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A Soil Compaction Control Technology Assessment and Demonstration

PROJECT TEAM

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Abstract

The effectiveness of soil compaction control technologies and the reliability of quality control test results are among the major factors that impact reinstatement of utility cuts and the performance of the pavement restored. Therefore, in order to evaluate the compaction control testing procedures currently available and most frequently used, the New York City Department of Environmental Protection (NYCDEP) in collaboration with New York City Department Of Transportation (NYCDOT) and Brooklyn Union - A KeySpan Energy Corporation, have co-sponsored a site demonstration and technology assessment project on a selected NYCDEP site.

This project involved compaction control tests with three techniques generally used in the New York metropolitan area, including: The Gamma Densitometer, The Dynamic Cone Penetrometer, and the more recently developed Soil Compaction Meter. The project also included the assessment of the PANDA - a French developed soil compaction control technology. The tests were conducted in six different trenches with typical sandy backfill material compacted under different pre-selected site conditions.

Analysis of the test results demonstrated the reliability, efficiency, as well as the main advantages and limitations of each testing procedure. In particular, it was demonstrated that the PANDA provides a highly reliable tool for post-construction compaction quality control, which, due to its user-friendly software, is practically operator independent.

This report briefly presents the main field test data along with site observations and summary of the main features, technical performance and cost details related to each testing procedure.

Acknowledgments

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A Soil Compaction Control Technology Assessment and Demonstration

By
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1. Objectives

The objective of this study is to compare the reliability and efficiency of four soil compaction control testing procedures.
The PANDA.
The Gamma Densitometer.
The Soil Compaction Meter.
The Dynamic Cone Penetrometer.
Soil compaction control tests were conducted under conditions typical to trenches. The results are briefly presented below.

2. Site Description

Site location: DEP Repair Center, 855 REMSEN Avenue, Brooklyn, NY, US.
Date: 15th - 16th of June 1999.
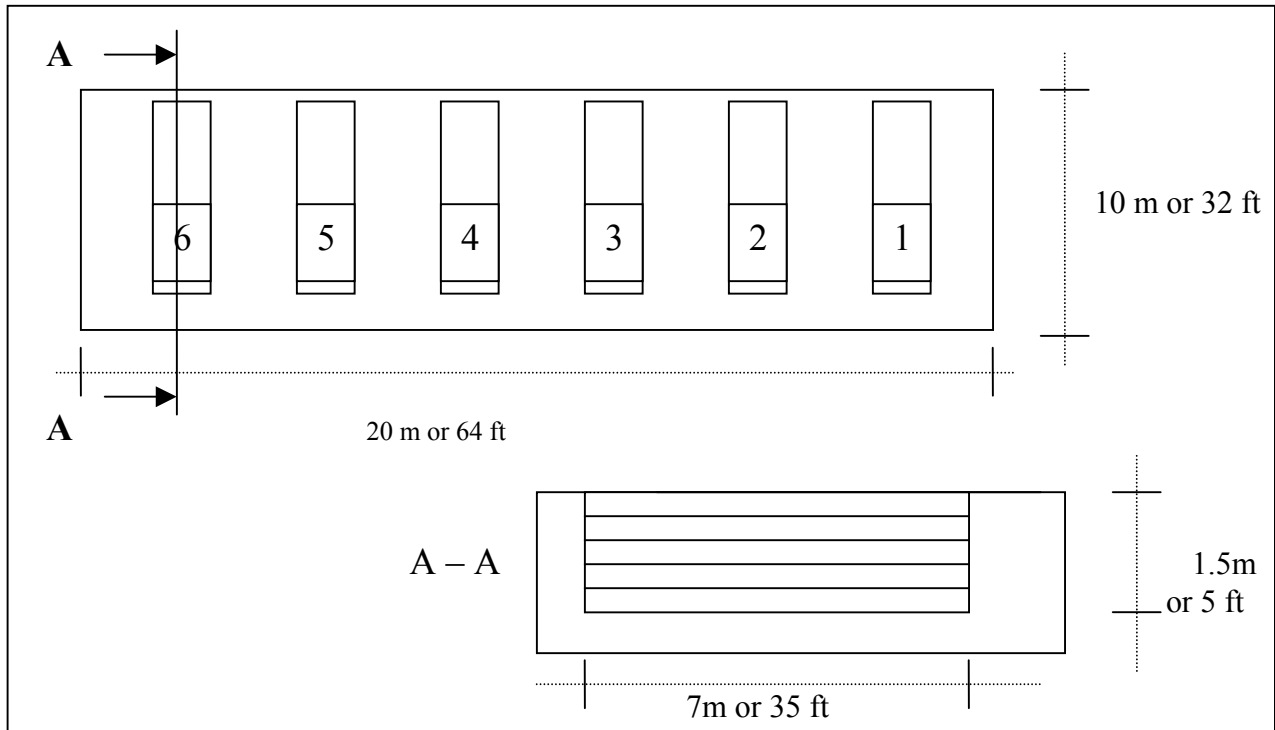
Figure 1 – Site Plan

(*) Professor; Director of the Urban Utility Center
(**) Graduate student

Figure 2 – The four soil compaction control technologies

3. Backfill Materials

DEP has provided the backfill materials, including Sand and RAP (Recycled Asphalt Pavement). Figures 3 and 4 show respectively the Grain Size Distribution and the Proctor Test Results for the selected sand.

<u>**Sand**</u>
The Sieve Analysis yields:
Soil Classification:
American Classification**: A1 – b (ASTM D3282 – 93)**
French Classification**: D1 (NF P 11-300)**
The Proctor Test Results yield:
The Optimum Moisture Content**: 6.3%**
The Maximum Dry Density**: 16.4 KN/ m^3**
Site specification requires 95 % of γd_{max} at w_{opt} (±2%)

<u>**RAP (Recycled Asphalt Pavement)**</u>
The RAP is Recycled Asphalt Pavement coming from the renovation of street. This backfill material is used mixed with sand (1 volume of each). This mixture has been used to assess the efficiency of the testing procedure in evaluating the in-situ compacted performance of this material.
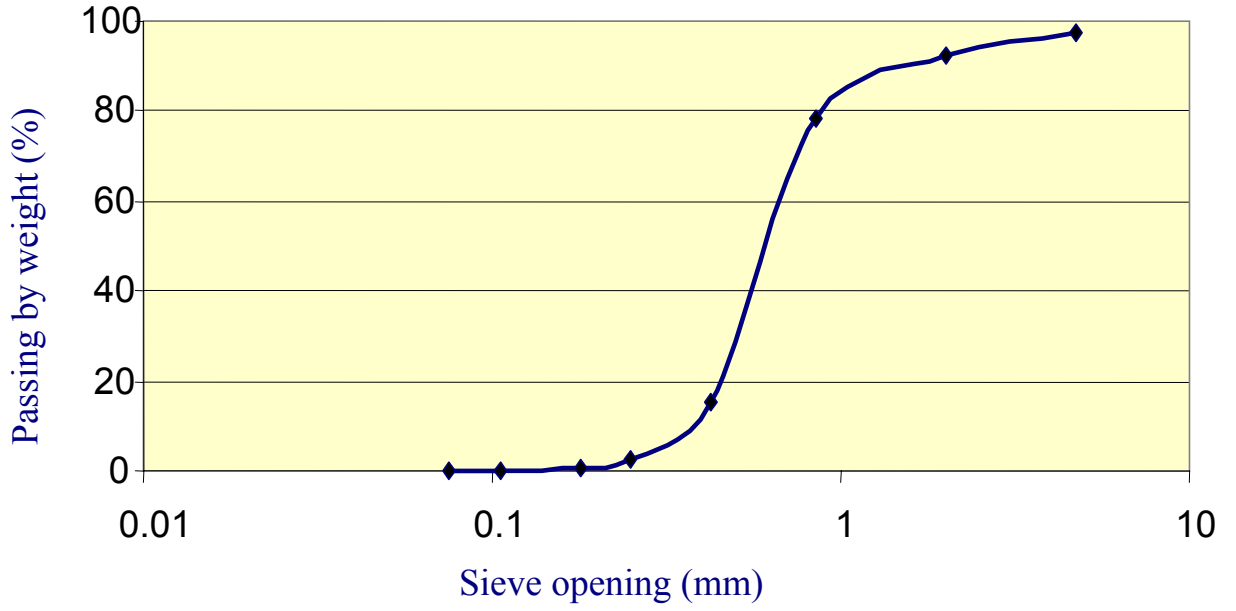
Figure 3 – Grain Size Distribution
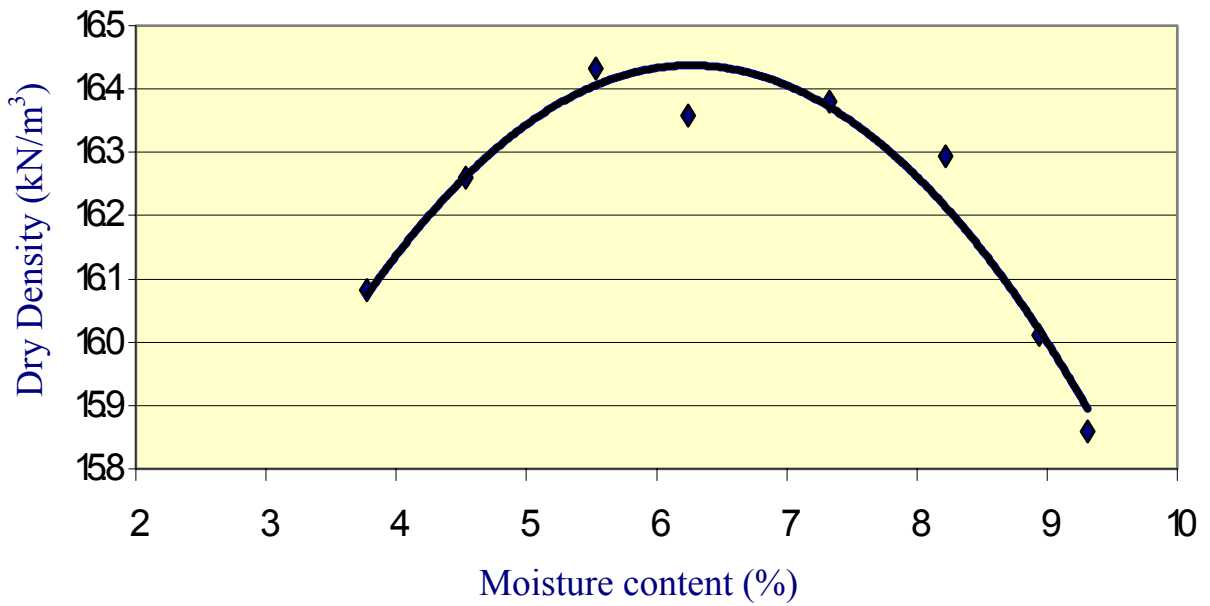
Figure 4 – Proctor test

4. Trenches Description

The demonstration site involved six different trenches with typical sandy backfill material and RAP, compacted under different pre-selected site conditions, including:
5 trenches have been filled with sand.
1 trench has been filled with a mixture of 50 % RAP and 50 % of Sand (1/1volume)
Figure 5 illustrates the pre-selected compaction requirements for each trench.

TRENCH 1

Well compacted
(five passes)

TRENCH 2

Poorly compacted
(one pass)

TRENCH 3

Middle layer
not compacted

TRENCH 4

Compaction
@ 2 layers

TRENCH 5

Surface compaction
(five passes)

TRENCH 6

Mixture of RAP and sand
(five passes)
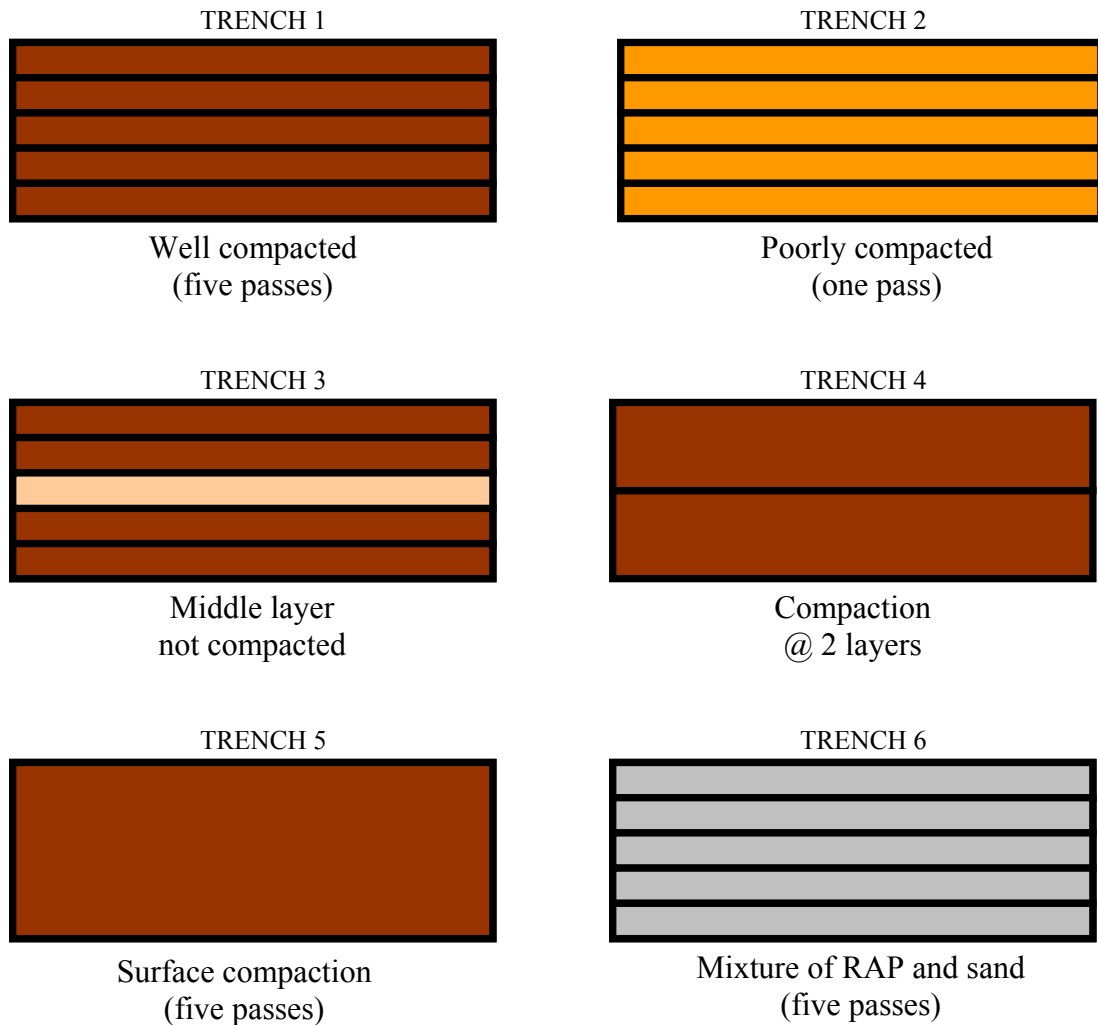
Figure 5 – Trenches Description

5. Testing Program

A total of 269 compaction control tests were conducted. Table 1 presents the testing program for each trench.

