SHRP 2 Reliability Project R07

Earthwork Performance Specification Integrating Proof Mapping and Alternative In Situ Testing

SHRP 2

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Earthwork Performance Specification Integrating Proof Mapping and Alternative In Situ Testing

TRANSPORTATION RESEARCH BOARD
Washington, D.C.
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EARTHWORK PERFORMANCE SPECIFICATION INTEGRATING PROOF MAPPING AND ALTERNATIVE IN SITU TESTING

Demonstration Project Report: SHRP 2 R07
MoDOT Hwy 141, Chesterfield, MO
November 2010 – December 2011

Prepared By

David J. White, Ph.D.

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Acknowledgments

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Introduction

Earthwork and pavement foundation construction are high impact opportunities for development of performance specifications. Moving in this direction is consistent with some of the European practices for road building, is in-line with results from interviewing contractors and state agency personnel, and is consistent with feedback collected from the intelligent compaction workshops (e.g., White and Vennapusa 2012). The SHRP 2 R07 team developed a pilot study program in partnership with Missouri Department of Transportation (MoDOT) to investigate effectiveness and impacts of incorporating selected quality assurance/quality control (QA/QC) testing technologies that provide performance measurements. The focus of the pilot study was to develop and evaluate performance specifications for proof mapping prepared subgrade with intelligent compaction and to use modulus and strength based in situ testing for QA/QC operations for embankment construction. Two guide specifications were developed and refined based on this project and are provided separate from this project data report.

This report presents results from the pilot investigation conducted on the US-141 highway project in Chesterfield, Missouri, to evaluate new concepts for geotechnical performance specifications involving embankment and pavement foundation construction. Alternative in situ testing methods and use of prototype intelligent compaction (IC) technologies were investigated and compared to traditional QA/QC testing involving nuclear density/moisture testing. The intelligent compaction systems used on this project included a Caterpillar CS-563E self-propelled smooth drum roller equipped with machine drive power (MDP) and compaction meter value (CMV) measurement technologies and an 815F impact roller equipped with MDP technology. The machines were equipped with real time kinematic (RTK) global positioning system (GPS) and onboard display and documentation systems. The high accuracy RTK-GPS provided the opportunity to determine compacted lift thicknesses.

The project involved constructing and testing several test areas consisting of silty clay embankment fill and crushed limestone aggregate used for mechanically stabilized earth (MSE) wall backfill or pavement subbase (i.e. Type 5 base). The intelligent compaction measurement values (IC-MVs) were evaluated by conducting nuclear density/moisture content tests, dynamic cone penetration tests to determine the California bearing ratio (CBR), plate load tests to determine the modulus of subgrade reaction, and rut depth from proof rolling with a loaded tandem axle dump truck. MoDOT field personnel, contractor's personnel (Fred Weber Inc.), representatives from the IC roller manufacturer (Caterpillar), and SHRP R07 research team participated in the field testing phase of the project.

The overall goals of the pilot project were to

- Identify suitable QA/QC testing technologies to improve test frequency and construction process control;

- Develop effective reporting, analysis, and evaluation protocols;

- Link the design approach with construction monitoring and develop performance models that include a long-term performance aspect;

- Study the impact of two alternative performance specifications on the responsibilities and actions of parties involved; and

- Assess the cost/benefit of implementing the performance specification.

The research plan was geared toward achieving the goals defined above. The plan involved four primary tasks provided below:

- Develop pilot specifications (a proof mapping specification and a more comprehensive embankment specification)

- Develop onsite training plans

- Develop experimental plans and conduct field testing

- Conduct data analysis and submit final report

These tasks were completed working closely with MoDOT to identify a suitable project and developing pilot specifications. The initial phase of the project involved field demonstration to provide experience to the contractor and MoDOT. Near the completion of the project, the QA/QC operations and IC roller operations were turned over completely to the project personnel.

The results described in this report present an exciting advancement with performance specifications for earthworks and pavement foundations. One of the significant outcomes of this project was using intelligent compaction and mechanistic related QA/QC testing methods that were evaluated on a full-scale project. Effective implementation of these innovative construction technologies have the potential to provide the contractors and project owners improved job safety, faster construction, greater cost savings, and improved performance and life-cycle cost of the pavements.

In the project planning phase of this effort Table 1 was develop to provide a list of how the current constraints in development and implementation of geotechnical performance specifications could be mitigated as an outcome of this project. As presented in the table, several of the mitigation strategies were investigated. There remains significant work to fully implement the technologies studied in this research. As presented in the exit interviews, however, there is generally positive feedback from all involved to continue to investigate ways to implement and benefit from intelligent compaction and in situ performance measurements.

Table 1: Mitigation strategies for improved performance specifications for earthwork and pavement foundations

No.	Constraints	Mitigation Strategies
1	Lack of information to quantify variability and reliability for design	Use statistically robust methods to better quantify uncertainty in measurement systems and their relationships to mechanistic parameters, and use IC measurements to address variability.
2	Poor understanding of mechanism(s) of the system or lack of suitable design methodology	Integrate 100% coverage IC data correlated with mechanistic parameters along with long-term performance data to calibrate numerical models and further the understanding of the behavior of pavement systems.
3	Poorly understood or lack of suitable QA/QC testing technologies	Obtain QA/QC measurements that are mechanistically related, e.g., stiffness/modulus and shear strength.
4	Lack of understanding of material behavior in the long term	Conduct resilient modulus/ repeated loading triaxial testing (to determine resilient and permanent deformation properties) on representative samples with anticipated in situ moisture contents/densities (during construction), and on samples in different environmental conditions (e.g., following freeze/thaw cycles, saturation, etc.).
5	Undocumented long-term durability/performance	Monitor some select sections of the project over a period of 5+ years with periodic falling weight deflectometer (FWD) testing, pavement condition surveys, ground water and temperature fluctuations in the foundation layers, and in-ground stresses.
6	Need for greater frequency of testing for design and construction	Calibrate IC measurement values to mechanistic parameter values and use the 100% coverage information.
7	Requirement for more upfront laboratory work and field test sections	Conduct laboratory testing on materials at different moisture-density combinations on foundation layer materials.
8	No suitable cost/benefit of life-cycle cost analysis model	Document project cost information and integrate long-term performance data as it becomes available to develop a reliable life-cycle cost analysis model. Provide a rational basis to set pay factors.

This report presents brief background information for the IC-MVs evaluated in this study (MDP, and CMV), documents the results and analysis from the field testing, and documents the field demonstration activities. Geostatistical methods were used to quantify QA/QC results of the embankment subgrade and subbase materials. Regression analysis was performed to evaluate correlations between IC-MVs and in situ soil properties determined using point-MVs. The correlation results were used to establish target values. Density and moisture content tests were performed using nuclear gauges at several locations independently by the QC and QA inspectors. Plate load test (PLTs) and dynamic cone penetrometers were used to evaluate stiffness and strength properties.

The results and correlations provided in this report should be of significant interest to the pavement, geotechnical, and construction engineering community and are anticipated to serve as a good knowledge base for implementation of IC compaction monitoring technologies and various new in situ testing methods into earthwork construction practice.

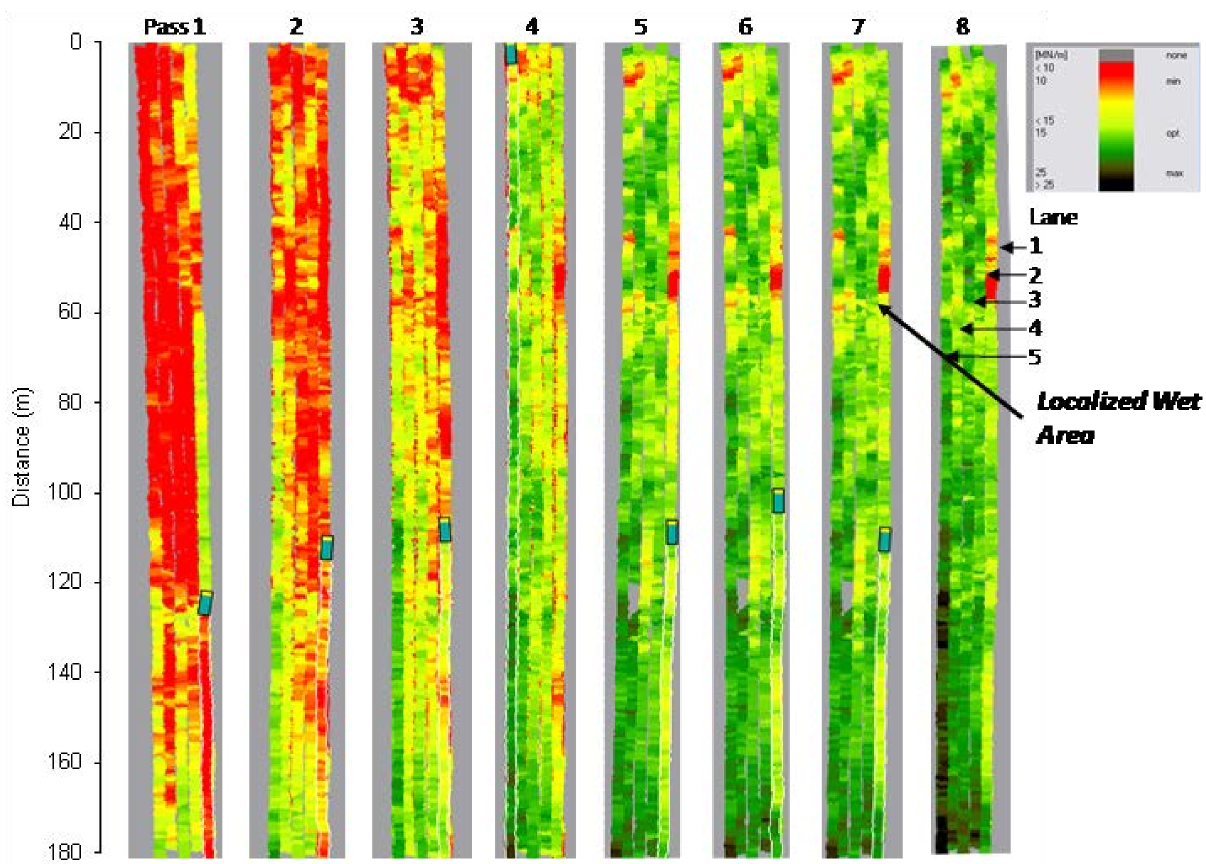
Background

Roller compaction monitoring technologies with GPS documentation offer 100% coverage information with real-time data visualization of compaction data, a significant improvement over traditional quality control/assurance (QA/QC) procedures involving tests at discrete point locations. Several equipment manufacturers have been developing these technologies applicable to both earthwork and hot-mix asphalt materials over the past 30+ years. By making the compaction machine a measuring device, the compaction process can potentially be managed and controlled to improve quality, reduce rework, maximize productivity, and minimize costs. With data provided in real time, process control parameters (e.g., moisture control, lift thickness, and so on) can be altered to insure acceptance requirements are met the first time. Project schedules are thereby reduced and delays for post-process inspections can be avoided.

To date, results from research and demonstration projects have shown promise in application of the intelligent compaction technologies for earthwork construction, although results are somewhat limited. A few pilot specifications have and are being developed by state agencies in the United States (e.g., MnDOT) and a few specifications exists from European countries. A review of these specifications indicates a weakness in that they are technology and material specific, and there are no widely accepted specifications in the United States. Lack of experience and proper education/training materials, correlations on a wide range of materials between roller measurement values and traditionally used QA/QC testing tools, poor database and documentation of existing data/case histories, standard protocols for data analysis/management, and standardized specifications inclusive of various intelligent compaction technologies are major obstacles for successful implementation of the intelligent compaction technologies. This proposal identifies tasks to make advancements in these areas for more effective implementation and use of the technologies for MoDOT.

As an example, Figure 1 shows spatial maps of roller compaction values from a padfoot roller on a clay subgrade material from pass 1 to 8 over a test section of approximately 180 m in length (red indicates low stiffness and dark green indicates high stiffness). In the past, research studies, were performed to validate roller measurements and correlate results with a variety of in situ test devices measuring relative compaction, moisture content, stiffness/modulus, and shear strength. Some commonly used in situ test devices are shown in Figure 2. The correlations are typically obtained by constructing test sections and conducting in situ test measurements at discrete point locations in conjunction with roller compaction operations and correlate with spatially referenced roller measurement values. Results indicated that roller measurement values can be empirically correlated to dry density measurements but generally require multiple regression analysis, particularly for cohesive soils (Thompson and White 2008). While density and moisture content measurements are widely accepted measures of compaction, these physical property measurements are not necessarily direct measures of performance. There has been growing interest in obtaining in situ measurements that provide mechanistic parameters (e.g., stiffness/modulus, strength, and so on) as an alternative to traditional moisture-dry density measurements (see White et al. 2007a, 2009). Some of the new emerging technologies that measure mechanistic properties in situ include light weight deflectometer (LWD) and falling weight deflectometer (FWD).

By comparing roller compaction measurements with mechanistic measurements, performance attributes in terms of an assessment of the design stiffness values and the spatial variability are captured. This approach will surely improve construction process control and provide assurance that the "quality statements" described earlier have been achieved.



Source: White et al. 2008a

Figure 1. Padfoot roller measurement color coded maps for different passes on a cohesive clay subgrade from Texas.

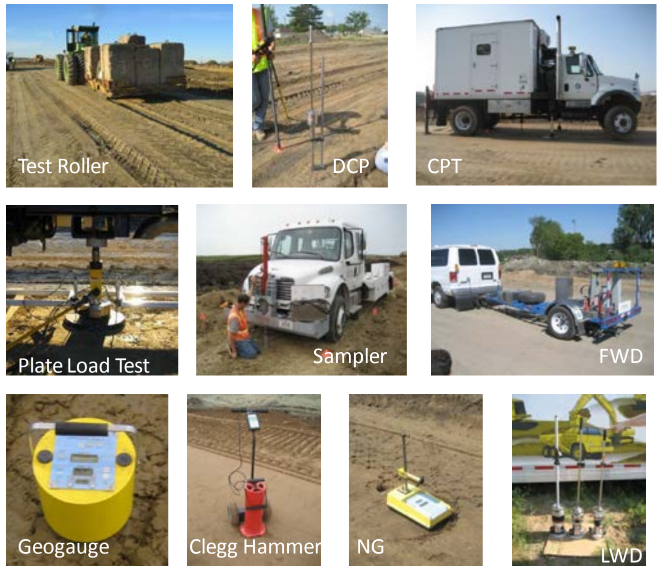


Figure 2. In situ QA/QC test equipment typically used in correlations

The Caterpillar CS-563E smooth drum IC roller was used on the project. The roller is shown in Figure 3. A digital display unit employing proprietary software is mounted in the roller cabin for onboard visualization of roller position, IC-MVs, coverage information, amplitude/frequency settings, speed, and so on. The rollers were outfitted with a real-time kinematic (RTK) global positioning system (GPS) to continuously record the roller position information. Some key features of the rollers are summarized in Table 2. Caterpillar CS-563E roller recorded machine drive power (MDP_{40}) and compaction meter value (CMV). A brief description of the IC-MVs are provided in the following discussion.

The Caterpillar 815F impact roller was also used on this project. This machine was equipped with a prototype intelligent compaction monitoring system based on the MDP measurement system. Figure 4 shows the roller and Figure 5 shows the operator display.

Figure 3. Caterpillar CS-563E Smooth drum roller.

Figure 4. Caterpillar 815F impact roller.

Figure 5. Caterpillar roller operator display.

Table 2. Key features of the IC rollers used on the project

Feature	Caterpillar CS-563E and 815F Rollers
Drum Type	CS563E – Smooth drum; 815F impact foot configurations
Frequency (*f*)	CS563E - 30 Hz; 815F static only
Amplitude (*a*) Settings	Static, 0.90 mm (low amplitude), and 1.80 mm (high amplitude)
IC-MV	MDP_{40} (shown as CCV in the output) and CMV and RMV (CS-563E ony)
Display Software	AccuGrade®
GPS coordinates	Based on local arbitrary coordinates at the base station
Output Documentation	Date/Time, Location (Northing/Easting/Elevation of left and right ends of the roller drum), Speed, CCV, CMV, RMV, Frequency, Amplitude (theoretical), Direction (forward/ backward), Vibration (On/Off)
Data frequency	About every 0.2 m at the center of the drum (for a nominal *v* = 4 km/h)
Output Export File	*.csv
Automatic Feedback Control (AFC)	No

Machine Drive Power (MDP) Value

MDP technology relates mechanical performance of the roller during compaction to the properties of the compacted soil. Detailed background information on the MDP system is provided by White et al. (2005). Controlled field studies documented by White and Thompson (2008), Thompson and White (2008), and Vennapusa et al. (2009) verified that MDP values are empirically related to soil compaction characteristics (e.g., density, stiffness, and strength). MDP is calculated using Eq. 1.

$$\mathrm{MDP} = \mathrm{P_g} - \mathrm{Wv}\left(\mathrm{Sin}\alpha + \frac{\mathrm{A'}}{\mathrm{g}}\right) - (\mathrm{mv} + \mathrm{b}) \qquad (1)$$

Where MDP = machine drive power (kJ/s), P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), A' = machine acceleration (m/s^2), g = acceleration of gravity (m/s^2), α = slope angle (roller pitch from a sensor), *v* = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al. 2005). MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values indicate material that is more compacted than the calibration surface (i.e. less roller drum sinkage). The MDP values obtained from the machine were recalculated to range between 1 and 150 using Eq. 2 (referred to as MDP_{40}). In Eq. 3, the calibration surface with MDP = 0 kJ/s was scaled to MDP_{40} = 150 and a soft surface with MDP = 54.23 kJ/s (40000 lb-ft/s) was scaled to MDP_{40} = 1.

$$\mathrm{MDP}_{40} = 150 - 2.77(\mathrm{MDP}) \tag{2}$$

Compaction Meter Value (CMV) and Resonant Meter Value (RMV)

CMV is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed), and is determined using the dynamic roller response (Sandström 1994). It is calculated using Eq. 3, where C is a constant (300), $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, A_{Ω} = the acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004). Correlation studies relating CMV to soil dry unit weight, strength, and stiffness are documented in the literature (e.g., Floss et al. 1983, Samaras et al. 1991, Brandl and Adam 1997, Thompson and White 2008, White and Thompson 2008).

$$\mathrm{CMV} = \mathrm{C} \cdot \frac{\mathrm{A}_{2\Omega}}{\mathrm{A}_{\Omega}} \tag{3}$$

RMV provides an indication of the drum behavior (e.g. continuous contact, partial uplift, double jump, rocking motion, and chaotic motion) and is calculated using Eq. 4, where $A_{0.5\Omega}$ = subharmonic acceleration amplitude caused by jumping (the drum skips every other cycle). It is important to note that the drum behavior affects the CMV measurements (Brandl and Adam 1997) and therefore must be interpreted in conjunction with the RMV measurements (Vennapusa et al. 2010).

$$\mathrm{RMV} = \mathrm{C} \cdot \frac{\mathrm{A}_{0.5\Omega}}{\mathrm{A}_{\Omega}} \tag{4}$$

regression Analysis Methods

Simple linear and non-linear regression relationships between IC-MVs and in-situ point measurement values (Point MVs) were developed by spatially pairing the data obtained from the test beds. The analysis was performed by considering point-MVs as “true” independent variables and IC-MVs as dependent variables using the models shown in Eqs. 7 to 8, where b_0 = intercept and b_1, b_2 = regression parameters.

$$\text{Linear model: } \mathrm{IC{-}MV} = b_0 + b_1 \cdot \mathrm{Po\,int\,MV} \quad (5)$$

$$\text{Non-linear power model: } \mathrm{IC{-}MV} = b_1 (\mathrm{Po\,int\,MV})^{b_2} \quad (6)$$

Statistical significance of the independent variable was assessed based on *p*- and *t*-values. The selected criteria for identifying the significance of a parameter included: *p*-value < 0.05 = significant, < 0.10 = possibly significant, > 0.10 = not significant, and *t*-value < -2 or > +2 = significant. The best fit model is determined based on the strength of the regression relationships assessed by the coefficient of determination (i.e., R^2) values. For the analysis and discussion in this report, an R^2 value ≥ 0.5 is considered acceptable following the guidelines from European specifications. A statistical prediction interval approach for determining “target” values from the regression relationships would account for R^2 values in the relationships (see NCHRP 21-09, 2010). A regression relationship with lower R^2 values would result in higher target value and a regression relationship with higher R^2 value will result in lower target values.

Experimental Testing

Description of Test Areas

A total of eleven test areas including embankment subgrade materials silty clay), pavement subbase Type 5 crushed limestone, and MSE wall backfill were studied. Data on material index properties and Standard Proctor compaction values were provided by MoDOT. A summary of test beds with material conditions and tests performed is provided in Table 3. A summary of material index properties is provided in Table 4. Details regarding construction and testing of each test bed are provided in the discussion later. The following specific objectives were targeted for the different test beds evaluated in this study:

- Capture data over wide measurement range to develop IC-MV and different in-situ point-MV correlations
- Demonstrate the usefulness of using IC-MV maps for selection of QA test locations
- Explore analysis methods to quantify and characterize spatial non-uniformity of embankment materials.
- Compare IC-MVs for two different roller configurations.

Figure 6 shows the Hwy 141 project layout.

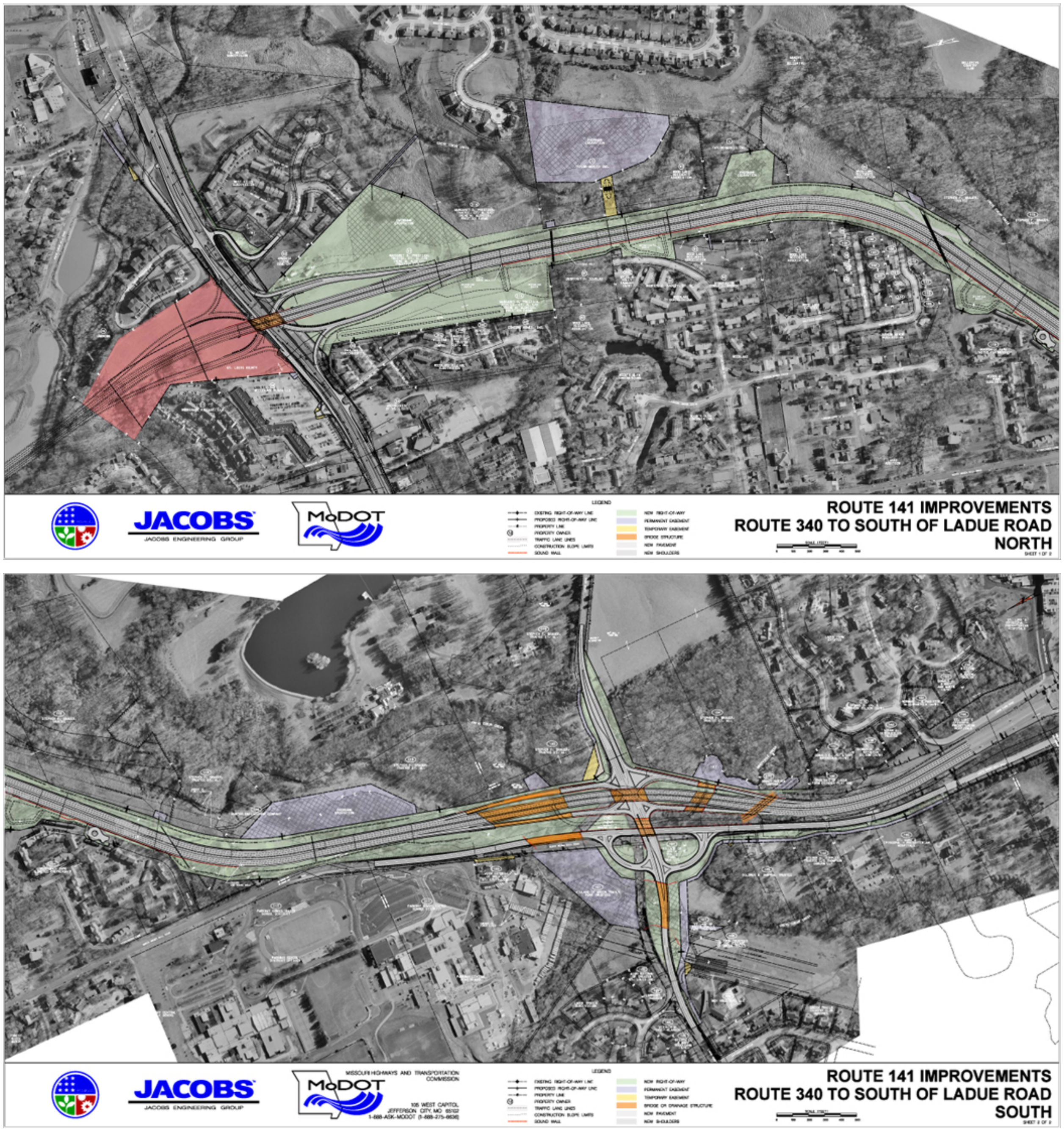


Figure 6: Hwy 141 pilot project layout (courtesy of MoDOT)

Table 3: Summary of test areas and in-situ testing

Test Area	Description	Material	Date	Machine	Total Passes	Amplitude setting, Speed (mph)*	Notes/In-situ Point Measurements
1	Calibration/ Training	Embankment Fill	08/17	CAT CS-563E	~4	Low amplitude, 2.5 High amplitude, 2.5	
2	Aggregate base on detour at North end of Project	Aggregate Base	10/14	CAT CS-563E	6 (1,3, 5 forward vibration; 2, 4, 6 satic reverse)	Low amplitude, static (2.3 -3.8)	Nuclear QC/QA and DCP at 9 locations
3	Double box culvert on south end of project (east side)	Silty Clay (Approx. 4 ft below top of box)	10/19 to 10/21	CAT CS-563E	variable	Low amplitude (1.5 -3.5)	DCP at 8 locations and Shelby tube for moisture/density DCP at 6 locations including QC/QA nuclear moisture/density Shelby tube profile 0 to 4 ft, BST at 1.5 ft
4	Embankment fill South of Olive near settlement plates	Silty Clay	10/20/10	CAT 815F	variable	—	DCP at 5 locations, Shelby tube samples, QC and QA nuclear density gauge tests (6 inch)
5	MSE wall backfill (middle of wall 10ft above footing)	4” minus crushed limestone	10/20 to 11/1	CAT CS-563E	4-12	Low amplitude	DCP at 3 locations, unable to perform nuclear density test due to rock size – use spec option for predetermined # (4) roller passes
6	Tuador Frontage Road	Crushed limestone	10/22	CAT CS-563E	Variable 1 to 4	Low amplitude passes 1-2, static passes 3-4	DCP NG, @ 8 points
7	Embankment Fill on North Bridge approach	Embankment Fill	11/03	CAT CS-563E	1	Low amplitude	PLT (18”), DCP, NG @19 locations
8	Cut/Fillsouth of Olive	Embankment Fill		CAT 815F	Variable	—	
9	MSE Wall by Bridge (adjacent to TB#7)	Crushed limestone	11/03	CAT CS-563E	4	Low amplitude	PLT (18”)

Test Area	Description	Material	Date	Machine	Total Passes	Amplitude setting, Speed (mph)*	Notes/In-situ Point Measurements
10	Production Area Compaction between box culverts on south end	Silty clay embankment fill		CAT 815F	Variable	—	NG
11	Embankment Fill – by old barn area	Silty clay embankment fill		CAT 815F	Variable	—	NG

Material Properties

Laboratory testing results were provided for two primary materials used on the project. The results are summarized in Table 3. Figure 8 shows the silty clay embankment fill material.

Table 4: Summary of material index properties

Parameter	Embankment Fill	Base
Standard Proctor Test Results (ASTM D698-00a)		
γ_{dmax} (pcf)	106.0	130.8
w_{opt}	17.0	10.2
Atterberg Limits Test Results (ASTM D4318-05)		
Liquid Limit, LL (%)	33	—
Plasticity Index, PI (%)	7	

Figure 7: Silty clay embankment fill material

InSitu Testing Methods

Three different in situ testing methods were used in this study to evaluate the in situ soil engineering properties (Figure 8): (a) plate load testing (b) Dynamic Cone Penetrometer (DCP) to determine California bearing Ratio (CBR), and (c) calibrated Humboldt nuclear gauge (NG)to measure moisture content (w) and dry unit weight (γ_d).

DCP tests were performed in accordance with ASTM D6951-03 to determine dynamic cone penetration index (DPI) and calculate CBR using Eq. 10. The DCP test results are presented in this report as CBR point values or CBR depth profiles. When the data is presented as point values, the data represents a weighted average CBR of the top 300 mm depth.

$$\mathrm{CBR} = \frac{292}{\mathrm{DPI}^{1.12}} \qquad (10)$$

Figure 9 shows the equipment used in this study.

(a) (b)

(c) (d)

Figure 8: In situ testing methods used on the project: (a) nuclear density gauges, (b) plate load test, (c) dynamic cone penetrometer, and (d) rutting measurement via proof rolling

Experimental Test Results

The results of the field investigation are organized by presenting results from the CS-563E intelligent compaction roller and then the 815F roller. For each roller several test areas were compacted along the length of the project involving the silty clay embankment fill, Type 5 aggregate base, and MSE wall backfill. For each of the test areas, pictures of the field conditions are provided where available along with color-coded IC roller maps and results from in situ point measurements. Key finding are highlighted for each of the analyzed test areas. For both rollers, Test Area #1 was designated as an initial setup and training opportunity and the results are not presented.

Test Area #2: CS-563E – Type 5 Aggregate Base

This test area was located on the north end of the project and involved compacting Type 5 aggregate base over a silty clay subgrade. Figure 9 shows the roller and Figure 10 shows the test area aggregate and subgrade. As shown in Figure 11, the test areas was rolled with 6 passes (3 forward and 3 reverse). Figures 11and 12 shows the CVM and MDP IC-MVs, respectively. Figure 13 shows the MDP map for the last pass with the point locations for QC/QA testing and the corresponding CBR profiles. The combined DCP and CBR profiles in Figures 14 and 15 shows that the Type 5 subbase was about 6 inches thick and that the underlying subgrade was relatively weak with a CBR value ranging from about 1 to 3. The low CMV values are attributed to the weak subgrade support conditions. Figure 16 shows the moisture-density zone of acceptance and the corresponding QC/QA test results. Several of the test point fall outside the defined acceptable zone.

