Embankment Quality Phase IV: Application to Unsuitable Soils

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16. Abstract

The Quality Management Earthwork (QM-E) special provision was implemented on a pilot project to evaluate quality control (QC) and quality assurance (QA) testing in predominately unsuitable soils. Control limits implemented on this pilot project included the following: 95% relative compaction, moisture content not exceeding +/- 2% of optimum moisture content, soil strength not exceeding a dynamic cone penetrometer (DCP) index of 70 mm/blow, vertical uniformity not exceeding a variation in DCP index of 40 mm/blow, and lift thickness not exceeding depth determined through construction of control strips. Four-point moving averages were used to allow for some variability in the measured parameter values. Management of the QC/QA data proved to be one of the most challenging aspects of the pilot project. Implementing use of the G-RAD data collection system has considerable potential to reduce the time required to develop and maintain QC/QA records for projects using the QM-E special provision. In many cases, results of a single Proctor test were used to establish control limits that were used for several months without retesting. While the data collected for the pilot project indicated that the DCP index control limits could be set more tightly, there is not enough evidence to support making a change. In situ borings, sampling, and testing in natural unsuitable cut material and compacted fill material revealed that the compacted fill had similar strength characteristics to that of the natural cut material after less than three months from the start of construction.

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EMBANKMENT QUALITY PHASE IV: APPLICATION TO UNSUITABLE SOILS

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Principal Investigator
David J. White
Associate Professor
Department of Civil, Construction, and Environmental Engineering, Iowa State University

Co-Principal Investigator
Charles Jahren
Associate Professor
Department of Civil, Construction, and Environmental Engineering, Iowa State University

Research Assistants
Brett W. Larsen and Joels Malama

Authors
David J. White, Brett W. Larsen, Charles Jahren, Joels Malama

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A report from
Center for Transportation Research and Education
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103
Fax: 515-294-0467
www.ctre.iastate.edu

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EXECUTIVE SUMMARY

Iowa State University has conducted a series of research projects from 1997 to 2007 to develop improvements to the Iowa Department of Transportation's (Iowa DOT's) construction practices for roadway embankments. Phase I research was initiated as a result of internal Iowa DOT studies that raised concerns about the quality of embankments currently being constructed, due to failures that occurred at several large embankments. The primary objective of Phase I was to evaluate the quality of embankments being constructed under the existing specifications at that time. Overall, an evaluation of the results of Phase I indicated that consistent embankment quality was not being attained due to the following: (1) inadequately trained field personnel; (2) problems inherent in the Iowa DOT's systems of field classification, testing, and quality control; and (3) placemement of fill at moisture contents well in excess of optimum that often lead to poor strength and performance.

Phase II research was initiated to investigate different methods and techniques that could be used to improve the Iowa DOT's soil classification and compaction control specifications based upon observations and data collected at small-scale pilot compaction studies. The results from these studies indicated that new specifications were required that better account for the differences between the behavior of cohesive and cohesionless soils. The Iowa Empirical Performance Classification system was developed. This new system considered many more of the factors that affect the engineering properties of soil, in comparison to the former specifications. The use of dynamic cone penetrometer (DCP) testing was also proposed as a supplement to field moisture-density quality control testing in both cohesive and cohesionless soil. The DCP provides in situ measurements of fill strength and can be used to asses the variability of fill strength with depth.

Phase III research focused on the creation of a comprehensive earthwork construction specification, the Quality Management Earthwork (QM-E) program, which incorporates the findings/recommendations of the previous two phases of research into a practical field construction specification. The QM-E was then implemented on a full-scale pilot project to field test and refine elements of the proposed program for cohesionless soils. The results of this pilot project were very promising. The soil classification system worked well in both the design and construction phases of the project, having required only minor modifications. The special provisions of the QM-E program, developed jointly with the Iowa DOT, also worked well and required minimal alteration. Ultimately, the overall quality of the embankment fill showed improvement as indicated by DCP testing and the additional disking that was required. The cost of this improvement was nominal, 3.3% for the additional disking and the application of the QM-E program, in comparison to the perceived improvement in quality.

Phase IV research was initiated due to concerns that the soil conditions from the Phase III pilot study were too ideal to properly assess the QM-E special provisions. While the costs of implementing the QM-E program on the previous project were relatively small, it was believed that if the fill material were considerably more difficult to moisture condition, as is the case with cohesive soils, the special provisions might prove unreasonable and expensive. Therefore, a second full-scale pilot project was conducted in cohesive soils. The goals of this pilot project were to (1) field test and refine elements of the QM-E program for cohesive soils, (2) train additional contractor and Iowa DOT on the Certified Grading Technician Level I program, and (3) review other state department of transportation (DOT) earthwork specifications for potential modifications to the QM-E special provision. Smaller field studies were also conducted prior to the pilot project to establish the state of practice throughout for construction of earthen embankments in unsuitable soil.

The QM-E special provision that was implemented at the pilot project in unsuitable material required dry unit weight, moisture content, soil strength, vertical uniformity, and lift thickness testing to control fill compaction. Quality control (QC) and quality assurance (QA) testing were conducted by the contractor and DOT, respectively, throughout the construction process. The QM-E special provision has set requirements for the number of QC/QA tests needed and control limits, that vary based upon soil type or are determined through the construction of test strips, for determining when the material is no longer meeting quality standards. All of these control limits are applied to a four-point running average of tests and not individual spot tests. The control limits that were used for this pilot project were dry unit weight not exceeding 95% relative compaction, moisture content not exceeding +/- 2% optimum moisture content, soil strength not exceeding a DCP index of 70 mm/blow, vertical uniformity not exceeding a variation in DCP index of 40 mm/blow, and lift thickness not exceeding depth determined through construction of control strips.

The field studies revealed that there are still challenges with control of moisture content and lift thickness for cohesive soils. These issues were identified in Phase I research as resulting in low-strength, highly variable fill with low dry unit weights. The observed values from the field studies often had low dry unit weights; however, the variability and strength were not alarmingly low. The application of the QM-E special provision to the full-scale pilot project in unsuitable soil was successful. Very few problems were encountered in the field; however, the management of the QC/QA data proved one of the more challenging aspects. The contractor chose not to implement the G-RAD data acquisition program and thus there was a greater volume of manual data entry than would otherwise have been expected. In general, the control limits for all the QC/QA tests seemed practical. There were very few "failures" that occurred, as defined by the QM-E program, throughout the course of the project; however, the moisture content testing tended to be the cause of a significant portion of the failures.

Based upon observations in the field and from analyzing the data collected at the pilot project, the following was concluded. First, a refinement to the existing QM-E special provision requirements is needed to address apparent problems with unnoticed changes in material properties. Relative compaction values observed on this project regularly exceeded 105%, and some values were greater than 110%. Regardless of whether these problems were the result of changes in material properties, it makes practical sense to require more testing in the event that values begin to regularly exceed 105%. Secondly, a new technique was developed to create soil-specific control limits for DCP testing. While the data from the pilot project suggests that the current method is adequate, it remains crude and does not account for many of the factors that affect soil strength and performance. The new technique utilizes CBR testing across a range of moisture contents to determine DCP index criteria. This method has potential to eventually eliminate dry unit weight testing from the QM-E program. Finally, the strength of the compacted fill was assessed for the Crow Creek embankment using cone penetration testing. The results of this testing showed that the strength of the material was equivalent to that of the natural cut material very shortly after completion of the embankment. Even greater gains in strength would be expected with time.

INTRODUCTION

Iowa State University (ISU) has conducted a series of research projects from 1997 to 2007 to develop improvements to the Iowa Department of Transportation's (Iowa DOT's) construction practices for roadway embankments. The different phases of research focused on identifying inadequacies in the construction methods that lead to poor overall embankment quality, developing new construction methods and practices to ensure improved quality, and developing a system to identify problems throughout the construction process. The body of this research is summarized below.

Phase I Summary

Phase I research was initiated as a result of internal Iowa DOT studies that raised concerns about the quality of embankments currently being constructed. Some large embankments had recently developed slope stability problems resulting in slides that encroached on private property and damaged drainage structures. In addition, pavement roughness was observed shortly after roads were opened to traffic, especially for flexible pavements at transitions from cut to fill and on grade and pave projects. This raised the questions regarding the adequacy of the Iowa DOT embankment construction specifications. The primary objective of Phase I was to evaluate the quality of embankments being constructed under the current specifications. Overall, an evaluation of the results of Phase I indicated that consistent embankment quality was not being attained under the existing Iowa DOT specifications.

A summary of field and laboratory construction testing and observations from the Phase I research is as follows:

- *Field personnel (Iowa DOT and contractors)* appeared to be generally conscientious and trying to do a good job but were (1) misidentifying soils in the field, (2) lacking the necessary soil identification skills, and (3) relying heavily on the soils design plan sheets for classification, which often resulted in a soil misplacement.
- *Current Iowa DOT Specifications* – The current method of identifying unsuitable, suitable, and select soils may not be adequate. One-point Proctor does not appear adequate for identifying all soils or for field verification of compaction. Also, a "sheepsfoot walkout" is not, for all soils, a reliable indicator of degree of compaction, compaction moisture content, or adequate stability.
- *Construction observations and testing of cohesive soils* – The sheepsfoot walkout specification produced embankments where soils are placed wet of optimum and near 100% saturation, which can potentially result in embankments with (1) low shear strength/stability (2) high pore pressure development; and (2) potential for slope failures and rough pavements. In addition, disking and lift leveling specifications were not always enforced and overly thick lifts were being placed on overcompacted and undercompacted soils.
- *Construction observations and testing of cohesionless soils* – Compaction was attempted with sheepsfoot rollers where vibratory compaction was necessary and degree of compaction was monitored using the standard Proctor testing, which is an inappropriate method and can grossly overestimate degree of compaction.

Phase II Summary

Phase II research was initiated to evaluate alternative specifications and to develop efficient, practical, and economical field methods for compaction control and soils identification.

Field investigations and small pilot compaction studies were used to develop improved field soil classification methods and proper construction practices. Due to differences in soil engineering properties and compaction methods, soils were divided into two categories for research: (1) cohesionless soils and (2) cohesive soils.

Cohesionless Soils

The following were the general conclusion as to the construction of highway embankments with cohesionless/granular materials:

- The current Iowa DOT specification for highway embankment construction as it pertains to cohesionless materials is inadequate.
- Current practice does not recognize the differences in behavior among cohesionless materials or between cohesionless and cohesive materials.
- The standard Proctor test is an inadequate test for cohesionless materials. The bulking characteristics and maximum dry density should be determined by the Iowa modified relative density test. Furthermore, maximum placement moisture content must be identified at soil saturation.
- Vibratory compaction is required for adequate compaction of cohesionless materials.
- Compacted lifted thickness of up to 12 in. may be acceptable for clean cohesionless materials.
- Increasing passes of a roller does not necessarily increase density and may decrease density.
- Moisture control is essential for cohesionless materials with and appreciable amount (>15%) of fines (passing the No. 200 sieve).
- The dynamic cone penetrometer (DCP) is an adequate in situ testing tool for cohesionless materials in order to evaluate field in-place density.

Cohesive Soils

The major conclusion derived from Phase II research pertaining to cohesive soils was as follows:

- The current Iowa DOT specification for sheepsfoot roller walkout is not, for all soils, a reliable indicator of degree of compaction, adequate stability, or compaction moisture content.
- During fill placement, much of the fill material is typically very wet and compacted at high levels of saturation, which causes instability. Moreover, highly plastic materials are more likely to have high levels of saturation after compaction and consequently low shear strengths by comparison with lower plasticity clays. Field moisture control for highly plastic clays is an effective means of controlling deleterious soil properties.

- Earthwork construction processes including lift thickness and roller passes were not consistent at several embankment projects. Compacted lift thickness was measure to vary from 7 to 22 in., and roller passes average about four to five passes.
- Reduction of clod size and aeration of wet soils by disking, which are currently a part of the Iowa DOT specifications, are rarely enforced in the field. Thus, a renewed emphasis should be placed on educating earthwork contractors and Iowa DOT field personnel about the necessity of disking.
- The DCP was found to be a valuable tool for quality control. From penetrations up to 39 in., plots of soil strength and lift thickness were generated. Furthermore, by testing for soil stability, shortcomings from density tests (density gradients) were avoided. It is evident from the field data that stability and shear resistance are measure by the DCP are increased by compaction and reduced by high moisture contents. The DCP, however does not appear to correlate well to moisture/density measurements.
- Through experiments involving different rolling patterns and equipment it was found that a rubber-tired load scraper (90 psi tire pressure) effectively compacts loose lifts of heavy fat clay up to 14 in.. With the correct tire pressure and because of large contact area, rubber-tired rollers are effective at achieving high surface density, achieving density in underlying layers, and locating weak spots below the surface. However in spite of the fact that rubber-tired rolling results appear favorable; the method will have to be assessed for efficiency in the future.
- Based only on appearance and feel, predicting the physical performance and judging the suitability of cohesive soils for embankment construction are difficult. The proposed Iowa Empirical Classification (EPC) chart better takes into account complex engineering properties such as swell potential, frost susceptibility, and group index weighting. Also, the EPC will facilitate design and field identification of soil because it only requires testing of Atterberg limits and percent passing the No. 200 sieve, which can be done relatively quickly in the field.
- Cone penetration test (CPT) shear strength measurements showed that combined overly thick lifts observed during construction and wet highly saturated soil resulted in extremely variable embankment shear strength with depth. Differential settlement would be anticipated based upon these results.

Phase II Recommendations

Short term:

1. Adopt proposed soils design and construction specifications
   - Iowa EPC chart A (granular soils)
   - Iowa EPC chart B (fine and coarse-grained plastic soils)
2. Adopt soil specific moisture control requirements
   - Iowa MCC A and B
   - Iowa modified relative density
3. Adopt DCP index and test strip construction specifications
   - Minimum 50 x 500 ft. area, 30 in. deep
   - Approximately 5-8 test strips per project
   - Guidelines for minimum DCP index requirements:

a. Granular Soils
    - Select ≤ 35 mm/blow
    - Suitable ≤ 45 mm/blow
b. Fine and coarse-grained plastic soils
    - Select ≤ 75 mm/blow
    - Suitable ≤ 85 mm/blow
    - Unsuitable ≤ 95mm/blow

4. Develop and initiate soil certification program for Iowa DOT personnel
    - Soil classification (liquid limit, plasticity index, and grain size analysis)
    - Lab testing (standard Proctor compaction and Iowa modified relative density)
5. Design and let a pilot project based on proposed soils design and construction specifications

Long term:

1. Develop training program and workshops for field personnel
    - Identification of soils and classification
    - Soil compaction basics
    - Certification programs through the Iowa DOT for design engineers, field personnel, and contractors.
2. Establish quality control/quality acceptance program
    - Ensure embankment materials are properly identified and placed
    - Ensure embankment soils are properly moisture conditioned and compacted

Phase III Summary

Phase III research was initiated to develop a Quality Management Earthwork (QM-E) program and to test this program on a full-scale pilot project. The pilot project was used to design, field test, and refine the proposed soil classification system and construction specifications; as well as to evaluate the feasibility of implementing a contractor QC and Iowa DOT QA program for earthwork grading in the future.

Tables 1 and 2 summarize the type of soil and values of field data collected from the pilot project.

Table 1. Soil properties from Phase III pilot project

Soil ID	AASHTO Classification	Passing No. 200 (%)	LL	PI	Opt. MC (%)	Standard Proctor Max Dry Unit Weight (kN/m^3)
B-Suitable	A-7-6 (16)	70.0	40.6	26.9	15.9	17.50
B-Select	A-7-6 (12)	68.6	37.9	20	15.6	17.71
D-Suitable	A-7-6 (7)	62.2	28.9	15.6	12.9	18.21
M-Select	A-3	2.0	NA	NA	NA	Relative Density

Table 2. Statistical summary of field data collected at Phase III pilot project

	DCP Index (mm/blow) *for 300 mm lift*			**Variation in DCP Index (mm/blow)**			**Relative Compaction (%)**			**Relative Moisture Content (%)**		
Soil ID	μ	σ	c_v (%)	μ	σ	c_v (%)	μ	σ	c_v (%)*	μ	σ	c_v (%)*
B Suitable	47.9	16.3	34.0	17.5	12.0	68.3	100.6	3.3	0.9	1.1	1.4	10.2
B Select	56.7	24.9	44.0	20.5	14.1	68.6	97.2	3.5	1.3	1.6	1.7	9.9
D Suitable	52.3	30.0	57.3	27.2	27.0	99.0	96.0	2.9	3.0	2.6	1.2	7.4
M Select	48.5	19.5	40.2	17.2	10.9	63.6	86.9[a]	12.3	2.7	-	-	-

*Based upon non-normalized values
Note a: relative density

Based upon the results of Phase III research, the following conclusions were reached:

1. The new proposed soil classification system worked well during the Iowa DOT soils design phase. The only modification required was the addition of color and carbon content determination for topsoil identification. The system also worked well in the field during construction.
2. The training and certification program materials developed for the project were sufficient and required minor adjustments. The one-week (five-day) training period appears adequate. The DMACC laboratory and training facilities and Iowa DOT supplied equipment are good and will become better with continued development.
3. The contractor QC and Iowa DOT QA special provisions developed jointly by Iowa DOT and ISU personnel worked well for the project and required minor modifications during construction. The ability of Iowa DOT personnel to conduct the required QA testing was hampered by state budget reductions and project manpower shortage.
4. Proposed and provided field equipment and laboratory facilities for the project were adequate and generally very good.
5. Surficial density testing was shown not to be adequate for indicating the uniformity and stability of embankment soils. The DCP test was able to detect non-uniformity, and development of "Oreo cookie" effects requiring corrective action. On this project "Oreo cookies" were likely a result of thick lifts and not variable compaction effort or moisture content.
6. One of the primary questions for Phase III was whether or not the quality of the subgrade was improved. The project involved a "quality conscious" contractor, well-qualified and experience Iowa DOT field personnel, a good QC consultant technician, and some of the best soils in the state. In the authors' opinion quality was improved for this project, as evidenced by the DCP test data and the amount of disking required to reduce the moisture content within the acceptable control limits. Undoubtedly even greater improvements could be expected on other projects under less ideal circumstances. Most importantly the quality is now quantified and documented.

7. The Class 10 and select backfill costs per cubic meter for this project were lower than previous years' contract process. This is possible due to the generally good quality project soils.
8. The QM-E QC costs added $0.03 per cubic meter, or 1.6% to the total cost of this project. Disking added about $0.04 per cubic meter, or 1.7% to the total project costs. In our opinion, this is a very nominal cost increase to improve quality. Future contractor innovations have the potential for negating this increase.

Phase III Recommendations

1. Begin a three- to four-year phase-in of the new soils design classification system training and classification program and QM-E special provisions. It is suggested that one to two projects be designed and let per year in various construction residences involving a variety of soil types.
2. Continue training and certification of contractor, Iowa DOT, and consultant personnel around the state.
3. Encourage counties to consider adopting these embankment construction specifications following phase-in by the state.

Phase IV Introduction

The results of Phase I, II, and III research indicated that the proposed QM-E program, Grading technician level I certification, and lab training equipment were adequate but needed some slight modifications, especially for "unsuitable soils." A full-scale pilot project in unsuitable soils was initiated to address these concerns. The primary tasks for Phase IV research consisted of the following:

1. Review of the QC/QA practices of other state departments of transportation (DOTs) and agencies for potential applications in the proposed QM-E program
2. Demonstrate the QM-E program on ~~a~~ full-scale pilot projects in unsuitable soils.
3. Train and certify additional contractor and Iowa DOT field personnel for Grading Certification Level I.
4. Refine the QM-E program.
5. Improve data collection, management, and report generation for QC/QA operations.

Research was conducted at the Highway 34 Bypass earthwork construction project in Fairfield, Iowa, from May to December 2006. In addition to the pilot project, field testing at several projects in Iowa occurred from 2003 to 2004. The results and findings from these projects are also described in this report.

REVIEW OF EMBANKMENT CONSTRUCTION SPECIFICATIONS IN THE MIDWEST

The earthwork construction specifications for several Midwestern state DOTs and agencies were reviewed. A brief overview of the Iowa DOT's embankment construction specification is given, and then the practices of other DOTs and agencies are briefly discussed.

Iowa DOT Specification

Fill material for embankment construction is classified according to the Iowa DOT material classification criteria (Table 3). The borrow material is generally classified into one of three categories based upon data from common soil classification tests (Iowa Specification 2102.06). The Iowa DOT construction specifications states explicit rules for the use of these material in the construction of roadways and embankments; and the material is compacted using one of three methods.

Table 3. Iowa DOT borrow material classification

Soil type	Grade	Classification criteria
Cohesive	Select	• 45% > passing No. 200 • 110 pcf (1750 kg/m^3) ≤ dry density (AASHTO T99 Proctor density) • Plasticity index > 10 • A-6 or A-7-6 soils of glacial origin
	Suitable	• 95 pcf (1500 kg/m^3) ≤ dry density (AASHTO T99 Proctor density) • AASHTO M 145-91 group index ≤ 30
	Unsuitable	• Soils not meeting above criteria (see Iowa DOT Specification 2102.6 for uses)
Cohesionless	Select	• 15% > passing No. 200 • 110 pcf (1750 kg/m^3) ≤ dry density (AASHTO T99 Proctor density) • Plasticity index ≤ 3 • A-1, A-2, or A-3 (0)
	Suitable	• 95 pcf (1500 kg/m^3) ≤ dry density (AASHTO T99 Proctor density) • AASHTO M 145-91 group index ≤ 30

Compaction by Roller Walkout Method

For this method, the material is compacted a minimum of one roller pass per inch of lift thickness and compaction is continued until the roller tamping feet penetration does not exceed more than 3 in. for an 8-in. layer or 33% of the layer. A slight variant of this method specifies the number of disking and roller passes required for each lift.

Compaction with Moisture and Density Control

Compaction with moisture and density control is another method for preparation of embankment fill. This method requires that fill be placed or conditioned within the specified moisture limits and lifts be compacted to 95% maximum density determined in accordance with Iowa DOT Materials Laboratory Test Method 103.

Compaction with Moisture Control

Compaction with moisture control is yet another method allowed for compaction control of embankment fill. The fill is placed or conditioned within the specified moisture control limits and compacted using the "walkout" technique described above.

Compaction Control in Other Midwestern States

The compaction control specifications of Midwestern states including Illinois, Indiana, Kansas, Missouri, Minnesota, Nebraska, South Dakota, and Wisconsin, were reviewed. The key elements of each specification are shown in Table 4. The requirements of each specification have been largely developed based upon local experience and conditions, and thus caution is required in implementing any of the above methods.

Innovative Construction Specifications in the United States

There are a number of innovative earthwork construction specifications that are being used throughout the country and have been identified by the Federal Highway Administration. The following is a brief summary of some of the applicable specifications.

The Wisconsin Department of Transportation (WisDOT) has developed a quality management plan (QMP) for embankment construction. The QMP utilizes contractor QC and DOT QA testing to verify quality of compacted fill. Control charts are utilized to plot test data, and the contractor is required to take corrective action when the four-point moving average of sequential test data exceeds the control limits set within the QMP or when two consecutive 4 point averages fall within a 'warning band'. Other than the use of "warning bands," the WisDOT QMP and the Iowa DOT QM-E, described throughout this paper, are similar.

The Florida Department of Transportation (FDOT) earthwork specification (120-10.1.4, 2004) contains a unique clause in its use of the specific density procedure that requires "the engineer" to perform verification testing when QC computed dry densities exceed 105%. If verification test results in a density equal to or greater than 105%, "the engineer will investigate compaction methods; examine applicable standard Proctor maximum density and material description."

Table 4. Summary of compaction control methods of Midwestern states for embankment

State Earthwork Specification	Compaction Quality Control Method	Type of Embankment	Compaction Requirements	Loose Lift Thickness	Moisture Control Requirements	Alternative Methods	Alternative Methods
Illinois (2007)	Specified Density	Embankment less than 3-ft in height	Upper 1 1/2 ft compacted to 95% First lift for embankments greater than 1 1/2 ft to 90% with remainder 95%	8-in.	Top 2 ft. not more than 120% optimum Such that adequate compaction is achieved	NA	NA
		Embankment greater than 3-ft in height	Lower 1/3 of the embankment to 90% First lift above lower 1/3 to 93% with remainder to 95%				
Indiana (2006)	Specified Density	All embankments	95% relative compaction	8-in.	-2% to +1% Opt MC. -3% to 0% Opt.MC. for loessial soils	Compaction without density control for material not easily compacted	Proofrolling when specified
Iowa (2006)	Roller walkout	All embankments, when specified	Compacted a minimum of 1 pass per 1-in of loose fill until the tamping feet penetrate 3-in or less into an 8-in lift.	Variable, such that walk out is achieved	Variable such that walk out is achieved	Compaction with moisture control	Quality Management Earthwork (QM-E)
	Specified Density	All embankments, when specified	95% relative compaction	Variable, such that adequate compaction is achieved	Variable such that adequate compaction is achieved		
Kansas (1990)	Specified Density	All embankments	As specified within construction plans	8-in.	Specified on construction plans unless approved by Engineer	NA	NA
Missouri (1999)	Specified Density	Embankments more than 50-ft below the top of finished subgrade, within 100-ft of structures, or within 18-in. fo subgrade	95% relative compaction	8-in.	Such that adequate compaction is achieved 0 to +3% Opt. MC for loessial soils	NA	NA
		All other embankments unless otherwise noted	90% relative compaction				
Minnesota (2005)	Specified Density	Upper 3-ft. of embankment or portions adjacent to structures	100% relative compaction	8-in.	65-102% optimum moisture content	Quality Compaction: compaction until no evidence of further consolidation to the satisfaction of the engineer	DCP for granular materials
		Below upper 3-ft and not adjacent to structures	95% relative compaction	12-in[a]	65-115% optimum moisture content		
Nebraska (2007)	Method	Class 1	Each lift minimum of 1 pass from 10 ton crawler tractor	12-in[b]	No explicit requirement	NA	NA
	Method	Class 2	Each lift minimum of 2 passes plus hauling distributed over the entire area equally.	8-in	No explicit requirement		
	Specified Density	Class 3	Requirements shown on plans	8-in	Requirments shown on plans		
South Dakota (2006)	Specified Density	All embankments	95% relative compaction	8-in[c]	If Opt. MC<15%: +/- 4% Opt MC	NA	NA
			97% relative compaction for material at the toe of a berm slope extending to a line 100-ft from the bridge		If Opt. MC>15%: -4 to +6 Opt. MC[d]		
Wisconsin (2006)	Specified Density	Embankments less than or equal to 6-ft high or within 200-ft of a bridge abutment	95% relative compaction	8-in.	Such that the material does not rut excessively and such that the material can be compacted properly	Quality Management Plan (QMP)	NA
		Embankments greater than 6-ft	Material 6-ft or less below the finished grade to 95% Material more than 6-ft below finished grade to 90%				

Notes:
a - Refer to Section 2105.3 for exceptions
b - 6-in lift if adjacent to structures
c - May be greater when specified density is achieved for entire depth
d - Optimum moisture content cannot exceed 25% for material at the toe of a berm extending to a line 100-ft from the bridge end

The Minnesota Department of Transportation (Mn/DOT) has recently begun implementation of an alternative to the specified density method using the DCP. The specification utilizes measurements from this field device to determine whether fill compaction has been acceptably achieved based upon set control limits that are a function of moisture and particle size distribution of the soil. Currently this specification is only applicable to granular or cohesionless soils. However, additional research was conducted on behalf of Mn/DOT by the University of Minnesota to investigate the effects of moisture and density on a variety of in situ testing devices in cohesive soil (Swenson 2006).

TEST METHODS

The research team conducted numerous field and laboratory tests throughout this research project. The following section summarizes the test methods that were used and notes deviations from the applicable ASTM standards. A new system, Geotechnical Remote Acquisition of Data System (G-RAD), for recording and managing field test data electronically is also discussed.

Field Testing Methods

ISU conducted independent field investigations at a series of earthwork construction projects across Iowa throughout the course of this research. The field testing was conducted in accordance with applicable ASTM standards for:

- DCP testing (ASTM D 6951-03)
- In situ moisture content and density determination with nuclear gauge (ASTM D 3017 and ASTM D 2922)
- In situ density determination with drive cylinder (ASTM D 2937)
- Thin walled tube sampling of soil for geotechnical testing (ASTM 1587)

Dynamic Cone Penetrometer

DCP tests are conducted by driving a 20 mm diameter, 60° cone into the ground under the force of an 8 kg hammer being dropped 575 mm (Figure 1).

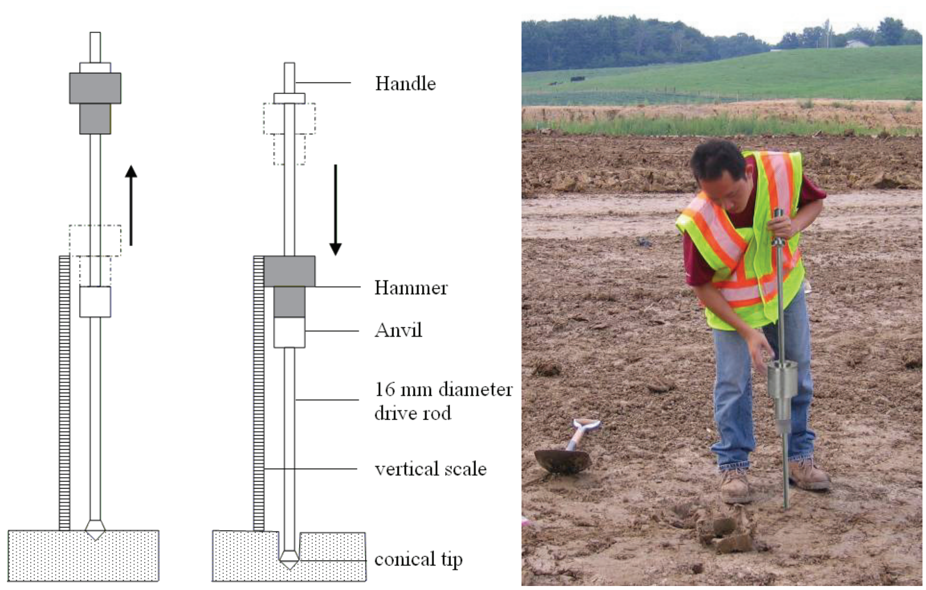

Figure 1. Dynamic cone penetrometer

DCP measurements are reported in millimeters of penetration divided by the number of hammer blows and are referred to as DCP indices. The DCP index is recorded over a desired test layer for each test, in the case of the pilot project this was set at one lift thickness (~200 to 300 mm). The

DCP index is inversely related to the penetration resistance and gives an indication of vertical uniformity. DCP index has been correlated to a number of strength related parameters. The most well established correlations are with California Bearing Ratio (CBR) values. The ASTM specification D 6951-03 has adopted the following correlations for estimating CBR from DCP measurements:

$$CBR = \frac{1}{0.002871(DCP)} \qquad \text{(CH soils)}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$CBR = \frac{1}{((0.017019)(DCP))^2} \qquad \text{(CL soil for CBR<10)}\ldots\ldots\ldots(2)$$

$$CBR = \frac{292}{DCP^{1.12}} \qquad \text{(All other soils)}\ldots\ldots\ldots\ldots\ldots..(3)$$

It is often convenient to reduce the data to a single average DCP index. There are numerous ways to attain an average DCP index for a given profile. The method used by ISU varies slightly from the ASTM standard's methods, instead using a weighted average method calculated in accordance with

$$\text{Average DCP Index} = \frac{1}{H}\sum_{i=1}^{n} d_i^{\,2} \qquad (4)$$

where n is the total number of blows, d_i is the penetration distance for the i^{th} blow, and H is the depth of the test layer.

Figure 2 shows two plots of DCP index vs. depth for two different sets of hypothetical DCP readings. The average DCP index is calculated in accordance with equation 4. Graphically this can be represented as the area to the left of the DCP profile shaded in gray, as shown in Figure 2. For both profiles A and B in Figure 2, the average DCP index for a test layer of 400 mm is 49 mm/blow.

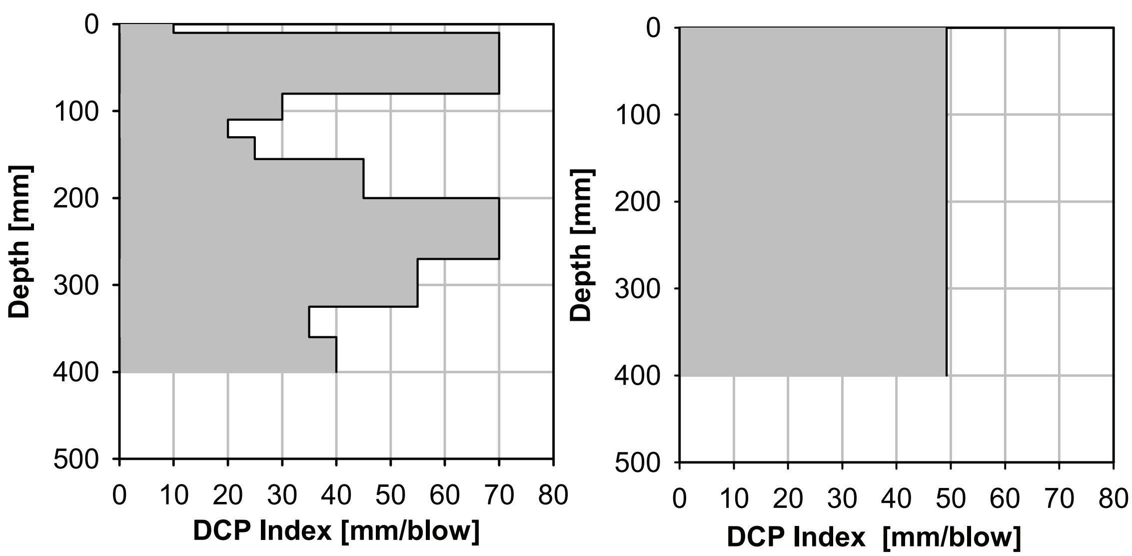

Figure 2. DCP depth profile A (right) and B (left)

In addition to determining an average DCP index for each profile using a slightly different method, a uniformity value is also determined. This parameter was developed by ISU to capture the vertical uniformity of a profile. By reducing a DCP profile to a single average DCP index there is a great deal of information lost. The DCP profiles shown in Figure 2 are very different; however the average DCP index for a 400 mm lift is the same. The uniformity or variation in DCP index for a given profile is determined by

$$\text{Variation in DCP index} = \frac{1}{H}\sum_{i=2}^{n}\left|d_i - d_{i-1}\right| \cdot d_{i-1} \qquad (5)$$

where n is the total number of blows, d_i is the penetration distance for the i^{th} blow, and H is the depth of the desired test layer. Figure 3 shows an example of the uniformity or variation in DCP index vs. depth for profile A in Figure 2.

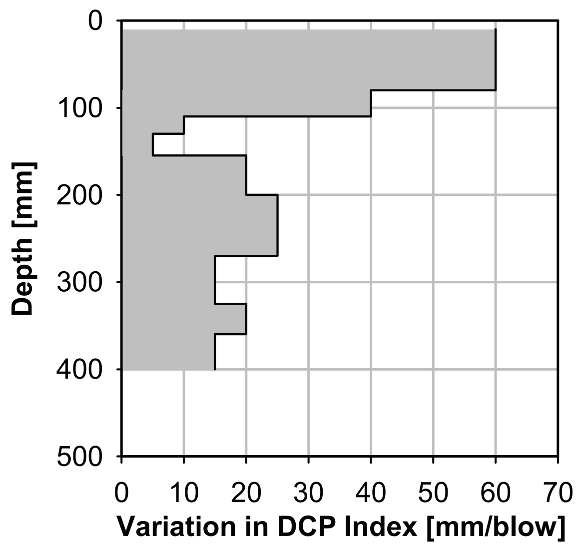

Figure 3. Uniformity or variation in DCP index depth profile

The variation in DCP index for this profile was 26 mm/blow over a test layer of 400 mm. The uniformity or variation in DCP index parameter was developed specifically to identify the "Oreo cookie" effect, whereby lifts of material have alternating layers of hard and soft soil that often result from overly thick lift compaction. Spatial subgrade non-uniformity has been shown to affect the fatigue life of PCC pavements and more research is required to better establish the use of this parameter for subgrade quality control.

Nuclear Moisture-Density Gauge

A Humboldt HS-5001B122 nuclear moisture-density gauge, shown in Figure 4, was used in accordance with ASTM D 3017 and ASTM 2922 to obtain measurements of soil dry unit weight and moisture content. The gauge was used in direct transmission mode and the average of two measurements was recorded as the in situ dry unit weight and moisture content.

Figure 4. Humboldt nuclear moisture-density gauge

Drive-Cylinder

Moisture and density measurements were also obtained using a drive-cylinder and thin walled tubes in accordance with ASTM 2937. Three-inch diameter and four-inch diameter tubes were used for sampling. Moisture samples were obtained from the center of each tube and determined in accordance with ASTM D2216.

Shelby Tube Sampling

Undisturbed samples of soil were obtained using a hydraulic drill rig and three-inch diameter thin walled Shelby tubes (Figure 5). The sampling methods utilized were in accordance with ASTM D 1587. Samples obtained from the field were sealed and returned to the laboratory for classification and testing.

Figure 5. Shelby tube soil sampling in the field (right) and sample extrusion (right)

Laboratory Testing

Soil Index Properties

Particle-size analysis was conducted in accordance with ASTM D422-63(2002). The coarse grained analysis was performed on samples of approximately 2000 g of air dried soil. Material retained on the No. 10 sieve was washed and oven dried prior to sieving. Fine-grained analysis was conducted using the hydrometer method on approximately 60 g air dried soil, passed through the No. 10 sieve. Following the completion of the hydrometer test, the material was washed through a No. 200 sieve and oven dried prior to sieving.

Atterberg limit testing was conducted in accordance with ASTM D4318-05 using the “wet preparation” method. Liquid limit tests were performed using the multipoint method.

Utilizing the results of the above testing, each sample was classified using the AASTHO and Iowa DOT classification systems.

The specific gravity of each sample was also determined in accordance with ASTM 854-06 on oven-dried samples.

Compaction Characteristics

The moisture-dry unit weight relationships for samples were determined in accordance with ASTM D698. The appropriate method was chosen based upon the grain-size distributions for each sample. In most cases, method A was acceptable. The tests were performed for a minimum of three different moisture contents and the optimum moisture-density characteristics were obtained based upon hand generated curves that were fit to the data.

Soil Strength Testing

Unconfined compressive strength testing was conducted on undisturbed samples obtained from three-inch diameter Shelby tubes in accordance with ASTM D2166-06.

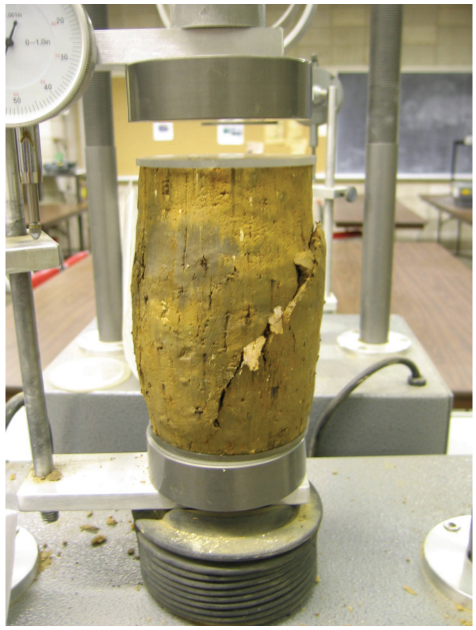

Figure 6. Unconfined compressive strength testing

CBR tests were also conducted on remolded, unsoaked samples over a range of moisture contents, in accordance with ASTM 1883-05.

QC/QA Data Collection and Management

The collection and management of QC/QA data is one of the most challenging aspects of implementing construction specifications that rely on in situ testing devices, like the DCP. These types of devices tend to provide results in a fraction of the time of conventional density and moisture testing, however they tend to have unique data processing requirements that make them slightly more cumbersome to implement. For this reason, researchers at Iowa State University have developed a personal digital assistant (PDA) software that can be used improve and increase the efficiency of DCP testing. This system is called G-RAD. G-RAD is a compilation of data collection and processing programs that can be placed on a pocket PC to use in field data collection and processing. G-RAD also has supporting desktop spreadsheets that can be used at an office.

G-RAD Overview

G-RAD consists of a package of programs which include: G-RAD, G-Control, and Area calculator, all which can be operated on a desktop or pocket PC. There is also a GPS attachment for the pocket PC which allows for GIS style data collection. Figure 7 shows a pocket PC with the GPS attachment.

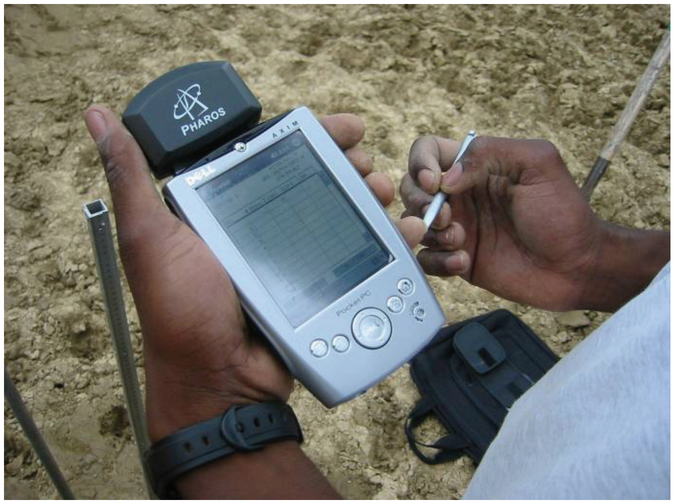

Figure 7. G-RAD system with GPS attachment on a Dell pocket PC

G-Control

G-Control is a program that can collect GPS coordinates, DCP index, variation in DCP index, moisture, density, and lift thickness for each test location. When a number of the tests results have been collected, control charts of each engineering parameter can be displayed to help the inspector make decisions for quality control. The data recorded can be saved for later viewing as well.

Area Calculator

Area calculator is a program that uses GPS coordinates of corners of a given polygon taken in directional sequence, without crossing lines, to calculate the area of that polygon. To calculate an estimate of the volume of material moved, an average lift thickness can be added to calculate the volume. This program is useful in estimating the number of tests that need to be performed based on the size of the area being tested and the volume of material being placed.

G-RAD Spreadsheets

In addition to the control charts produced on the pocket PC, regular PC version of G-Control was developed. Using a spread sheet program, for example Microsoft Excel, test data can be entered and control charts produced. This is a tool that can be used for quality control from the office. The spread sheets produce charts for DCP data, moisture data, density data, and lift thickness data.

DCP Data

The data entered into this spreadsheet is the GPS coordinates where available, the mean DCP data and the mean change in DCP from each test point. A moving average of the mean DCP data is then calculated. Control parameters are the maximum DCP index values for a required minimum strength required and the maximum change in mean DCP values to control the uniformity.

Figure 8 shows the spreadsheet for data entry of the mean DCP and the control limits for mean DCP and for the change in mean DCP. The program automatically creates control charts for strength and uniformity as shown in Figure 9 and Figure 10. The charts produced can be used as visual aids in the decision making process for quality control.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1																
2		Strength		Uniformity		QC	Four Point	QA				QC	Four Point	QA		
3	Soil					Mean	Moving Avg					Mean	Moving Avg		Suitable/	
4		Location	Latitude	Longitude	Elevation	dcp index	dcp index		Unsuitable	Suitable	select	change	change		Unsuitable	Select
5		0							95	85	75				40	35
6		1				17.2			95	85	75	6.5			40	35
7		2				13.9			95	85	75	8.8			40	35
8		3				28.0			95	85	75	5.8			40	35
9		4				29.3	22.1		95	85	75	5.3	6.6	5.8	40	35
10		5				28.4	24.9		95	85	75	3.9	5.9		40	35
11		6				19.8	26.4	24.0	95	85	75	3.5	4.6		40	35
12		7				12.4	22.5		95	85	75	2.9	3.9		40	35
13		8				13.0	18.4		95	85	75	3.9	3.5		40	35
14		9				13.7	14.8		95	85	75	2.2	3.1		40	35
15		10				12.9	13.0		95	85	75	3.7	3.2		40	35
16		11				11.6	12.8	4.0	95	85	75	2.9	3.2	5.2	40	35
17		12				14.5	13.2		95	85	75	4.3	3.3		40	35
18		13				13.9	13.2	11.0	95	85	75	2.9	3.5		40	35
19		14				15.0	13.8		95	85	75	3.4	3.4		40	35
20		15				15.2	14.7		95	85	75	3.7	3.6		40	35
21		16				14.0	14.5		95	85	75	2.3	3.1		40	35
22		17				12.1	14.1		95	85	75	1.7	2.8		40	35
23		18				12.4	13.4		95	85	75	2.0	2.4		40	35
24		19				11.5	12.5		95	85	75	2.5	2.1		40	35
25		20				13.3	12.3	48.0	95	85	75	3.3	2.4	5.6	40	35
26		21				14.0	12.8		95	85	75	2.7	2.6		40	35
27		22				15.4	13.6		95	85	75	5.7	3.5		40	35
28		23				14.3	14.3		95	85	75	6.8	4.6		40	35
29		24				14.1	14.5		95	85	75	2.0	4.3		40	35
30		25				28.3	18.0		95	85	75	12.1	6.6		40	35
31		28							95	85	75				40	35

Strength / Uniformity / Strength&uniformity / Sheet2 / Sheet3

Figure 8. Data entry for strength and uniformity

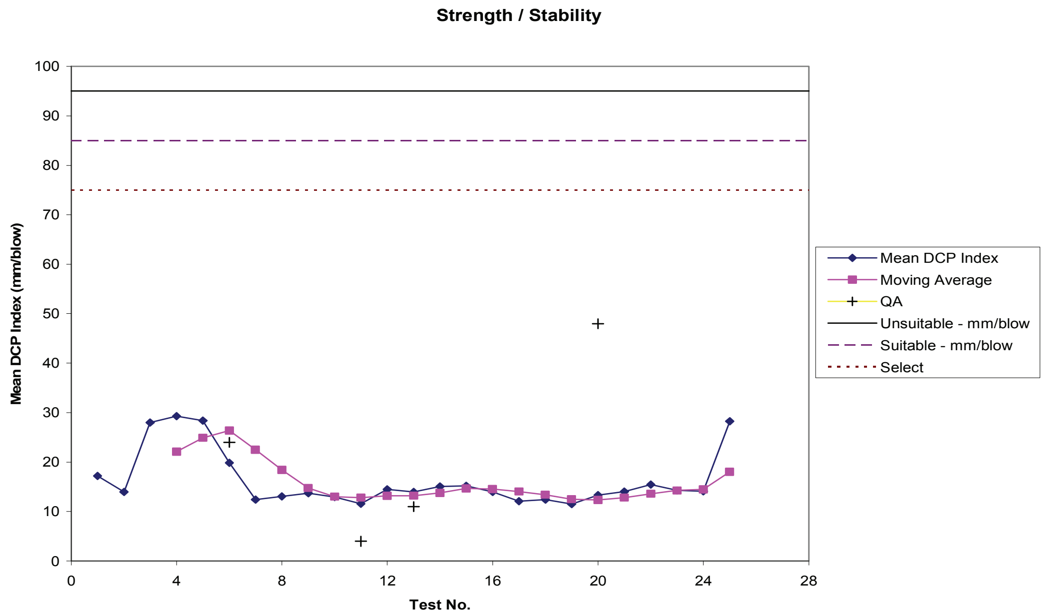

Figure 9. Control chart for strength/stability

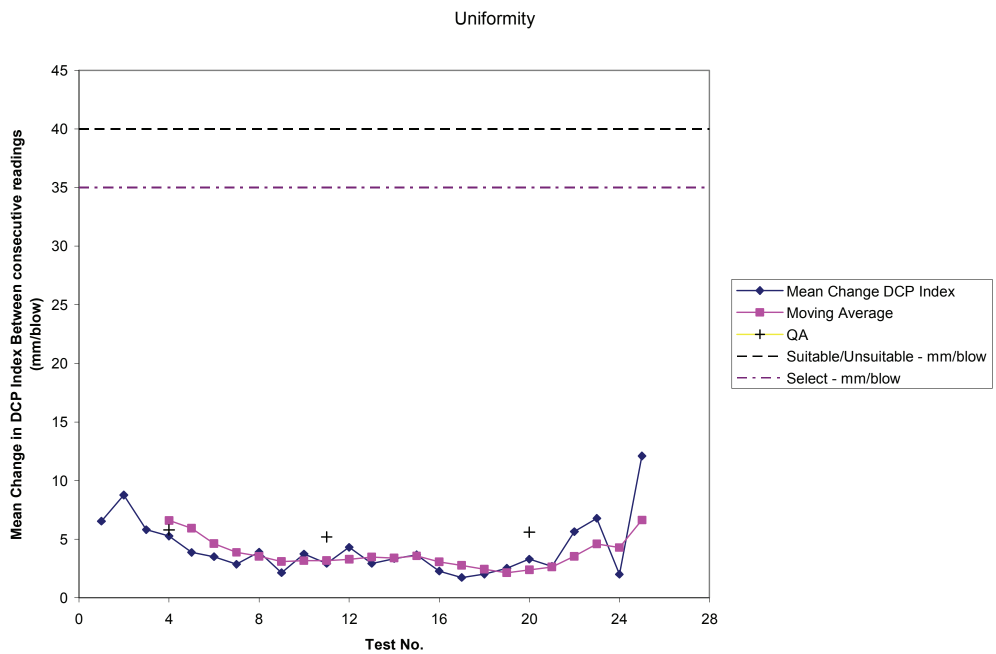

Figure 10. Control chart for uniformity

Moisture Data

Moisture content data is entered into this spreadsheet for every test point. The program then automatically determines the four-point moving average for the data. Control limits for the moisture content are then entered. Figure 11 shows the data entry spreadsheet with the control limits for the moisture content, and Figure 12 shows an example control chart.

	A	B	C	D	E	F	G	H	I	J
1										
2					-	2	+	3		
3			QC	Four Point		Lower		Upper		
4				Moving Avg		Control	Optimum	Control		
5		Location	% M	%m	QA	Limit	%M	Limit		
6		0				14.3	16.3	19.3		Moisture Control
7		1	16.00			14.3	16.3	19.3		
8		2	17.40			14.3	16.3	19.3		
9		3	16.05			14.3	16.3	19.3		
10		4	16.05	16.38	17.55	14.3	16.3	19.3		
11		5	17.55	16.76		14.3	16.3	19.3		
12		6	16.10	16.44		14.3	16.3	19.3		
13		7	15.40	16.28		14.3	16.3	19.3		
14		8	14.80	15.96		14.3	16.3	19.3		
15		9	14.85	15.29		14.3	16.3	19.3		
16		10	13.40	14.61		14.3	16.3	19.3		
17		11	13.90	14.24		14.3	16.3	19.3		
18		12	15.55	14.43	18.50	14.3	16.3	19.3		
19		13	15.70	14.64		14.3	16.3	19.3		
20		14	16.40	15.39		14.3	16.3	19.3		
21		15	15.55	15.80		14.3	16.3	19.3		
22		16	15.50	15.79		14.3	16.3	19.3		
23		17	13.65	15.28		14.3	16.3	19.3		
24		18	13.65	14.59		14.3	16.3	19.3		
25		19	16.20	14.75		14.3	16.3	19.3		
26		20	15.85	14.84	14.10	14.3	16.3	19.3		
27		21	16.95	15.66		14.3	16.3	19.3		
28		22	14.85	15.96		14.3	16.3	19.3		
29		23	16.05	15.93		14.3	16.3	19.3		
30		24	13.90	15.44		14.3	16.3	19.3		
31		25	14.80	14.90		14.3	16.3	19.3		
32		[illegible]				14.3	16.3	19.3		

Sheet2 Sheet3

Figure 11 . Data entry for moisture control

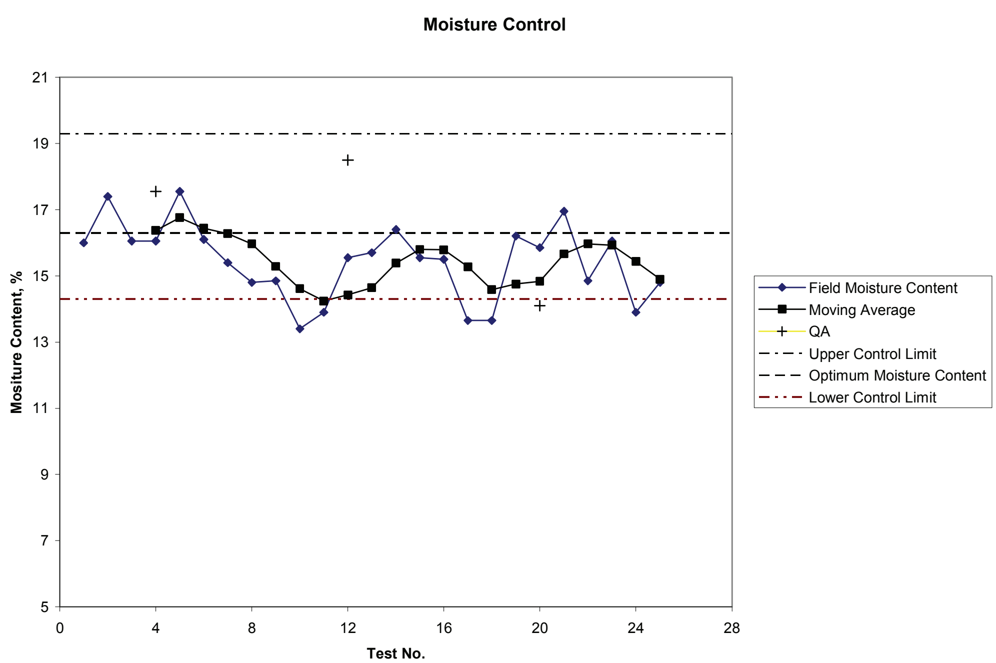

Figure 12. Control chart for moisture content

Density Data

Density data is entered into this spreadsheet for each test point. The program automatically determines the four-point moving average for the data. Control limits entered for the density are as follows: maximum density from the Proctor test for the soil tested, and minimum relative compaction required in percent. Figure 13 shows the data entry spreadsheet with the control limits for the density, and Figure 14 shows an example control chart.

Control Rel. Compaction= 95 %
Maximum density = 112 lb/ft³

Density Control

Location	QC Dry Density lb/ft³	Four Point Moving Avg lb/ft³	QA	Minimum Density
0				106.4
1	103.0			106.4
2	104.0			106.4
3	107.0			106.4
4	105.0	104.8	107.5	106.4
5	108.0	106.0		106.4
6	105.6	106.4		106.4
7	106.8	106.4		106.4
8	105.9	106.6		106.4
9	102.3	105.2		106.4
10	107.0	105.5		106.4
11	110.5	106.4		106.4
12	111.2	107.8	108.5	106.4
13	106.8	108.9		106.4
14	109.0	109.4		106.4
15	106.8	108.5		106.4
16	104.0	106.7		106.4
17	106.5	106.6		106.4
18	110.5	107.0		106.4
19	105.0	106.5		106.4
20	105.9	107.0	104.1	106.4
21	107.0	107.1		106.4
22	104.9	105.7		106.4
23	106.1	106.0		106.4
24	110.9	107.2		106.4

Chart2 input Sheet3

Figure 13. Data entry for density control

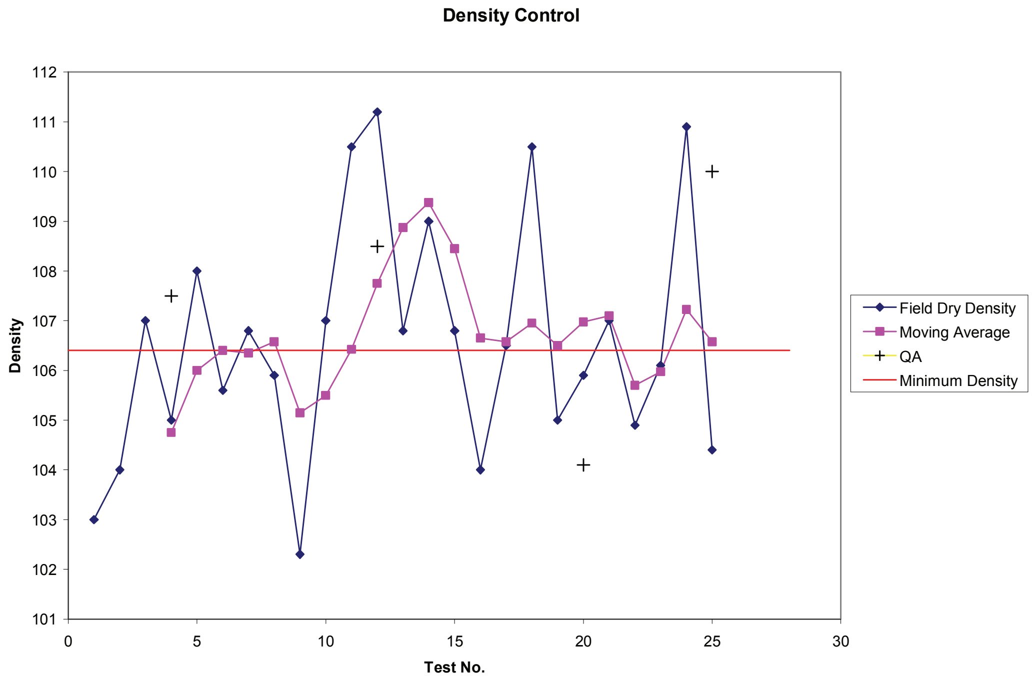

Figure 14. Control chart for density

Lift Thickness Data

Data entered for this spreadsheet is the lift thickness from each test point. From this data, a four-point moving average is calculated. Figure 15 shows the data entry spreadsheet for the lift thickness and Figure 16 shows the completed control chart.

Location	Lift (cm)	4-point Moving Avg	QA
0			
1	15.20		
2	20.30		
3	22.80		
4	12.70	17.75	12.75
5	15.20	17.75	
6	12.70	15.85	
7	10.20	12.70	
8	15.20	13.33	
9	12.20	12.58	
10	12.70	12.58	
11	30.50	17.65	
12	22.80	19.55	20.30
13	10.10	19.03	
14	12.70	19.03	
15	15.20	15.20	
16	25.40	15.85	
17	20.30	18.40	15.20
18	20.30	20.30	
19	15.20	20.30	
20	22.80	19.65	
21	12.70	17.75	
22	20.30	17.75	17.50
23	10.10	16.48	
24	20.30	15.85	
25	17.80	17.13	

Figure 15. Lift thickness entry screen

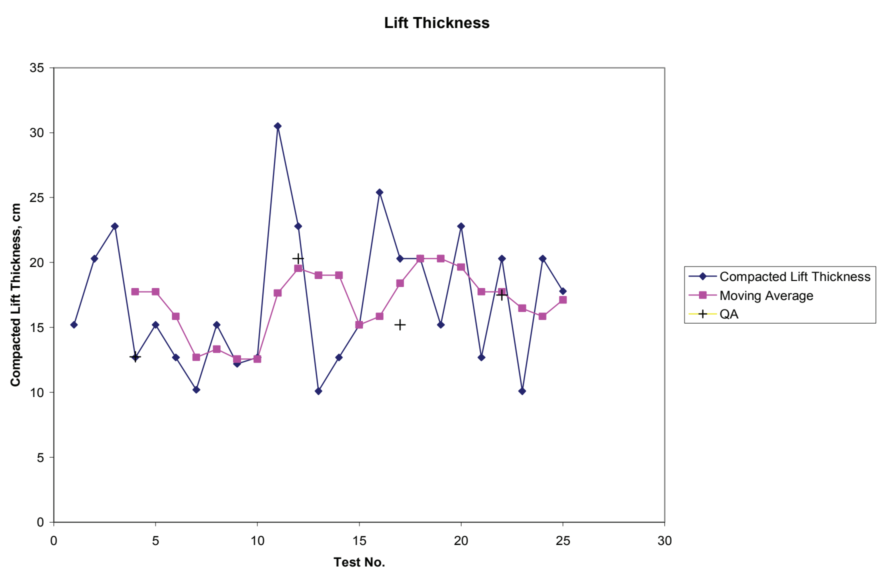

Figure 16. Plot of lift thickness

The G-RAD software package enables fast, easy and efficient analysis of DCP and other in situ test data. More importantly the software automatically manages and creates the necessary control charts for each QC/QA test parameter, dramatically reducing the time and effort required to manage and process the large amounts of data. The system also has the potential to further increase efficiency, when improved methods of in situ characterization of soil moisture content are developed.

