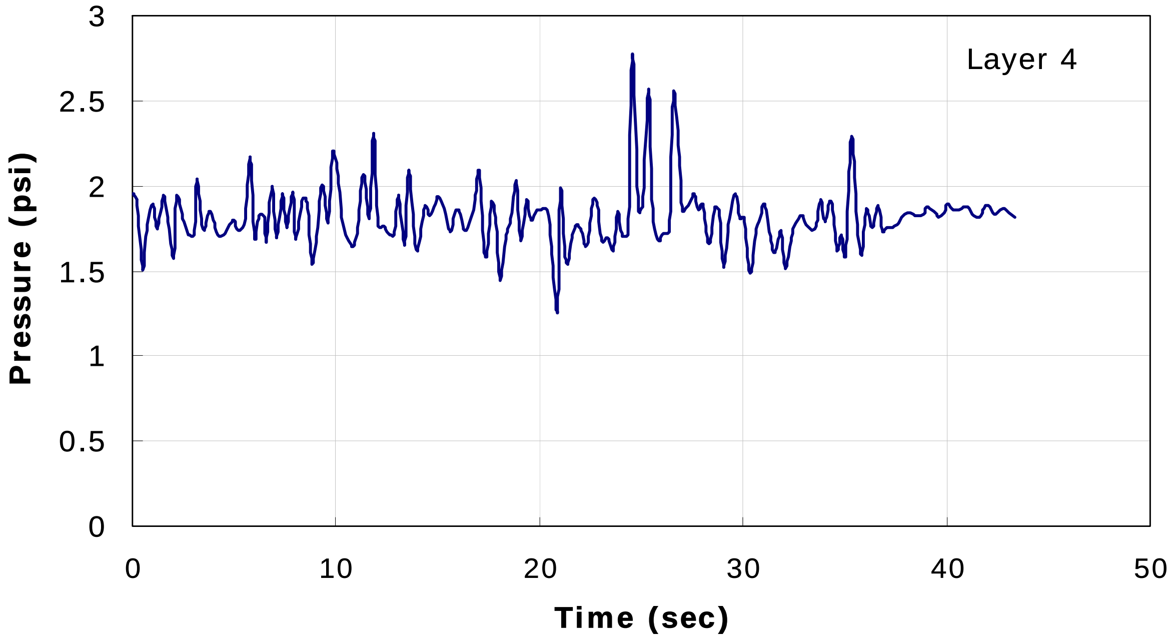

Figure 102 – Earth pressure in the fourth soil lift

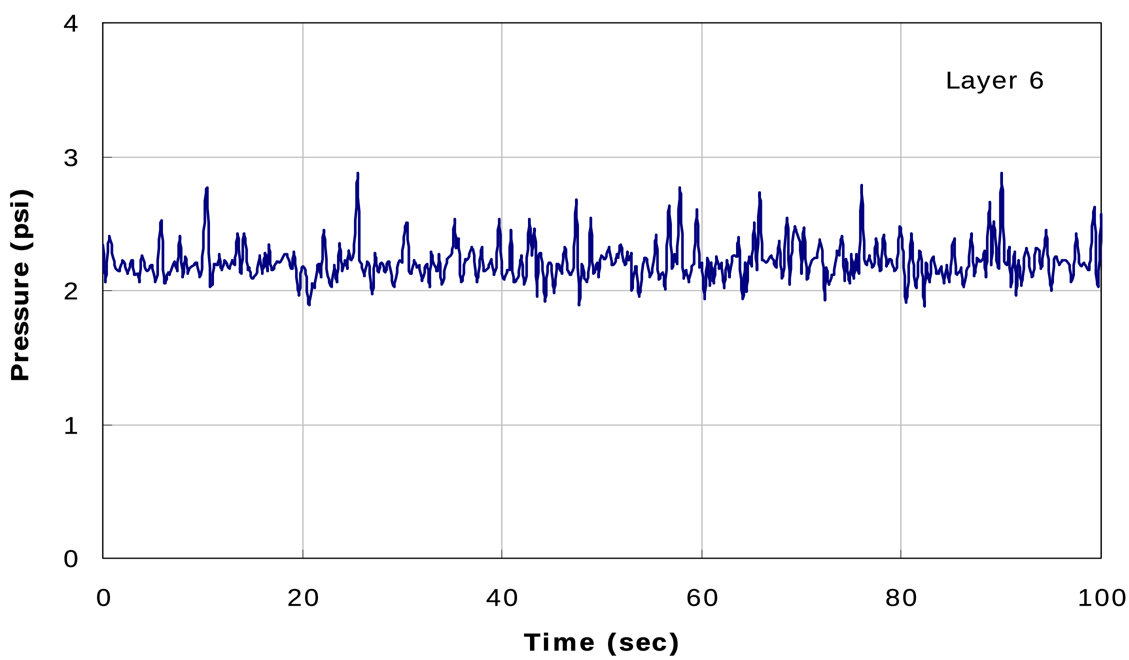

Figure 103 – Earth pressure in the sixth soil lift

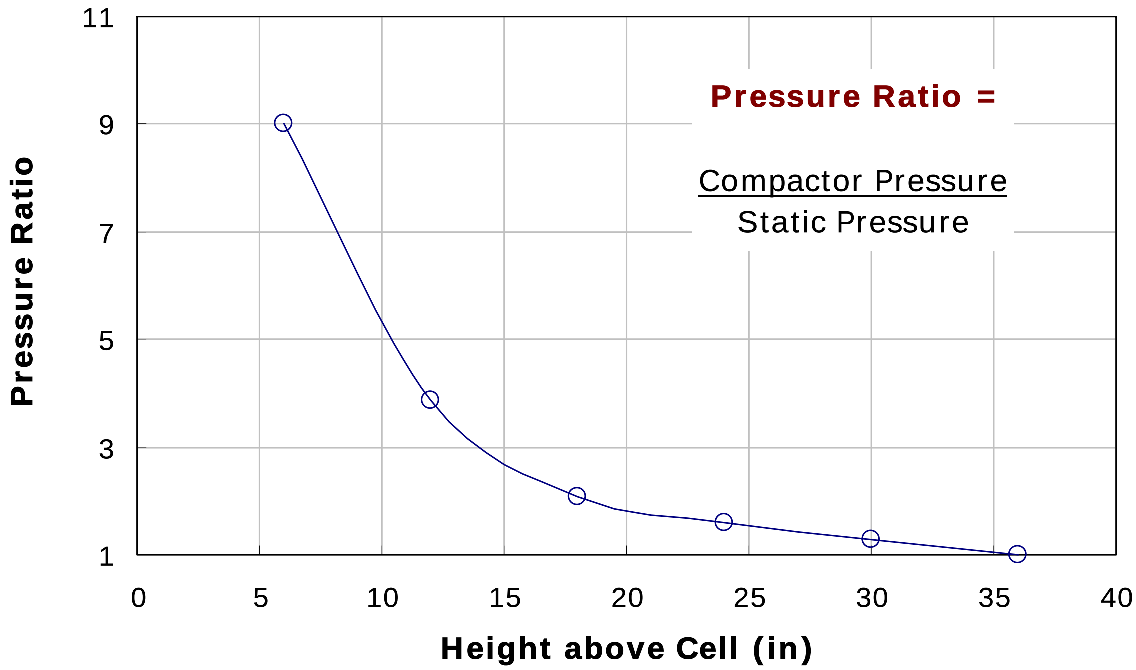

Figure 104 – Change of soil pressure above the pipe with soil height

Forensic Analysis of Trench Layers

The trench section 'NJ-Sand' was re-excavated after the completion of the testing program to evaluate the effect of compacting the top layers of soil on the density of the bottom layer. The excavation was performed by removing the top layer and measuring the relative compaction of the lower layers.

The excavation process was performed a few weeks after the construction of the trench. The measurements of soil properties in layers 4 and 5 are shown in Table 29. The table shows the measurements during the initial compaction and the ones taken after the excavation of the trench.