Figure 9: IC roller on Test Area #2 on north end temporary detour road on aggregate base

Figure 10: Test area #2 on north end temporary detour road on aggregate base

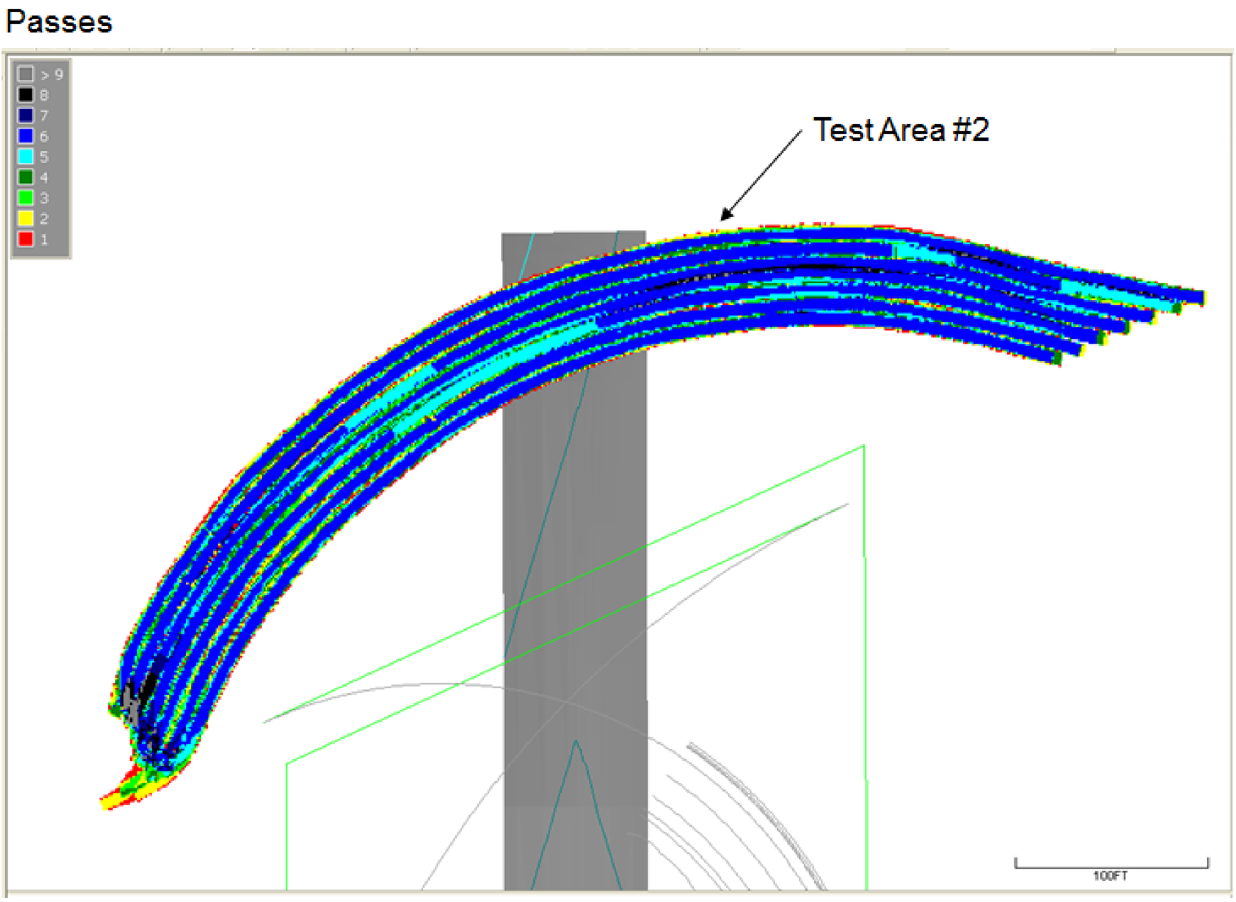


Figure 11: Test area #2 pass coverage

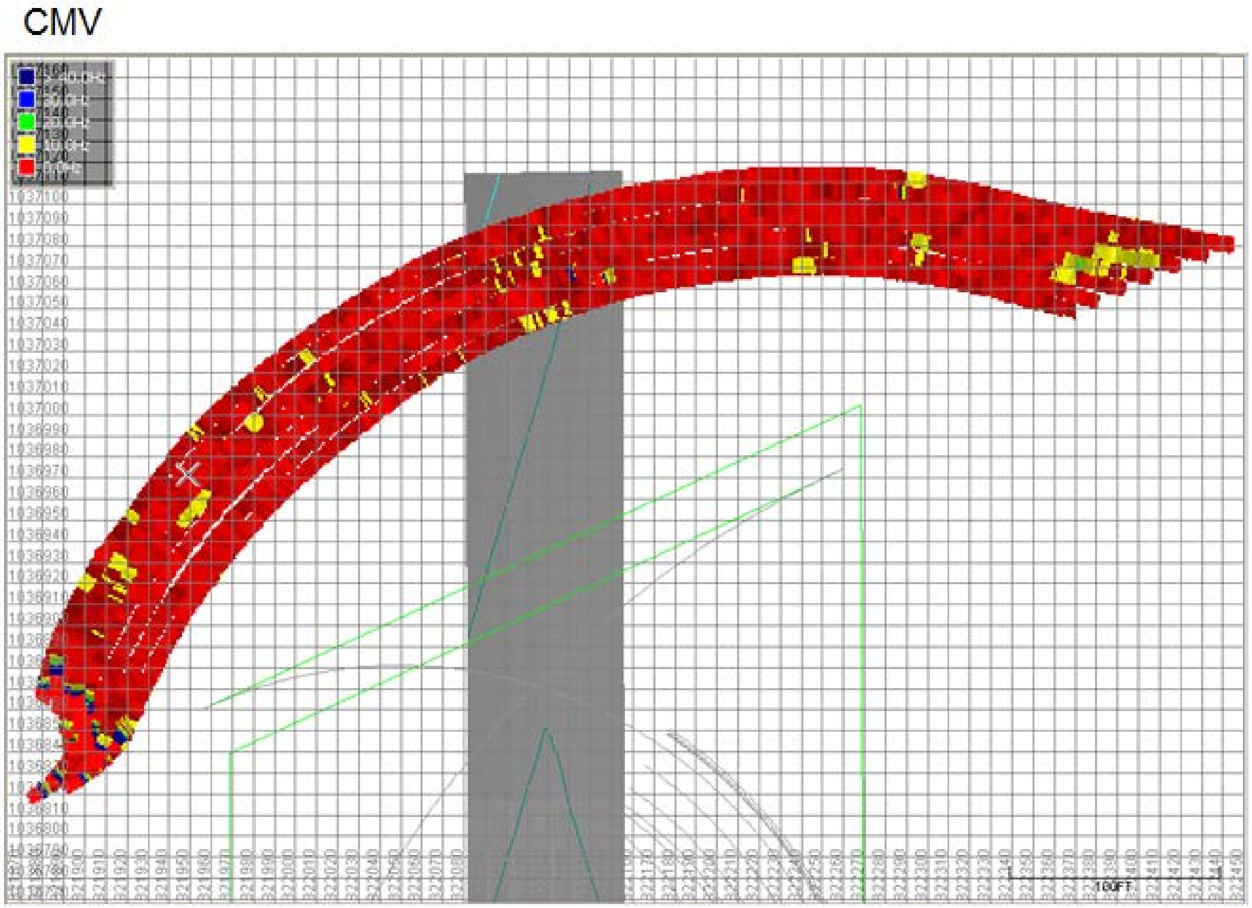


Figure 12: Test area #2 CMV results showing relatively low values reflecting the low strength underlying subgrade

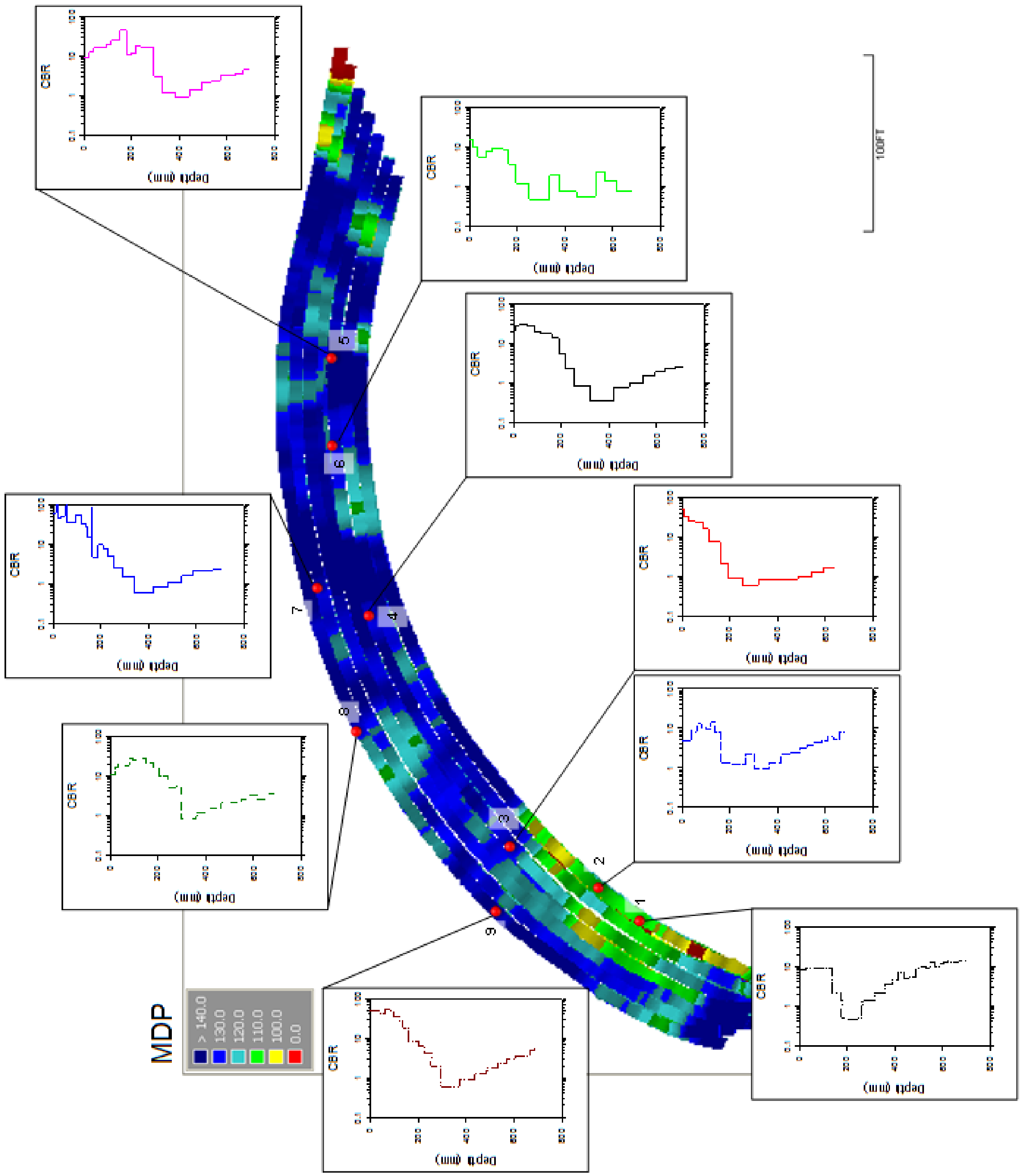


Figure 13: Test area #2 showing MDP values and DPC test locations and results

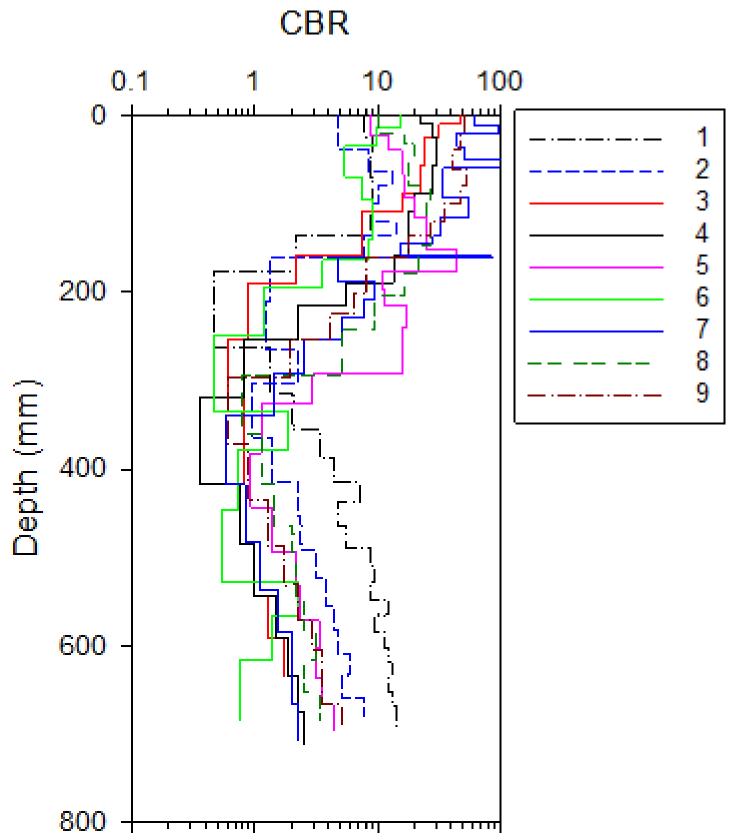


Figure 14: Test area #2 DCP test results

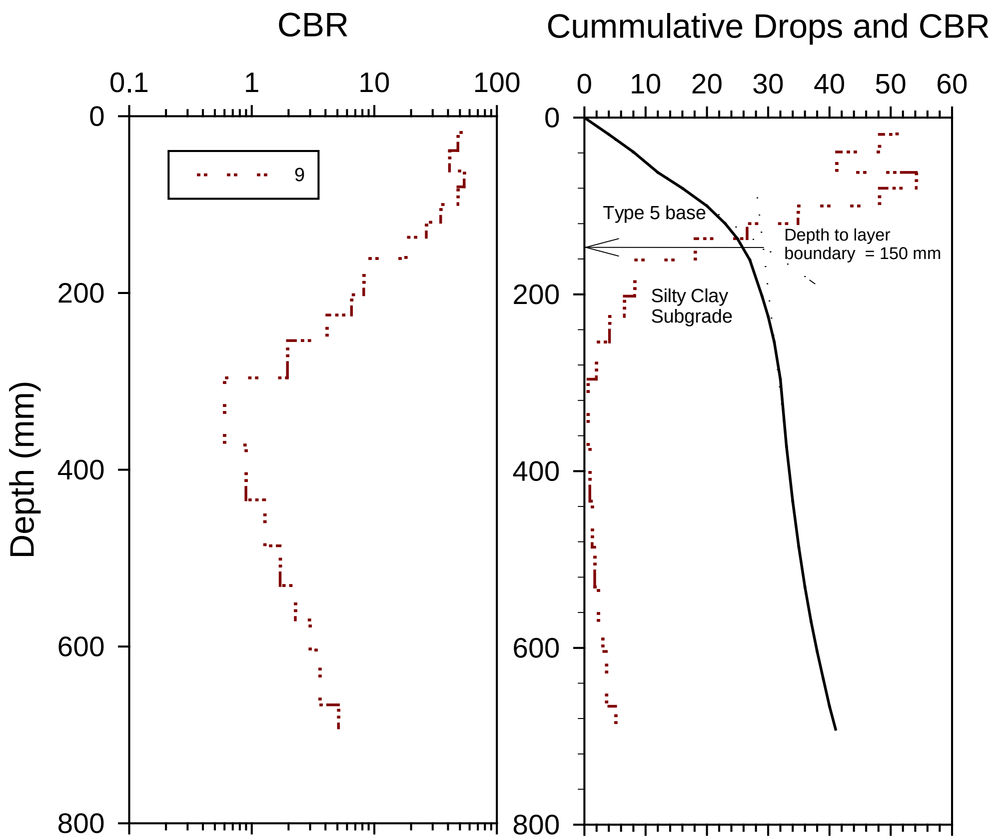


Figure 15: Test area #2 DCP test for no. 9 showing thickness determination for Type 5 aggregate base

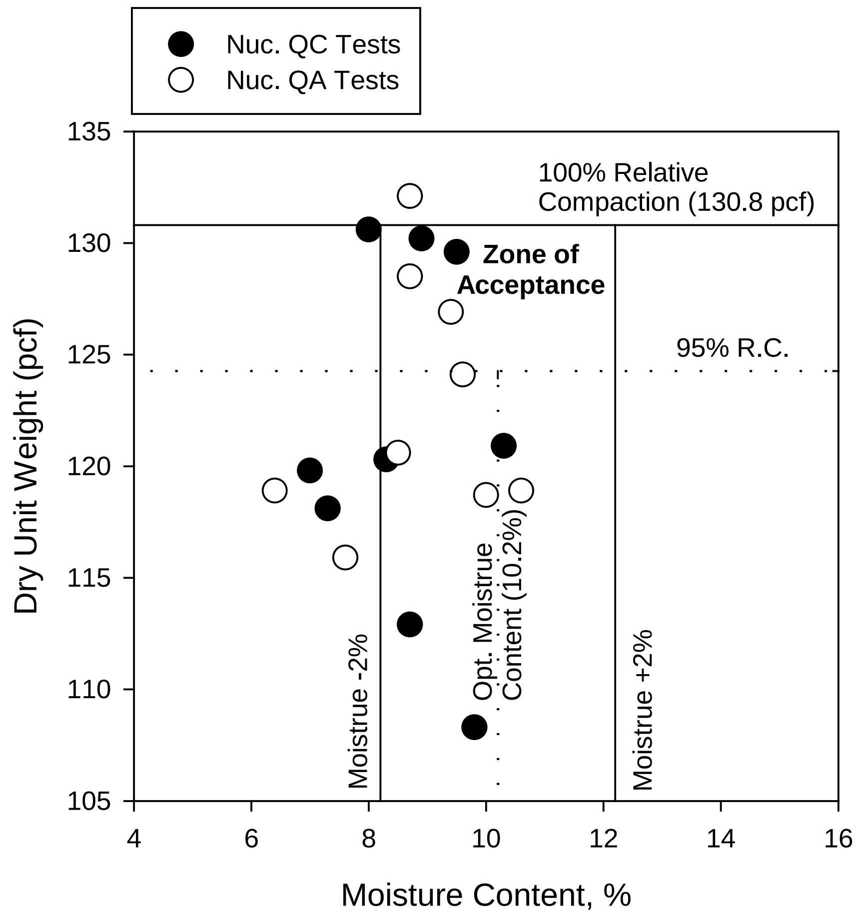


Figure 16: Test area #2 QA/QC nuclear density gauge test results

Test Area #3: CS-563E – Backfill Adjacent to Double Box Culvert

A double box culvert was being constructed near the south end of the project. This provided the opportunity to evaluate the IC roller and fill conditions in what is typically a difficult compaction area because the box creates an obstacle, compaction close to the box, and generally poorer foundation support conditions. Figure 17 shows the test area conditions.

Figures 18 and 19 show the plan view, cross sectional view, and profile view (east side) using the RTK-GPS position information and IC-MVs. Figure 20 shows the east side DCP test locations. Tests performed at this elevation coincided with approximately the bottom of the box culvert (Figure 21). The DCP tests show that the CBR values are generally about 1 to 10 to a depth of about 2 ft. Figure 22 shows the IC-MVs map on a compacted layer about 2 ft below the top of the box. The corresponding DCP tests shown in Figure 23 revealed that the compacted backfill CBR values range from 0.5 to 2, which is considered a very weak condition.

Figures 24 to 30 show the time history of MDP values and layer lift thicknesses. Using RTK-GPS allows for a relatively accurate assessment of compacted lift thickness. Figure 31 shows the results of detailed analysis of the compaction history in this area. For 42 measurement points analysis the average lift thickness was 0.88 ft and the average number of roller passes was 5. Both parameters, however, have significant variation. This result is particularly interesting because lift thickness and pass coverage are extensively used in current specifications, but often with great difficulty to document and measure. Here the IC system provided a great deal of data and only required relatively simple investigation on a computer to determine field values.

Figure 32 shows the moisture-density zone of acceptance for QC/QA nuclear density testing independent Shelby tube samples collected by the research team. The results show relatively high moisture content and confirm the low CBR as determined form the DCP tests. In one of the Shelby tube holes, an in situ borehole shear test (BST) was performed to measure the effective stress shear strength parameters values. Figure 33 shows that the friction angle was 23.5 degrees and the cohesion was about 4 kPa. Figure 34 shows real-time display of the coverage area for a pass.

Figure 17: Test Area #3 at double box culvert at south end of project

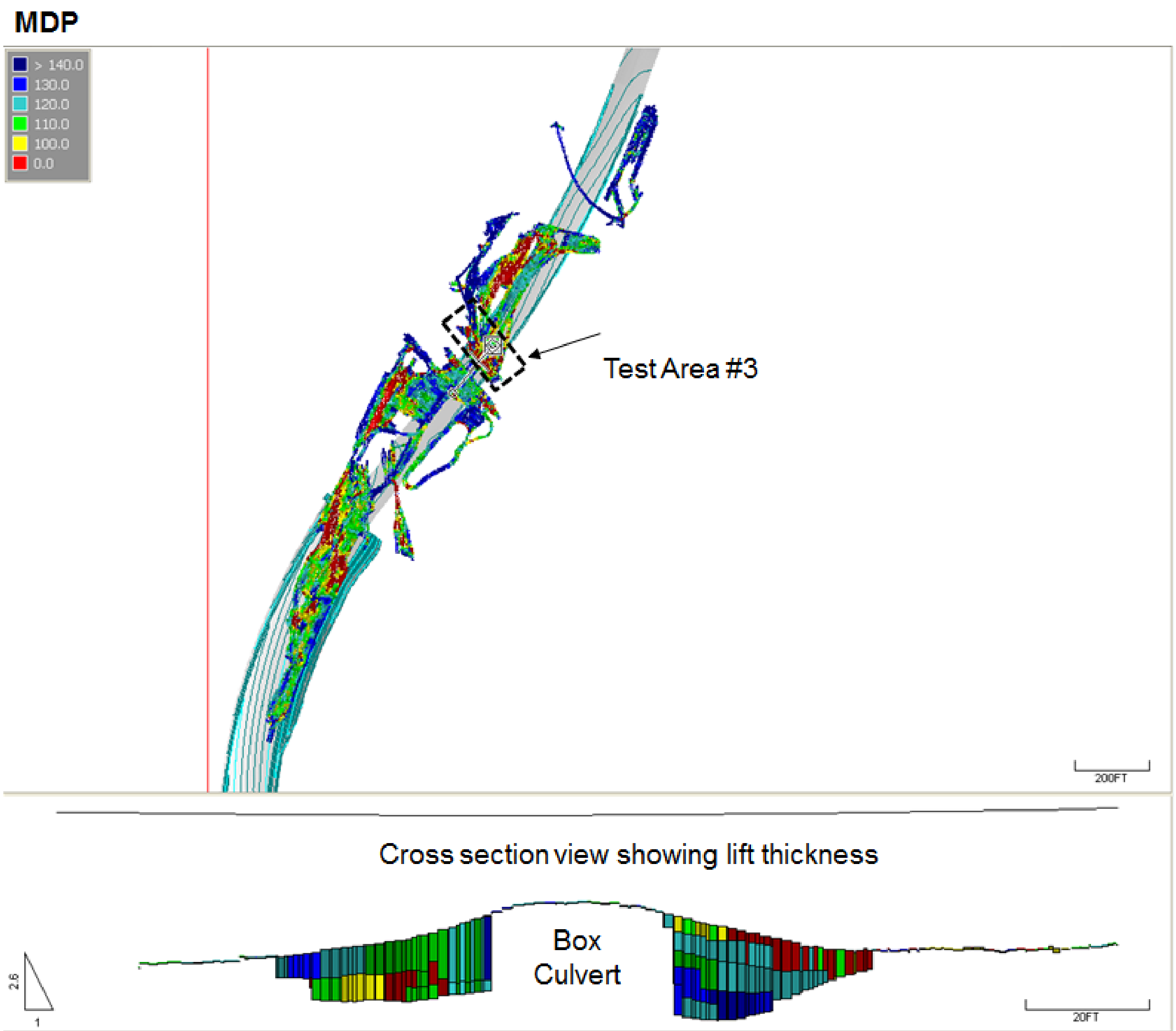


Figure 18: Test bed #3 compaction area

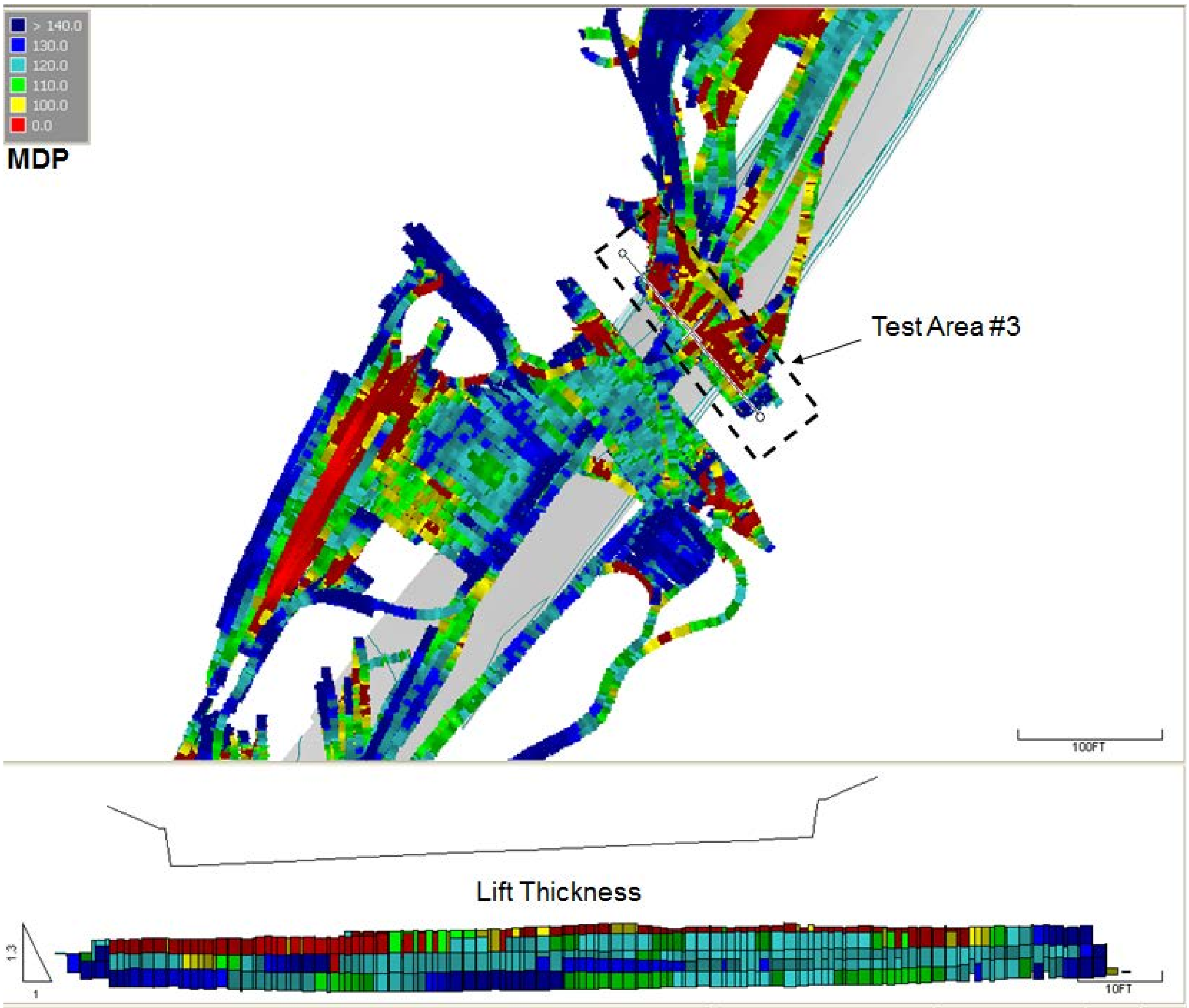


Figure 19: Test bed #3 compaction area

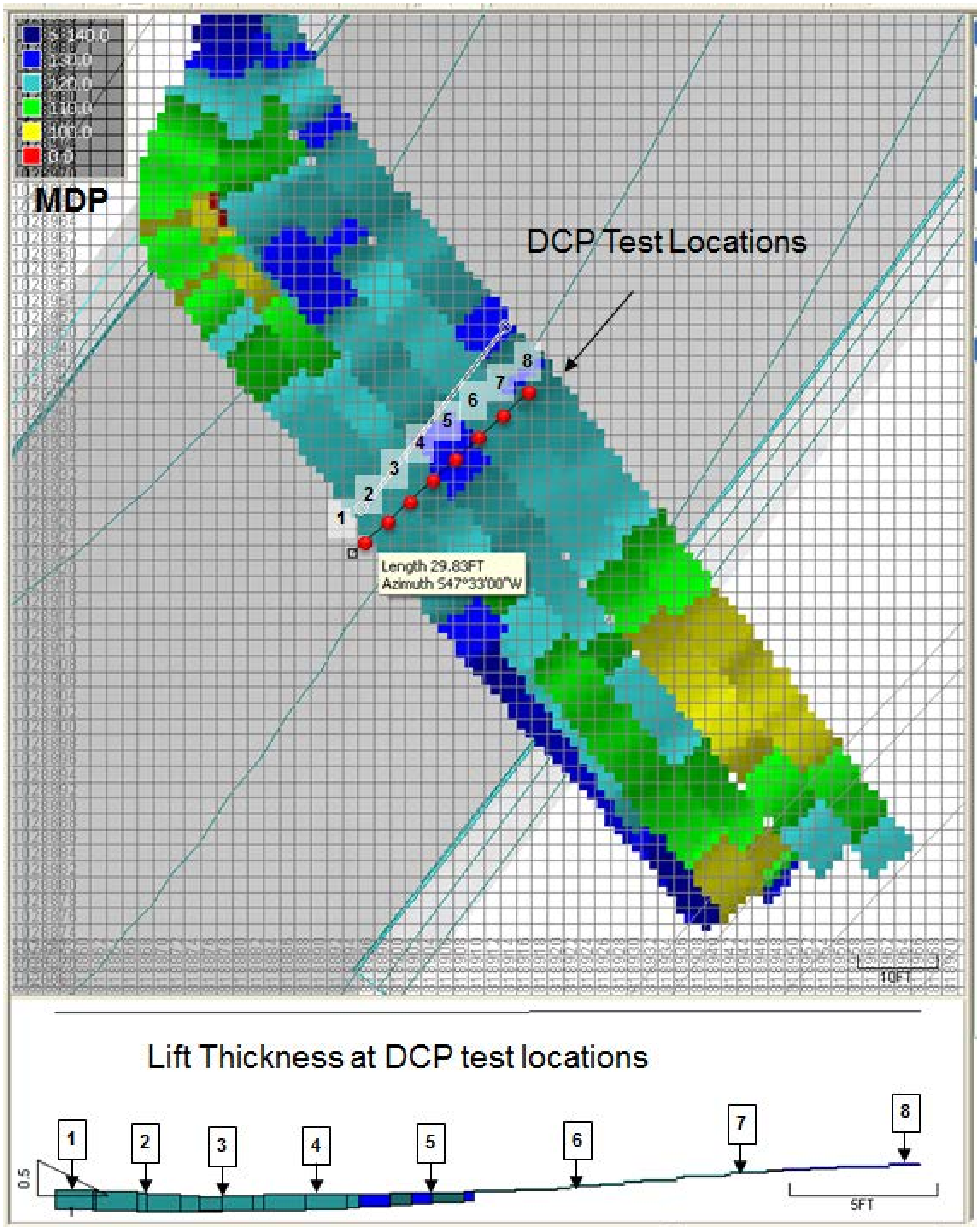


Figure 20: Test area #3 MDP results for lift no. 1 showing plan and cross section views adjacent to box culvert