FIELD STUDIES OF EXISTING PRACTICE

Seven field studies were conducted at highway construction projects in Iowa between June 2003 and August 2004. The goal of these studies was to document common earthwork construction practices on projects with unsuitable soil in Iowa. At each study, the construction techniques were observed and supplemented with performance and material testing, including moisture-density measurements, DCP testing, standard Proctor testing, and soil classification. Table 4 summarizes the soil index properties determined for samples taken at each field study.

Table 4. Summary of soil index properties

Project No.	Soil ID	LL	PL	PI	F_{200} (%)	Opt. dry unit wt. (kN/m^3)	Opt. MC (%)	AASHTO	USCS	Iowa DOT Grade
1	1A	27	16	11	54	18.7	11.9	A-6	CL	Select
	1B	29	13	16	56	18.8	10.8	A-6	CL	Select
2	2	35	18	16	91	16.8	17.0	A-6	CL	Select
3	3A	40	24	16	97	16.6	17.1	A-6	CL	Suitable
	3B	69	21	47	89	14.6	25.3	A-7-6	CH	Unsuitable
4	4	70	26	44	92	15.0	24.0	A-7-6	CH	Unsuitable
5	5	34	25	9	99	16.5	18.2	A-4	CL	Unsuitable
6	6	39	23	15	95	16.3	18.5	A-6	CL	Suitable

Project No. 1: Highway 34 - Batavia Bypass

This project was part of the Highway 34 Batavia bypass in Jefferson County, Iowa. Field testing was conducted on June 18, 2003.

At the engineered borrow pit, the contractor operated two excavators: a John Deere 450C LC and a Hitachi Ex 450 LC. The soil was hauled by Volvo A40 trucks and Caterpillar D400D trucks. Construction engineers operated a Caterpillar 140G grader and a Caterpillar D7H Bulldozer. For compaction, a sheepsfoot roller was used, pulled by a 7110 international tractor, as shown in Figure 17.

Figure 17. Tractor-pulled sheepsfoot roller

The recommended lift size was 203mm, with one pass per 25 mm of fill placed; however, from observation, the lift thickness varied from 305 mm to about 510 mm. The number of passes was also inconsistent, varying from 4 to 25 passes. Moisture-dry unit weight testing was conducted with a nuclear gauge at a few test locations. Table 5 below notes the results of these tests. Figures 18 and 19 show moisture/density measurements and the corresponding standard Proctor curves.

Table 5. Field data from project 1

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)
1A	1	17.8	14.6	95.1	+2.7
1A	2	17.5	18.8	93.7	+6.9
1B	1	18.1	14.6	96.1	+3.8
1B	2	18.3	14.6	97.1	+3.8

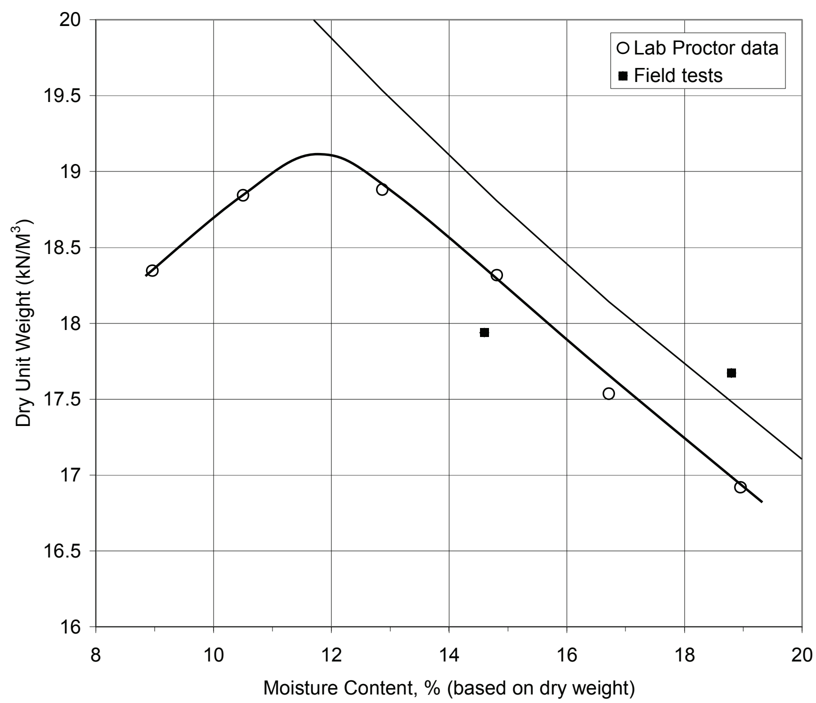

Figure 18. Unit weight-moisture plot for soil 1A

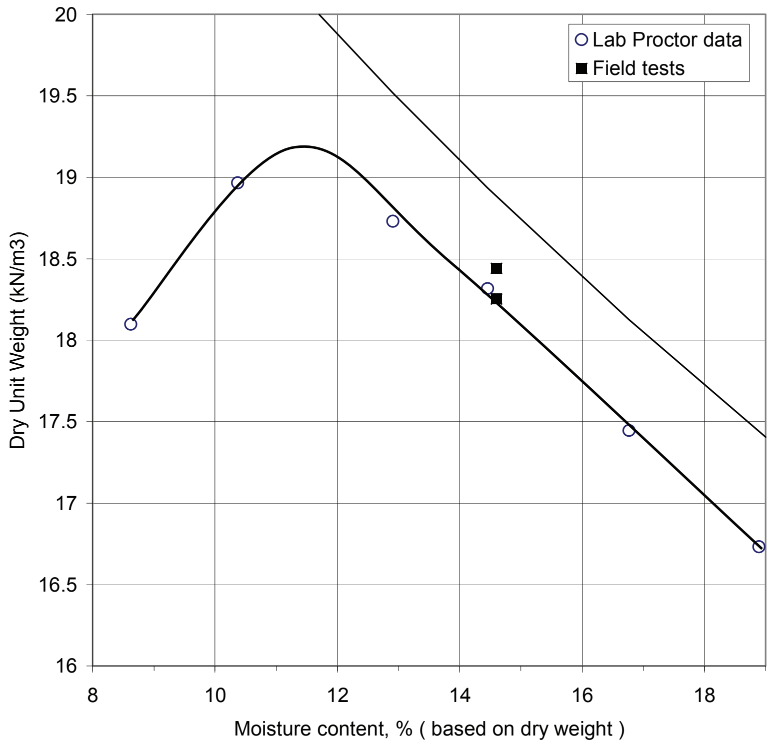

Figure 19. Unit weight-moisture plot for soil 1B

As indicated by the moisture-dry unit weight plots in Figure 18 and Figure 19, the moisture content of the fill was always wet of optimum and the resulting dry unit weights of the fill were below standard Proctor maximum dry unit weight. The average relative compaction and relative moisture contents observed at this project were 95.5% and 4.3 % above optimum, respectively.

Project No. 2: Highway 218 - South of Mt. Pleasant

This project was part of the expansion of Highway 218 south of Mt. Pleasant in Henry County, Iowa. Field testing was conducted at this site on June 18, 2003.

At this project site, the soil was hauled from the borrow sites by Caterpillar scrapers. A bulldozer was used to level the fill material before a tractor-pulled sheepsfoot roller was used to compact the soil.

Table 6. Field data from project 2

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)
2A	1	14.7	26.4	87.1	+9.4
2A	2	15.4	22.1	91.4	+5.1
2A	3	15.4	21.5	91.3	+4.5

Three randomly selected locations were tested using a nuclear density gauge. Representative samples of soil were obtained for laboratory testing. Tests results are reported in Table 6. Figure 20 documents the moisture-dry unit weight relationship for the site soil.

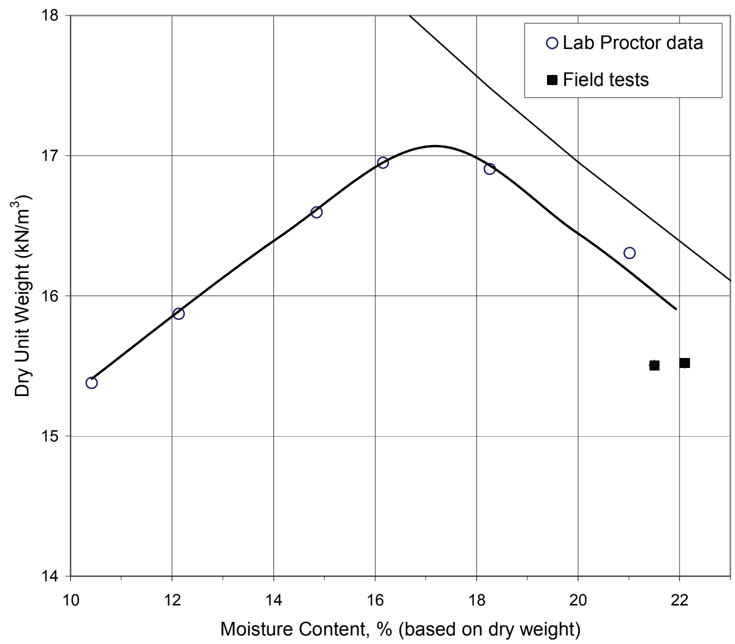

Figure 20. Unit weight-moisture plot for soil 2A

The soil was specified to be compacted using roller walkout. Roller walkout was not achieved, and the roller operator was instructed to move to a different site. As a result, there were inconsistencies in the number of roller passes. Figure 20 shows that the soil was placed wet of the optimum moisture content. The average relative compaction and relative moisture content at this project were 89.9% and 6.3 %, respectively.

Project No. 3: Highway 34 - West of Fairfield

This project was part of the expansion project of Highway 34. The section that was tested was west of Fairfield in Jefferson County, Iowa. Field testing was conducted on June 25, 2003 and July 2, 2003. The soil was hauled by scrapers. A Caterpillar D7H Bulldozer was used to spread the soil and a sheepsfoot roller was pulled by a 7110 International tractor.

Five random locations were chosen to conduct field testing. Two sets of tests were performed at the five different locations; each test set was conducted after the roller operator finished rolling the strip, before placement of the next lift. Representative samples of the material were collected for laboratory testing.

Figure 21. DCP testing conducted by ISU research team

Figure 21 shows DCP testing conducted by the ISU research team. Figure 22 shows moisture-density field measurements and the corresponding standard proctor curves. DCP test results are listed in Table 7.

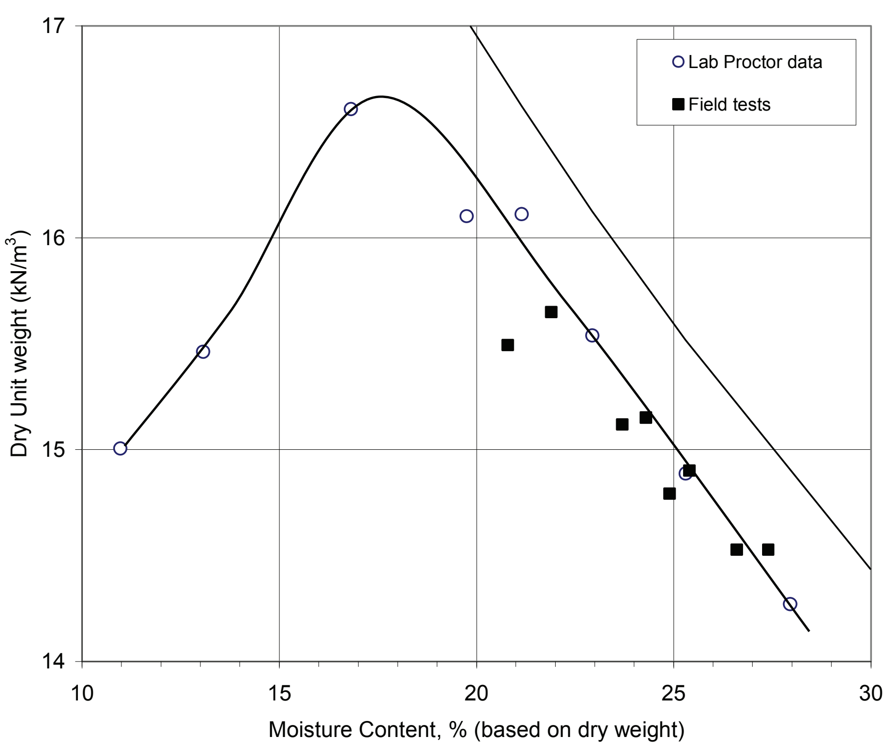

Figure 22. Unit weight-moisture plot for soil 3A

Table 7. Field data from project 3 (June 25, 2003)

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
3A	1	15.6	21.9	94.2	+4.8	74.0	41.0
3A	2	14.9	25.4	89.7	+8.3		
3A	3	15.1	23.7	91.0	+6.6		
3A	4	15.2	24.3	91.2	+7.2		

The recommended lift size was 203 mm with one roller pass per 25.4 mm of fill placed; however, it was observed that the lift thickness varied from 305 mm to 500 mm. It was also noted that most of the field tests were wet of optimum moisture content.

As previously mentioned, the project was revisited on July 2, 2003. The site featured the same equipment from the first visit. Figure 23 shows the Proctor test results of material collected on the second visit to this site.

Table 8. Field data from project 3 (July 2, 2003)

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
3B	1	14.4	29.4	98.2	+4.1	33	6
3B	2	15.4	24.1	105.3	-1.2	47	16
3B	3	15.5	23	106.1	-2.3	67	18
3B	4	15.6	22.9	106.9	-2.4	40	7
3B	5	14.2	23.5	97.2	-1.8	43	8
3B	6	15.5	22.5	105.9	-2.8	46	16
3B	7	15.1	23.4	102.9	-1.9	42	9
3B	8	15.5	23.4	105.8	-1.9	34	9
3B	9	15.7	21.9	107.4	-3.4	38	7
3B	10	15.8	22.1	108.1	-3.2	33	7

The average relative compaction and relative moisture content from testing on June 25, 2003 was 90.9% and 6.5 %, respectively, with an average DCP index of 74 mm/blow. The average relative compaction and relative moisture content from testing on July 2, 2003 was 105% and -1.6%, respectively, with an average DCP index ranging from 43 to 67 mm/blow.

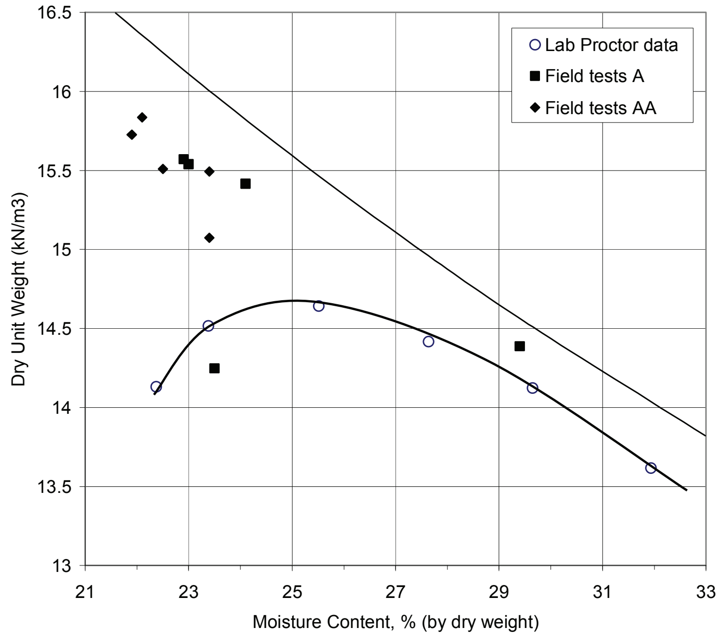

Figure 23. Unit weight-moisture plot for soil 3B

Project No. 4: Highway 218 - South of Mt. Pleasant by Salem Road

This project was part of the expansion of Highway 218 at Salem road south of Mt. Pleasant in Henry County, Iowa. Field testing was conducted on July 1, 2003.

Density and moisture content testing was performed using a nuclear gauge, in addition to DCP testing. Three sets of tests were performed at the five different locations. Testing was conducted on the final as-compacted lift. Representative samples of the material were collected for laboratory testing. The results of these tests are documented in Table 9. Figure 24 shows the field moisture-dry unit weight measurements from the nuclear gauge and corresponding standard Proctor curve.

Table 9. Field data from project 4

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
4A	A1	14.4	28.7	95.2	+4.7	33	7
4A	A2	14.4	24.2	95.4	+0.2	45	10
4A	A3	16.3	20.5	108.1	-3.5	23	4
4A	A4	14.6	28.2	96.5	+4.2	33	5
4A	A5	15.4	24.8	101.7	+0.8	31	4
4A	B1	14.1	26.6	93.7	+2.6	33	5
4A	B2	14	28.1	92.8	+4.1	29	5
4A	B3	15.1	25.6	99.8	+1.6	38	8
4A	B4	14.4	22.1	95.7	-1.9	39	9
4A	B5	13.9	27.4	92.1	+3.4	28	7
4A	C1	15.3	23.6	101.4	-0.4	34	6
4A	C2	15.7	21.6	103.8	-2.4	30	5
4A	C3	16.1	19.4	106.5	-4.6	30	5
4A	C4	15.4	20.5	108.6	-3.5	44	10
4A	C5	15.5	20.8	102.4	-3.2	27	4

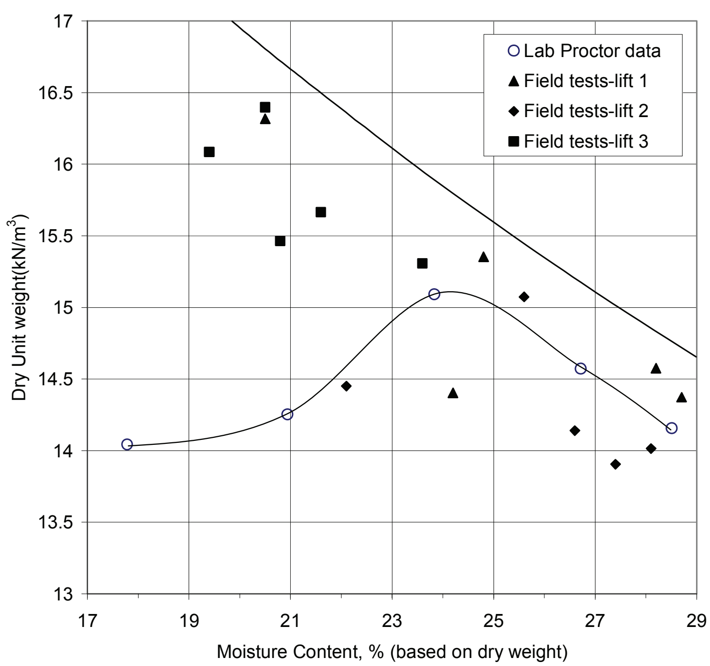

Figure 24. Unit weight-moisture plot for soil 4A

The material was hauled by Caterpillar scrapers. A bulldozer leveled the material before it was compacted by a tractor-pulled sheepsfoot roller. Figure 25 illustrates the equipment that was used on site.

Figure 25. Scraper hauling soil and tractor-pulled sheepsfoot roller

This project used the roller walkout specification; therefore neither moisture content nor density were evaluated for quality control. Observations from the results reveal a scatter of moisture content and density, ranging from 19% to 29% and 93% to 106% relative compaction, respectively.

Project No. 5: Exit Ramp of Highway 275 at I-29

This project featured the construction of an embankment for the exit ramp of Highway 275 at Interstate 29 in Council Bluffs, Iowa. Field testing, moisture-density testing with a nuclear gauge and DCP testing was conducted on July 21 and July 23, 2003.

On the first day of testing, three lifts were tested with six test points on the first two lifts and two tests on the third lift. On the second day, two lifts were tests with six tests spots on the first and five on the second lift. Representative samples of the soil were taken for laboratory testing. The results of the field tests are documented in Table 10. Figure 26 below shows the Proctor curve of the soil with data points from the field tests.

The recommended lift thickness was 203 mm and one roller pass per 25 mm of lift thickness. The lift thickness was not measured, nor was the roller pattern followed. The quality control method used on this project was roller walkout.

Table 10. Field data from project 5 for lifts 1–3 on 8/21/2003

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
5	1A	17.2	16	104.5	-2.2	19	7
5	1B	15.7	17.4	95.6	-0.8	17	7
5	1C	16.7	16.1	101.3	-2.2	16	5
5	1D	16.5	16.1	100.1	-2.2	17	5
5	1E	14.7	17.6	89.1	-0.6	16	4
5	1F	16.4	16.1	99.9	-2.1	21	3
5	2A	16.6	15.4	101	-2.8	13	2
5	2B	16.9	14.8	102.8	-3.4	14	4
5	2C	17.5	14.9	106.1	-3.4	14	2
5	2D	17.3	13.4	105.1	-4.8	13	3
5	2E	18	13.9	109.2	-4.3	12	3
5	2F	17	15.6	103.2	-2.7	15	3
5	3A	16.2	15.7	98.4	-2.5	14	2
5	3B	16.2	16.4	98.5	-1.8	17	3

Table 11. Field data from project 5 for lifts 1 and 2 on 8/22/2003

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
5	1A	16.4	15.6	99.7	-2.7	15	3
5	1B	16.7	15.5	101.5	-2.7	14	2
5	1C	16.4	13.7	99.5	-4.6	12	2
5	1D	16.7	13.7	101.3	-4.6	12	2
5	1E	17.3	16.2	105.2	-2	12	3
5	1F	16.8	15.9	102.3	-2.4	13	3
5	2A	15.7	17	95.6	-1.3	14	2
5	2B	16.5	14.9	100.4	-3.4	18	6
5	2C	16.8	16.1	101.8	-2.2	15	4
5	2D	17.7	11.9	107.3	-6.3	15	2
5	2E	17.1	14.8	104	-3.4	16	5

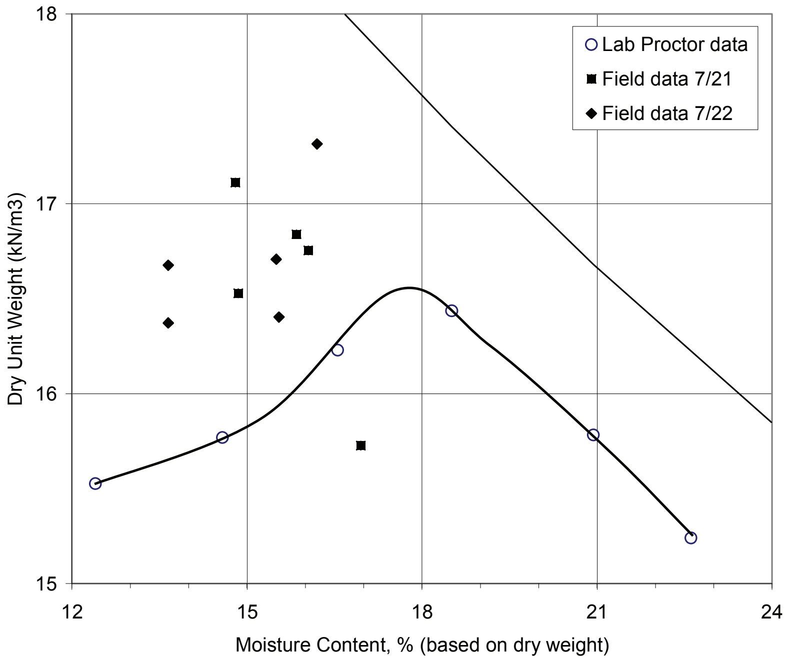

Figure 26. Unit weight-moisture plot for 5A

Some of the material used on the embankment was hauled using a Caterpillar 627 scraper (Figure 27a) from a stockpile while the rest of the material was hauled from a loess borrow site by side dump trucks.

(a) (b) (c)

Figure 27. Equipment used on the project: (a) scraper, (b) compactor, (c) tractor-pulled roller

A D4C dozer was used to level the material before two compactors rolled over the material. One of the compactors was the Caterpillar 816B (Figure 27b), and the other was a tractor-pulled sheepsfoot roller (Figure 27c).

The quality control for this project was based on roller walkout. Measurements of moisture and density of the site revealed that the soil was dry of the optimum moisture content, while the relative compaction ranged from 89% to 109%. Lift thickness was observed from DCP profiles ranging from 150 to 300 mm, whereas the specification was 203 mm loose material. The DCP testing indicated that the "Oreo cookie" effect was present in layers of compacted fill at this project.

Project No. 6: Highway IA 2 - Sydney Bypass

This project is part of the Iowa Highway 2 Sydney bypass east of Sydney in Fremont County, Iowa. The aim of the site visit was to perform several in situ tests including moisture tests, density tests, and DCP tests. Field testing was conducted on June 1, 2004, which included moisture-density testing with a nuclear gauge and DCP testing.

Fifteen different locations were randomly selected for testing. Testing was performed on final as-compacted lifts of material, prior to the placement of successive lifts of material. The results of the field tests are documented in Table 13.

Table 12. Field data from project 6

Soil ID	Test No.	Dry unit weight (kN/m^3)	Moisture content (%)	Relative compaction (%)	Relative moisture content (%)	Average DCP index (mm/blow)	Variation in DCP index (mm/blow)
6	1	14.2	22.5	86.9	+4.0	58	20
6	2	15.9	20.7	97.7	+2.2	43	12
6	3	15.4	22.1	94.4	+3.6	48	11
6	4	16.3	17.9	99.7	-0.6	42	9
6	5	15.6	24.9	95.5	+6.4	44	10
6	6	16.2	19.2	99.1	+0.7	61	24
6	7	15.9	20.2	97.2	+1.7	56	14
6	8	15.3	23.1	93.9	+4.6	67	9
6	9	15	23.3	91.7	+4.8	72	13
6	10	15.5	20	95	+1.5	58	13
6	11	15.8	18.4	97	-0.1	139	39
6	12	14.9	24.8	91.5	+6.3	64	17
6	13	15.5	22.5	94.8	+4.0	62	17
6	14	15.1	23.4	92.7	+4.9	68	15
6	15	15.3	23.8	94	+5.3	51	12

The area tested was a fill area with material transported by dump truck from a cut area several hundreds of meters away. A scraper was used to level the freshly placed fill and a tractor-pulled sheepsfoot roller was then used to compact the lift.

Material samples from the project site were collected for lab tests that included unit weight-moisture relationship, plasticity index, and sieve analysis. The plasticity index and the sieve analysis were performed for soil classification. Figure 28 plots the unit weight- moisture relationship. The maximum unit weight is 16.32 kN/m^3 given at a moisture content of 18.5 %. This stage of the project did not incorporate measures to monitor moisture or density control. Relative compaction ranged from 86.9% to 99.7%.

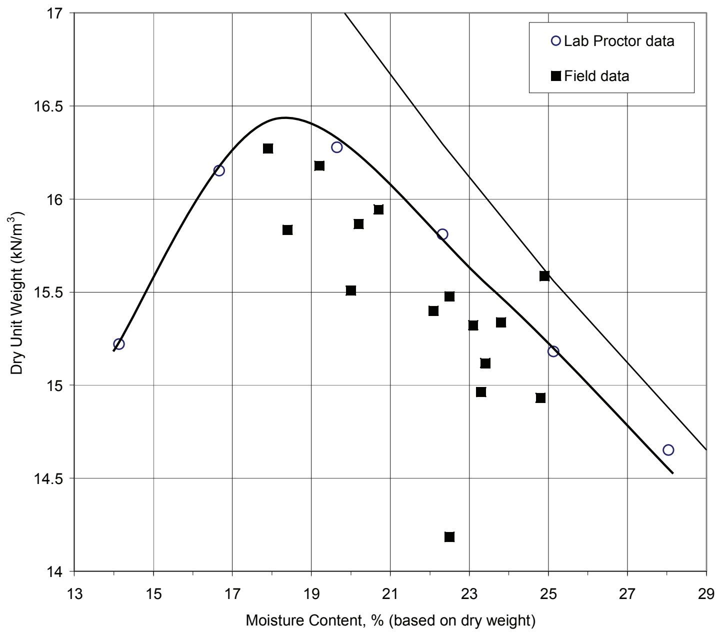

Figure 28. Unit weight-moisture plot for soil 6

The lift thickness, as estimated from the DCP plots, ranged from about 200 mm to 430 mm. The CBR values ranged from 6 to 10. Appendix B documents field DCP plots

Key Findings from Field Studies

The results of independent ISU field testing conducted at each study are summarized in Table 13.

The data shown in Table 13 illustrates some interesting trends. The data from soil 1, 2, 3A, and 6 show that when the fill was compacted at moisture contents more than 3% in excess of optimum moisture, the resulting relative compaction tended to be lower than 95%. The observed DCP index values, though only available for one soil, were relatively high.

When the fill was compacted excessively dry of optimum moisture, the relative compaction values were in excess of 100% and the resulting DCP index values were rather low, indicating stiff soil (characteristic of soils that are exceedingly dry).

Comparing these observed values with those values obtained from the Phase III pilot project reveals that for each project the values are similar. The most noticeable differences are the observed namely that the moisture contents from the Phase III study were rather consistently 1%–2% wet of optimum for each soil type, whereas the values from this field study spanned a much broader range. Yet despite this fact and that lift thicknesses were rather poorly controlled, the observed values from this pilot study are not exceedingly dissimilar from those obtained at the Phase III pilot study. The conclusions from these comparisons are slightly limited due to the lack of DCP data for soils 1, 2, and 3A; furthermore, direct comparisons of this type of data may be misleading due to variations in soil properties.

Table 13. Statistical summary of ISU field testing data collected during field studies

SOIL ID	Date	Average DCP Index (mm/blow)		Variation in DCP Index (mm/blow)		Relative Compaction (%)		Relative Moisture Content (%)	
		Mean	C_v (%)	Mean	C_v (%)	Mean	C_v (%)*	Mean	C_v (%)*
1	6/8/2003	-	-	-	-	95.5	2.0	+4.3	13.4
2	6/18/2003	-	-	-	-	89.9	2.7	+6.3	11.5
3A	6/25/2003	-	-	-	-	91.5	1.9	+6.7	6.1
3B	7/2/2003	42	23.8	10.3	43.9	102	3.6	0	9.1
4	7/1/2003	33	18.5	6.3	33.8	99.6	5.1	0	13.3
5	7/21/2003	16	16.1	3.8	44.2	101.1	4.9	-2.6	7.4
5	7/22/2003	14	13.3	3.1	44.5	101.7	3.1	-3.2	9.7
6	6/1/2004	62	37.4	15.7	48.9	94.7	3.5	+3.3	10.3

** Based upon non-normalized values*

Field samples were collected from the above field studies, as well as from the Phase II pilot studies. Shelby tube samples were obtained near locations of in situ DCP testing in attempt to establish a relationship between unconfined compressive strength and in situ DCP index. Figure 29 shows the correlation that was determined from this testing.

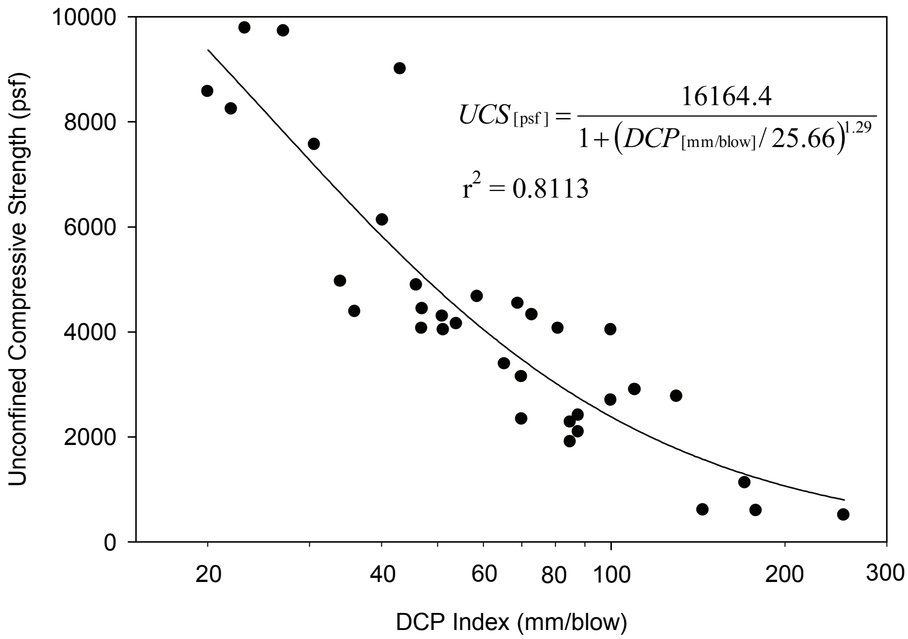

Figure 29. DCP index/unconfined compressive strength correlation

This information is very helpful and provides a more practical framework for establishing control limits for the DCP.

QUALITY MANAGEMENT-EARTHWORK PILOT SPECIFICATION

The QM-E program is one of the primary products of Phase III research. The program is an end-result specification that seeks to improve overall embankment quality while balancing the additional cost and time required attaining this improvement. This type of specification, in lieu of the former method-type specification (ie, sheepsfoot walkout and eight roller passes), has the potential to encourage and provide incentive for future contractor innovation. A brief summary of the QM-E provisions are listed below, the entire QM-E program is contained in Appendix A.

- The QC/QA requirements of the pilot specification constituted the most significant changes in comparison to the former specification. The compaction of embankment fill is monitored using five different QC/QA tests: moisture content, dry unit weight, lift thickness, and stability/uniformity.
- Moisture content testing was required once for every 500 m^3 of fill placed. The moisture control limits specified for the pilot project were ± 2% of standard Proctor optimum moisture content for all types of fill material. The contractor's and DOT's moisture testing were considered similar if the moisture content was within ± 1% moisture content.
- The dry unit weight testing was also required once for every 500 m^3 of fill placed. The dry unit weight control limits from the pilot specification required that all fill must exceed 95% maximum standard Proctor dry unit weight. The contractor's and DOT's dry unit weight measurements were specified to be similar if within ±0.8 kN/m3.
- The lift thickness was measured once for every 500 m^3 of fill placed. Control limits are established during the construction of test strips, which is discussed later.
- The stability/uniformity of the compacted lift was measured by testing with the DCP. The pilot specification required that the maximum stability and uniformity values met set control limits to ensure adequate lift compaction. These control limits varied depending on the borrow material type and grade. For the unsuitable cohesive soils of the pilot project the control limit for average DCP index and variation in DCP index were, 70 and 40 mm/blow, respectively.
- All of the QC/QA test data were recorded in control charts. Control charts are graphs of a given QA test parameter versus a running test count. The contractor maintained the control chart records for each different identified soil. The use of control charts and multiple point averaging for statistical quality control provided a simple process to accept or reject material based upon a collection of data. Furthermore, control charts are convenient for quickly observing the QC/QA test results and identifying trends in the data. Each control chart contained each individual contractor QC and QA test as well as the four-point running average of the contractor QC data. The control limits for each QC/QA test parameter apply only to the four-point running average of the contractor tests. This serves to make account for inherent variability associated soil property measurements.
- Test strips were compacted areas of fill measuring 50 m long, 10 m wide, and one lift thickness deep that were incorporated into the embankment. They served to establish proper rolling patterns, number of roller passes, and lift thicknesses required to attain acceptable compaction. Upon completion of a test strip, four random locations are tested for lift thickness, moisture content, dry unit weight, stability, and uniformity. The test

sections was acceptable if all moisture contents were within the specified control limits, all dry unit weight measurements exceeded 95% maximum standard Proctor dry unit weight, and all of the stability/uniformity DCP tests met the acceptance criteria. The average lift thickness of the test strip was then used as the control limit for subsequent compaction layers and the same techniques used to construct the test strip were then used for compaction of all fill of the same type. Additional test strips were required in the event of a change in soil type, soil compaction methods or equipment; or if QC/QA testing reveals that the lifts were not meeting the applicable quality control criteria.

PILOT PROJECT

Several projects were considered for the Phase IV pilot project. Iowa DOT project NHSX-34-9(96)-3H-51 was selected based on soil type, fill thicknesses, and schedule. This project involved construction of the eastern portion of the bypass around Fairfield, Iowa, on Highway 34 in Jefferson County. The construction spans approximately 4.6 km and the plans require construction of three bridges (represented as gray rectangles), five bridge embankments, and four ramp sections (named A–D) shown in Figure 30. In total, 699,527 m^3 of fill was compacted for this project with quality control from the QM-E special provision.

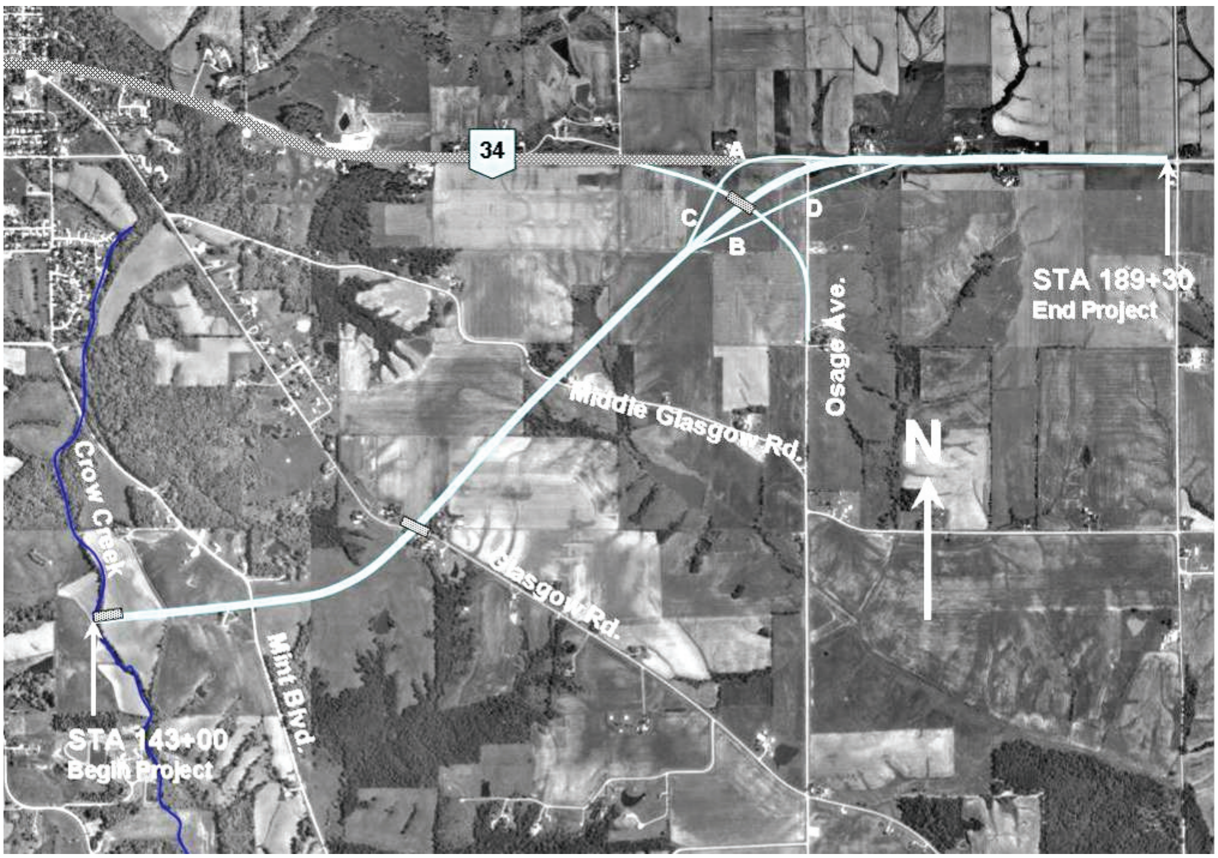

Figure 30. QM-E pilot project, Iowa DOT project NHSX-34-8(96)-3H-51

The main objective of this project was to evaluate the QM-E program for construction in "unsuitable" soils. This was accomplished by assessing the functionality and practicality of the QM-E special provision for unsuitable soil and by documenting the quality of compacted fill throughout the construction process. The behavior of one of the completed embankments will then be briefly discussed.

Geologic Description

Fairfield is in the southeast corner of Iowa in a geologic area known as the Southern Iowa Drift Plain. This area has been subject to significant erosion since the last period of glaciation. Many of the topographical features associated with glaciations have therefore been lost and the landscape has developed well established systems of drainage and discernable topographical relief. Figure 30 gives an indication of the topographical relief of the project site via contrast differences in the photo.

Erosion in this area was not uniform over time and this has resulted in stepped landscape surfaces. This area is dominated by four main surfaces: the Yarmouth-Sangamon surface, the late Sangamon surface, the Wisconsin (or Iowan) surface, and the Holocene surface. The Yarmouth-Sangamon surface is the oldest surface and tends to be found at higher areas of the landscape. The surface is comprised of an ancient soil known as the Yarmouth-Sangamon paleosol. This soil is gray in color and tends to have high clay content, so high in fact that perched water tables are common and in general infiltration of water into this soil is poor. The late Sangamon surface is slightly younger than the Yarmouth-Sangamon surface. This surface is comprised of a reddish-brown paleosol that is also high in clay content, though not as significantly as the Yarmouth-Sangamon paleosol. The Iowan erosion surface is even younger than the previously mentioned surfaces. Erosion has removed all of the paleosols and only Pre-illinoian glacial till remains. This surface was formed at approximately the same time as deposition of loess which covers the Yarmouth-Sangamon and late Sangamon surfaces at varying thicknesses. The youngest surface in this area is Holocene surface and is marked by deposits of postglacial alluvium (Figure 31).

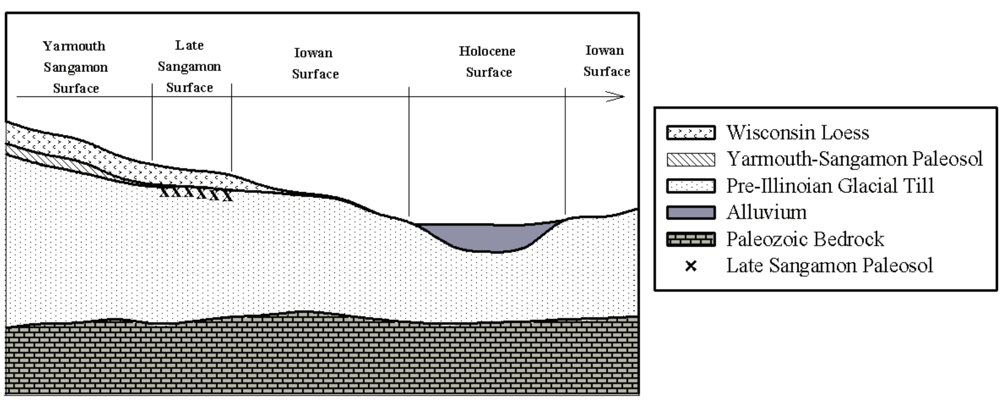

Figure 31. Southern Iowa drift plain landscape model

This landscape model was useful in reference to this project and in general it was fairly representative of the conditions at the site. The majority of unsuitable soil found on this project is located in layers of weathered loess and paleosol, both commonly having more than 60% passing the No. 200 sieve. Construction in such soils is complicated by the fact that the natural moisture content of the soil tends to be higher than the Proctor optimum moisture content by a few percent and that soil variability across the project is high, as indicated by the landscape model. The use of the QM-E special provision on this project truly tested the ability to control the quality of the embankment, without excessive delay to the project.

The Crow Creek embankment was an area of particular concern on this project, occurring from STA 143+00 to STA 148+00. Not only was it one of the largest embankments on the project, but it was built atop some of the poorest soils, of greatest concern was the alluvial deposits around Crow Creek. A majority of the testing conducted by ISU at this project was focused in this area, including QA testing, CPT, soil borings, and examination of settlement behavior, the results of which are discussed later in this report.

QM-E PILOT PROJECT RESULTS AND DISCUSSION

There was a combined effort in performing testing at this project by the Iowa DOT, the contractor, and ISU. A majority of this testing is in the form of QC/QA testing by the contractor and the Iowa DOT. ISU also conducted CPT testing and soil borings and monitored an inclinometer at the Crow Creek embankment. The following sections include discussions of the contractors QC testing conducted by the contractors and independent testing conducted by ISU, descriptions of observed trends in the contractor QC data, and finally the performance of the Crow Creek embankment is discussed.

Contractor QC Data

The contractor QC data and DOT QA data were reported in the form of control charts that monitored the stability, uniformity, dry unit weight, and moisture content of compacted lifts. Control charts are graphs of a given test parameter for a soil type or a portion of a construction project versus a running test count. The test counts tend to be arranged in chronological order with the earliest tests having low test numbers and the most recent tests having high test numbers. The charts shown below are all arranged by soil classification. On this pilot project there were five main classifications, as shown in Table 14. A total of 24 Proctor tests were conducted by the contractor on this project; however, these 5 classifications accounted for approximately 85% of the testing conducted and thus for simplicity discussion will focus on these five alone. Refer to Appendix B for contractor Proctor testing results.

Table 14. Contractor soil type summary

Soil ID	AASHTO Classification	DOT Soil Grade	Classification Date	Proctor Maximum Dry Unit Weight (kN/m3)	Proctor Optimum Moisture Content (%)
A	A-7-6 & A-6-2	Suitable	5/25/2006	18.3	14.0
B	A-7-6	Unsuitable	7/11/2006	16.2	19.6
C	A-7-6	Unsuitable	4/27/2006	15.8	21.0
D	A-7-6	Unsuitable	6/6/2006	15.5	21.2
E	A-7-6	Unsuitable	6/13/2006	15.2	22.7
F	A-7-6 & A-6	Select	9/7/2006	18.7	12.6

Figure 32 through 37 show the control charts for soil A through F, respectively. Each control chart shows the individual contractor test points, DOT quality assurance test points, the four-point running average of each test parameter, and the applicable control limits. It should be noted that the DCP index values shown are recalculated from contractor records due to some misunderstandings by the contractor about how to calculate the DCP index. These errors resulted in DCP index values that tended to be lower than they should have been.

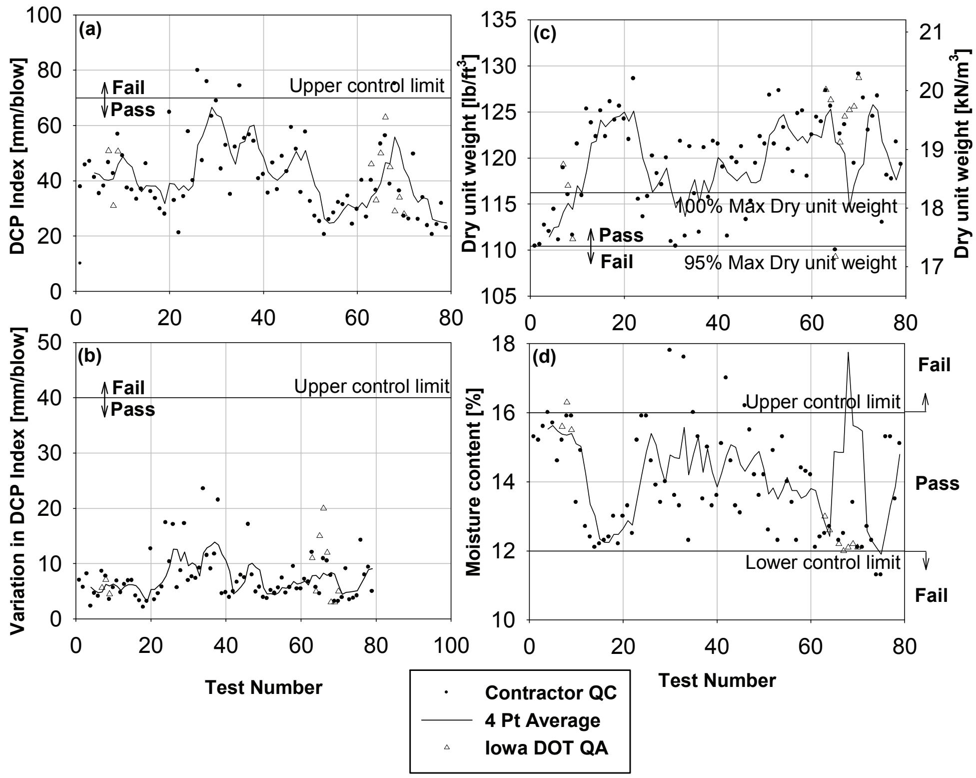

Figure 32. Control charts for soil A

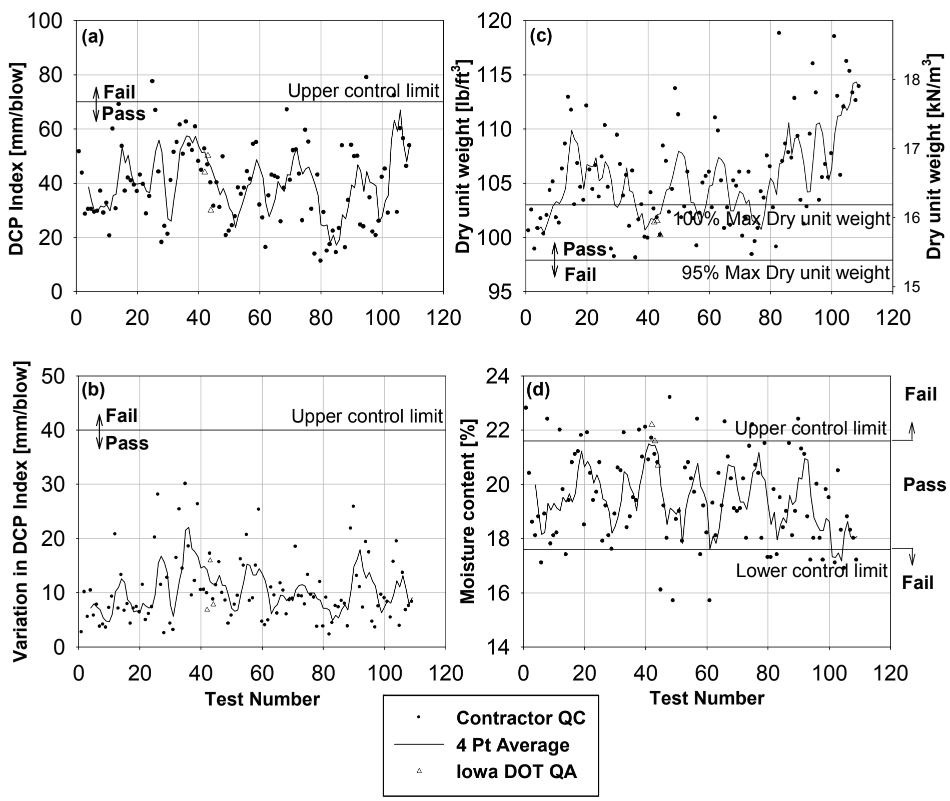

Figure 33. Control charts for soil B

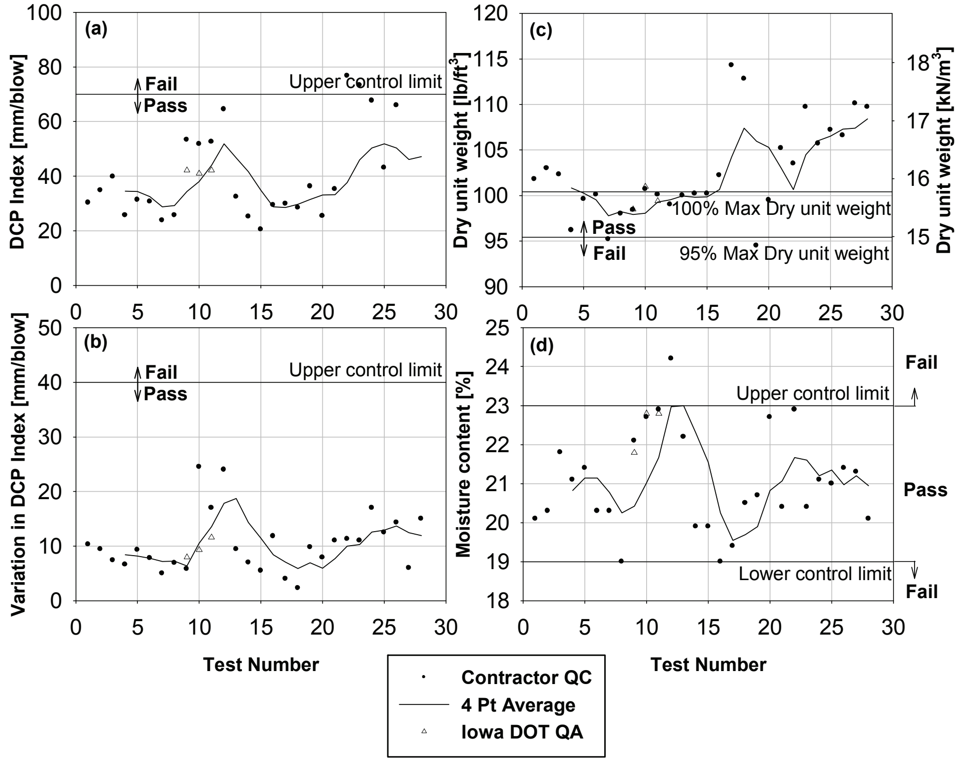

Figure 34. Control charts for soil C

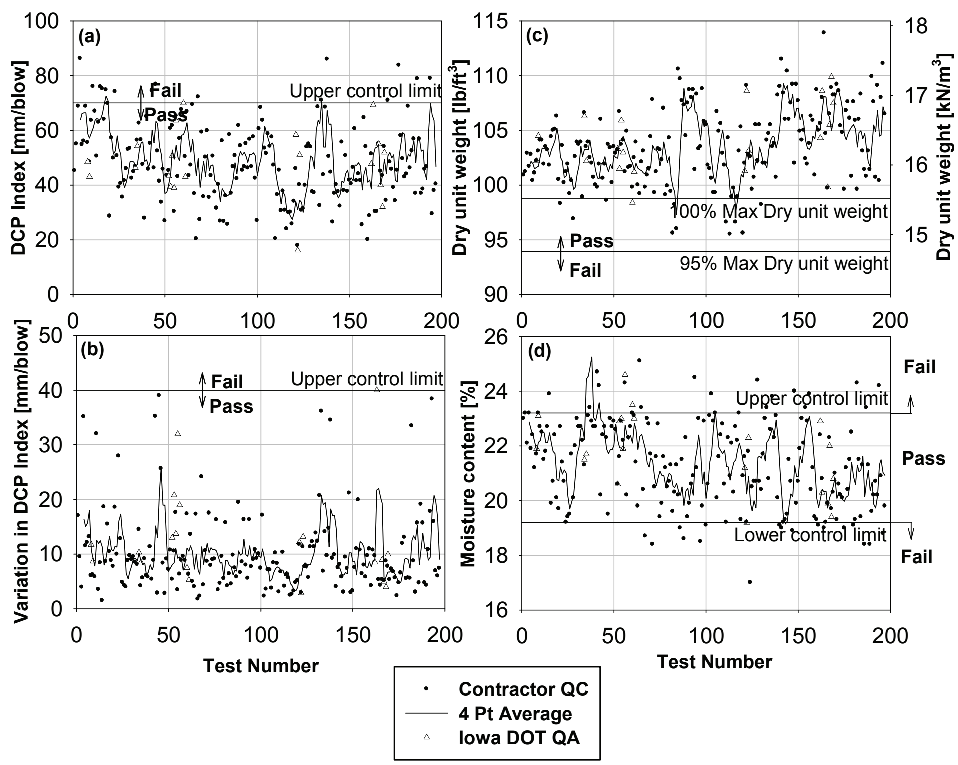

Figure 35. Control Charts for soil D

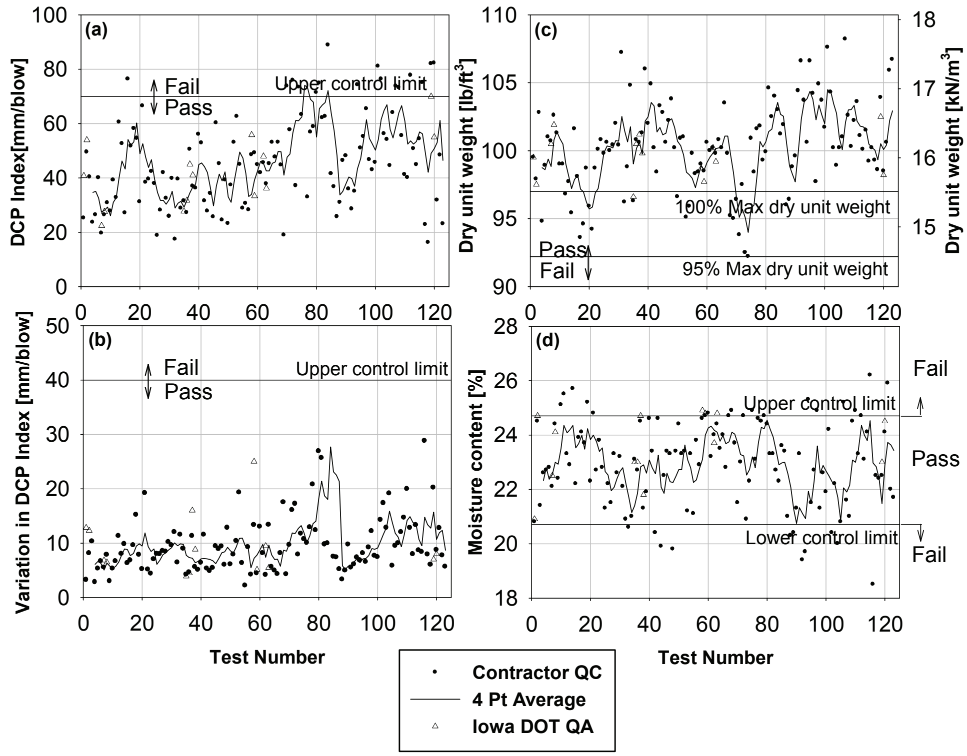

Figure 36. Control charts for soil E

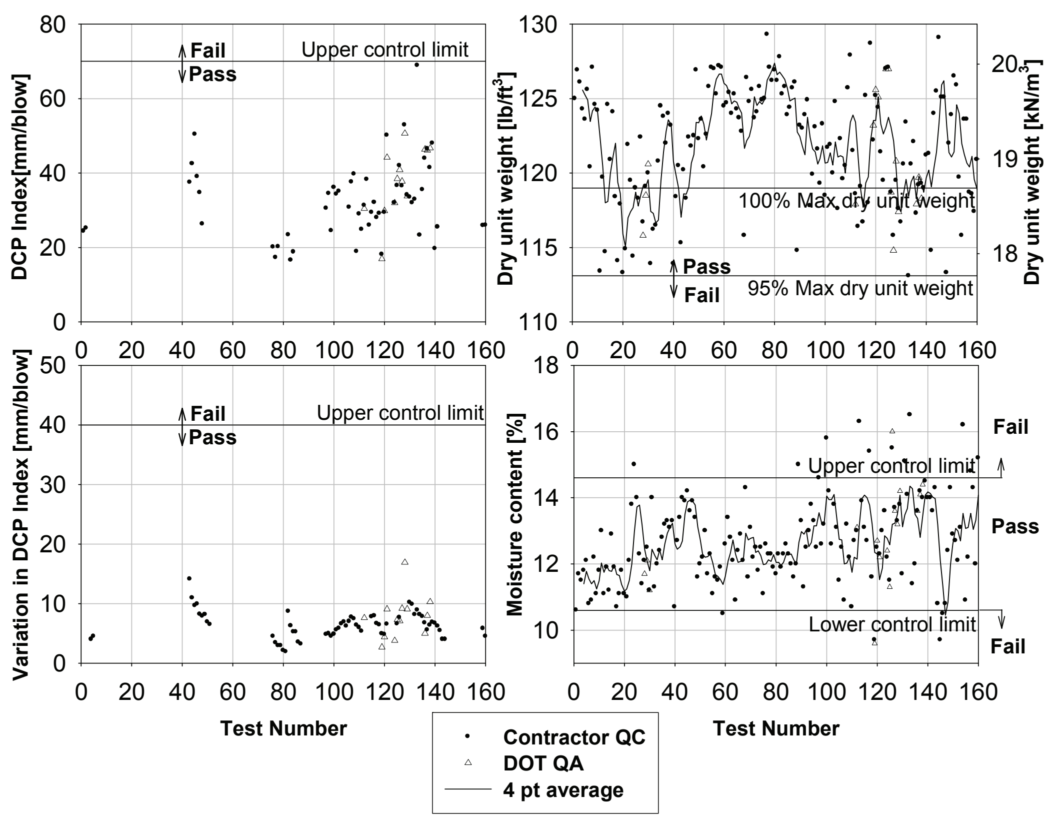

Figure 37. Control charts for soil F

There are a few general trends that can be identified from the above control charts. The DCP index control charts show that the contractor's four-point running average for DCP index never exceeded the control limit of 70 mm/blow for either suitable or unsuitable soil. In fact very few single test points even exceeded this limit for any soil group. Although the recalculated four-point average for DCP index tends to be higher than the contractor running average, the recalculated four-point running average rarely exceeded the control limit. These trends are repeated in the data for the variation of the DCP index. All of the contractor's testing was well within the control limit of 40 mm/blow for uniformity, with a majority of the tests not exceeding 20 mm/blow. This suggests that the lift thickness was maintained sufficiently well throughout the project. These observations in the DCP data may also suggest that the control limits for DCP testing could be more tightly set and this will be examined in greater detail later. The dry unit weight control charts also show that the contractor testing never failed the lower control limit of 95% optimum dry unit weight and only one individual test didn't meet these criteria. In most cases the four-point running average was above 100% optimum dry unit weight. One interesting trend among all of the dry unit weight control charts is that the four-point running average tends to remain at the higher values for a considerable number of consecutive tests. At times some of these higher values even approach 110% relative compaction. Finally, the moisture control chart shows that the four-point average exceeded the control limits of ±2% optimum moisture content once, for soil C. There is no discernible trend within the moisture data, since it is rather variable with respect to time. It is likely that the variability of the moisture control charts was largely influenced by rainfall on the project.