Due to the rainy season, the soil was wet and measurements reflected a large increase of soil water content.

Table 29 – Results of forensic analysis of trench

Layer	NDG Relative Compaction (%)		NDG Water content (%)		DCP		Geogauge		10-Kg Clegg Hammer	
	Comp.	Exec.	Comp.	Exec.	Comp.	Exec.	Comp.	Exec.	Comp	Exec.
4	95.2	92.1	8.8	21.4	6	5	33.42	24.4	7.9	7.9
5	94.8	93.6	9.4	19.5	5	4	32.17	25.37	7.3	6.6

CONCLUSIONS

A summary of the performance evaluation of each device is presented in this Chapter, followed by the conclusions of the testing program.

Device Evaluations

The Nuclear Density Gauge

The Nuclear Density Gauge (NDG) was used as an "in-process" compaction-measuring device (QC). It is an easy to use device that measures density and moisture content and produces relatively consistent results.

Soil moistures measured by the NDG were higher than the readings obtained from the oven dried tests. The moisture contents were also higher near the sidewall of the cut. The effect of the sidewall varied according to the depth of the trench and it was negligible at a distance of about one foot from the wall.

Due to the effect of wall boundaries on the results of the NDG, the device is not suitable for compaction measurements in small bellholes and keyhole sections. Although the device could be calibrated to minimize the sidewall effects, the need to calibrate the device at each soil lift makes it impractical in this application.

Table 30- Summary of the Pros and Cons of the NDG

Pros	Cons
- Rapid non-destructive testing (60 seconds) - Portable - Easy to use - Ability to store and download data - Has ASTM Standard (ASTM D5195) - Measures moisture content (ASTM D5220)	- Operator must be trained and licensed - Company must have EPA approval - Storage, transport and disposal of unit must be monitored - High initial cost - Readings near wall of trench/bellhole (within 1 ft) are affected by sidewall boundaries

Sand-Cone Density Apparatus

The sand-cone apparatus was not one of the devices evaluated, but was used to verify the NDG measurements. The device required periodic calibration and its accuracy depended on the experience of the operator. Furthermore, the calculation of soil dry density required the determination of the soil moisture content using the oven-dry method. Accordingly, the device is not practical for use as a compaction control tool in field applications.

Table 31- Summary of the Pros and Cons of the Sand-Cone

Pros	Cons
- Has ASTM standard (D1556) - Method commonly used as a control in geotechnical applications - Incorporates ASTM standard (D2216) test for calculating dry density	- Typically has poor results in stony soils and dry sands - Operator "technique" may influence results - Destructive testing method - Time consuming, 24 hours in oven to determine moisture content

Soil Compaction Supervisor (SCS)

The device is portable, economical, and easy to operate. The maximum achievable compaction, as indicated by the SCS, does not necessarily equal the target relative compaction if compaction equipment, soil height, or soil moisture are not according to the specifications.

The device is practical for use with granular backfills in confined trenches and bellholes. Further modifications with respect to storing and downloading the data may enhance its use as a QC tool during compaction.

Table 31- Summary of the Pros and Cons of the SCS

Pros	Cons
- Economic - Simple to use, minimal training - Red light correlated with 90% relative compaction in sand - Identifies type of compaction device used - Produces data file for each hole/trench lift by lift (needs enhancement)	- Does not give output value to correlate to relative compaction and moisture content - red light had weak correlation with relative compaction in clay - Faulty disks occurred approximately 10-15% of the time - Difficulty in obtaining signal when compacting higher than 30” - No ASTM Standard

Utility Dynamic Cone Penetrometer (Utility-DCP)

The calibration of the device in various soils yielded a better correlation with relative density in silty-clay soils than in sand and stone-base soils. The correlation between the number of blows and relative compaction was sensitive to soil moisture content.

The output of the device is an integer number (number of blows) which makes it insensitive to the small changes in soil relative compaction. The results of the device were consistent and can be used for compaction control.