Testing Program for each Trench	PANDA	Gamma Densitometer	DCP	SCM	Total
Trench 1 **Layer 1;2;3;4;5** **Full depth**	3/layer 3	3/layer 0	2/layer 0	3/layer 0	58
Trench 2 **Layer 1;2;3;4;5** **Full depth**	3/layer 3	3/layer 0	2/layer 0	3/layer 0	58
Trench 3 **Layer 1;2;4;5** **Layer 3** **Full depth**	3/layer 3/layer 3	3/layer 3/layer 0	2/layer 0 0	3/layer 3/layer 0	56
Trench 4 (2 layers) **Layer 1;2** **Full depth**	3/layer 3	3/layer 0	2/layer 0	3/layer 0	25
Trench 5 (1 layer) **Layer 1** **Full depth**	3/layer 3	3/layer 0	2/layer 0	3/layer 0	14
Trench 6 **Layer 1;2;3;4;5** **Full depth**	3/layer 3	3/layer 0	2/layer 0	3/layer 0	58
Total	87	69	44	69	269

Table 1 – Testing Program

6. The PANDA (French standard XP P 94-105).

6.1. Testing Procedure

The test is done by driving a cone (of 2, 4, or 10 cm^2) into the soil with rods by blowing a standard hammer on the head of the piston. For each blow, an electronic box records the speed of impact, which allows establishing the driving energy, the masses being known. Simultaneously the other sensor measures the settlement and the recorder yields the accumulated driving depth of the cone. The principle of the PANDA testing is illustrated in Figure 6. For each blow using the measured data, the computer calculates the dynamic cone resistance q_d from the Dutch formula and records the values of q_d and the corresponding depths.

6.2. Pre-calibration and Interpretation

For a selected material and compaction energy level, pre-calibration tests need to be conducted in order to establish the reference curves. Sol Solution France has conducted an extensive series of pre-calibration tests on standard backfill materials (**NF P 11-300**) and the corresponding reference curves are available in the PANDA database. For the purpose of this demonstration project the selected sand was identified as **D1** (French classification) and the relevant reference curves have been retrieved from this database. The software yields refusal and reference curves.

Studies, conducted in France, have demonstrated the reliability of the results obtained as compared to standard in situ tests. All the test data can be transferred to a microcomputer P.C. and analyzed with the PANDA Windows software. The software allows to printout these data and compare the site specific penetrograms obtained with the reference curves. For the purpose of compaction control, test results obtained with the PANDA are compared with the pre-calibrated reference curves. Figure 7 illustrates the PANDA penetrograms obtained for Trench 1 and the reference curves established for D1 sand.

7. The Gamma Densitometer (ASTM D 3017-88/2922-91)

7.1. Testing Procedure

This method operates either in drilled holes or from the ground surface. For density measurements a radioactive source such as Cesium 137 emits gamma rays. Geiger-Muller tubes are used to detect how many gamma rays photons are reflected to the surface (backscatter mode) or are transmitted from the depth source to the surface (direct transmission mode) rather than being absorbed by the soil during a standard test period of 1 minute. For moisture content measurements a source of high-velocity neutrons, such as americium 241, is employed in the backscatter mode. The principle of the Gamma Densitometer testing is schematically illustrated in Figure 8.
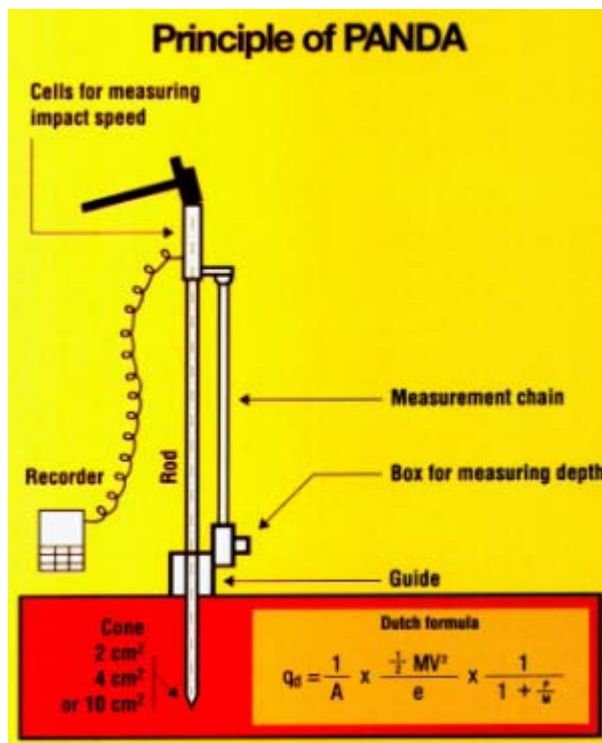
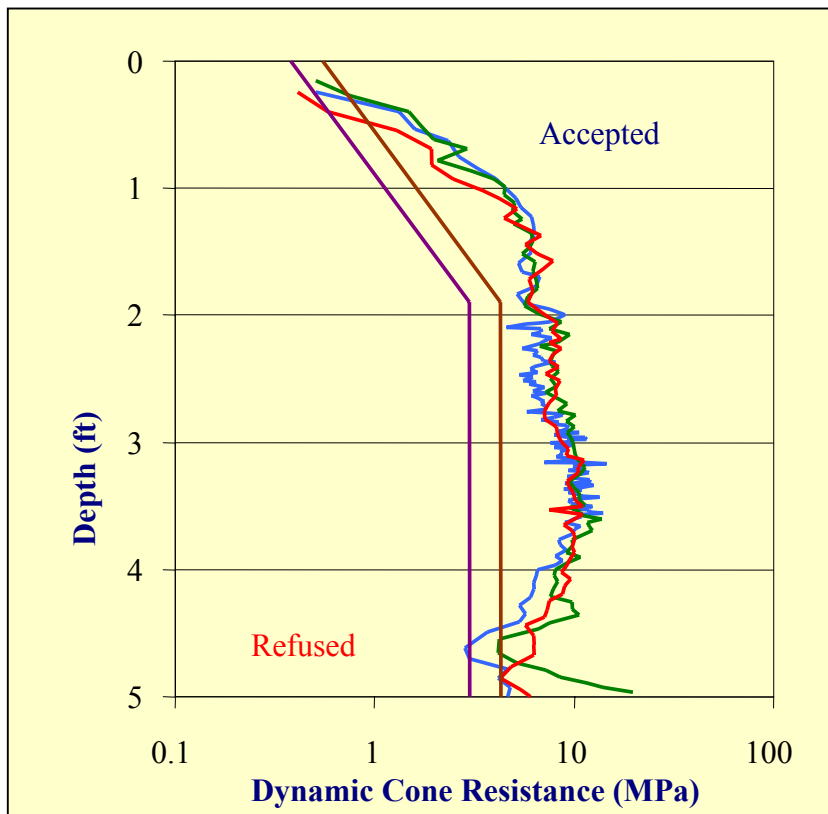**Figure 6** – Principle of the PANDA

Figure 7 – PANDA Penetrograms and Reference Curves
TRENCH 1

The gamma ray absorption law yields directly for the two selected radioactive sources the dry density and the moisture content. The mass absorption coefficient has been established soil and no further pre-calibration tests are required.

7.2. Interpretation

For a selected material a Standard Proctor Test is performed in order to established the Maximum Dry Density as a reference value for compaction control. The on-site Standard Proctor Test yielded the following:

Optimum Moisture Content**: 3.4%**
Maximum Dry Density**: 17.9 KN/ m3**

Figure 9 illustrates the variation of the Gamma Densitometer test data obtained at the level of each layer for Trench 1, as a function of the layer grade (i.e. depth below final surface grade). Also plotted for reference are the required compaction level of 95% of the maximum dry density obtained from the Proctor tests.

8. The Soil Compaction Meter (no standards)

8.1. Testing Procedure

The Soil Compaction Meter (SCM) is a small, hand-held, battery operated, electronic device, which indicates to the tamper operator when maximum compaction has been achieved for a given soil layer. Workers place layers and compacts each one until the stoplight indicates that the desired density has been reached. When the back filling is completed, the sensor wire is cut, leaving the disposable sensor in the compacted soil.

8.2. Pre-calibration and Interpretation

A disposable piezoelectric sensor produces voltage proportional to the pressure wave amplitude that is transmitted through progressively denser soil. Signals are fed into a meter that calculates a continuously refined maximum theoretical soil density for each layers and tracks actual density relative to the maximum as the layer is compacted. When a factory-set cutoff point is reached, a stoplight goes on. It is not dependent upon matching field backfill soils to a specific "sample" used for laboratory reference.

The principle of the SCM testing is schematically illustrated in figure 10. Figure 11 illustrates the variation of the SCM test data obtained at the level of each layer (i.e. the number of roller passes required to achieve the specified compaction level) for trench 1, as a function of the layer grade (i.e. depth below final surface grade).
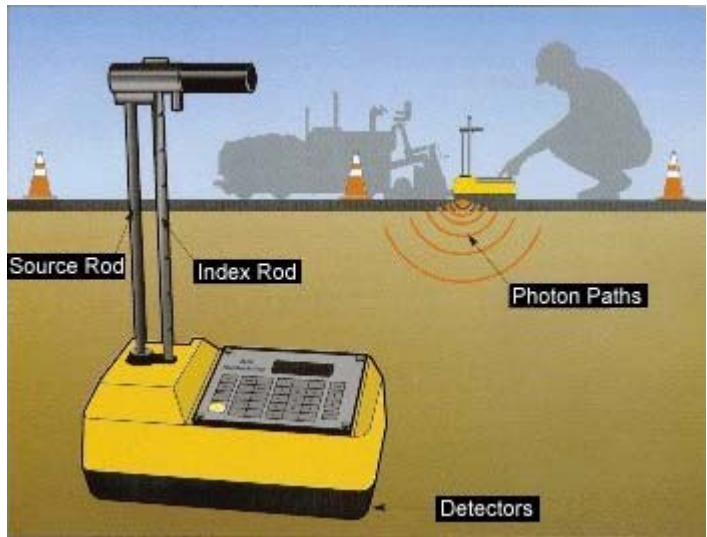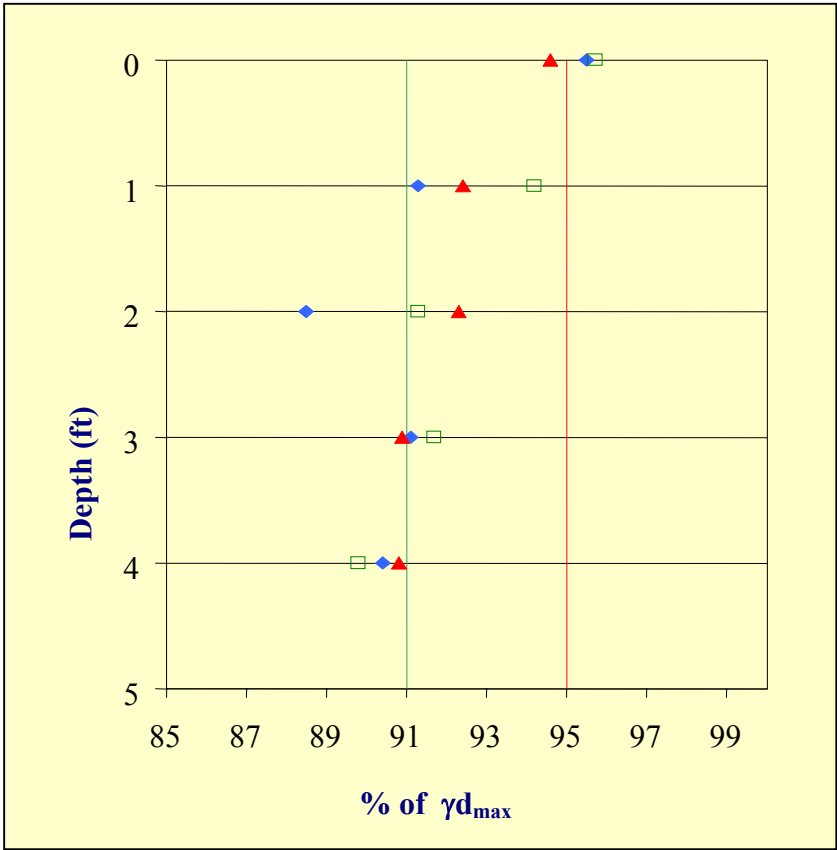
Figure 8 – Principle of the Gamma Densitometer