The contractor QC tests and DOT QA tests are all shown in the above control charts. A statistical analysis of the QC/QA data is contained in Table 15.

Table 15. Statistical data for each soil types from contractor QC data

SOIL ID	DCP Index (mm/blow)			Variation in DCP Index (mm/blow)			Relative compaction (%)			Relative moisture content (%)		
	μ	σ	c_v [%]	μ	σ	c_v [%]	μ	σ	c_v* [%]	μ	σ	c_v* [%]
A	41.0	13.9	34.0	7.4	5.2	70.3	102.8	4.4	4.3	-0.1	1.7	12.1
B	40.2	16.2	40.2	10.4	5.6	54.0	102.1	4.4	4.3	0.0	1.7	8.9
C	40.5	16.9	41.7	10.4	5.4	51.9	102.4	5.1	5.0	0.0	1.3	6.1
D	49.3	16.1	33.3	11.2	6.8	60.7	104.7	3.6	3.5	0.2	1.6	7.3
E	46.3	18.3	39.5	10.7	5.7	53.3	103.7	3.4	3.3	0.1	1.6	7.0
F	47.7	18.4	38.6	12.5	7.7	6.9	101.9	3.6	3.0	0.4	1.6	12.1

*Coefficient of variation for non-normalized data

Interestingly, the average DCP index values recalculated from the contractor data for all of the different soil types fall in a relatively narrow range from 40 to 49 mm/blow with a coefficient of variation ranging from 33.% to 42%. The average variation in DCP index recalculated from contractor data also fall in a narrow range from 7 to 11 mm/blow with a coefficient of variation ranging from 52% to 70%. The recalculation was necessary because the contractor misunderstood how to perform the calculations. The average relative compaction for all soil types exceeds 100% and the average values of relative moisture tend to be close to 0%. All of these values are fairly consistent with data collected at the Phase II pilot project and the prior field studies. The one exception is that the mean relative compaction values are high in comparison to values obtained at the other field studies.

The QM-E requires that the dry unit weight and moisture QC/QA testing be within acceptable ranges of difference. Table 16 shows the average difference between contractor QC and DOT QA for all the testing shown in the above control charts for each soil.

Table 16. Average difference between contractor QC and DOT QA testing for each soil

	Soil ID				
Test Type	**A**	**B**	**C**	**D**	**E**
DCP Index [mm/blow]	8.8	5.1	0.3	7.6	6.4
variation in DCP index [mm/blow]	3.4	1.7	3	6.4	4.3
Dry unit weight [kN/m^3]	0.09	0.08	0.08	0.16	0.08
Moisture content [%]	0.27	0.40	0.21	0.31	0.31

Based upon the calculations shown in Table 16, the testing met the difference criteria of 0.8 kN/m^3 and 1.0% for dry unit weight and moisture content respectively.

ISU Evaluation of Contractor QC Testing

Throughout the construction of this project the contractor conducted QC testing in accordance with the QM-E special provision. The original data sheets used for field testing were filed for later use and electronic records of the quality testing were maintained with one of the programs from the G-RAD software package. One of the objectives of this project was not fulfilled when the contactor elected not to use the G-RAD system in its entirety for this project.

One objective of this research was to independently evaluate the QC/QA data that was collected by the contractor and the Iowa DOT at this project. This data set was ideal for evaluating the QM-E; however, first it was necessary to show that the data was relatively unbiased and reasonably accurate. This was accomplished with independent spot testing conducted by Iowa State University. Numerous samples were collected for classification and sets of tests were conducted throughout different phases of construction. In total, 15 different samples were classified and 79 independent tests were conducted, including DCP, moisture, and dry unit weight testing. This testing has been subdivided into test sets, representing tests conducted on the same lift for the same fill material. A summary of the soil properties from each set of independent ISU field tests are shown Table 17. The DCP profiles and data for each test location are contained in appendix D.

This discussion will focus on testing conducted at the Crow Creek embankment (STA 143+00 to STA 148+00) on August 16 and 17, 2006 (Figure 38).

Table 17. Summary of soil properties for ISU QA test sets

Test Set ID	Date	Location	STA	Opt. MC (%)	Max dry unit weight (kN/m^3)	F_{200} (%)	LL	PI	Iowa DOT Classification	AASHTO classification
A	8/16/06	Highway 34 connector	22007	18.8	17.4	92	46	27	Suitable	A-7-6 (26)
B	8/16/06	Mainline WB "Crow creek"	145	17.1	17.0	85	51	35	Unsuitable	A-7-6 (30.5)
C	8/17/06	Mainline EB "Crow creek"	144	19.0	16.3	83	54	39	Unsuitable	A-7-6 (33)
D	9/19/06	Mainline WB "Crow creek"	144	10.9	19.5	54	28	15	Suitable	A-6 (5)
E	9/19/06	Mainline EB "Crow creek"	144	11.7	19.2	53	31	17	Suitable	A-6 (5)
F	9/29/06	Mainline EB	183	12.3	18.9	57	25	9	Suitable	A-6 (2)
G	9/26/06	Mainline EB	164	22.2	15.4	98	65	43	Unsuitable	A-7-6 (48)
H	9/26/06	Osage Berm Deceleration ramp	14102	19.0	16.4	99	45	25	Suitable	A-7-6 (27)
I	10/10/06	Mainline WB	173	11.0	19.6	52	21	6	Suitable	A-6 (0)

Figure 38. ISU QA testing on 8/16/06 at Crow Creek embankment (looking west)

Figure 39 shows the results of the testing conducted in the westbound lane on August 16th and in the eastbound lane on August 17, both in unsuitable fill. This testing corresponds to test sets B and C, respectively. It is important to note that thought these comparison plots show both contractor and ISU test data, the locations and times of the testing are not necessarily the same. However as previously mentioned, all of the tests were conducted on the same lift of material.

Figures 39a and 39b show control charts for DCP index values from contractor and ISU testing for test sets B and C. The ISU values for test set B range from 31 to 92 mm/blow, with an average DCP index of 46 mm/blow, standard deviation of 168 mm/blow, and a coefficient of variation of 34% based upon 16 tests. The contractor's test results for this same lift range from 30 to 55 mm/blow, with an average DCP index of 46 mm/blow, standard deviation of 10 mm/blow, and a coefficient of variation of 22% based upon 5 tests. The ISU values for test set C range from 31 to 65 mm/blow, with an average DCP index of 50 mm/blow, standard deviation of 12 mm/blow, and coefficient of variation of 25% based upon 11 tests. The contractor tests for this same lift range from 30 to 70 mm/blow, with an average DCP index of 46 mm/blow, standard deviation of 16 mm/blow, and a coefficient of variation of 35% for 5 tests. The test data from both of these data sets seems to show fairly good agreement between contractor and ISU QC/QA testing. The average DCP index values for contractor/ISU tests tend to be within a few mm/blow and the four-point average of all of the data sets was well within the control limit. The variation that occurs within a test set may seem high; however it is typical for DCP testing. It is not uncommon for sets of DCP measurements to have coefficients of variation as high as 40% (White, 2002).

The control charts for variation in DCP index (Figures 39c and 39d) again show reasonable agreement between contractor and ISU DCP testing. The ISU values for test set B fell in a very narrow range from 3 to 19 mm/blow, with an average variation in DCP index of 7 mm/blow, standard deviation of 4 mm/blow, and a coefficient of variation of 52% based upon 16 tests. The contractor's test results were in a slightly narrower range from 5 to 9 mm/blow, with an average variation in DCP index of 7 mm/blow, standard deviation of 2 mm/blow, and a coefficient of variation of 26% based upon 5 tests. The ISU values for test set C ranged from 4 to 10 mm/blow, with an average variation in DCP index for the lift of 7 mm/blow, standard deviation of 2 mm/blow, and coefficient of variation of 21% based upon 11 tests. The contractor tests for this same lift ranged from 4 to 7 mm/blow, with an average variation inn DCP index of 6 mm/blow, standard deviation of 1 mm/blow, and a coefficient of variation of 20% for 5 tests.

The dry unit weight control charts (Figures 39e and 39f) seem to show more variation between contractor and ISU testing than the DCP control charts. In situ measurements of dry unit weight were conducted using a drive core sampler for all ISU, contractor, and DOT testing; except for test set B where a nuclear gauge was used. Measurements with the nuclear gauge were avoided after test set B due to difficulties with properly seating the gauge due to sheepsfoot roller indentations. One reason the moisture and dry unit weight data for test set B may appear to be peculiar and variable may be that some degree of error was introduced due to improper seating of the device. ISU dry unit weight measurements for test set B ranged from 14.3 to 16.2 kN/m^3, with an average dry unit weight of 15.2 kN/m^3, standard deviation of 0.7 kN/m^3, and a coefficient of variation of 5% based upon 8 tests. Proctor testing on samples collected in this area resulted in optimum moisture content being 17.1% and optimum dry unit weight being 17.0 kN/m^3. In comparison, the contractor tests ranged from 15.7 to 17.9 kN/m^3, with the average dry unit weight being 16.9 kN/m^3, standard deviation of 0.8 kN/m^3, and a coefficient of variation of 0.8% based upon 5 tests. The optimum moisture and dry unit weight used by the contractor for this material were 21.2% and 15.5 kN/m^3, respectively. Testing from set C ranged from 17.4 to 18.7 kN/m^3, with an average dry unit weight of 18.0 kN/m^3, standard deviation of 0.5 kN/m^3, and coefficient of variation of 3% based upon 5 tests. The optimum moisture and dry unit weight of this material was determined to be 19.0% and 16.3 kN/m^3, respectively. Contractor testing in this area ranged from 16.4 to 17.2 kN/m^3, with an average dry unit weight of 16.8 kN/m^3, a standard deviation of 0.3 kN/m^3, and a coefficient of variation of 0.3% based upon five tests.

The ISU data from the moisture control chart in Figure 39g range from 18.6% to 27.8%, with an average moisture content of 23.1%, a standard deviation of 2.7%, and a coefficient of variation of 12% base upon 16 tests. Once again the Proctor testing on this sample resulted in an optimum moisture content of 17.1%. The contractor data (Figure 39g) for test set B ranged from 19.0% - 22.3%, with an average moisture content of 20.2%, standard deviation of 1.2%, and a coefficient of variation of 6%, based upon 5 tests. The optimum moisture content used by the contractor for this material was 21.2%. ISU data from test set C (Figure 39h) ranged from 19.7% to 25.5%, with an average moisture content of 22%, a standard deviation of 1.6%, and a coefficient of variation of 7% based upon 11 tests. Proctor optimum moisture content was determined to be 19.0%. The contractor data (Figure 39h) for test set C ranged from 19.2% to 21.0%, with an average moisture content of 20.1%, a standard deviation of 0.8%, and a coefficient of variation of 4%.

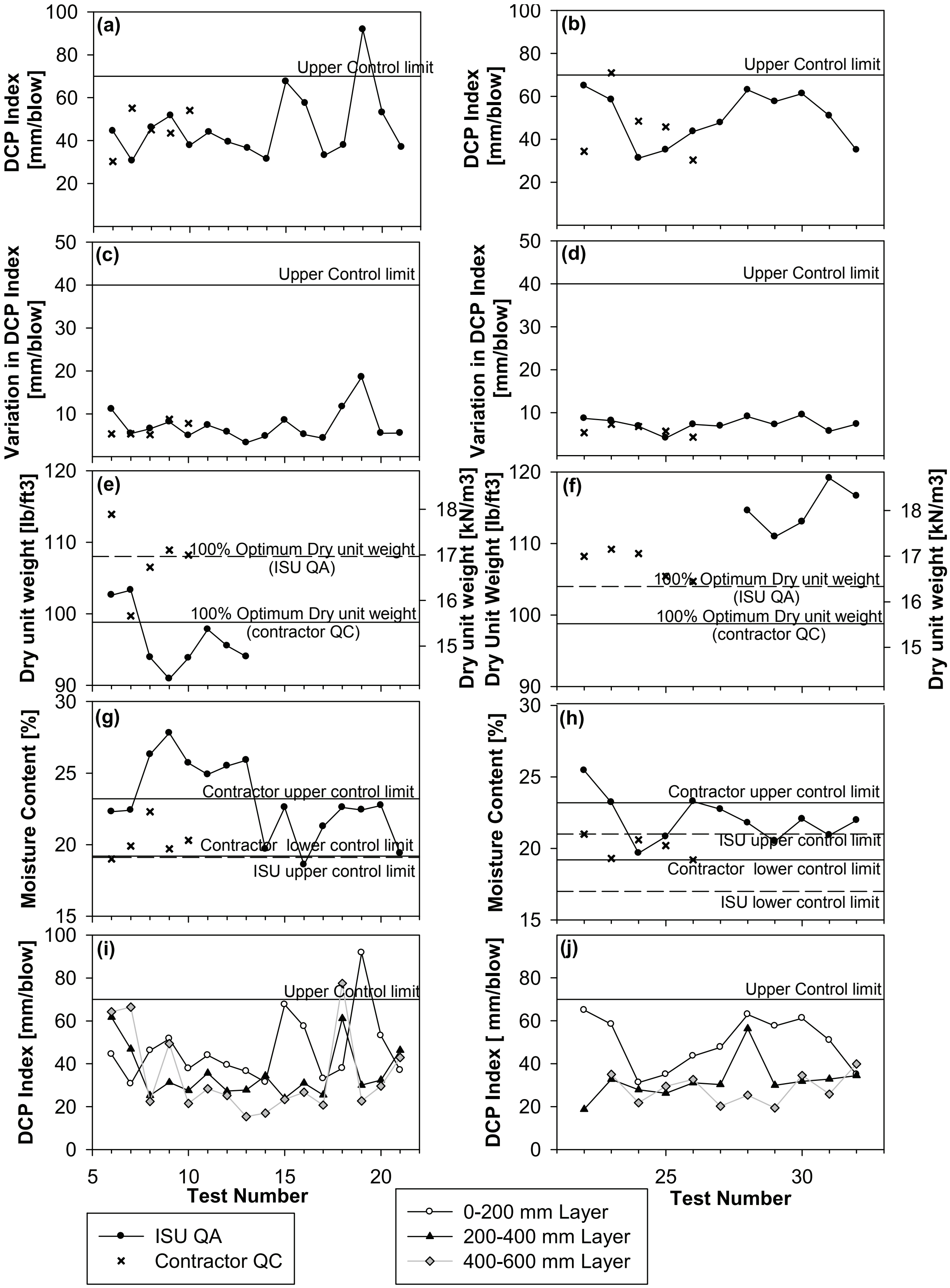

Figure 39. Contractor QC/ISU QA comparison for test sets B (left) and C (right)

The final set of graphs, shown in Figures 39i and 39j, show the DCP index values determined from full depth DCP testing conducted at test sets B and C at successive 200 mm intervals. This plot shows that the compacted lifts appear to gain strength/stability with the compaction of successive lifts of material. These trends are also apparent in the results from other test sets (see Appendix E). It is also interesting to note that in general the variability of DCP index values in deeper lifts is decreased. Both of these occurrences are positive and may give cause to worry less about refining the DCP control limits, given that an appreciable strength gain tends to occur with the compaction of successive lifts.

Table 18 shows comparisons of the mean, standard deviation, and coefficient of variation of the other sets of ISU tests where contractor testing was conducted in the same area. In certain instances, there was no contractor testing conducted in the same area as ISU testing and thus no contractor values are shown. Comparison plots for the all of the test sets, similar to those shown in the previous figures, are available in Appendix E.

Figure 40 shows a graph that compares the mean values of contractor QC and ISU QA established for each test set for DCP index, variation in DCP index, moisture content, and dry unit weight. The solid line represents an ideal condition in which the contractor and ISU test data are in exact agreement. The dashed lines in each figure represent one standard deviation from the ideal case, with the standard deviation being the average of standard deviations for the ISU test sets for each applicable parameter. Figure 40 shows that there were significant variations between contractor and ISU testing for moisture content and dry unit weight. It is possible that these differences resulted from slight variations in the test methods and procedures that were used to obtain these measurements. For instance the contractor conducted moisture and dry unit weight testing on site. Moisture content was determined using the microwave method on drive core samples taken in the field. In contrast, ISU tests were conducted on samples transported to Ames, Iowa, that were sealed in plastic bags to prevent moisture loss and samples were dried in ovens. While precautions were taken to prevent the detrimental effects of transporting all the samples, it is possible that these factors contributed to the differences between contractor and ISU testing. The contractor and ISU test data appear to be in much better agreement for DCP testing. This is reassuring because it indicates that the contractor data set is of sufficient quality to use for more detailed statistical analysis. This also indicates that the testing frequency requirements of the QM-E are adequate to produce reasonable estimates of compacted lift stability and uniformity.

Table 18. Comparison of mean, standard deviation, and coefficient of variation for ISU test sets and contractor QC

Test Set	Statistical value	Moisture content [%]		Dry unit weight [kN/m3]		DCP index 0-200 mm [mm/blow]		Variation in DCP index [mm/blow]	
		ISU tests	Cont. QC	ISU tests	Cont. QC	ISU tests	Cont. QC	ISU tests	Cont. QC
A	n	5	2	5	2	5	2	5	2
	μ	23.6	21.6	17.7	16.8	53.1	56.5	16.1	18.9
	σ	2.2	1.1	0.8	0.3	14.6	4.9	10.1	11.5
	cv [%]	9.2	5.2	4.6	0.3	27.6	8.8	62.9	60.6
B	n	16	5	8	5	16	5	16	5
	μ	23.1	20.2	15.2	16.9	46.2	45.6	7.3	6.5
	σ	2.7	1.2	0.7	0.8	15.8	10.0	3.8	1.7
	cv [%]	11.6	6.1	4.6	0.8	34.2	22.0	52.3	25.8
C	n	11	5	5	5	11	5	11	5
	μ	22.0	20.1	18.0	16.8	49.9	46.0	7.3	5.8
	σ	1.6	0.8	0.5	0.3	12.2	15.9	1.5	1.2
	cv [%]	7.3	4.0	2.8	0.3	24.5	34.6	21.1	20.2
D	n	8	0.0	0.0	0.0	8	0.0	8	0.0
	μ	10.7	-	-	-	19.5	-	6.2	-
	σ	0.6	-	-	-	4.7	-	4.2	-
	cv [%]	5.5	-	-	-	24.0	-	68.4	-
E	n	6	2	2	2	6	2	6	2
	μ	10.9	14.3	21.1	18.9	21.4	33.0	3.3	6.5
	σ	1.3	1.1	0.9	0.3	12.4	4.2	1.1	3.5
	cv [%]	11.8	7.9	4.4	0.2	57.8	12.9	33.4	54.4
F	n	9	0.0	3	0	9	0	9	0
	μ	12.5	-	18.4	-	21.5	-	3.6	-
	σ	0.9	-	1.0	-	3.5	-	1.3	-
	cv [%]	7.2	-	5.3	-	16.3	-	36.0	-
G	n	8	3	3	3	8	3	8	3
	μ	25.7	21.2	14.9	15.9	48.4	46.4	10.2	11.9
	σ	1.7	0.5	0.3	0.2	11.8	6.2	2.7	4.6
	cv [%]	6.7	2.2	2.3	0.2	24.5	13.4	26.2	38.3
H	n	8	3	4	3	8	3	8	3
	μ	24.2	15.9	15.5	16.9	26.8	50.2	5.4	8.8
	σ	0.9	2.4	0.3	1.6	6.6	18.7	2.0	1.4
	cv [%]	3.7	15.1	2.1	1.5	24.4	37.2	37.8	16.0
I	n	8	3	2	3	8	3	8	3
	μ	12.9	12.4	19.0	20.0	33.0	21.9	12.4	2.9
	σ	0.7	0.2	0.2	0.3	9.0	3.9	17.5	1.4
	cv [%]	5.5	1.6	2.1	2.0	27.3	17.8	141.4	48.3

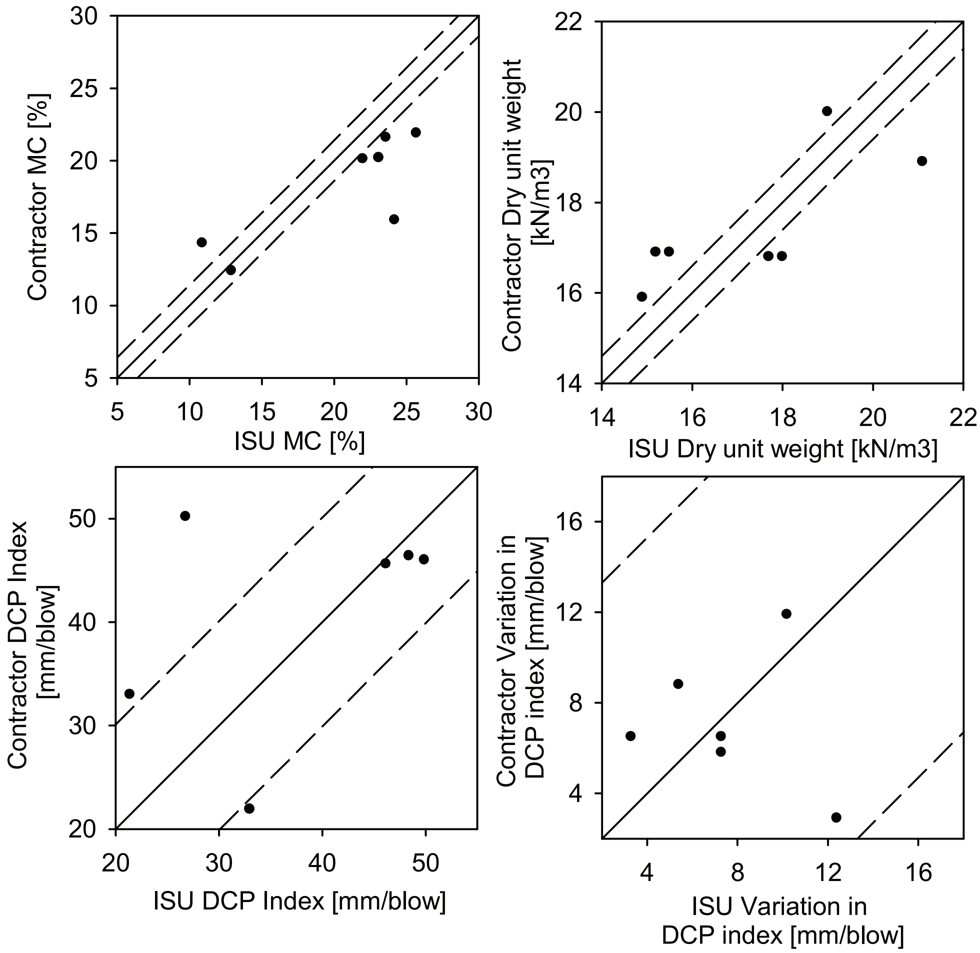

Figure 40. Comparison of contractor QC and ISU mean measurements from test sets

Evaluation of QM-E Target Values

The target values used by the QM-E program for DCP testing, moisture content, and dry unit weight testing were all determined based upon field experience from pilot projects and based upon common earthwork construction practices throughout the country. As was discussed earlier, the target values for dry unit weight and moisture content for the compaction of earthen embankments are similar from state to state throughout the Midwest. The DCP, on the other hand, has been used far less for the quality control processes on earthwork projects and strength based testing of any type for earthwork quality control is relatively rare. There are likely numerous reasons for this; however one of the more fundamental challenges with strength based QC is determining the proper control limits. Strength, unlike density or unit weight, is a parameter that is much more sensitive to changes in moisture content, soil properties, and compaction; thus developing a blanket control limit for all conditions becomes problematic. The QM-E program currently accounts for a handful of the parameters that contribute to overall soil performance with the use of the three different soil classifications; select, suitable, and unsuitable. The QM-E program can seems somewhat crude when the few parameters that are tested are compared to the many parameters that effect soil performance. It is therefore important to show that the control limits that are being utilized are effective for earthwork quality control.

Target values should be chosen base upon the level of overall soil properties such that some minimum specified value is achieved, with some limiting amount of acceptable variability. The following discussion first focuses on the distributions of the data collected at the pilot project and then provides comments regarding the existing DCP target values.

Pilot Project QC Data Distributions

Histogram and distribution plots were created for each test parameter for soils A–E from the pilot project. The histograms and distributions are helpful for more detailed mathematical examination of the test data. Normal distributions were used for relative moisture content and relative compaction. Logarithmic distributions were used for DCP index and variation in DCP index. The histogram-distribution plots for soil A–E are shown in Figures 41–45.

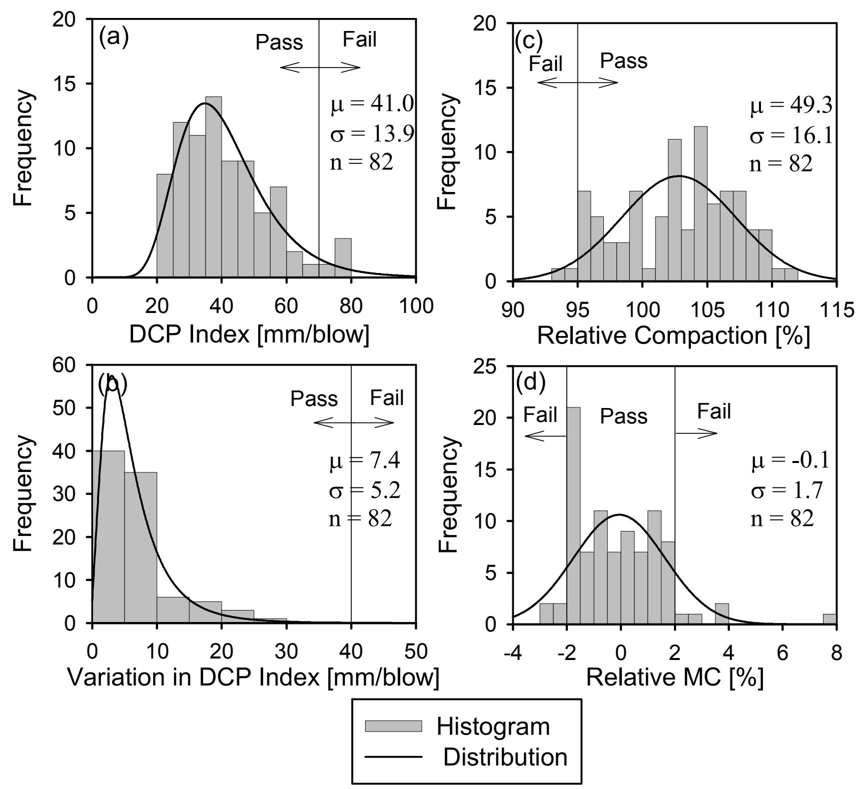

Figure 41. Distributions of QC test data for soil A

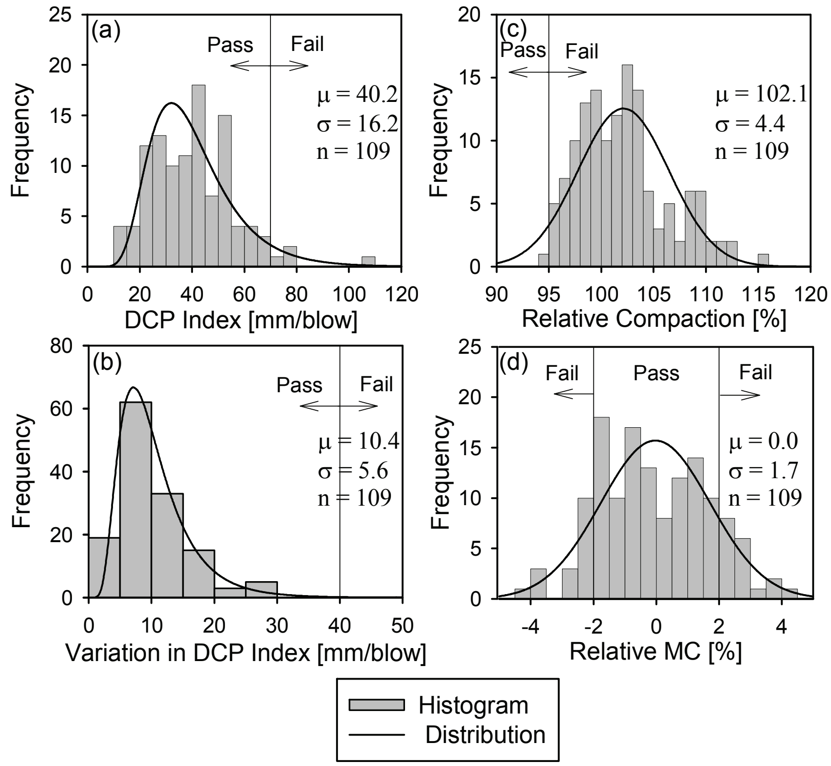

Figure 42. Distributions of QC data for soil B

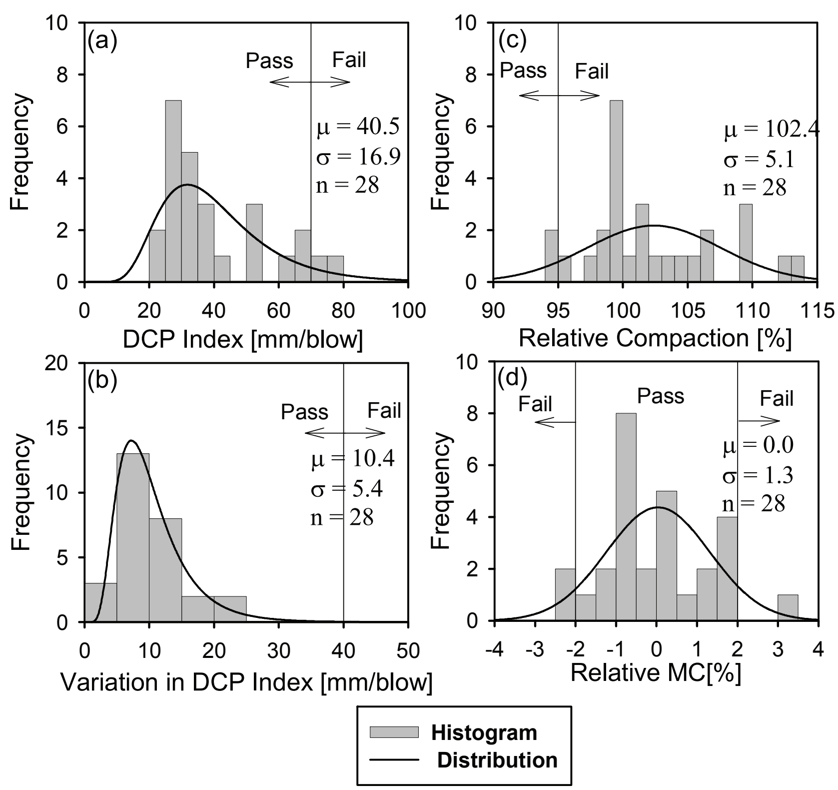

Figure 43. Distributions of QC data for soil C

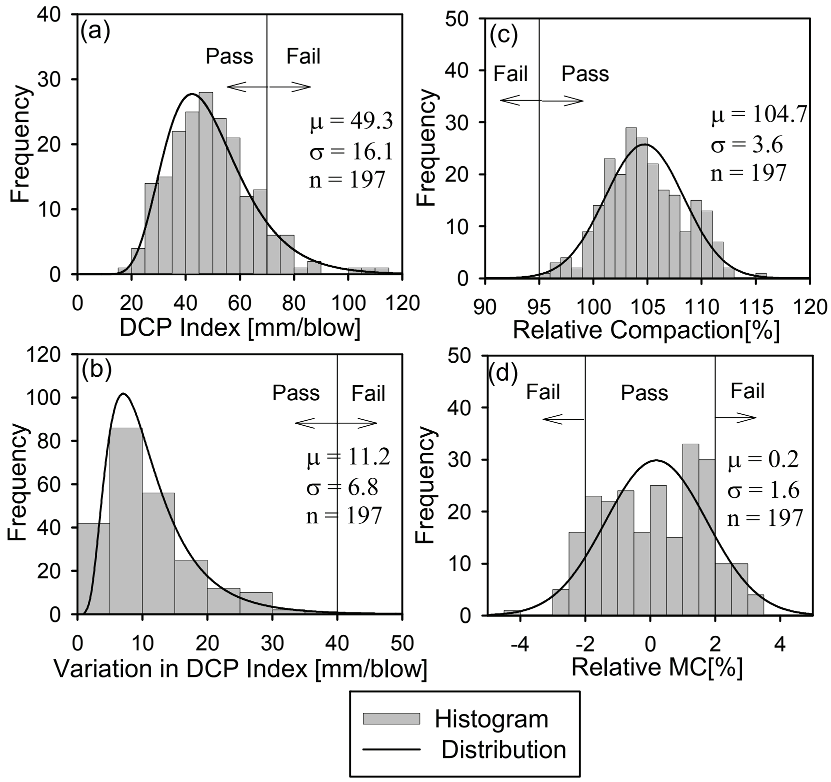

Figure 44. Distributions of QC data for soil D

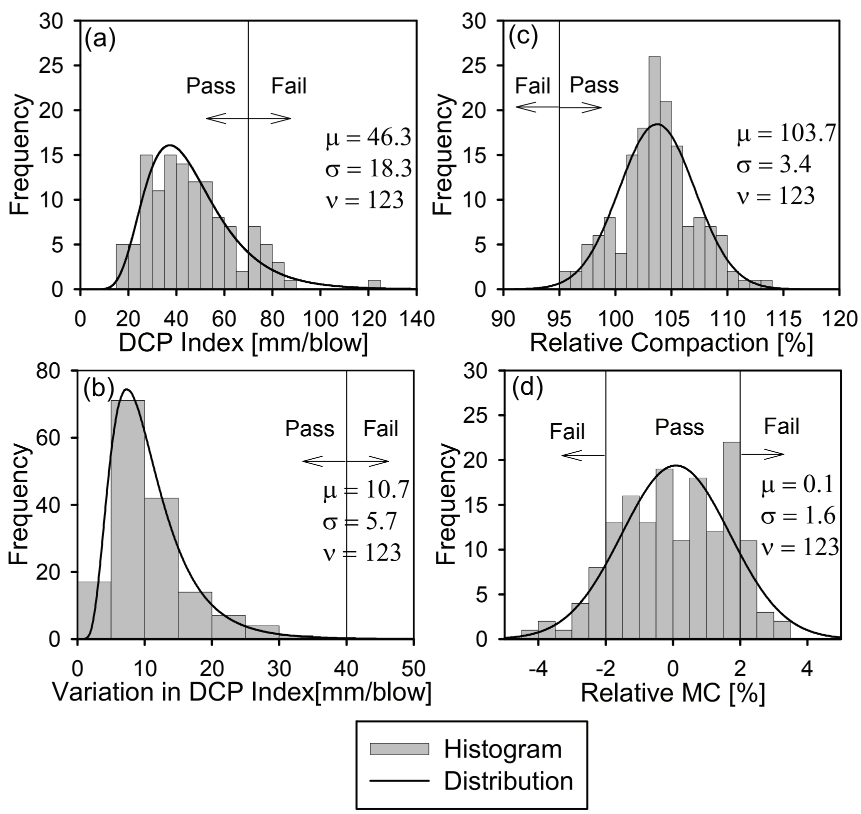

Figure 45. Distributions of QC data for soil E

The distributions and histograms shown above provide some interesting insights into the nature of the data. In general, a lognormal distribution seems to fit the DCP data well. The histograms clearly illustrate that the DCP index and variation in DCP index testing are well within control limits required by the QM-E. The plots for dry unit weight and moisture content reveal some peculiarities. The range of observed relative compaction values appear to be broad for each of the soil types. It seems likely that this variability is the result of unnoticed changes in material properties, and not natural variability.

DCP Index Target Values

DCP target values can be developed using one of two different techniques:

1. By correlating the DCP results with observed dry unit weights, and selecting a target that would cause the failure rate for dry unit weight measurements (95% relative compaction criteria) to be the same as that for DCP measurements
2. By using empirically derived correlations between DCP measurements and other more widely accepted measures of soil strength, a minimum strength, or design strength can be chosen

The problem with the first method is that strength and dry unit weight are not well correlated. Therefore the assumption that each would have similar failure rates is likely to be poor. In fact high DCP measurements are much more often the result of high moisture contents than poor compaction. The second method is slightly more promising, since numerous correlations exist between the DCP and CBR as well as unconfined compressive strength; however this method still requires the choice of a control limit for the other strength test. This information could come from the values that were assumed for design or if design are not readily available than a minimum acceptable strength must be selected.

The current DCP index control limits from the QM-E were generated from numerous DCP tests conducted prior to the Phase III embankment research. For simplicity, DCP index control limits were generated for the different types of fill material; unsuitable, suitable, and select. This method happens to be convenient; however the strength behavior of different soils within anyone of these groups can be very different. At the same time, creating soil-specific criteria based upon on-site laboratory work also poses some logistical challenges for a project’s QC/QA operations. Being mindful of some of these concerns, ISU conducted some exploratory investigations into methods that might be used to develop DCP index control limits based upon soil compaction properties. The method that proved most viable, involved conducting CBR testing in accordance with ASTM D1883-05 over a range of moisture contents. An acceptable zone of DCP index values was then determined using the CBR-DCP index correlation for “all other soils,” equation 3, in ASTM D 6951-03 for the moisture control limits specified by the QM-E. This procedure was used on material collected during testing on August 17, 2006 from the Crow Creek embankment (test set C from ISU QA testing). The results are shown in Figure 46. The acceptance zone determined from this testing were DCP index values ranging from 18 to 54.8 mm/blow and a moisture range from +/- 2% optimum moisture content.

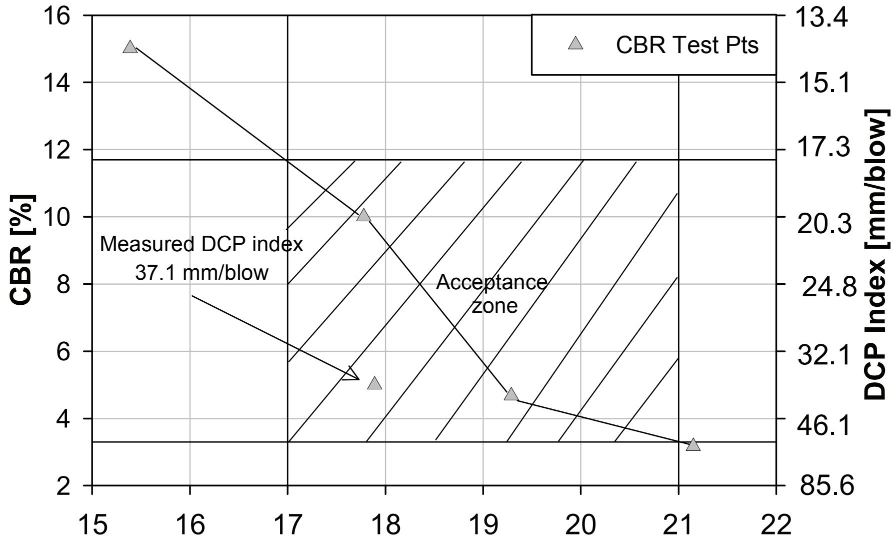

Figure 46. CBR testing results for unsuitable soil sample

Figure 47 shows the application of the modified control limits determined using the CBR method to the contractor QC and ISU QA data collected in test set B and C. Using these modified control limits six out of eleven ISU QA tests from set C passed the DCP index criteria, four out of eleven passed the moisture criteria, and only three out of eleven tests would have passed both criteria. In contrast, four out of five contractor QA tests passed the DCP index criteria, five out of five passed the moisture criteria, and four out of five passed both tests. For set B ISU data, 12 out of 14 tests passed the DCP index criteria, 3 out of 14 passed the moisture content criteria, and only 2 out of 14 passed both criteria. The contractor QC for test set B had 4 out of 5 tests pass the DCP index criteria, 4 out of 5 pass the moisture content criteria, and 3 out of 5 passed both criteria.

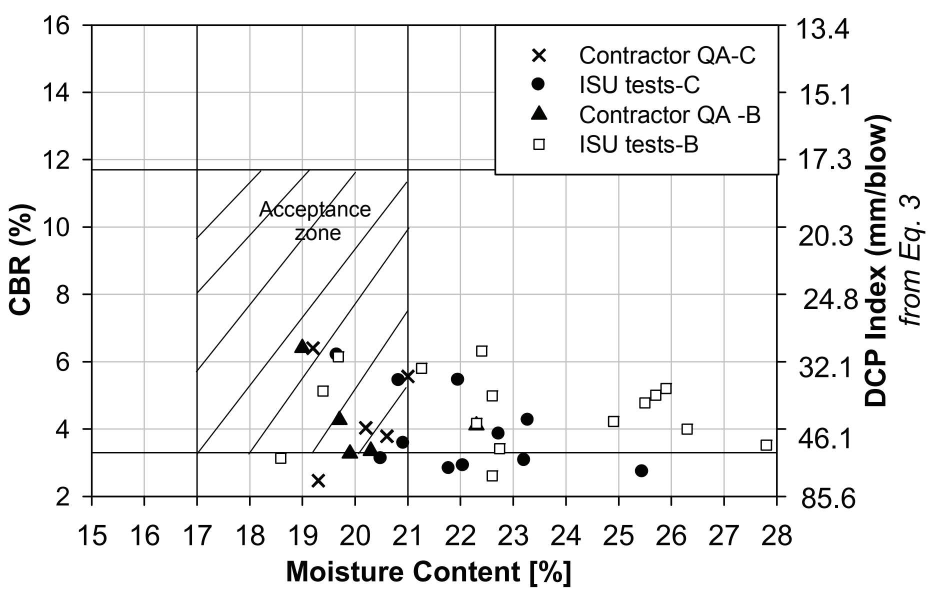

Figure 47. Contractor QC and ISU QA data from test set C with modified control limits

Based upon this preliminary testing, this new method appears to have significant potential to better develop DCP index acceptance criteria for fill material. The current QM-E DCP index target values are set based upon DOT soil classification. While the Iowa DOT soil classification takes into account some of the factors that affect the strength and performance of fill material, the system still represents a considerable simplification of reality. This new method would allow for greater flexibility and better accounts for effects of moisture on soil strength. Furthermore, with additional research this procedure could be utilized to completely eliminate the need for density testing from the QM-E special provision. This would improve the efficiency of applying the QM-E to embankment construction projects because the time required implement a density based quality control program would be much greater than the time to conduct supplemental strength testing on each set of Proctor tests.

Variation in DCP Index Target Values

The variation in DCP index control limits were developed in much the same way as the DCP index control limits. DCP testing was conducted on lifts of material that were purposely compacted to create the "Oreo cookie" effect. Trends among the collected DCP test data were then used to generate control limits for each soil type. Based upon an examination of DCP testing conducted throughout this study, a few issues were then identified with the equation that was used for determining variation in DCP index.

First, the variation in DCP index equation parameter relies primarily on the differences between successive DCP measurements. This has two effects on the calculation. First, the method is somewhat biased amongst soil types. DCP tests profiles in soils that tend to have lower or stronger average DCP index values are much less likely to exceed the variation in DCP index control limit than those in generally weaker soil. This is partially addressed by having various control limits for select, suitable, and unsuitable soil; however the differences amongst these limits are fairly modest.

The other problem with the calculation method is that the differences between successive DCP blows are multiplied by corresponding depths from the profile in attempt to use a weighted average method of calculation, as is the case for the DCP index equation. This averaging method works well for DCP index measurements because it weights the measurements for weaker soils more heavily resulting in a more conservative averaging of the values. Using this method for the variation in DCP index is problematic because the differences between successive DCP blows are not associated with a given depth from the profile. Furthermore, since there will always be one less difference between DCP measurements than there are measurements, this averaging system tends to result in an unconservative value. For example, if 10 DCP measurements are collected, there will be a total of 9 differences in values. Assuming that the difference between successive DCP index values for all measurements is 10, the resulting variation in DCP index will be less than 10 and thus unconservative in comparison to an averaging technique that involves each of the measurements.

An alternative method is proposed to determine the variability of a soil profile using DCP test data using equation 5.

$$\text{Average Variation in DCP Index} = \frac{1}{H}\sum_{n=1}^{x}\left|DCP_i - \mu\right| * h_i \qquad (5)$$

where H is the depth of the test layer, x is the number of DCP blows, μ is the average DCP index for the test layer, DCP_i is the DCP index of the i^{th} blow, and h^i is the layer depth associated with the DCP index of the i^{th} blow. Figure 48 shows a hypothetical DCP profile, the resulting variation in DCP index is 30.8 mm/blow. The new proposed variation in DCP index equation is graphically represented for the same profile in Figure 49, the average variation in DCP index using the modified method is 21.0 mm/blow.

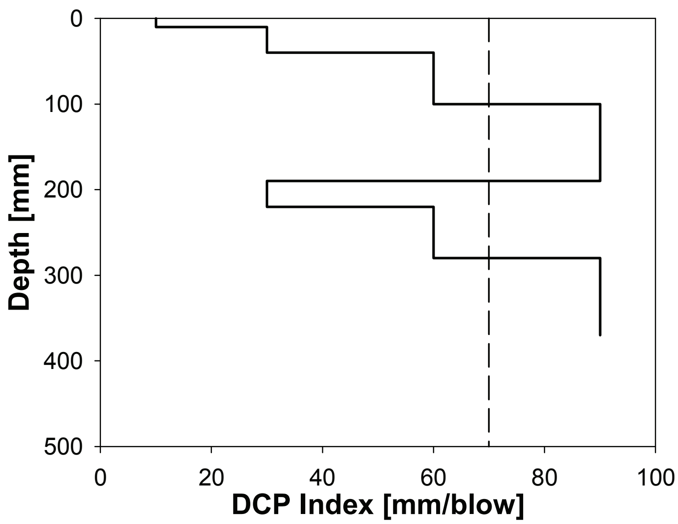

Figure 48. Hypothetical DCP Profile

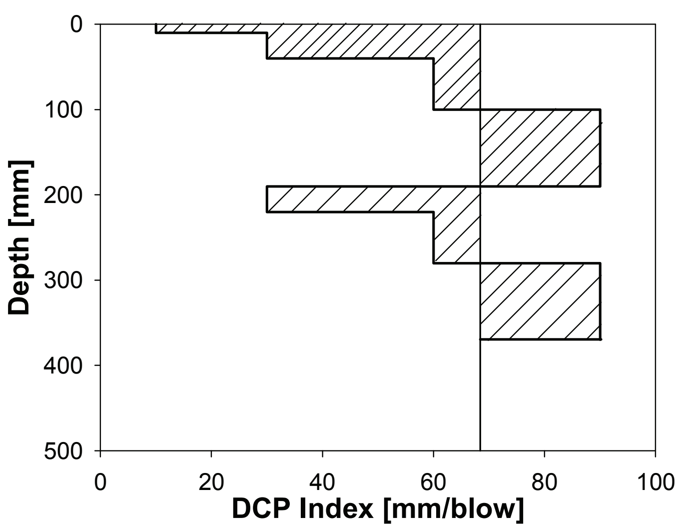

Figure 49. Graphical representation of alternative method for determination of average variation in DCP index

This alternative method represents a more robust calculation technique for the determination of the variability of a soil profile. Figure 50 shows a histogram using the modified method to calculate the variation in DCP index values for all of the data collected at the pilot project. This data indicates that the control limit of 40 mm/blow is too high for this new calculation technique. While additional research would be required to select suitable control limits for this new technique, the current control limit should be retained until additional research has been conducted.

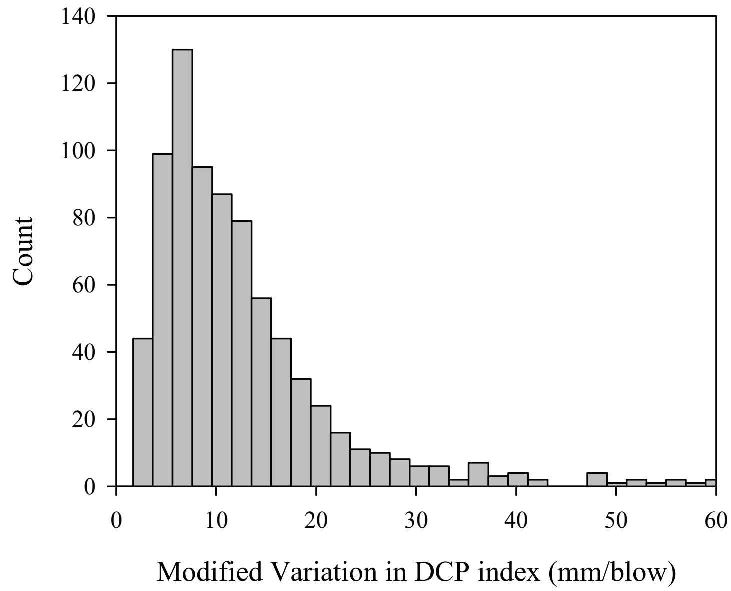

Figure 50. Histogram of modified variation in DCP index values calculated for pilot project test data

Crow Creek Embankment Performance

Iowa State University conducted a series of tests on the Crow Creek embankment in order to better assess the performance of the embankment. It was the largest embankment on the project required fill to heights as great as six meters and spanned approximately 0.5 km. Of greatest concern was that the natural subgrade soil in this area was compressible alluvial deposits. Before construction began longitudinal drains were installed and filled with erosion stones to allow for faster drainage of the soil. An approximately 1 m thick granular blanket was placed atop the existing grade to make the area stable for earth moving equipment.

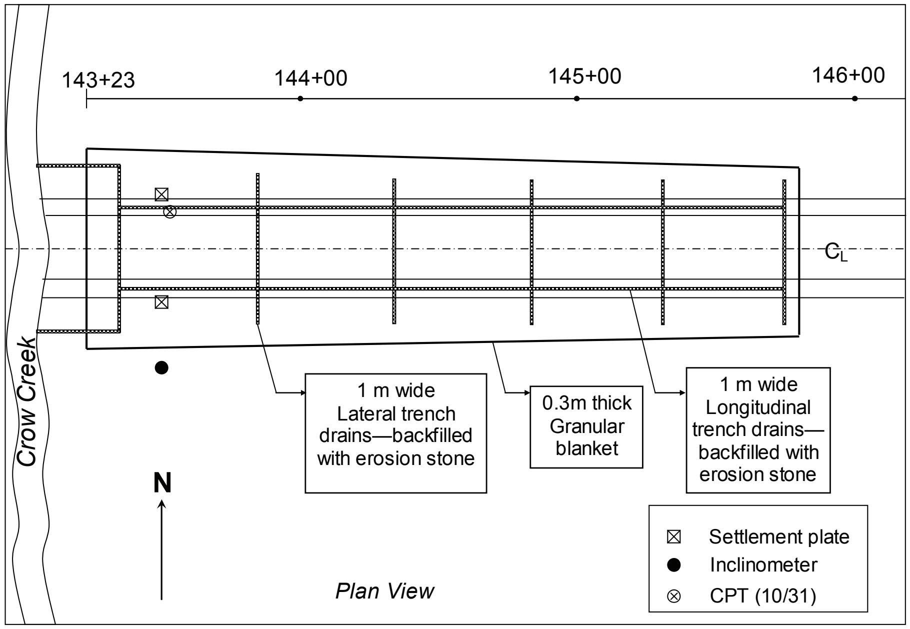

Figure 51. Plan view of Crow Creek embankment showing approximate locations of key design features and performance testing

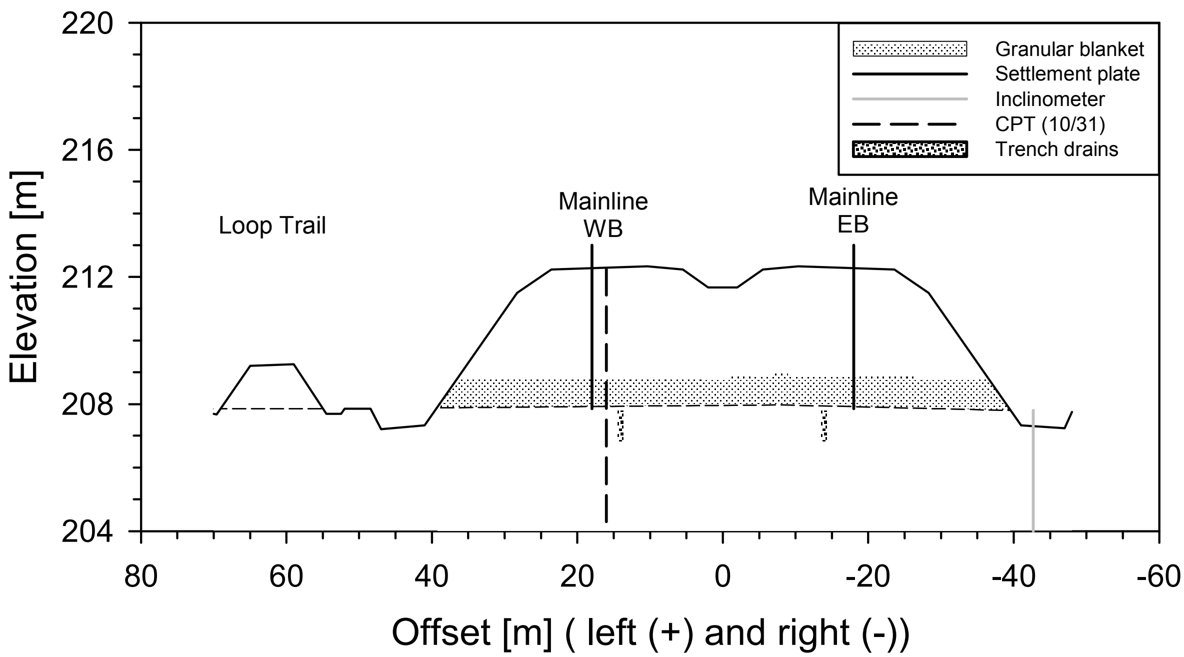

Figure 52. Profile view of Crow Creek embankment at STA 143+50 showing approximate locations of key design features and performance testing

Three cone penetration (CPTU) soundings and soil borings were also conducted at various times throughout the construction of the embankment to evaluate the strength of the embankment fill material.

The first two CPTU soundings were conducted on May 12, 2006. One sounding was conducted at STA 143+50 16 m right of centerline. This sounding was conducted to classify the strength of the natural material at the foundation of the embankment. The second sounding was conducted at STA 150+50 on centerline. This sounding was conducted in an unsuitable cut area to quantify the strength of undisturbed, future fill material. A soil boring was also taken in this cut area and unconfined compressive strength and soil classification testing was conducted. The results of both of the CPT soundings are shown in Figure 53 and Figure 54 and the results of laboratory work on the soil boring are shown in Figure 55.