Table 33- Summary of the Pros and Cons of the Utility-DCP

Pros	Cons
- Economic - Simple to use, minimal training - Results are operator independent - correlated better in silty-clay soil	- Lacks internal storage/recording ability - May give false blow counts in rocks or soft spots in the backfill - No ASTM Standard

The Geogauge

The correlation between the Geogauge stiffness number and soil relative compaction was better in silty-clay soils than in sand. No correlation was obtained from the tests in stone-base soils.

The device was sensitive to the seating above the soil and it failed to show the variations in stiffness readings when a steel plate was placed at various depths beneath the gauge. Tests were not performed to verify the manufacturer's claim that the device reads up to 9 inches of soil depth.

Table 34- Summary of the Pros and Cons of the Geogauge

Pros	Cons
- Rapid results (75 seconds per test) - Data storage and download capabilities - Simple to use, minimal training - Has ASTM standard (D6758)	- Sensitive to seating procedure, Poor correlation in sand and stone - Sensitive to the stiffness of the top 2 inches of soil - Fairly expensive

Clegg Hammers (10 Kg and 20 Kg)

The correlation between the Clegg's Impact Value (IV) and soil relative compaction was better in the silty-clay than in the sand and stone backfills. Both devices had similar performance and provided consistent results. The 20-Kg Clegg was heavy and not practical in confined bellholes and keyholes. Both devices require some modifications to improve their durability for use in the field.

Table 35- Summary of the Pros and Cons of the Clegg Hammers

Pros	Cons
- Simple to use, minimal training - Rapid results (4 hammer drops) - Has ASTM specifications (ASTM D5874) - Operator independent	- Does not have data storage or download abilities - 20-Kg hammer is heavy and not practical - weak connections for field use

Standard Dynamic Cone Penetrometer (Standard-DCP)

The device is a post-compaction tool and can be used by utility companies as a QA device. It can be operated manually or attached to a readout box for data storage and display.

The device was suitable for identifying the inter-layer variations in soil densities and detecting weak layers. The results were better defined in terms of 'Blow-Index' (number of blows/inch) instead of the more common 'Penetration Index' (inches/blow).

Table 36- Summary of the Pros and Cons of the Standard-DCP

Pros	Cons
- Simple to use, minimal training - Relatively inexpensive - Has ASTM specifications - Add-on data collector available - Operator independent	- Minimum of 2 people to operate - Add-on data collector expensive - Needs more correlation data with soil relative density

The Panda

The device is used as a Quality Assurance tool for post compaction and the output curves from the software program show the acceptance/refusal criteria for compaction control.

The use of the device is simple and the device was suitable for identifying the inter-layer variations in soil densities and detecting weak layers. However, data reduction and interpretation require training and knowledge of soil classification and specifications. The output produces charts with lines representing acceptance and refusal values. The lines were sensitive to the operator's selection of soil type and compaction specifications. Soil classification is based on correlation between US standards and the French Specifications.

Table 37- Summary of the Pros and Cons of the Panda

Pros	Cons
- Operator independent and consistent results - Produces acceptance/refusal graph with depth - Stores collected data and creates detailed testing report	- Requires technical training for equipment use and data reduction - Require some prior knowledge of soil properties. Sensitive to the selection of soil parameters for classification - Fairly expensive

Ag Moisture Gauges

Agricultural moisture gauges were used as a tool to estimate soil moisture content quickly and inexpensively. Laboratory tests showed that the mid-point readings of these gauges were a good indication that the soil was at its optimum moisture contents.

Table 38- Summary of the Pros and Cons of the Moisture Gauges

Pros	Cons
- Very inexpensive ($10-$20) - small and portable - Immediate results, fair indication of optimum moisture - Operator independent	- Not extremely accurate - Moisture scale changes according to soil type - Not particularly durable

Conclusions Summary

The compaction measuring devices evaluated in the testing program were strength or stiffness measuring devices which monitor the change of soil response due to the application of impact or vibrating force on the soil. All the devices, however, provided a measure of soil densification.