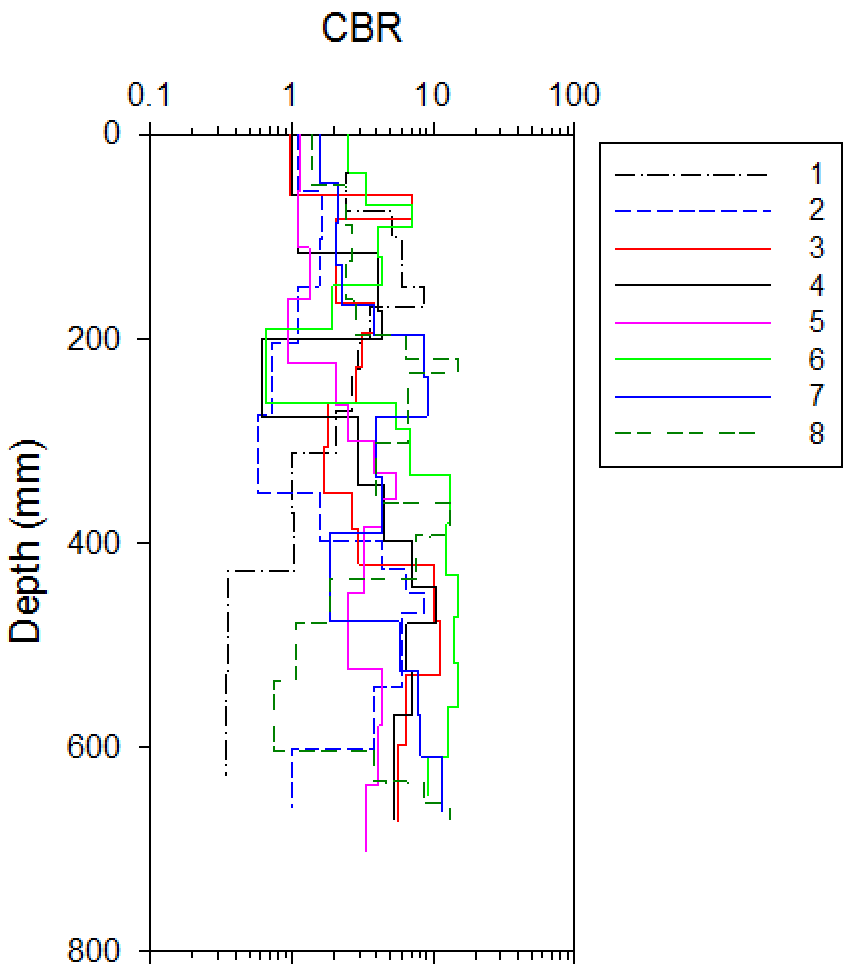


Figure 21: DCP test results for lift no. 1 adjacent to box culvert

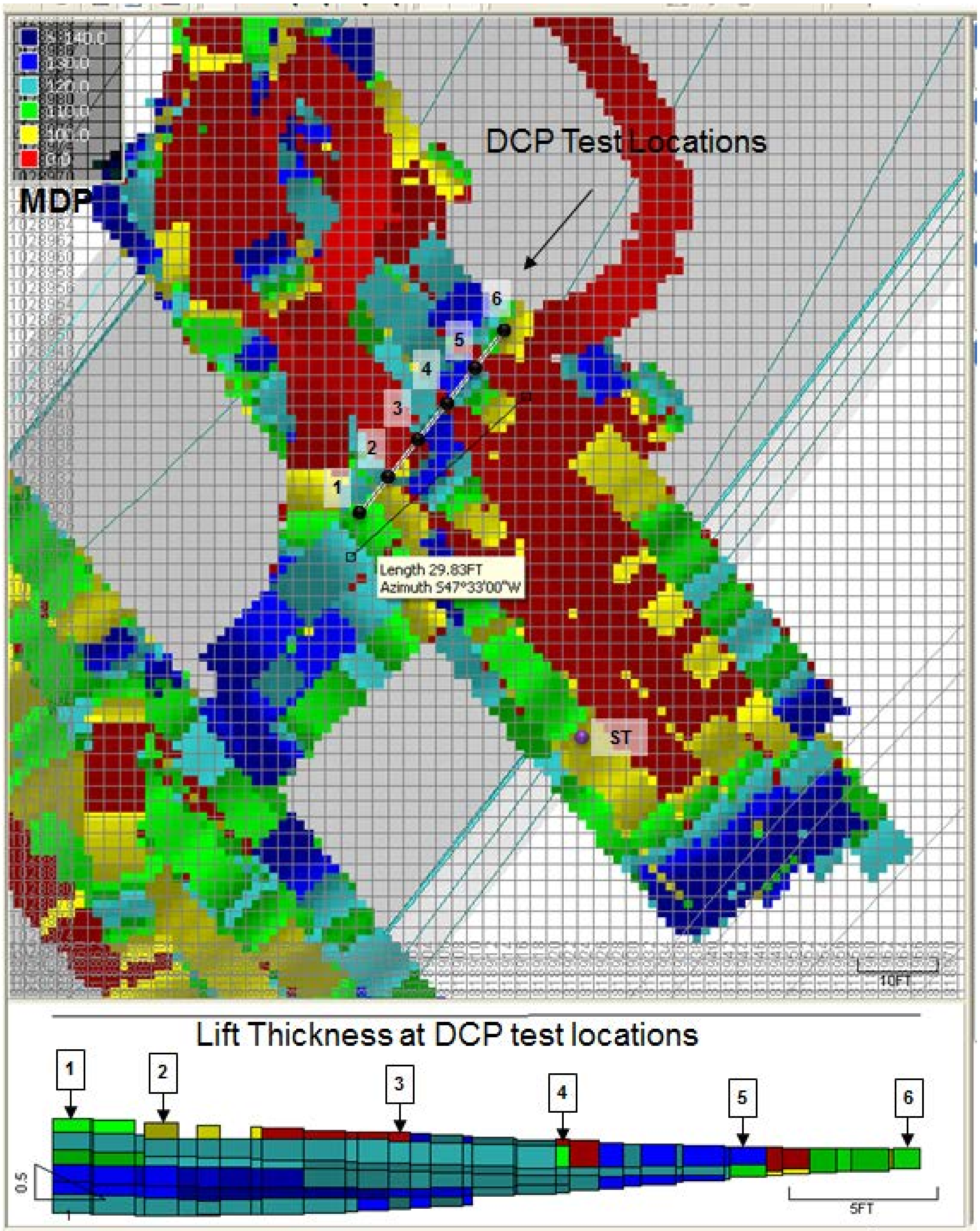


Figure 22: DCP test locations adjacent to box culvert in Test Area #3

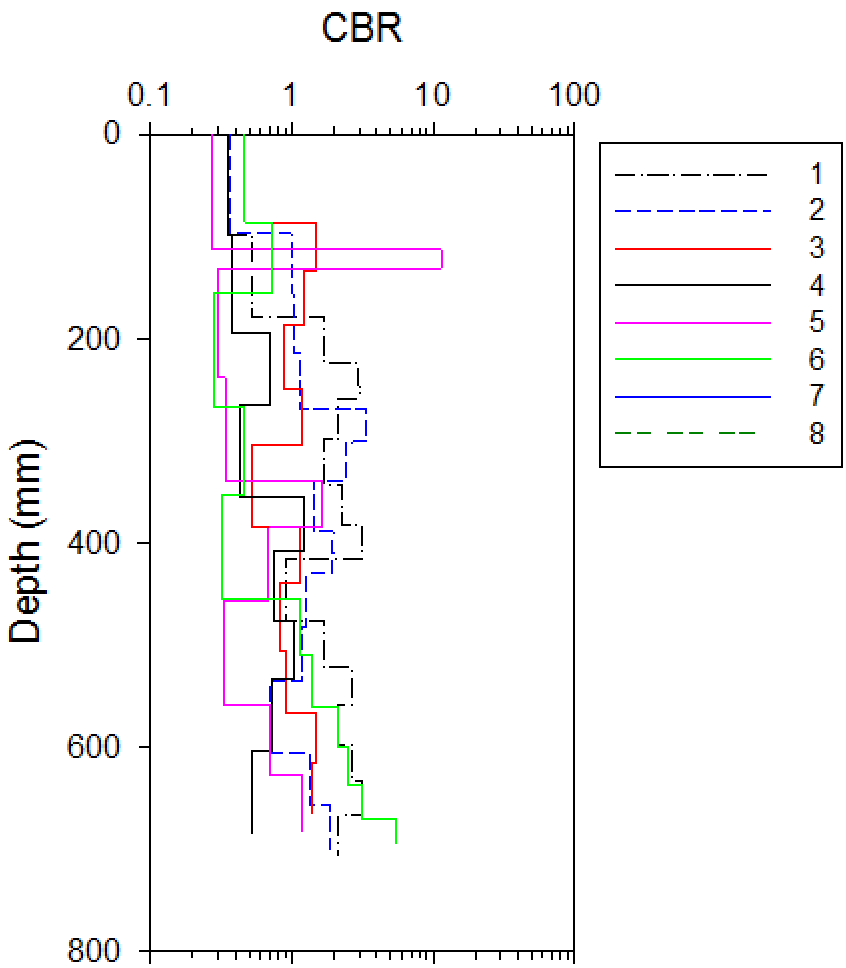


Figure 23: DCP test results for final lift adjacent to box culvert

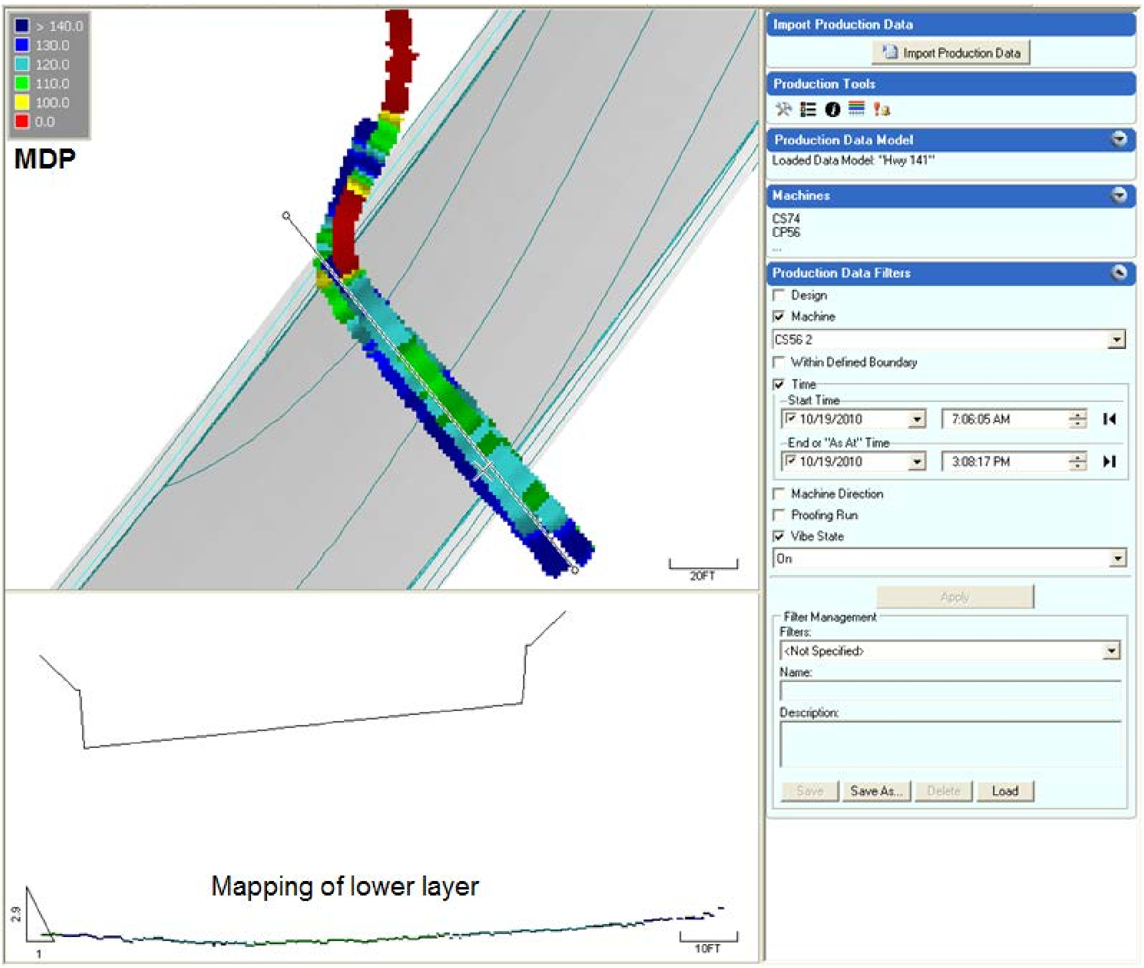


Figure 24: Initial mapping Test Area #3

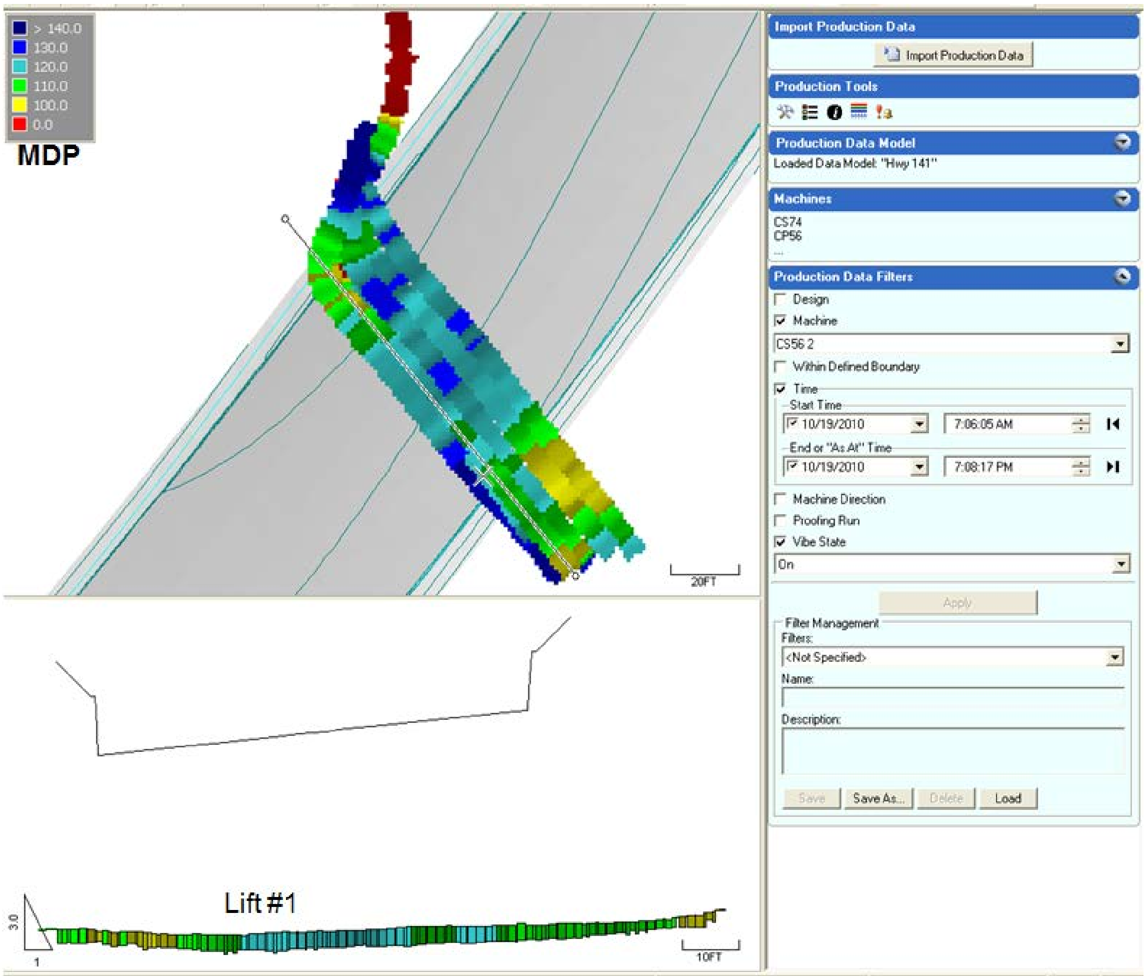


Figure 25: Lift #1 mapping Test Area #3

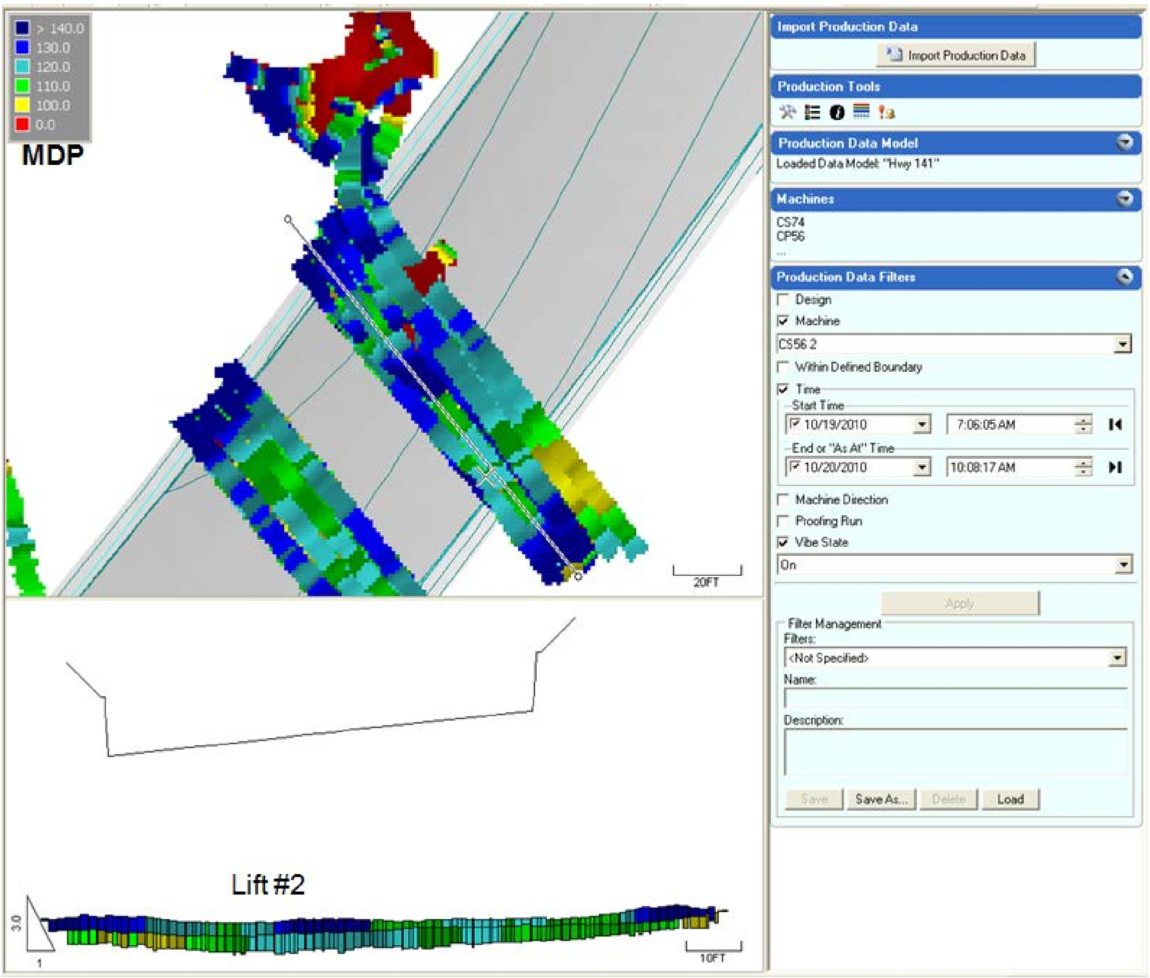


Figure 26: Lift #2 mapping Test Area #3

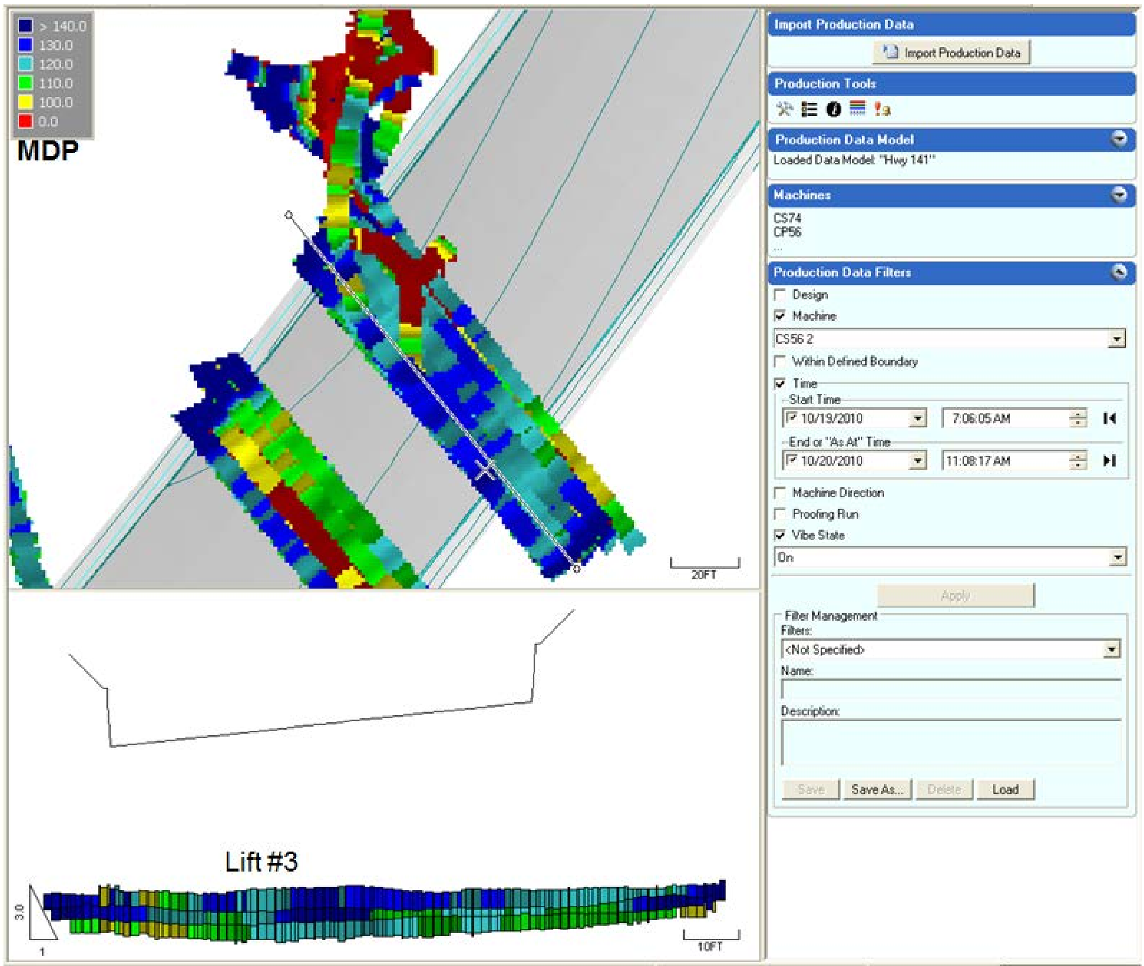


Figure 27: Lift #3 mapping Test Area #3

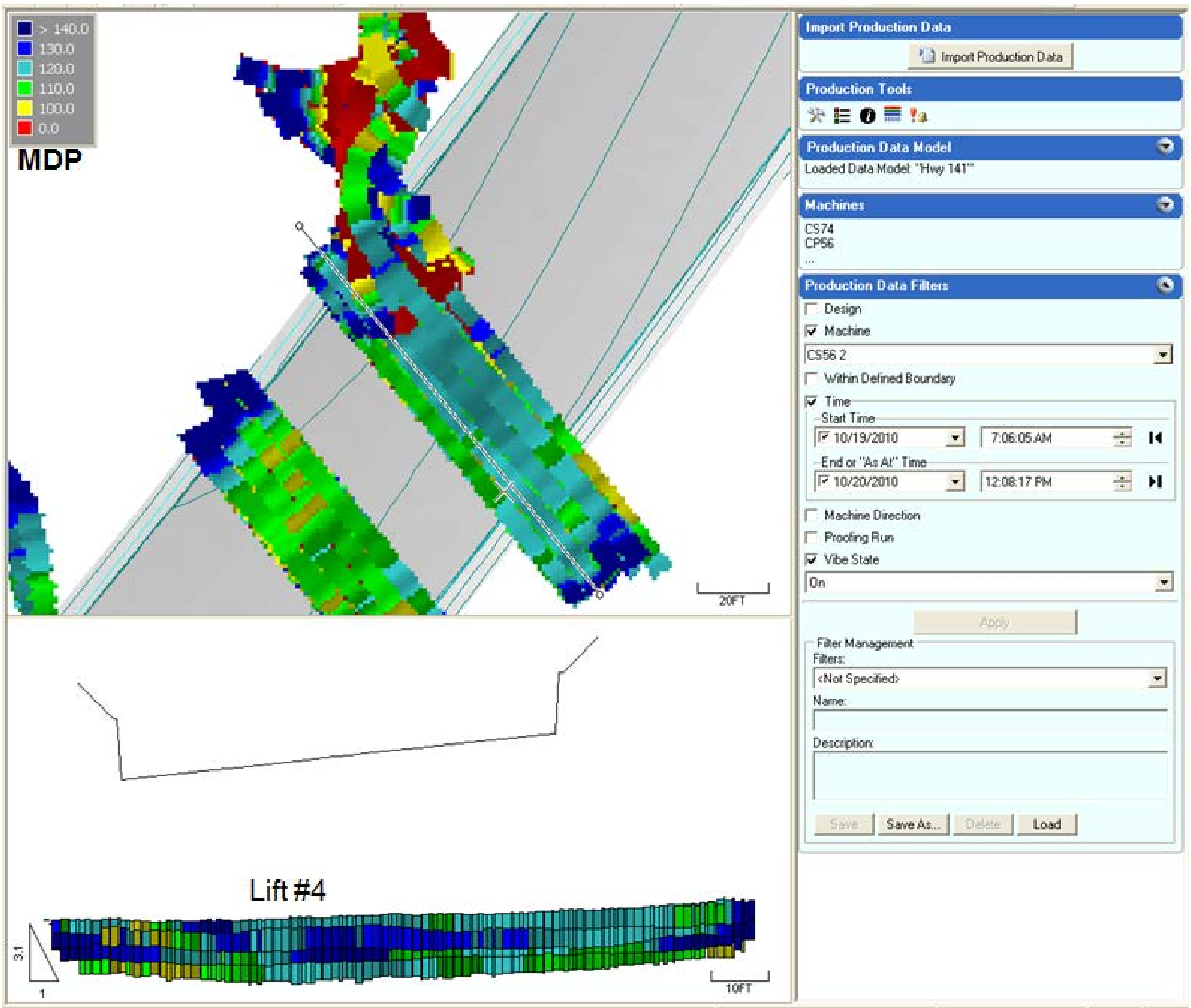


Figure 28: Lift #4 mapping Test Area #3

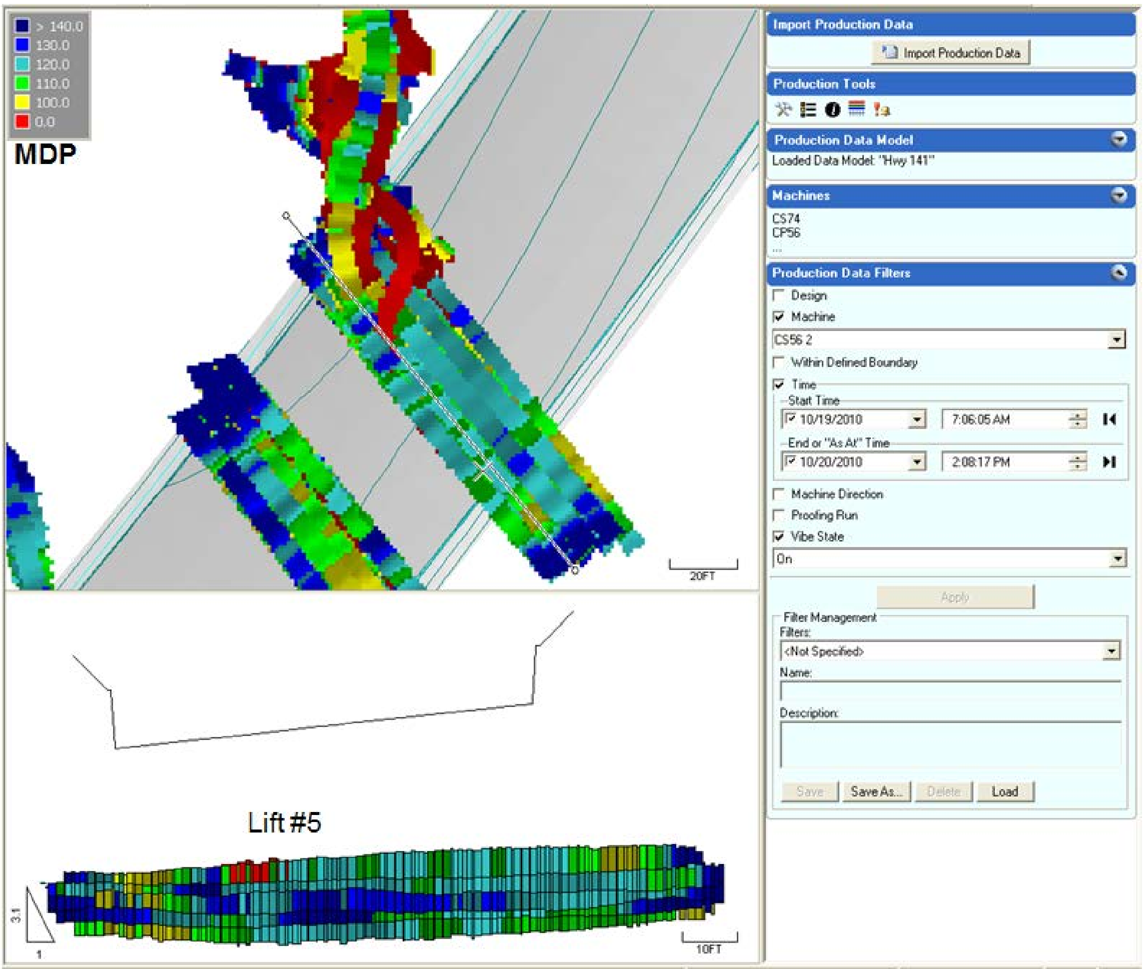
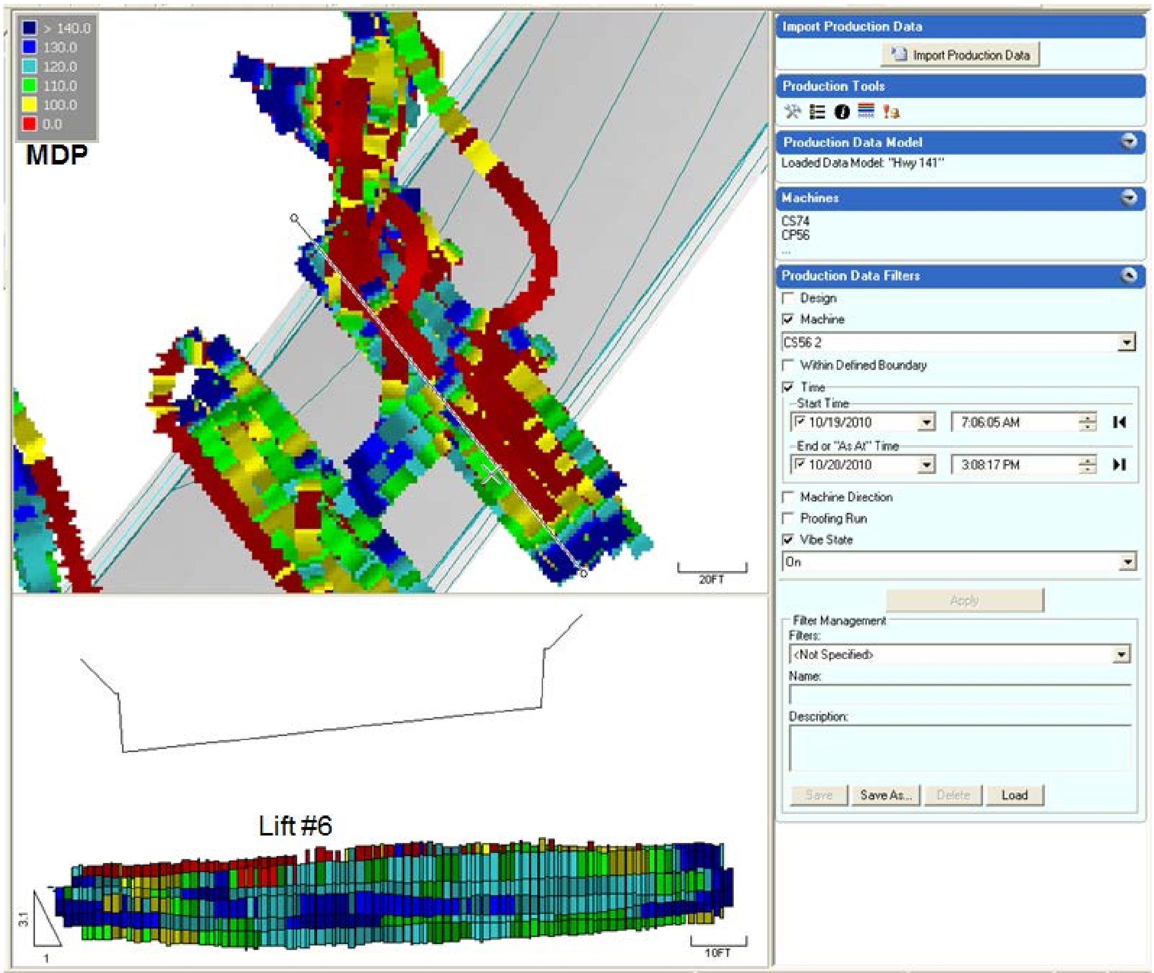


Figure 29: Lift #5 mapping Test Area #3



Layers Verified with
Compaction Time:
Map 0: 14:38 10/19
Layer 1: 16:02 10/19
Layer 2: 08:40 10/20
Layer 3: 10:28 10/20
Layer 4: 11:34 10/20
Layer 5: 13:43 10/20
Layer 6: 14:37 10/20

Figure 30: Lift #6 mapping Test Area #3 and summary of time filters for each lift

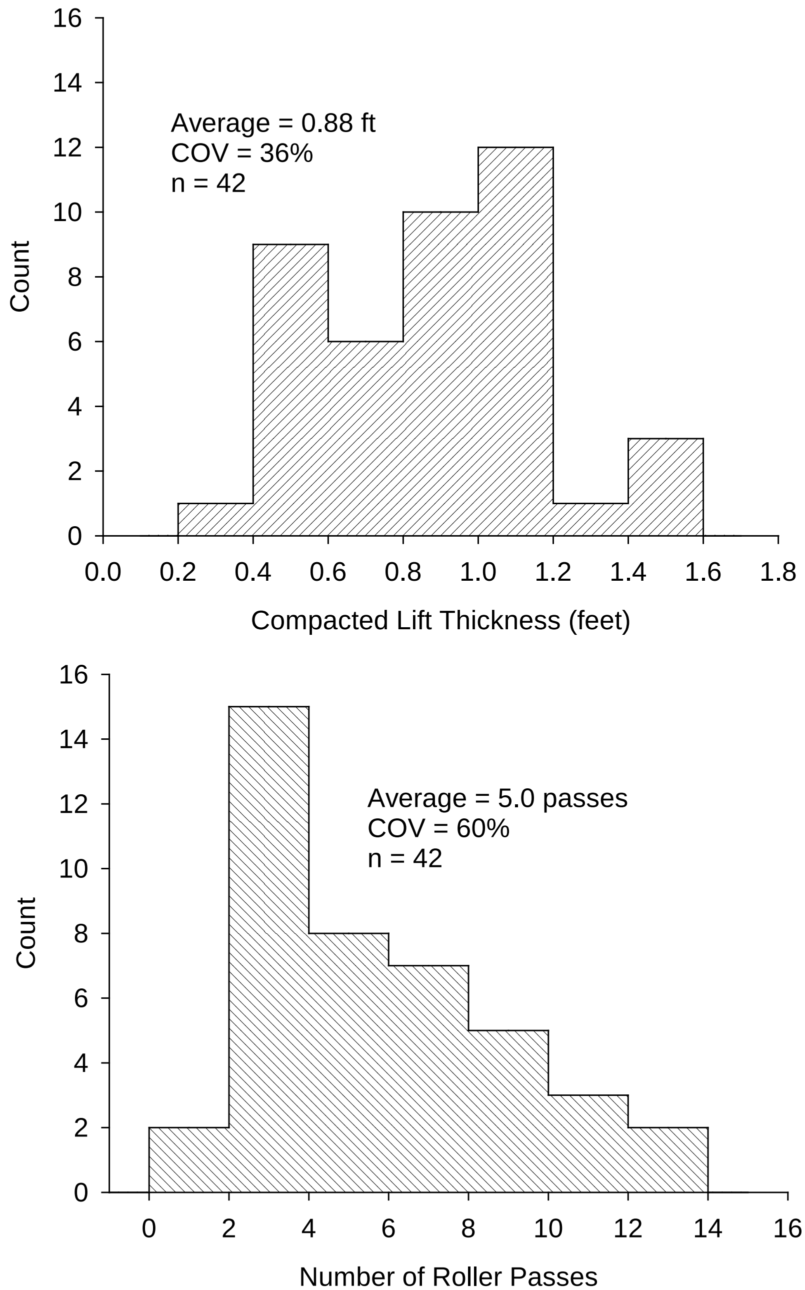


Figure 31: Results of compacted lift thickness and number of roller passes at several locations in box culvert fill

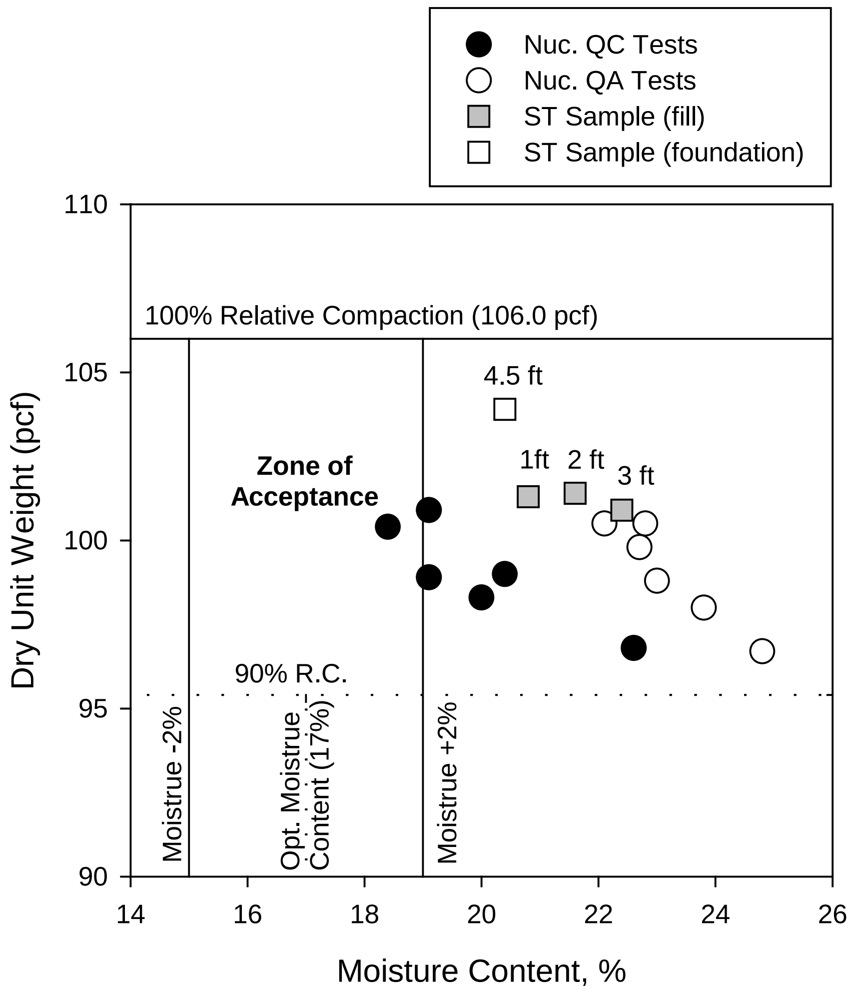


Figure 32: Tets area #3 results from QC/QA nuclear gauge tests and independent Shelby tube samples adjacent to box culvert

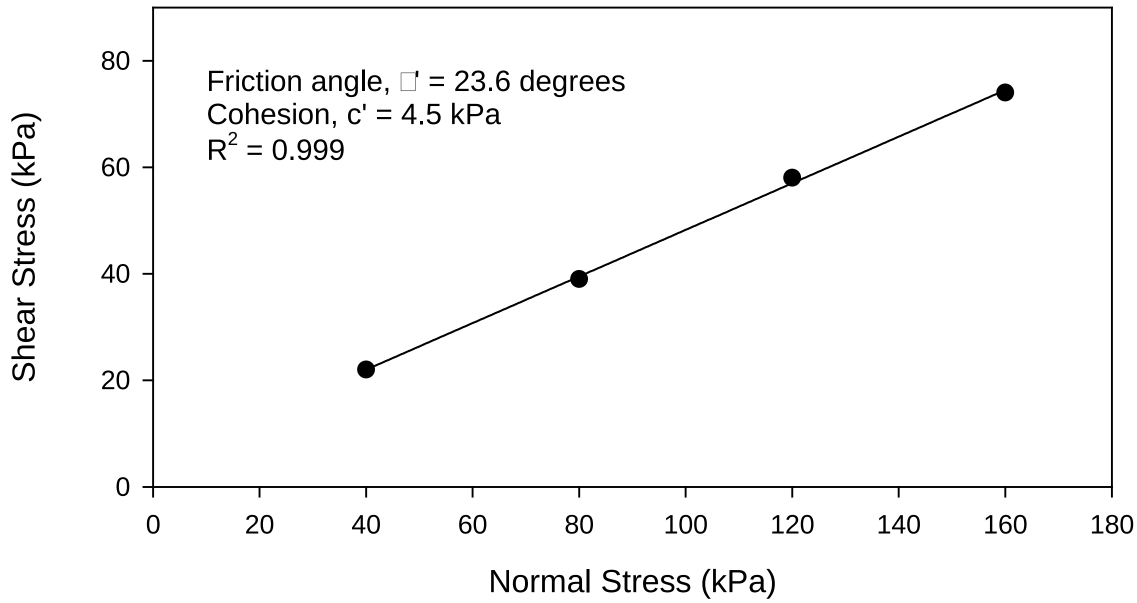


Figure 33: In situ borehole shear test (BST) in compated box cuvlert backfill

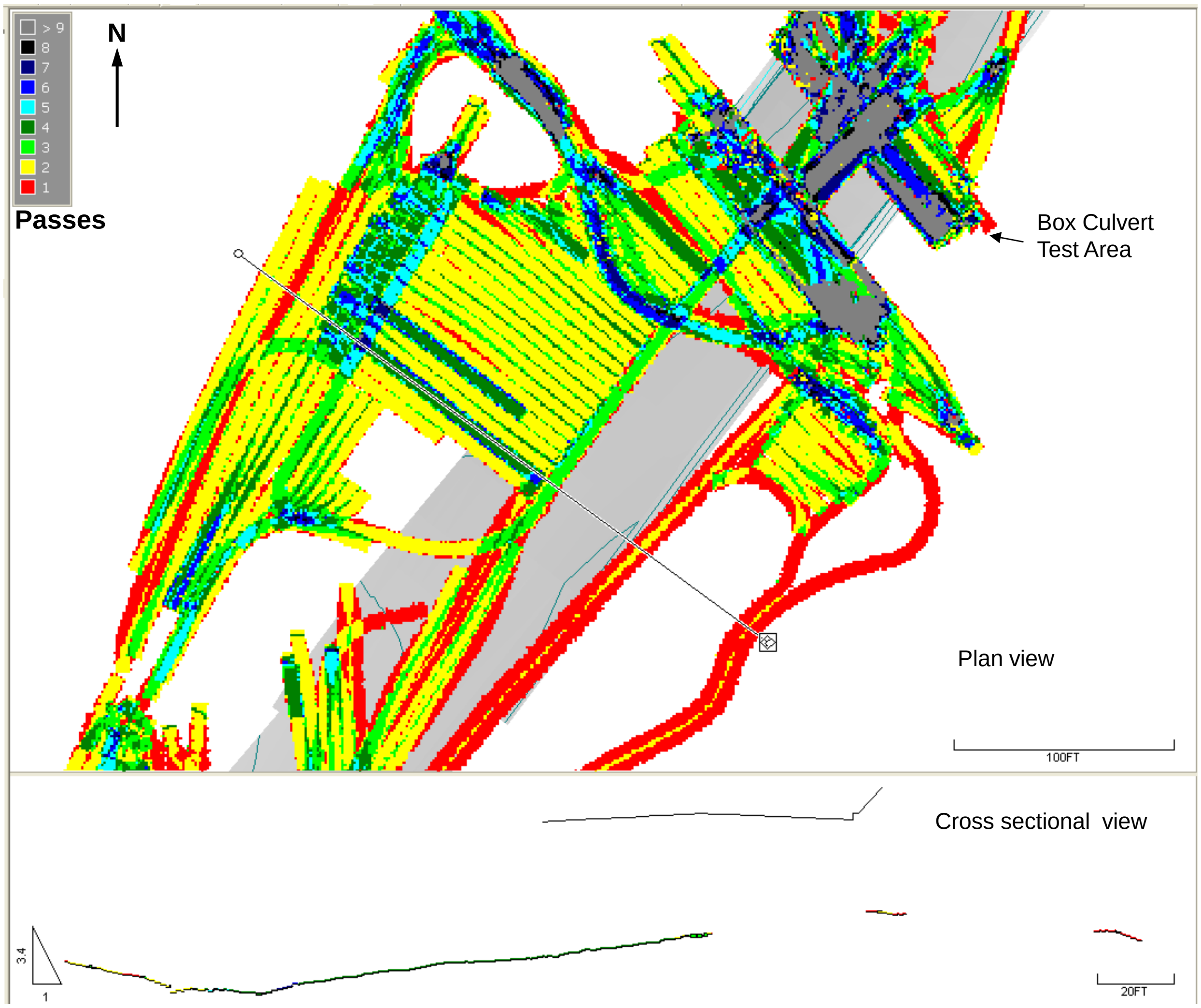


Figure 34: Example of roller operator using the real-time display to carefully control the pass coverage

Test Area #5: CS-563E – MSE Wall Backfill

The tier MSE wall near the south end of the project also provided an interesting opportunity to evaluate IC technology. This particular wall was constructed with a larger crushed limestone aggregate that makes direct transmission nuclear density gauge testing extremely difficult. Ordinarily a method specification is therefore used (i.e., specified roller passes). Further compaction equipment are normally not allowed with a distance of about 3 feet to prevent high lateral stresses from moving the facing panel out of plumb during construction. For both of these prescriptive roller operating conditions, the IC documentation system provided useful information. Figures 35, 36 and 37 show the MSE wall construction.