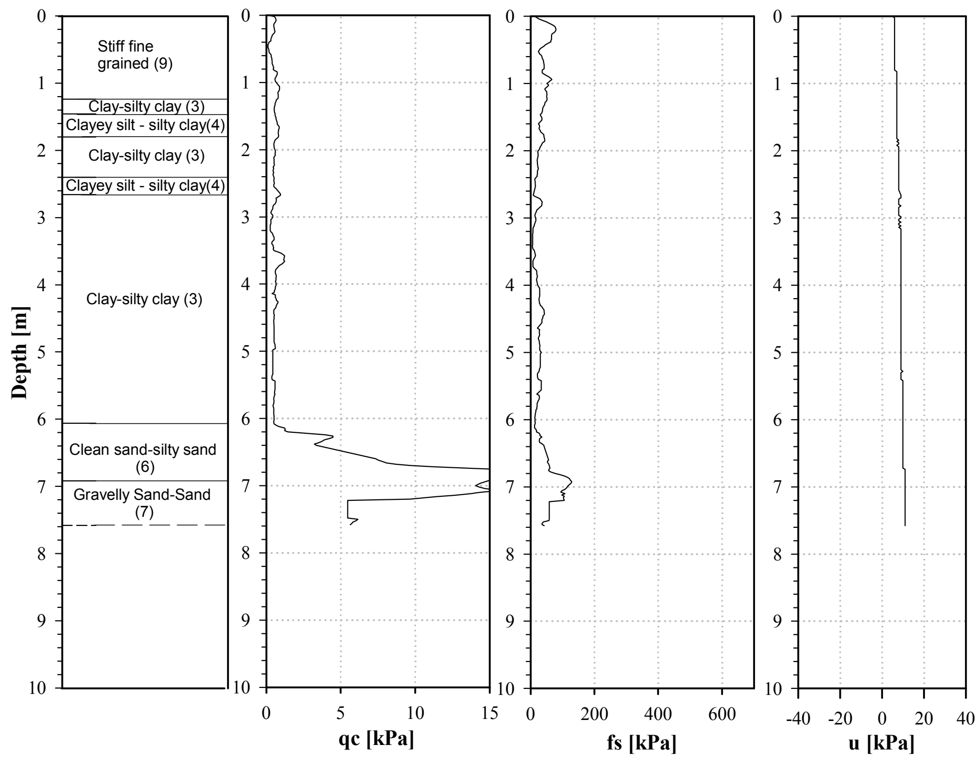

Figure 53. CPTU profile at STA 143+50 R CL 16 m on 5/12/2006

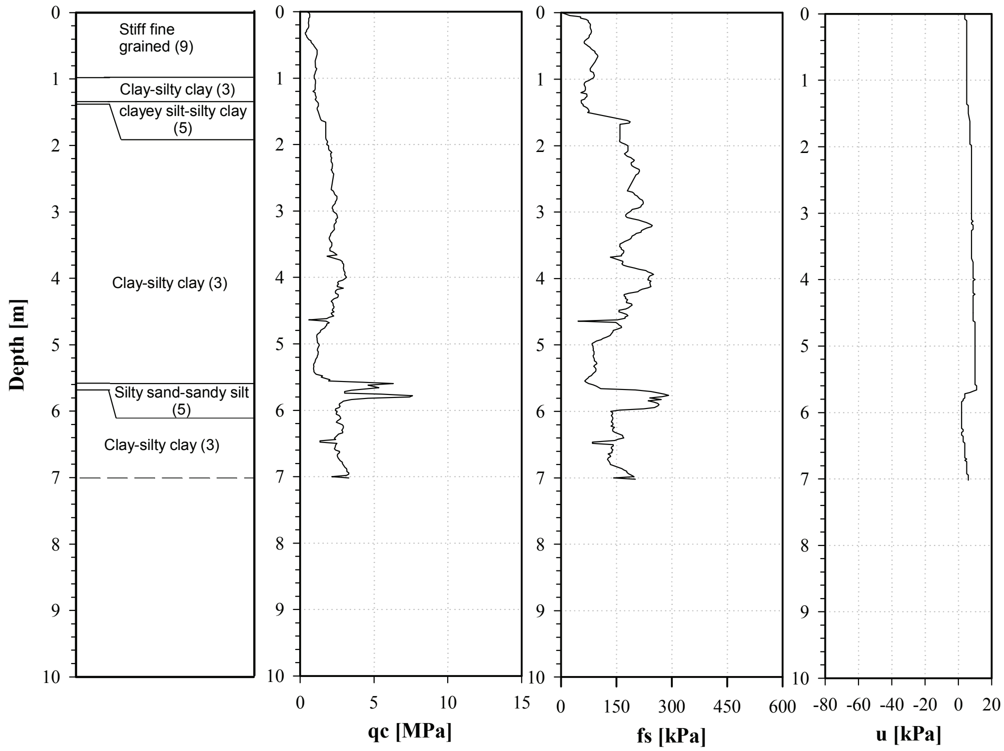

Figure 54. CPTU profile at STA 150+50 CL on 5/12/2006

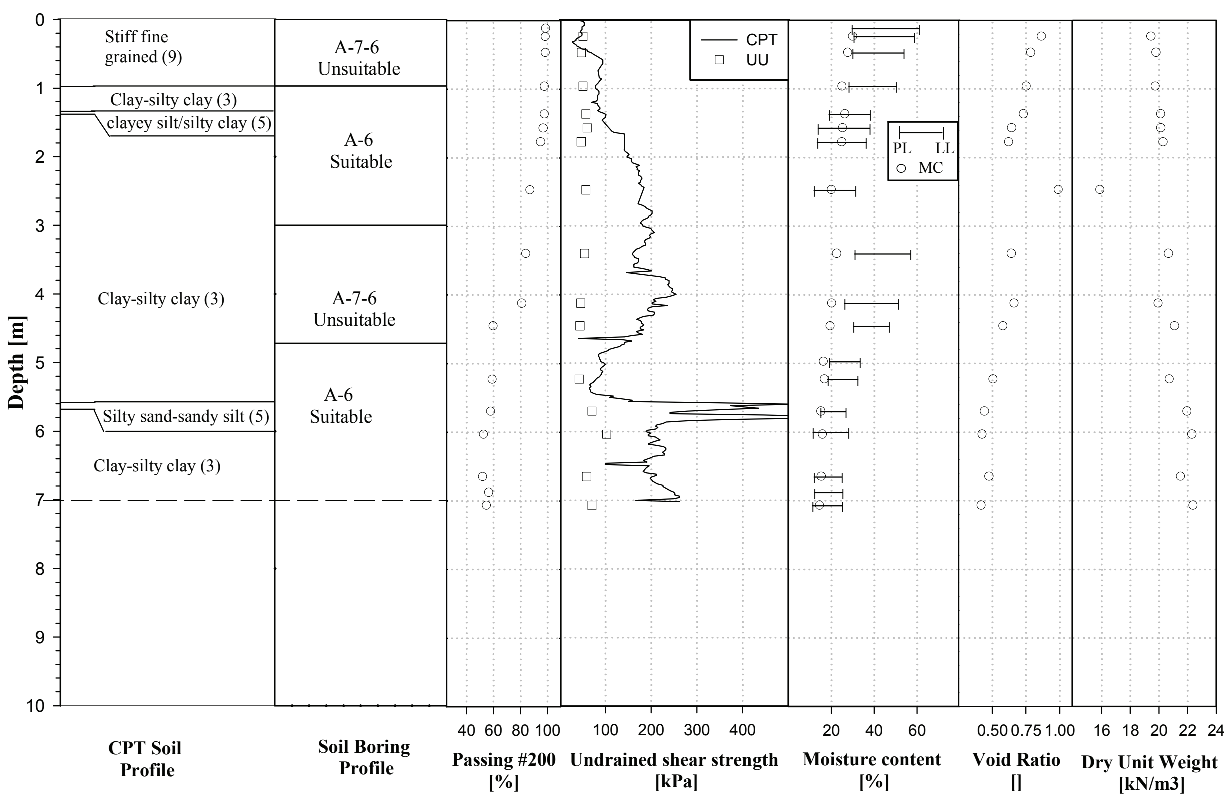

Figure 55. Soil profile at STA 150+50 CL

A final CPT sounding and soil boring were taken on October 31, 2006 at STA 143+50 left 14 m from centerline (Figure 56 and Figure 57). At the time of this test the embankment was at its final grade, with 4.4 meters of compacted fill. The results of the CPTU testing and laboratory testing on the soil boring are shown in Figure 58 and Figure 59, respectively.

Figure 56. CPTU testing conducted at STA 143+50 westbound Crow Creek embankment on 10/31/06

Figure 57. ISU soil boring at STA 143+50 westbound Crow Creek embankment on 10/31/06

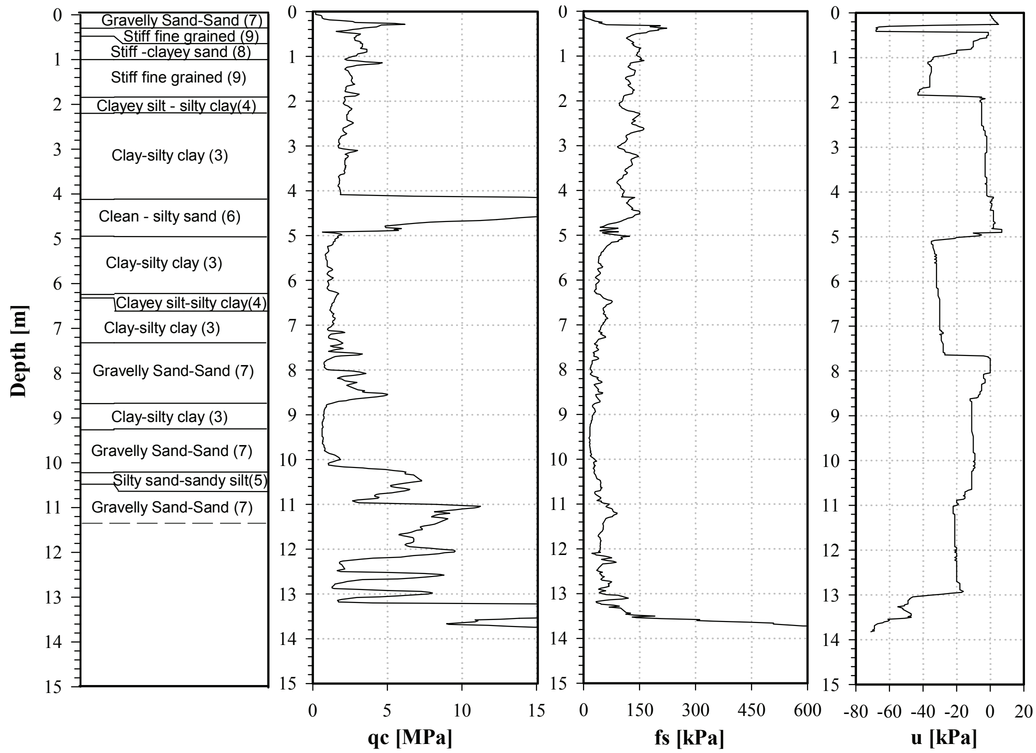

Figure 58. CPTU profile at STA 143+50 CL on 10/31/2006

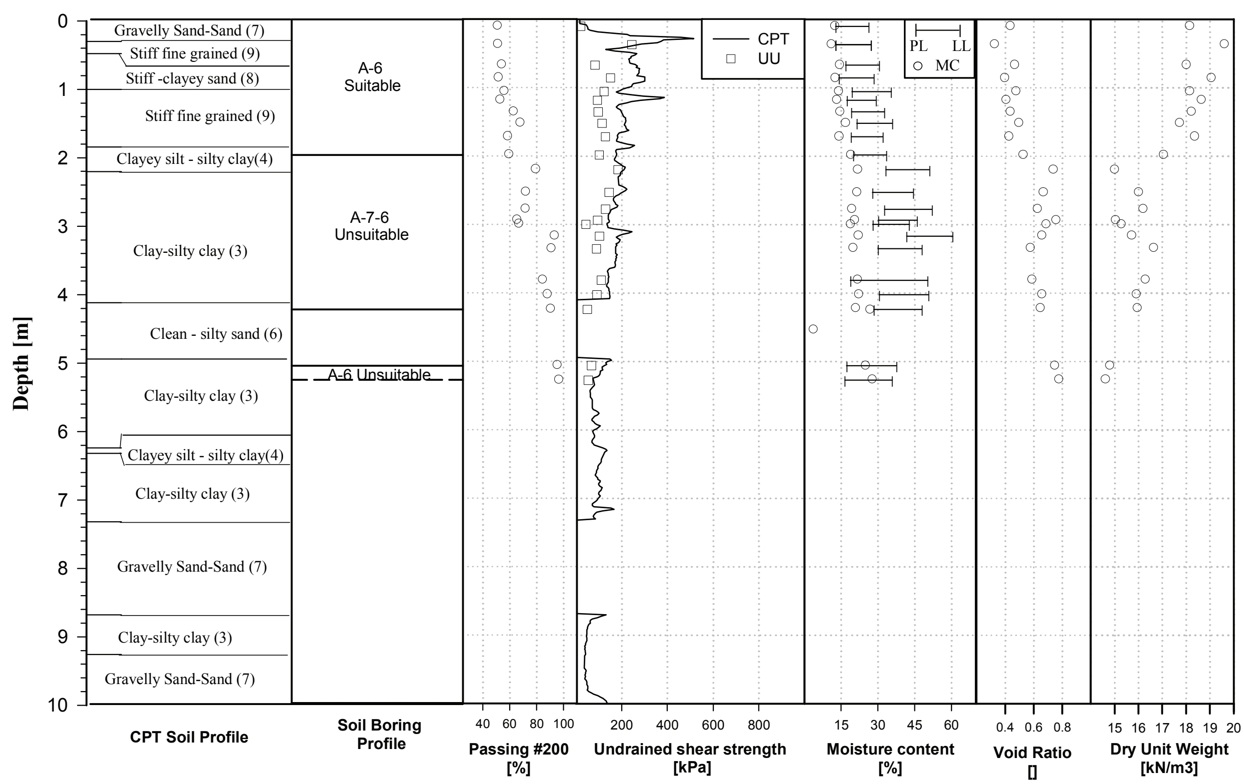

Figure 59. Soil profile at STA 143+50 CL

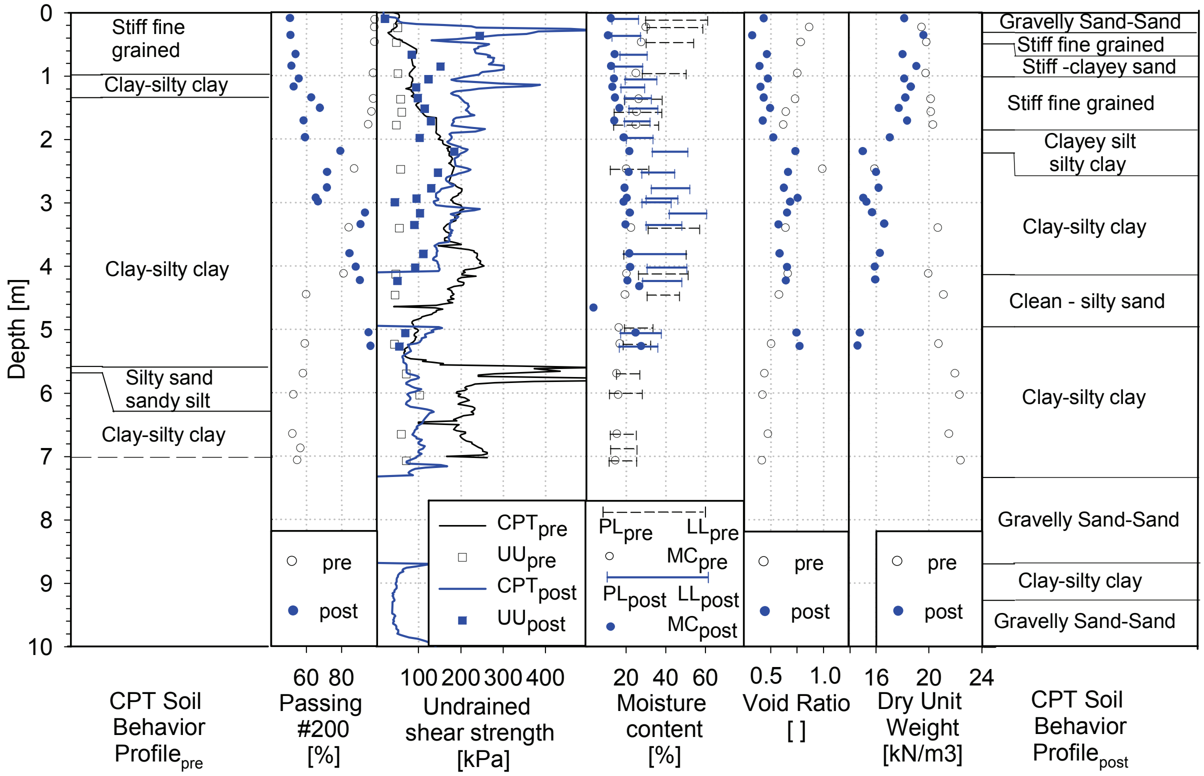

Figure 60. Comparison of soil performance and classification properties from CPTU and soil boring investigation at the Crow Creek embankment

The purpose of conducting this testing was to quantify the strength of the natural, undisturbed unsuitable fill material with the strength of the compacted unsuitable fill. In the boring conducted at STA 150+50 on May 12, 2006, the unsuitable material was present from depth 0 to 0.97 m and 3 to 4.72m. The average point resistance from CPT testing over these depth ranges was 0.77 MPa and 2.37 MPa, respectively. The average undrained shear strength of samples collected over the same ranges was 48.6 kPa and 49.4 kPa, respectively. In the boring conducted at STA 143+50 on October 31, 2006, the unsuitable material occurred from a depth of 1.98 to 4.12 m. The average point resistance from the CPT testing over this depth range was 2.19 MPa. The average undrained shear strength of samples collected over the same range was 93.6 kPa.

Although these results do not represent proof to a given level of statistical significance, they do suggest that the compacted unsuitable fill was stronger than the natural uncompacted soil; the compacted fill is at least not weaker. There are also a few interesting trends between the soil profiles in uncompacted cut material, Figure 55 , and compacted fill material, Figure 59. In Figure 55 the soil tends to decrease with regard to the fines content, increase with regard to the dry unit weight, and decrease with regard to the void ratio with increasing depth; however in Figure 59 all of these trends are reversed. These trends are not exactly surprising, but they may explain why the strength of the compacted soil is only as strong if not slightly weaker than the natural uncompacted fill.

Figure 61 shows a composite plot of all of the CPTU test soundings. The gray shaded area represents increased point resistance or shaft resistance resulting from compaction of the material. It is difficult to draw conclusions from this plot due to variations in soil properties from one soil boring to the next; however it is at least clear that the strength of compacted fill is not considerably larger than the strength of the uncompacted material.

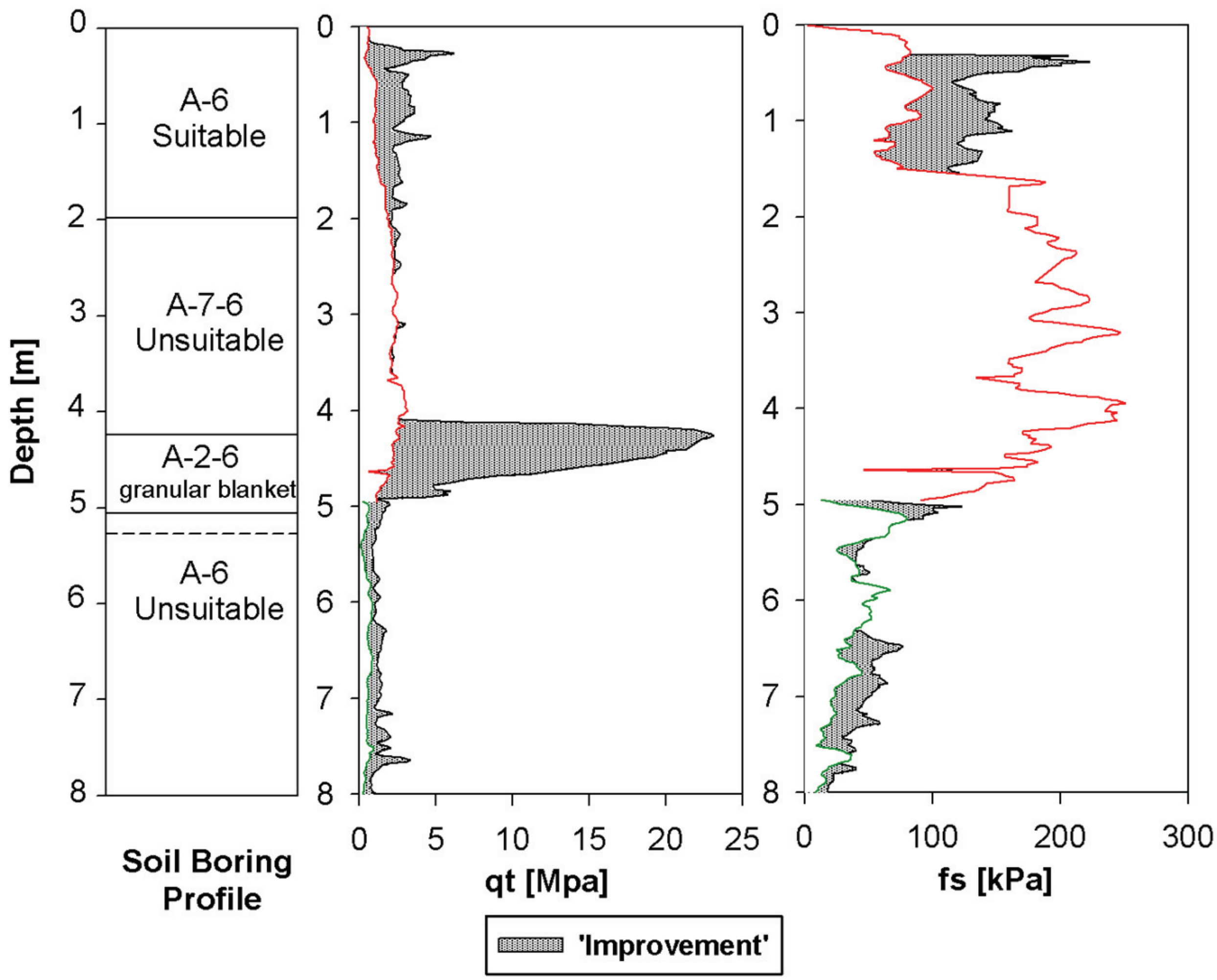

Figure 61. CPTU comparison plot illustrating "improvement" of subgrade

Settlement plates and an inclinometer were installed slightly before construction began to monitor the settlement and lateral spreading of the alluvial deposits at the foundation of the embankment. Two settlement plates were installed in the Crow Creek embankment: plate one was installed at STA 143+50 18 m left of centerline and plate two was installed at STA 143+50 18 m right of centerline. A Digitilt Indicator inclinometer was also installed at STA 143+50 42.7 m right of centerline on the south side of the embankment.

Figure 62 shows the results of settlement plate and fill height measurements throughout construction of the Crow Creek embankment. The dashed lines on the figure represent the dates of inclinometer readings. The settlements observed at plate one and two were 20 cm and 53 cm in April 2007, respectively. It is difficult to explain the large differences between the observed settlements at two plates that are so close to each other. One of the peculiarities of the settlement data is the increase in settlement that occurs at settlement plate one in March.

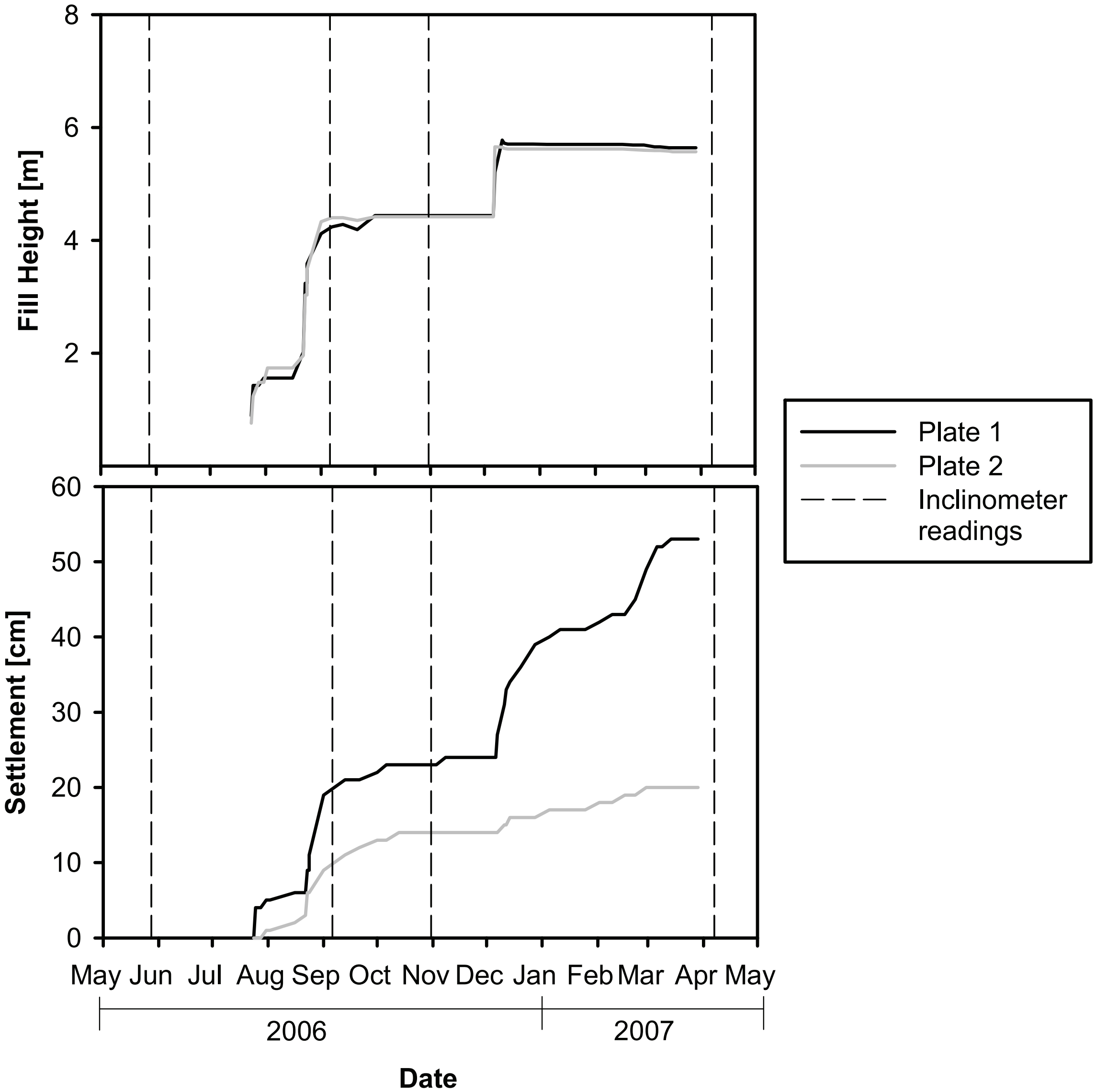

Figure 62. Settlement and fill height at plate 1 and 2 with time

Figure 63 shows the results of the inclinometer readings. Readings along the A-axis are positive in the south direction and negative in the north direction and readings on the B-axis are positive to the west, towards Crow Creek, and negative towards the east, away from Crow Creek. It appears that the top few readings may be in error or the casing was knocked out of alignment sometime between the time of installation and the first reading. The trend in the data is that there is increasing lateral movement away from the embankment and away from Crow Creek. However these movements are relatively small. The peak movement in the A direction (north – south) is 0.87 cm to the south at a depth of 3.7 m. The peak movement in the B direction (east-west) is 0.23 cm to the east at a depth of 6.7 m.

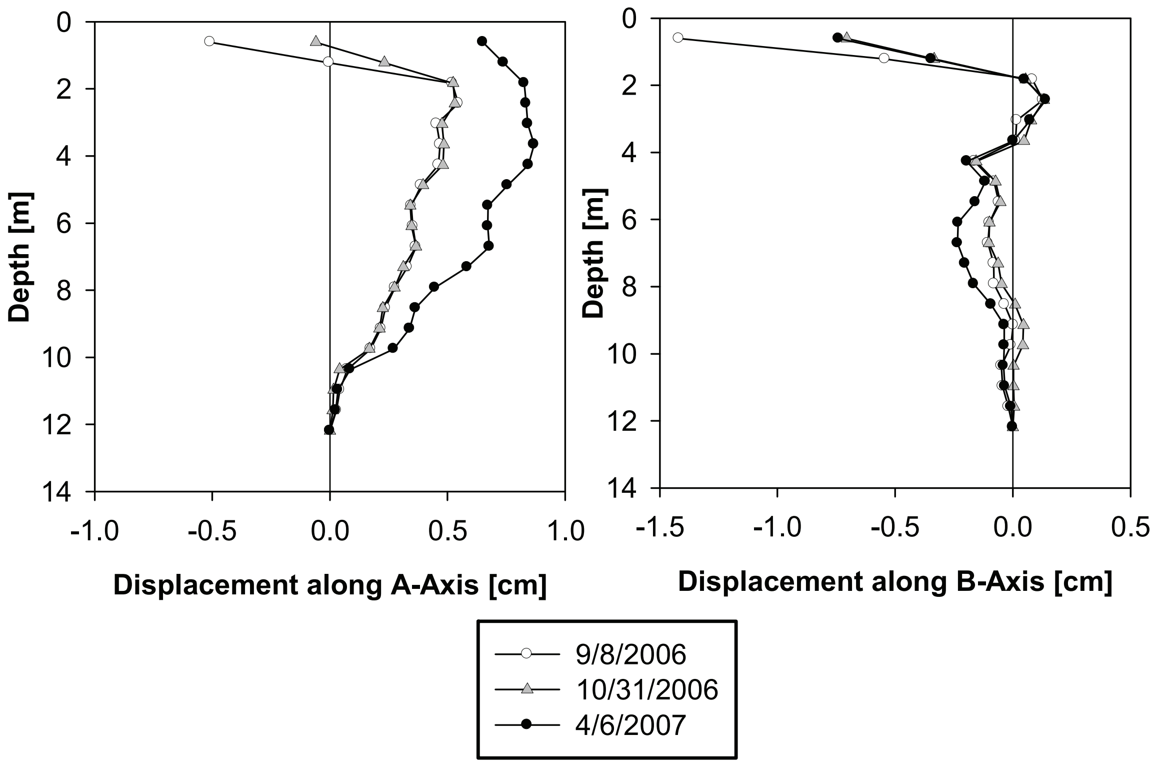

Figure 63. Inclinometer displacements for each reading in A and B directions

SUMMARY AND CONCLUSIONS

Based upon the results of this pilot project the following conclusions were reached:

1. The QM-E program was successfully implemented as a pilot project in predominately unsuitable soil with minimal delay. Management of the QC/QA data proved to be one of the most challenging aspects of the pilot project; however the G-RAD system was not utilized and if it had been used it is likely that the system would have alleviated some of the problems.

2. Comparisons between ISU determined values of Proctor optimum moisture content and dry unit weight and those used by the contractor often varied greatly. More aggressive proctor testing by the contractor would likely reduce these differences. One-point Proctor testing was primarily used and that is considered inadequate for most quality control programs. In many cases, results of a single Proctor test were used to establish control limits that were used for several months without retesting. In general, the number soil classification tests conducted by both the contractor and the DOT were less than the amount expected for good practice. In the future, only multipoint Proctors should be used to establish requirements for the dry density of compacted soil.

3. While the data collected for the pilot project seemed to indicate that the DCP index control limits could be set more tightly, there is not enough evidence to support making a change. However a new procedure was developed that aids in the establishment of appropriate DCP control limits. This new method utilizes CBR testing, conducted across a range of moisture contents to develop a DCP index acceptance zone. Preliminary testing seems to show this method has considerable potential because if it were successfully implemented it could eliminate the need to include density testing in the QM-E pilot specification. Additional research is required to confirm that this method should be implemented,

4. CPT testing in natural unsuitable cut material and compacted fill material revealed that the compacted fill had similar strength characteristics to that of the natural cut material after less than three months from the start of construction.

RECOMMENDATIONS

Based upon the results of this pilot project the following recommendations are made:

1. Implement G-RAD data collection system at upcoming projects throughout Iowa, to develop and refine the software for more widespread use. This software has considerable potential to reduce the time required to develop and of maintain QC/QA records for projects using the QM-E special provision; however the software has limited field testing.

2. Investigate the possibility that a link exists between the performance of subgrades and the observed vertical uniformity. It is possible that additional research will reveal that the variation in DCP index parameter could prove to be as important as soil strength for indicating the future performance of subgrade materials; however currently little investigation has been done regarding this link.

3. Revise the existing QM-E provisions to require additional material classification testing in the event that the four-point running average of relative compaction exceeds 105%. The Florida Department of Transportation , for example, currently includes such a provision in their requirement for construction projects, and based upon observations of the pilot project, this provision is required so that changes in material properties are detected as quickly as possible.

4. Consider investigating the use of the proposed CBR technique for the creation of soil specific DCP target values. This method addresses some of the shortcomings of using blanket control limits for broad ranges of soils classifications. Also, researchers believe that the additional time required to execute this additional testing is relatively small in comparison to other testing required by the QME specification; however, further investigation is required to assess the practicality of this method.

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APPENDIX A. QM-E SPECIAL PROVISION

Iowa Department of Transportation

SPECIAL PROVISIONS
FOR
QUALITY MANAGEMENT – EARTHWORK
(QM - E)

Jefferson County
NHSX-34-8(96)—3H-51

Effective Date
September 20, 2005

THE STANDARD SPECIFICATIONS, SERIES 2001, ARE AMENDED BY THE FOLLOWING MODIFICATIONS AND ADDITIONS. THESE ARE SPECIAL PROVISIONS AND THEY SHALL PREVAIL OVER THOSE PUBLISHED IN THE STANDARD SPECIFICATIONS.

INDEX

01xxx.01 DESCRIPTION.

A. GENERAL

Quality Management – Earthwork (QM-E) embankment construction shall consist of construction of test sections, documentation of test results, and placement and compaction of excavated materials in accordance with requirements obtained during the test sections.

It shall be the responsibility of the Contractor to test and ensure that the moisture content of the material is within the range for the particular soil being placed. The control limits for the moisture content of compacted embankment material shall be +/-2.0 percent of standard Proctor optimum moisture content (based on dry weight).

The test section involves construction of an embankment lift to determine the lift thickness and compaction procedures necessary to achieve required density and strength as determined by the Dynamic Cone Penetrometer (DCP) within the specified moisture limits.

B. DEFINITIONS:

Dynamic Cone Penetrometer – a penetration device used to assess the in situ strength of compacted soils. The device is operated by driving the DCP tip into compacted soil by lifting an 8 kg sliding hammer to a reference height and then releasing it. The total penetration for a given number of blows is measured and recorded in mm/blow, which is then used to describe soil strength.

DCP Index – Penetration per blow is the difference in cumulative penetration for each set of hammer blows divided by number of hammer blows between test readings (mm/blow). (See example calculation in Appendix A)

Average DCP Index – Sum of the DCP index values multiplied by the penetration depth for each calculated DCP index value divided by the total penetration depth. (See example calculation in Appendix A)

Variation in DCP Index – Sum of the change between consecutive DCP index values multiplied by the penetration depth for each calculated DCP index value divided by the total penetration depth. (See example calculation in Appendix A)

4-Point Moving Average – the average value of any consecutive four data points.

01xxx.02 CONSTRUCTION

A. QUALITY CONTROL PROGRAM

The Contractor shall provide and maintain a Quality Control Program, defined as all activities of training, sampling, testing, process control inspection, and necessary adjustments for construction of embankments to meet the requirements of this specification.

As part of the Quality Control Program, the Contractor shall provide a technician who will be trained to perform the required testing on all embankment and subgrade soils placed on this project. The technician shall be dedicated full-time to testing and quality control, and shall be present on the project when embankment is being placed. As a minimum, the technician shall have a high school education and knowledge of earthwork construction.

The Contracting Authority will provide training for the technician to become a 'Certified Grading Technician I'. After the contract has been executed and prior to starting embankment work on this project, the technician shall be available for three days of full-time training in soil classification and testing at Iowa State University in Ames and two days of full-time training at the project site. The technician shall successfully complete the training course and examinations. The Contracting Authority will provide training for up to three of the Contractor’s technicians. Training at Iowa State University will be conducted prior to initiating construction as agreed upon by all parties.
In an emergency, the Contractor will be allowed to operate a total maximum of two working days during the contract without a Certified Grading Technician I on the project site. Embankment placement and compaction during this period shall be as per Article 2107.09 of the Standard Specifications. During the two working days, the Engineer will determine moisture limits and perform tests for moisture content. Moisture limits shall be those specified in Article 01xxx.01. Test frequency for moisture content shall be every 500 m^3 of compacted volume. After two working days, if the

Contractor cannot provide a trained Certified Grading Technician I, the Engineer will suspend construction operations.

B. QM-E FIELD LABORATORY

1. Facilities Furnished by Contractor

The plans require one Field Laboratory as per Section 2520 of the Standard Specifications and one separate QM-E Field Laboratory. The QM-E Field Laboratory shall meet the requirements of Section 2520 of the Standard Specifications with the following additions:

a. A deep wash sink with potable water supply.

b. A portable shed with minimum dimensions of 3.1 m by 3.1 m and 2.44 m of headroom shall be provided on a 0.15 m concrete floor on grade. This facility shall be adjacent to and considered as part of the QM-E Field Laboratory. It shall be able to support equipment for Proctor compaction and a Rapid Soil Processor (185 kg, 115V 60Hz).

   As an alternative, the Contractor may provide a utility tool trailer capable of housing and supporting this equipment and providing adequate working room for testing. The trailer is subject to approval of the Engineer. The shed or tool trailer shall be weather tight and include adequate lights and electrical outlets. The door shall be wide enough to allow passage of a Rapid Soil Processor frame, which is approximately 1 m by 1 m.

The following QM-E Field Laboratory testing equipment shall be supplied by the Contractor. The Contractor shall retain ownership of this testing equipment after completion of the contract. The following list of specific models are recommended. Other equivalent equipment may be furnished with approval of the Engineer.

(1) Rapid Soil Processor, Model H-4215, purchased from Humboldt Mfg. Co., or approved equal;
(2) Two Atterberg Limit test sets (plastic limit and liquid limit);
(3) Two sets of 0.425 mm and 0.075 mm sieves (8 inch diameter);
(4) Standard Proctor set with compaction molds (two 4-inch diameter molds and one 6-inch diameter mold) and one standard Proctor drop hammer;
(5) Dynamic Cone Penetrometer deluxe test kit with an additional 500 disposable cone tips, purchased from Kessler DCP, Inc., or approved equal;
(6) Bench laboratory grade oven (approximate capacity 35 L or greater);
(7) Laboratory grade microwave oven;
(8) Kessler Field Moisture Oven, Model FMO200, or approved equal;
(9) Electronic balance (capacity 12,000 g to +/- 0.1 g);
(10) Two metal sawhorses and one 1.22 m by 2.44 m sheet of 19 mm thick plywood
(11) 0.5 m box electric fan; and
(12) Computer and laser printer for data logging, analysis, reports, and e-mail. Minimum requirements: Pentium IV 500 MHz, Windows XP, spreadsheet, word processing, 56K modem, and Internet access.

2. Facilities Furnished by the Contracting Authority.

The following QM-E Field Laboratory testing equipment will be supplied by the Engineer. The Contractor shall return this equipment to the Engineer following completion of the contract.

(1) Two G-RAD (Geotechnical – Remote Acquisition of Data) Pocket PC and GPS system for data collection, analyses, and control chart generation; and
(2) Microsoft Excel spreadsheets for data entry and analysis.

C. TEST PROCEDURES

All test procedures and equipment shall conform to applicable Materials I.M.'s, Iowa DOT Materials

Laboratory Test Methods, or to equivalent standards of the AASHTO or ASTM standards.

Equivalent standards shall be subject to review by the Engineer and mutually agreed upon by the Engineer and Contractor.

Acceptable test methods for determining moisture content are:

Oven drying	AASHTO T 265
Pan drying	ASTM D 4959
Microwave	**ASTM D 4643**
Nuclear gauge	Materials I.M. 334

AASHTO T 265 oven drying method shall be considered the reference method for calibration. The minimum sample size for moisture content is 500 g.

D. CONSTRUCTION EQUIPMENT

1. Equipment for Compaction

For embankments constructed on this project, any type of compaction equipment may be used which produce the desired end results as demonstrated by the test section test results.

2. Equipment for Moisture Conditioning Soil

The distributor shall be equipped to distribute water evenly over the intended area. The equipment used for disking shall be capable of mixing and aerating the entire placed lift.

E. TEST SECTIONS

1. General

A representative soil sample shall be taken prior to construction of the test section. The soil shall be classified as per Article 2102.06 of the Standard Specifications, including tests to determine standard Proctor (Iowa DOT Materials Laboratory Test Method 103), optimum water content, and maximum dry density.

An initial test section shall be constructed prior to embankment construction. Additional test sections shall be constructed when the optimum moisture content change by 2 percent.

The Engineer will be given the opportunity to witness the construction of the test section(s).

After the test section(s) are performed, all embankments shall be constructed using the same compaction equipment, minimum number of equipment passes, and lift thickness indicated by test sections for each soil classification unless the Engineer approves modifications.

Test sections shall be incorporated into the embankment.

2. Dimensions of Test Section

Minimum dimensions of the test section shall be:

Length: 50 m
Width: 10 m
Depth: one lift thickness

3. Testing Requirements

Four random locations within each test section shall be tested for:

a) Thickness of compacted lift
b) Moisture content of compacted lift
c) Density of compacted lift

d) Average DCP Index of compacted lift
e) Variation in DCP Index of compacted lift

Tests shall be conducted the same days as the test section construction.

4. Moisture Requirements.
Moisture content shall be calculated and reported to the nearest 0.1 percent based on dry weight of soil.

All moisture contents measured in test sections must be within the specified moisture control limits.

5. Density Requirements of Compacted Soil
It shall be the responsibility of the Contractor to test and ensure that the compacted dry density of the material in the tests sections is at least 95 percent of the standard Proctor maximum dry density for the particular soil being placed.

Dry density shall be calculated and reported to the nearest 1 kg/m^3 based on dry weight of soil.

The 4-point moving average of dry density must be within equal to or above 95 percent of standard Proctor maximum dry density.

6. DCP Index Requirements
DCP Index shall be measured for the full depth of the compacted lift using the DCP as described in ASTM D 6951.

The Average DCP Index value for each test shall not be greater than that shown below for a four point moving average. Further, the Variation in DCP Index between consecutive readings in a single test shall not be greater than that shown below:

Soil Classification		Average DCP Index (mm/blow)	Variation in DCP Index (mm/blow)
Cohesive	Select	65	35
	Suitable	70	40
	Unsuitable	70	40
Granular	Suitable	45	45
	Select	35	35

DCP index values shall be calculated and reported to the nearest 1 mm. An example data sheet and sample calculation procedures to determine Average DCP Index and Variation in DCP Index are provided in Attachment A.

During test section construction tests to determine the dry density and DCP index values shall be performed at the same locations for comparison. If from the test section evaluations it can be shown that 95 percent of standard Proctor maximum dry density can be achieved at higher DCP index values (refer to table above), the Engineer will evaluate the results and establish a new maximum Average DCP Index and Maximum Variation in DCP Index to be used for the remainder of that soil type or until the next test section is constructed.

7. Compaction Effort and Lift Thickness
From the test results of the test sections, acceptable lift thickness, compaction equipment, and number of passes shall be determined.

Compacted lift thickness shall be measured and recorded concurrently with moisture, density, and DCP index tests.

8. Documentation requirements
The following information shall be documented from each test section.

a) Equipment type and weight,
b) Minimum number of equipment passes,
c) Maximum compacted lift thickness,
d) Moisture content,
e) In-place dry density,
f) DCP Index values,

Documentation shall be provided to the Engineer on the same day.

F. EMBANKMENT CONSTRUCTION

The embankment shall be constructed in accordance with the lift thickness, moisture content limits, DCP index values, and compaction procedures determined in the test sections.

1. Preparation of Site

When Class 10 material is placed in areas where unstable soils have been excavated and the thickness of backfill placed is 0.6 m or more, the condition of underlying soil may limit the amount of compaction to be done in the bottom 0.3 m of embankment or subgrade treatment. In exceptionally wet or unstable areas, the Contractor may be permitted to end dump the first 0.3 m of backfill material and doze it into position with only partial compaction. For this first 0.3 m, the requirements of Article 01xxx.02, E, will not apply. For this first 0.3 m, the requirements of Article 01xxx.02, F, will not apply except for part (3), Moisture Content of Compacted Lifts. Material above the bottom 0.3 m in such areas shall be compacted as provided in these Special Provisions.

2. Depositing Embankment Material

Except for granular blankets, embankments shall be deposited in horizontal layers at uniform thickness. The outer portion of an embankment shall be kept lower than its center, and wherever construction is to be suspended for a period during which rain is likely to occur, the surface shall be smoothed to produce a surface sufficiently smooth and compact to shed water. Soils containing quantities of roots, sod, or other vegetable matter shall be deposited outside of the shoulder line and within the outer 1 m of the embankment. Tree stumps and other large woody/organic objects shall not be deposited in embankments. Embankments shall not be constructed on frozen ground, and frozen material ($\leq 0°C$) shall not be used in construction of embankments.

3. Moisture Control of Deposited Material

It shall be the responsibility of the Contractor to test and ensure that the moisture content of the material is within the specified range for the particular soil being placed.

If the deposited soil material contains moisture in excess of the specified moisture limits, disking to remove excessive moisture shall be done to uniformly dry the material to within the specified moisture limits prior to compaction of the layer.

Should the deposited material be dry to the extent that it is not within the specified moisture limits, the material shall be moistened uniformly to the required limits before it is compacted.

Aeration and compaction operations shall proceed in an orderly fashion without unreasonable and unnecessary delay. Compensation will not be allowed for delays associated with drying or moistening the soil.

Moisture content shall be calculated and reported to the nearest 0.1% based on dry weight of soil.

All moisture contents measured in test sections must be within the specified moisture control limits.

4. Compaction of Deposited Material
After the surface of the layer has been smoothed and before material for the next layer is deposited upon it, the layer shall be compacted using the equipment and rolling pattern as indicated by the test section. In addition, compaction shall continue until the required DCP index values are achieved.

If rubber tired or steel drum type rollers are used for compaction of cohesive soils, the finished surface shall be roughened by a light disking or other approved means to provide interlock between lifts.

5. Lift Thickness
The 4-point moving average of lift thickness shall not exceed the value established in the test section. If lift thickness exceeds the established value, a new test section shall be conducted.

6. DCP Index Control Limits
The control limits for Mean DCP Index and Mean Change in DCP Index shall be in accordance with Article 01xxx.02, E, 6.

G. TEST REQUIREMENTS DURING TEST SECTION AND EMBANKMENT CONSTRUCTION
Lift thickness, moisture content, and DCP index tests shall be obtained at the same location and measured for each lift of embankment being placed. DCP index tests shall be taken to a penetration depth equal to the full depth of the compacted lift.

Test	**Minimum Test Frequency**
Lift Thickness	Concurrently every 500 m^3
Moisture Content	
DCP	
Determination of soil classification, standard Proctor maximum dry density, and optimum moisture content	Every 20,000 m^3

Four random locations within a test section shall be used to establish an average for subsequent fill placement of the same soil classification.

H. FIELD RECORDS

The Contractor shall be responsible for documenting all observations, records and inspection, changes in soil classification, soil moisture content, fill placement procedures, and test results on a daily basis. The results of the observations and records of inspection shall be noted as they occur in a permanent field record. Copies of the field DCP index tests, field moisture tests, lift thickness measurements, running average calculation sheets, soil classification, field test section construction procedures, and soil classification shall be provided to the Engineer on a daily basis. The original testing records (G-RAD data files and raw field and lab data sheets) and control charts shall be provided to the Engineer in a neat and orderly manner within five calendar days after completion of the project.

I. CONTROL CHARTS

Standardized control charts shall be maintained for each grading area by the Contractor for field DCP index, field moisture, field density tests, and compacted lift thickness measurements. The charts shall be posted at a location agreed upon by the Contractor and the Engineer. Test results obtained by the Contractor shall be recorded on the control charts the same day the tests are conducted. The results for the described field data shall be recorded on the standardized control charts for all randomly selected subgrade cut and fill locations tested.

Both the individual test point and the moving average of four data points shall be plotted on each chart. The Contractor's test data shall be shown as black (filled) circles and the moving average in unfilled circles. Additional tests or retests, which have been randomly selected, shall be plotted in gray. Other means of chart plotting may be used when approved by the Engineer. Legends used on the control charts shall be consistent throughout the project. Refer to Attachment A for format and examples of Control Charts.

J. CORRECTIVE ACTION

The Contractor shall notify the Engineer when a single Moisture Content test or DCP value is out of the limits. The Contractor shall make corrections before the next lift is placed.

1. End-Result Tests (Moisture, Density, and DCP Index Values)

If the corrective action improves the failed field test such that the new moving average, after a re-test, is within the control limit, the Contractor may continue subgrade cut or fill material placement.

If the new moving average point is still outside of the control limit after the re-test, the subgrade fill material in the recently tested area shall be considered unacceptable. If the embankment material is considered unacceptable, the Contractor shall perform additional corrective action(s) to improve the fill material until the new 4-point moving average, after re-tests, fall within the control limits.

2. Incorrect Data

If the Contractor's initial control data is later proven incorrect, which results in a corrected single Moisture Content or a corrected 4-point moving average of Average DCP Index or Variation in DCP Index falling outside of the control limits, the subgrade fill material represented by the incorrect test data shall be considered unacceptable. The Contractor shall employ the methods described above for unacceptable material.

K. ACCEPTANCE TESTING

1. Required Testing and Personnel Requirements

The Engineer will conduct acceptance tests on split samples taken by the Contractor for soil classification, laboratory compaction testing, and soil moisture content limits determination. These samples may be from sample locations chosen by the Engineer from anywhere in the process. The frequency of testing for the split samples will be equal to or greater than 10 percent of the tests taken by the Contractor. The acceptance test results will be provided to the Contractor within one working day after the Contractor's quality control test results have been reported.

The frequency of acceptance testing for the field DCP index, field moisture tests and compacted lift thickness measurements will be equal to or greater than 10 percent of the tests taken by the Contractor. The results of testing and measurement will be provided to the Contractor on the day of testing.

The Engineer will periodically witness field testing being performed by the Contractor. If the Engineer observes that the quality control field tests are not being performed in accordance with the applicable test procedures, the Engineer may stop production until corrective action is taken.

The Engineer will notify the Contractor of observed deficiencies, promptly, both verbally and in writing. The Engineer will document all witnessed testing.

2. Testing Precision

The Engineer's laboratory acceptance tests will be conducted on a split sample of the Contractor's quality control test; field acceptance tests will be conducted on the same lift and within 0.3 m distance of the quality control tests.

In the event comparison test results are outside the following allowable differences, the Engineer will investigate the reason immediately. The Engineer's investigation may include testing of other locations, and review of observations of Contractors testing procedures, equipment, and calculations.

a) Moisture Content

Moisture content shall be calculated and reported to the nearest 0.1percent. Differences between the Contractor's and the Engineer's moisture content test results will be considered acceptable if moisture content is within 0.5percent based on dry weight of soil.

b) Optimum Moisture

Differences between the Contractor's and the Engineer's Proctor test results will be considered acceptable if the optimum moisture is within 0.5 percent based on dry weight.

c) Dry Density

Dry density shall be calculated and reported to the nearest 1 kg/m^3. Differences between the Contractor's and the Engineer's dry density test results will be considered acceptable if density is within 25 kg/m^3 based on dry weight of soil.

d) DCP Index

There is no accepted reference value for the DCP index test. Therefore, bias cannot be determined.

3. Referee Testing

If a difference in procedures for sampling and testing and/or test results exists between the Contractor and the Engineer which they cannot resolve, the Iowa DOT Central Materials Laboratory or another mutually agreed upon independent testing laboratory will be asked to provide referee testing. The Engineer and the Contractor shall abide by the results of the referee testing. The party found in error shall pay service charges incurred for referee testing by an independent laboratory.

L. ACCEPTANCE

The Engineer will base final acceptance of tests and materials on the results of the Contractor's quality control testing as verified by the Engineer's acceptance test results.

01xxx.03 METHOD OF MEASUREMENT

All excavation in preparation for and construction of QM-E embankment shall be included in Class 10 Excavation in accordance with Article 2102.13 of the Standard Specifications. The construction of embankment will not be measured separately for payment except as follows:

A. QUALITY CONTROL PROGRAM

The item will be the lump sum for the Quality Control Program.

B. QM-E FIELD LABORATORY

The Engineer will count the QM-E Field Laboratory.

01xxx.04 BASIS OF PAYMENT

Except as listed herein, the work of building QM-E embankments will not be paid for directly, but will be considered as incidental to the price bid for the specific bid items.

A. QUALITY CONTROL PROGRAM

The cost associated with the pre-construction training and the furnishing of a full-time Certified Grading Technician I, during construction shall be included in the item for Quality Control Program. This shall include all labor, sampling and testing, process control inspection, documentation, and necessary adjustments for construction of test sections and embankments to meet the requirements of this Special Provision.

B. QM-E FIELD LABORATORY

For the QM-E Field Laboratory furnished, the Contractor will be paid the contract unit price for QM-E Field Laboratory. This payment shall be full compensation for furnishing, moving, and maintaining the QM-E Field Laboratory, including a shed or trailer to house additional testing equipment, and for furnishing the utilities and sanitary facilities.

Mean DCP Index and Mean Change in DCP Index Data Sheet

Project_______________________________________ **Date**______________________

Test Location and Elevation_____________________ **Personnel**_________________

Weather Conditions____________________________ **Hammer Weight**____________

Material Classification___________________________ Moisture Content____________

Point No. (1)	**Number of Blows (2)**	**Penetration Depth, (mm) (3)**	**Change in Depth between Consecutive Readings (mm) (4)**	**DCP Index (mm/ blow) (5)**	**Change in DCP Index between Consecutive Readings (6)**
1	1	115	115	115	
2	1	223	108	108	7
3	2	270	47	24	85
4	1	354	84	84	61
5	1	475	121	121	37
6	3	540	65	22	99
7	3	599	59	20	2
8	3	652	53	18	2
9	1	703	51	51	33
10	2	748	45	23	29
11	1	823	75	75	53
12					
13					
14					
15					
16					
17					
18					
19					
20					

(7) Average DCP Index	=	**73.**
(8) Variation in DCP Index	=	**34.**

(1) Point number for each DCP Index increment consecutively starting at 1.
(2) Number of hammer drops to penetrate at least 25 mm. Record every blow separately for penetration per blow ≥ 25 mm
(3) Total penetration depth starting from zero.
(4) Depth change per penetration depth reading (Column 3) (e.g. = depth for point no. 2 – depth for point no. 1)
(5) DCP Index = [column 4/column 2]
(6) Change in DCP index per reading (e.g. = absolute value of [DCP index point no. 2 – DCP Index point no. 1])
(7) Average DCP Index = (Sum of all points [column (4) x column (5)]) / [Total Penetration Depth]
(8) Variation in DCP Index = (Sum of all points [column (4) x column (6)]) / [Total Penetration Depth]

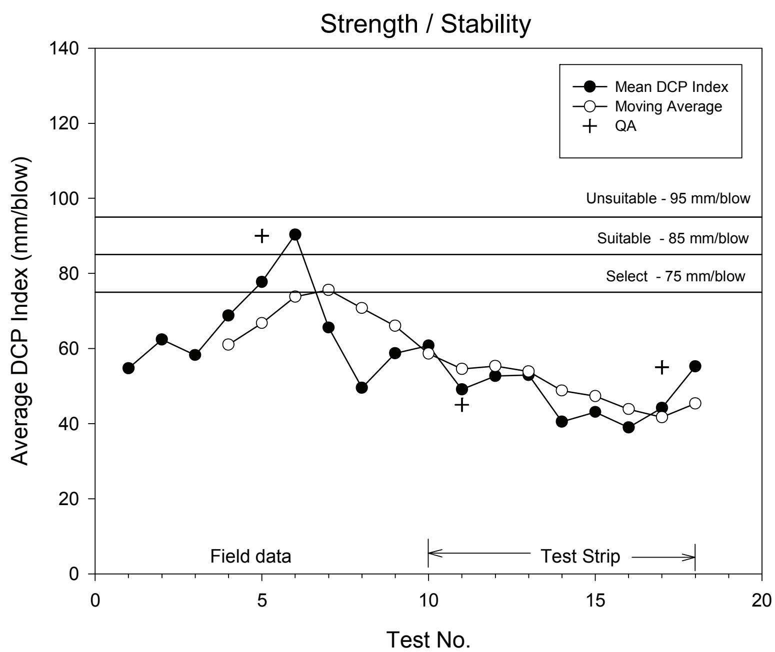


Figure 1. Mean DCP Index control chart

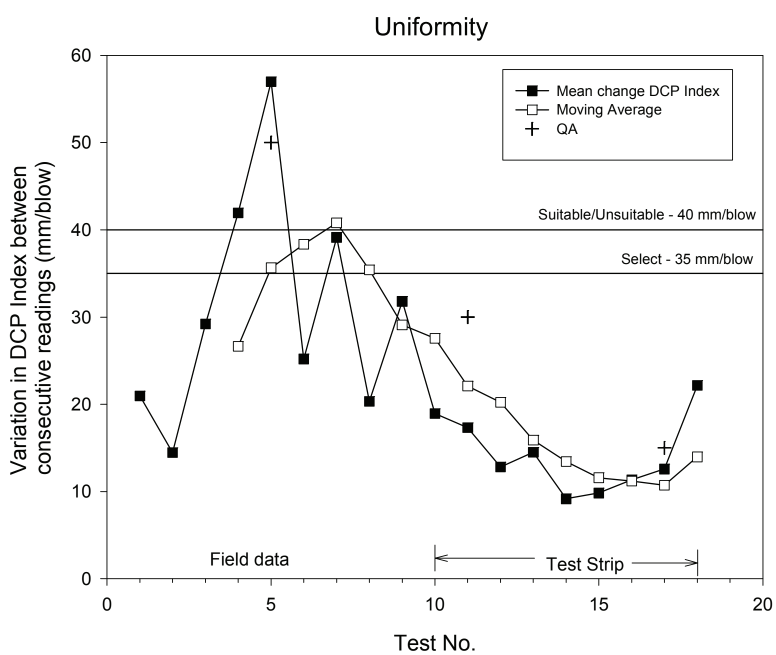


Figure 2. Mean change in DCP Index between consecutive readings control chart

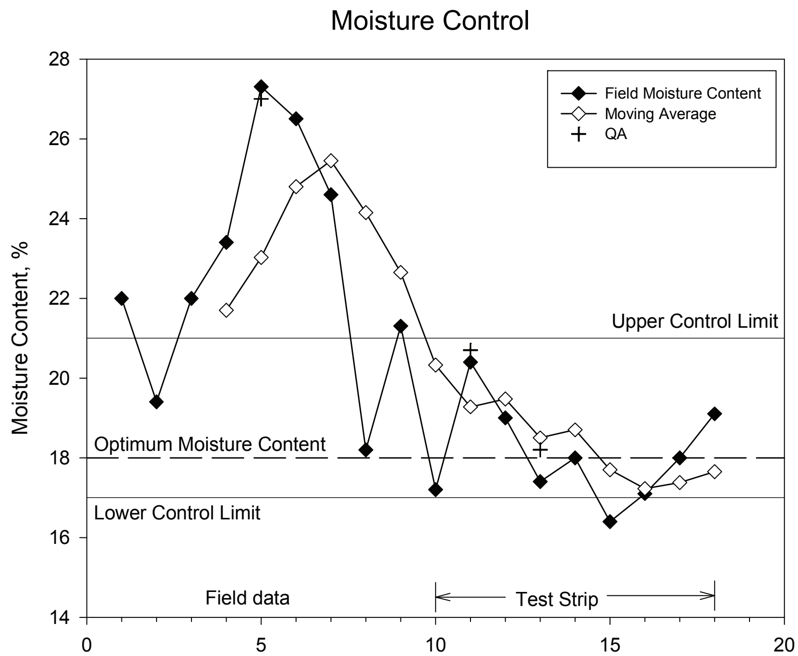


Figure 3. Moisture control chart

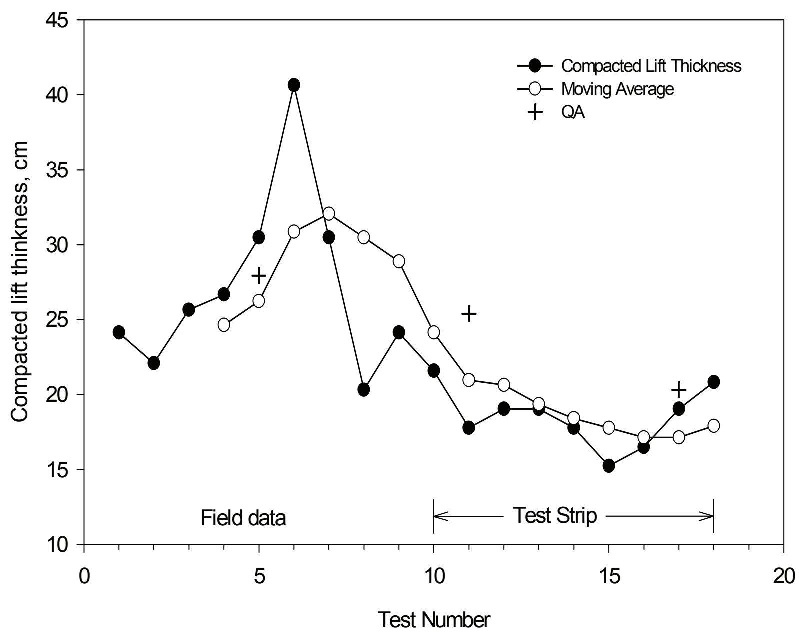


Figure 4. Lift thickness control chart

APPENDIX B. CONTRACTOR PROCTOR DATA

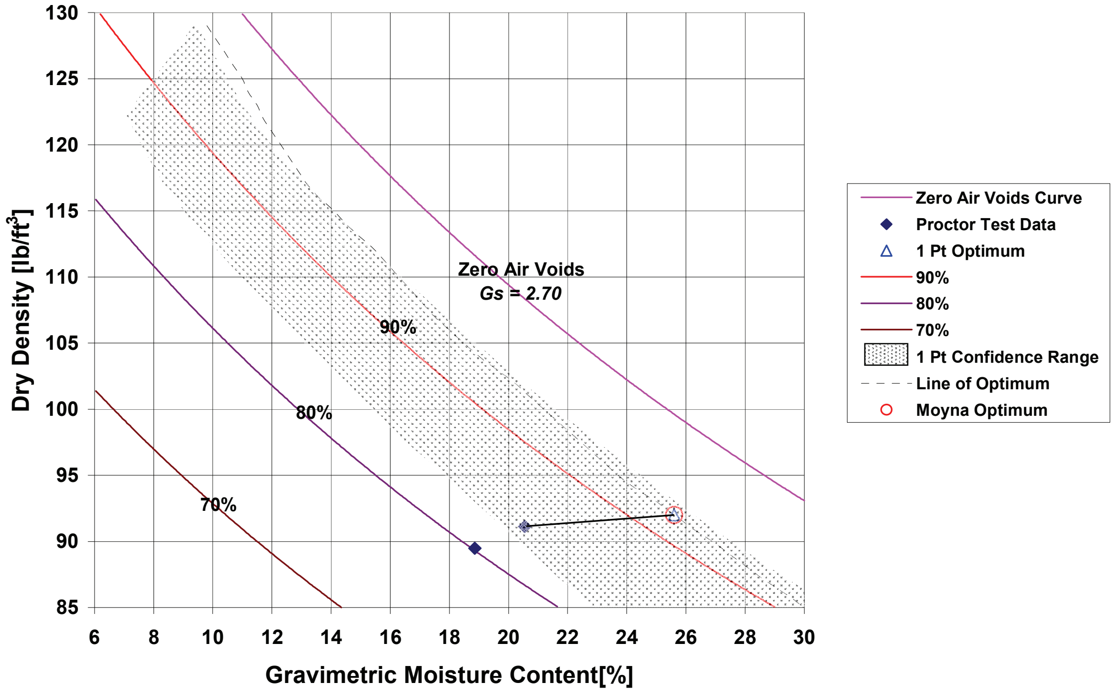


Figure B.1. Contractor Proctor test on 4/13/2006 in "A-7-6" soil near Mainline STA 150+50 40 m L CL