Figure 9 – Gamma Densitometer test data and reference values
for compaction control - TRENCH 1

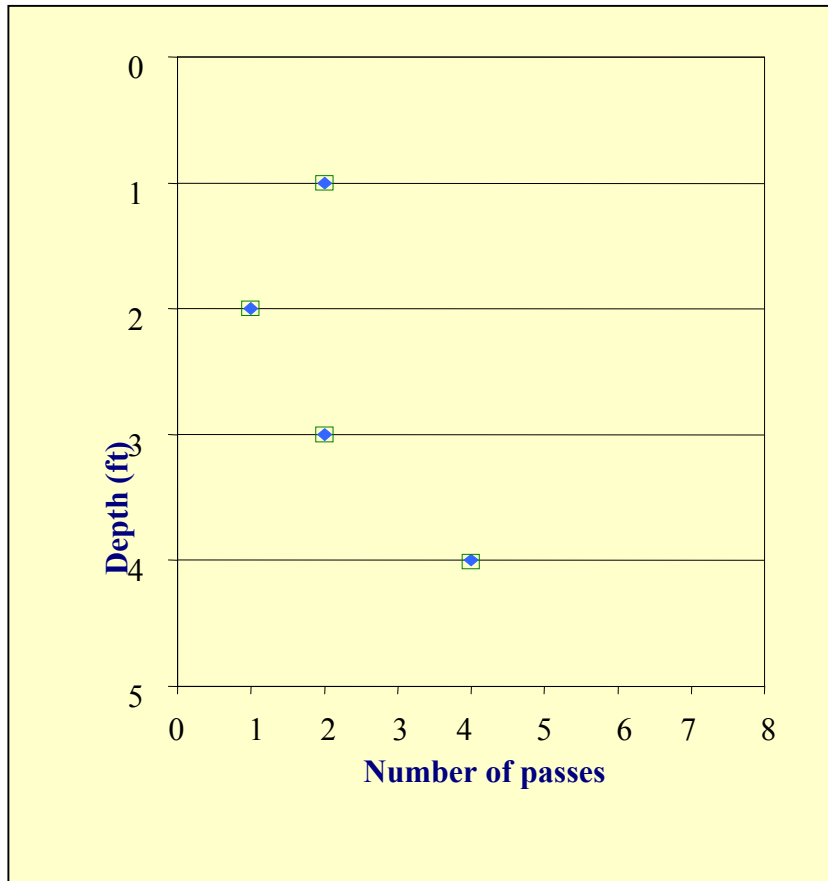**Figure 10** − Principle of the SCM

Figure 11 − SCM test data - TRENCH 1

9. The Dynamic Cone Penetrometer (no standards)

9.1. Testing Procedure

The Dynamic Cone Penetrometer (DCP) consists of a steel rod with a cone attached to one end. The cone is driven into the soil by dropping a hammer onto an anvil located on the rod. The device penetrates soils to depths of 6.5 inches. Test results are the number of blows needed to drive the rod from 3.25 inches to 6.5. A DCP test can usually be conducted in less than ten minutes

9.2. Pre-calibration and Interpretation

For the purpose of soil compaction control the number of blows obtained is compared with a reference value. This reference value depends on the soil type, the moisture content and the required dry density of the material. It is established by precalibration tests. Considering the selected site conditions (sand, dry density required: 95 % of γd_{max}) and in reference to the Brooklyn Union Standard, the reference value is **7 blows**.

Figures 12 and 13 illustrate respectively the equipment and the variation of the DCP test data obtained at the level of each layer (i.e. the number of hammer blows required to achieve the depth of 6.5 inches) for Trench 1, as a function of the layer grade (i.e. depth below final surface grade).
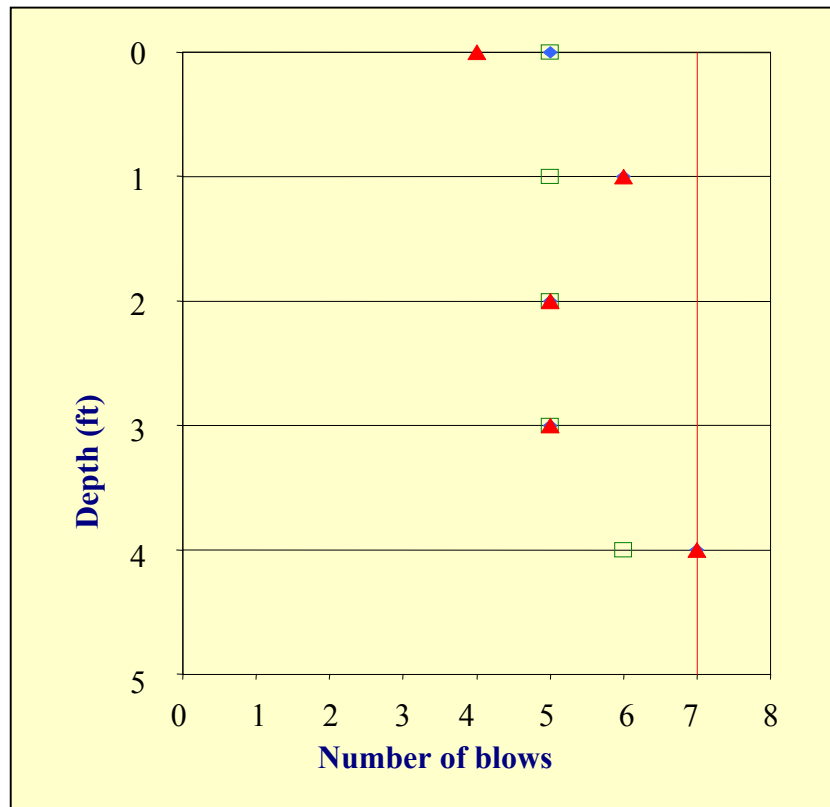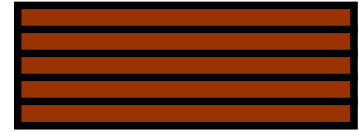
Figure 12 – DCP testing

Figure 13 – DCP test data and reference values - TRENCH 1

10. Interpretation

10.1.   Trench 1

Figures 14 to 17 present the test results obtained for this trench, illustrating the following:

The **PANDA** penetrograms indicate that control test results are higher than the reference curve. **The compaction meets site specifications**. (*)
The **Gamma Densitometer** indicates that 4 test results over 5 reach an average value of 91% to 93% and are therefore lower than 93% of γd_{max}. **The compaction doesn't meet site specifications**. (**)
The **Soil Compaction Meter** stoplight is turned on after two passes of the vibro tamper**. The compaction meets site specifications.**
The **Dynamic Cone Penetrometer** control test results are lower than the reference curve. **The compaction doesn't meet site specifications.**

10.2.   Trench 2

Figures 18 to 21 present the test results obtained for this trench, illustrating the following:

Two of the three **PANDA** penetrograms indicate that control test results are higher than the reference curve. **The compaction meets site specifications**. (*)
The **Gamma Densitometer** indicates that 4 test results over 5 reach an average value of 89% to 93% and are therefore are lower than 93% of γd_{max}. **The compaction doesn't meet site specifications**. (**)
The **Soil Compaction Meter** stoplight is turned on after one passe of the vibro tamper. **The compaction meets site specifications**
The **Dynamic Cone Penetrometer** control test results are lower than the reference curve. **The compaction doesn't meet site specifications.**

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*Note: The Panda test is performed when the compaction of all the backfill layers is completed, while all the other tests, including the Gamma Densitometer are conducted after compaction of each layer. Therefore the PANDA penetrograms represent the final state of compaction at each layer, which is significantly improved through the compaction process as compared with results obtained with other tests, Gamma Densitometer included.
**Note: On-site Standard Proctor Tests conducted for the Gamma Densitometer yield a maximum dry density of 17.9 kN/m^3, which is significantly higher than the average maximum dry density value of 17.2 kN/m^3 established by the laboratory Standard Proctor Test for the PANDA reference curves. The difference in maximum dry density may explain the differences in the compaction control evaluation.

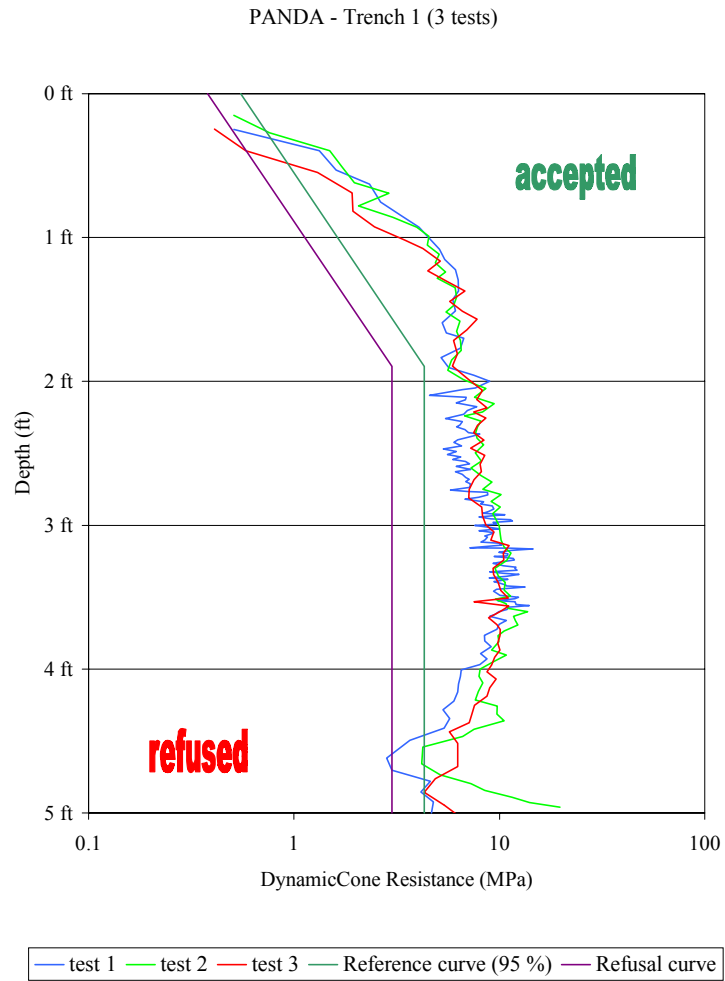**Figure 14** - PANDA penetrograms
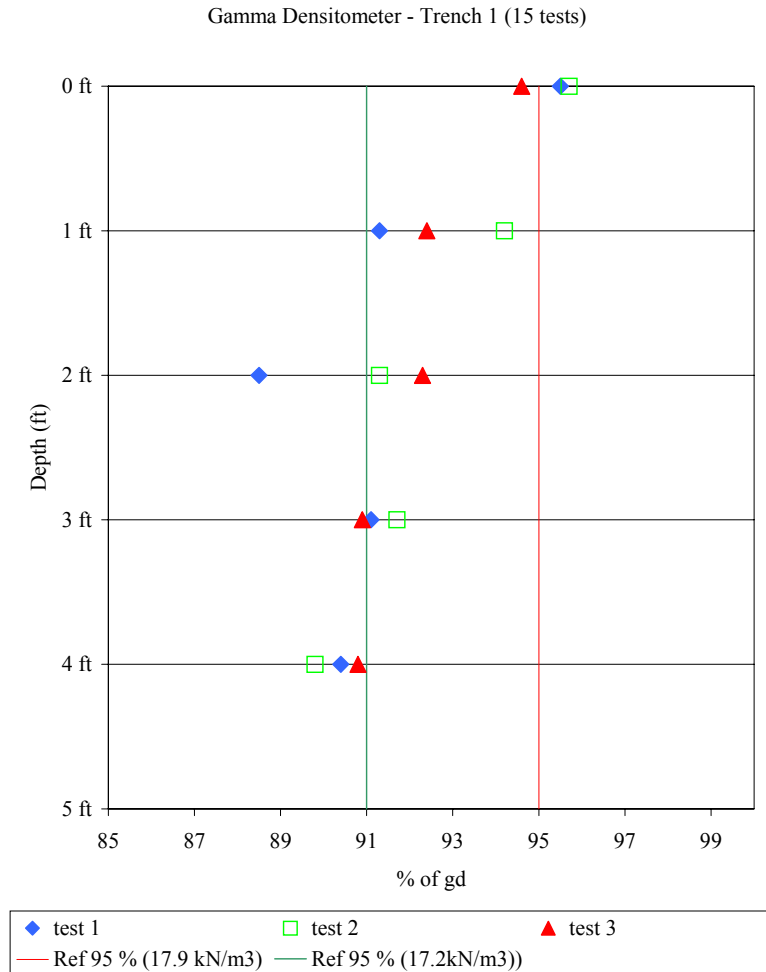
Figure 15 – Gamma Densitometer

The Soil Compaction Meter - Trench 1 (10 tests)