Figures 38, 39, and 40 8 shows IC results from CMV and RMV (resonant meter value) measurements and locations of dynamic cone penetration (DCP) tests. The CMV results in this area were generally high and ranged from 25 to 70. In portions of this area, the RMV values were high (> 6) indicating that the the vibratory roller was starting to bounce, which is a result of very stiff to hard well compacted material. The DCP results (Figure 41) show that the area within 3 ft of the MSE wall is less compact (based on the CBR profile) compared to the material subjected to rolling, where CBR values where > 50 at depths of 8 inches (200 mm) and deeper. Application of IC to MSE wall backfill compaction provided value in terms of pass coverage and location information and indicating the strength/stiffness of the compacted material.

Figure 35: Test area #5 Two-tiered retainaing wall backfill

Figure 36: Test area #5 Mutliple tiered MSE wall construction

Figure 37: Upper MSE wall tier after IC roller compaction and mapping

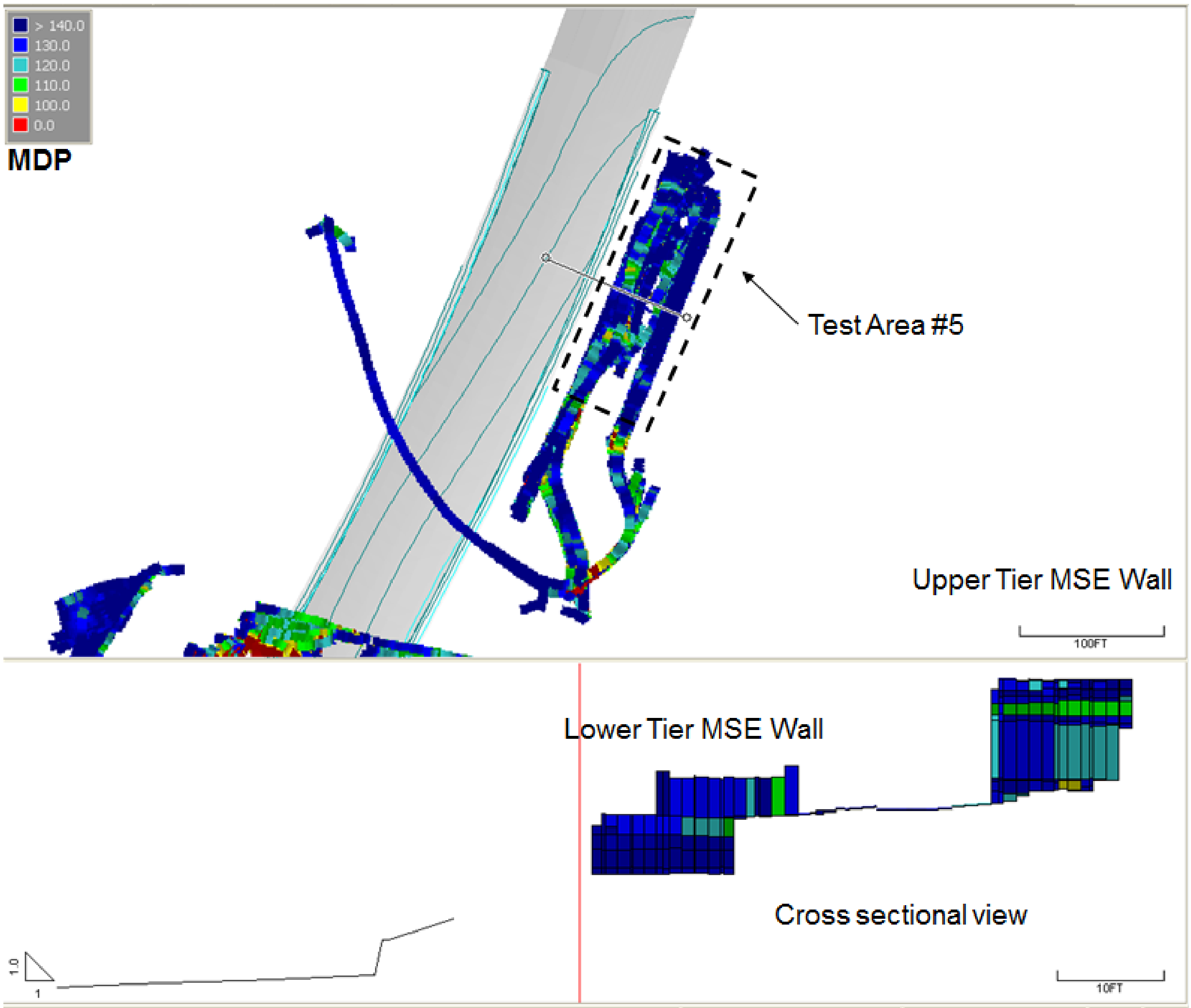


Figure 38: Test are #5 MSE wall – plan and cross sectional view

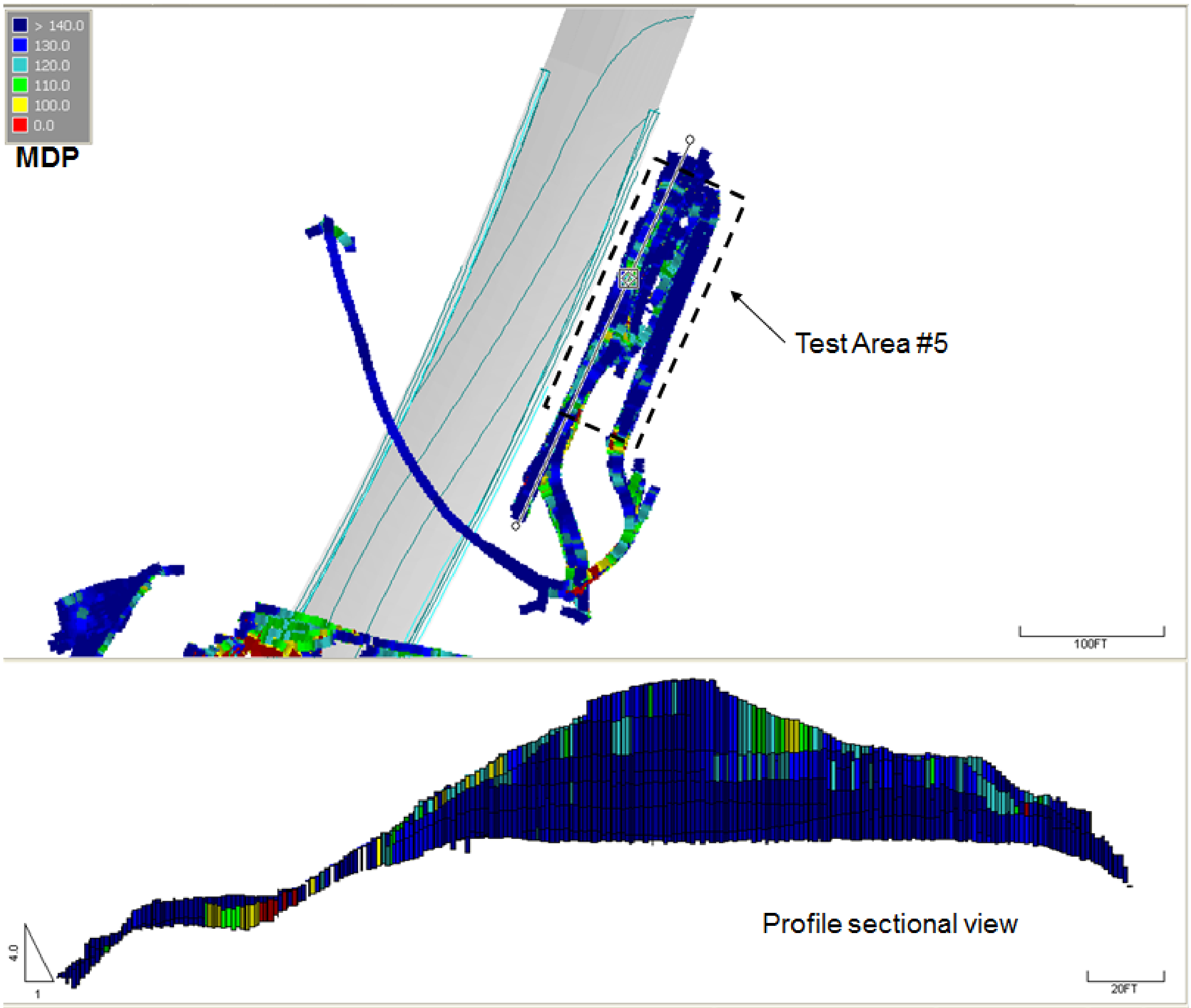


Figure 39: Test are #5 MSE wall – plan and prifile view

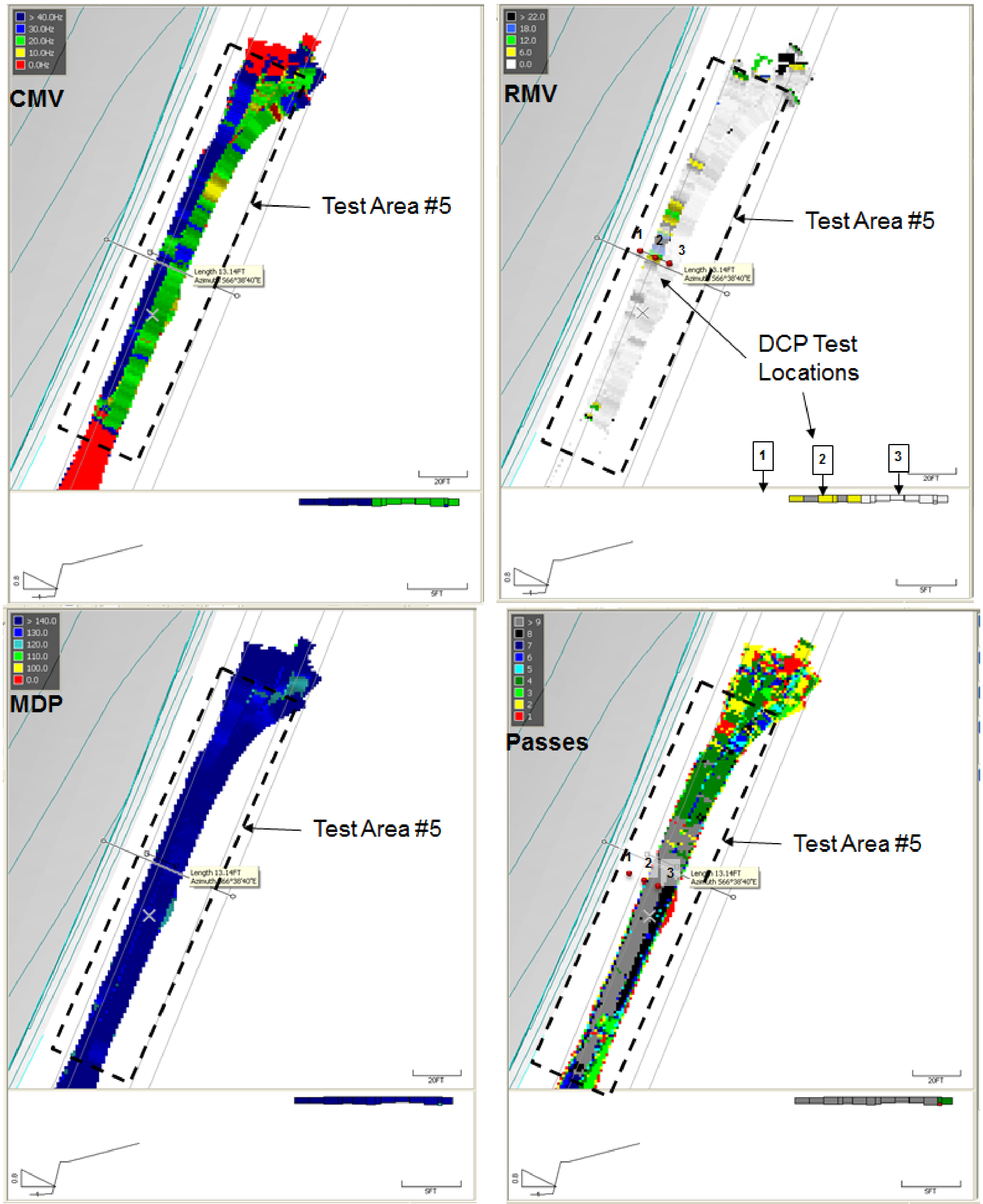


Figure 40: Comparison of Test Area #5 IC compaction MVs

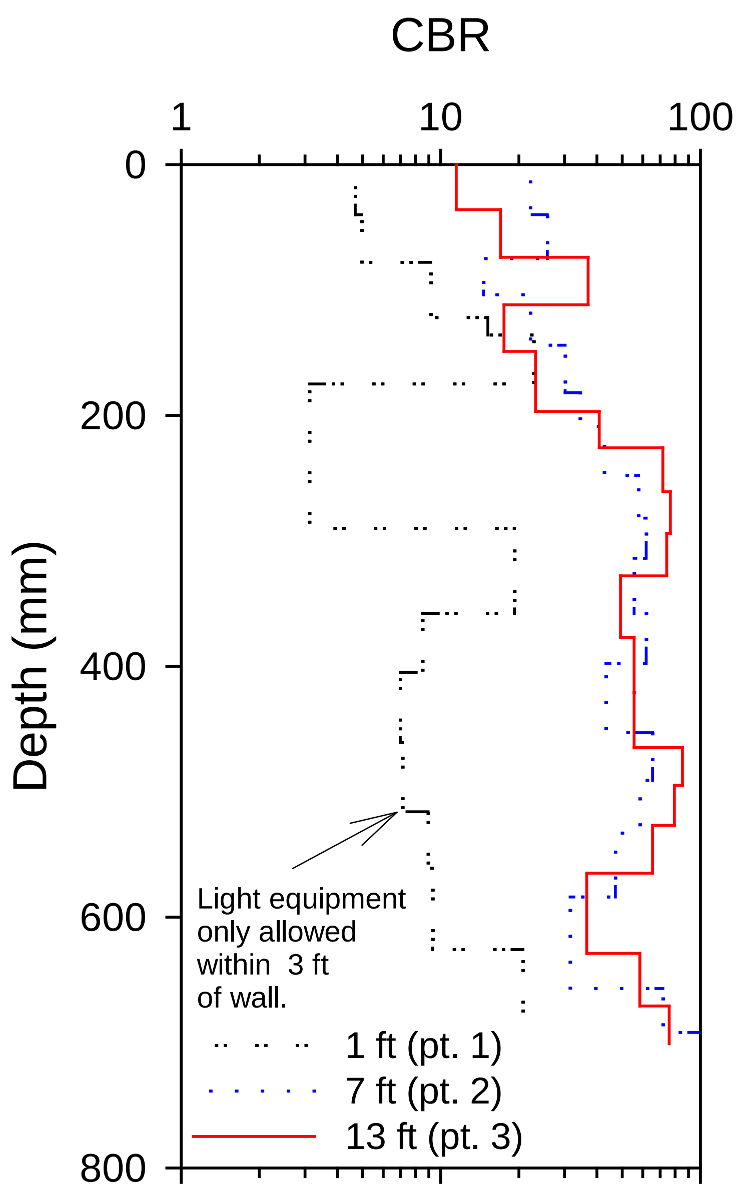


Figure 41: DCP test results for test are #5 at differnet distances form the MSE wall

Test Area #6: CS-563E – Type 5 Subbase at Tuador Road

Figure 42 shows the test area and compacted Type 5 base. Figure 43 shows the pass coverage information with passes from about 1 to 5 depending on location. The MDP values shows in Figure 44 indicate that the values were generally at the high end of the scale, while CMV values were generally low (Figure 45). It is believed that the CMV values were reflecting the low stiffness of the underlying subgrade layer. The CBR profile from DCP testing in this location are shown in Figure 46. Results shows that CBR values were variable ranging from about 2 to 40 in the Type 5 layer and about 10 in the subgrade. Nuclear gauge density-moisture QA/QC test results in this area are shown in Figure 47. All of the measurements indicated that the results were outside the acceptance zone for moisture content (i.e. too dry in this case).