The readings of the devices were correlated to soils relative compaction at the optimum moisture contents. At constant compactions, the readings increased with the increase in soil moisture content up to a maximum moisture value.

Tables 1 through 3 summarized the results of the evaluation and correlation tests. The conclusions from evaluation criteria of the QC devices are:

- Due to the effect of the side boundaries of the cuts, the NDG is not suitable for compaction measurements in small bellholes and keyholes. Although the device could be calibrated to minimize the sidewall effects, the need to calibrate the device at each soil lift makes it impractical in these applications.
- The Utility-DCP and the 10-kg Clegg Hammer had the highest overall performance of the QC devices.
- The SCS performed well in confined bellholes and keyholes. The device was not consistent at depths higher than 30 inches above the sensor. It also lacked a numerical display to enable calibrating the output to soil relative compaction.
- The performance of the 20-kg Clegg Hammer was similar to the 10-kg device. However, it was heavier and less durable than the light-weight device.
- The measurements of the Geogauge were affected by the side boundaries of the cut and had weak correlation in sand and stone backfills.

The recommended improvements of the selected devices are related to increasing their durability, improving their data display and download capabilities and adding stand-alone or integrated moisture measurement capabilities.

Recommended Modifications of Soil Compaction Measuring Devices

Clegg Hammer – 10kg

1. Redesign of guide tube – This will allow for easier transport and mobility and substantially reduce the overall weight. The redesign will eliminate the possibility of the hammer being removed from the guide tube and provide stops to control drop height.
2. Improve cable connection from hammer to readout box.
3. Ability to store the measurements and easily download – Gives the device the ability to provide a record of the compaction activities with data protected from manipulation.
4. Easy user interface for location information – Simple GPS with time and date stamp.
5. Add-on moisture measurement – Allow for material to be checked for proper moisture levels prior to backfilling.
6. Handle extension for use in small-hole excavations.
7. Carrying case and cart – Used if needed to transport to various locations on jobsite.

NOTE: Items 3 thru 7 should be able to be purchased as options to basic hammer.

Utility Dynamic Cone Penetrometer (DCP)

1. Improve drop height stop/handle design – During testing the upper drop height stop became loose and slid down rod lessening the drop height.
2. Add-on drop weight – Additional weight that increases drop weight for use in cohesive soils to equalize blow counts with granular materials.
3. Include confinement plate – For use in sandy soils to confine top 2”-3” of sand for better lift measurements.
4. Improve tip – Add small radius to tip to reduce occurrences of tip bending or breaking off that could result in poor blow count accuracy.
5. Ability to store and easily download the blow counts – Gives the device the ability to provide a permanent record of the compaction activities with data protected from manipulation.
6. Easy user interface for location information – Simple GPS with time and date stamp.

7. Add-on moisture measurement – Allow for material to be checked for proper moisture levels prior to backfilling.
8. Handle extension for use in small-hole excavations – Allow for above ground penetration monitoring.

NOTE: Items 5 thru 8 should be able to be purchased as options to basic DCP.

Soil Compaction Supervisor (SCS)

1. Include numerical readout – This will give the device the ability to display a relative compaction value, based on values obtained when compared with the nuclear density gauge, for the compacted backfill.
2. Improve sensor reliability – Currently sensors are faulty 10-15% of the time.
3. Increase sensor reception – Modify sensor to allow for it to detect compaction more that 30” deep.
4. Add button and/or light for new hole and new lift – This will make it easier for the user to ensure the correct information is being recorded.
5. Add indicator to identify soil type – This information will be stored with the relative compaction number.
6. Improve compactor type identification – This improves the ability of the device to sense which type of compaction device is being used.
7. Modify data storage – Make the data to be in a more usable form. This includes the ease of download ability and to protect data from manipulation.
8. Easy user interface for location information – Simple GPS with time and date stamp.
9. Add-on moisture measurement – Allow for material to be checked for proper moisture levels prior to backfilling.

NOTE: Items 8 and 9 should be able to be purchased as options to basic SCS.

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