The Dynamic Cone Penetrometer - Trench 1 (15 tests)
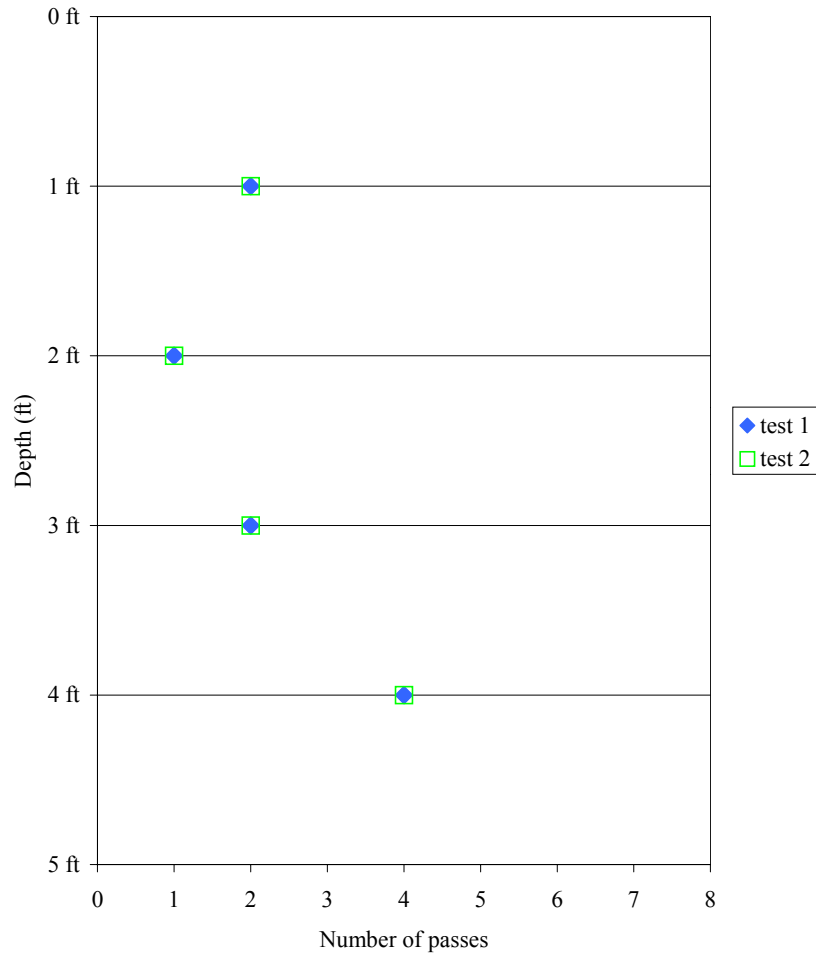
Figure 16 – The soil compaction meter

Figure 17 – The Dynamic Cone Penetrometer
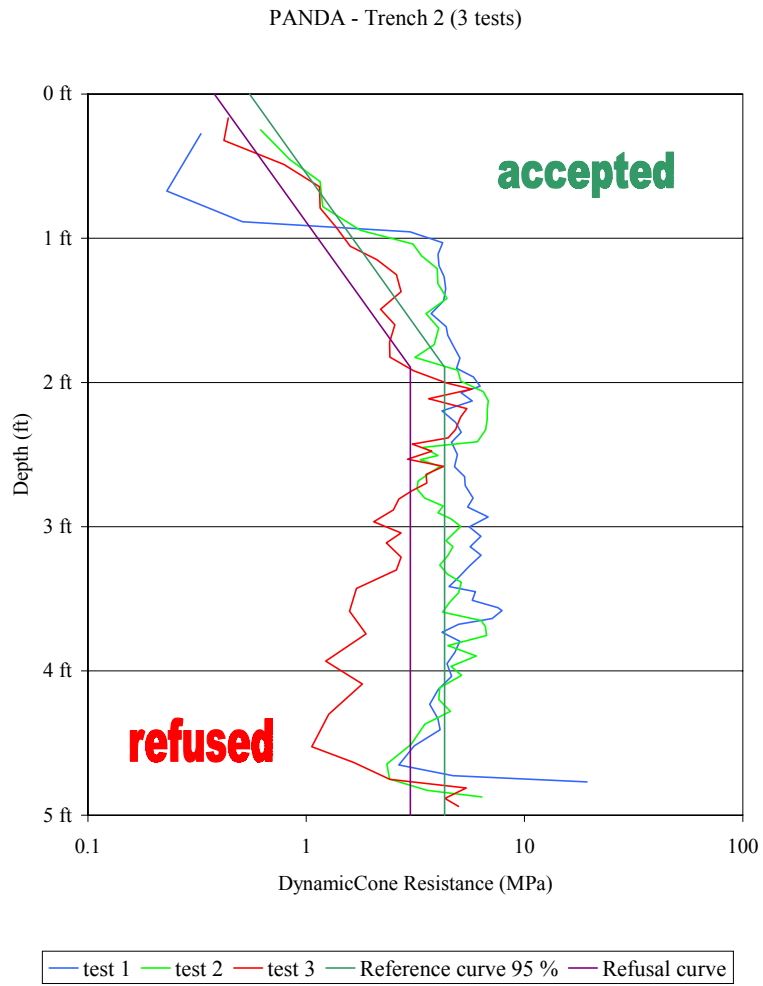
Figure 18 - PANDA penetrograms
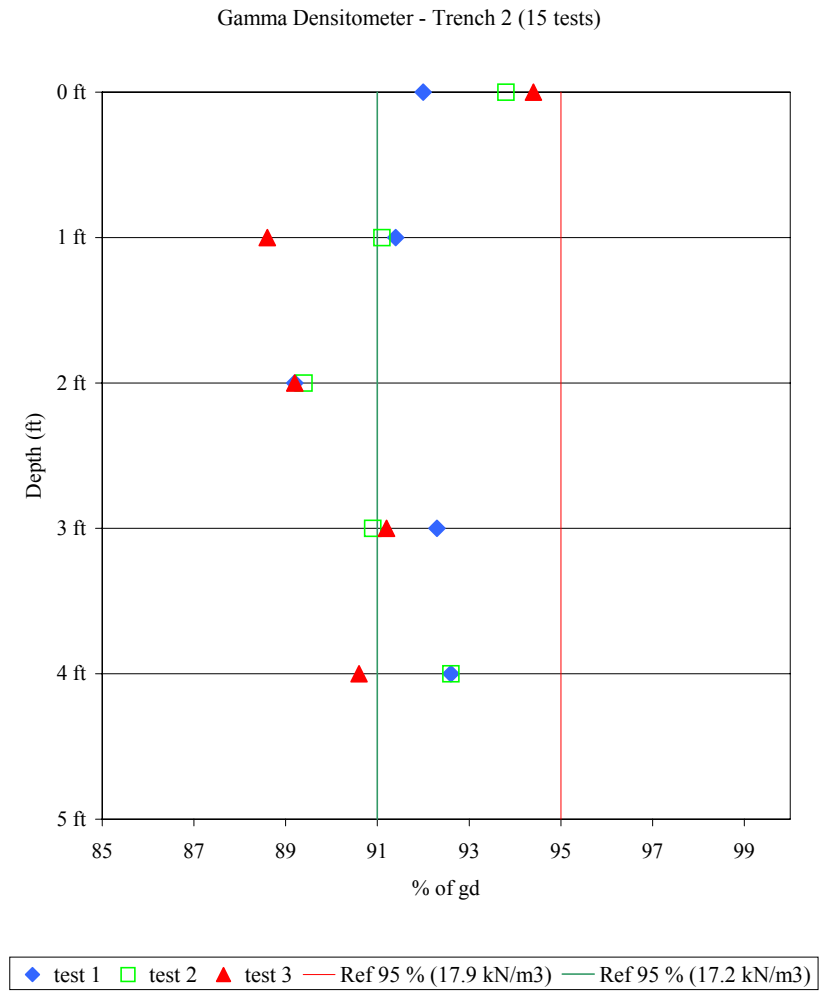
Figure 19 – Gamma Densitometer
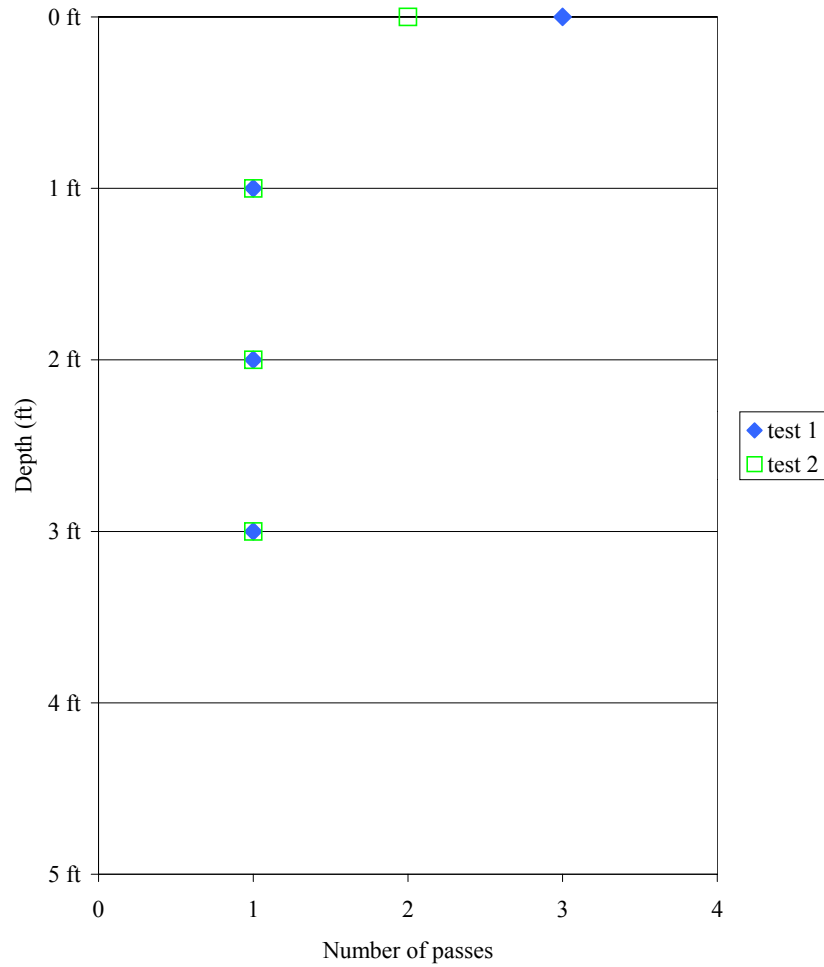
Figure 20 – The soil compaction meter

Figure 21 – The Dynamic Cone Penetrometer

10.3. Trench 3
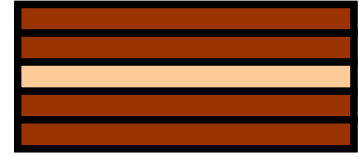
Figures 22 to 25 present the test results obtained for this trench, illustrating the following:

The **PANDA** penetrograms indicate that at the depth of 75 cm, for about 20 cm, the test results are lower than the reference curve. **The compaction, in the middle layer, doesn't meet site specifications.**
The **Gamma Densitometer** indicates that for the third layer we have reached less than 86 % of γd_{max}. **The compaction doesn't meet site specifications.** (*) (**)
The **Soil Compaction Meter**, for the third non-compacted layer and the fourth layer, indicates no compaction (no stop light turned on)**. The compaction doesn't meet site specifications**.
*For the fifth layer, The **Soil Compaction Meter** stoplight is turned on after two passes of the vibro tamper.*
The **Dynamic Cone Penetrometer** control test results are lower than the reference curve. **The compaction doesn't meet site specifications.**

10.4. Trench 4

Figures 26 to 29 present the test results obtained for this trench, illustrating the following:

The PANDA penetrograms indicate that, between the depth of 50 cm and 75cm, the test results are lower than the reference curve. The same remark can be made for the depths of 110 cm and 150 cm. **The compaction doesn't meet site specifications.**
The **Gamma Densitometer** indicates the test results are close to 95 % of γd_{max}. **The compaction meets site specifications**. (*) (**)
The stop light of the **Soil Compaction Meter** is turned on after two passes of vibro tamper. **The compaction meets site specifications.**
The **Dynamic Cone Penetrometer** control test results are higher than the reference curve. **The compaction meets site specifications.**

Figure 22 - PANDA penetrograms

Figure 23 – Gamma Densitometer

The Soil Compaction Meter - Trench 3 (8 tests)