Figure 42: Tets Area #6 at Tuador frontage road compaction on aggrgeate base

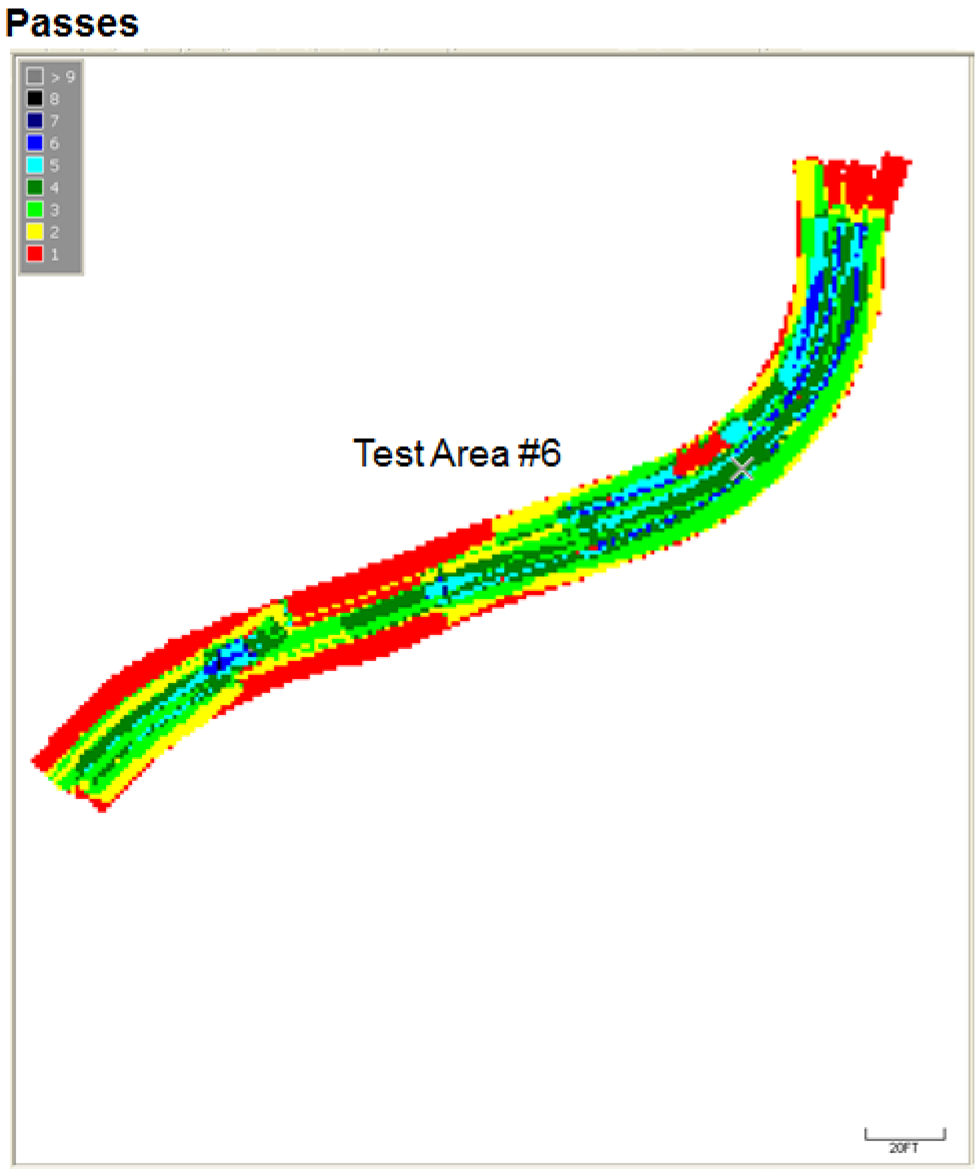


Figure 43: Test area #6 on Tuador frontage road – Type 5 crished limestone base

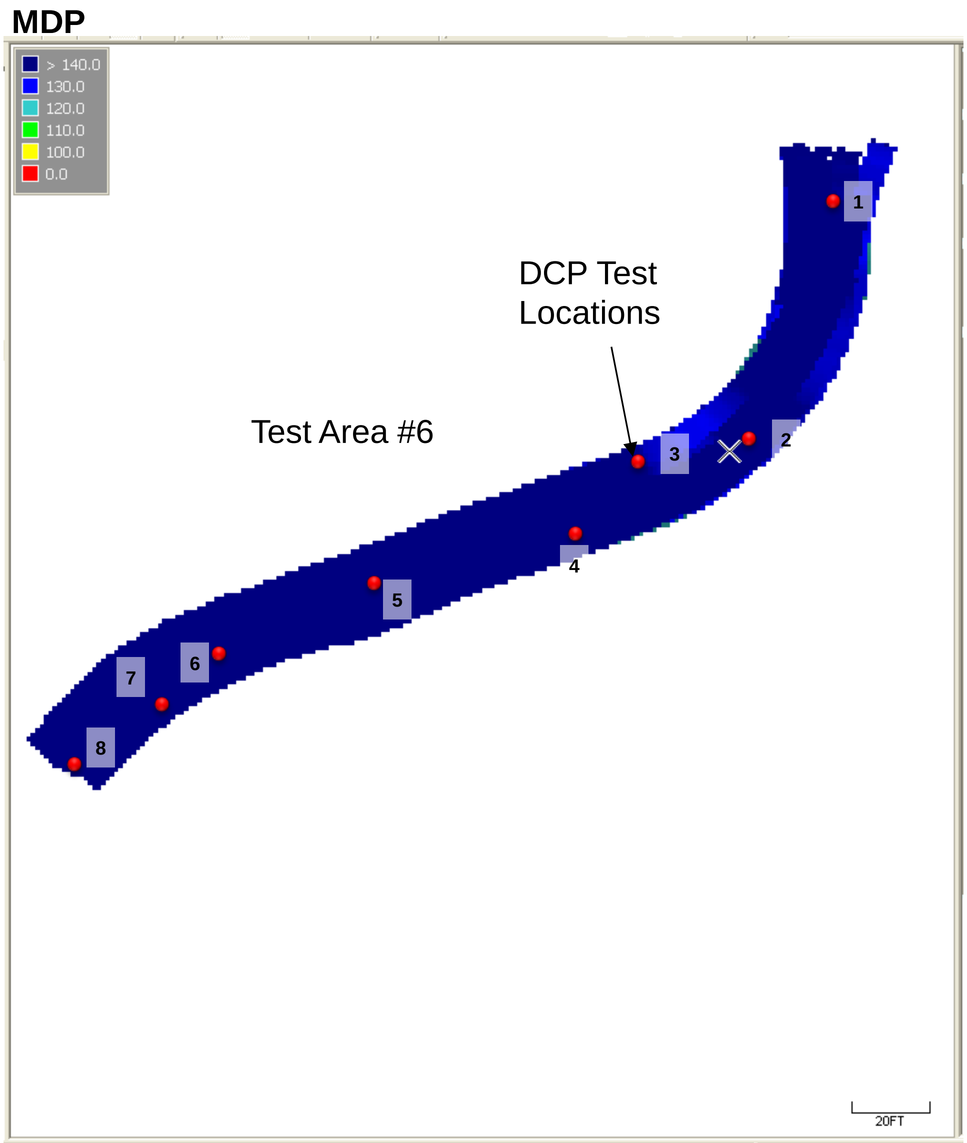


Figure 444: Test area #6 showsing MDP results

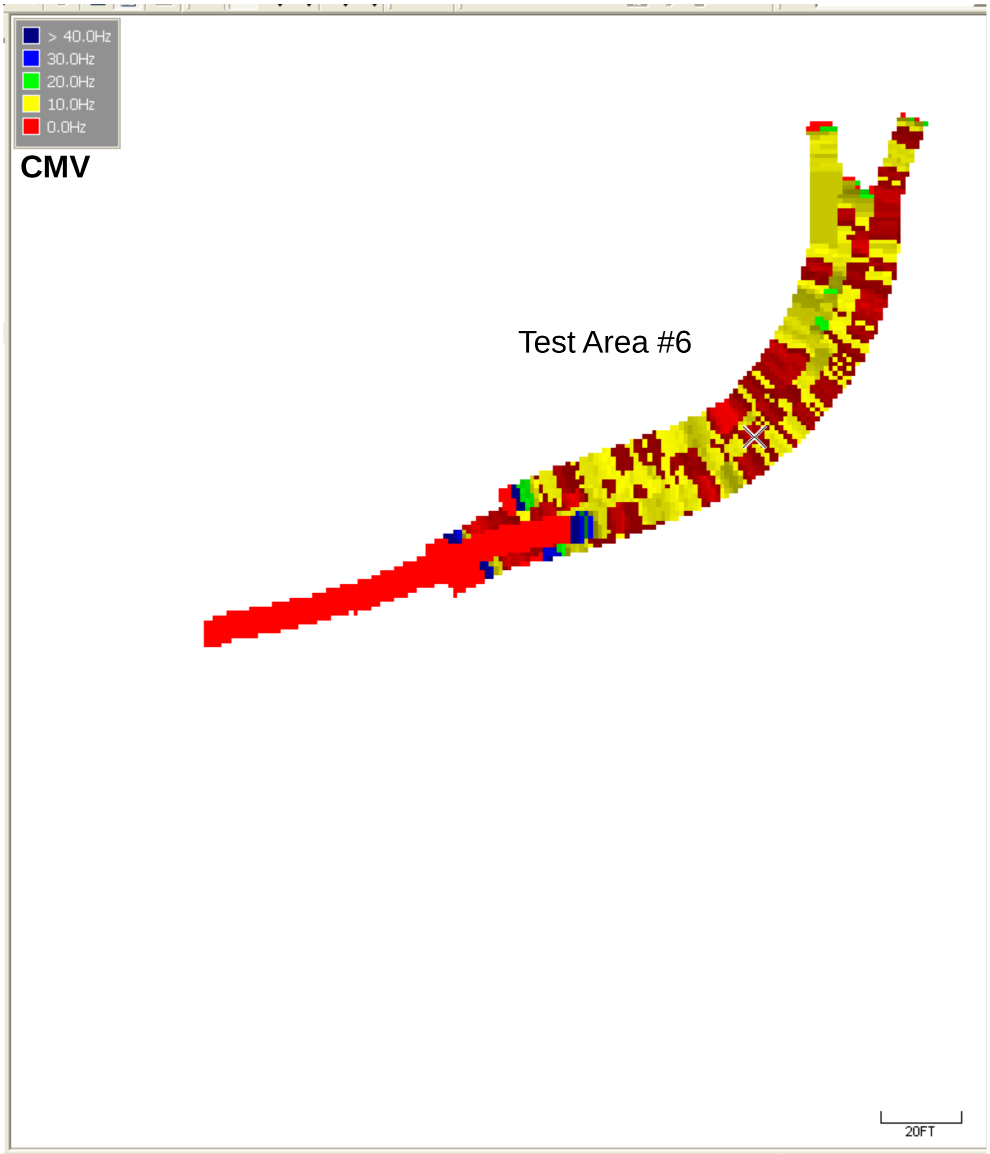


Figure 455: Test area #6 showsing CMV results

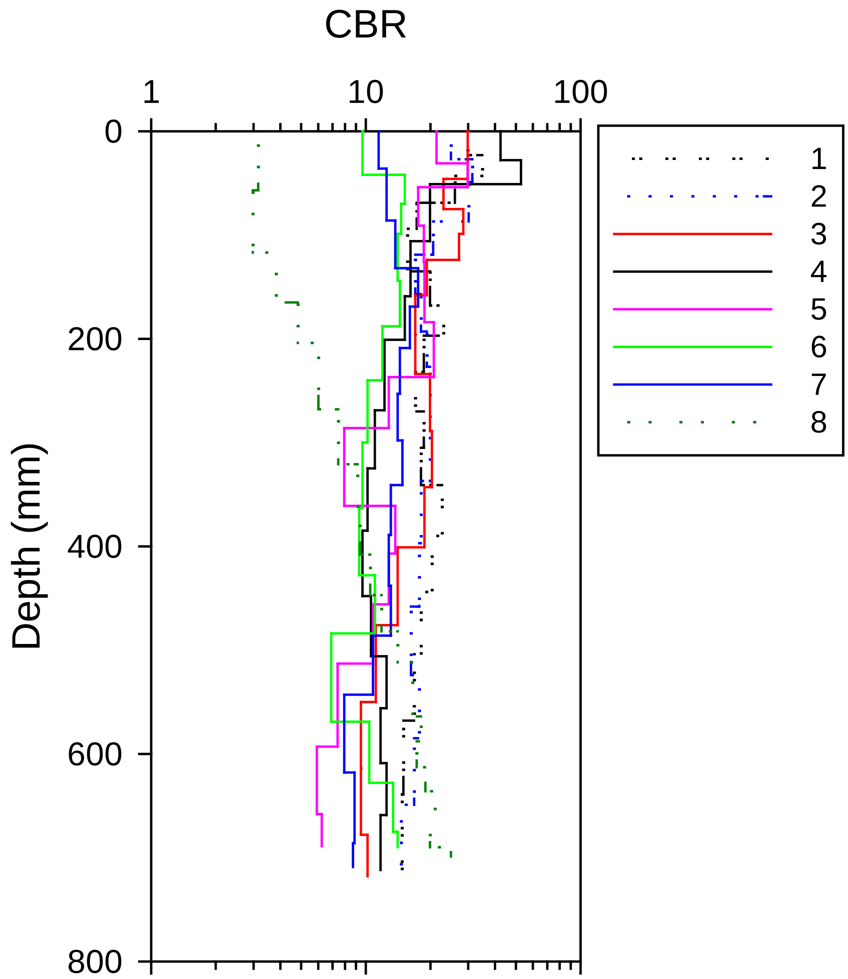


Figure 466: Test area #6 DCP test results in Type 5 aggrgeate base

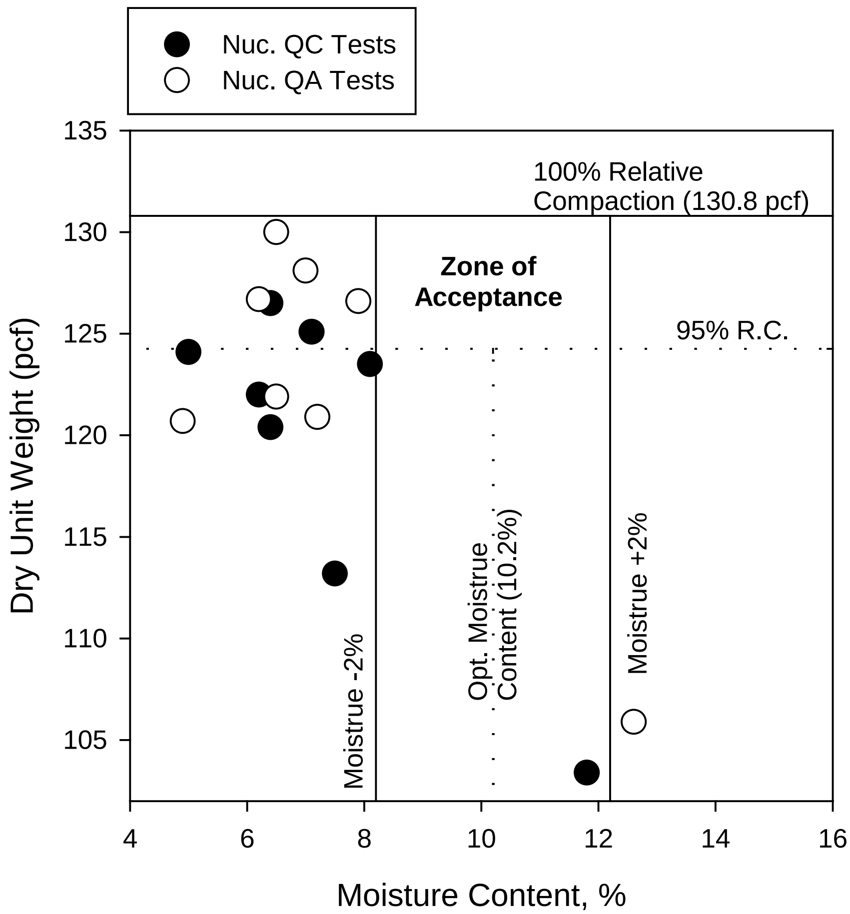


Figure 477: Test area #6 nuclear density gauge QA/QC results

Test Area #7 through 11Subgrade Proof Mapping and Calibration

Several tests areas within the silty clay embankment fill areas were compacted with the CS-563E and 815F rollers. Near the south end of the project, a large area (Figure 48) was mapped with both IC rollers and various QA/QC tests were performed to evaluate the ability of the IC machines to identify areas of non-compliance (i.e., areas of wet fill material). Figures 49 through 54 show an area approximately 70 ft wide by about 700 ft long that was mapped with the CS-563E IC roller. Figure 55 shows the results of nuclear gauge density-moisture tests in this area. DCP tests show that the CBR values in this area were variable between 0.1 and about 20 (Figure 56). Correlations analysis using MDP and CMV versus PLT modulus of subgrade reaction tests are reported in Figure 57. Results correlation analysis of plate load test results in this area showed that the MDP values for the CS-563 demonstrated that a positive correlation for k-values less than about 100 pci is possible. In contrast, the CMV values were not sensitive to variations in k- values. The lack of correlation for CMV to k-values is primarily due to the material being at the low end of the CMV measurement range (i.e., CMV values less than about 10). Other studies have shown that for CMV values greater than about 10, correlations do exist between CMV and plate load test results (White et al. 2011).

The 815F roller (Figures 58 and 59) also mapped this area and the results are shown in Figure 60 and 61. The variation in color of the MDP values helped identify areas of wet soil conditions (see MDP scale in upper left corner and notes on w%). Static plate load tests were conducted in this test area (see Figures 62 and 63) at several locations based on the variations observed on the MDP map and confirmed soft and wet areas of noncompliance. Figure 64 shows that some rolling operations occurred in what were later determined to be cut areas. Figure 65 shows the embankment geometry and location of the test area being rolled. Compared to the CS-563E roller IC-MVs. The 815F MDP map shows similar geospatial variations in ground stiffness.

To better understand how the 815F results relate to traditional proof rolling with a loaded tandem axle dump truck (Figure 66), several areas along the extent of the project were proof rolled and compared to the MDP results at selected locations. Figure 69 shows the project areas selected for proof testing. The results from this exercise demonstrated that the MDP values can be correlated to both rut depth (Figures 68 and 71) and k-values (Figure 70). A MDP target value of 123 was determined from the rut depth (Figure 71) and CBR test results (Figure 72) for IC production mapping conducted by the contractor. Compared to the QA/QC nuclear moisture-density-moisture results however, the MDP values were poorly correlated (Figures 73 and 74).

To field assess the effectiveness of the MDP target value to field control of compaction quality, the contractor operated the machine for several months and used these target values to create compaction reports. Figures 75 and 76 are examples of a compaction report showing isolated areas of non-compliance (i.e., MDP values < 123). In this production area, the compaction report provided the following information: (1) 77% of the area met the minimum requirement; (2) the compaction area was 17,092 ft^2 ; and (3) the compaction map in this area was completed in approximately 111 minutes. Similar analyses were performed in other test areas (see Figures 77 to 82).

Figure 48: Test area #7 Subgrade proof mapping metzer4

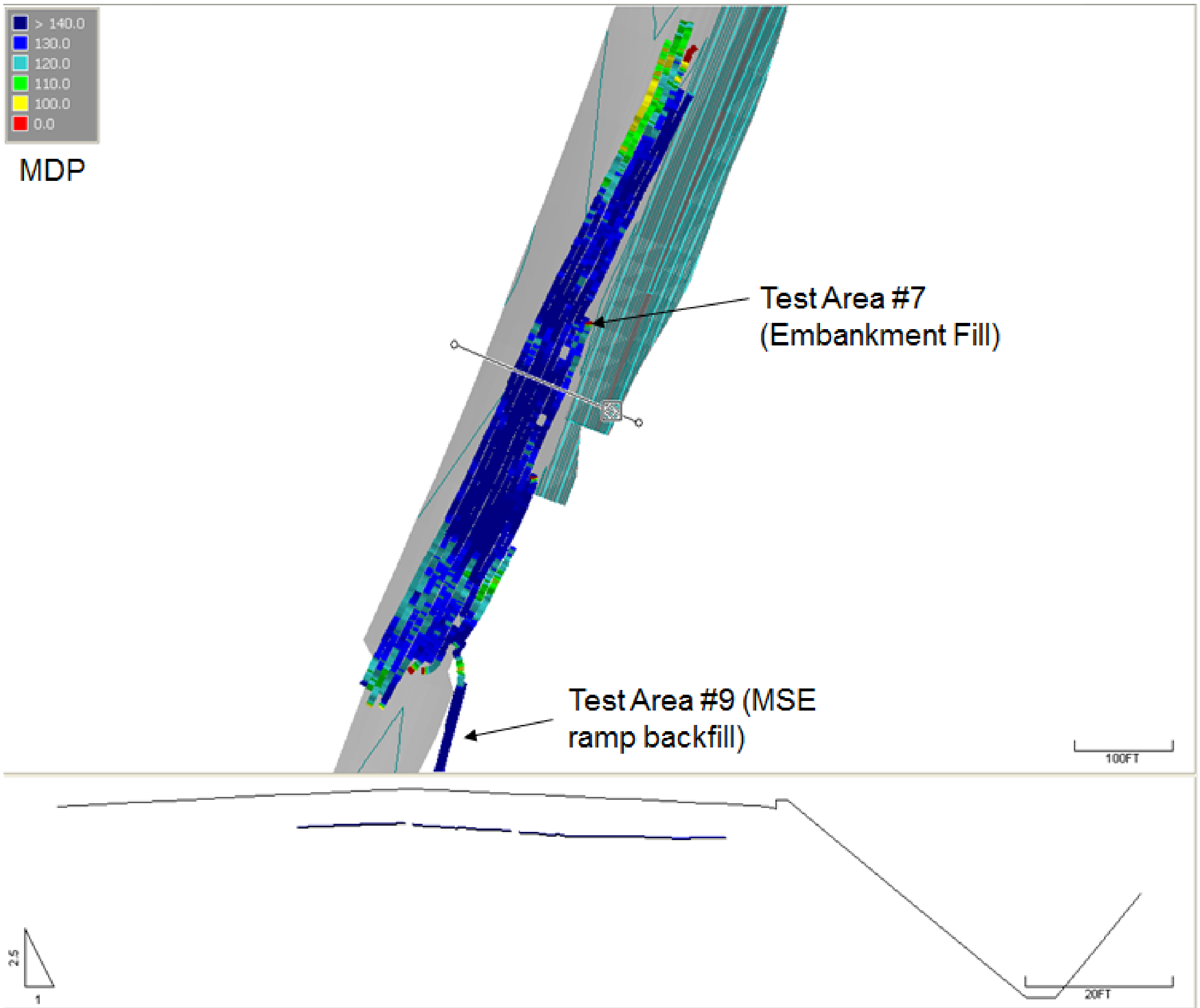


Figure 49: MDP results for test area #7 embankment fill #9 MSE ramp—crushed limestone aggregate backfill

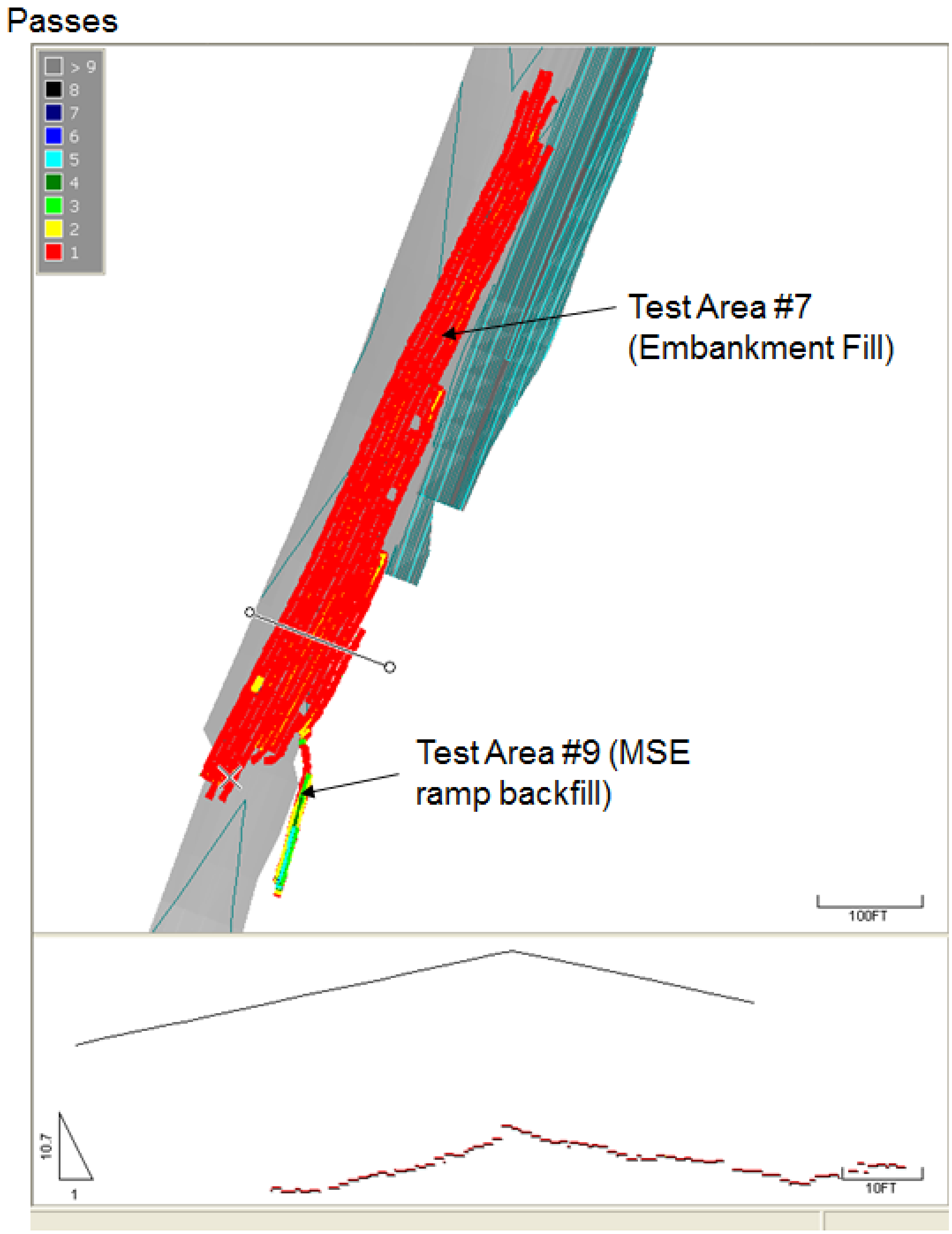


Figure 50: Pass count results for test area #7 embankment fill #9 MSE ramp—crushed limestone aggregate backfill