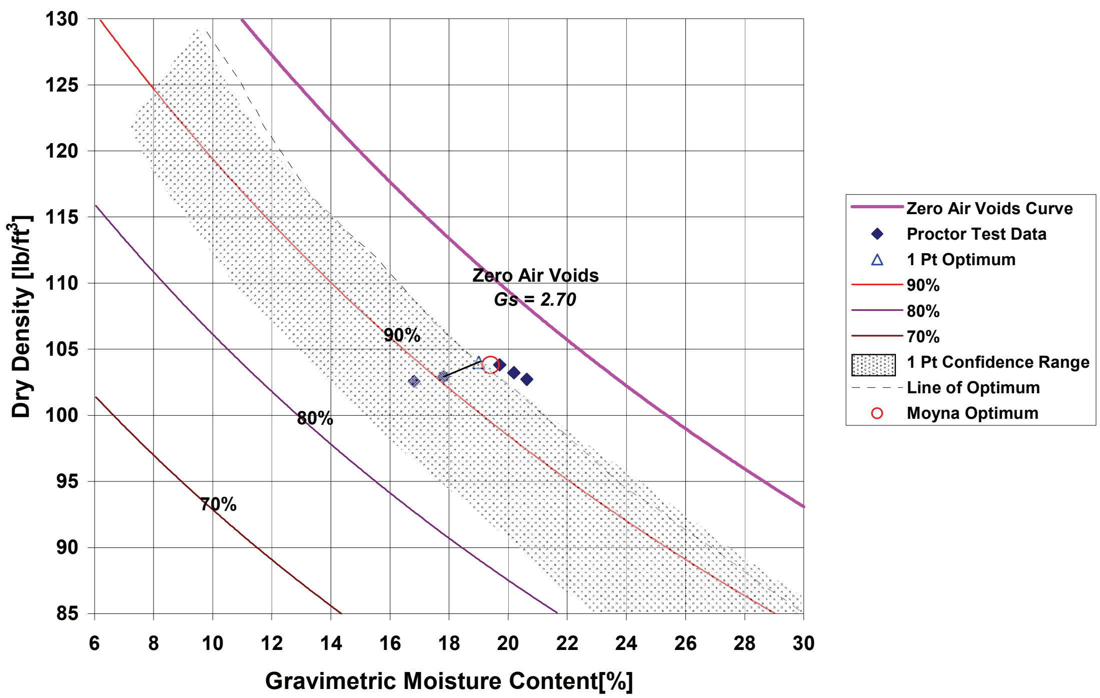


Figure B.2. Contractor Proctor test on 4/14/2006 in "A-7-6" soil near South Glagow berm STA 10155+50

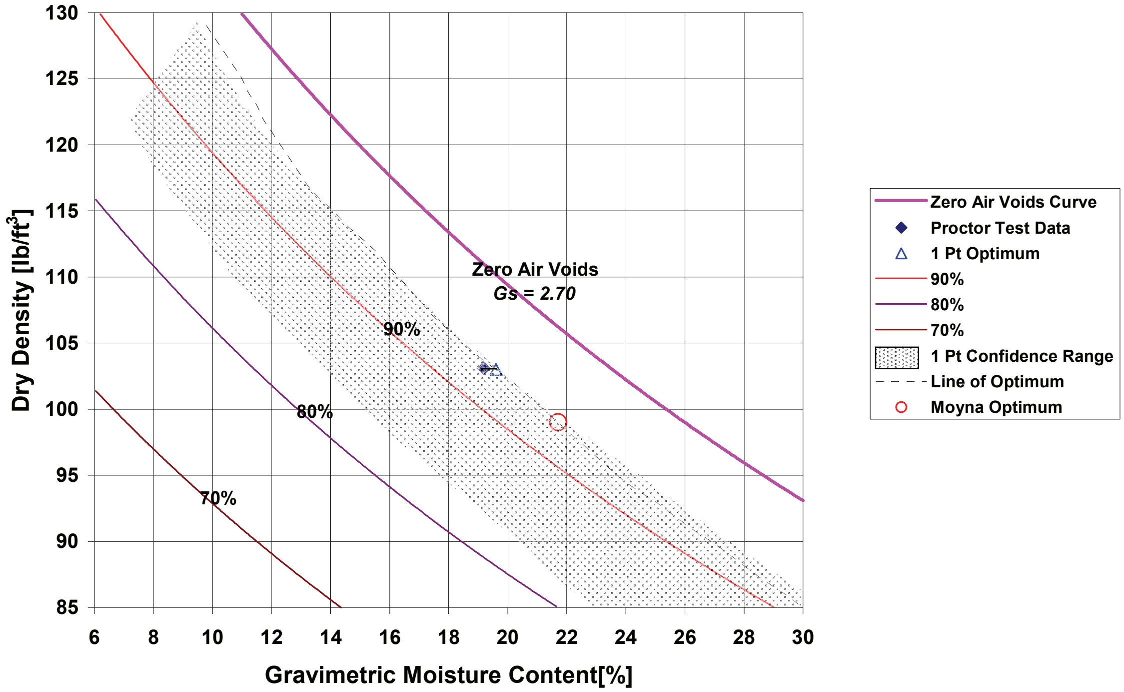


Figure B.3. Contractor Proctor test on 4/20/2006 in “A-7-6” soil near South Glagow berm STA 10155+50

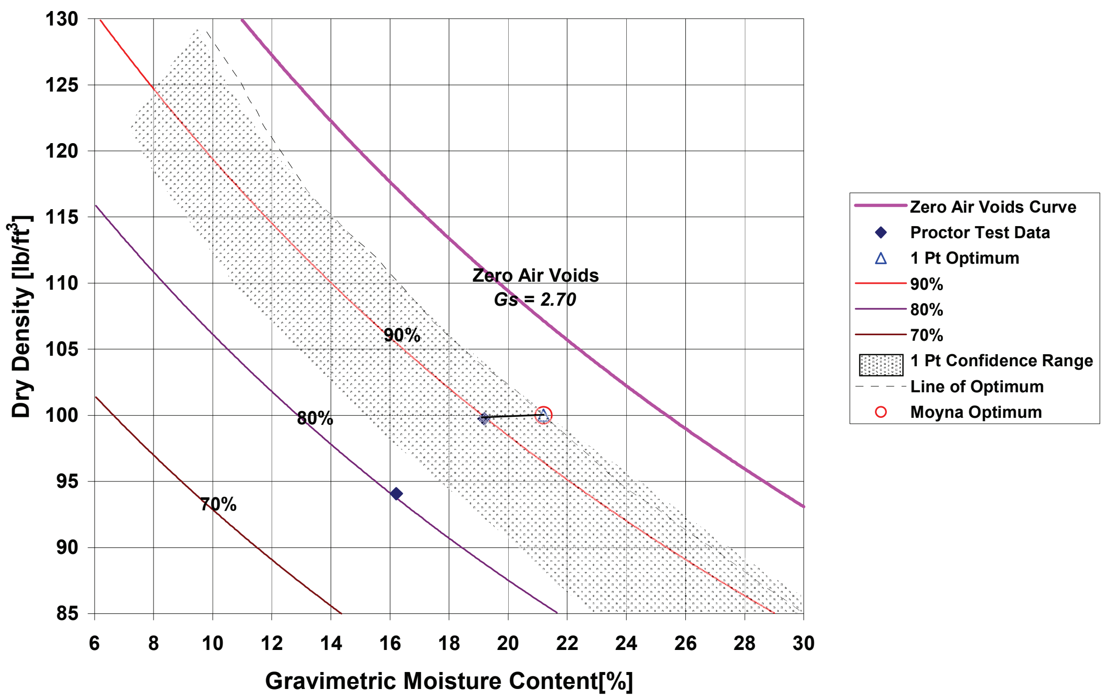


Figure B.4.. Contractor Proctor test on 4/27/2006 in “A-7-6” soil near Glasgow berm

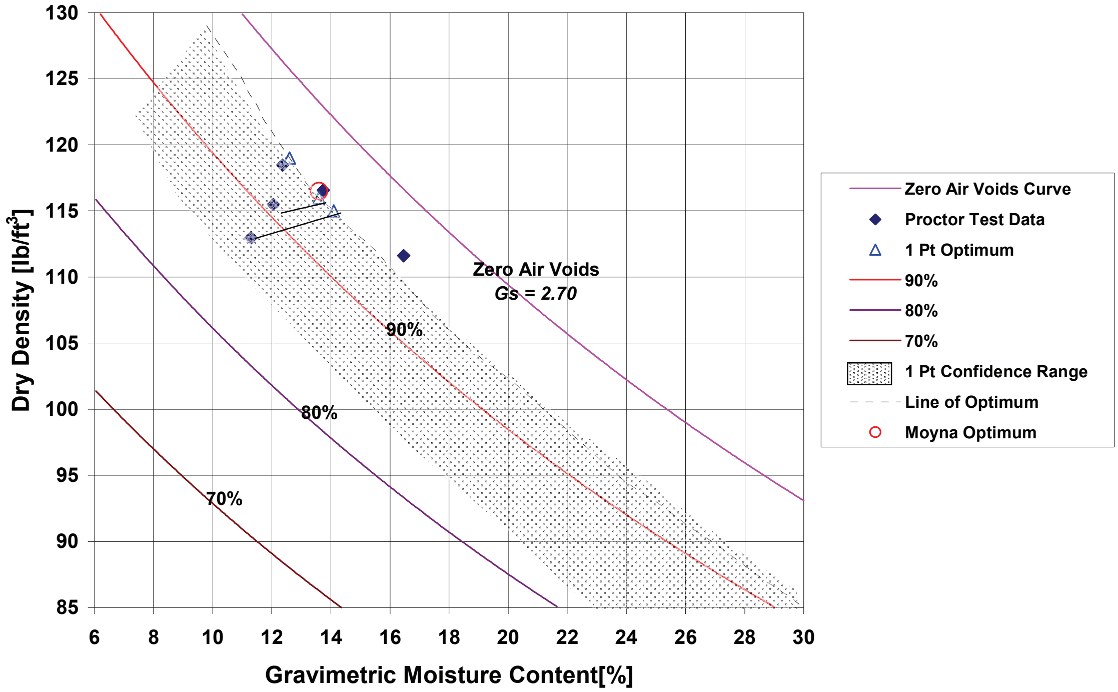


Figure B.5. Contractor Proctor test on 5/5/2006 in "A-7-6" soil near Mainline STA 147+25

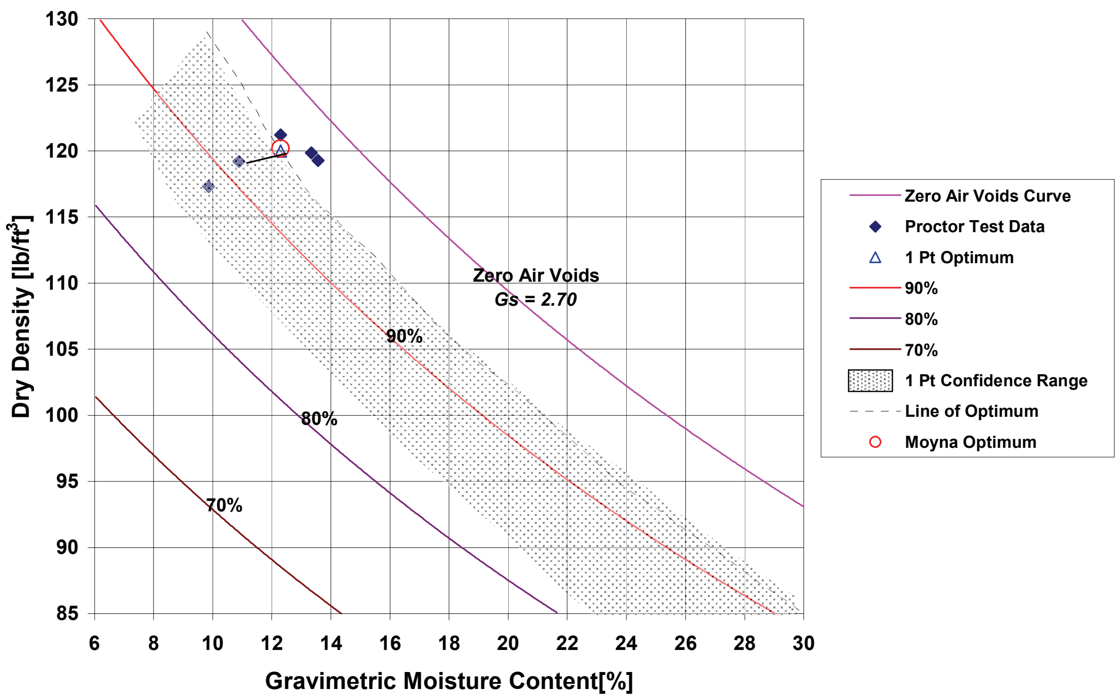


Figure B.6. Contractor Proctor test on 5/22/2006 in "A-6-2" soil between Mainline STA 148+50 – 149+50

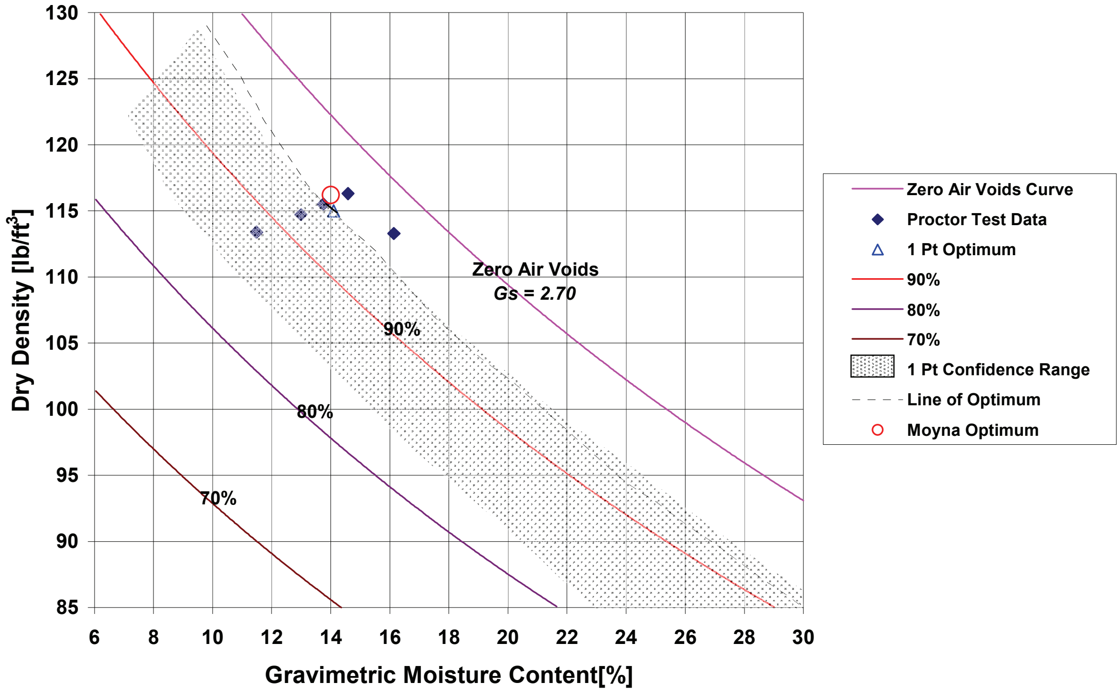


Figure B.7. Contractor Proctor test on 5/25/2006 in "A-6-2 and A-7-6" soil near Loop Trail

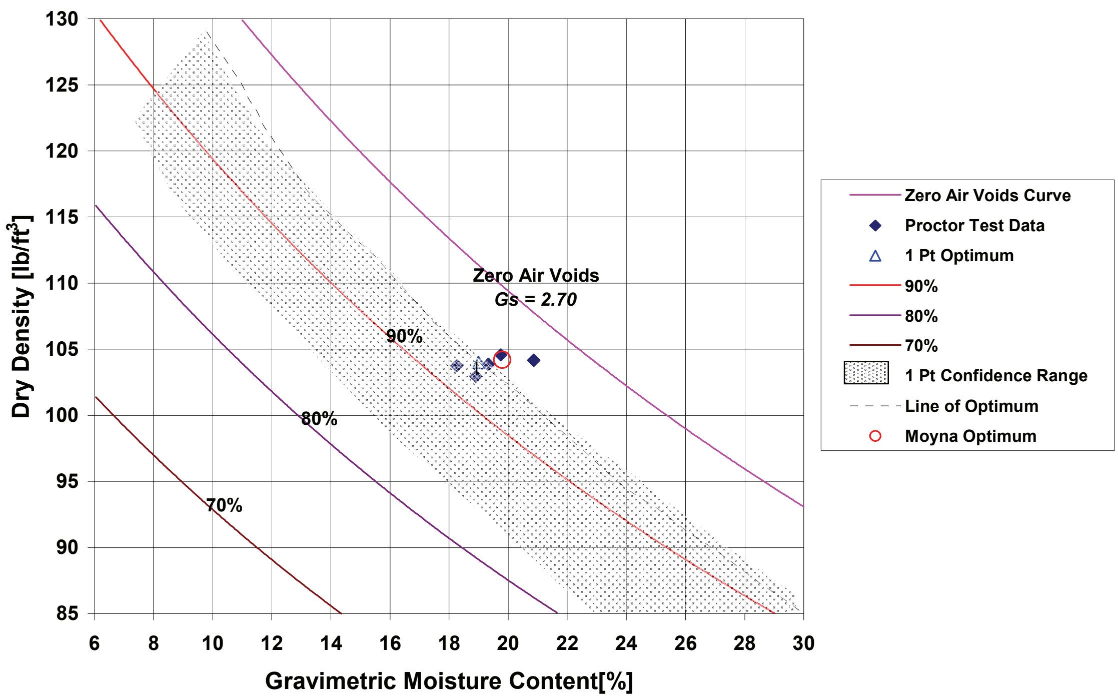


Figure B.8. Contractor Proctor test on 6/5/2006 in "A-7-6 and A-7-5" soil near Mainline STA 170+75

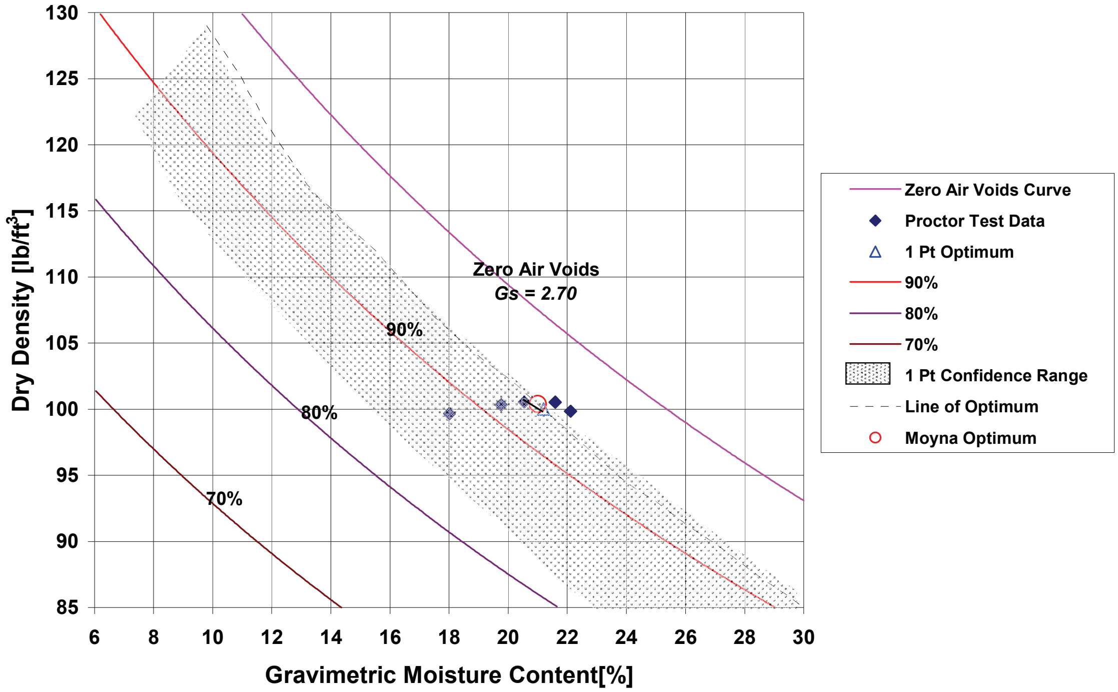


Figure B.9. Contractor Proctor test on 6/6/2006 in “A-7-6” soil near Osage berm

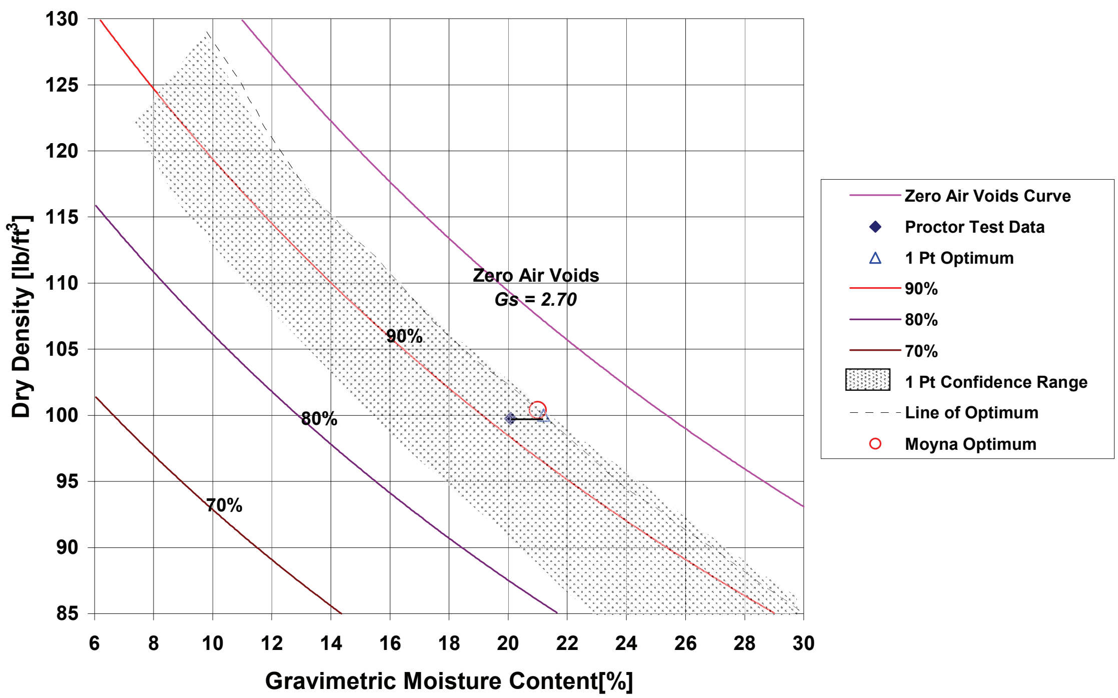


Figure B.10. Contractor Proctor test on 6/7/2006 in “A-7-6 and A-7-5” soil near Osage berm

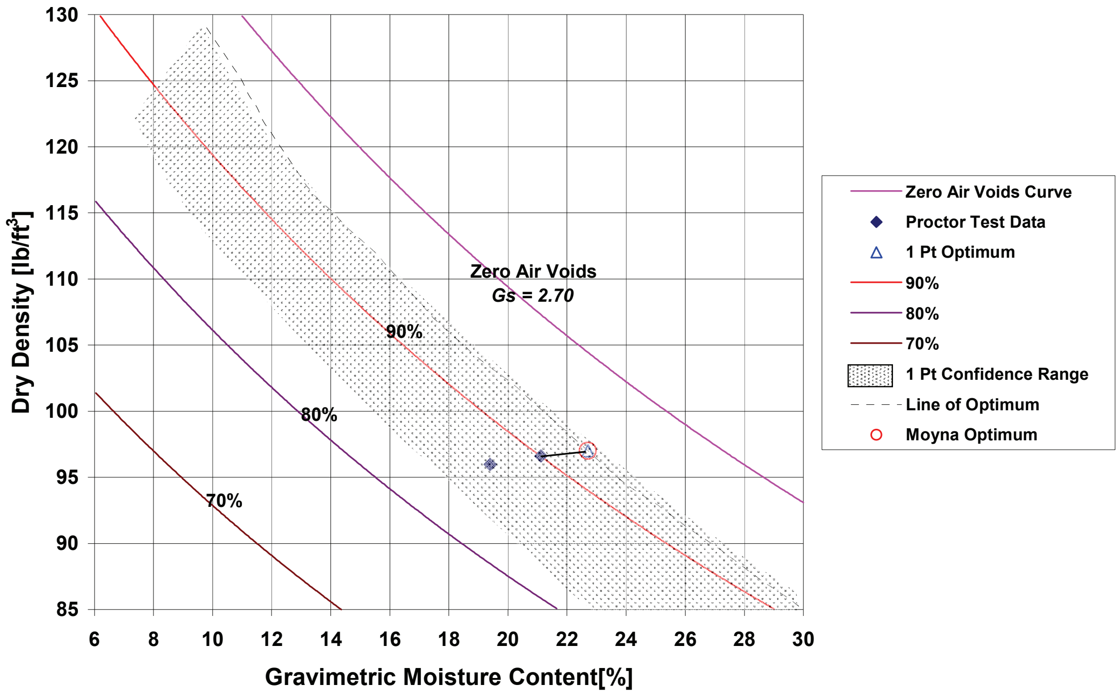


Figure B.11. Contractor Proctor test on 6/13/2006 in "A-7-6 and A-7-5" soil near Osage berm STA 17100-17103

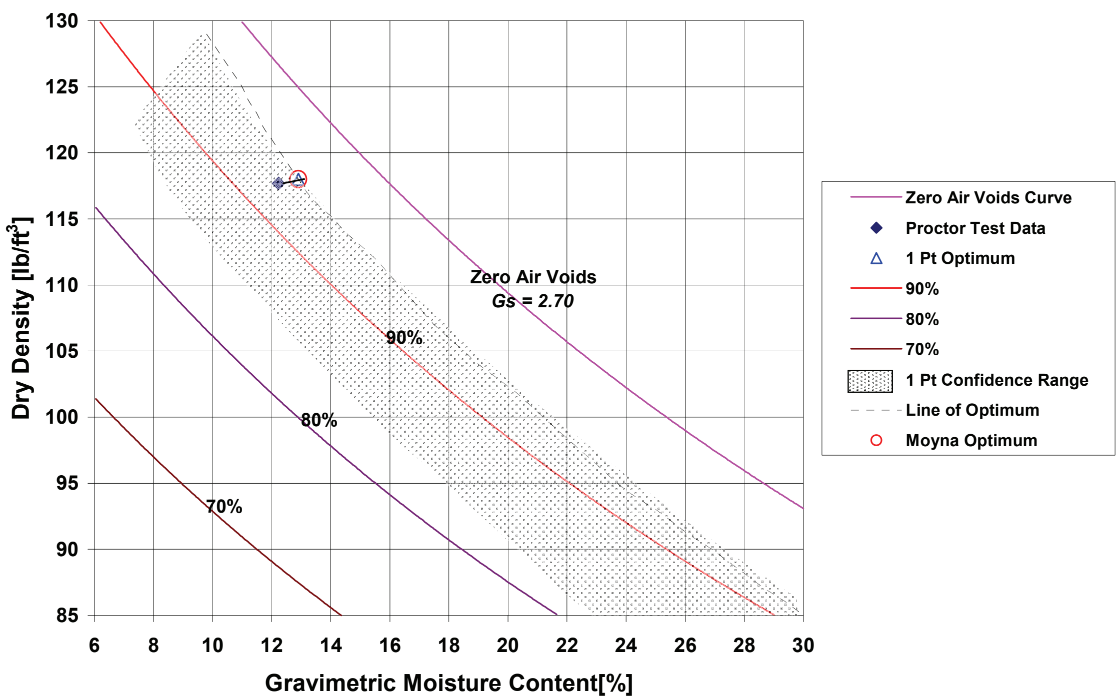


Figure B.12. Contractor Proctor test on 6/14/2006 in "A-7-6 and A-6" soil near Mainline STA 185+50

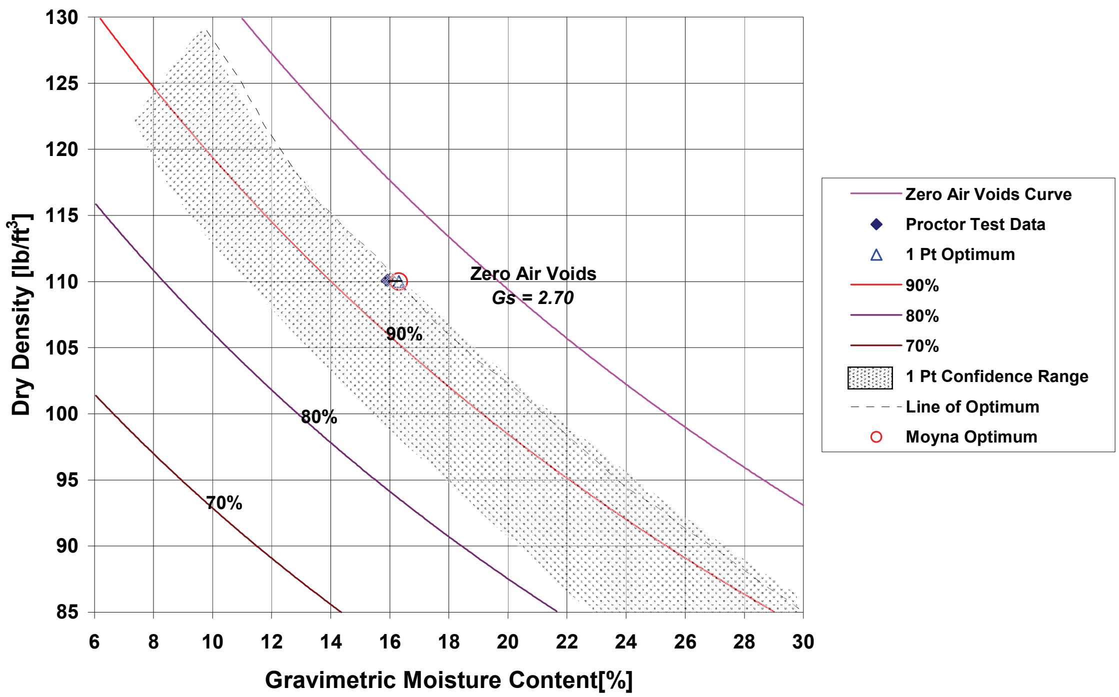


Figure B.13. Contractor Proctor test on 6/15/2006 in "A-7-6 and A-6" soil near Mainline STA 186+25

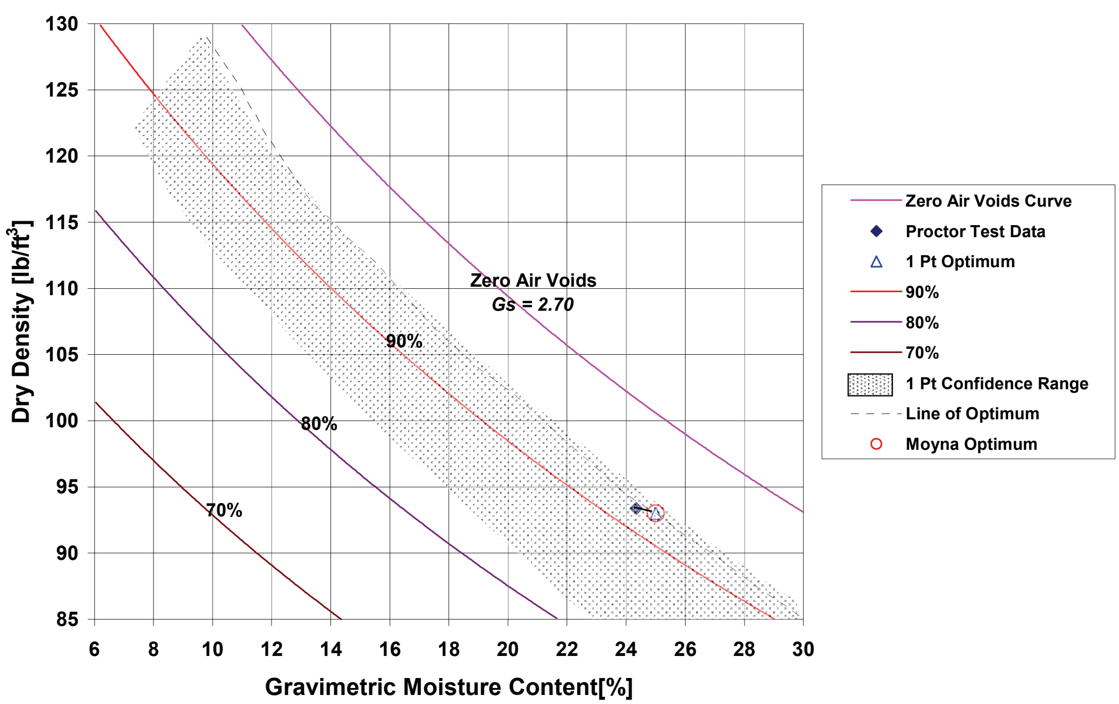


Figure B.14. Contractor Proctor test on 6/15/2006 in "A-7-6" soil near Mainline STA 186-188

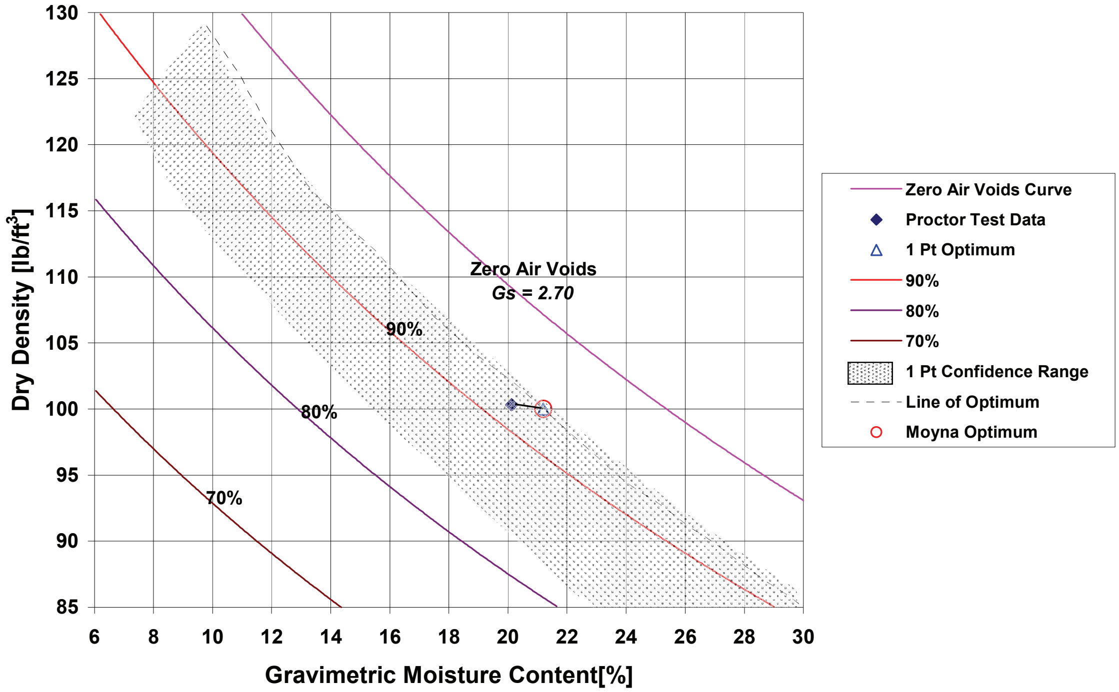


Figure B.15. Contractor Proctor test on 6/16/2006 in "A-7-6 and A-7-5" soil near Mainline STA 186+00

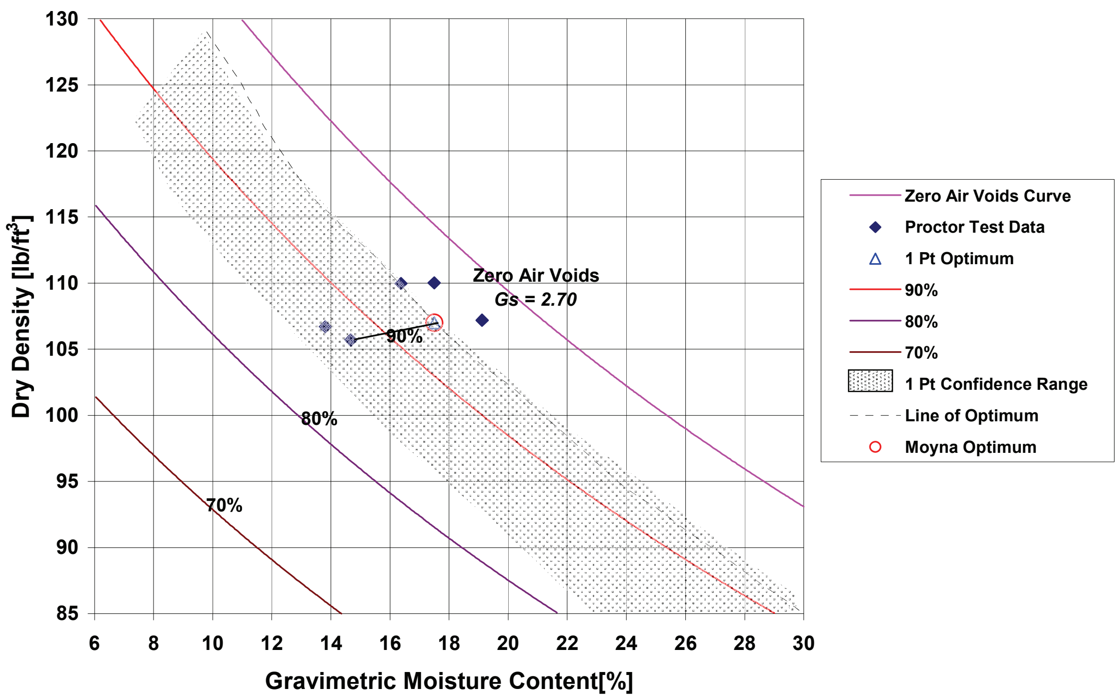


Figure B.16. Contractor Proctor test on 6/21/2006 in "A-7-6" soil near Mainline STA 185+00

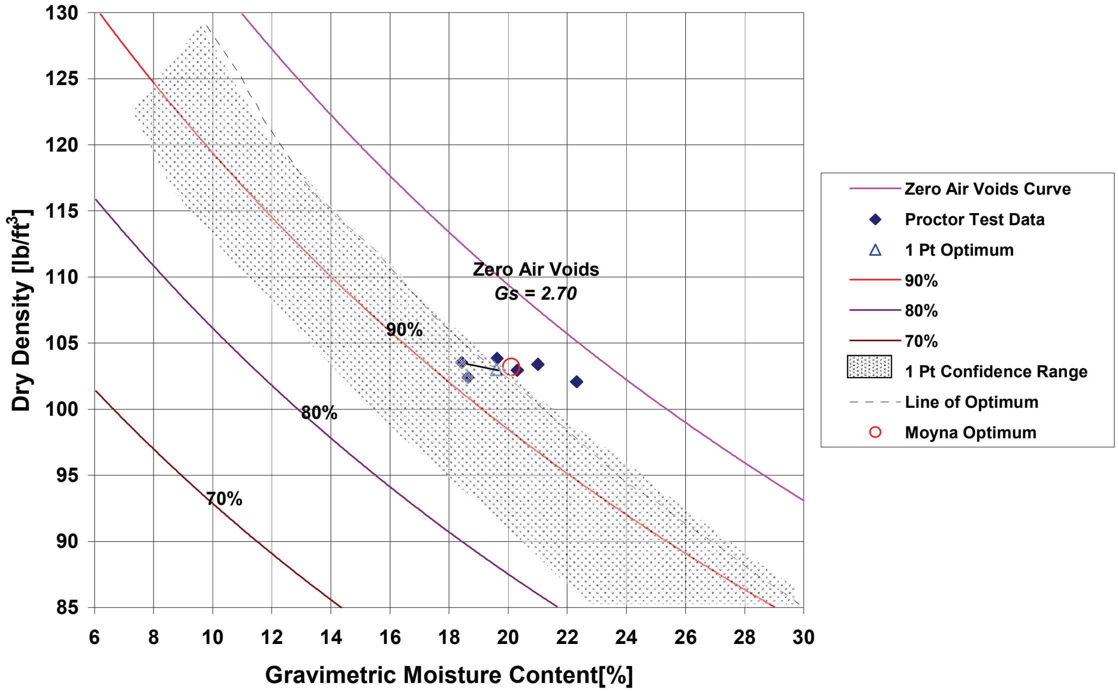


Figure B.17. Contractor Proctor test on 7/11/2006 in "A-7-6 and A-7-5" soil near Osage berm STA 11700

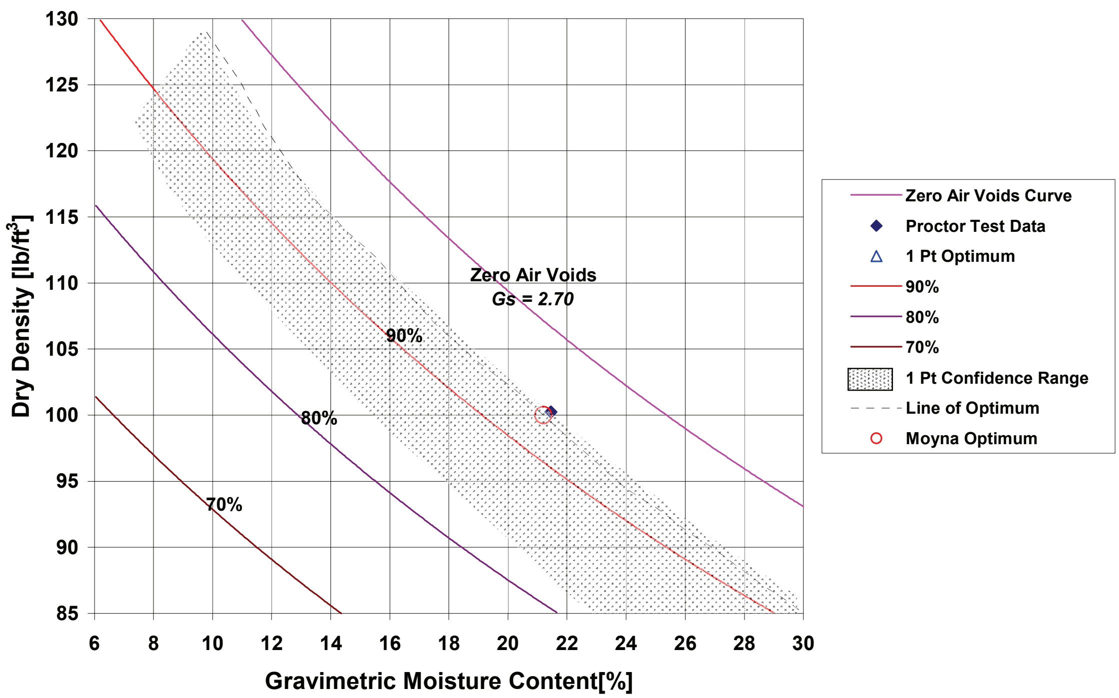


Figure B.18. Contractor Proctor test on 7/15/2006 in "A-7-6" soil near Mainline 149+00

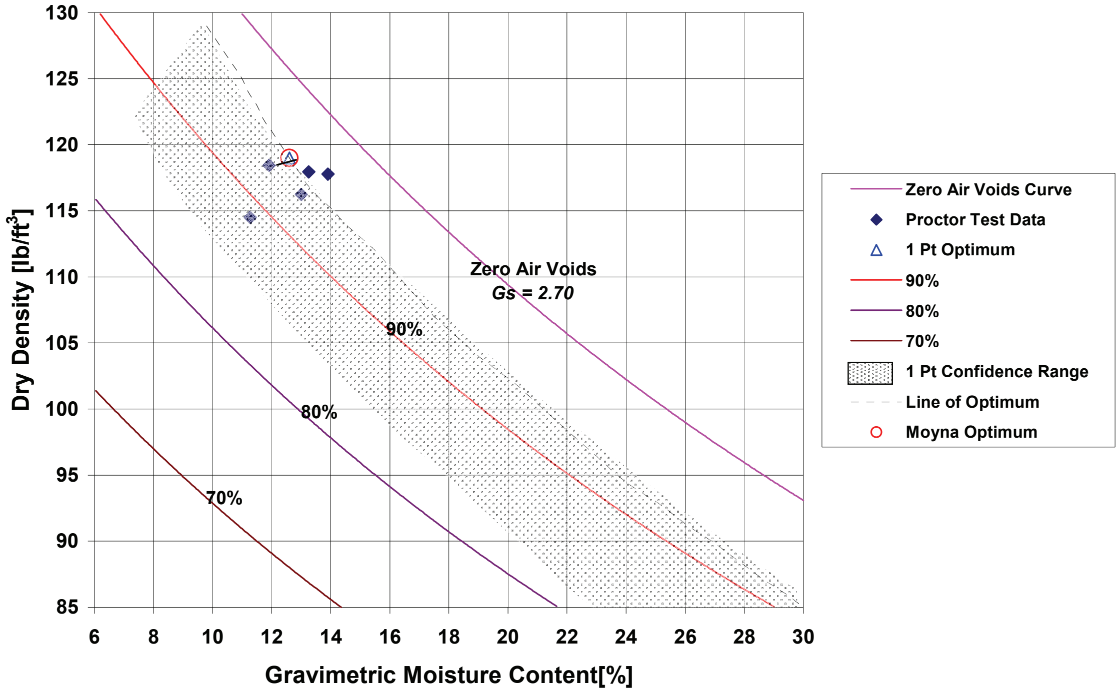


Figure B.19. Contractor Proctor test on 9/7/2006 in "A-7-6 and A-6" soil near Loop Trail cut

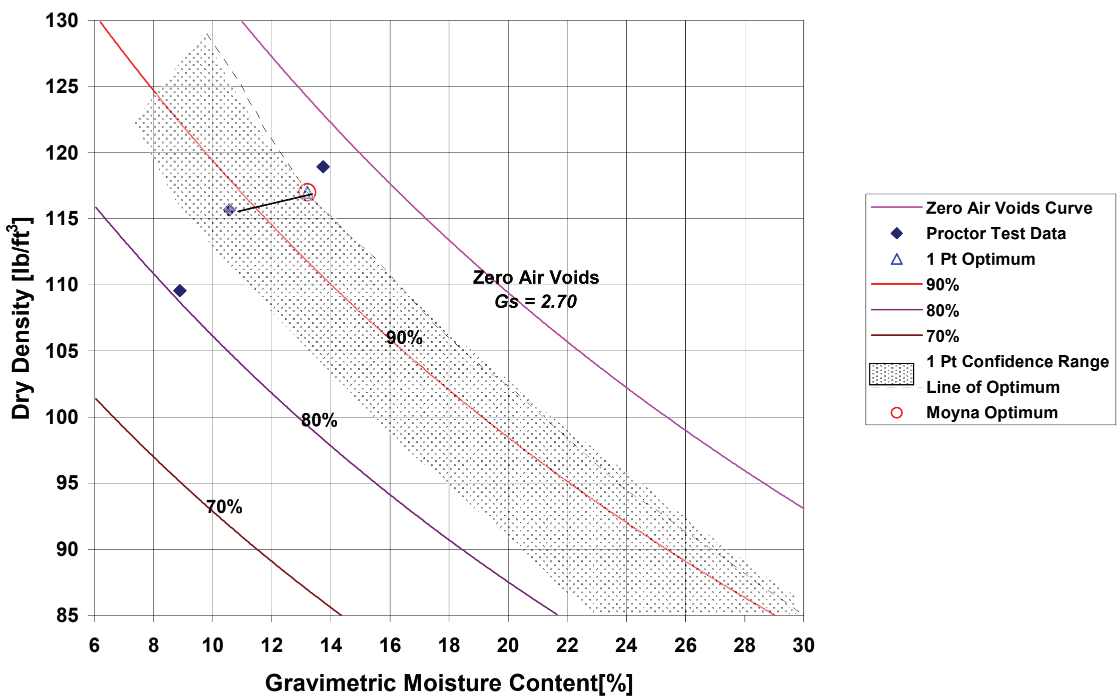


Figure B.20. Contractor Proctor test on 9/13/2006 in "A-7-6 and A-6" soil near Crow Creek median cut

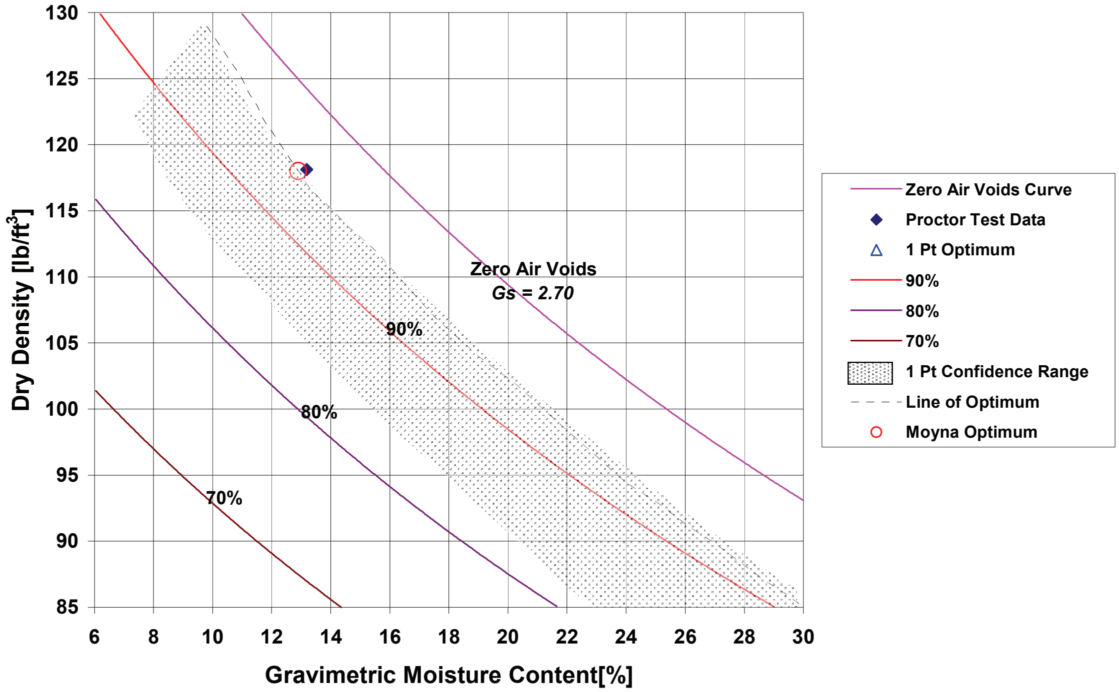


Figure B.21. Contractor Proctor test on 9/14/2006 in "A-7-6 and A-6" soil west of Crow Creek for fill North of US 34

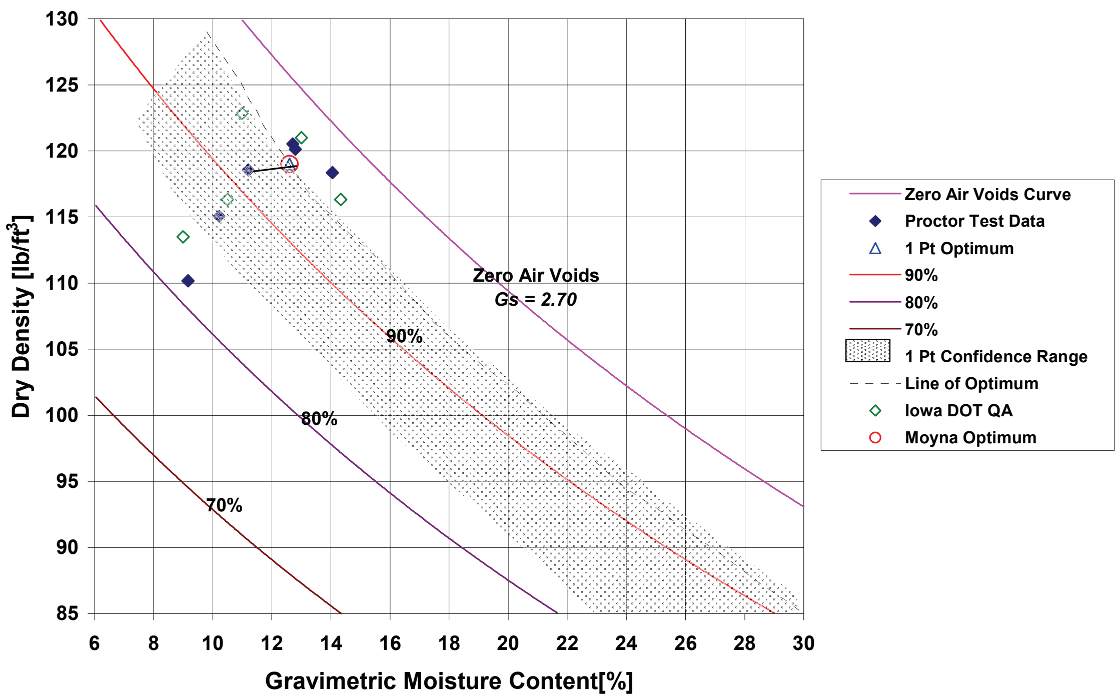


Figure B.22. Contractor Proctor test on 9/29/2006 in "A-7-6 and A-6" soil near Loop Trail Deep Cut

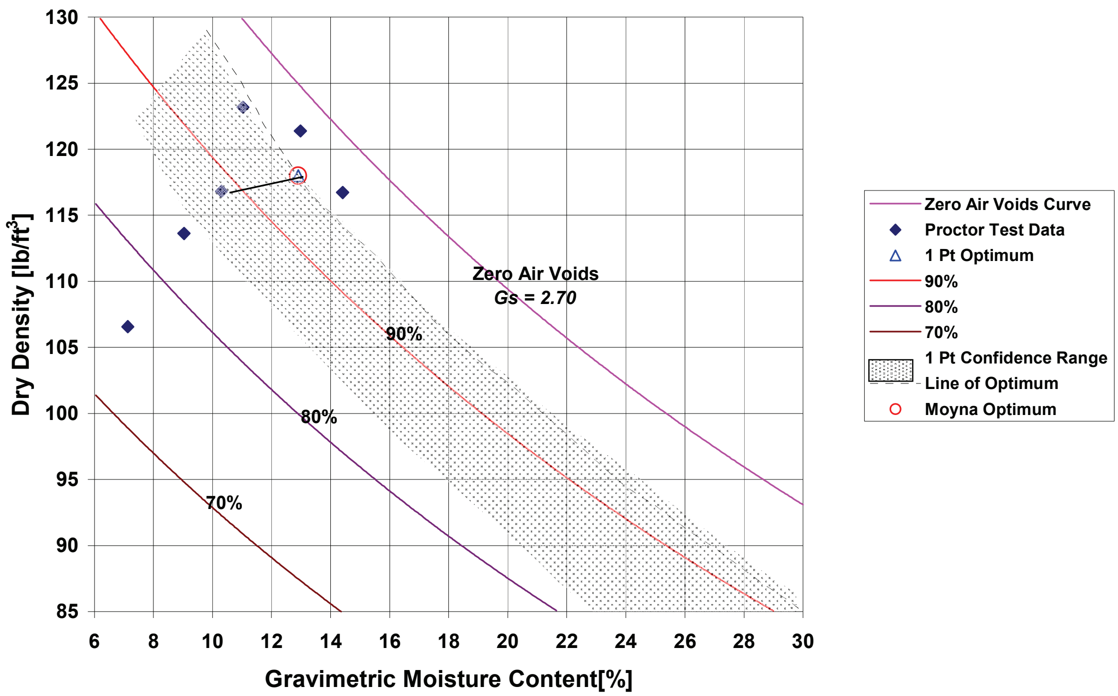


Figure B.23. Contractor Proctor test on 10/12/2006

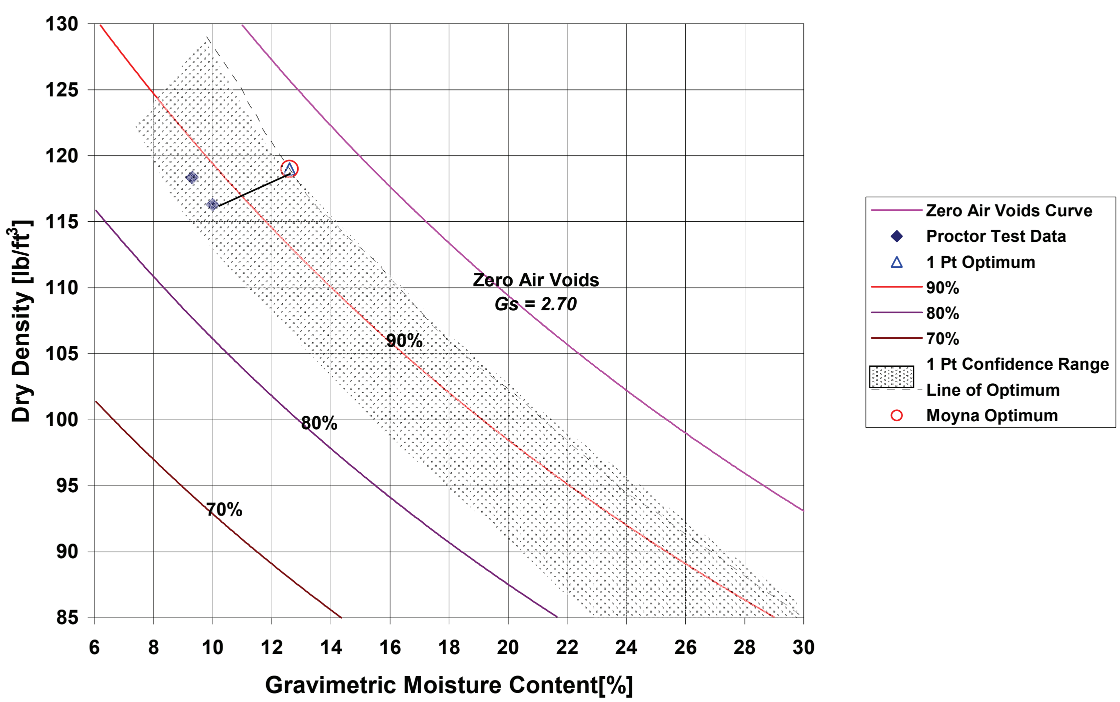


Figure B.24. Contractor Proctor test on 10/12/2006 in "A-6" soil near boring No. 506