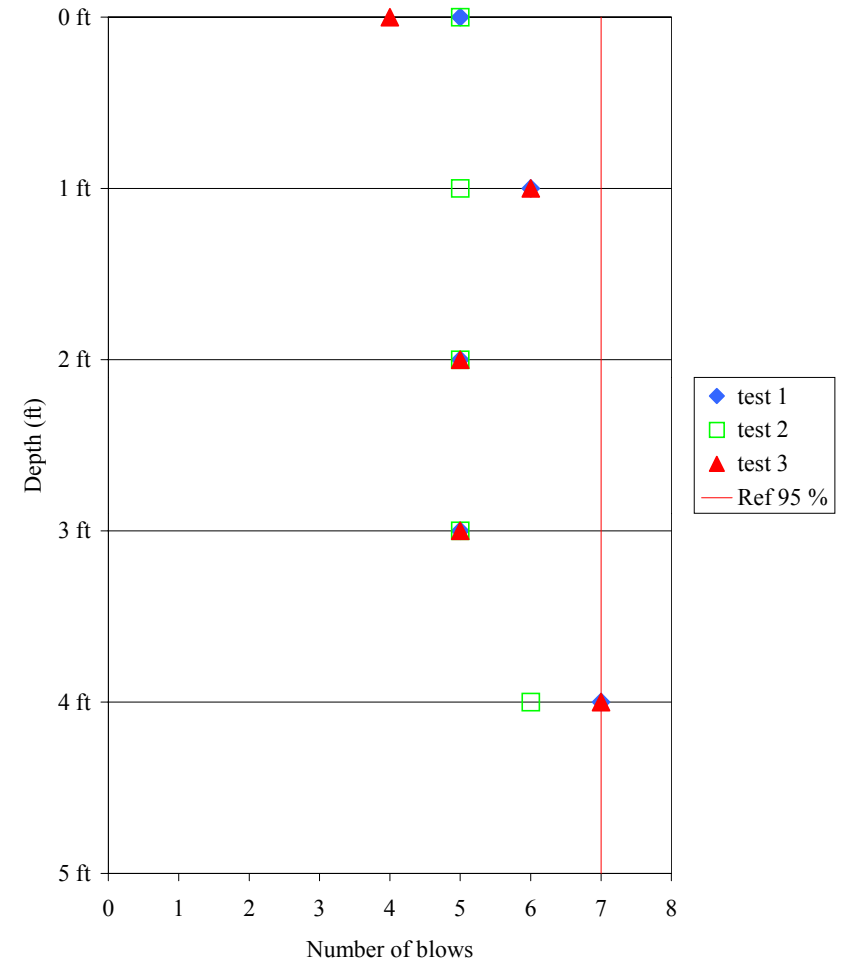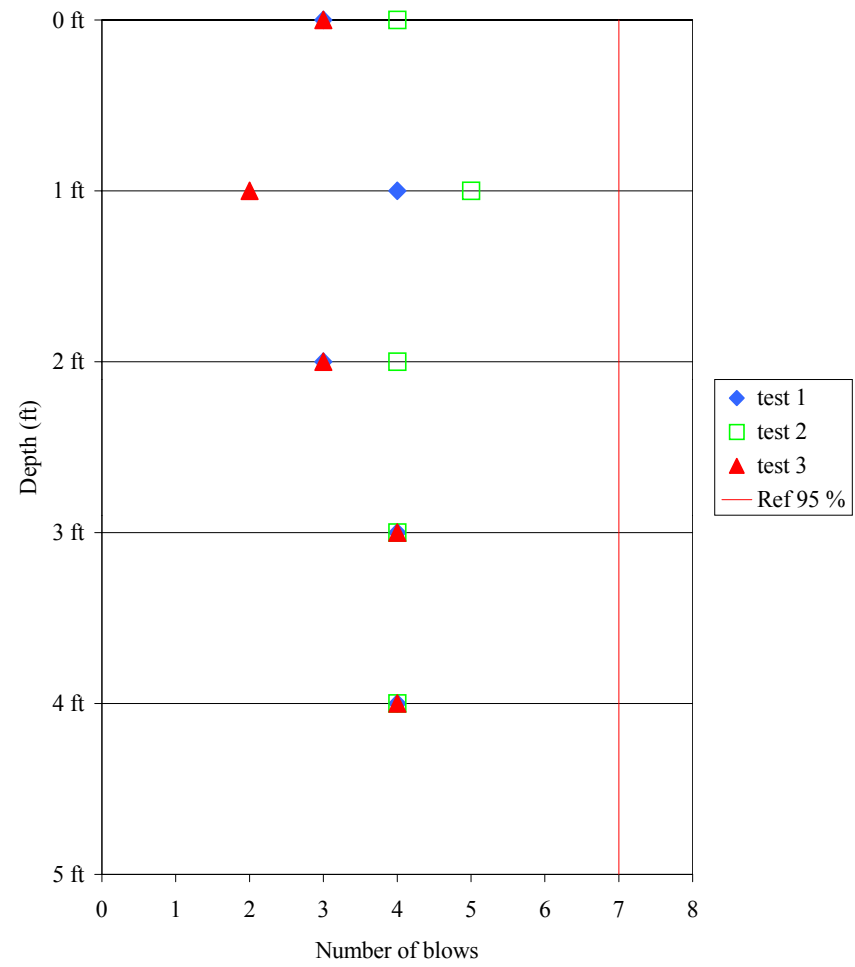The Dynamic Cone Penetrometer - Trench 3 (15 tests)

Figure 24 – The soil compaction meter

Figure 25 – The Dynamic Cone Penetrometer

PANDA - Trench 4 (3 tests)

accepted

refused

Depth (ft)

DynamicCone Resistance (MPa)

test 1 — test 2 — test 3 — Reference curve 95 % — Refusal curvel

Figure 26 - PANDA penetrograms

Gamma Densitometer - Trench 4 (6 tests)

Depth (ft)

% of gd

test 1 test 2 test 3 Ref 95 % (17.9 kN/m3) Ref 95 % (17.2 kN/m3)

Figure 27 – Gamma Densitometer

The Soil Compaction Meter - Trench 4 (5 tests)

The Dynamic Cone Penetrometer - Trench 4 (6 tests)

Figure 28 – The soil compaction meter

Figure 29 – The Dynamic Cone Penetrometer

10.5.   Trench 5

Figures 30 to 33 present the test results obtained for this trench, illustrating the following:

The **Panda** penetrograms indicate that at a depth exceeding 50 cm control test results are lower than the reference curve. **The compaction doesn't meet site specifications**
The **Gamma Densitometer** indicates that we have reached a value of 92% of γd_{max}. **The compaction doesn't meet site specifications**. (*) (**)
The **Soil Compaction Meter** stoplight is turned on after four passes of the vibro tamper**. The compaction meets site specifications.**
The **Dynamic Cone Penetrometer** control test results are lower than the reference curve. **The compaction doesn't meet site specifications.**
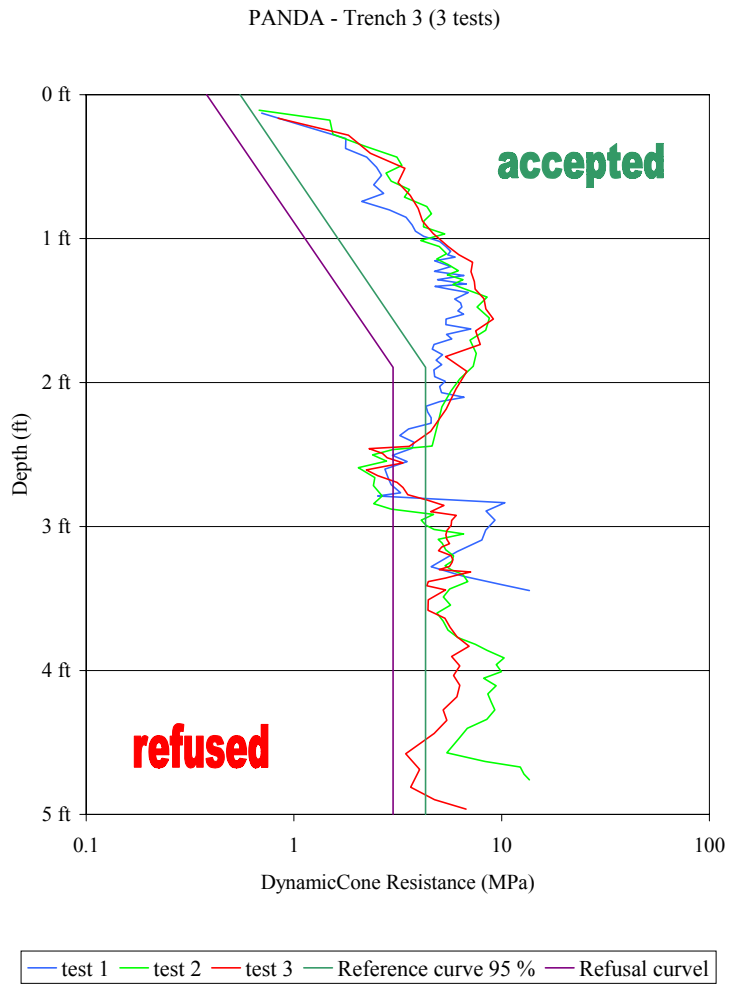
10.6.   Trench 6

Figures 34 to 37 present the test results obtained for this trench, illustrating the following:

The **Panda** penetrograms indicate that control test results are higher than the reference curve. **The compaction meets site specifications**.
The **Gamma Densitometer** indicates that we have reached an average value of 92% of γd_{max}. **The compaction doesn't meet site specifications**. (*) (**)
The stop light of the **Soil Compaction Meter** light after two passes of the vibro tamper**. The compaction meets site specifications.**
The **Dynamic Cone Penetrometer** control test results are higher than the reference curve. **The compaction doesn't meet site specifications.**

Figure 30 - PANDA penetrograms

Figure 31 – Gamma Densitometer

The Soil Compaction Meter - Trench 5 (2 tests)

The Dynamic Cone Penetrometer - Trench 5 (3 tests)

Figure 32 – The soil compaction meter

Figure 33 – The Dynamic Cone Penetrometer
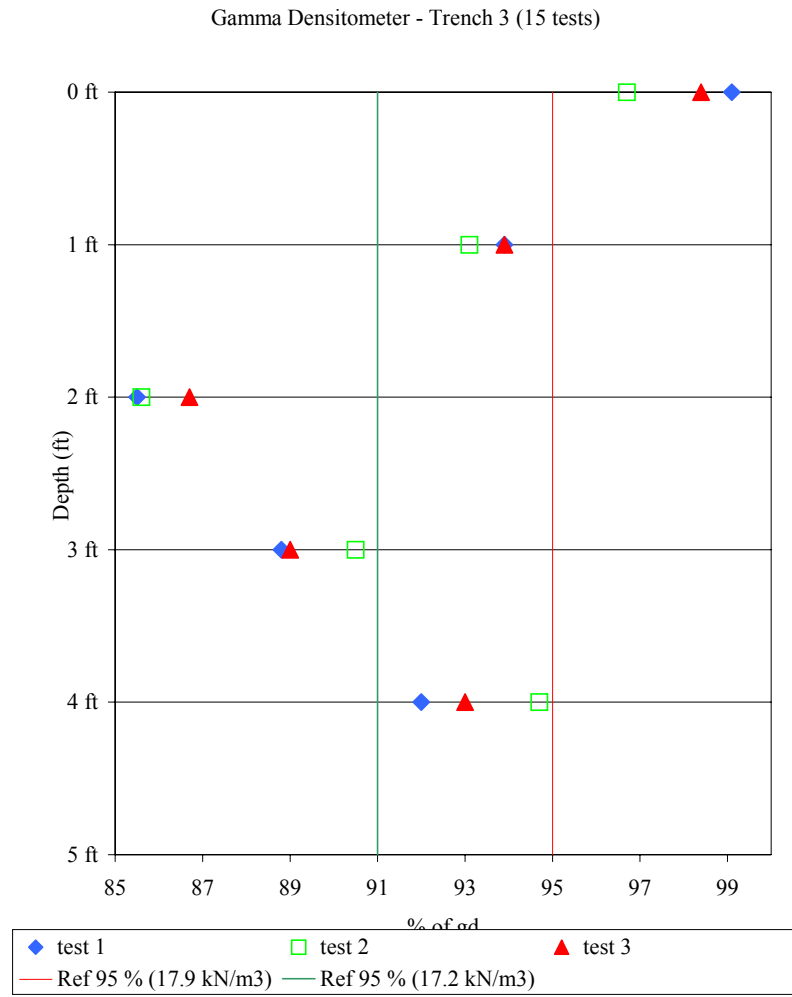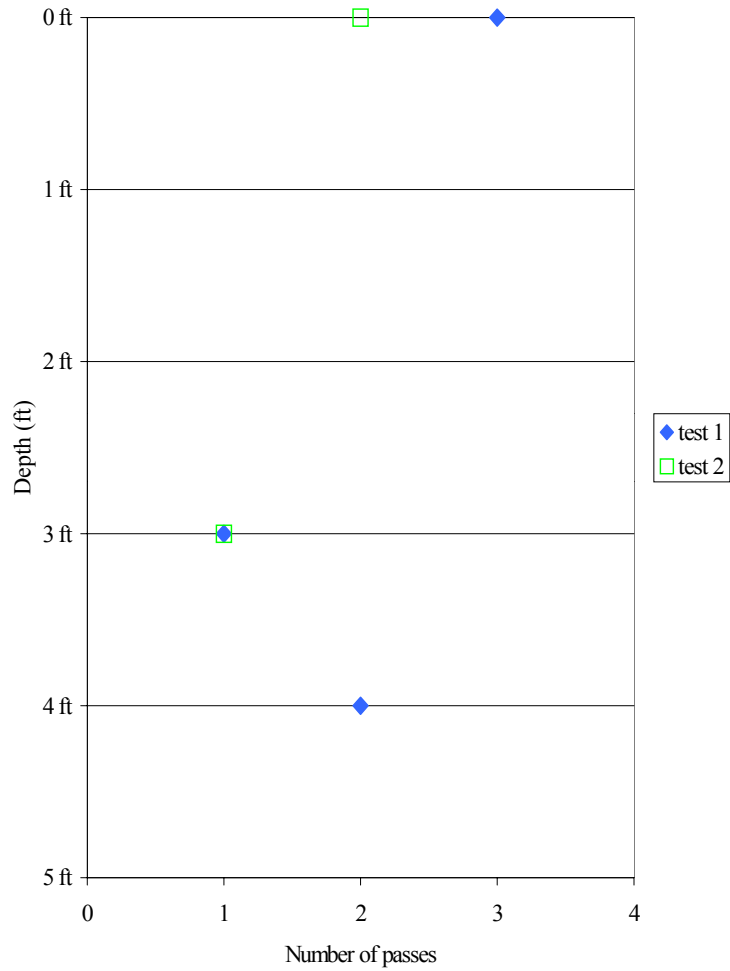
Figure 34 - PANDA penetrograms
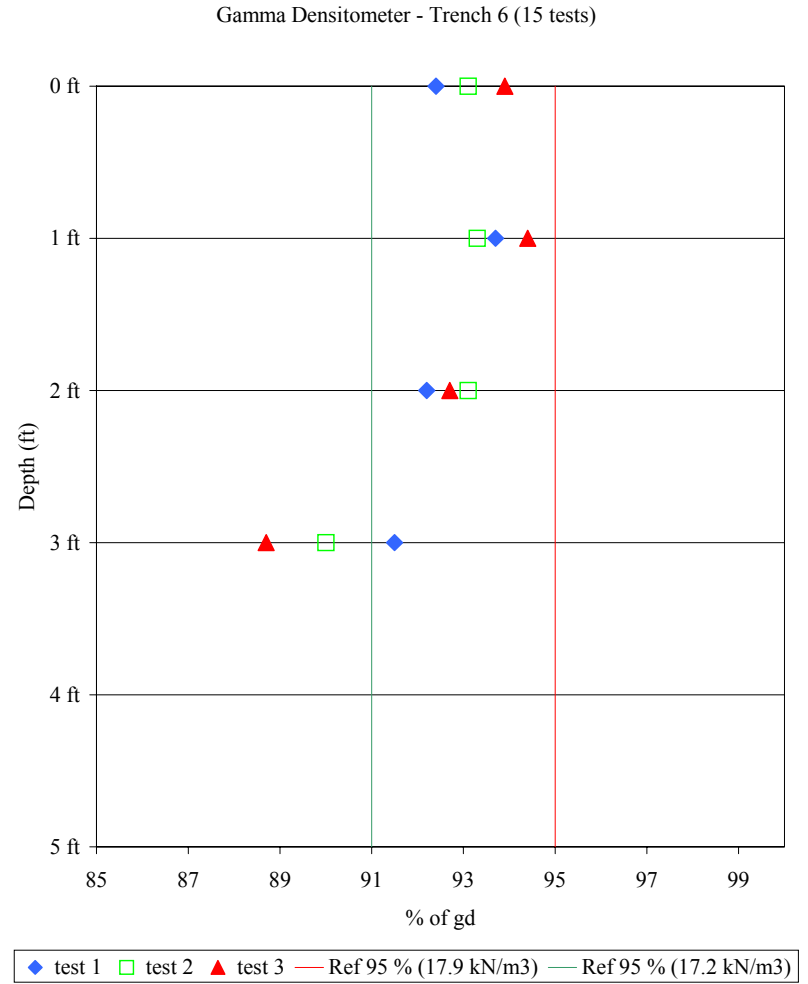
Figure 35 – Gamma Densitometer