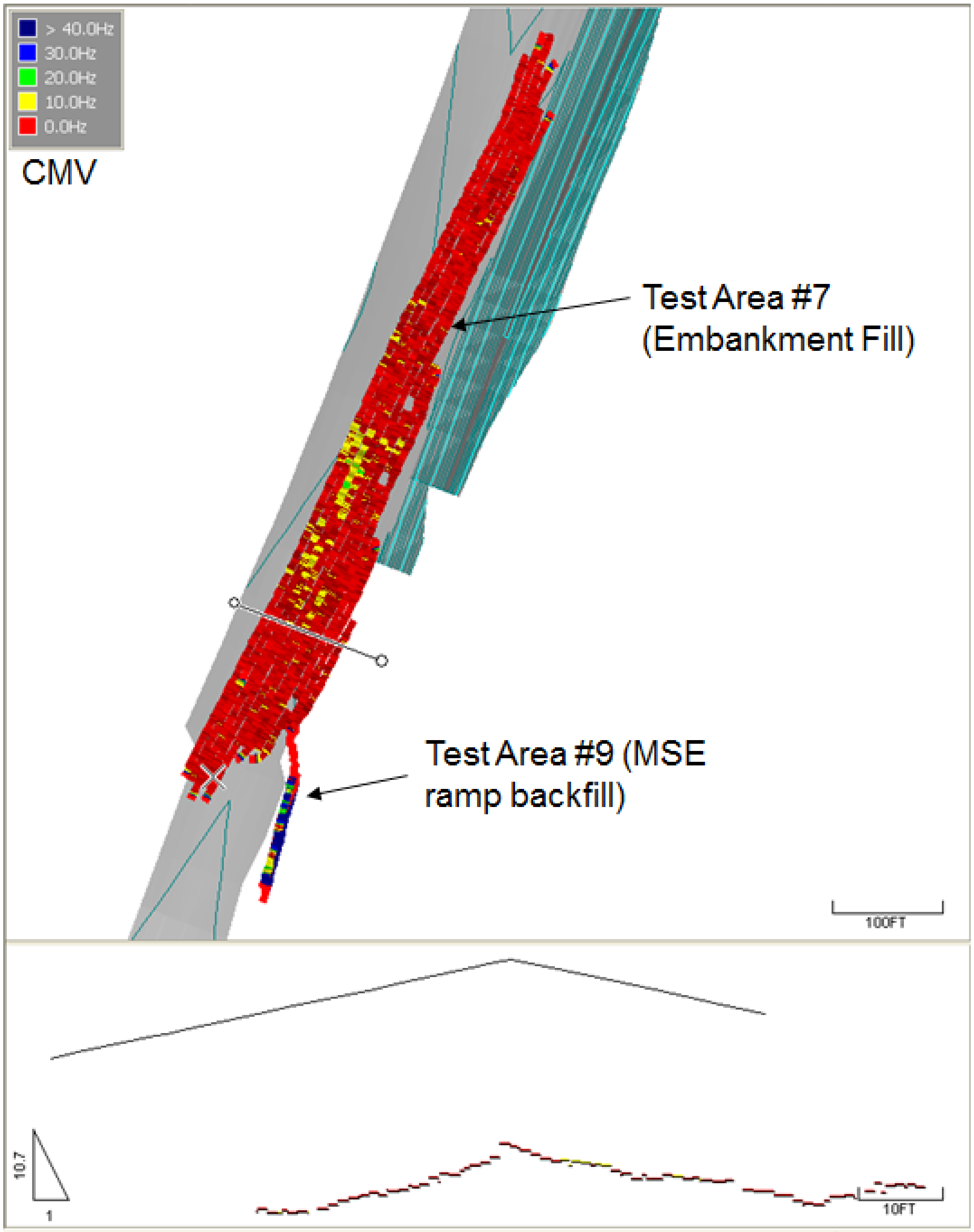


Figure 51: CMV results for test area #7 embankment fill #9 MSE ramp—crushed limestone aggregate backfill

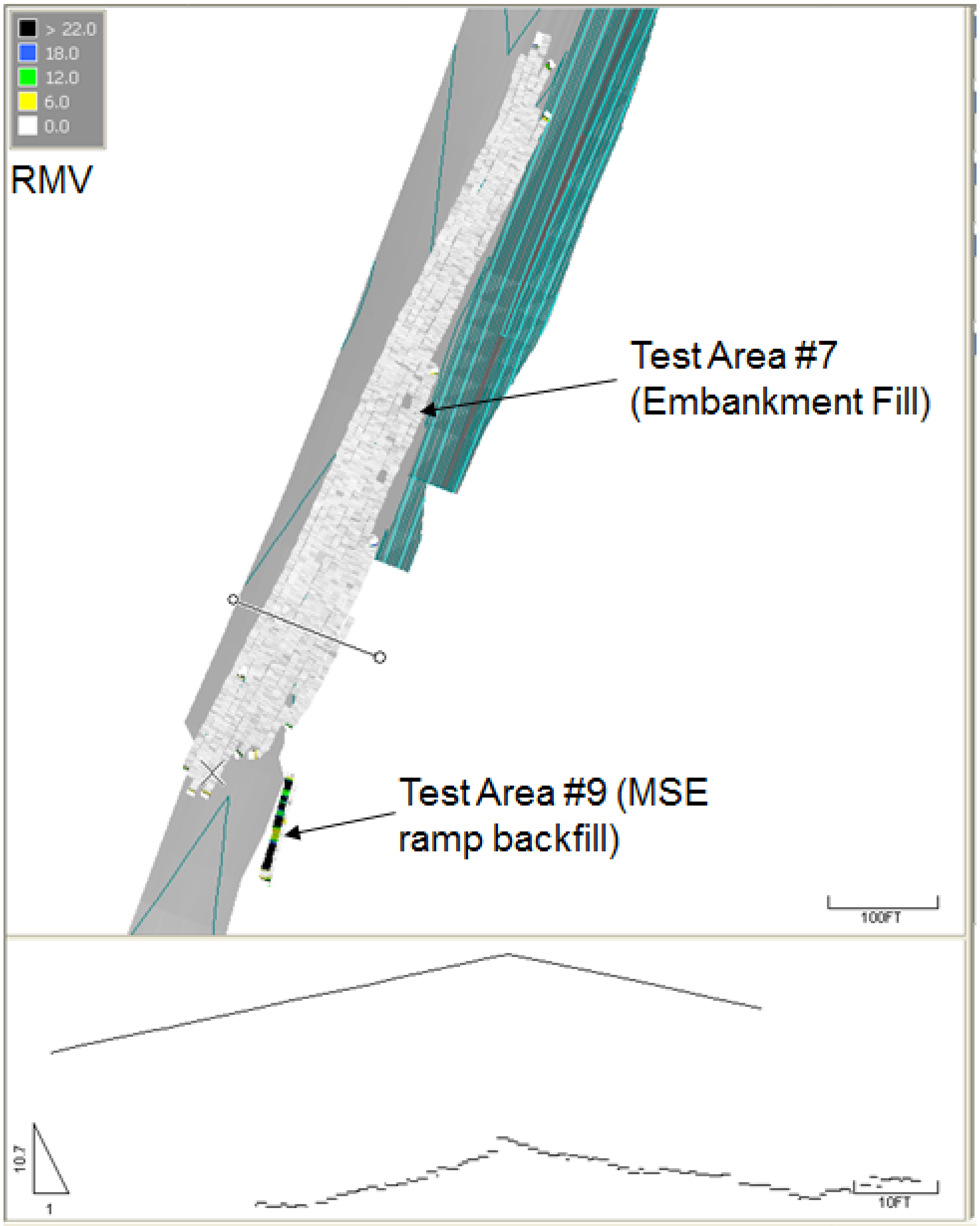


Figure 52: RMV results for test area #7 embankment fill #9 MSE ramp—crushed limestone aggregate backfill

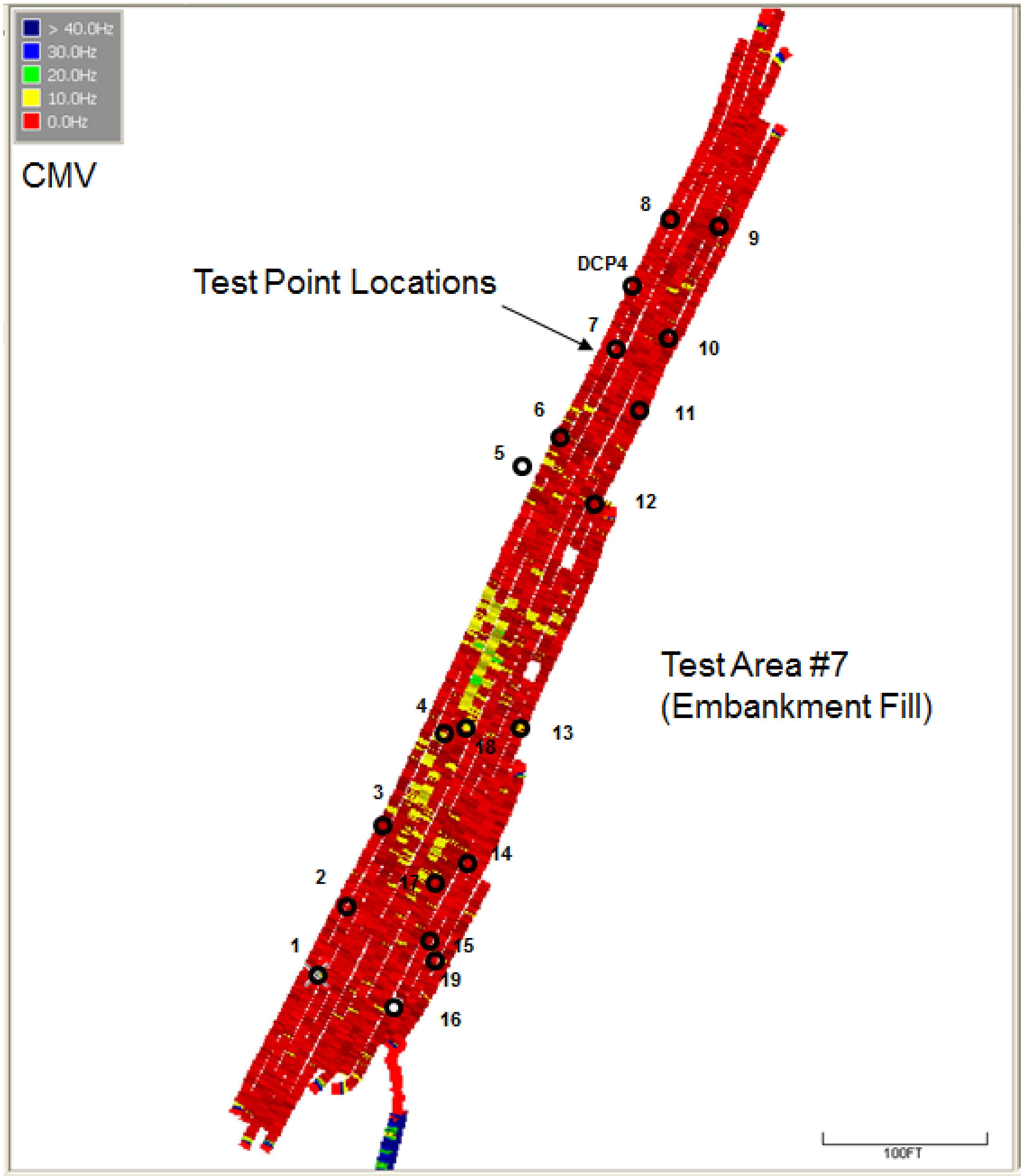


Figure 53: CMV map for test area #7 showing test point locations

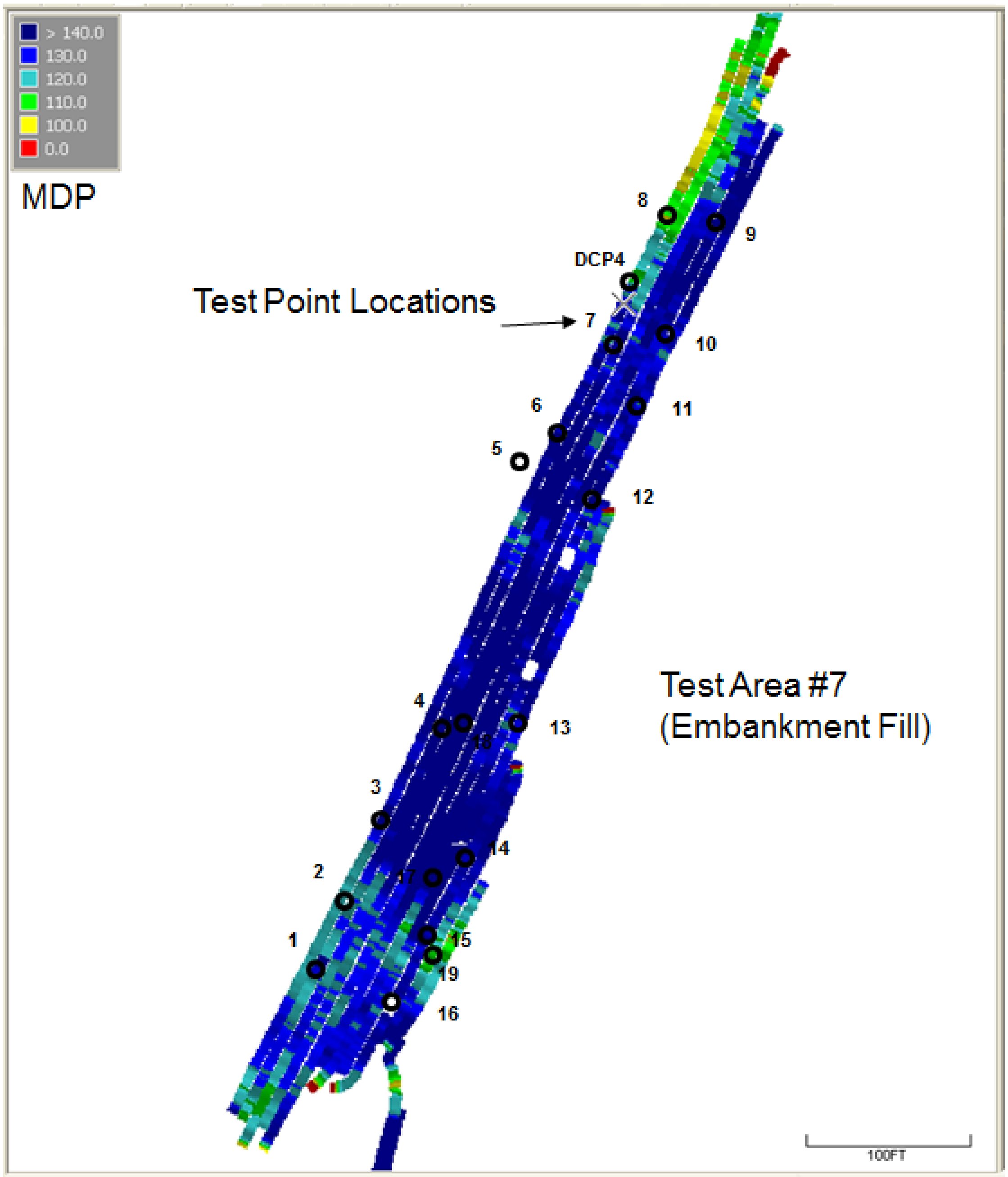


Figure 54: MDP map for test area #7 showing test point locations

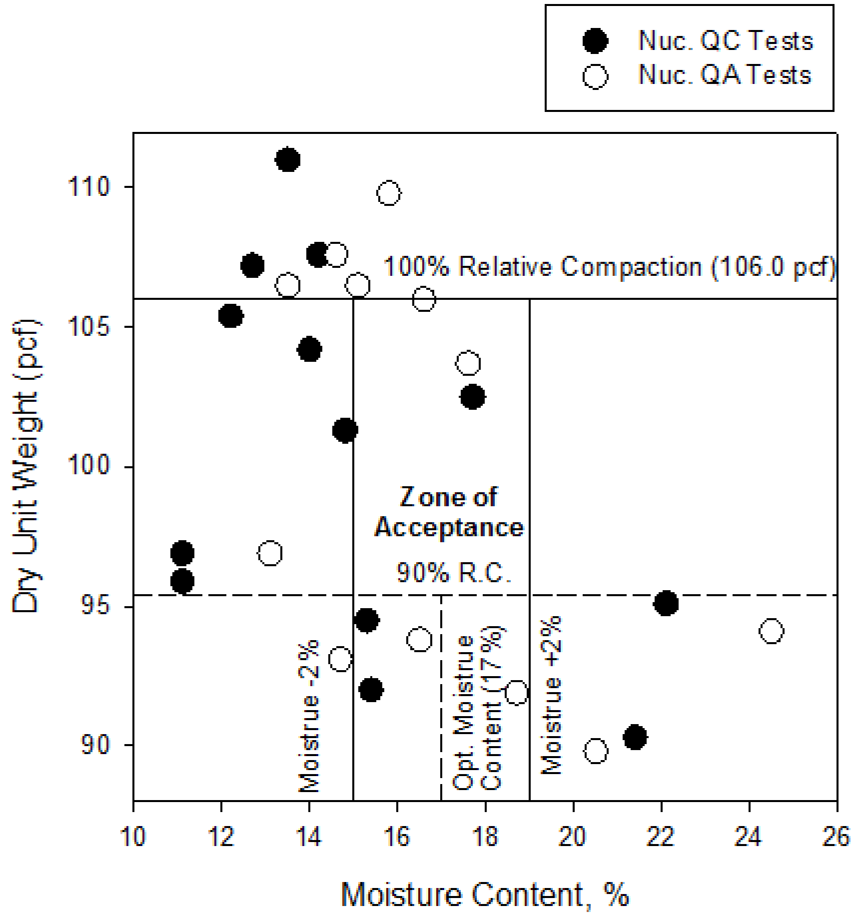


Figure 55: Test area 7 embankment fill QA/QC nuclear density gauge results

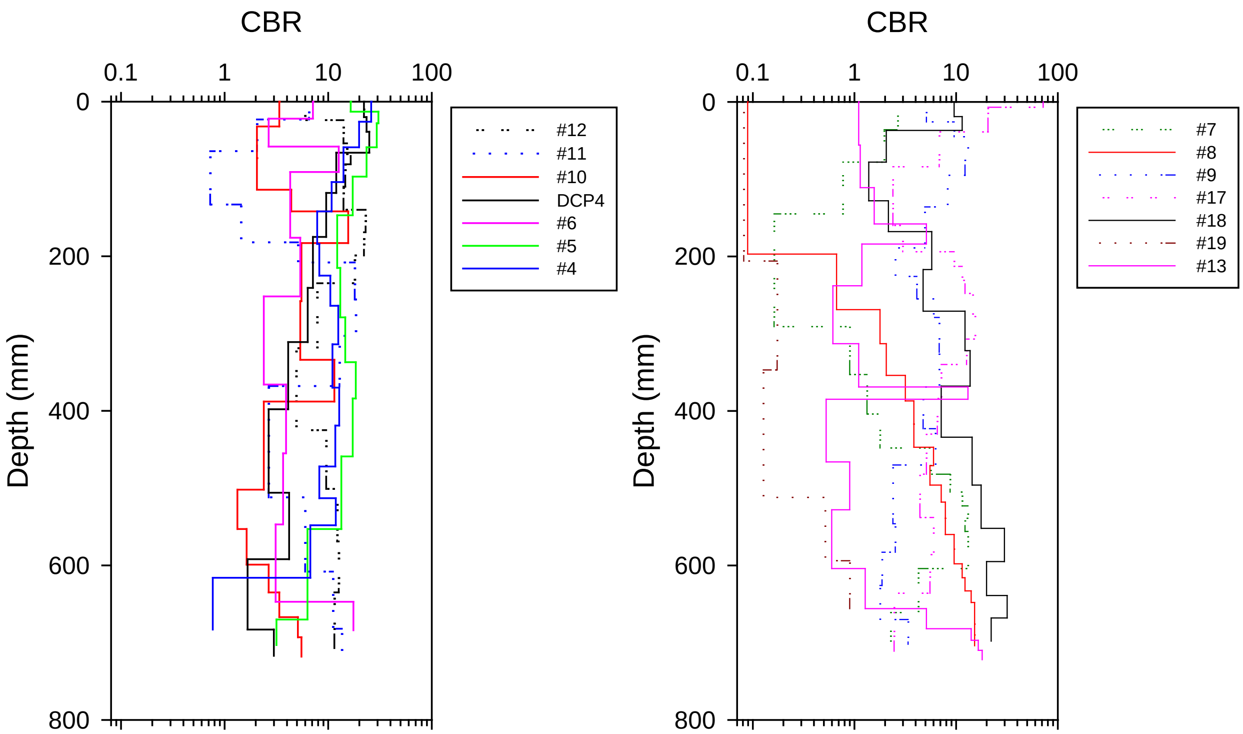


Figure 56: DCP test results for test area #7

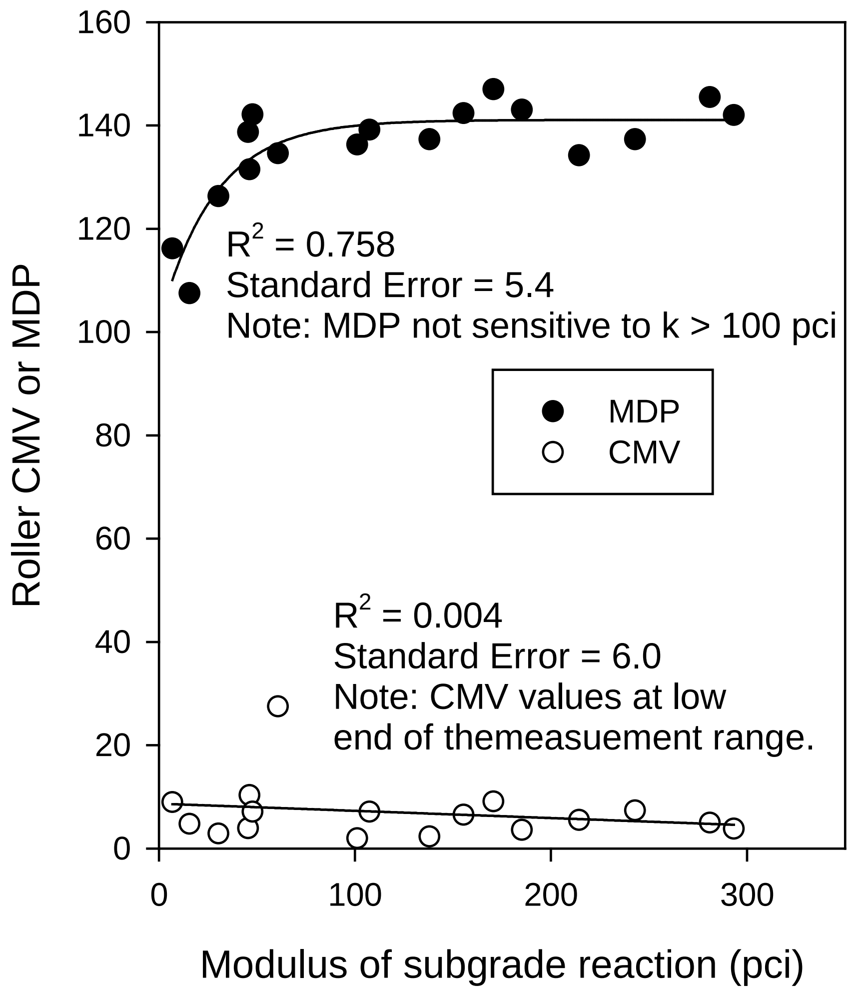


Figure 57: Plate load test modulus of subgrade reaction versus CMV and MDP for embankment fill—test area #7

Figure 58: Caterpillar 815F RICM Equipped Roller

Figure 59: 815F operator display

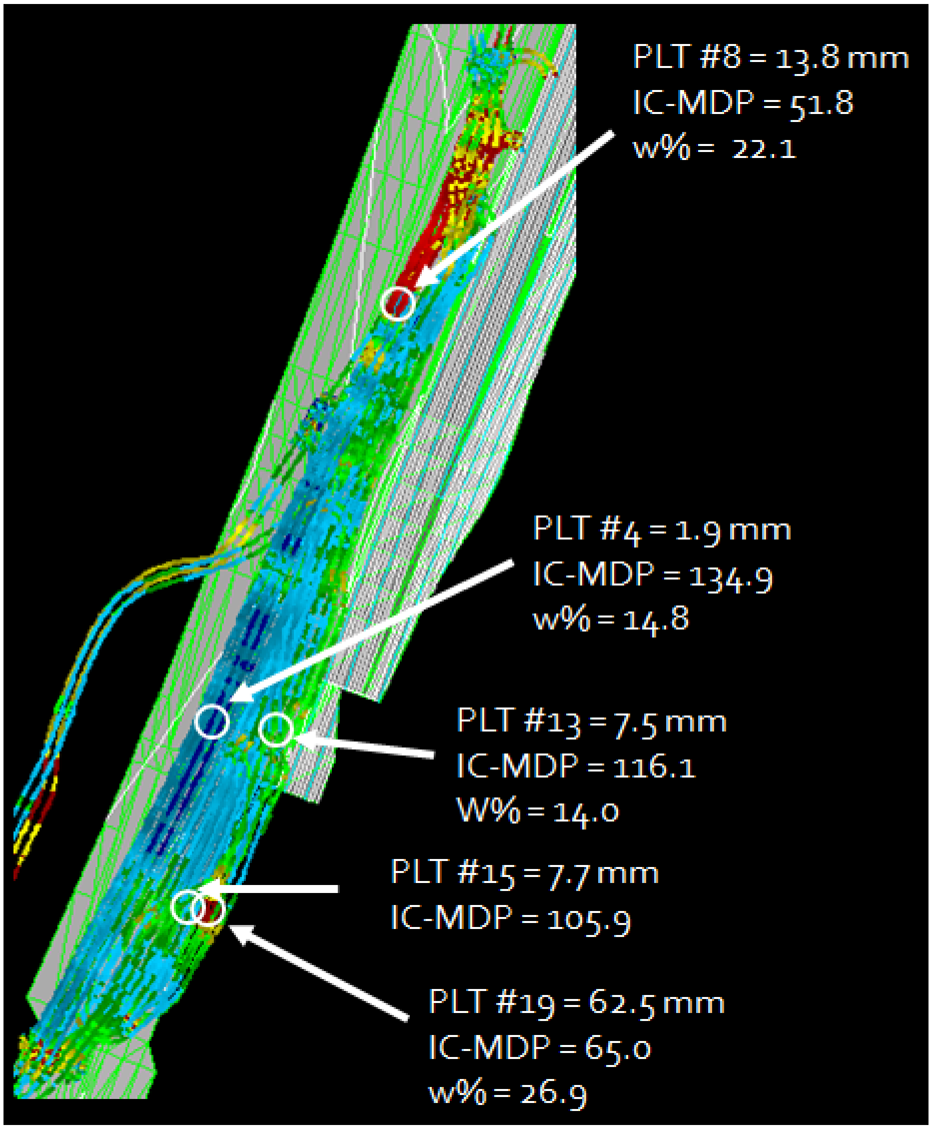


Figure 60: Results from test area #11 variations in IC-MVs, moisture content, and PLT deflection