APPENDIX C. ISU PROCTOR DATA

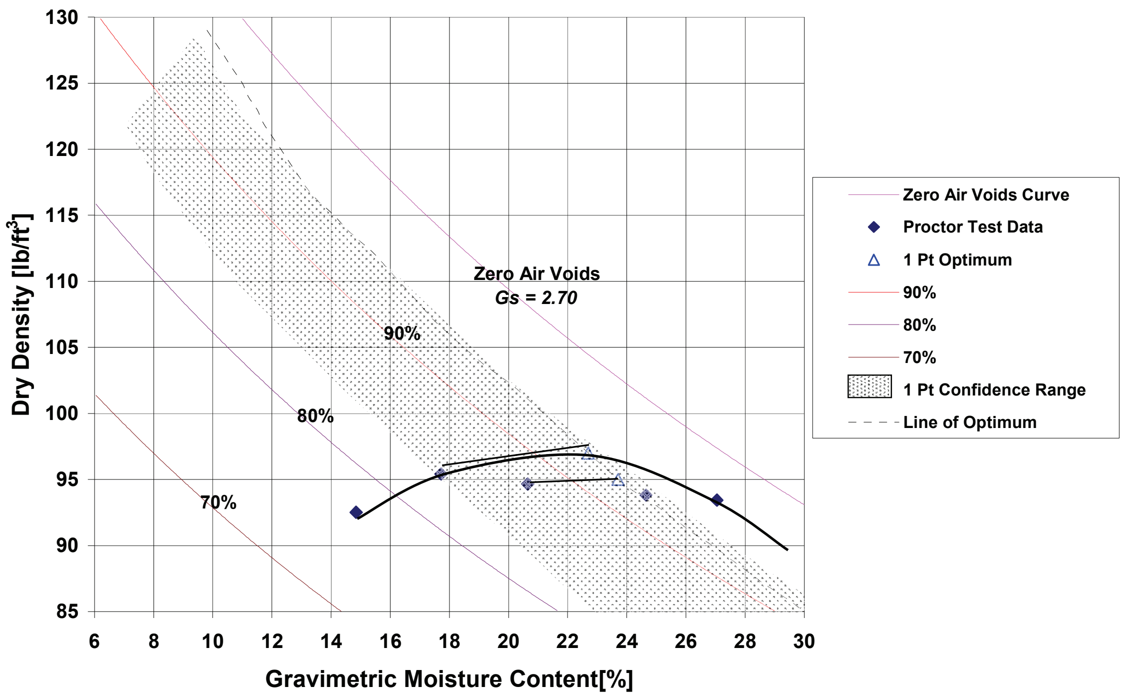


Figure C.1. ISU Proctor test on 7/10/2006 near Osage berm STA 14104+50 20m left of centerline

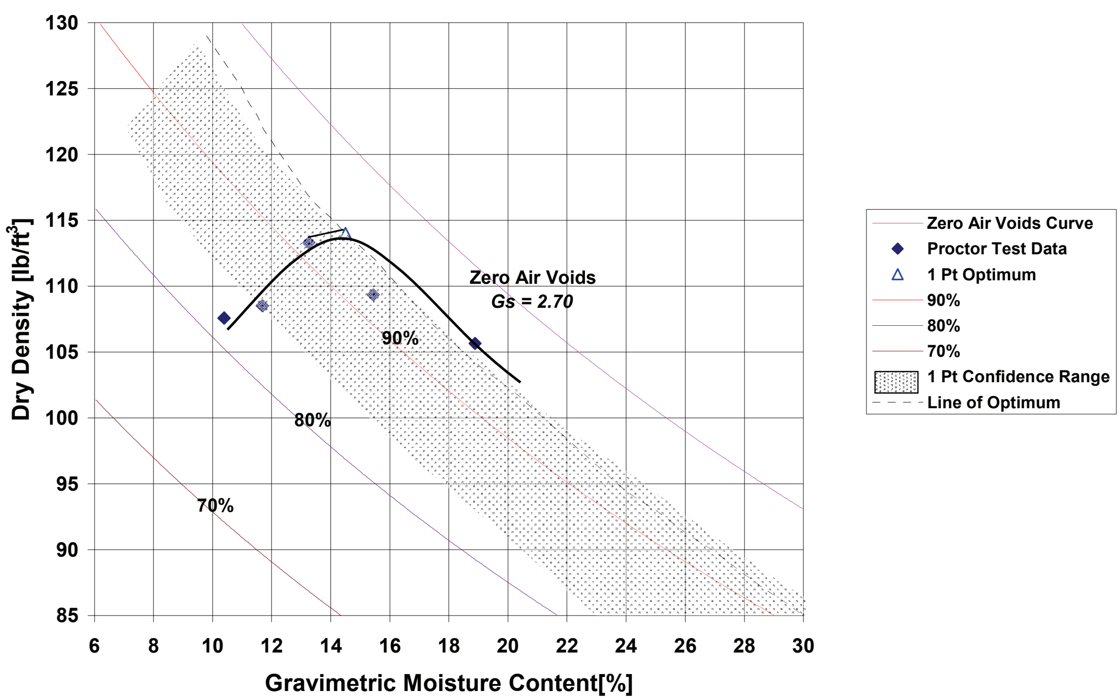


Figure C.2. ISU Proctor test on 8/3/2006 from open cut red-sandy soil (bottom layer) near Mainline STA 170+00

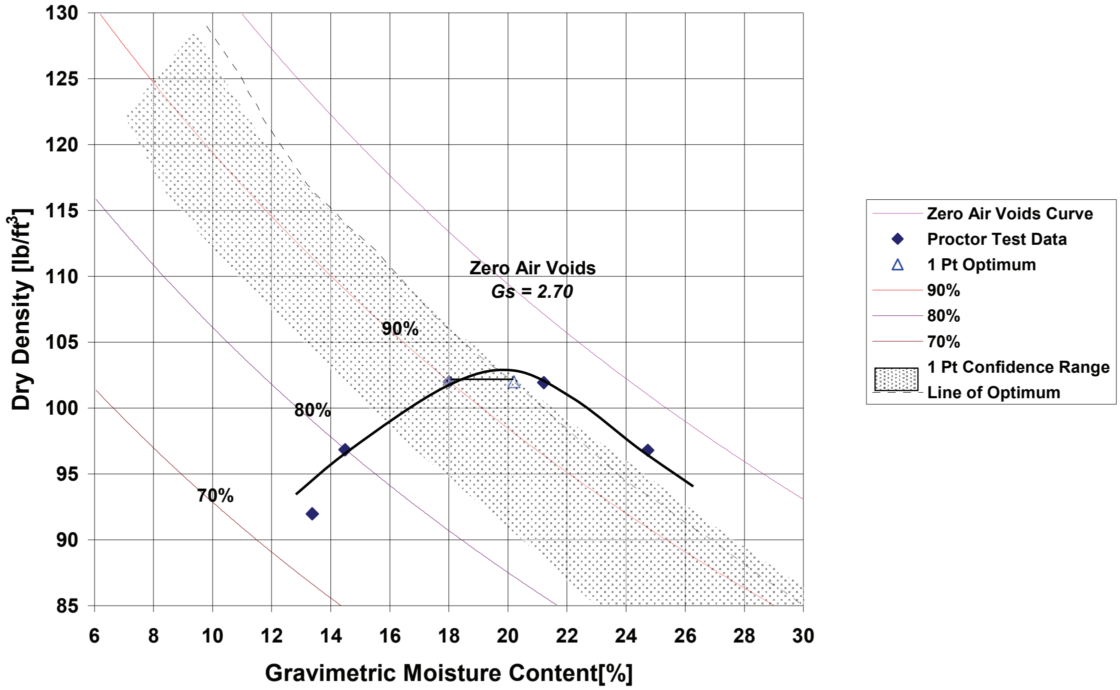


Figure C.3. ISU Proctor test on 8/3/2006 from open cut gray clayey soil (middle layer) near Mainline STA 170+00

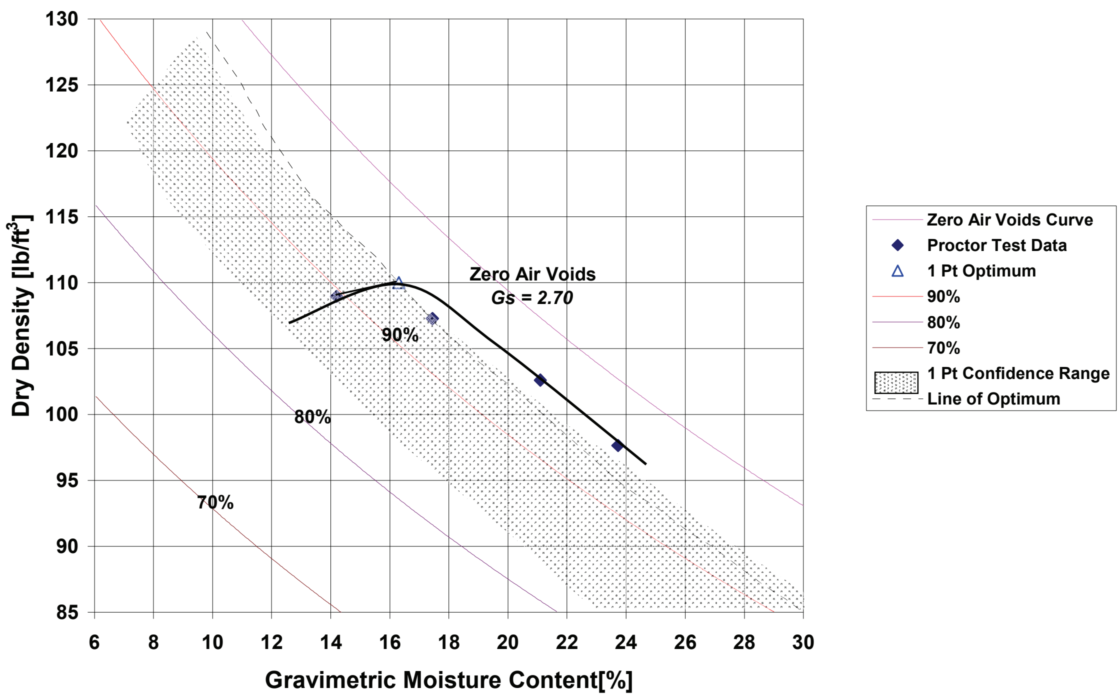


Figure C.4. ISU Proctor test on 8/3/2006 from open cut brownish clay (transitional layer) near Mainline STA 170+00

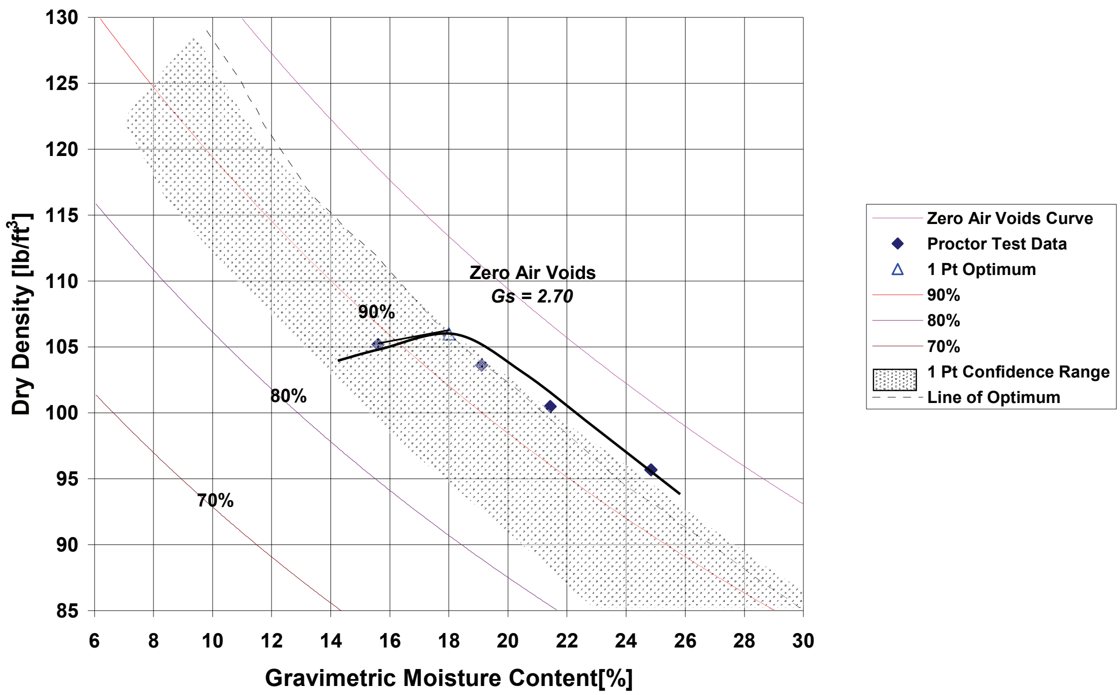


Figure C.5. ISU Proctor test on 8/3/2006 from Osage berm suitable STA 14104+75

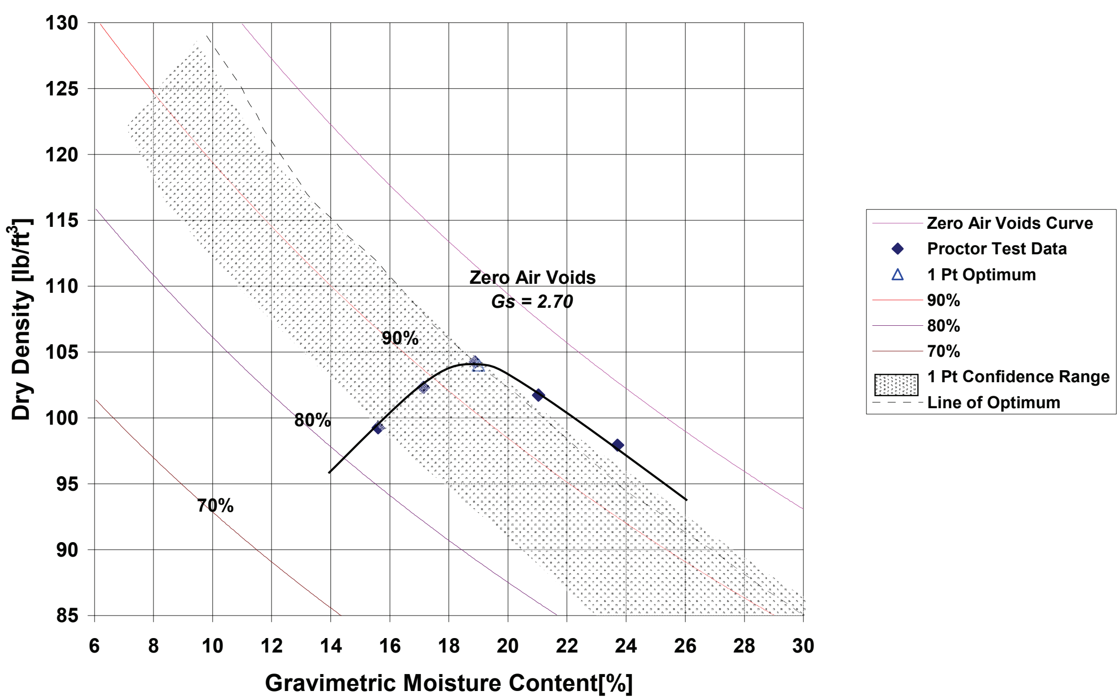


Figure C.6. ISU Proctor test on 8/3/2006 from open cut (top layer) near Mainline STA 170+00

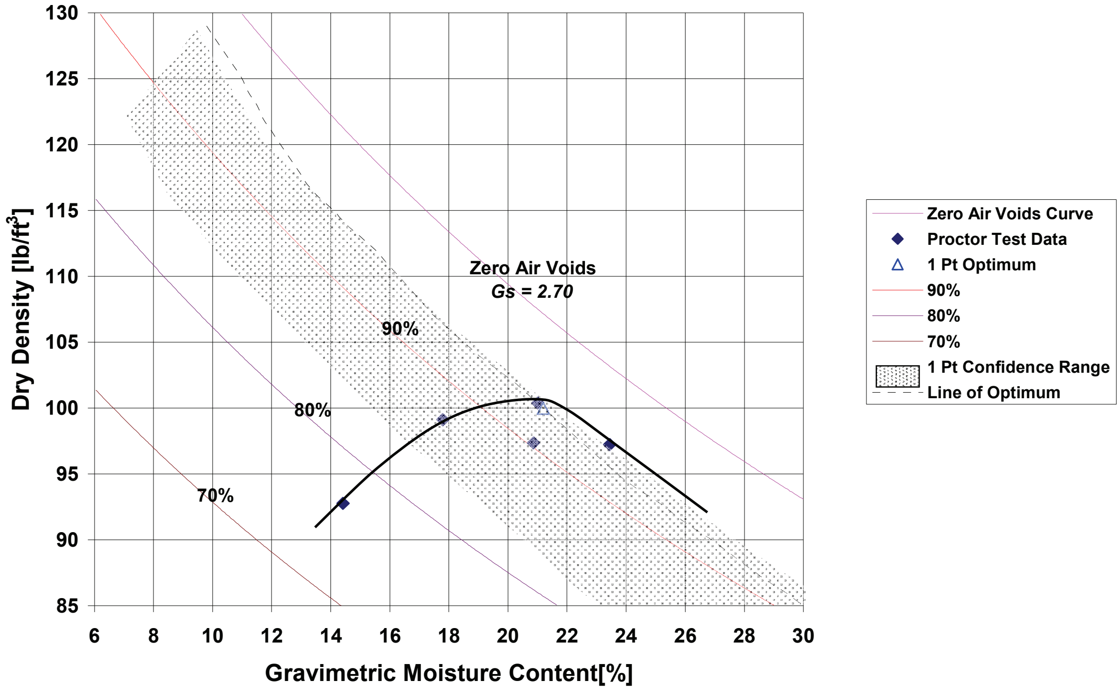


Figure C.7. ISU Proctor test on 8/3/2006 from Mainline STA 169+00 20 m left of centerline

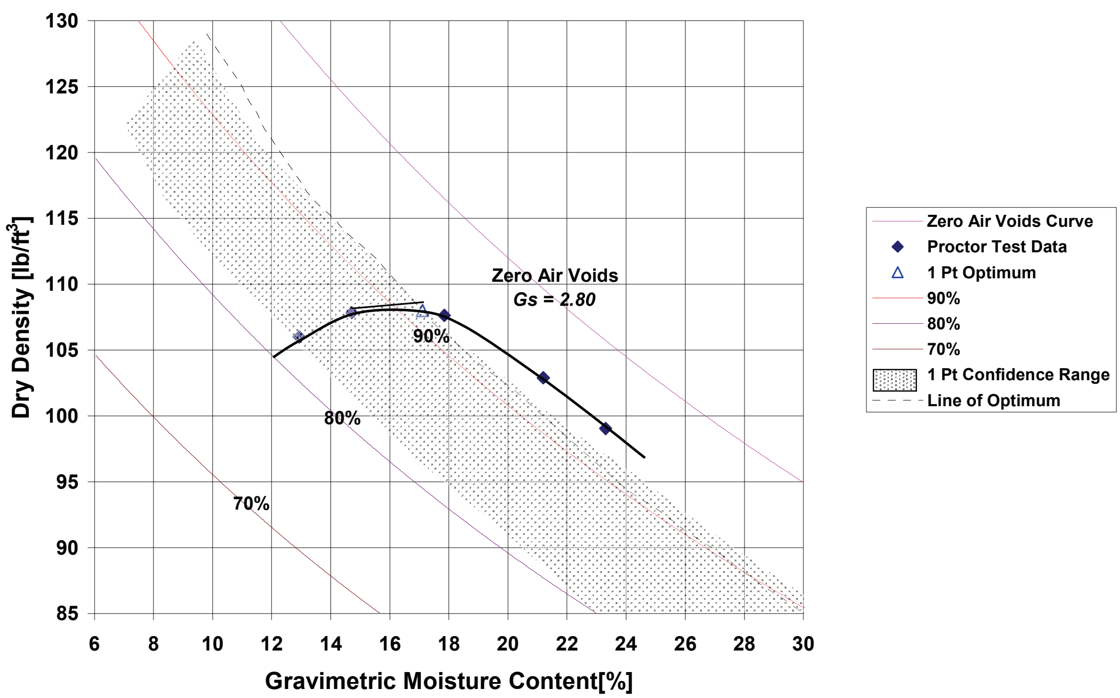


Figure C.8. ISU Proctor test on 8/16/2006 from Mainline STA 147+00 west bound

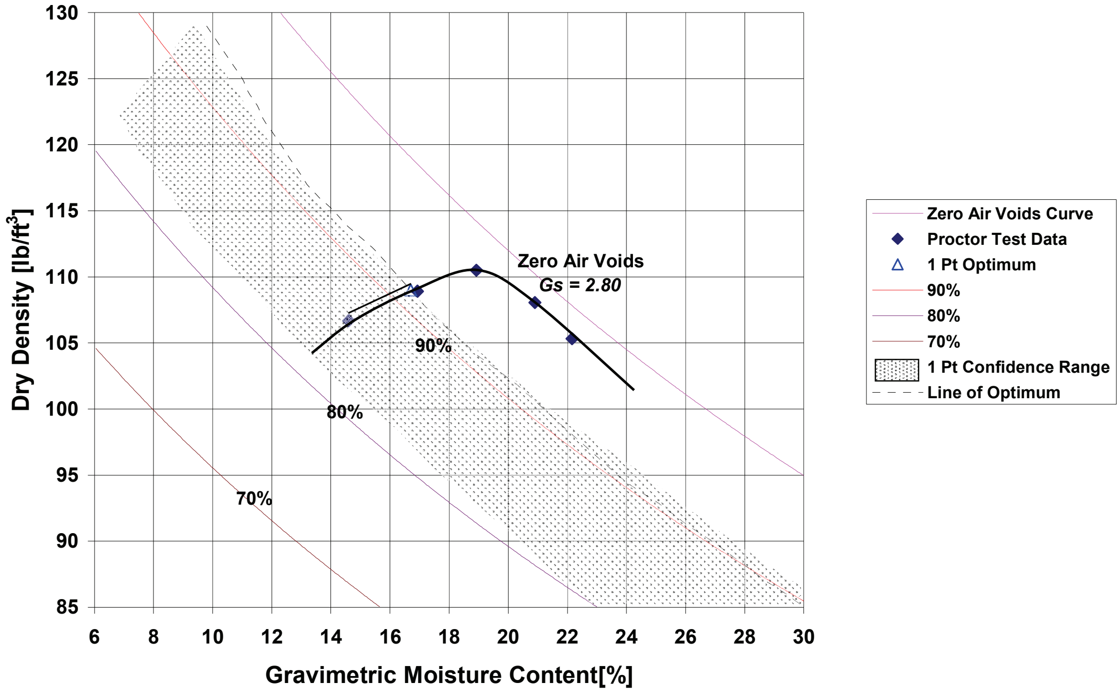


Figure C.9. ISU Proctor test on 8/17/2006 from Highway 34 connector STA 22005+25

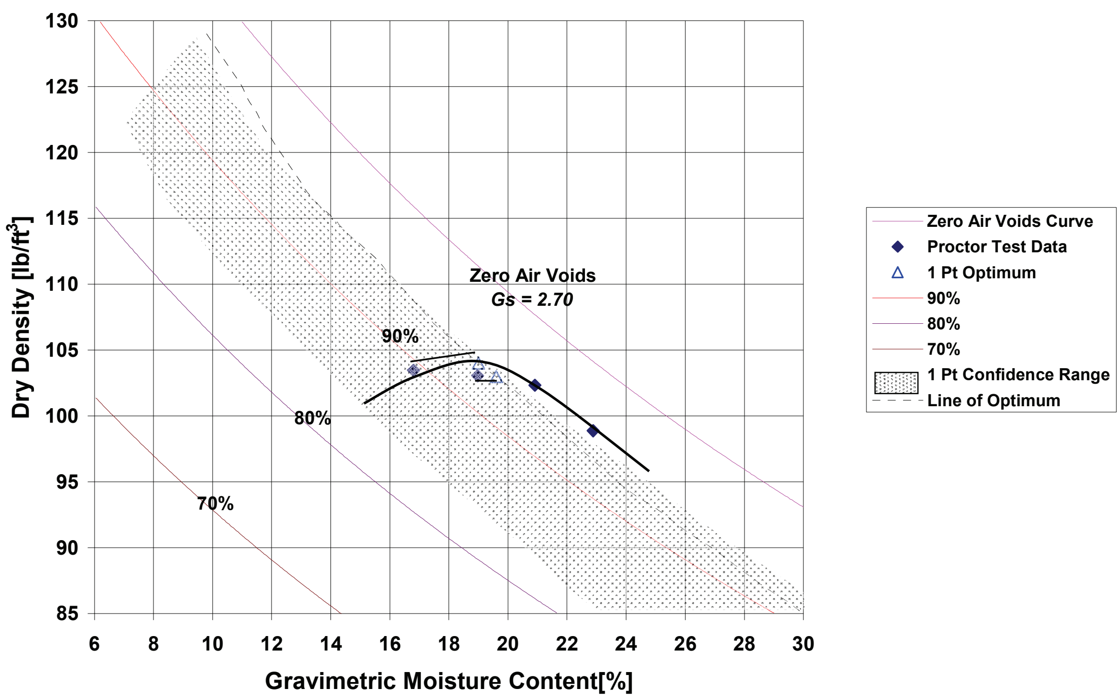


Figure C.10. ISU Proctor test on 8/17/2006 from Mainline STA 147+50 west bound

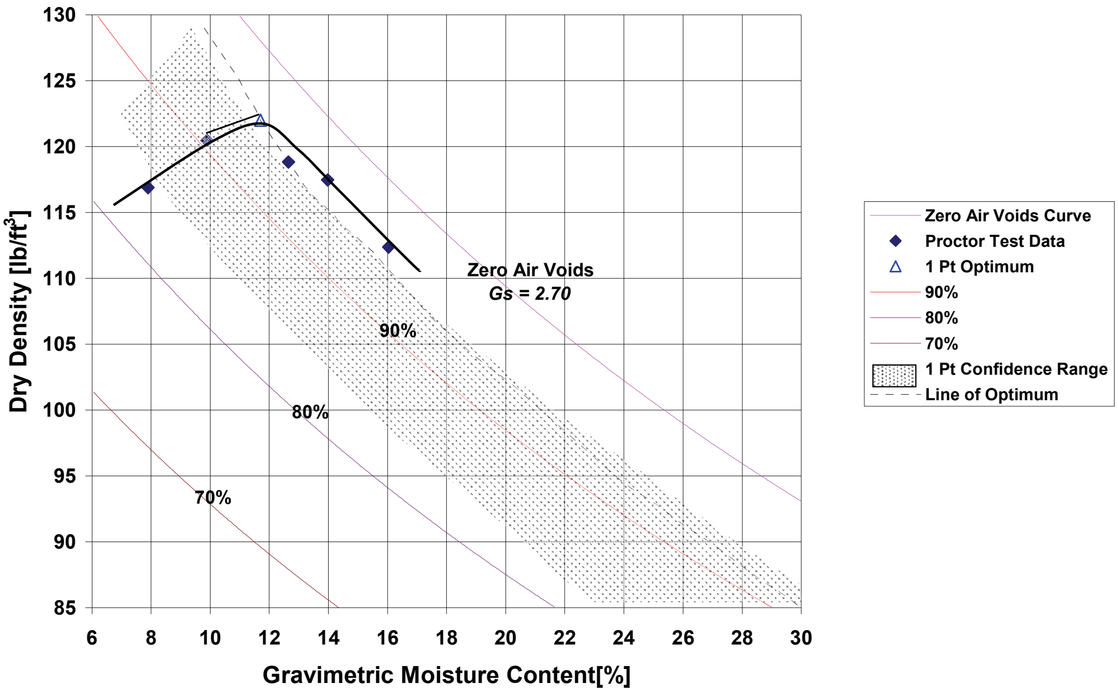


Figure C.11. ISU Proctor test on 9/20/2006 from Mainline STA 143+50 west bound

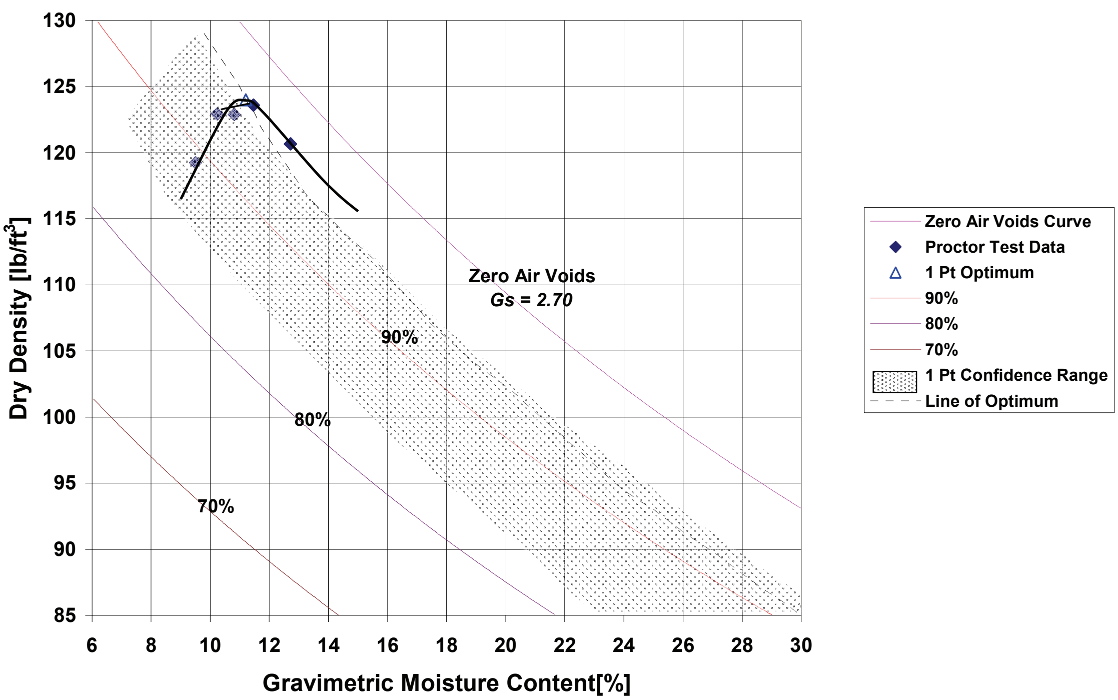


Figure C.12. ISU Proctor test on 9/20/2006 from Mainline STA 144+00 west bound

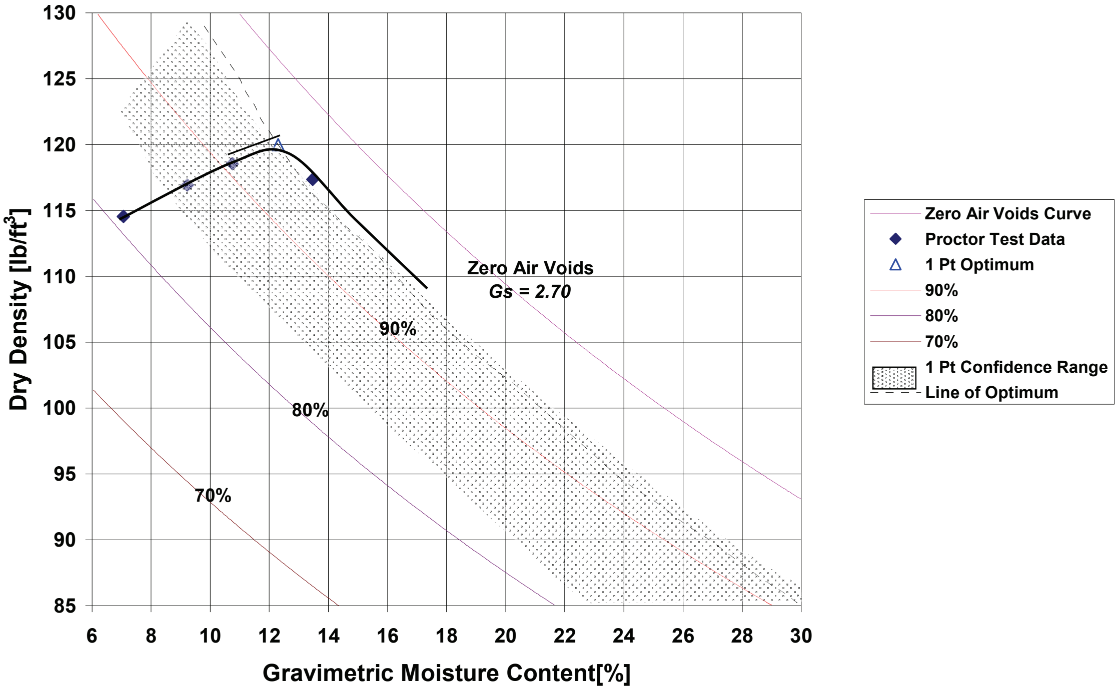


Figure C.13. ISU Proctor test on 9/26/2006 from Mainline STA 183+25 west bound

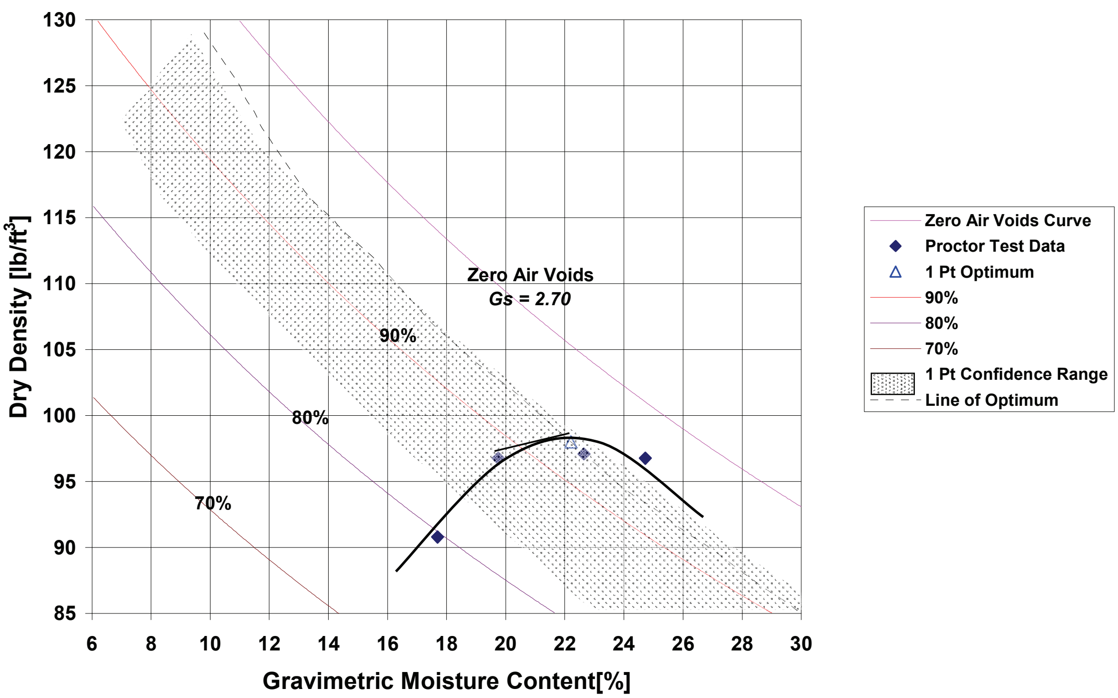


Figure C.14. ISU Proctor test on 9/26/2006 from Mainline STA 164+00 east bound

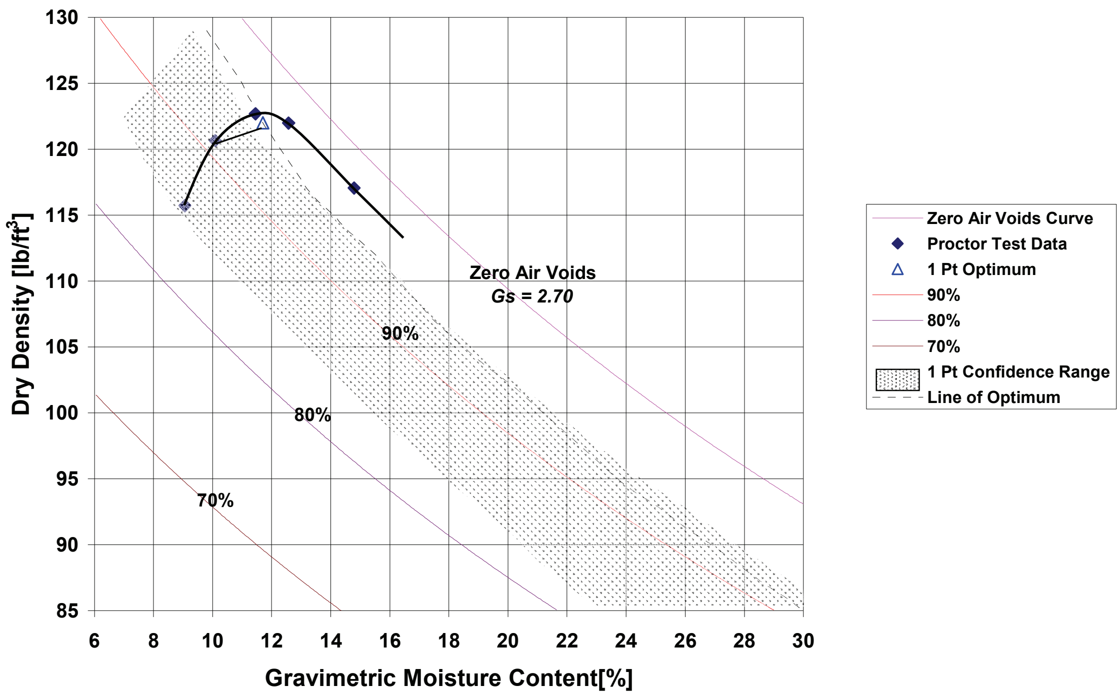


Figure C.15. ISU Proctor test on 10/2/2006 from Mainline STA 174+50 east bound

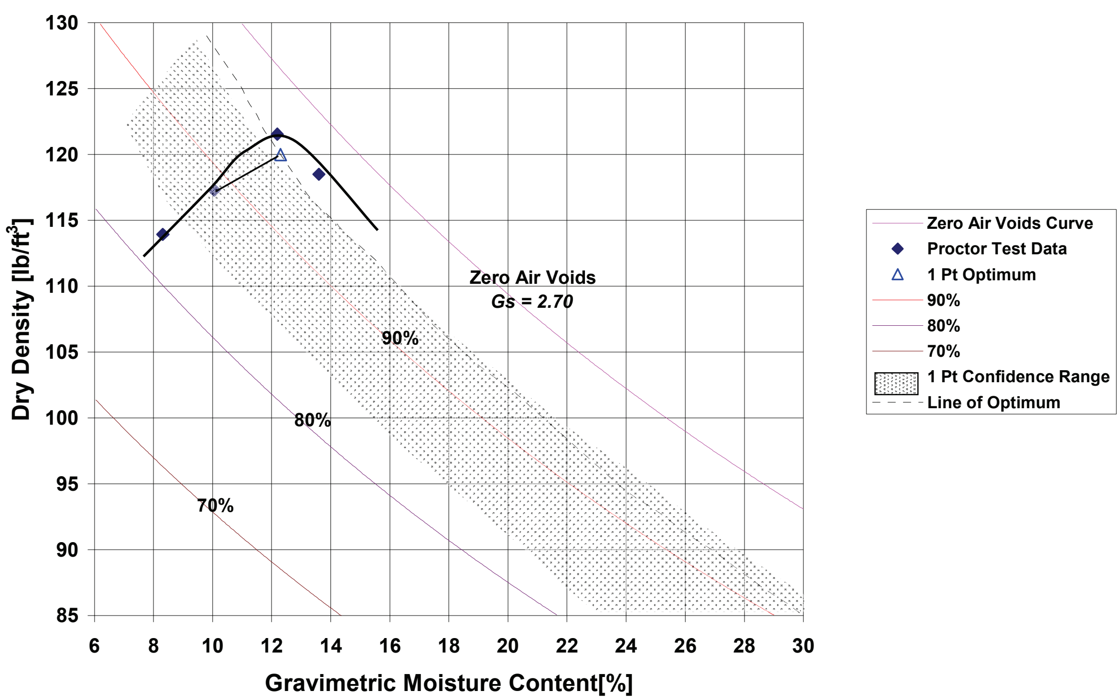


Figure C.16. ISU Proctor test on 10/2/2006 from Mainline STA 154+50 east bound

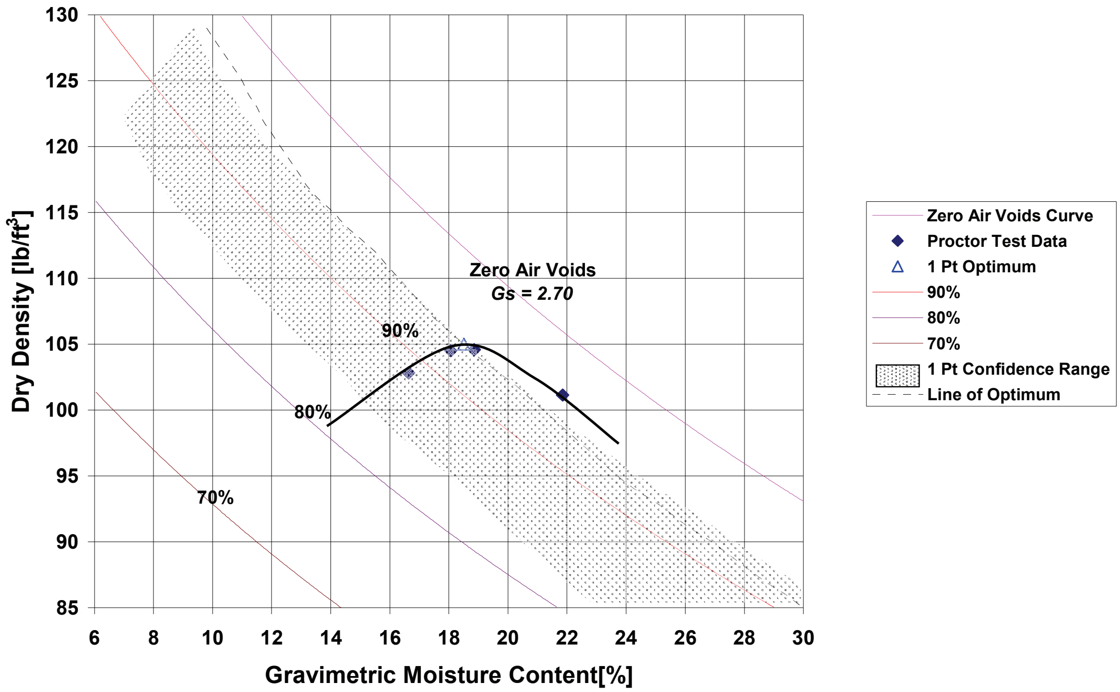


Figure C.17. ISU Proctor test on 10/10/2006 from Osage berm STA 14102+50 east bound

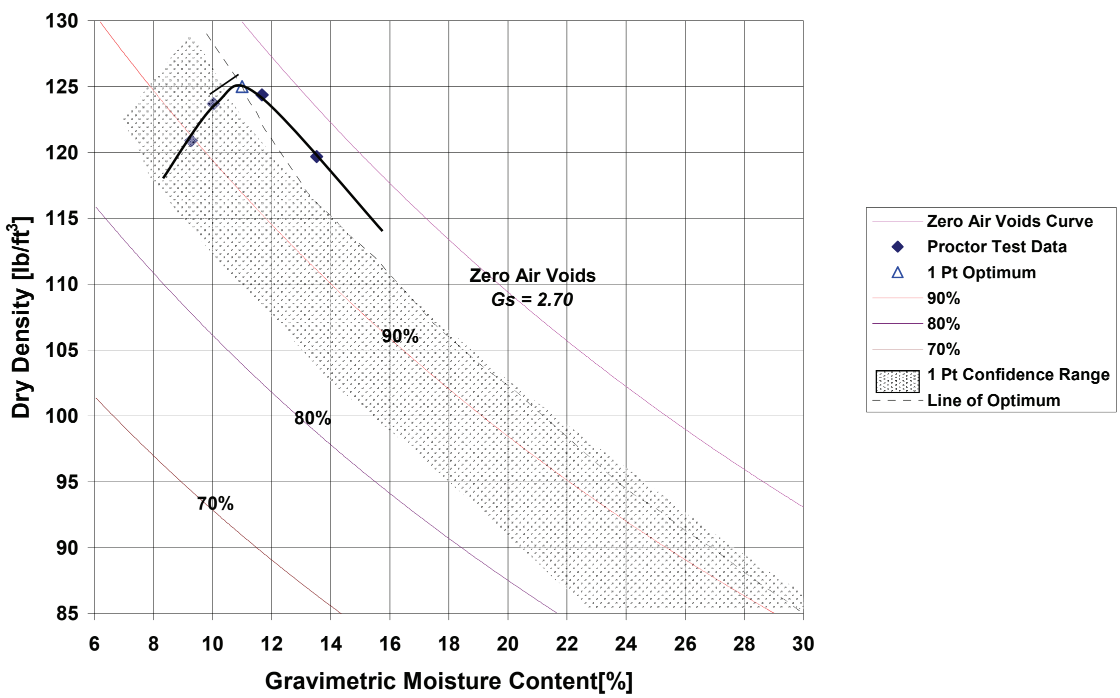


Figure C.18. ISU Proctor test on 10/10/2006 from Mainline STA 173+00 west bound

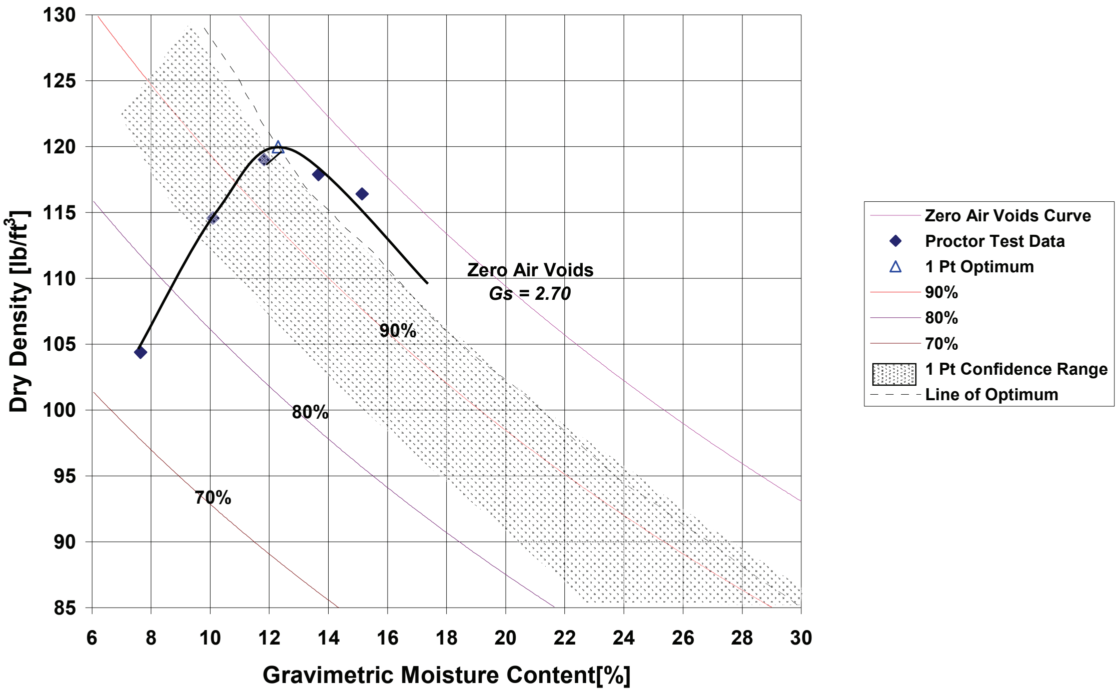
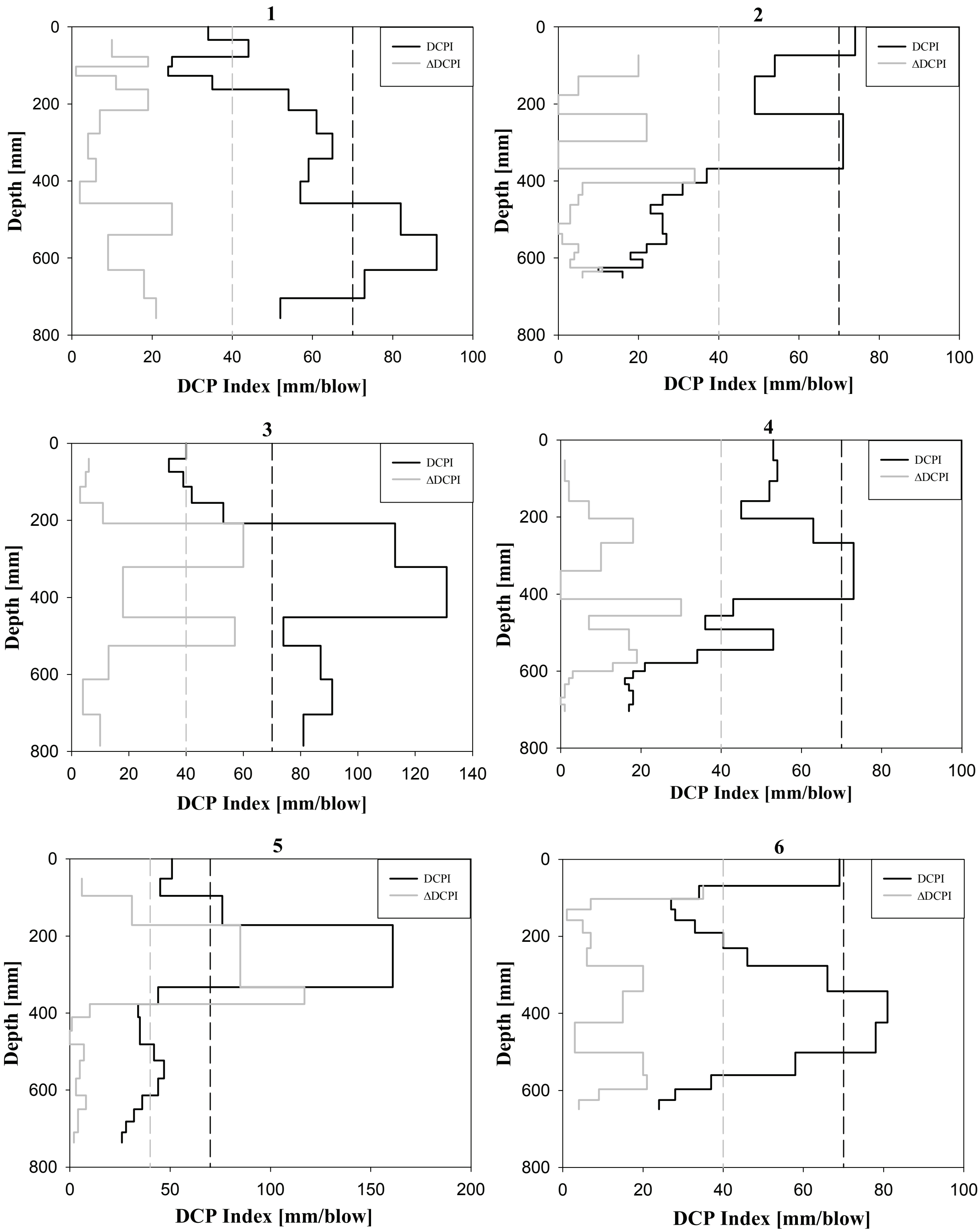


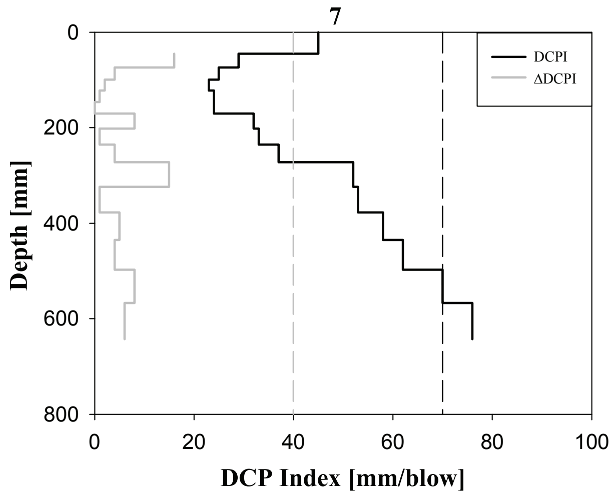
Figure C.19. ISU Proctor test on 12/19/2006 from Mainline STA 147+50 west bound

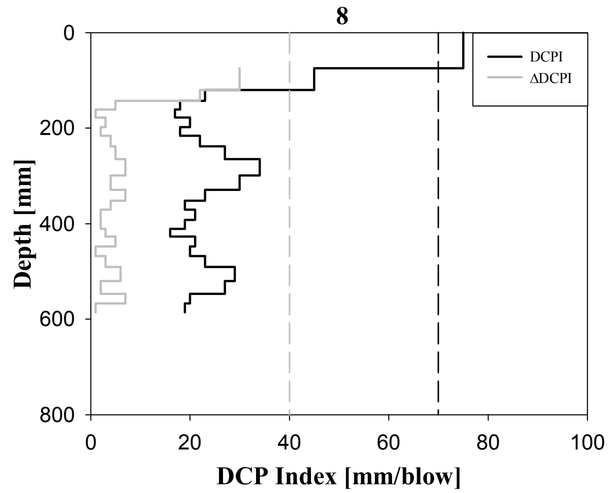
APPENDIX D. ISU DCP TEST PROFILES

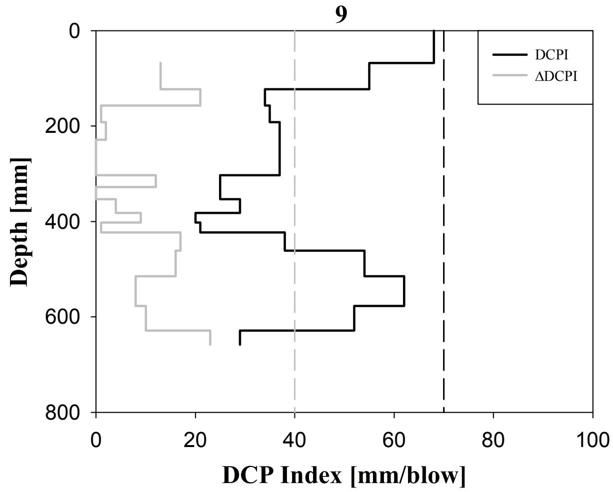
Table D.1. ISU QA Test summary

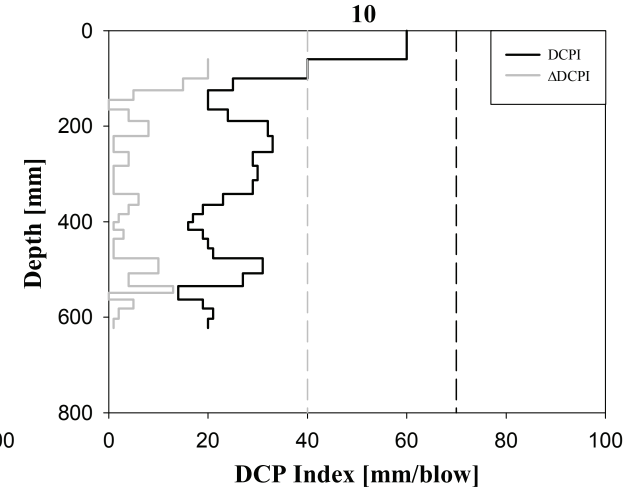
Test Set	Test No.	Date	Location Description	STA	OFF	Notes	Moisture content	Dry unit weight	DCP index 0-200 mm	DCP index 200-400 mm	DCP index 400-600 mm	Variation in DCP index
							[%]	[lb/ft3]	[mm/blow]	[mm/blow]	[mm/blow]	[mm/blow]
A	1	8/16/06	34 Connector	22007	30	8 m R CL	20.48	120.4	37.9	61.2	77.5	11.6
	2	8/16/06	34 Connector	22007	50	9 m R CL	23.55	113.7	59.6	62.7	25.8	7.8
	3	8/16/06	34 Connector	22007	70	10 m R CL	23.22	112.0	42.1	117.7	93.6	21.4
	4	8/16/06	34 Connector	22007	90	11 m R CL	24.21	108.3	51.4	69.3	42.5	8.3
	5	8/16/06	34 Connector	22008	10	12 m R CL	26.51	107.5	74.6	120.7	40.6	31.4
B	6	8/16/06	Mainline WB	145	0	10 m R CL	22.3	102.6	44.4	61.6	64.2	11.1
	7	8/16/06	Mainline WB	145	0	5 m R CL	22.4	103.3	30.7	46.8	66.4	5.4
	8	8/16/06	Mainline WB	145	25	10 m R CL	26.3	93.9	46.1	25.2	22.4	6.5
	9	8/16/06	Mainline WB	145	25	5 m R CL	27.8	90.9	51.6	31.3	49.4	8.1
	10	8/16/06	Mainline WB	145	50	10 m R CL	25.7	93.8	37.8	27.5	21.5	4.9
	11	8/16/06	Mainline WB	145	50	5 m R CL	24.9	97.8	43.9	35.6	28.4	7.4
	12	8/16/06	Mainline WB	145	75	10 m R CL	25.5	95.5	39.4	27.2	25.2	5.8
	13	8/16/06	Mainline WB	145	75	5 m R CL	25.9	94.0	36.5	27.8	15.4	3.2
	14	8/16/06	Mainline WB	144	38	8 m R CL	19.68		31.4	34.4	17.0	4.8
	15	8/16/06	Mainline WB	144	63	8 m R CL	22.6		67.5	23.9	23.4	8.5
	16	8/16/06	Mainline WB	144	88	8 m R CL	18.59		57.4	30.9	26.7	5.2
	17	8/16/06	Mainline WB	145	13	8 m R CL	21.26		33.1	25.4	20.8	4.3
	18	8/16/06	Mainline WB	145	38	8 m R CL	22.6		37.9	61.2	77.5	11.6
	19	8/16/06	Mainline WB	145	38	7 m R CL	22.42		91.8	30.0	22.6	18.6
	20	8/16/06	Mainline WB	145	50	8 m R CL	22.74		53.1	32.4	29.6	5.5
	21	8/16/06	Mainline WB	145	68	8 m R CL	19.39		37.0	46.2	42.9	5.5
C	22	8/16/06	Mainline EB	145	0	8 m R CL	25.45		64.9	18.8		8.6
	23	8/16/06	Mainline EB	145	25	8 m R CL	23.21		58.4	32.8	35.0	8.1
	24	8/16/06	Mainline EB	145	50	8 m R CL	19.66		31.2	27.9	21.8	6.8
	25	8/16/06	Mainline EB	145	75	8 m R CL	20.83		35.0	26.3	29.5	4.1
	26	8/17/06	Mainline EB	143	75	25m R CL	23.28		43.6	31.1	32.7	7.2
	27	8/17/06	Mainline EB	143	75	20m R CL	22.73		47.7	30.3	20.2	6.9
	28	8/17/06	Mainline EB	144	0	25m R CL	21.78	114.6	63.0	56.3	25.4	9.1
	29	8/17/06	Mainline EB	144	0	20m R CL	20.49	111.0	57.6	30.0	19.4	7.2
	30	8/17/06	Mainline EB	144	50	25m R CL	22.05	113.0	61.3	31.8	34.5	9.5
	31	8/17/06	Mainline EB	155	0	25m R CL	20.92	119.1	51.0	32.8	25.9	5.7
	32	8/17/06	Mainline EB	155	50	25m R CL	21.96	116.6	35.0	34.5	39.9	7.3
D	33	9/19/06	Mainline WB	143	50	20 m R CL	11.3		17.9	55.6	45.8	15.7
	34	9/19/06	Mainline WB	143	50	10 m R CL	10.5		14.4	27.7	20.5	3.2
	35	9/19/06	Mainline WB	143	75	20 m R CL	10		17.8	38.3	62.5	4.5
	36	9/19/06	Mainline WB	143	75	10 m R CL	11.3		27.0	59.2	43.9	8.1
	37	9/19/06	Mainline WB	144	25	20 m R CL	9.7		21.7	27.9	35.6	5.2
	38	9/19/06	Mainline WB	144	25	10 m R CL	10.9		16.6	29.3	34.4	2.9
	39	9/19/06	Mainline WB	144	0	20 m R CL	11.1		15.1	39.7	28.7	5.6
	40	9/19/06	Mainline WB	144	0	10 m R CL	10.8		25.2	24.9	39.2	4.0
E	41	9/19/06	Mainline EB	144	0	10 m R CL	9.9	138.6	13.4	20.2	28.5	2.5
	42	9/19/06	Mainline EB	144	0	20 m R CL	10.8		24.7	21.4	26.9	3.4
	43	9/19/06	Mainline EB	143	75	10 m R CL	10.2		13.4	20.3	0.0	2.8
	44	9/19/06	Mainline EB	143	75	20 m R CL	13.4	130.3	45.1	22.1	35.8	5.1
	45	9/19/06	Mainline EB	143	50	10 m R CL	10.5		14.4	17.6	31.1	2.0
	46	9/19/06	Mainline EB	143	50	20 m R CL	10.3		17.6	28.5	19.7	3.8
F	47	9/26/06	34 Connector	22005	25	10 m R CL	13.9	119.5	25.0	29.6	39.3	4.8
	48	9/26/06	34 Connector	22005	50	10 m R CL	12.3		27.1	44.0	30.9	5.2
	49	9/26/06	34 Connector	22005	75	10 m R CL	12.9	120.7	24.1	30.4	29.3	3.9
	50	9/26/06	34 Connector	22005	75	10 m R CL	12.7		16.5	39.6	29.4	5.4
	51	9/26/06	34 Connector	15110	75	10 m R CL	11.3		21.2	14.2	19.0	2.8
	52	9/26/06	34 Connector	15110	50	10 m R CL	12.6		21.1	18.9	17.0	2.8
	53	9/26/06	34 Connector	183	0	10 m R CL	13.3	109.4	17.3	25.4	22.7	1.6
	54	9/26/06	34 Connector	183	25	10 m R CL	11		21.6	29.8	23.0	3.5
	55	9/26/06	34 Connector	183	50	10 m R CL	12.6		19.5	28.3	22.6	2.6
G	56	9/26/06	Mainline EB	164	50	5 m R CL	25.7	96.1	61.4	79.9	40.6	13.2
	57	9/26/06	Mainline EB	164	25	5 m R CL	25.2		57.4	53.2	61.5	12.4
	58	9/26/06	Mainline EB	164	0	5 m R CL	25.2		53.3	60.4	48.4	6.4
	59	9/26/06	Mainline EB	163	75	5 m R CL	23.4	96.6	32.4	43.3	65.4	8.8
	60	9/26/06	Mainline EB	163	75	10 m R CL	27.9		62.8	56.4	36.8	7.1
	61	9/26/06	Mainline EB	164	0	10 m R CL	24.9		38.6	50.8	55.4	11.2
	62	9/26/06	Mainline EB	164	25	10 m R CL	28.5	92.5	36.8	47.8	55.9	9.1
	63	9/26/06	Mainline EB	164	50	10 m R CL	24.5		44.5	65.5	38.0	13.1
H	64	10/10/06	Osage Ave Deacell Ramp	14103	25	10m L CL	24.4	96.7	24.3	20.7	45.0	4.3
	65	10/10/06	Osage Ave Deacell Ramp	14103	25	10m R CL	23.7		20.8	17.5	28.3	3.9
	66	10/10/06	Osage Ave Deacell Ramp	14103	0	10m L CL	24.2		17.0	20.6	36.9	4.1
	67	10/10/06	Osage Ave Deacell Ramp	14103	0	10m R CL	25.7	97.5	35.3	20.1	22.1	6.7
	68	10/10/06	Osage Ave Deacell Ramp	14102	75	10m L CL	24	101.4	27.2	23.6	36.6	4.9
	69	10/10/06	Osage Ave Deacell Ramp	14102	75	10m R CL	24.9		34.3	27.2	25.6	9.9
	70	10/10/06	Osage Ave Deacell Ramp	14102	50	10m L CL	23.5		23.8	26.4	36.5	5.1
	71	10/10/06	Osage Ave Deacell Ramp	14102	50	10m R CL	22.8	98.0	32.0	21.6	21.4	4.1
I	72	10/10/06	Mainline WB	175	50	8m R SH	11.51		23.9	26.9	32.9	2.9
	73	10/10/06	Mainline WB	175	25	16m R SH	12.5		23.5	27.0	29.7	3.5
	74	10/10/06	Mainline WB	175	0	8m R SH	13.2	119.9	25.8	24.9	24.3	2.5
	75	10/10/06	Mainline WB	174	75	16m R SH	13		42.6	27.7	53.5	54.5
	76	10/10/06	Mainline WB	174	50	8m R SH	12.7		34.1	32.9	30.2	4.5
	77	10/10/06	Mainline WB	174	25	16m R SH	13.8		45.2	46.3	41.7	11.6
	78	10/10/06	Mainline WB	174	0	8m R SH	13.5		41.3	47.1	70.4	14.0
	79	10/10/06	Mainline WB	173	75	16m R SH	12.6	121.5	27.9	38.4	20.6	5.7