The Soil Compaction Meter - Trench 6 (10 tests)

Figure 36 – The soil compaction meter
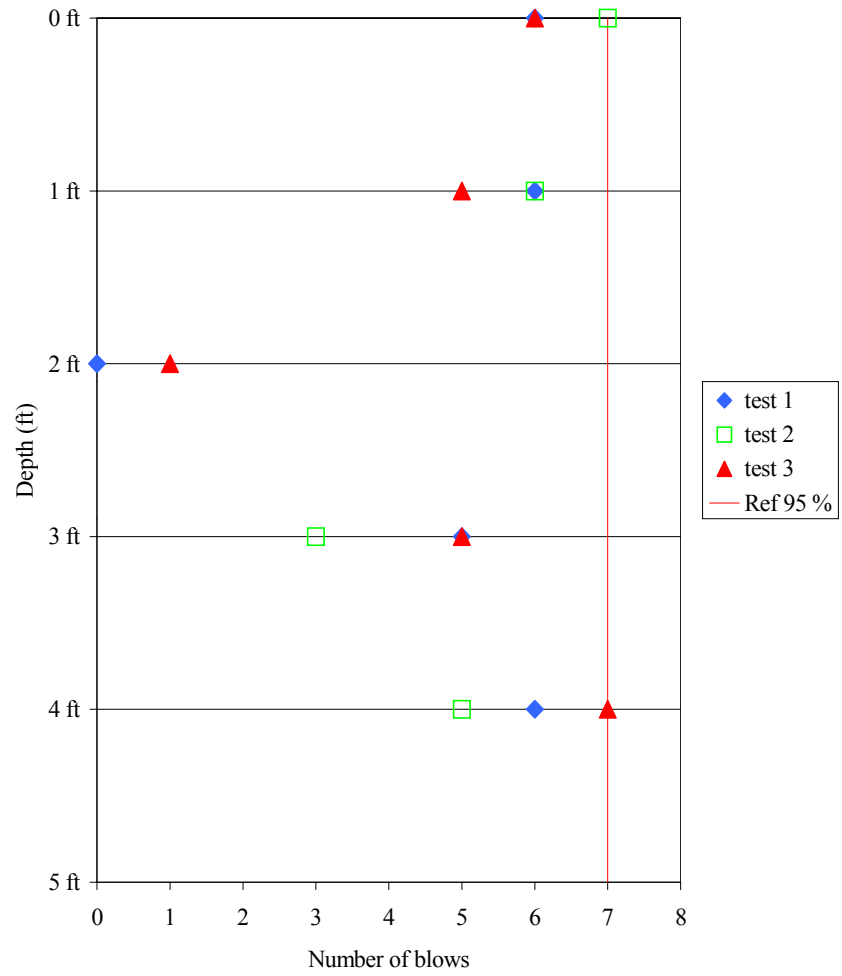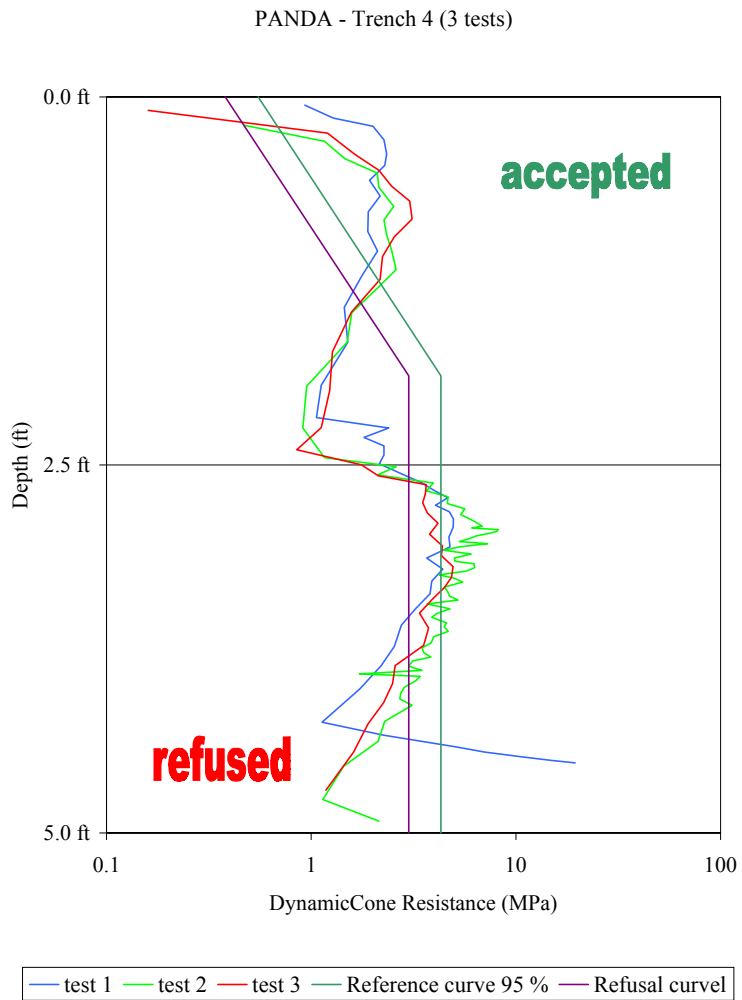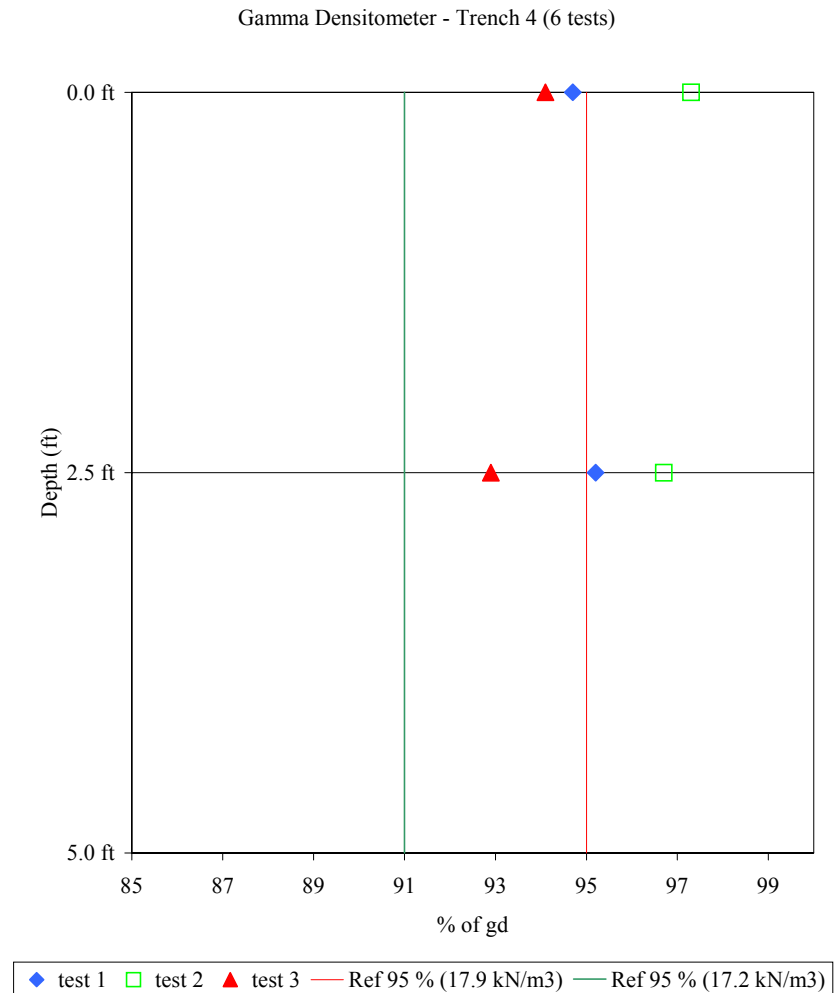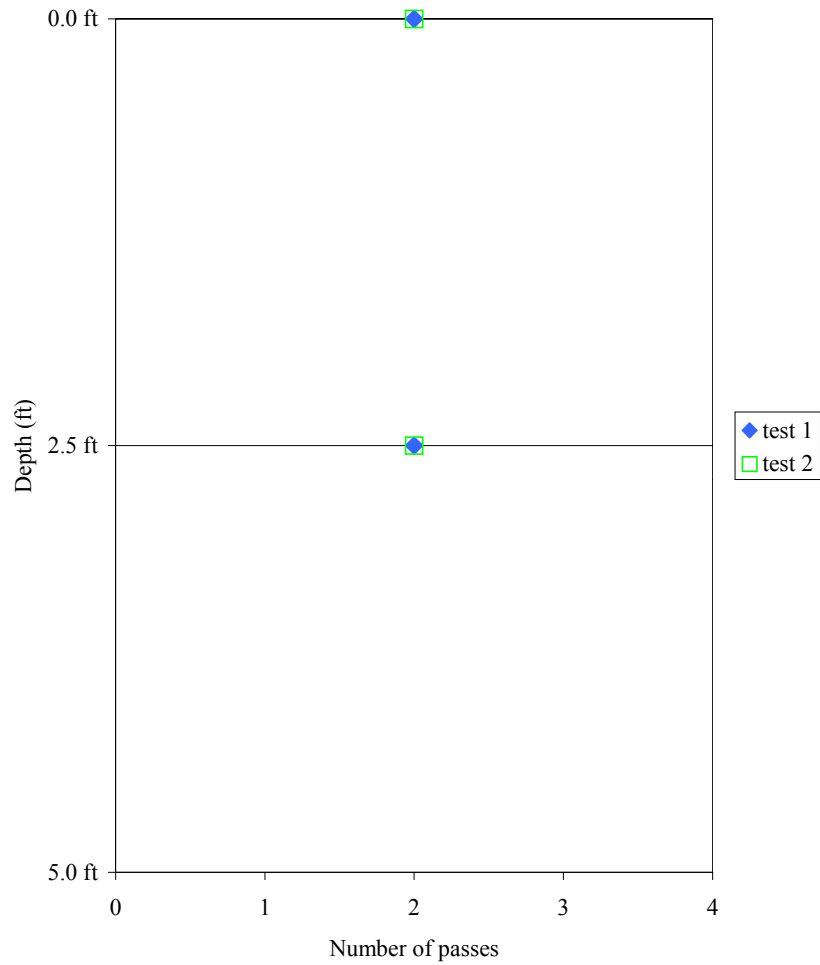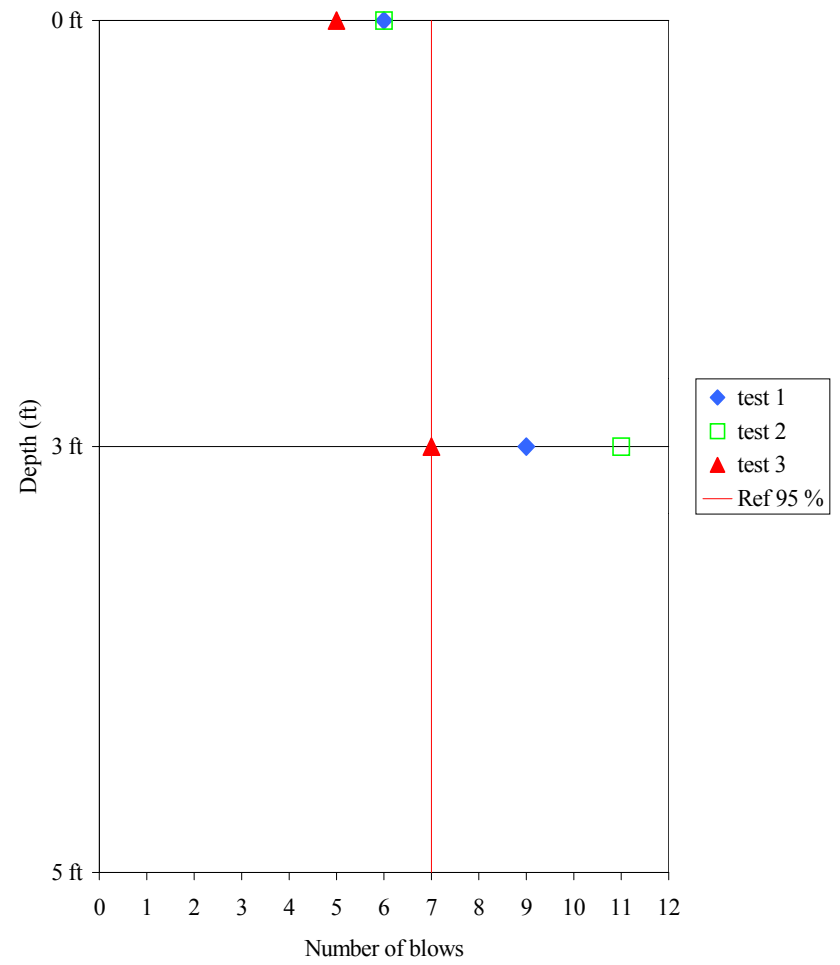