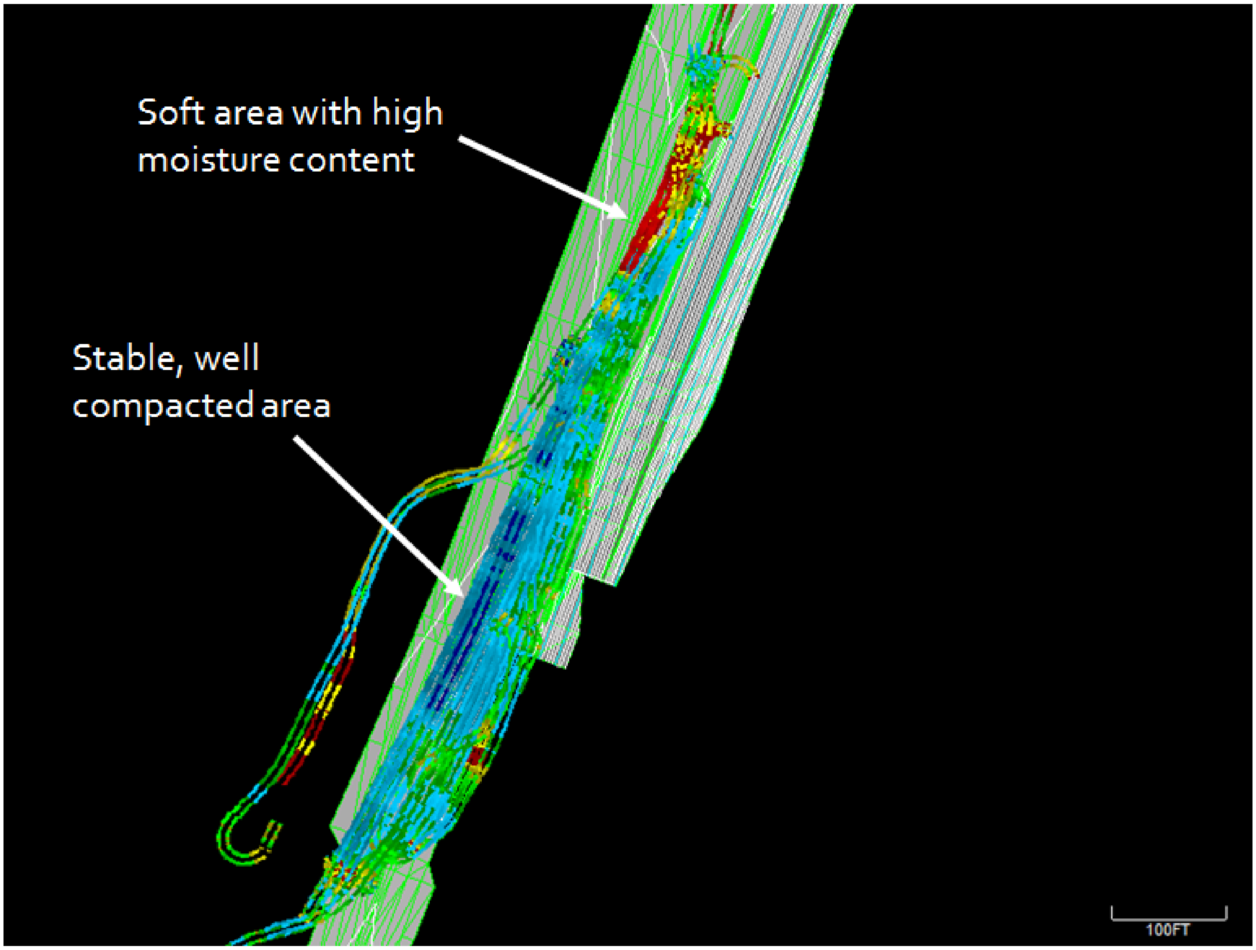
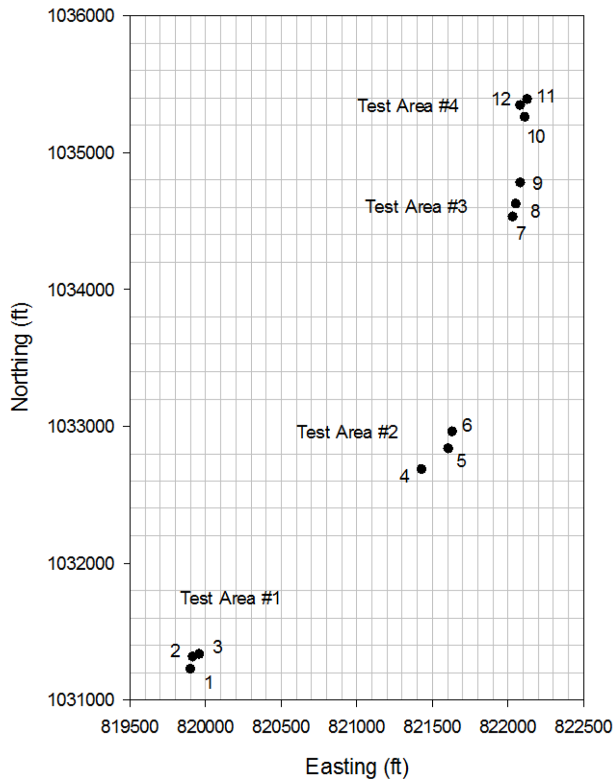


Figure 581: Results from test area #11 showing soft area related to high moisture content



300 mm plate load test setup

Figure 62: GPS location and PLT test setup to calibrate 815F roller

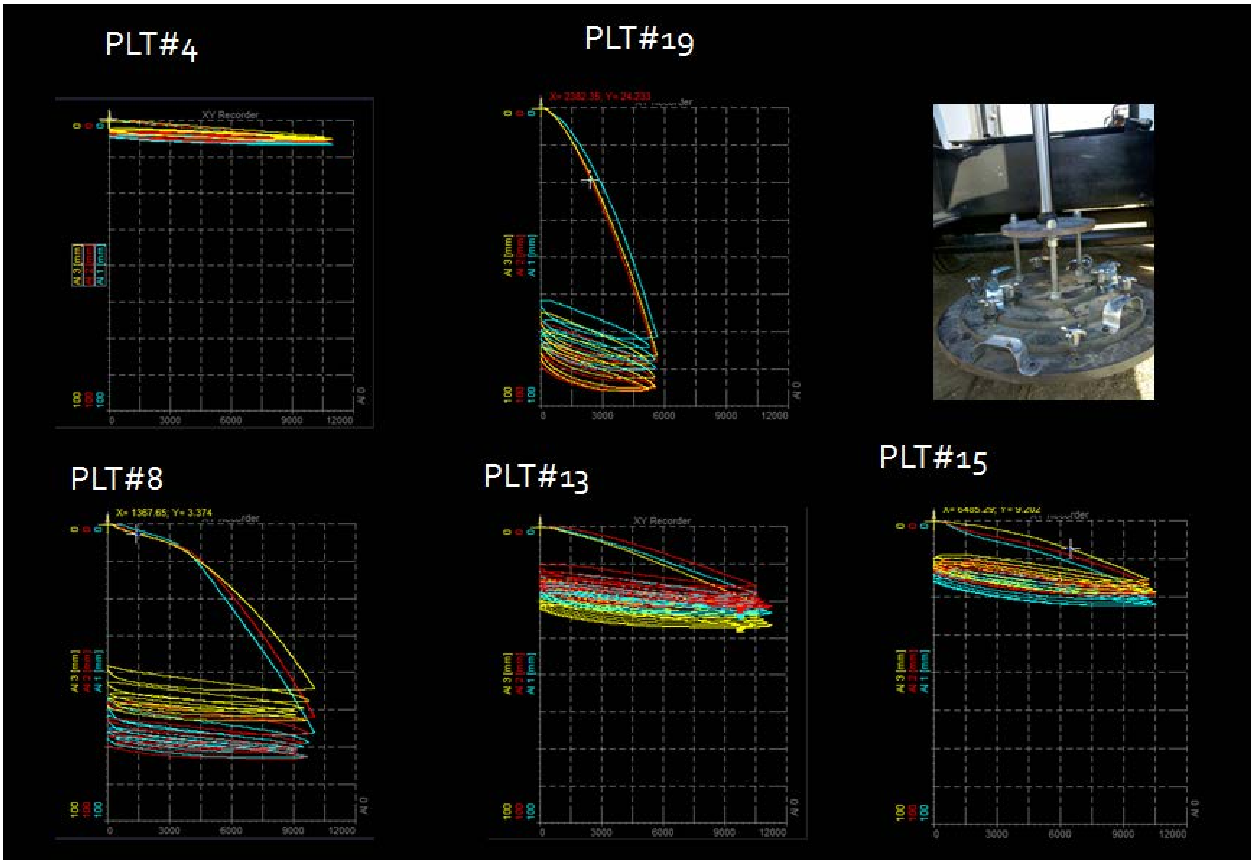


Figure 63: PLT test measurements used in calibration of 815F roller

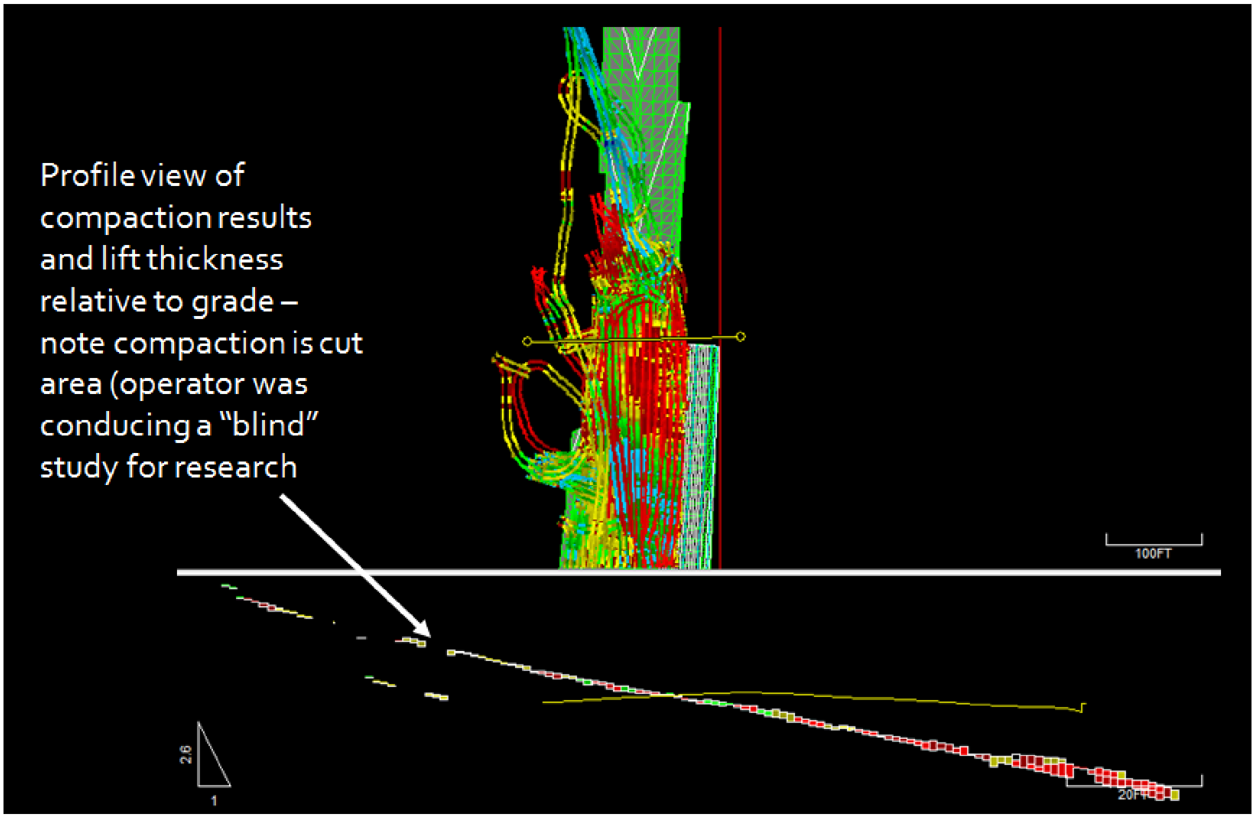


Figure 594: MDP IC-MV results for 815F in test area #8

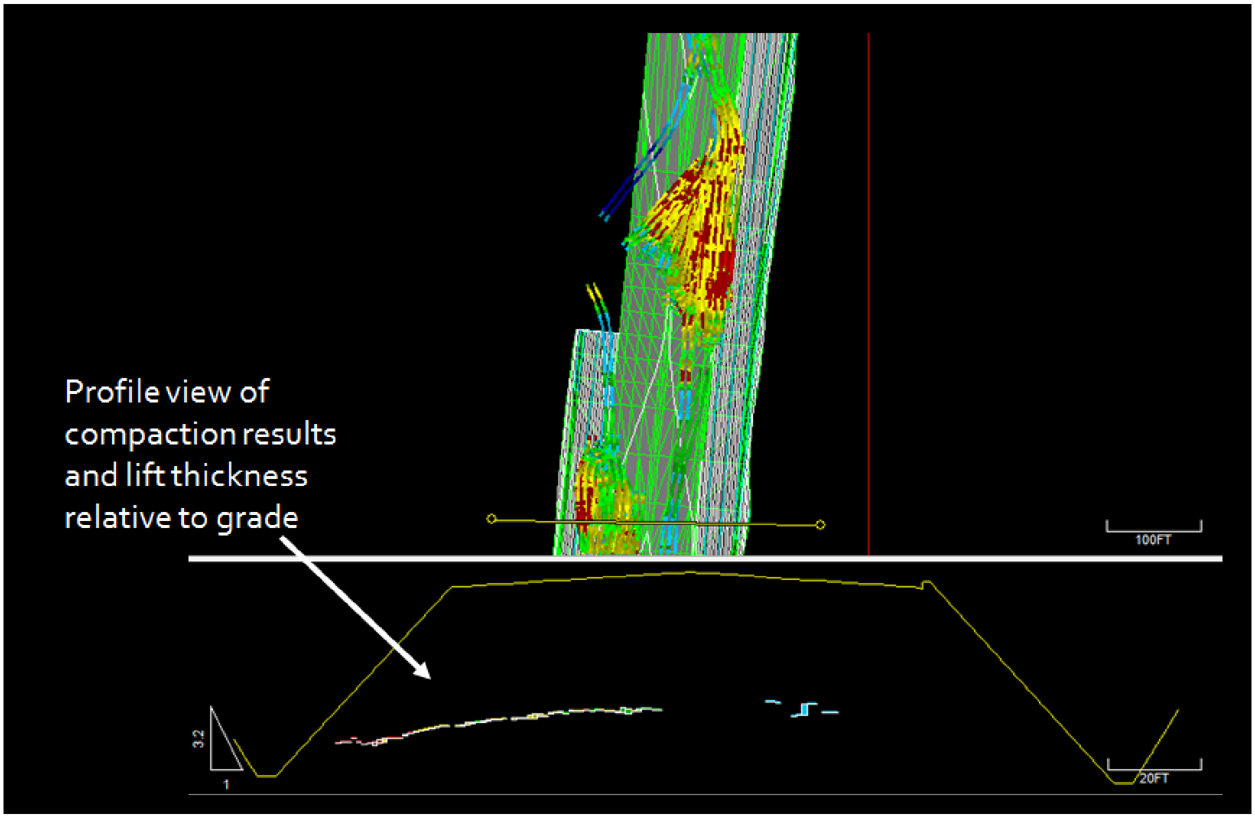


Figure 605: MDP IC-MV results for 815F in test area #11

Figure 616: Loaded dump truck for traditional proof roll to determine rut depth

Figure 67: Test area #2—significant rutting

Figure 68: Test area #2—rut measurement

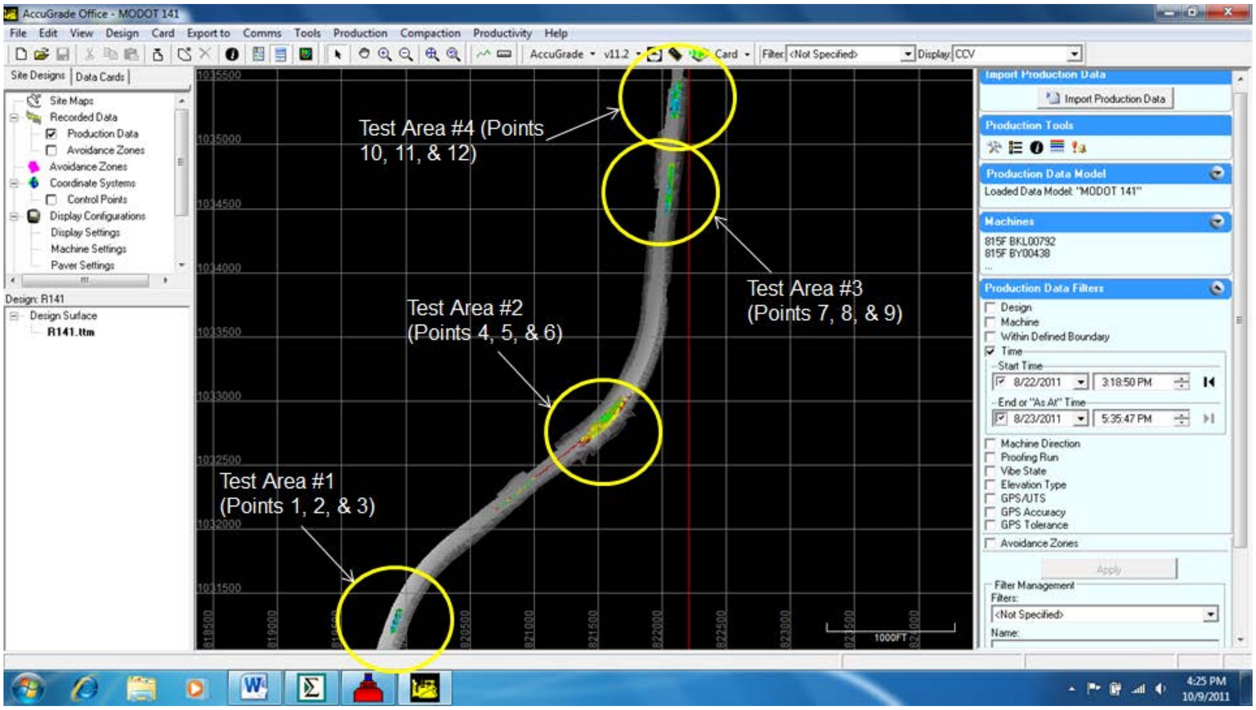


Figure 69: Project level proof mapping with 815F IC Roller

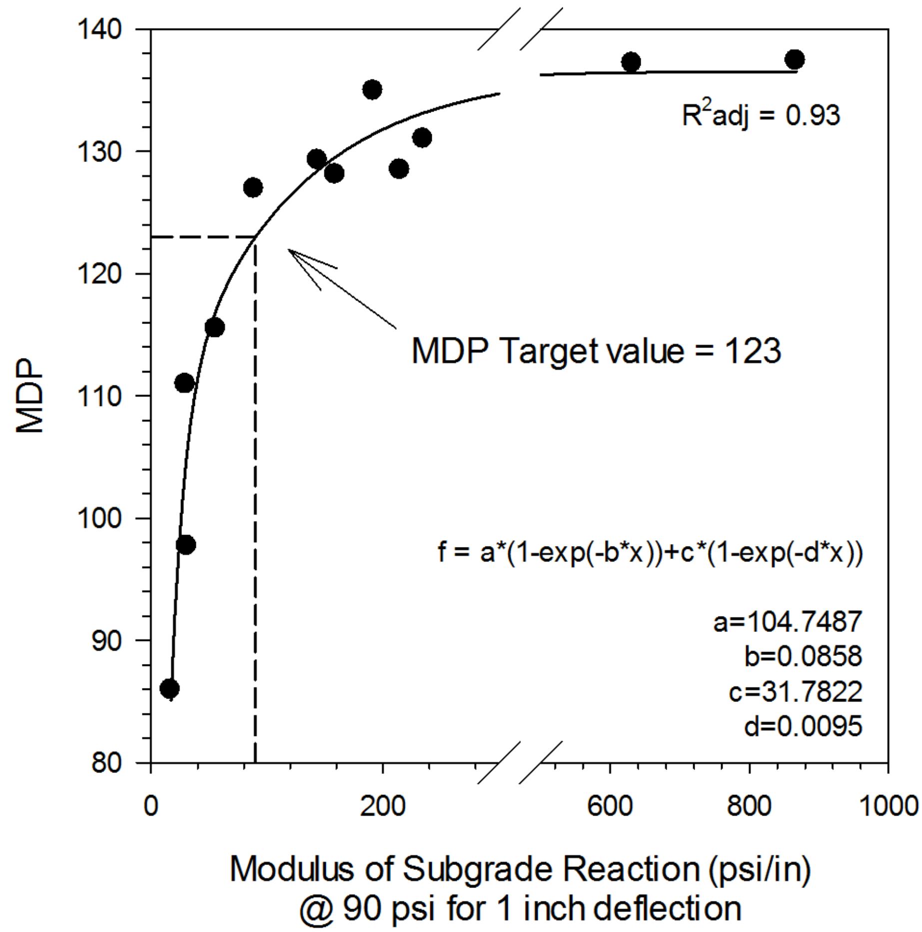


Figure 620: Correlation analysis for 815F impact roller for plate load test modulus of subgrade reaction

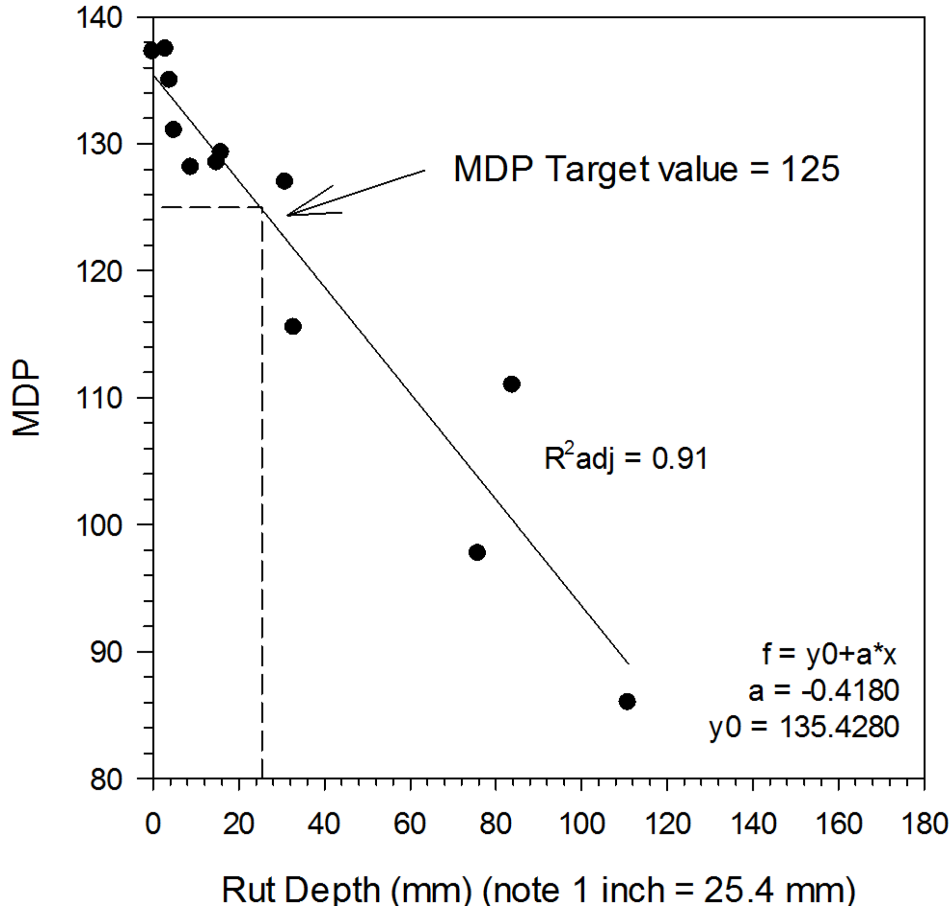


Figure 1: Correlation analysis for 815F impact roller for proof rolling rut depth

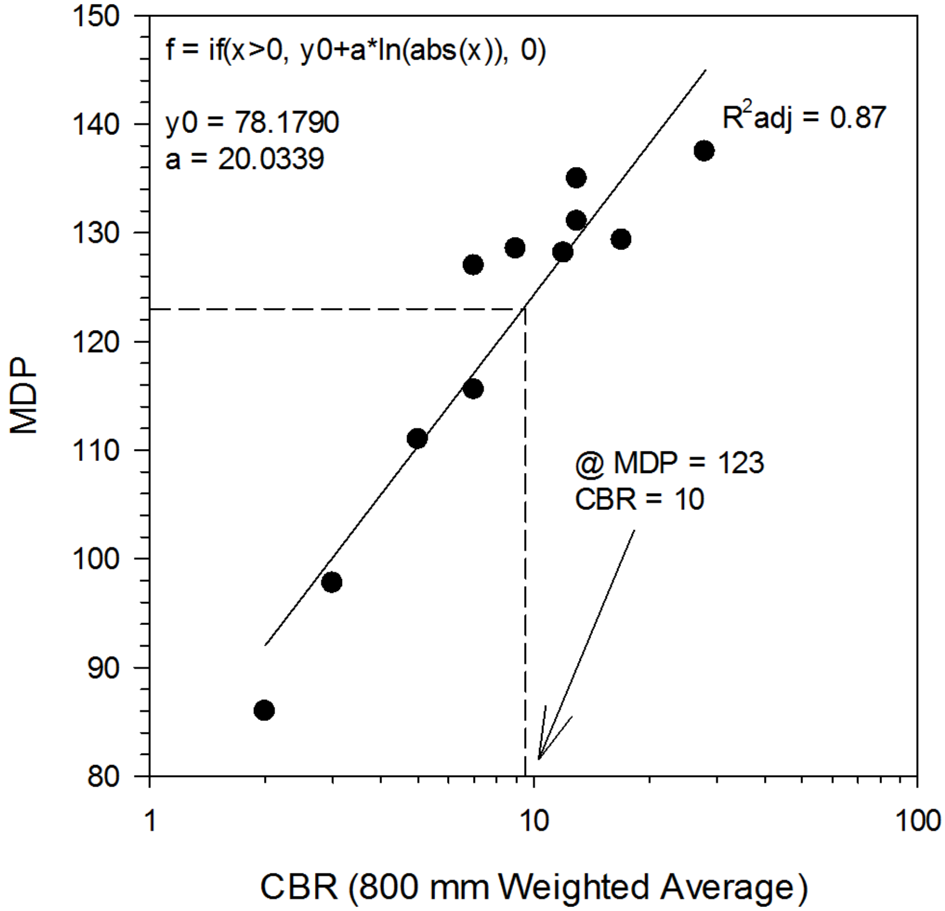


Figure 632: Correlation analysis for 815F impact roller for CBR

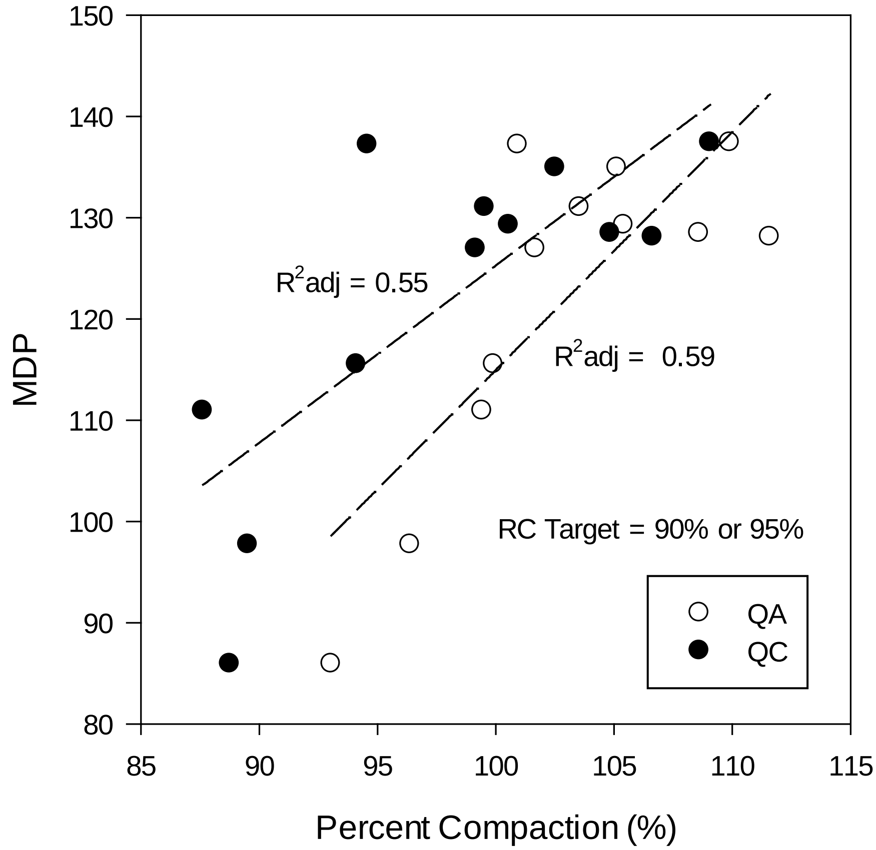


Figure 73: Correlation analysis for 815F impact roller for percent compaction

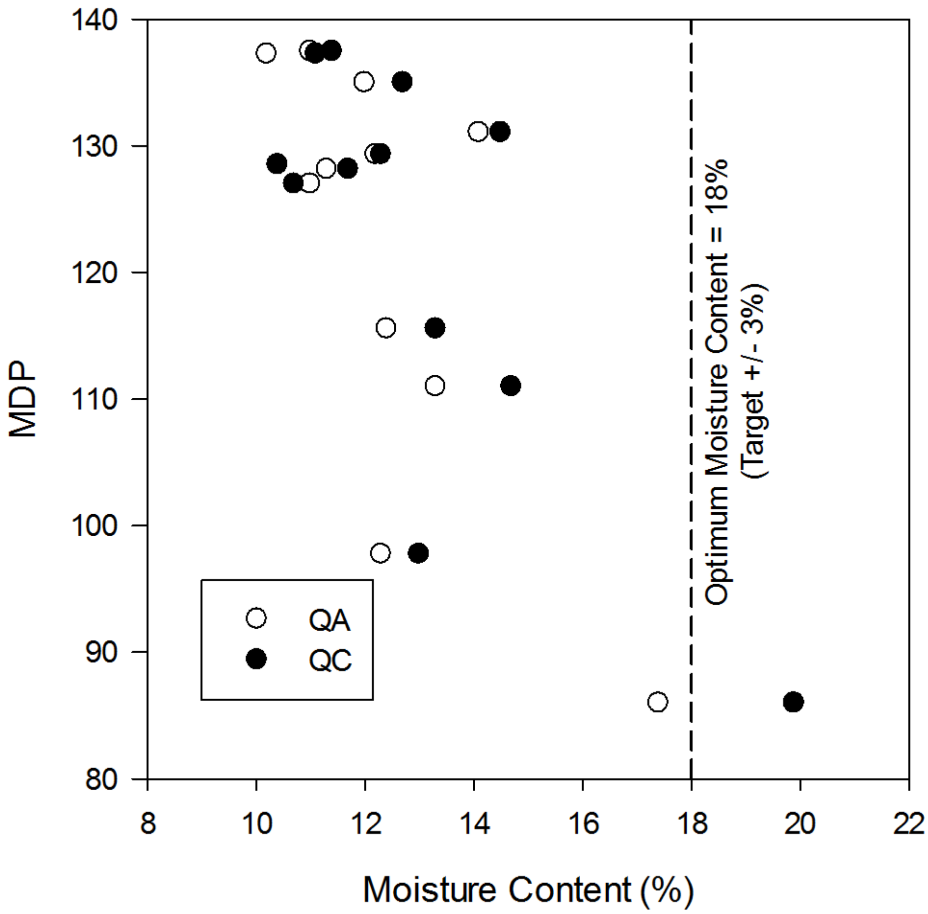


Figure 644: Correlation analysis for 815F impact roller for moisture content

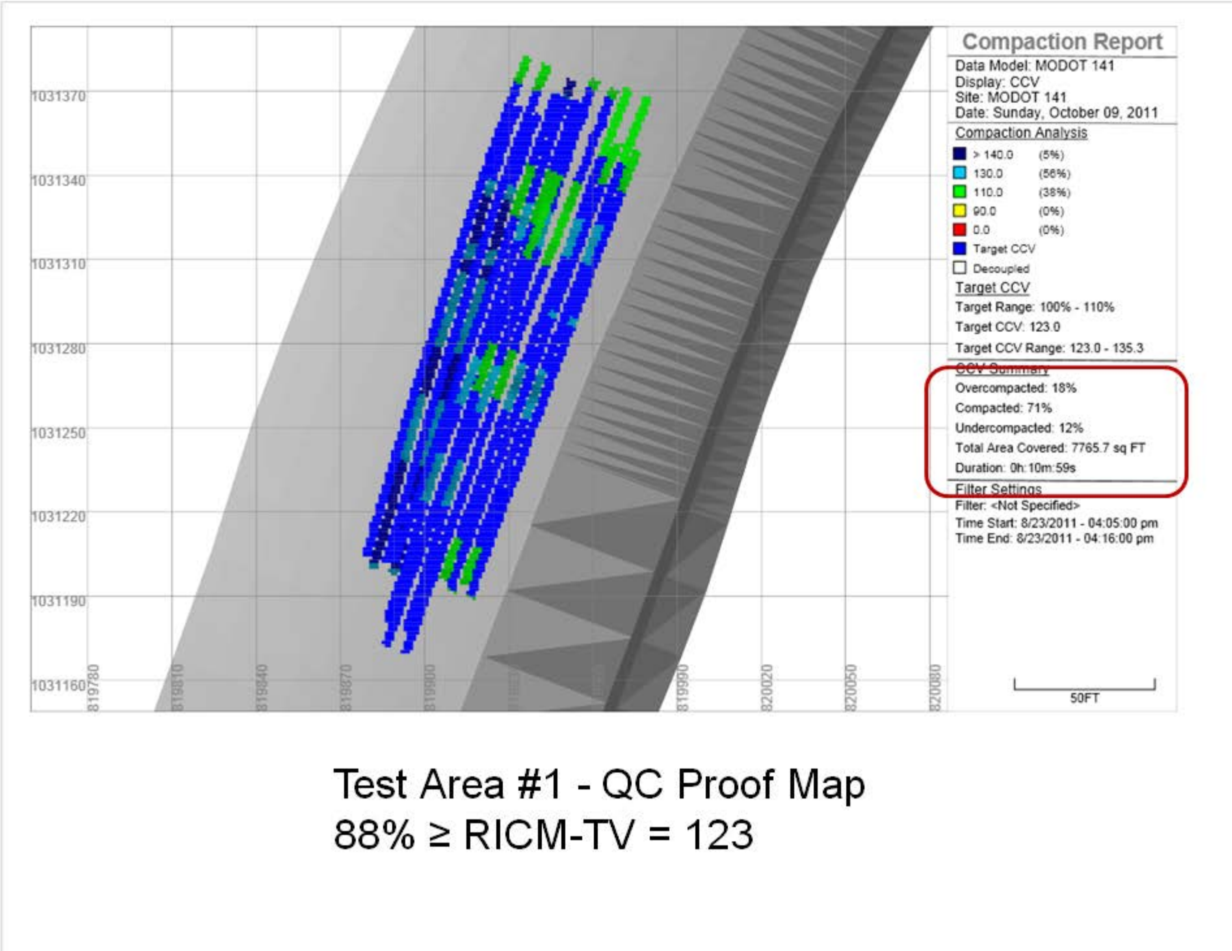


Figure 65: Production level analysis near Test Area #4 showing percentage meeting target value