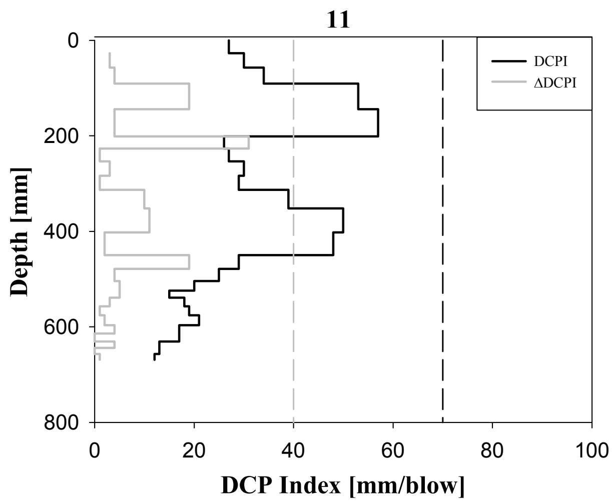

1
2
3
4
5
6
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100
120
140
50
150
200

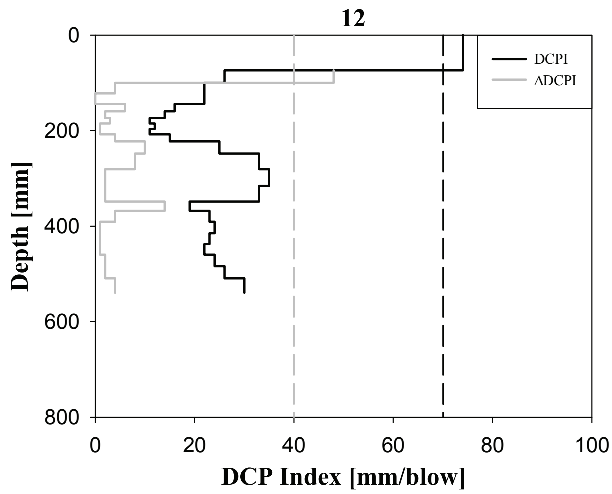

7
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]


8
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]

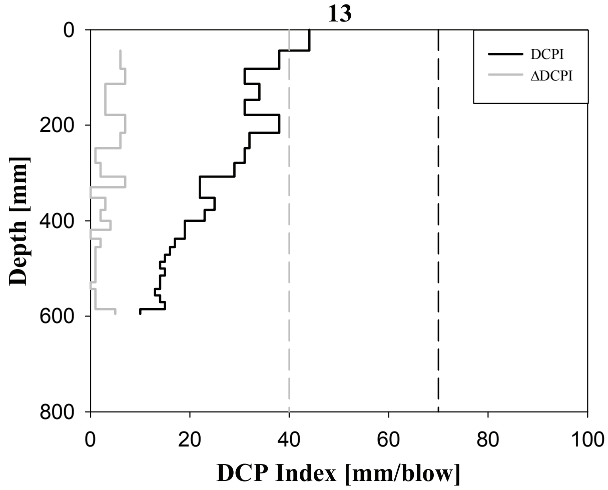

9
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]


10
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]

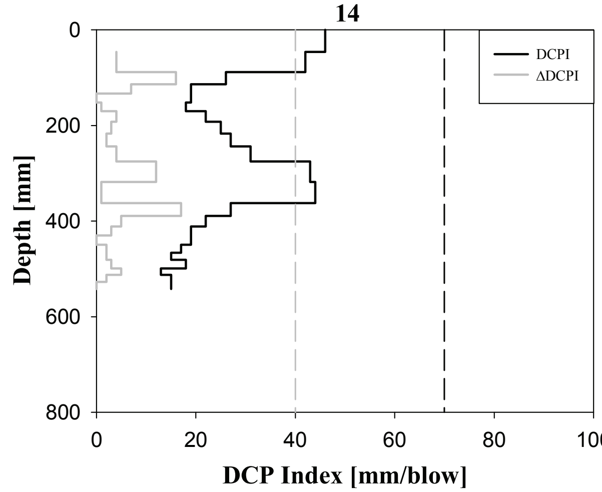

11
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]


12
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DCP Index [mm/blow]

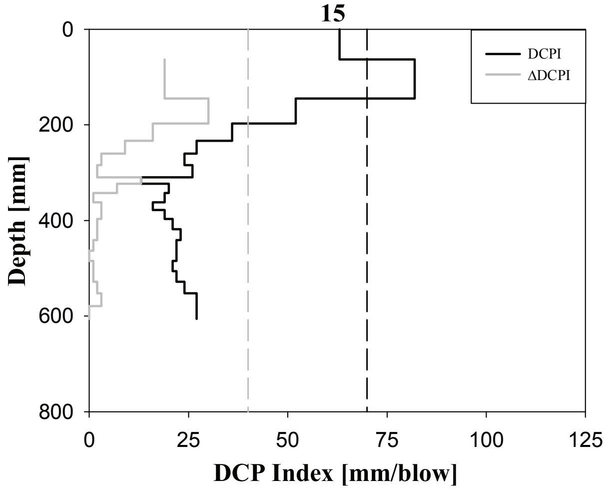
13



14



15



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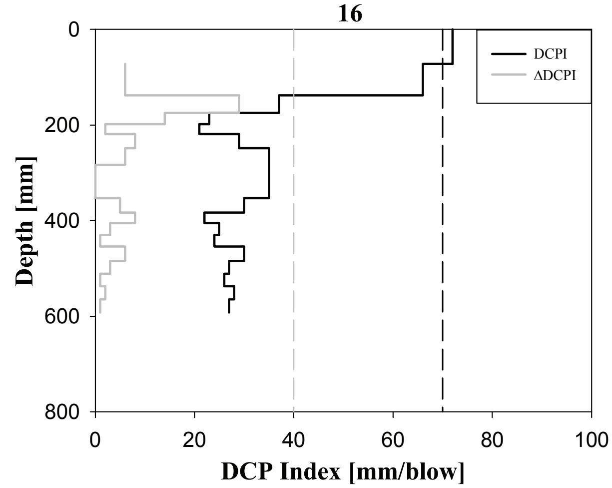

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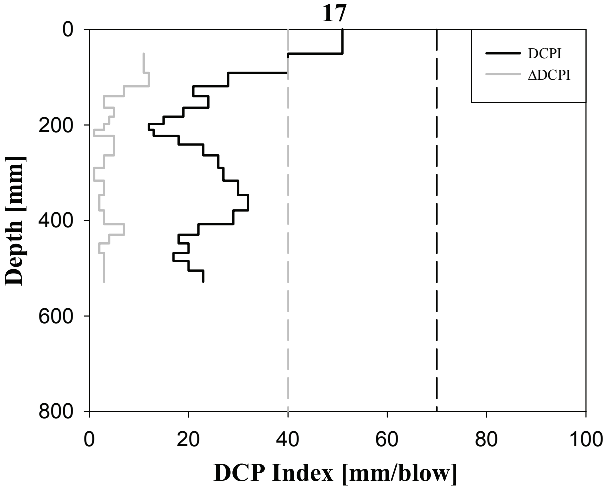
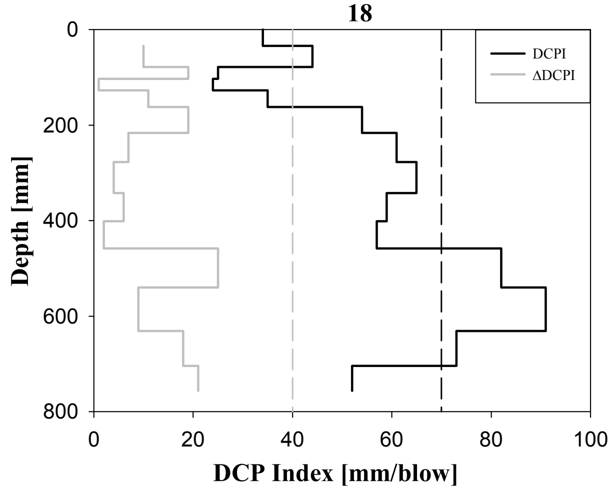
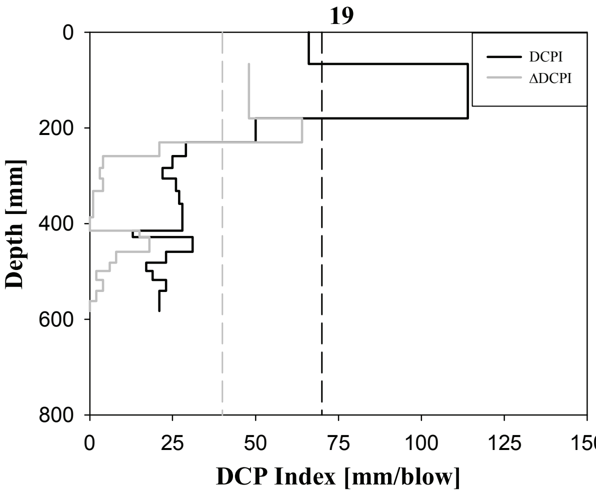
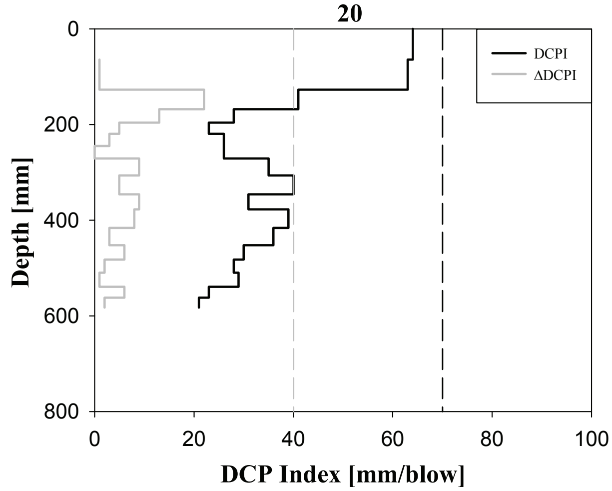
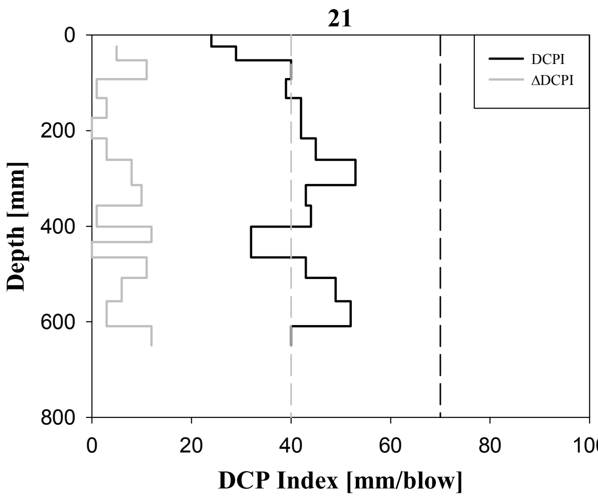


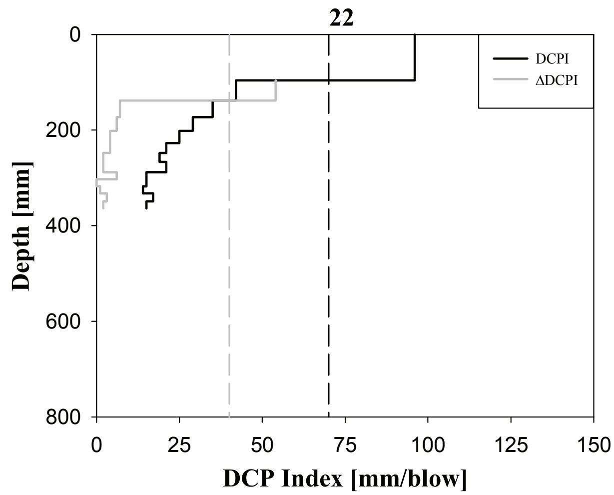
18

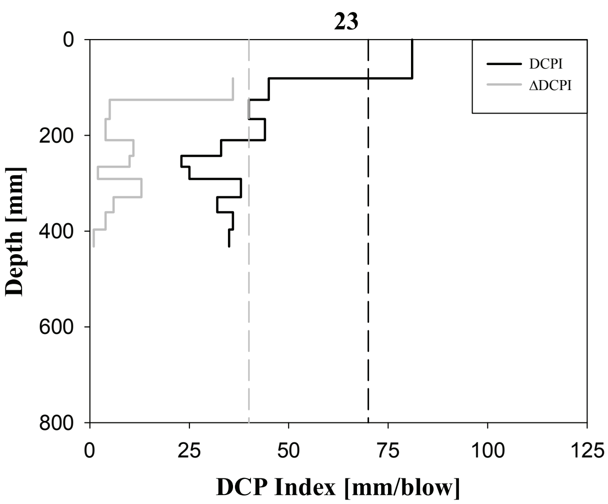


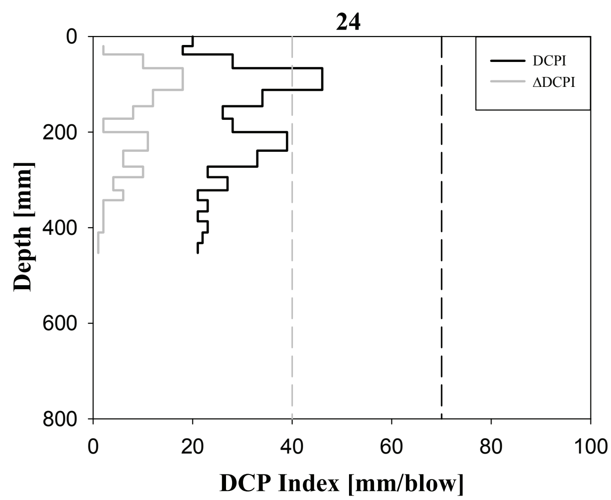

19
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 25 50 75 100 125 150

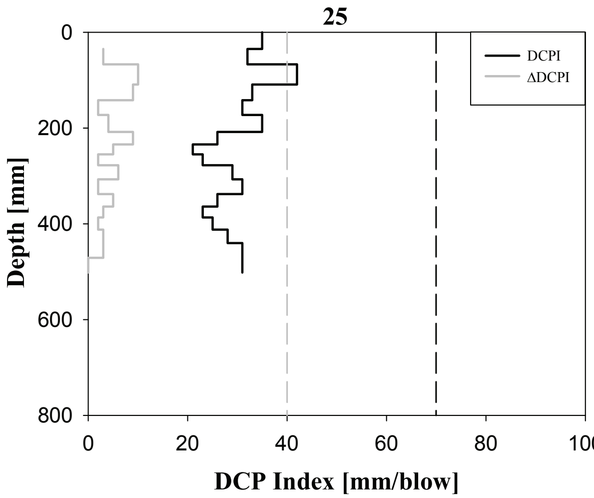

20
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 20 40 60 80 100

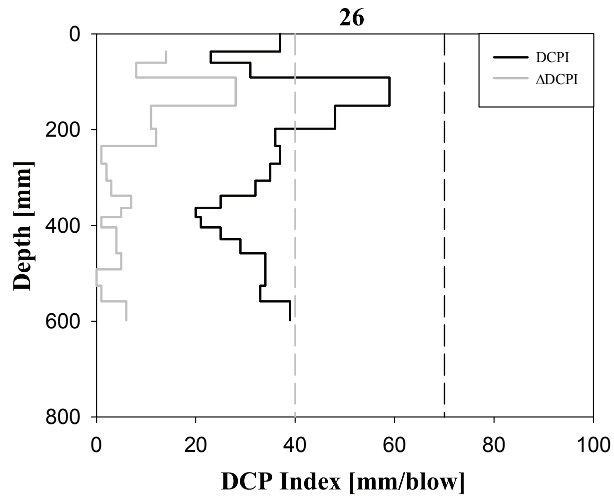

21
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 20 40 60 80 100

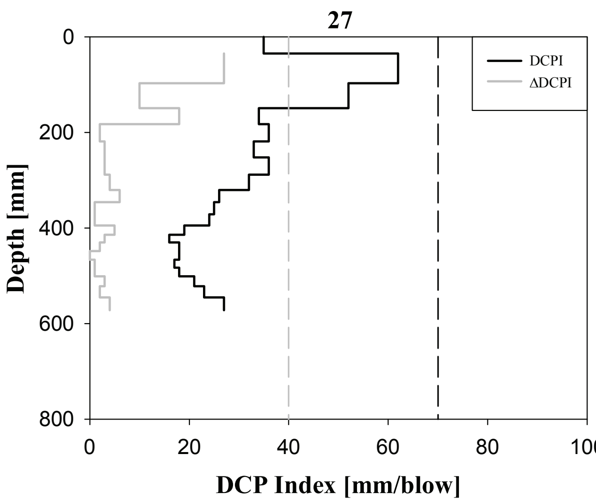

22
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 25 50 75 100 125 150

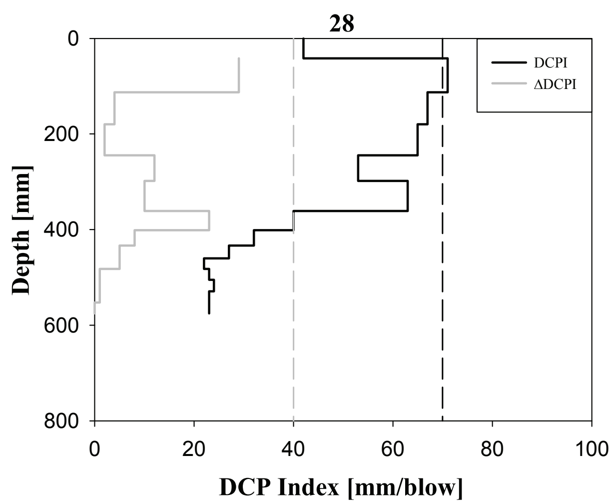

23
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 25 50 75 100 125

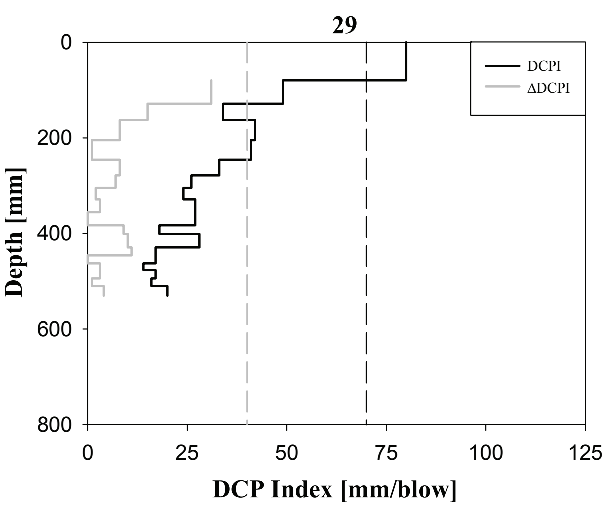

24
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0 20 40 60 80 100

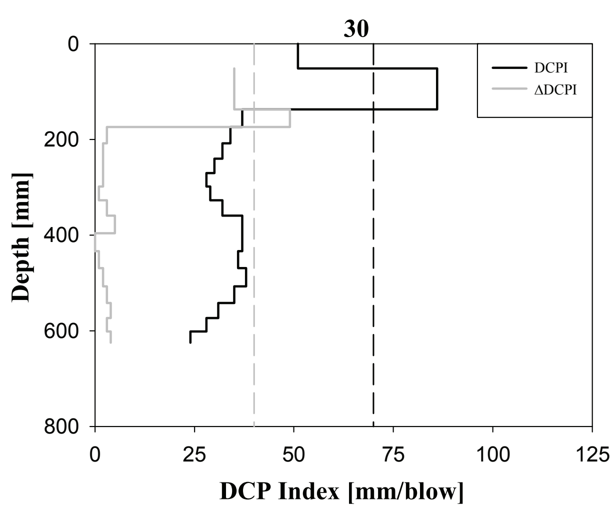

25
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

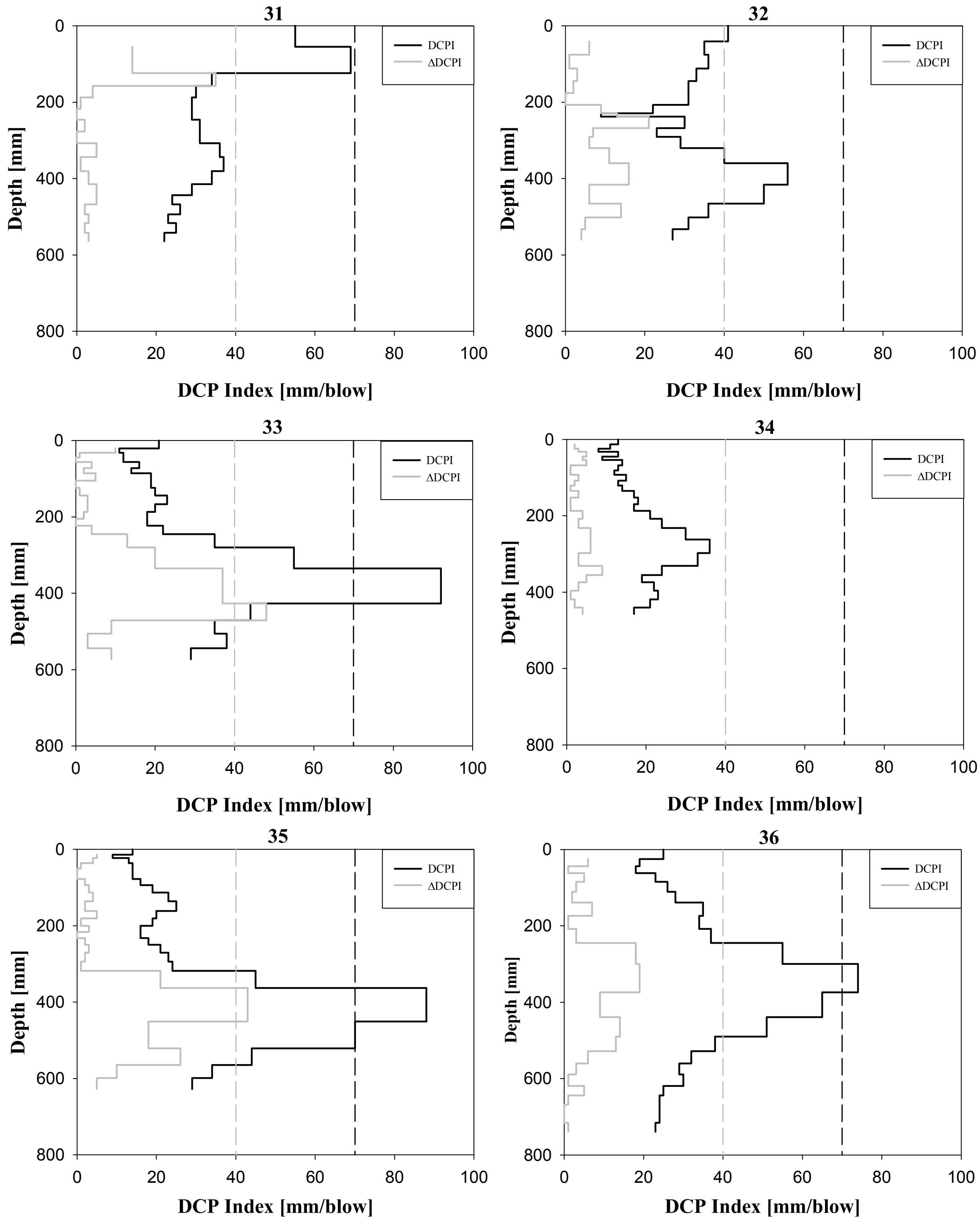

26
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

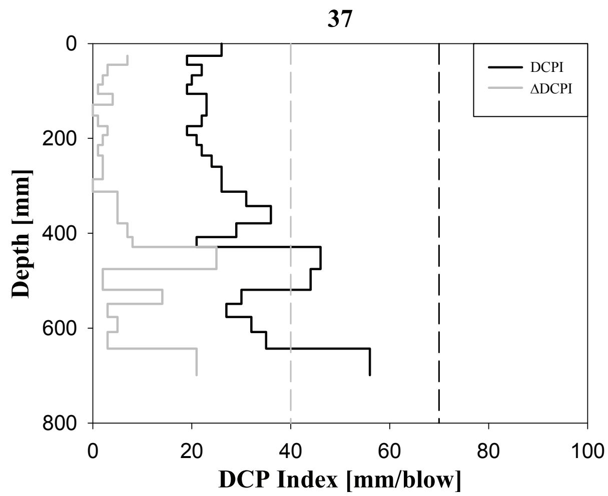

27
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

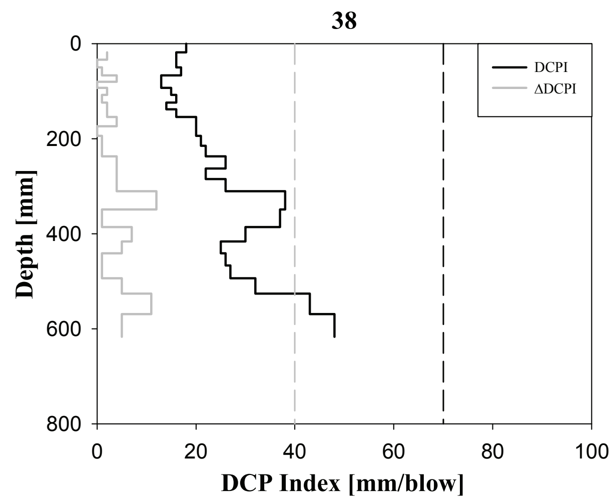

28
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

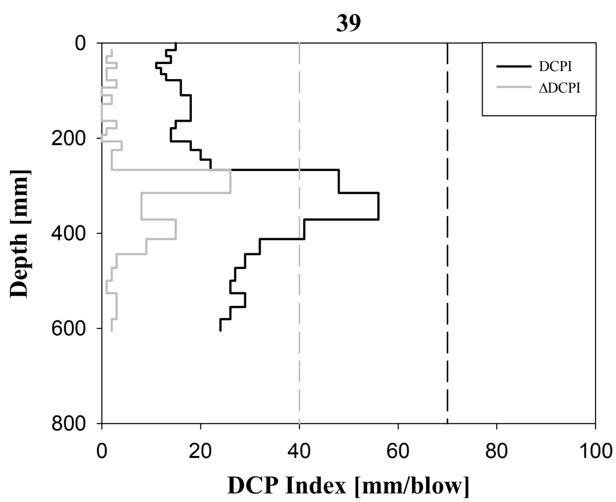

29
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

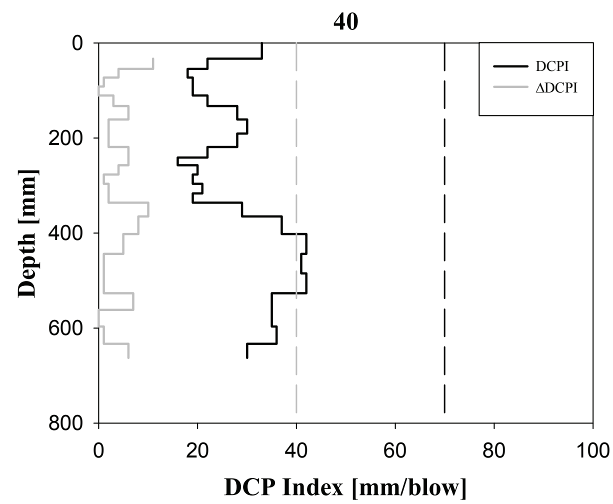

30
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

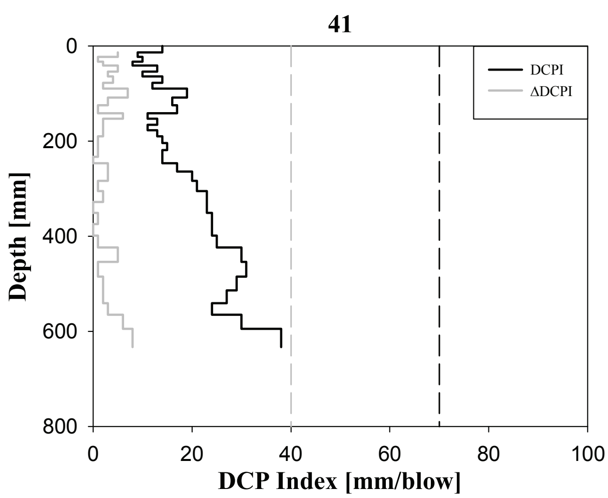

31
32
33
34
35
36
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100

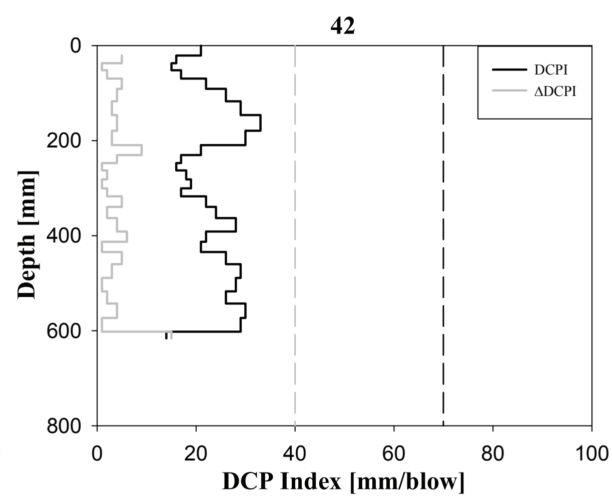

37
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

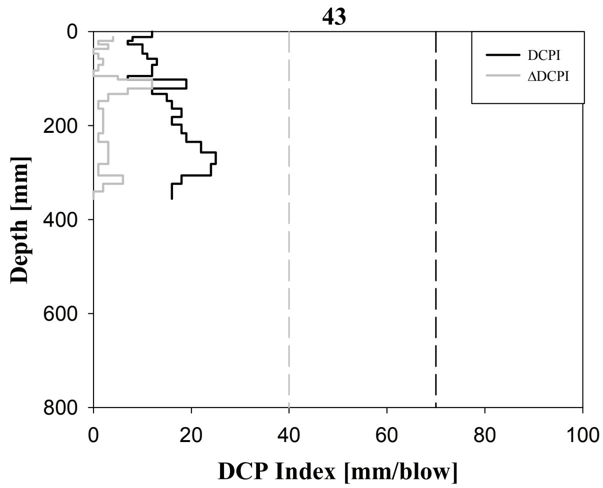

38
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

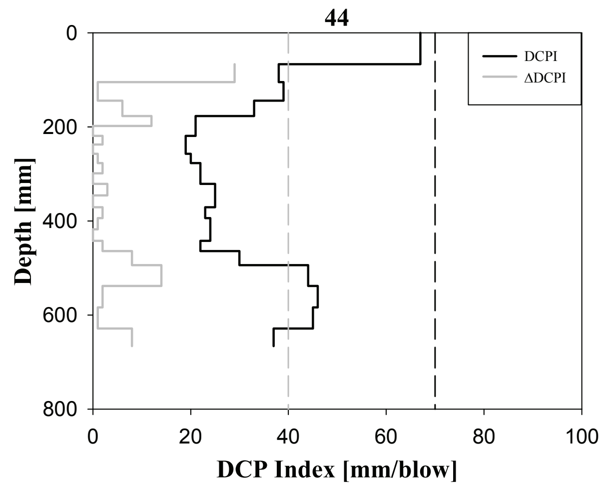

39
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

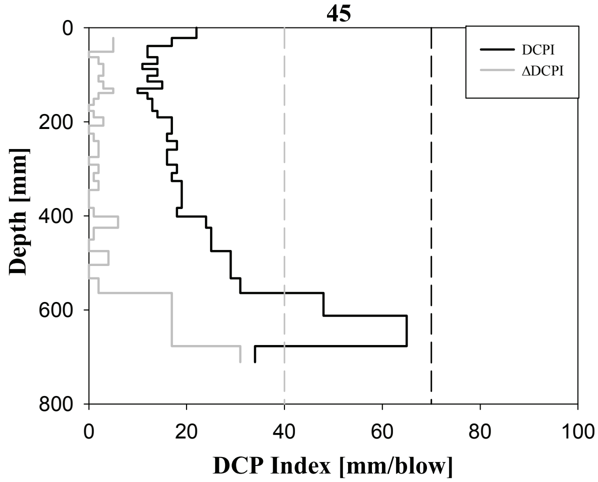

40
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

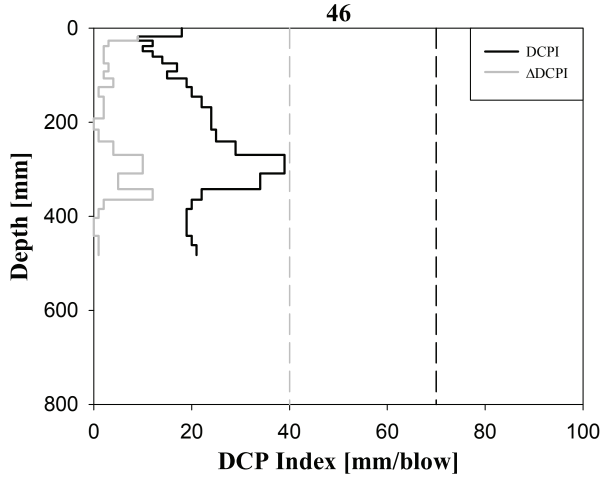

41
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

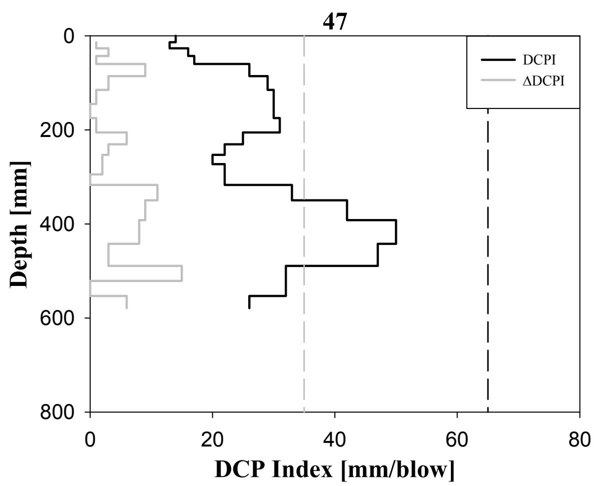

42
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

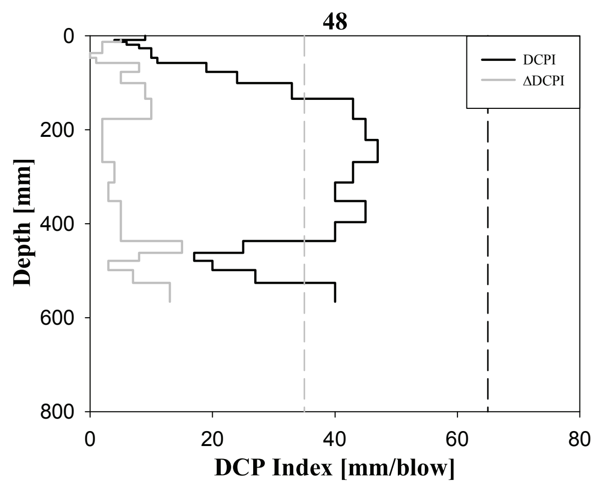

43
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

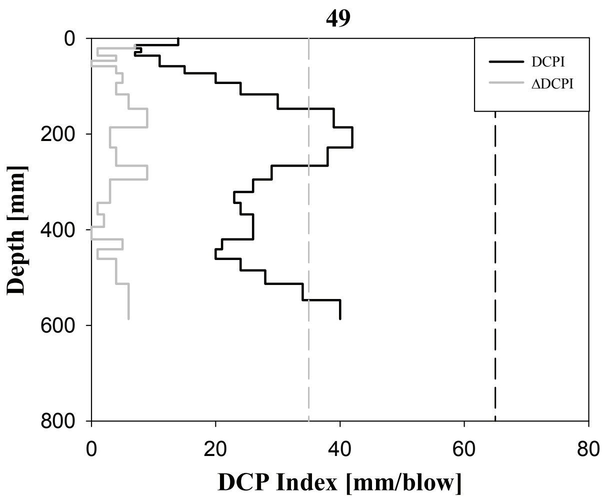

44
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

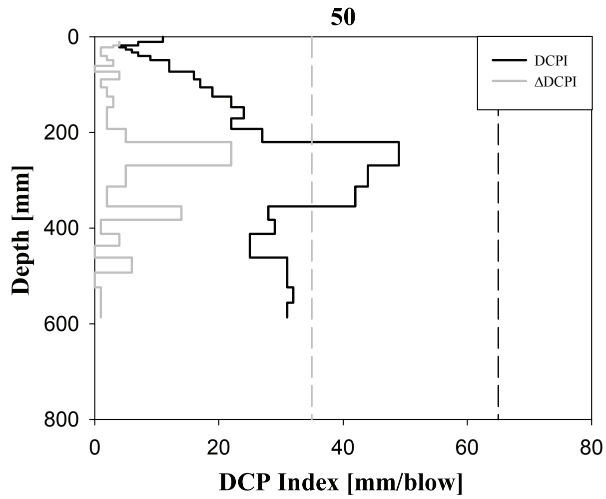

45
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

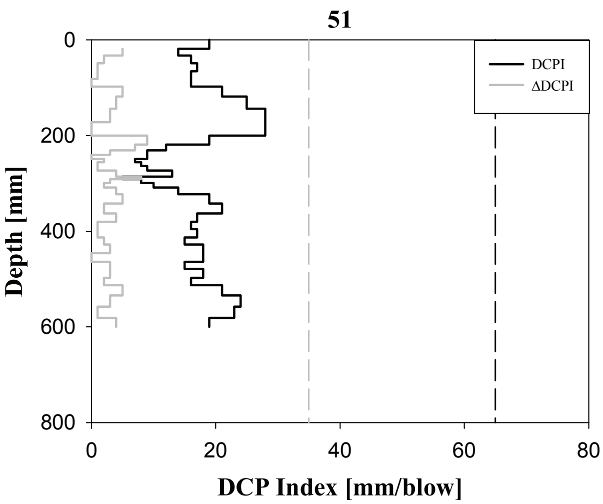

46
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

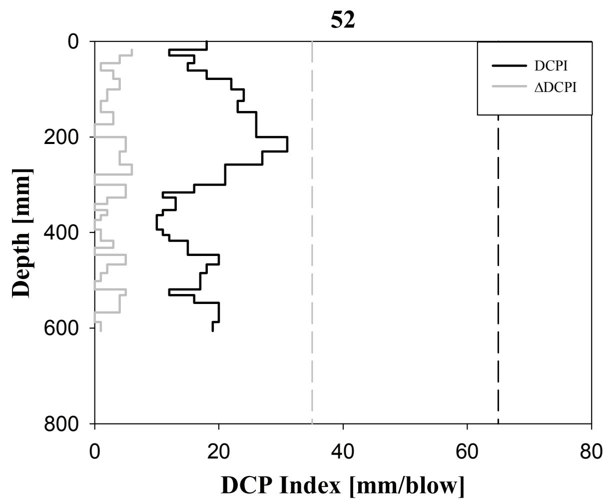

47
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

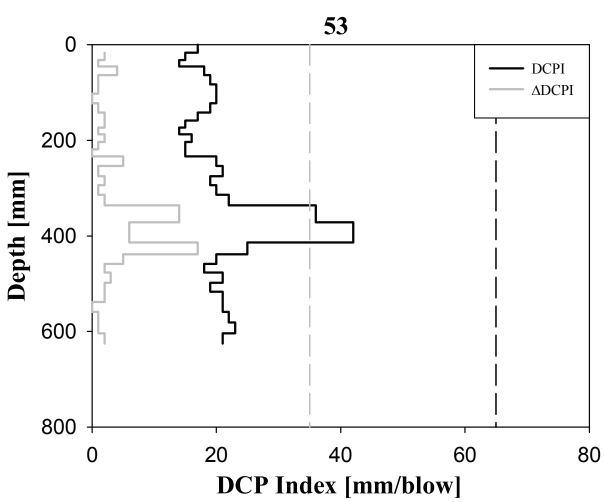

48
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

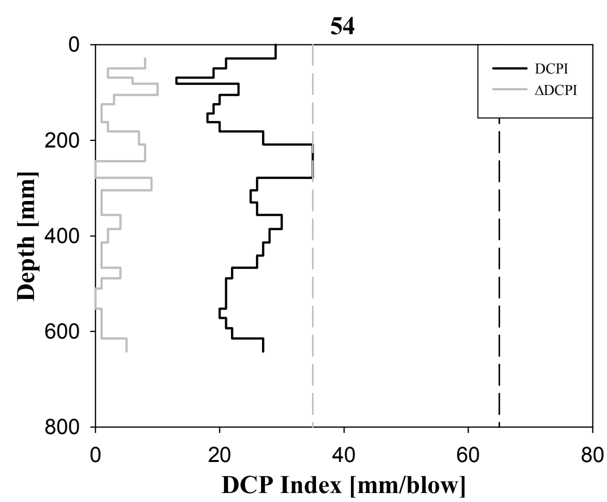

49
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

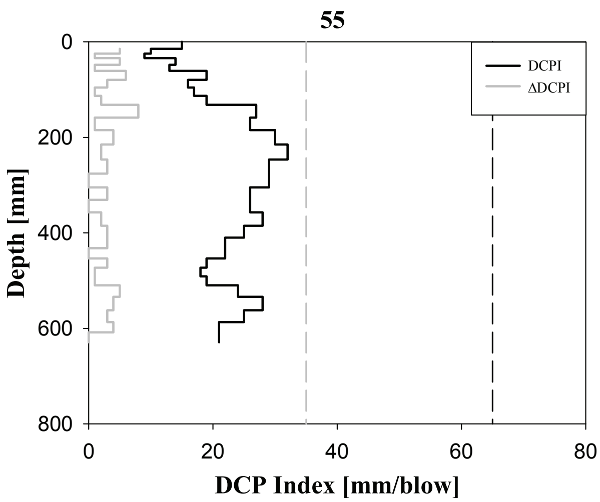

50
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

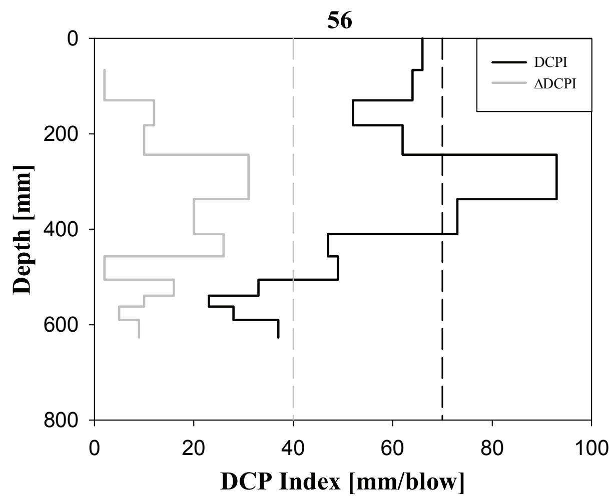

51
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

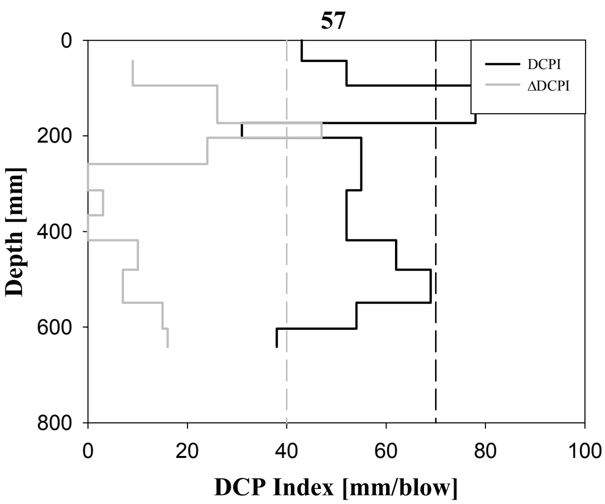

52
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

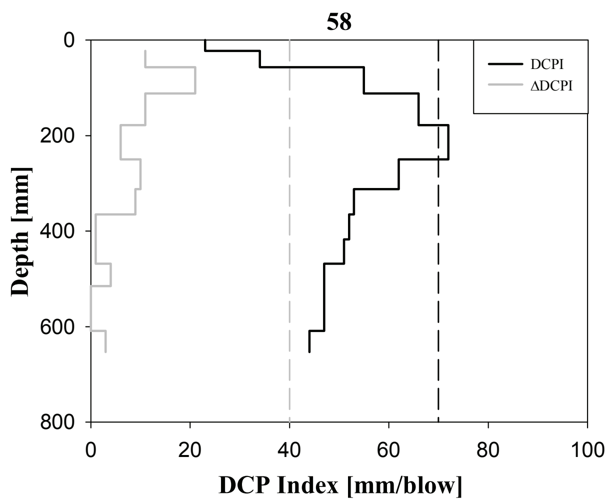

53
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

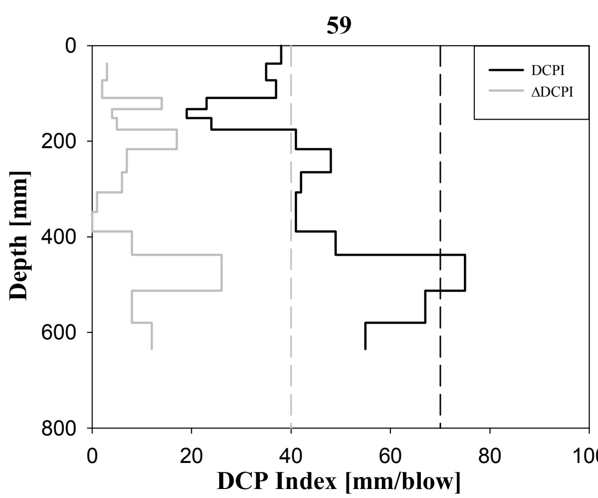

54
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

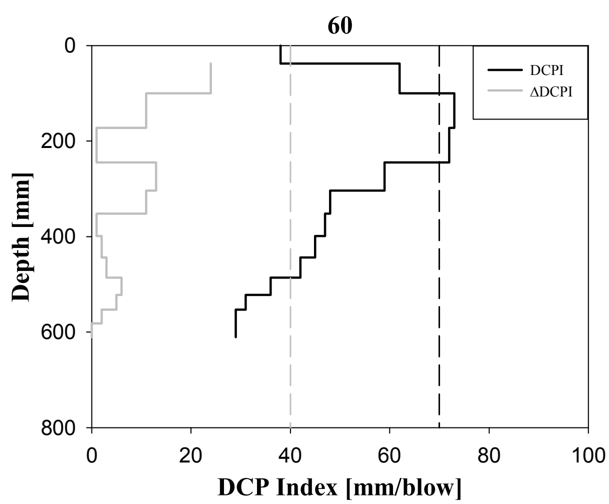

55
0
200
400
600
800
Depth [mm]
0
20
40
60
80
DCP Index [mm/blow]
DCPI
ΔDCPI

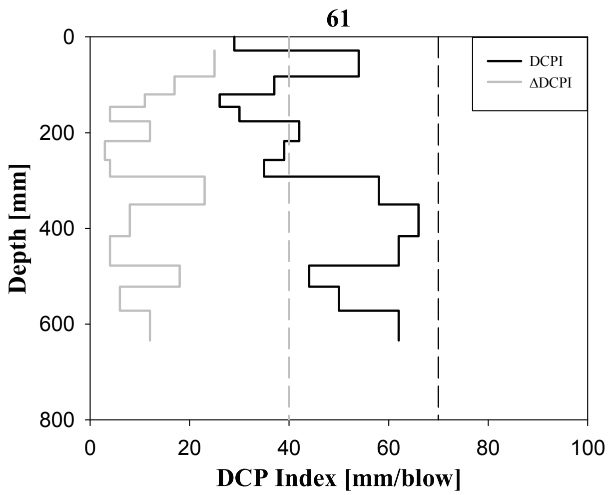

56
0
200
400
600
800
Depth [mm]
0
20
40
60
80
100
DCP Index [mm/blow]
DCPI
ΔDCPI

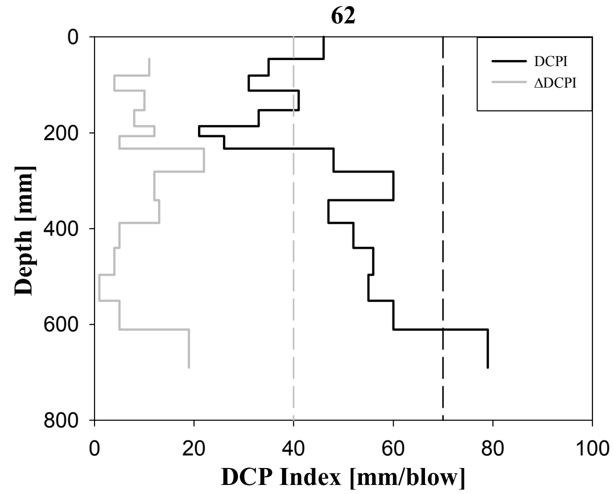

57
0
200
400
600
800
Depth [mm]
0
20
40
60
80
100
DCP Index [mm/blow]
DCPI
ΔDCPI

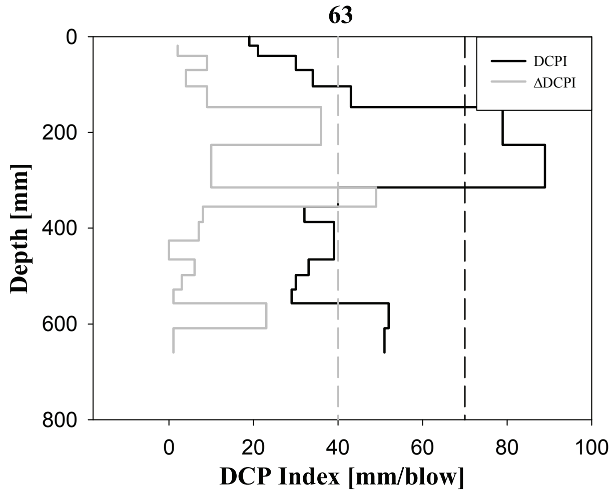

58
0
200
400
600
800
Depth [mm]
0
20
40
60
80
100
DCP Index [mm/blow]
DCPI
ΔDCPI

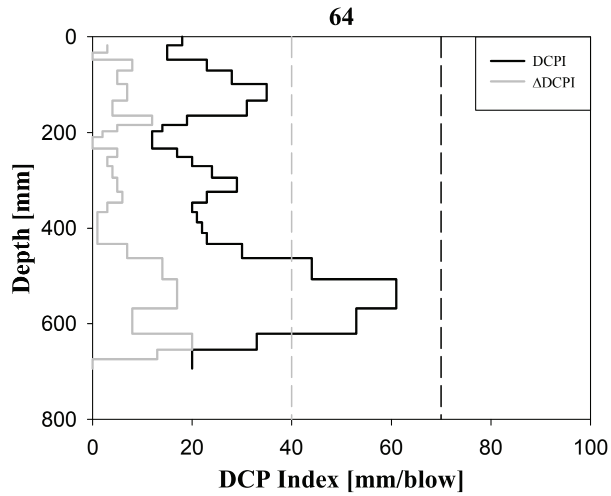

59
0
200
400
600
800
Depth [mm]
0
20
40
60
80
100
DCP Index [mm/blow]
DCPI
ΔDCPI

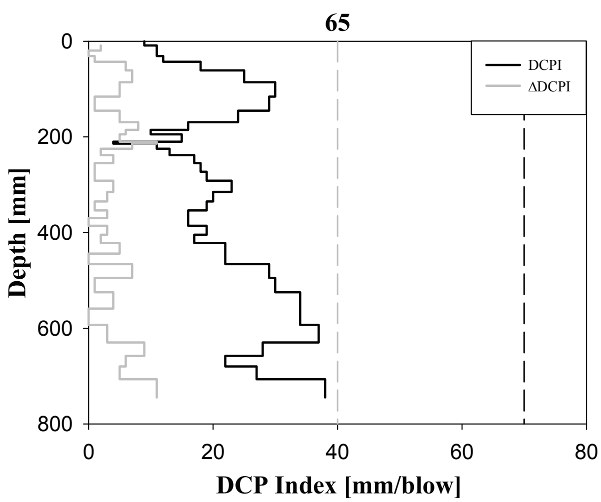

60
0
200
400
600
800
Depth [mm]
0
20
40
60
80
100
DCP Index [mm/blow]
DCPI
ΔDCPI

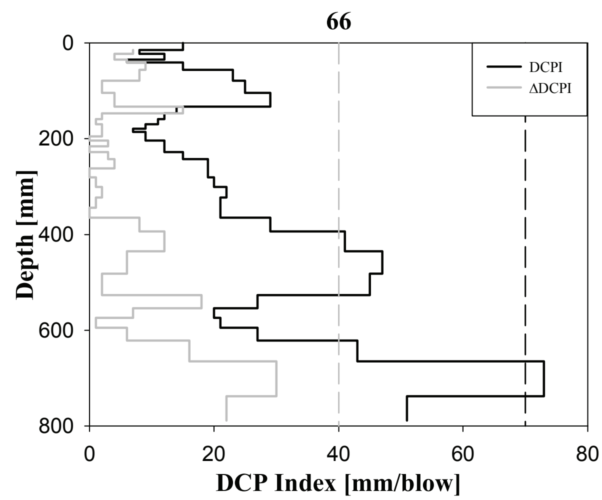

61
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100

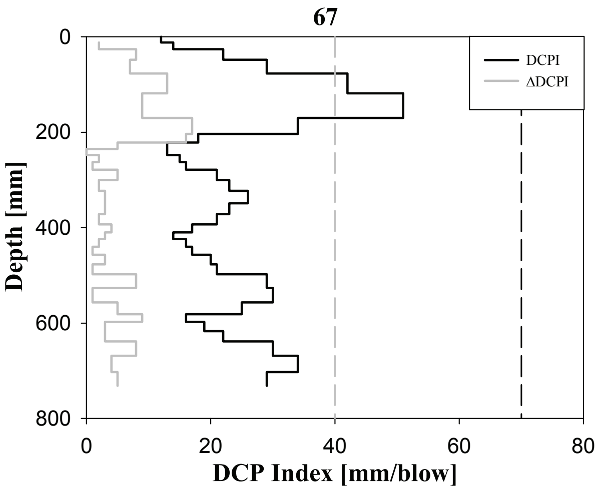

62
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100

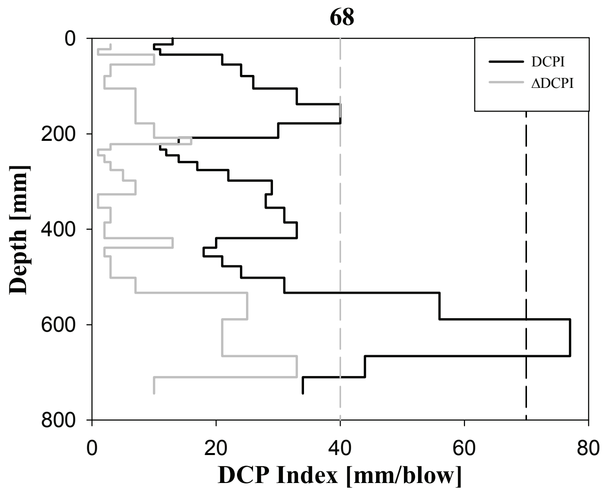

63
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100

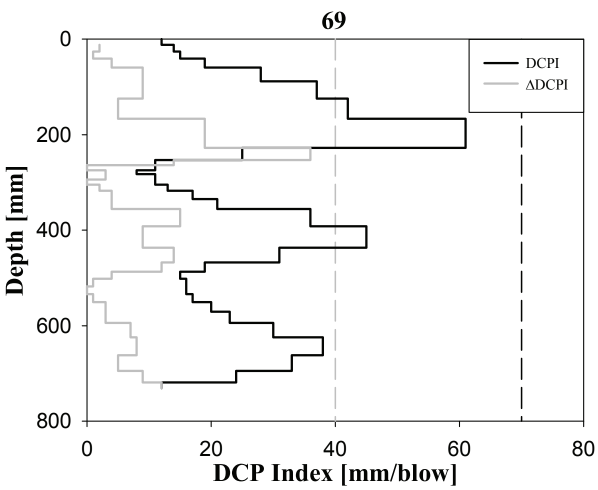

64
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80
100

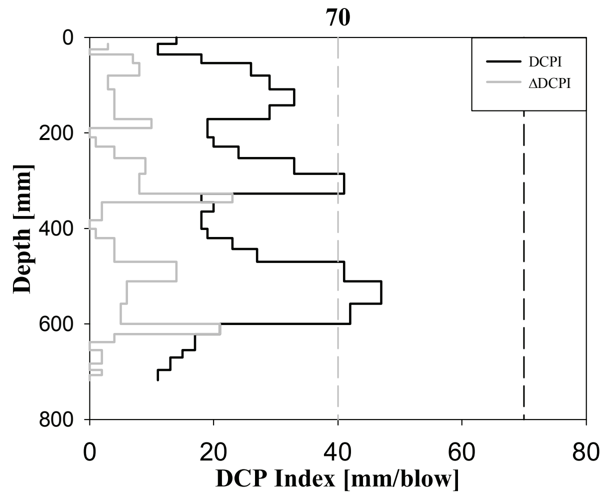

65
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80

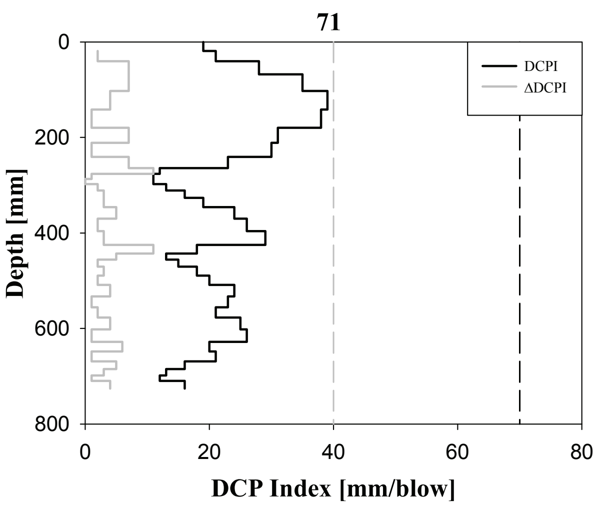

66
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]
0
200
400
600
800
0
20
40
60
80