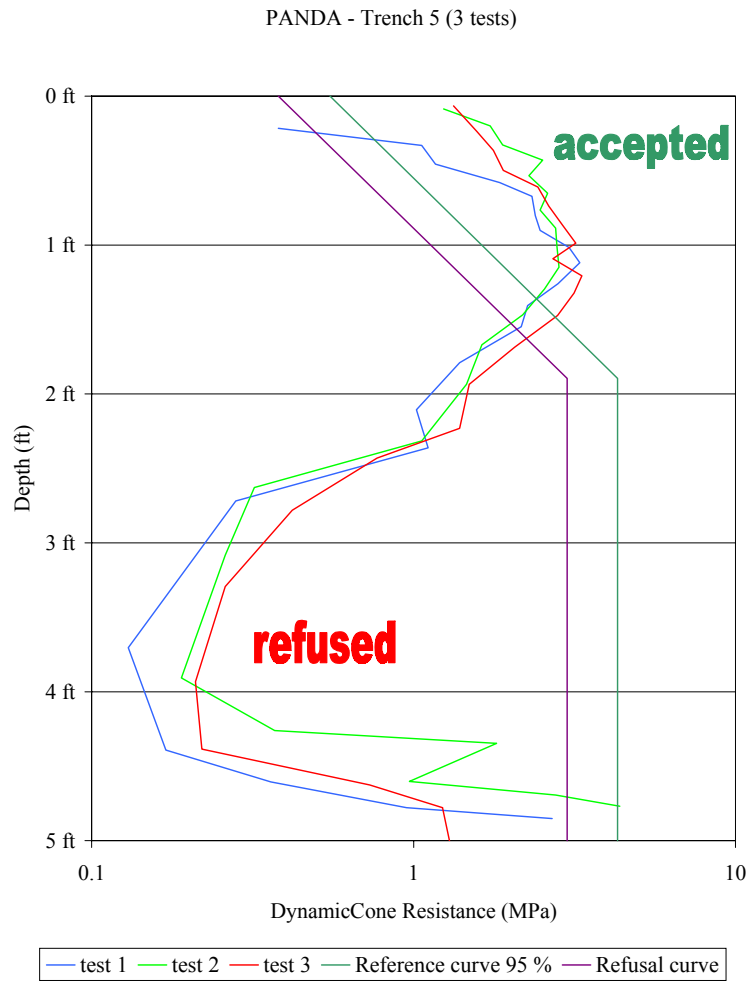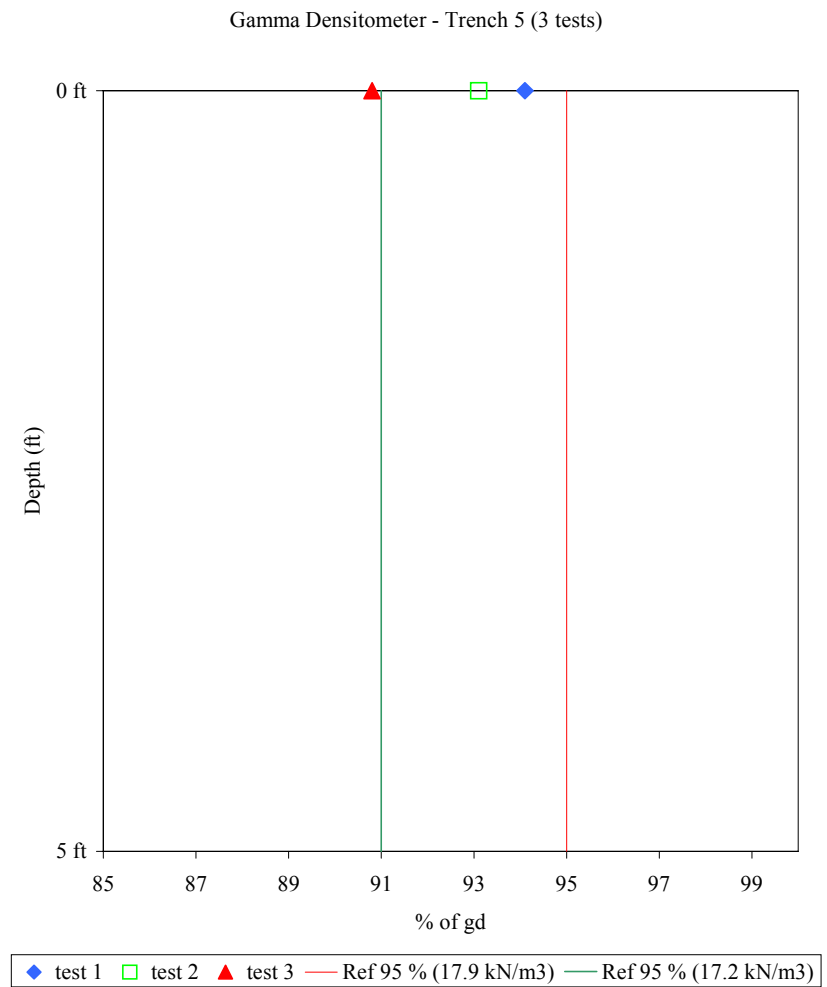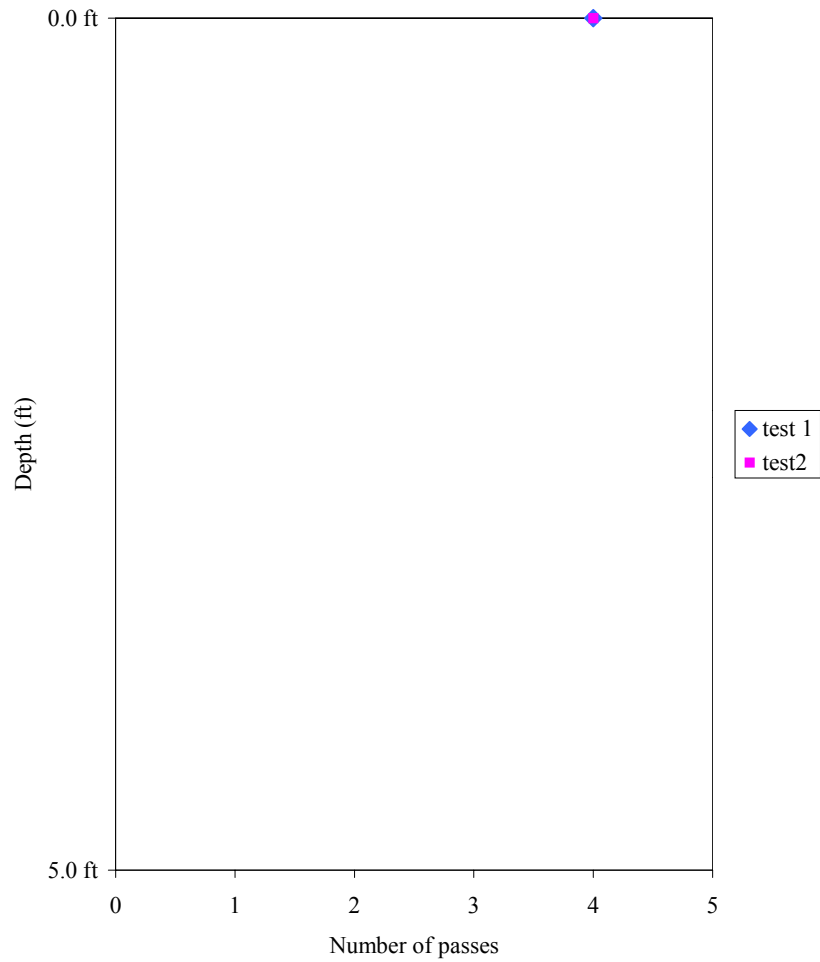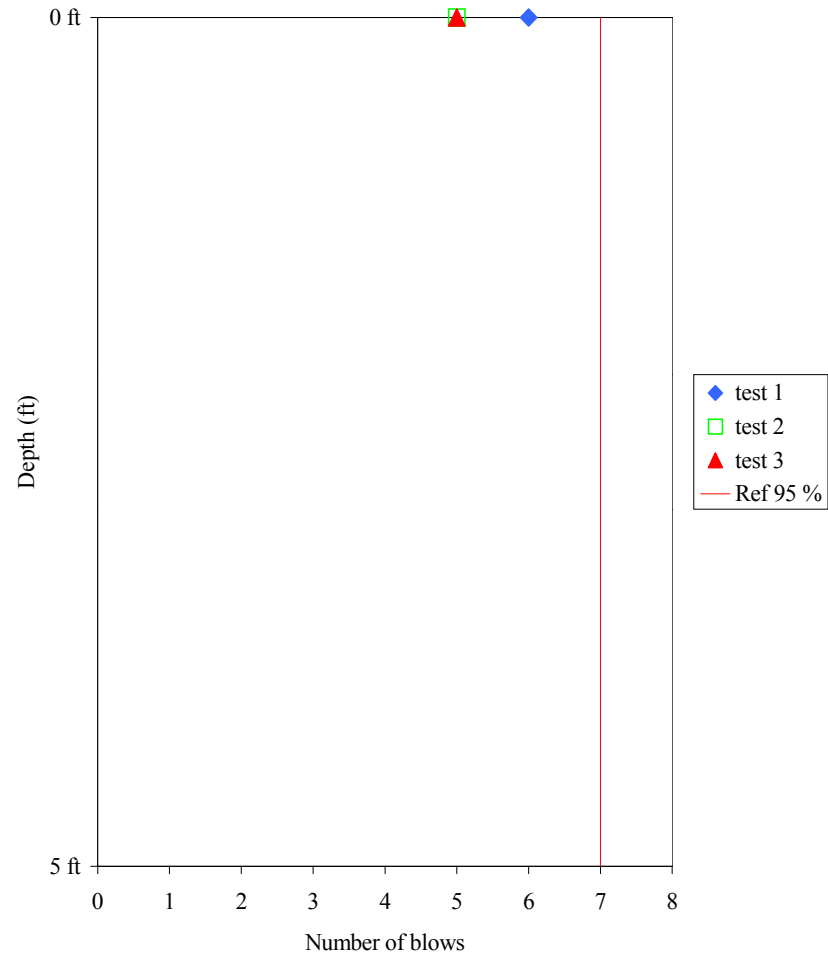
The Dynamic Cone Penetrometer - Trench 6 (15 tests)
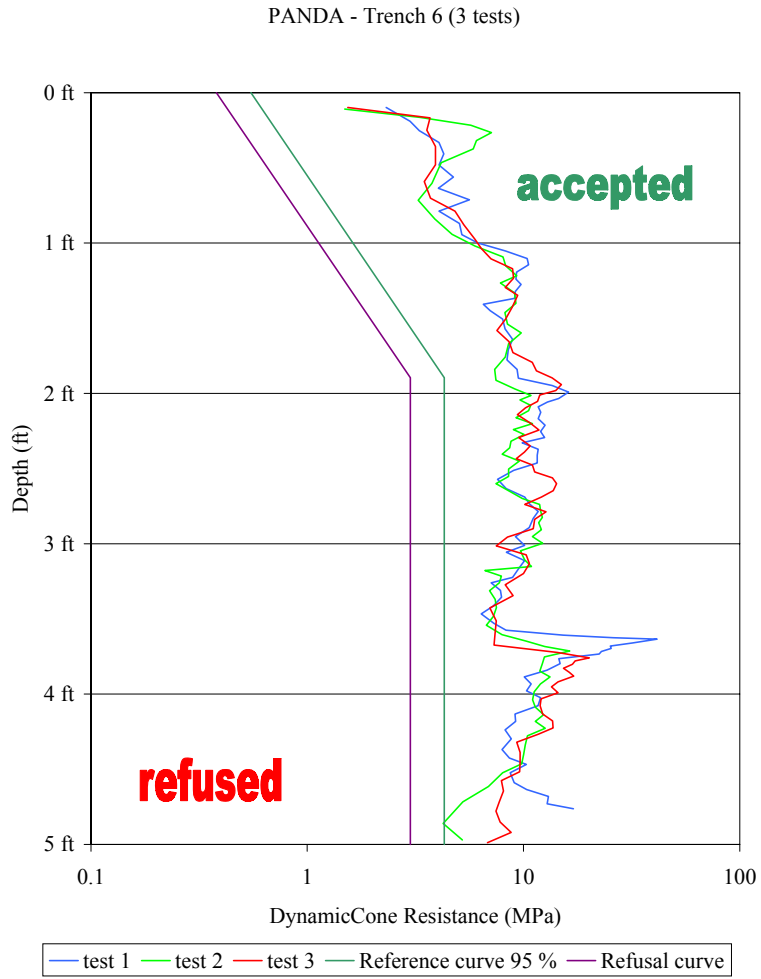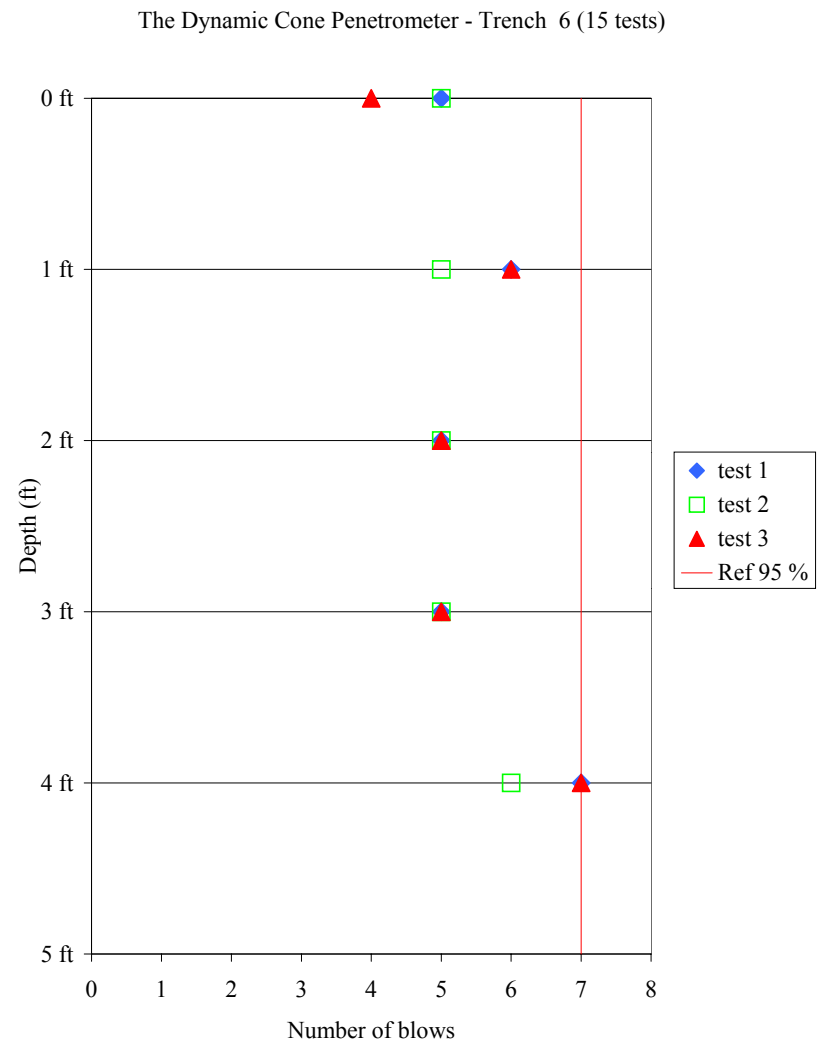

Figure 37 – The Dynamic Cone Penetrometer

11. Technical Performance Assessment
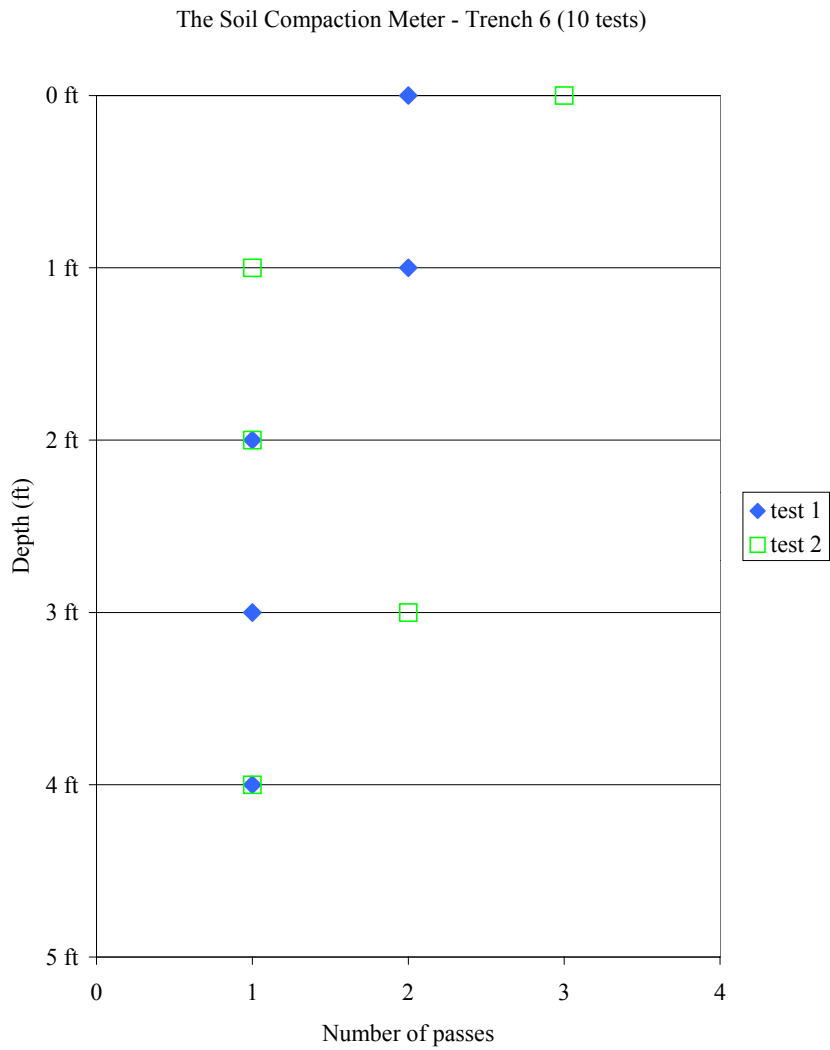
Tables 2 to 5 present a preliminary comparative assessment of the different testing techniques under consideration. This comparative assessment involves primarily (i) technical performance evaluation, (ii) efficiency and safety, (iii) user friendly data acquisition and reduction software, and (iv) cost and required technical level. Table 6 briefly summarizes the main features under consideration.

Criteria	PANDA	Dynamic Cone Penetrometer (DCP)	Gamma Densitometer (GD)	Soil Compaction Meter (SCM)
Availability of National and/or Regional Standards	French standard (XP P 94-105)	No standards Industry specific	ASTM D 3017-88 / D 2922-91	No standards Manufactures guidelines
Accuracy and Repeatability (*)	Highly repeatable	R_I = 60% (Marginal)	R_I = 80% (Good)	Highly repeatable
Dependency on equipment	Low	High	Low	Low
Precalibration for compaction control	Laboratory tests for reference curves	Local Experience	On site Proctor Tests	Manufacture data
Dependency on operator	Low	High	Low	Low
Sensitivity to the Compaction Process for Post Construction Inspection	High (Full soil profile)	Low (Half a layer)	Low (one foot layer)	Low (Surface local data)
Soil profile versus Local Data per Layer	Soil Profile	Local data	Local data	Local data
Depth affected	Full Trench	6.5 inches (half a layer)	One foot layer	Full Trench
Parameters for Soil Compaction Control	Operation independent measurements of q_d. Empirical correlations with soil density for compaction control.	Local correlations for soil compaction control.	Direct measurement of dry density and moisture content.	Yes/No for preset compaction control criteria.

Table 2 – Information Quality and Reliability

(*) Qualitative repeatability index R_I= 1-(MV/ER)

MV (Maximum Variation): Maximum variation between measured values for a given layer.

ER (Expected Range): The variation between the maximum measured value and the value obtained for the non-compacted layer.

Criteria	PANDA	Dynamic Cone Penetrometer (DCP)	Gamma Densitometer (GD)	Soil Compaction Meter (SCM)
Environmental impact	**No requirements**	**No requirements**	**License required**	**No requirements**
Testing during construction	**Yes**	**Yes**	**Yes**	**Yes**
Testing post construction	**Yes**	**No**	**No**	**No**
On site inspection	**During or Post construction Inspection**	**During construction**	**During construction**	**During Construction**
User friendly software	**Available for data acquisition, display, reduction and reporting**	**Non available**	**Non available**	**Non available**
Professional training requirements	**Technician**	**Worker**	**Technician**	**Worker**

Table 3 – Efficiency and safety

Criteria	PANDA	Dynamic Cone Penetrometer (DCP)	Gamma Densitometer (GD)	Soil Compaction Meter (SCM)
Software for data acquisition and display	**Yes Microsoft window software**	**No**	**No**	**No**
Availability of databases	**Extensive**	**Based on local experience**	**Extensive**	**Poor**
Reporting/data reduction and communication	**Automated Data processing and reduction (ASCII code)**	**Manual data processing**	**Manual data processing**	**No reporting Limited for on site compaction control**
Information security/dependency on the operator	**High Operator independent**	**Low On site data processing**	**Low On site data processing**	**Low On site direct information**

Table 4 – Data acquisition, reduction and analysis

Criteria	PANDA	Dynamic Cone Penetrometer (DCP)	Gamma Densitometer (GD)	Soil Compaction Meter (SCM)
Equipment	**N/A**	**$250**	**$5,000**	**$1,000**
Permits and Disposable Equipment	**N/A**	**N/A**	**License $1,500 / year**	**$10 disposable sensor per test**
Mob / Demob.	**None**	**None**	**safety requirements for transportation**	**None**
Person x time per test	**1/15 minutes**	**1/5minutes**	**1/15 minutes**	**1/rapid**
Cost/day	**N/A (20 tests per day)**	**$300**	**$900**	**Ø**

Table 5 – Cost study

Criteria	PANDA	Dynamic Cone Penetrometer (DCP)	Gamma Densitometer (GD)	Soil Compaction Meter (SCM)
Technical Performance, Information availability & Reliability	**Highly repeatable** **Full depth profile** **Surface testing Sensitive to compaction process**	**Marginal repeatability Half layer depth** **Surface testing Non sensitive to compaction process**	**Highly repeatable** **Layer by layer** **Surface testing Non sensitive to compaction process**	**Highly repeatable** **Full depth Local data points Surface testing Non sensitive to compaction process**
Initial Equipment Cost	**N/A**	**$250**	**$5,000**	**$1,000**
Other costs	**None**	**None**	**Permit $1,500/year**	**$10 Disposal sensor per Test**
Cost per day	**N/A (20 tests per day)**	**$300**	**$900**	**Ø**
Environmental Impact	**None**	**None**	**Permit required**	**None**
Requirements for In-situ inspection during construction	**Can be used for post compaction inspection**	**Required**	**Required**	**Required**
Software availability for data acquisition & processing	**Excellent**	**None**	**None**	**None**
Owner/contractor communication & reporting	**On site automated data reduction /reporting** **Operator independent data processing**	**Manual data processing** **Operator Involvement in data processing**	**Manual data processing** **Operator Involvement in data processing**	**No reporting** **Limited to on site compaction control**
Professional training requirements	**Technician**	**Worker**	**Technician**	**Worker**

Table 6 – Summary – Main Advantages and Disadvantages

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12. Conclusion

The demonstration project has illustrated the critical need for a reliable soil compaction control technology, capable of establishing the compaction process throughout the full depth of the compacted backfill material.

The PANDA seems to provide a most effective and user-friendly tool for addressing this critical need. It yields highly repeatable results and an engineering parameter q_d, which is practically operator independent. With its user-friendly software, the PANDA allows an on-site data acquisition, processing, display and reporting.

The other three soil compaction control technologies: Gamma Densitometer, Soil Compaction Meter and Dynamic Cone Penetrometer, provide useful tools for on-site compaction control. However, data acquisition, processing and reporting is manually done and is therefore dependent on the operator. These tests do not provide full depth profiles and therefore cannot be used for post-construction compaction control.

The PANDA can be most effectively used for post–construction site inspection as it yields a full depth compacted soil profile and, thereby, detects any anomaly/deviation in the compaction process. With a relevant enforcement policy the PANDA could become highly cost effective, minimizing the need for on site inspection during the construction.