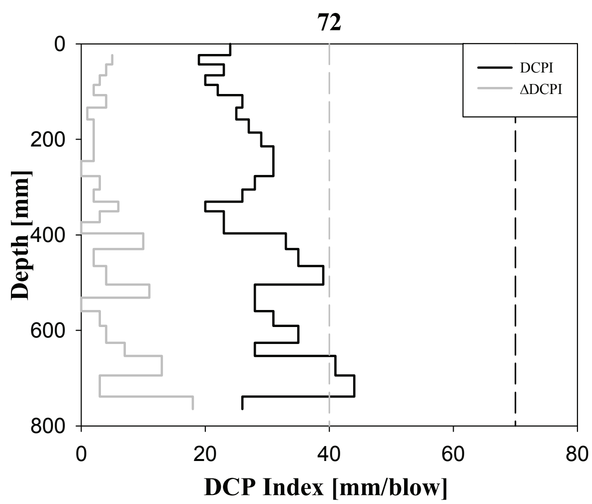

67
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

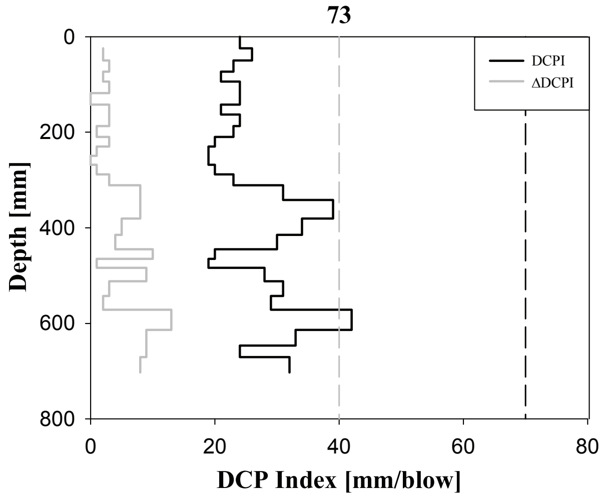

68
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

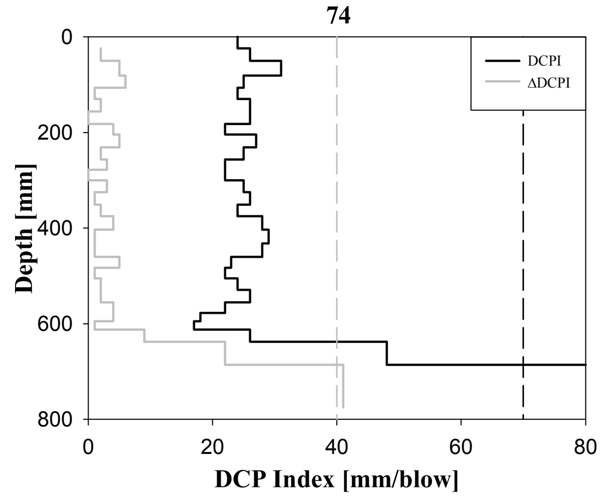

69
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

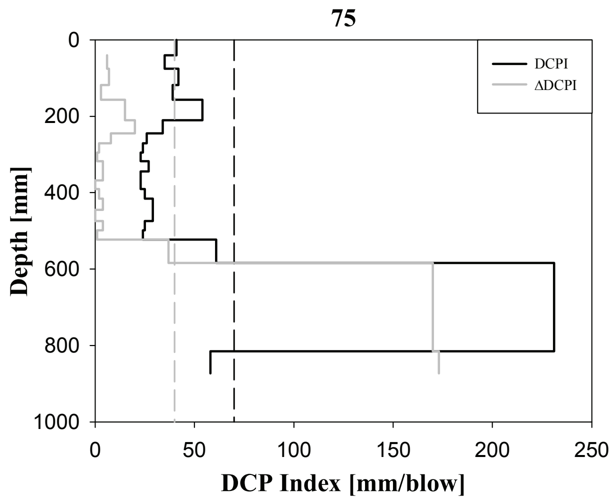

70
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

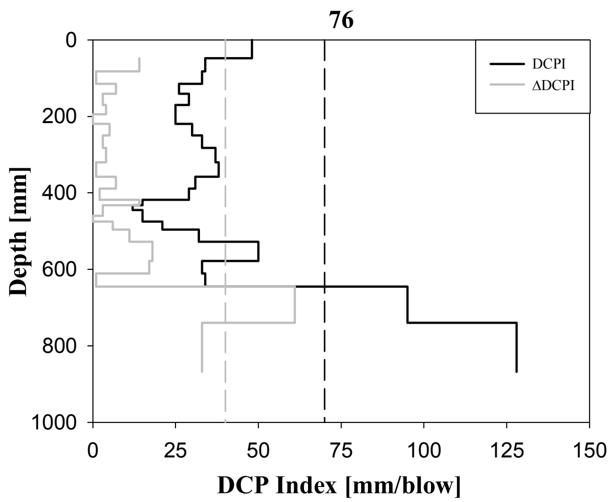

71
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

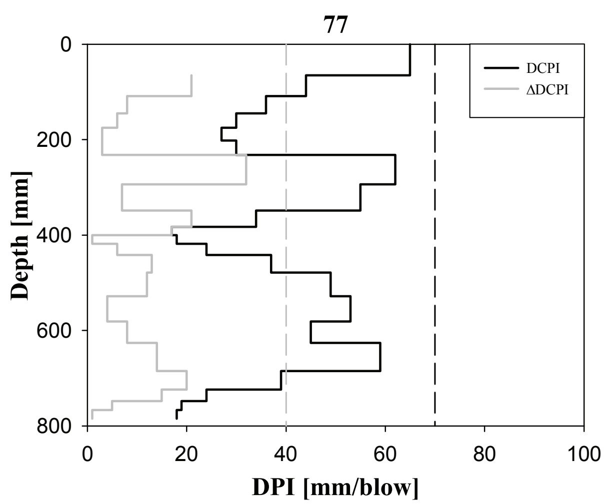

72
DCPI
ΔDCPI
Depth [mm]
DCP Index [mm/blow]

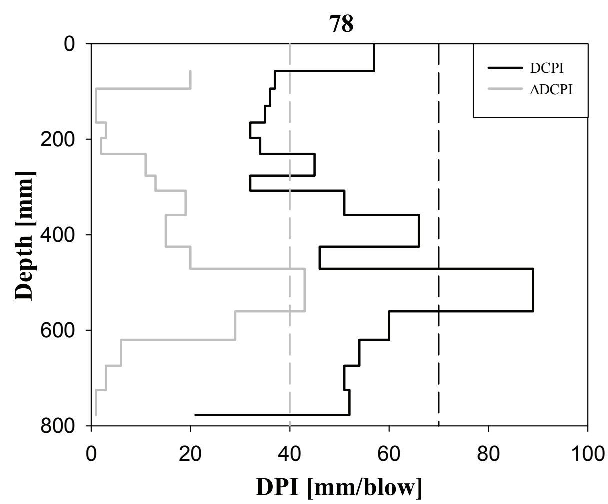

73
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

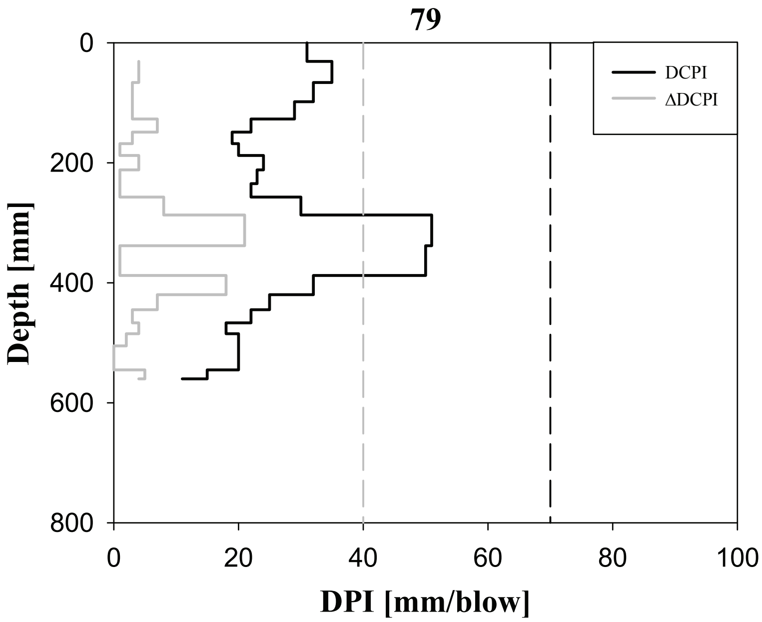

74
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI


75
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI


76
Depth [mm]
DCP Index [mm/blow]
DCPI
ΔDCPI

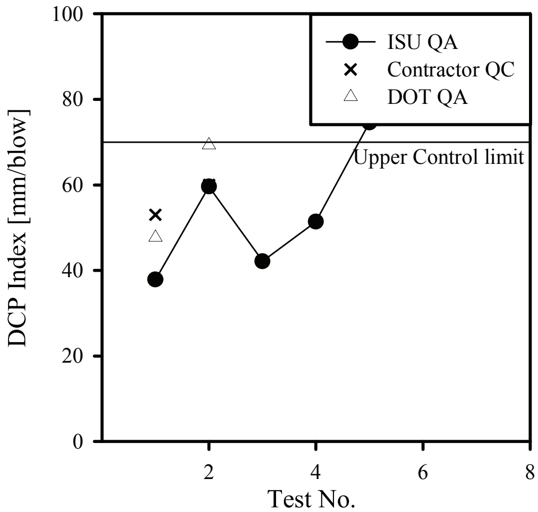

77
Depth [mm]
DPI [mm/blow]
DCPI
ΔDCPI

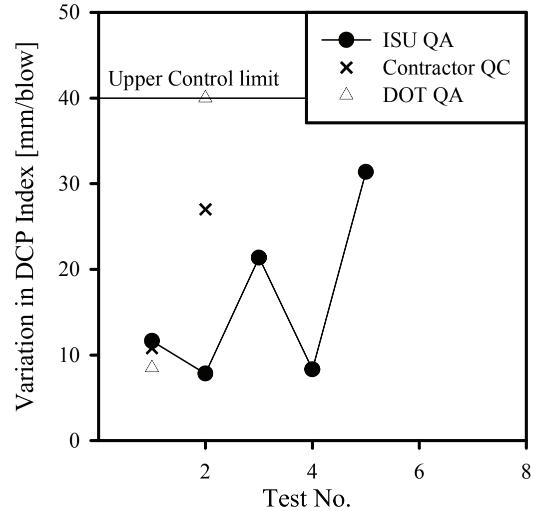

78
Depth [mm]
DPI [mm/blow]
DCPI
ΔDCPI

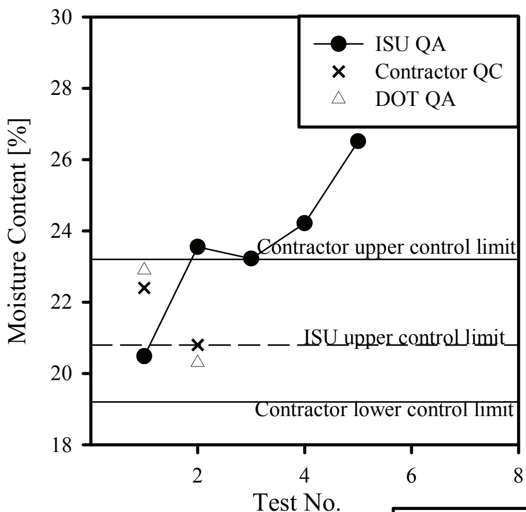

79
DCPI
ΔDCPI
Depth [mm]
0
200
400
600
800
0
20
40
60
80
100
DPI [mm/blow]

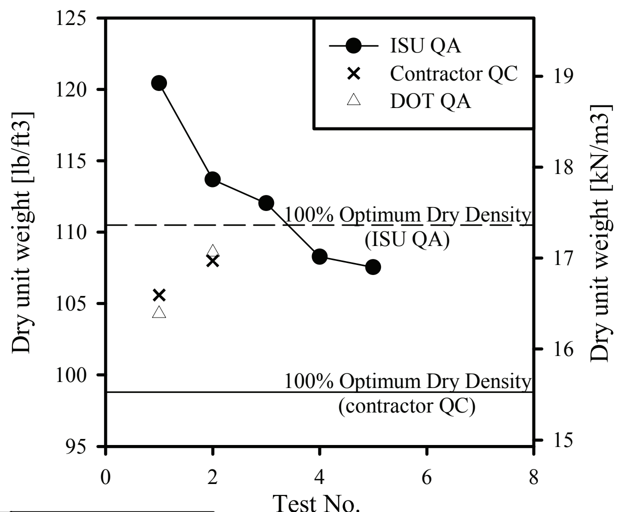
APPENDIX E. ISU QA COMPARISONS

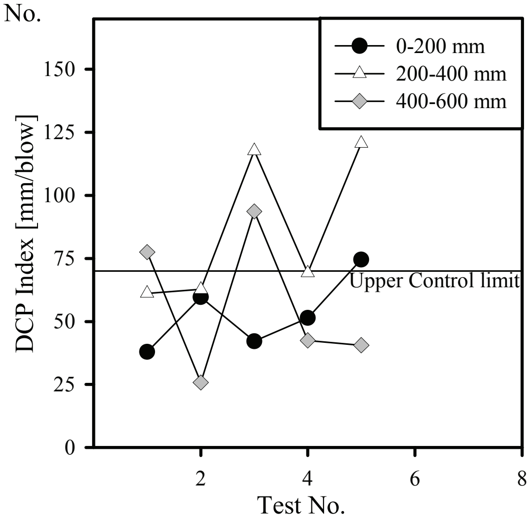
ISU QA test set A











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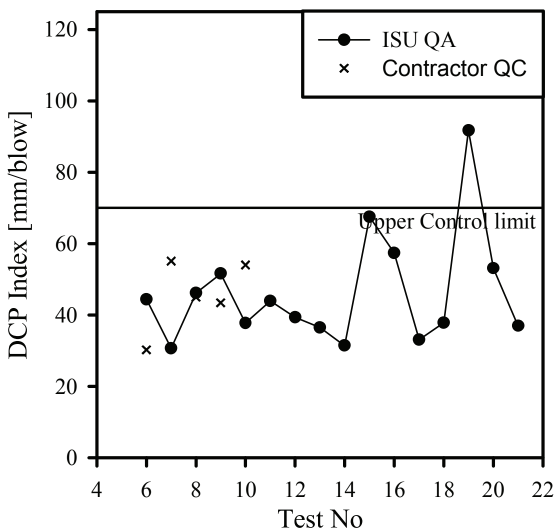

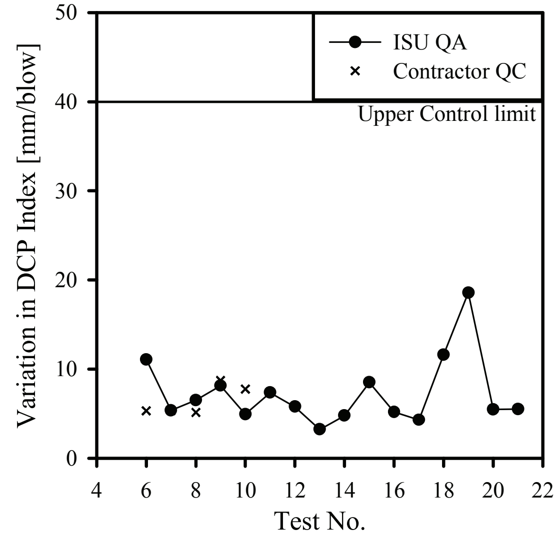

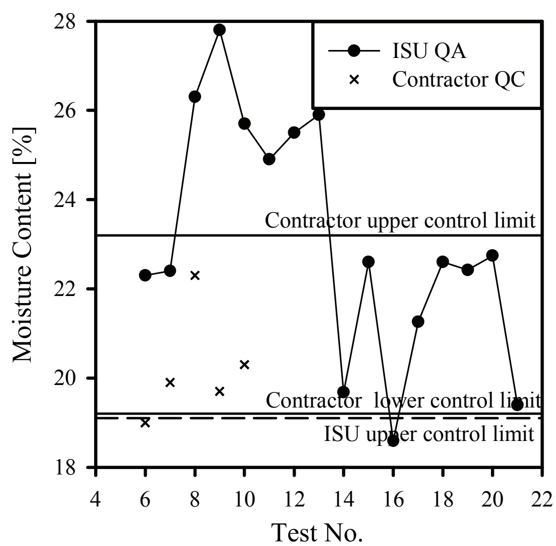

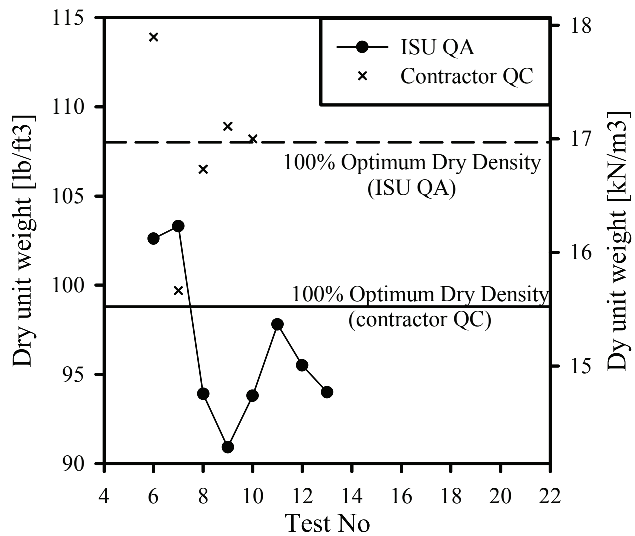

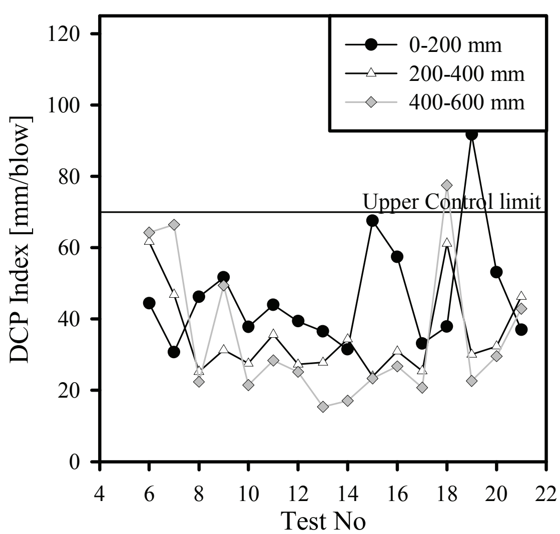

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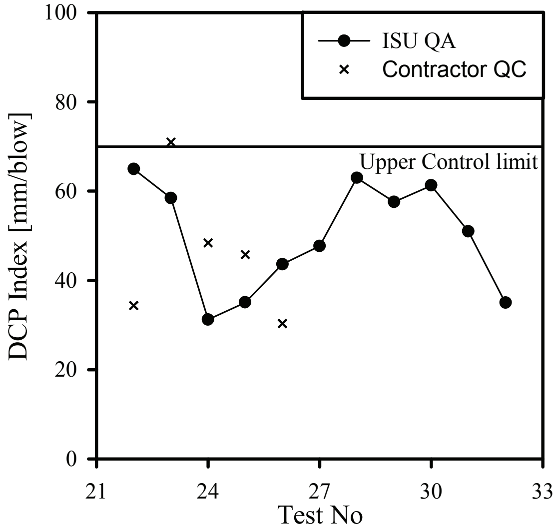

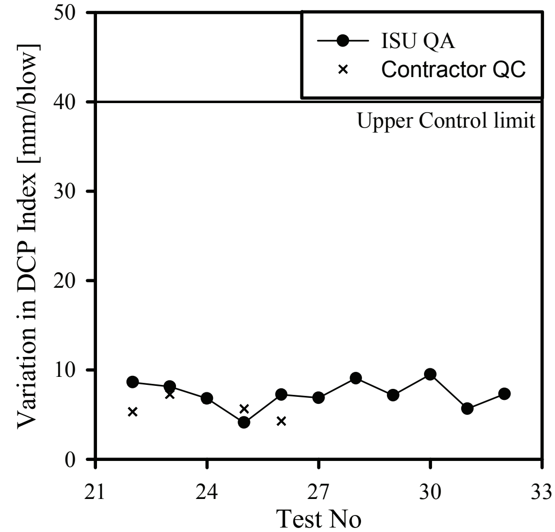

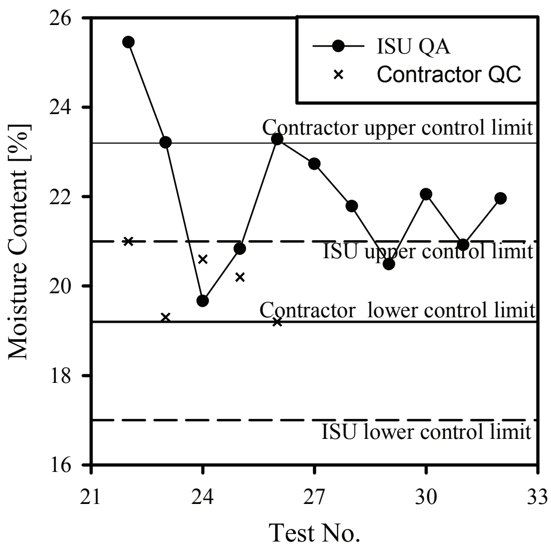

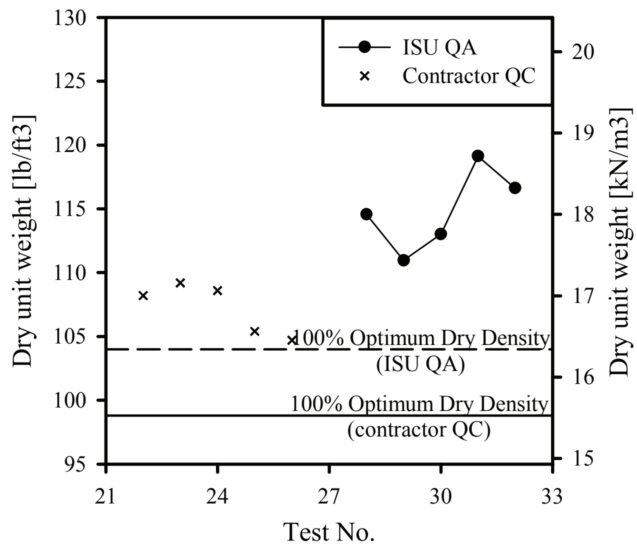

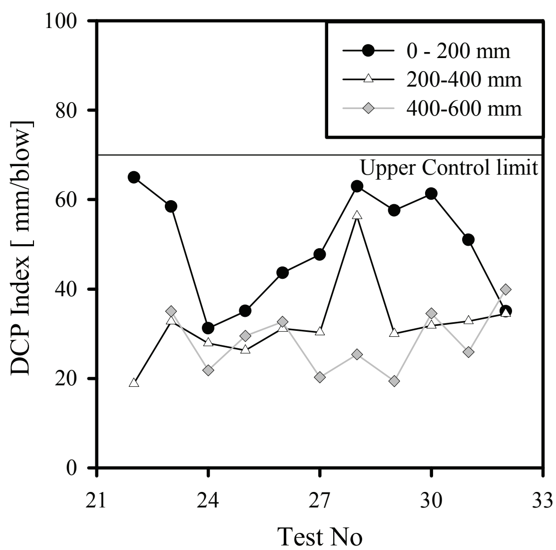

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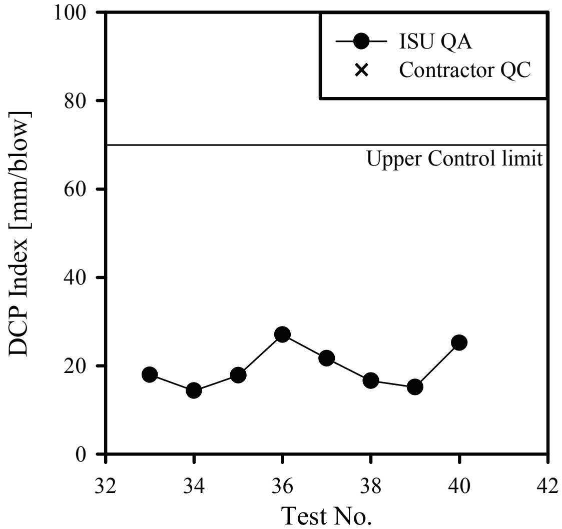

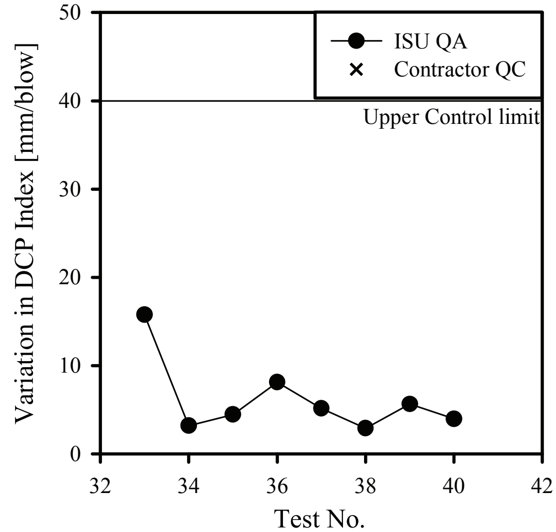

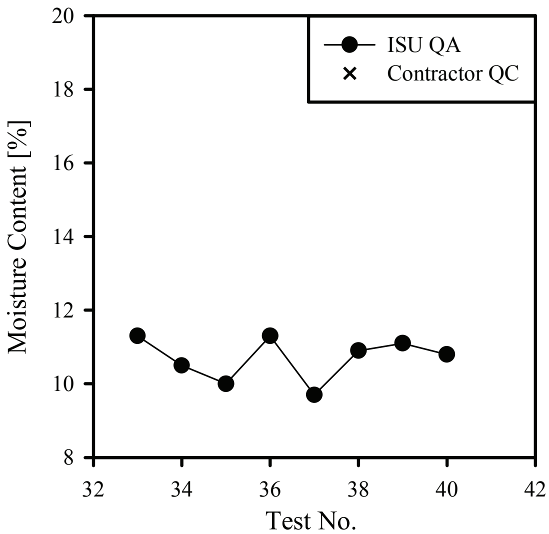

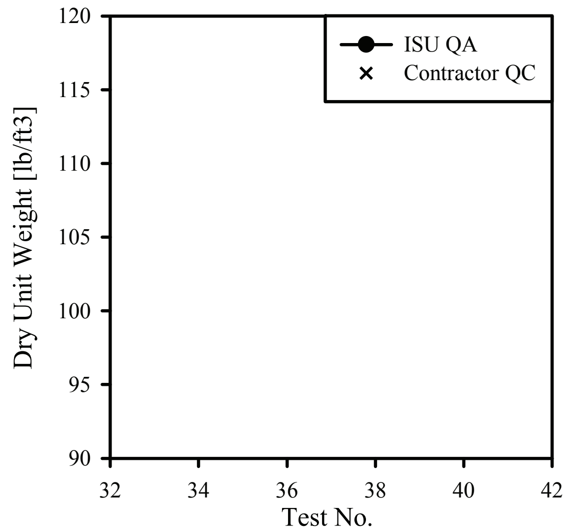

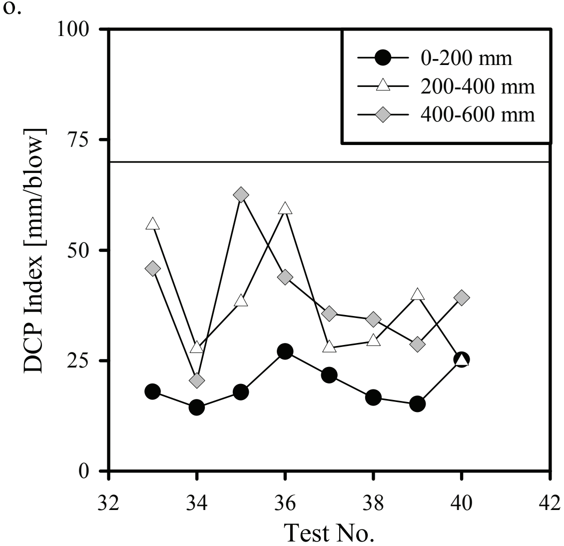

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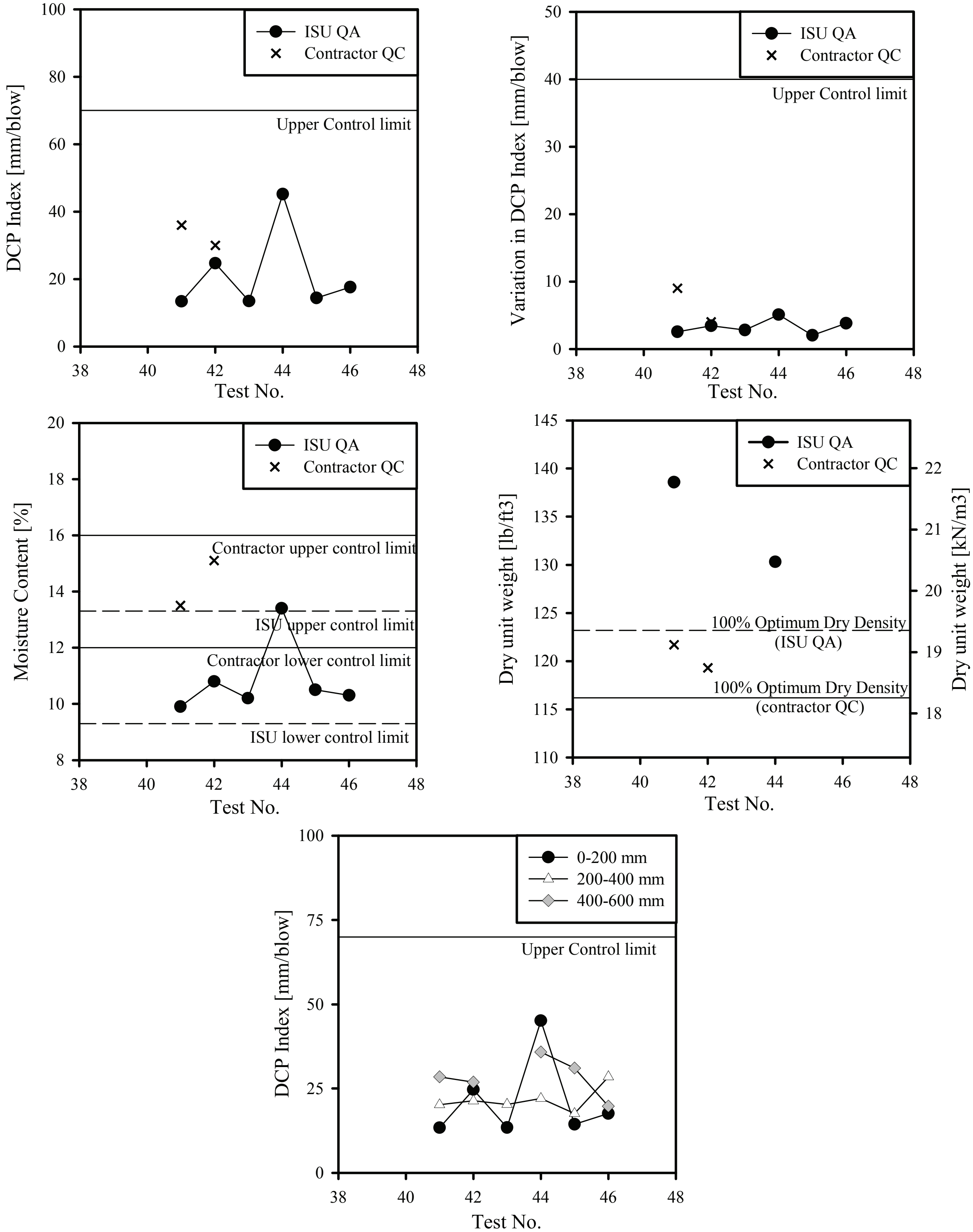

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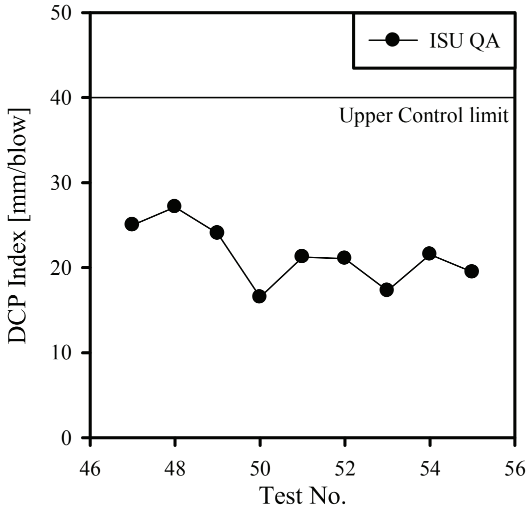

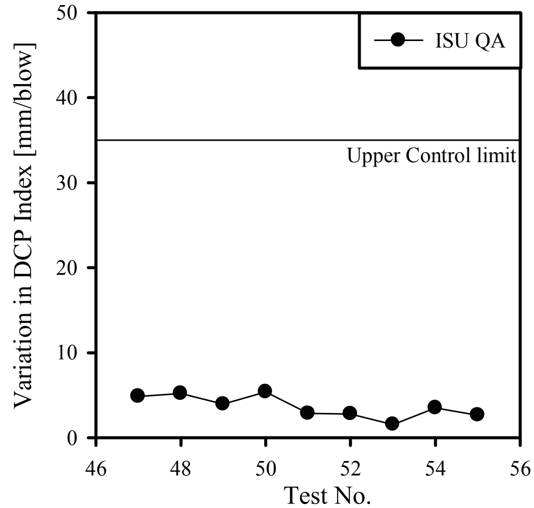

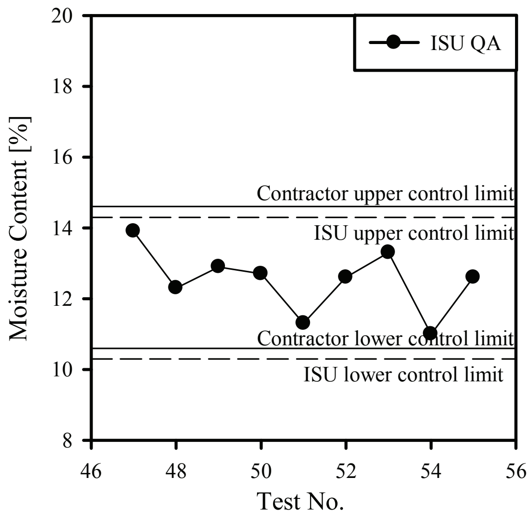

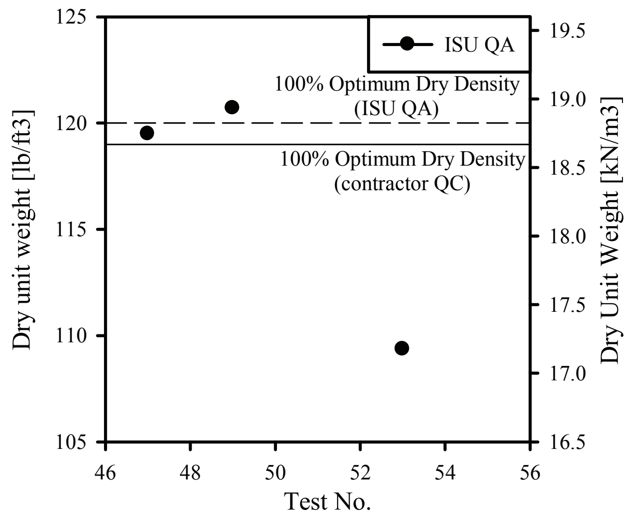

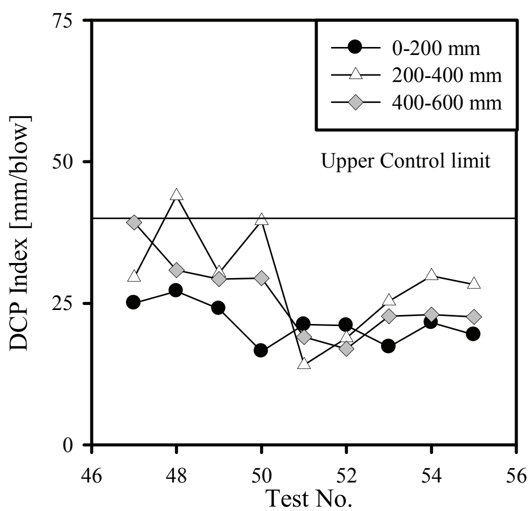

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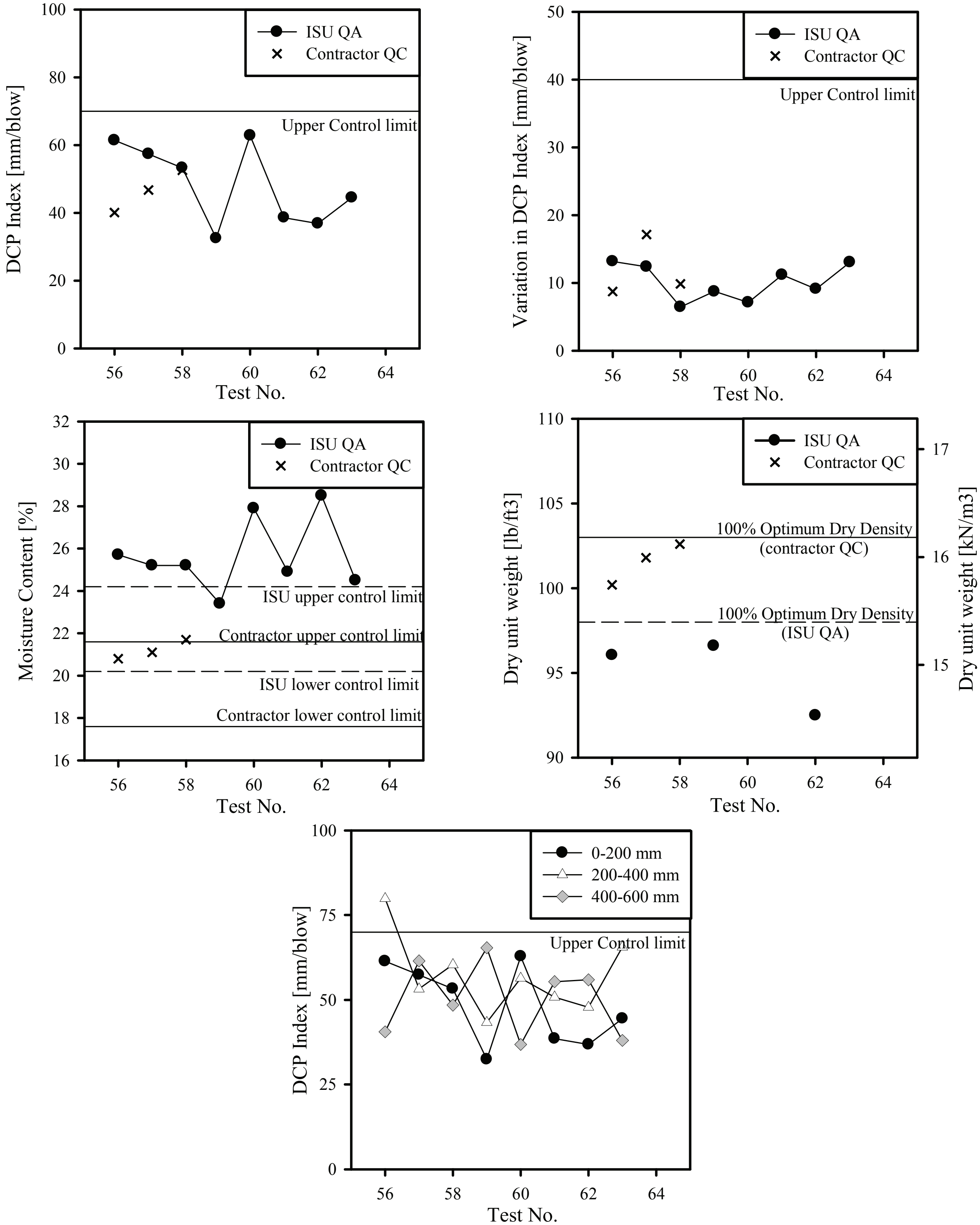

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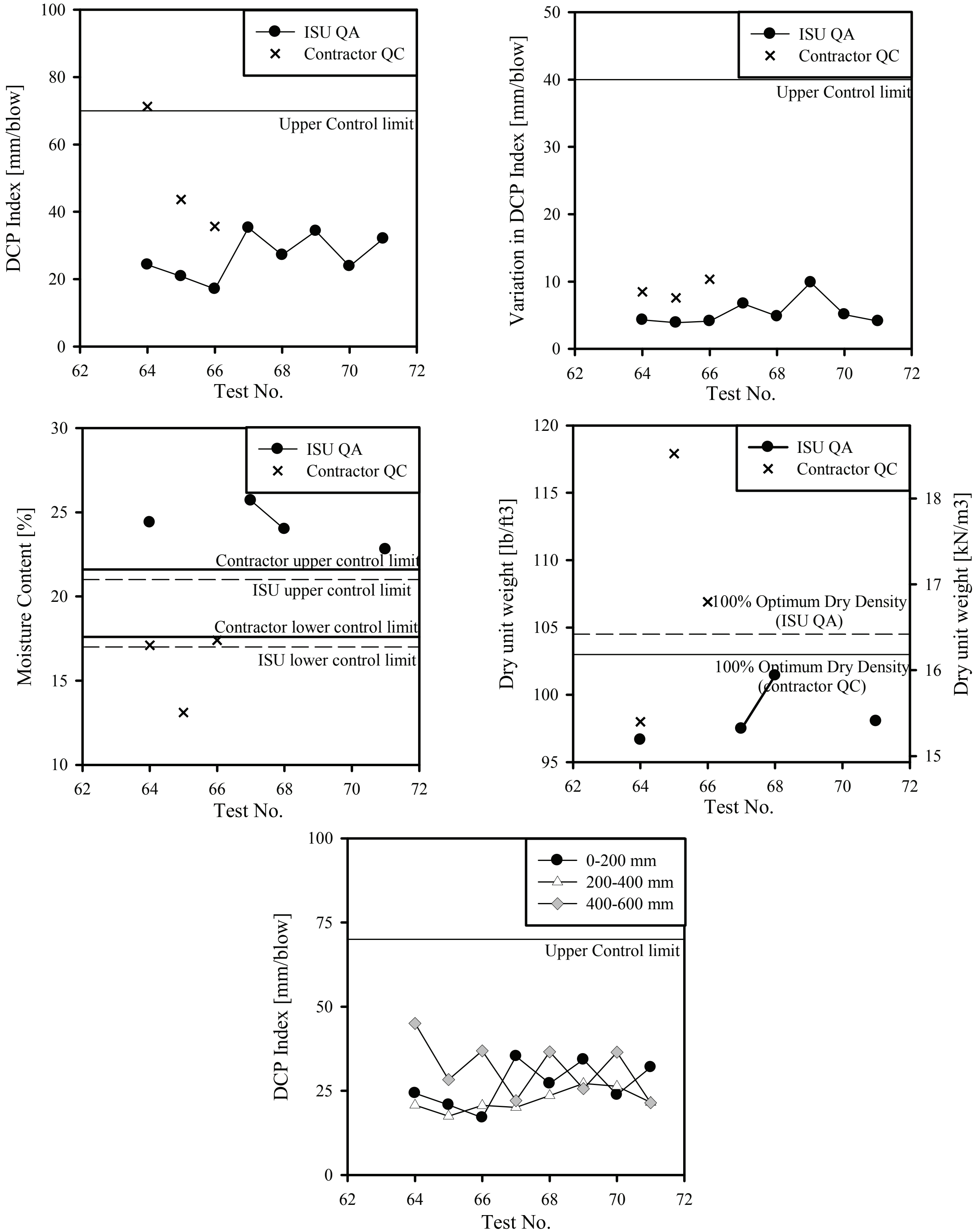
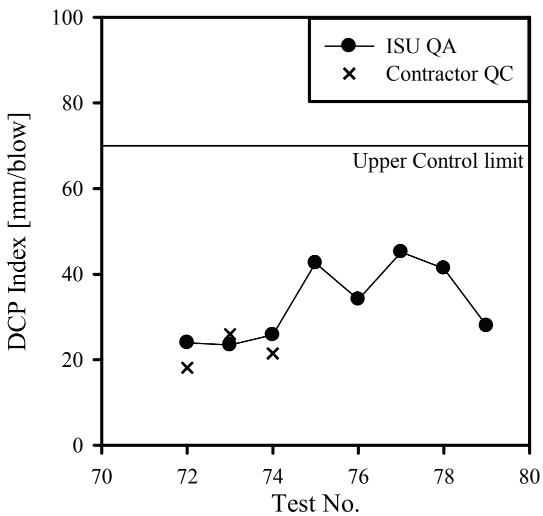
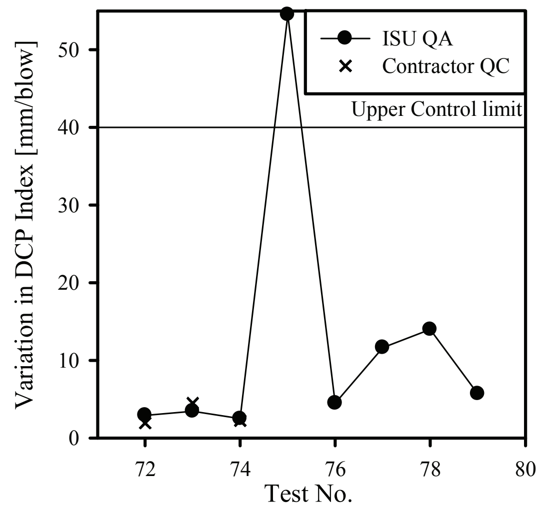
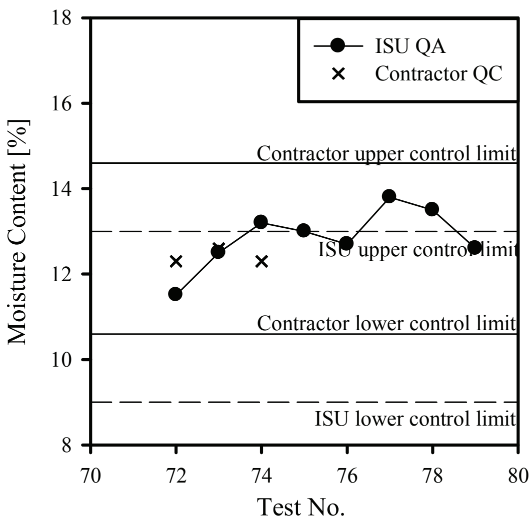
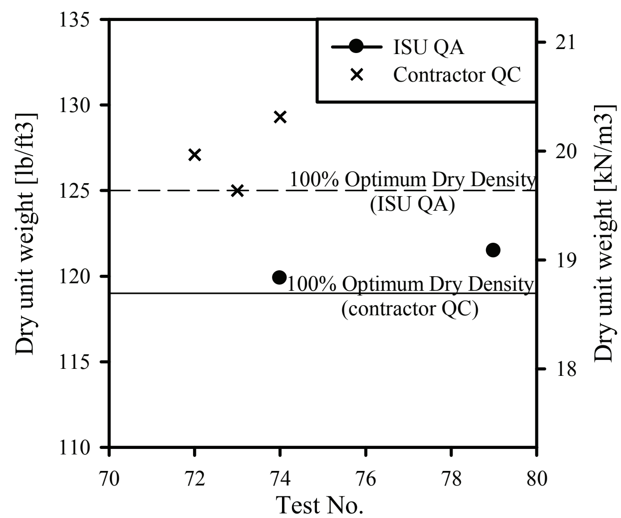


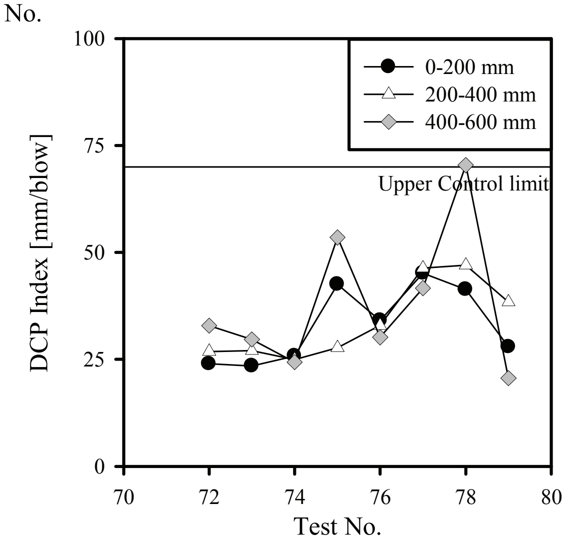
ISU QA test set I











APPENDIX F. SOIL BORING LOG

Boring Log

Date 5/22/2006
Project NHSX-34-8(96)-3H-51 Fairfield Bypass
STA 155+50

Logged by: BWL
Page: 1 **OF** 3

Depth [ft]	Sample ID	Mid Ht [ft]	MC [%]	e []	Wet Unit Weight [lb/ft^3]	Dry Unit Weight [lb/ft^3]	LL	PL	PI	F_{200} [%]	S_u [kPa]	Grade	USCS	AASHTO
	ST1A	0.3958					61	31.3	29.7	99.1		Suitable	CH	A-7-5
	ST1B	0.7917	30.25	0.87	124.0	95.2	58.7	28.1	30.6	98.9	51	Unsuitable	MH	A-7-6
1														
	ST1C	1.5625	27.89	0.79	126.2	98.7	53.9	23.9	30	99	47.7	Unsuitable	MH	A-7-6
2														
3	ST2	3.1667	25.24	0.76	125.9	100.5	50.3	22.1	28.2	98.3	51.4	Suitable	CH	A-7-6
4														
	ST3A	4.5	26.61	0.74	128.4	101.4	38.1	19.1	19	98.3	57.5	Suitable	CL	A-6
5														
	ST3B	5.1667	25.57	0.65	128.4	102.3	38	24.1	13.9	97.3	60.7	Suitable	CL	A-6
6	ST3C	5.8333	25.2	0.62	129.4	103.3	36.3	22.8	13.5	95.4	47.5	Suitable	CL	A-6
7														
8	ST4	8.125	20.28	0.99	101.2	84.2	31.3	19.3	12	87.5	57.5	Suitable	CL	A-6
9														
10														

Boring Log

Date	5/22/2006	**Logged by:**	BWL
Project	NHSX-34-8(96)-3H-51 Fairfield Bypass		
STA	155+50	**Page:**	2 **OF** 3

Depth [ft]	Sample ID	Mid Ht [ft]	MC [%]	e []	Wet Unit Weight [lb/ft^3]	Dry Unit Weight [lb/ft^3]	LL	PL	PI	F_{200} [%]	S_u [kPa]	Grade	USCS	AASHTO
11	ST5	11.167	22.8	0.65	131.8	107.3	57	26	31	84.4	54.7	Unsuitable	CH	A-7-6
12														
13	ST6A	13.54	20.4	0.67	127.2	105.7	51.2	25	26.2	81.4	46.3	Unsuitable	CH	A-7-6
14	ST6B	14.63	19.77	0.58	134.5	112.3	46.9	16.4	30.5	60.2	44.7	Unsuitable	CH	A-7-6
15														
16	ST7A	16.33	16.58				33.4	14.3	19.1				CL	
17	ST7B	17.17	17.12	0.51	132.2	112.9	32.4	13.9	18.5	59.5	43	Suitable	CL	A-6
18	ST8A	18.71	15.47	0.45	140.0	121.2	26.8	11.7	15.1	58.4	71	Suitable	CL	A-6
19	ST8B	19.71	16.22	0.43	142.2	122.4	28.1	16.6	11.5	53	102.9	Suitable	CL	A-6
20														

Boring Log

Date 5/22/2006 **Logged by:** BWL

Project NHSX-34-8(96)-3H-51 Fairfield Bypass

STA 155+50 **Page:** 3 **OF** 3

Depth [ft]	Sample ID	Mid Height [ft]	MC [%]	e []	Wet Unit Weight[lb/ft^3]	Dry Unit Weight [lb/ft^3]	LL	PL	PI	F_{200} [%]	S_u [kPa]	Grade	USCS	AASHTO
21														
22	ST9A	21.83	15.68	0.48	137.1	118.5	25	13	12	52.4	71	Suitable	CL	A-6
	ST9B	22.58	16.32				25.3	13.1	12.2	56.9		Suitable	CL	A-6
23														
	ST9C	23.21	14.87	0.42	142.7	124.2	25.2	13.9	11.3	55.1	71	Suitable	CL	A-6
24														
25														
26														
27														
28														
29														
30														

Boring Log

Date 10/31/2006 **Logged by:** BWL
Project Fairfield Hwy 34 Bypass
STA 143+50 **Page:** 1 **OF** 2

Depth [ft]	Sample ID	Mid Height [ft]	MC [%]	e []	Wet Unit Weight [lb/ft^3]	Dry Unit Weight [lb/ft^3]	LL	PL	LI	F_{200} [%]	S_u [kPa]	Grade	USCS	AASHTO
	ST1A	0.33	12.6	0.44	130.3	115.7	26.2	13.5	12.7	51.1	20.7	Suitable	CL	A-6
1														
	ST1B	1.21	11.1	0.33	138.8	124.9	27.2	14.4	12.8	51.3	244.6	Suitable	CL	A-6
2	ST2A	2.19	14.6	0.47	131.5	114.8	30.5	13.7	16.8	54.2	84.3	Suitable	CL	A-6
3	ST2B	2.81	12.7	0.4	136.9	121.4	28.3	14.3	14	51.9	151.9	Suitable	CL	A-6
	ST2C	3.46	14.2	0.48	132	115.6	35.4	16	19.4	56.1	123.5	Suitable	CL	A-6
4	ST3A	3.88	13.4	0.41	134.6	118.8	29.2	11.9	17.3	53.2	94.6	Suitable	CL	A-6
	ST3B	4.44	14.7	0.44	133.2	116.1	32.6	13.4	19.2	63.1	98.2	Suitable	CL	A-6
5	ST3C	4.98	16.9	0.5	132.1	113.0	35.9	14.5	21.4	68	114.5	Suitable	CL	A-6
	ST4A	5.63	14.3	0.43	133.8	117.0	32	12.9	19.1	58.8	129.4	Suitable	CL	A-6
6														
	ST4B	6.50	19.1	0.53	129.4	108.6	33.5	13.5	20	59.6	102.8	Suitable	CL	A-6
7														
	ST4C	7.21	21.9	0.74	116.6	95.6	51	17.8	33.2	79.6	184.6	Unsuitable	CH	A-7-6
8	ST5A	8.29	21.6	0.67	124.1	102.0	44.4	16.6	27.8	72.1	145.8	Suitable	CL	A-7-6
9	ST5B	9.10	19.5	0.63	123.4	103.3	52.1	19.4	32.7	72	129.9	Unsuitable	CH	A-7-6
	ST5C	9.63	20.6	0.76	115.6	95.9	46	15.9	30.1	65.7	95	Unsuitable	CL	A-7-6
10	ST6A	9.83	19	0.69	116	97.4	42.7	14.8	27.9	67	44	Suitable	CL	A-7-6

Boring Log

Date 10/31/2006
Project Fairfield Hwy 34 Bypass
STA 143+50

Logged by: BWL
Page: 2 **OF** 2

Depth [ft]	Sample ID	Mid Height [ft]	MC [%]	e []	Wet Unit Weight [lb/ft^3]	Dry Unit Weight [lb/ft^3]	LL	PL	LI	F_{200} [%]	S_u [kPa]	Grade	USCS	AASHTO
	ST6B	10.40	22.2	0.66	122.4	100.2	60.5	18.8	41.7	93.6	103.6	Unsuitable	CH	A-7-6
11	ST6C	11.00	20	0.58	127.2	106.0	47.9	17.9	30	91.1	90.4	Unsuitable	CL	A-7-6
12														
	ST7A	12.50	21.9	0.59	126.5	103.8	50.3	31.5	18.8	84.8	111.4	Suitable	CH	A-7-6
13	ST7B	13.20	22.3	0.66	124	101.4	50.6	20.1	30.5	88.4	92.1	Unsuitable	CH	A-7-6
14	ST7C	13.90	21	0.65	123	101.6	47.9	19.6	28.3	90.7	50.3	Unsuitable	CL	A-7-6
	ST8A	14.20	26.9											
15	ST8B	15.30	3.9											
16														
	ST9A	16.60	25.1	0.75	117.9	94.3	37.6	20.4	17.2	95.6	68.8	Unsuitable	CL	A-6
17	ST9B	17.30	27.9	0.78	119.1	93.2	35.8	19.6	16.5	96.8	54.9	Unsuitable	CL	A-6
18														
19														
20														