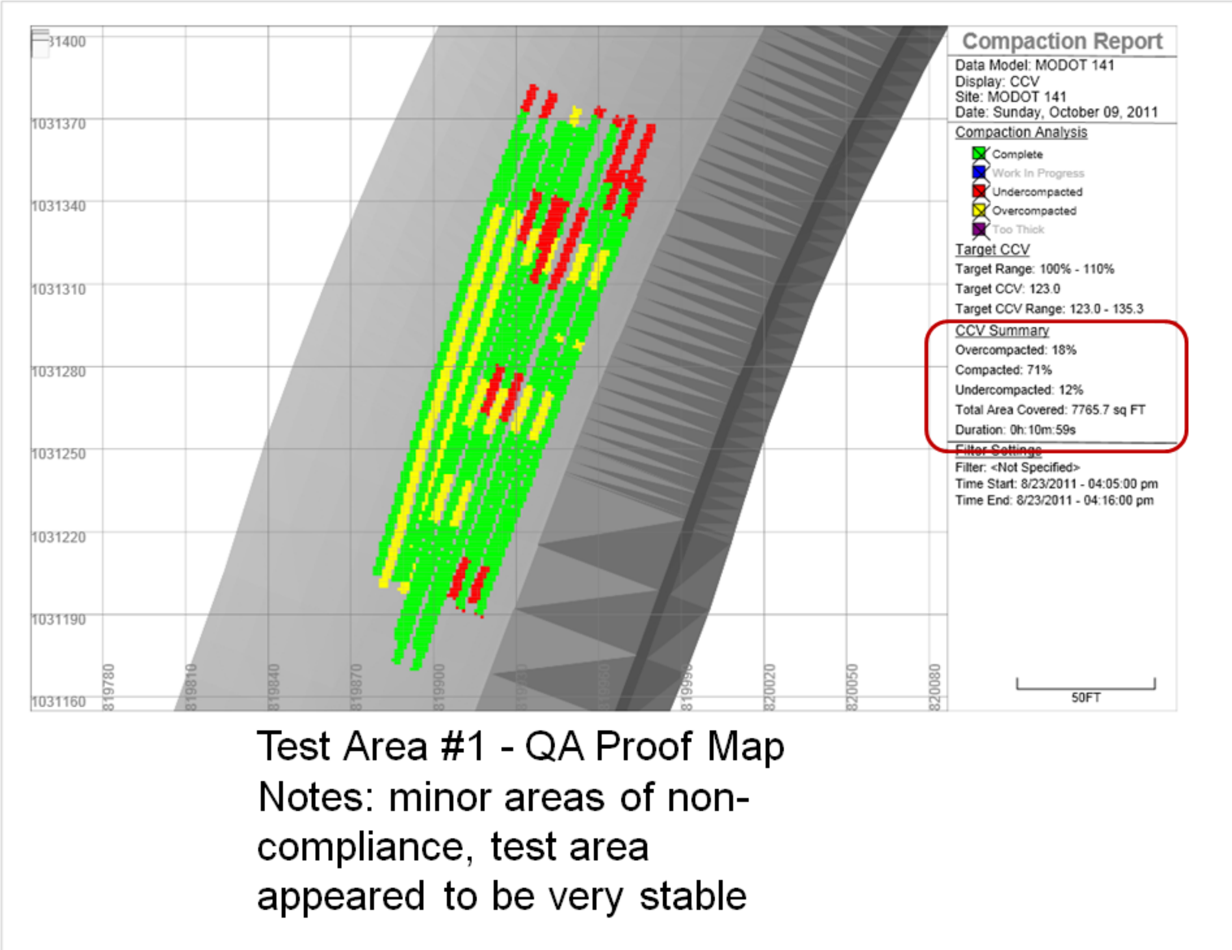


Figure 66: Production level analysis near test area #10 showing proof map with limited red areas indicating noncompliance

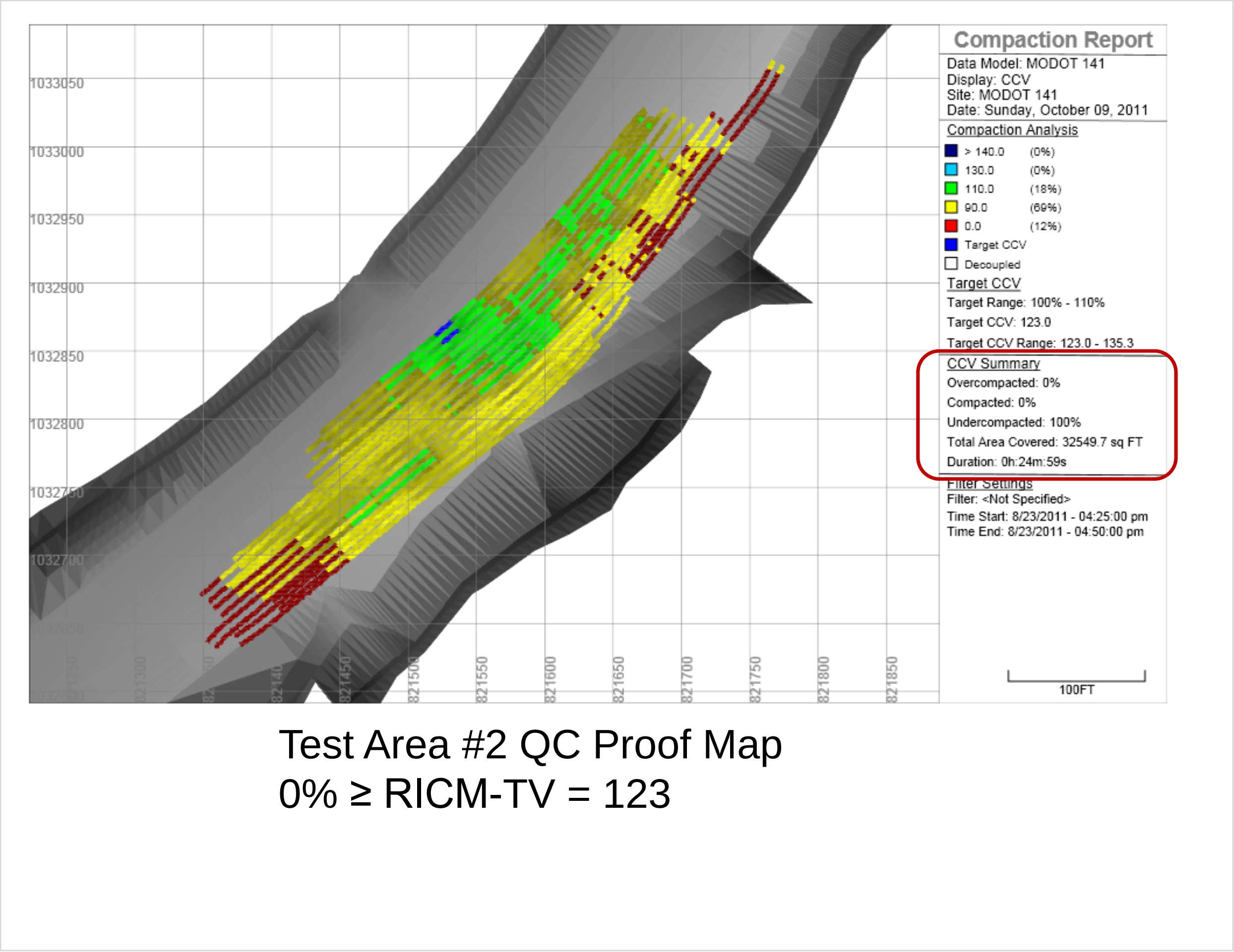


Figure 77: Production level analysis near test area #4 generally low IC-MVs

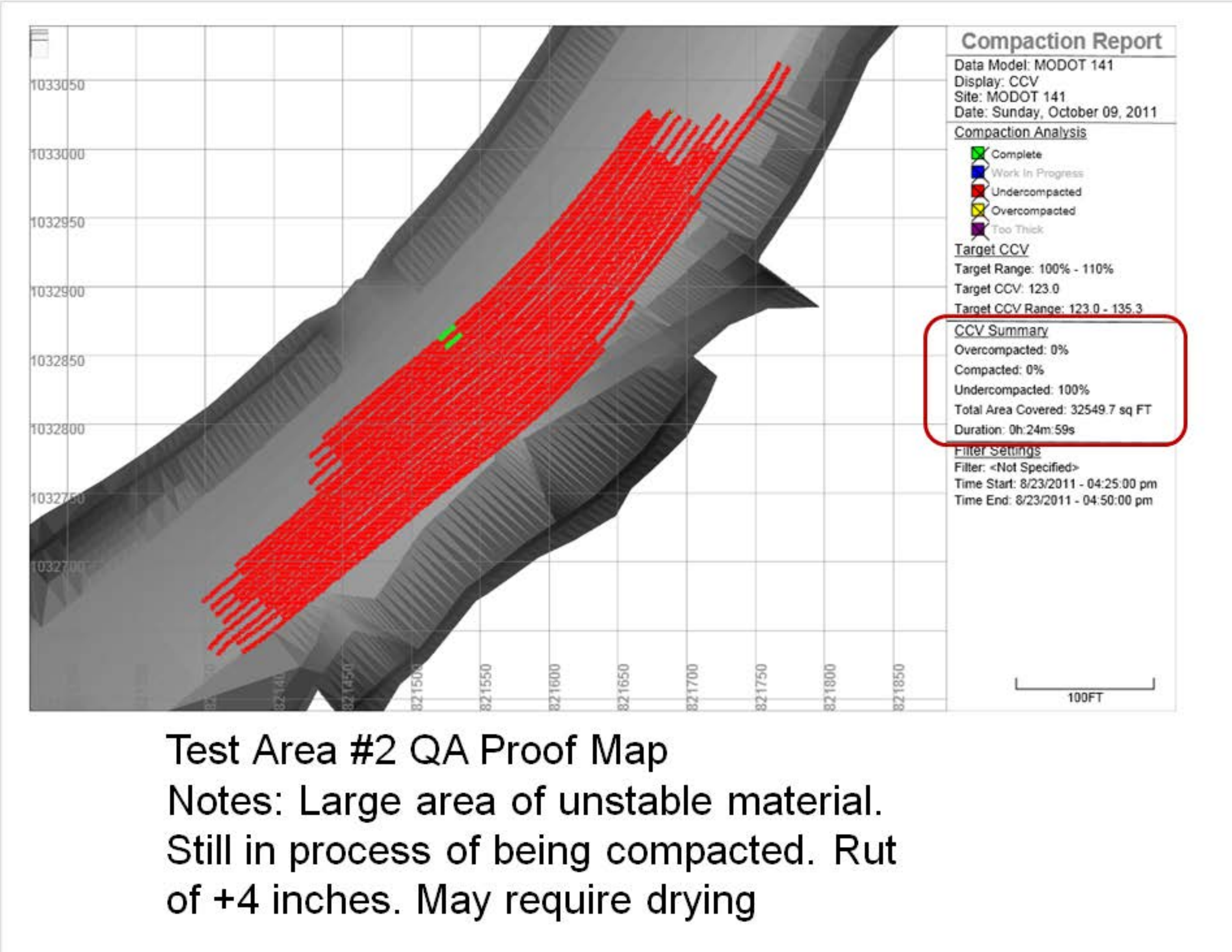


Figure 767: Production level analysis near test area #10 showing proof map with extensive red areas indicating noncompliance

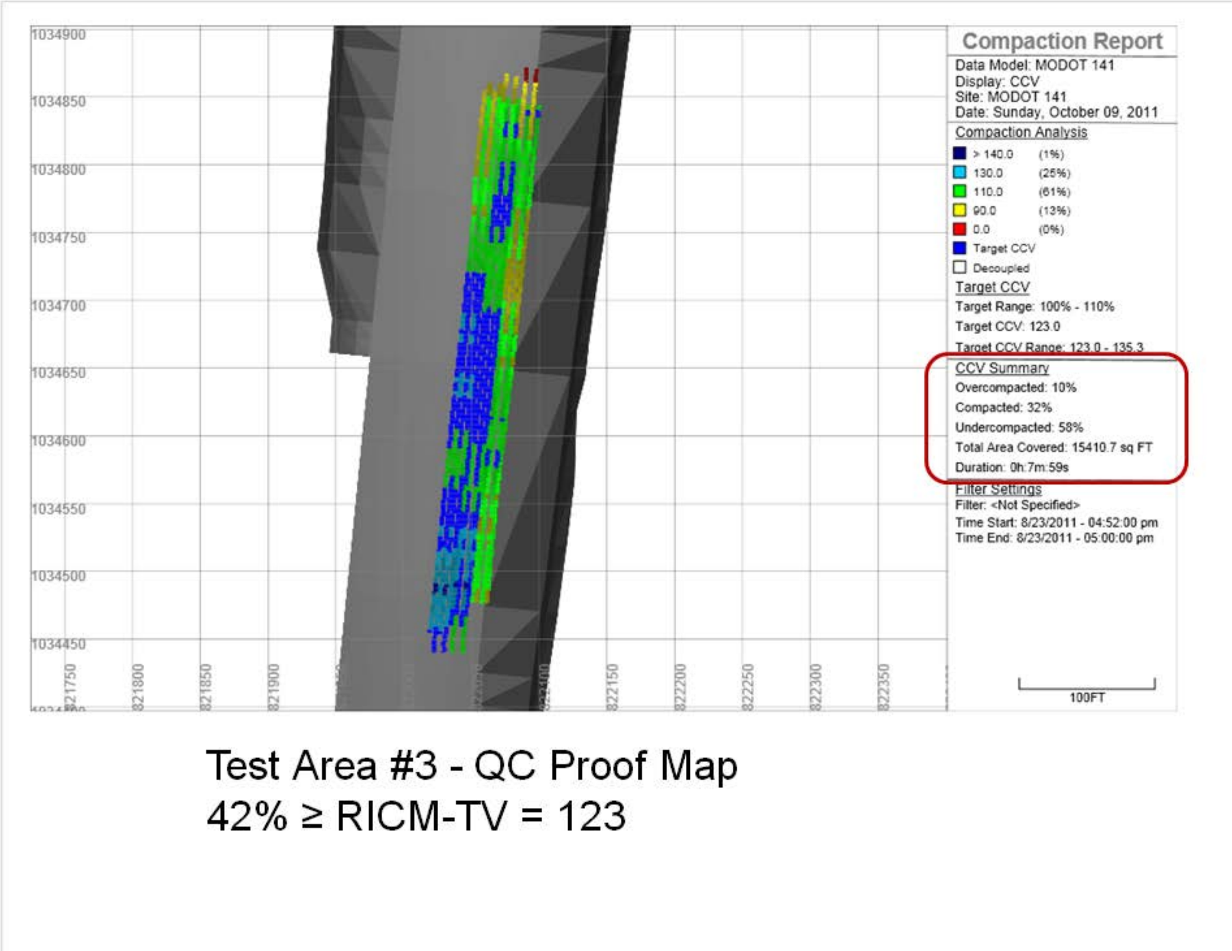


Figure 79: Production level analysis near test area #10 variable IC-MVs

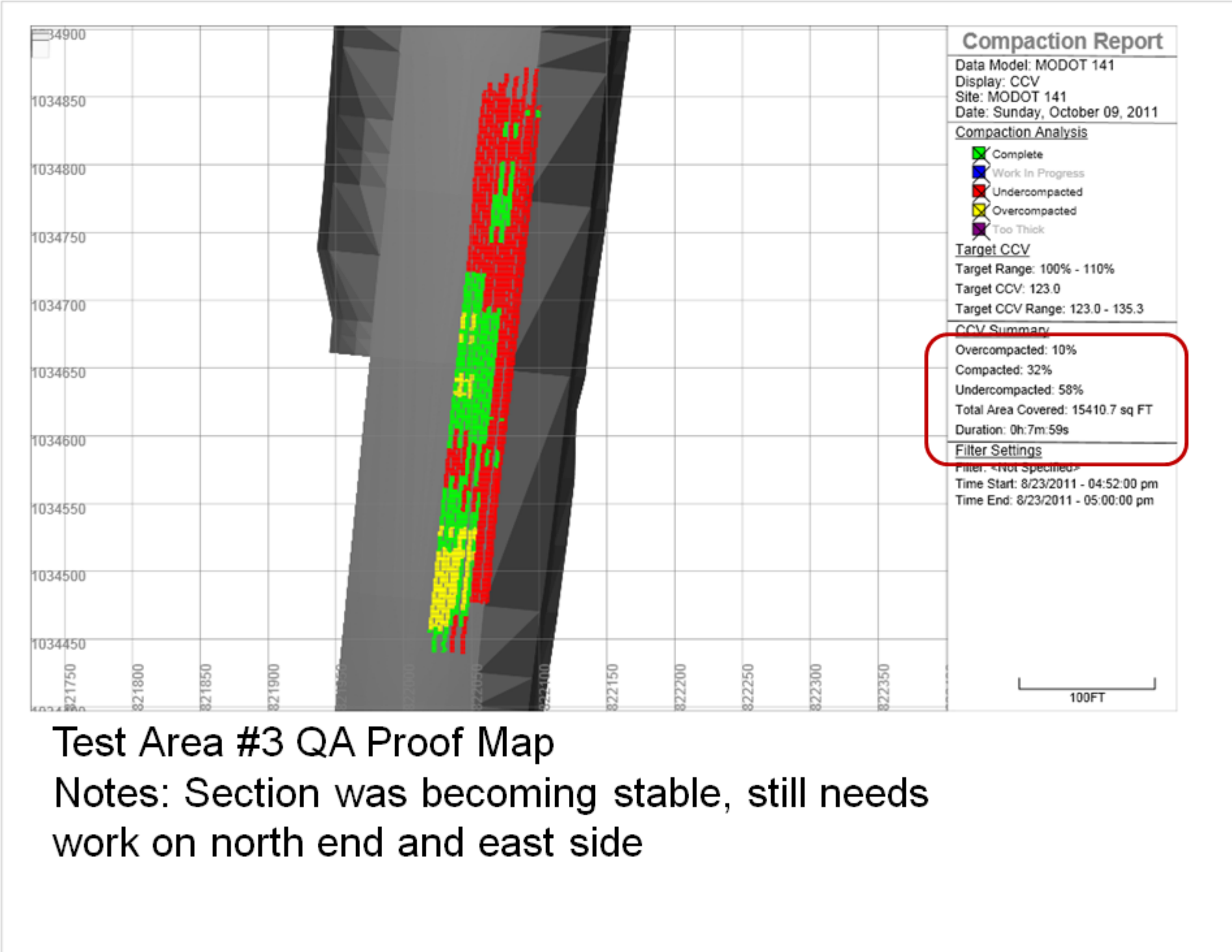


Figure 68: Production level analysis near test area #10 showing proof map with extensive red areas indicating noncompliance

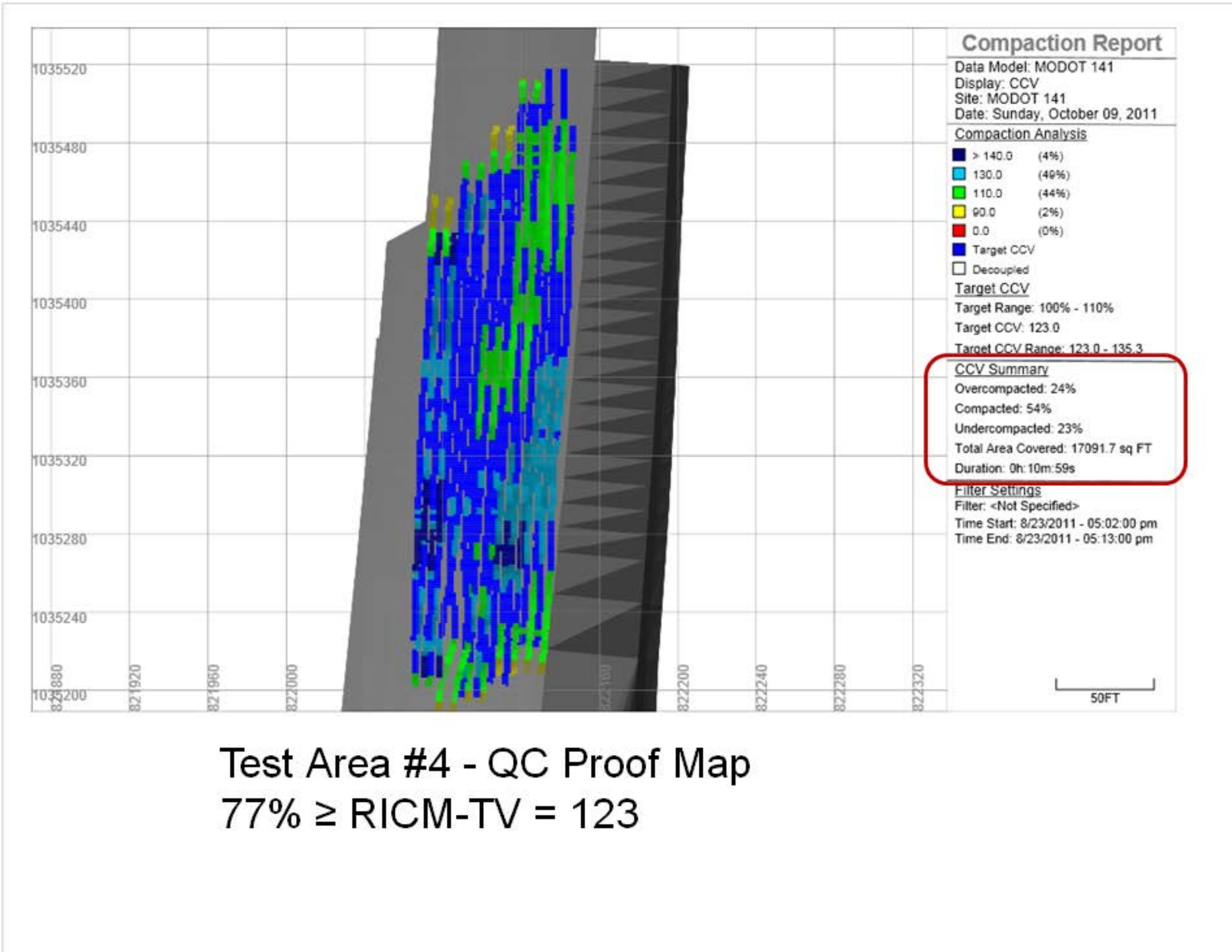


Figure 69: Production level analysis near test area #4 variable IC-MVs

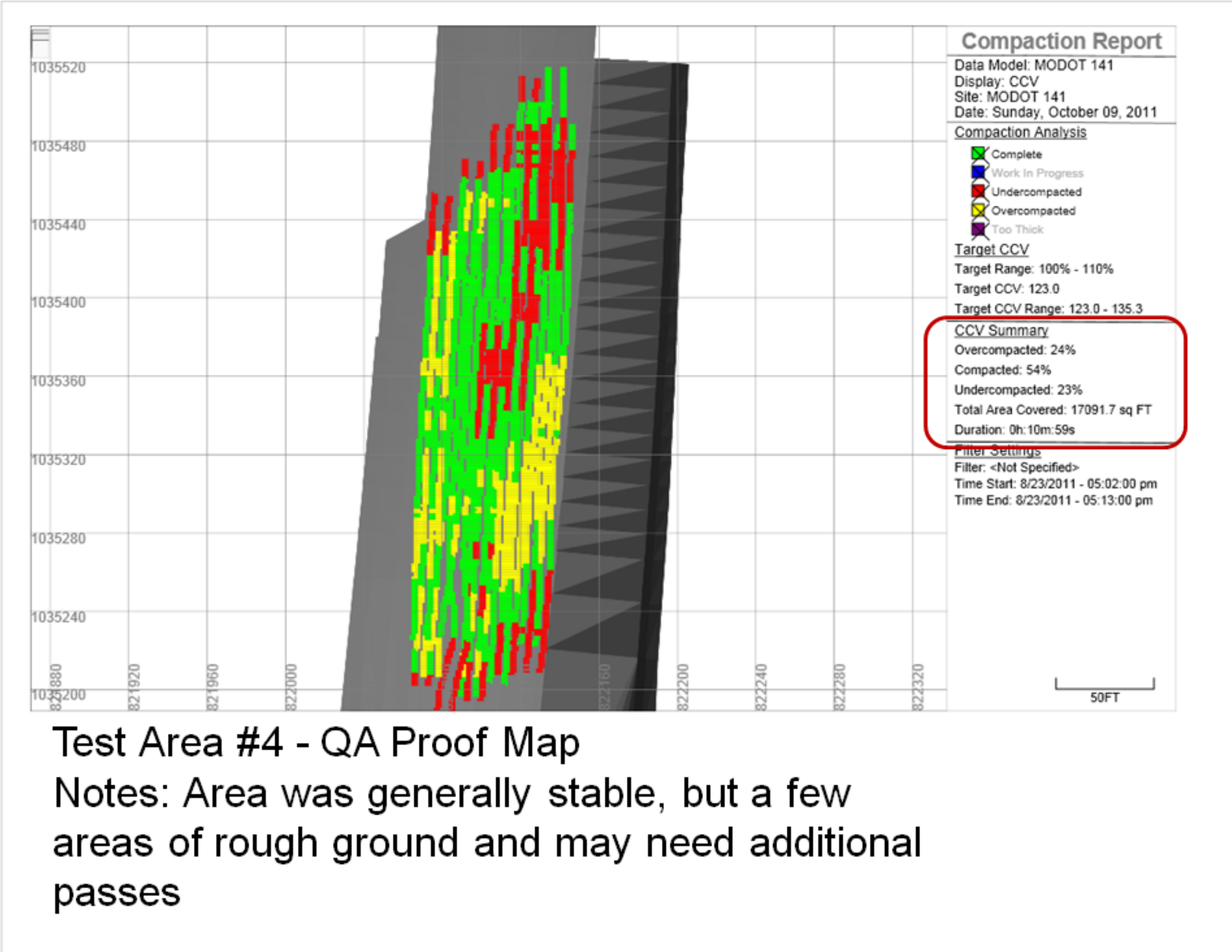


Figure 70: Production level analysis near test area #4 showing proof map with red areas indicating non-compliance

Comparison of Project Level QA/QC Results.

This project provided an excellent opportunity to analyze the measurement error of side-by-side nuclear density gauge results for QA and QC. Special effort was put into a testing plan by the inspectors to generate sufficient data to perform a statistical analysis of the results. The QA/QC data also provided the opportunity to characterize the reproducibility of results between QC and QA. Figure 83 shows the field equipment and effort to perform these side-by-side tests. Figure 84 shows the project level maps of IC values. Figure 85 shows a comparison between QA and QC in terms of wet density, moisture content, and percent compaction. All tests were performed using the direct transmission method and using the same probe penetration depth and measurement duration. Analysis of the difference between side-by-side measurements shows that the root mean square error (RMSE) of wet density, moisture content, and percent compaction for these measurements equals 4.2 pcf, 2.4% (dry soil basis), and 2.7% (relative to standard Proctor), respectively. These results should be considered when developing proper statistical analysis and sampling methods. For reference, ASTM D6938-10 presents reports a combined repeatability and reproducibility error for wet density as 0.74 pcf and 0.90 pcf for ML and CL soils, respectively, and 0.7% for moisture content for both CL and ML.

Figure 83: QA/QC operations to conduct nuclear density tests

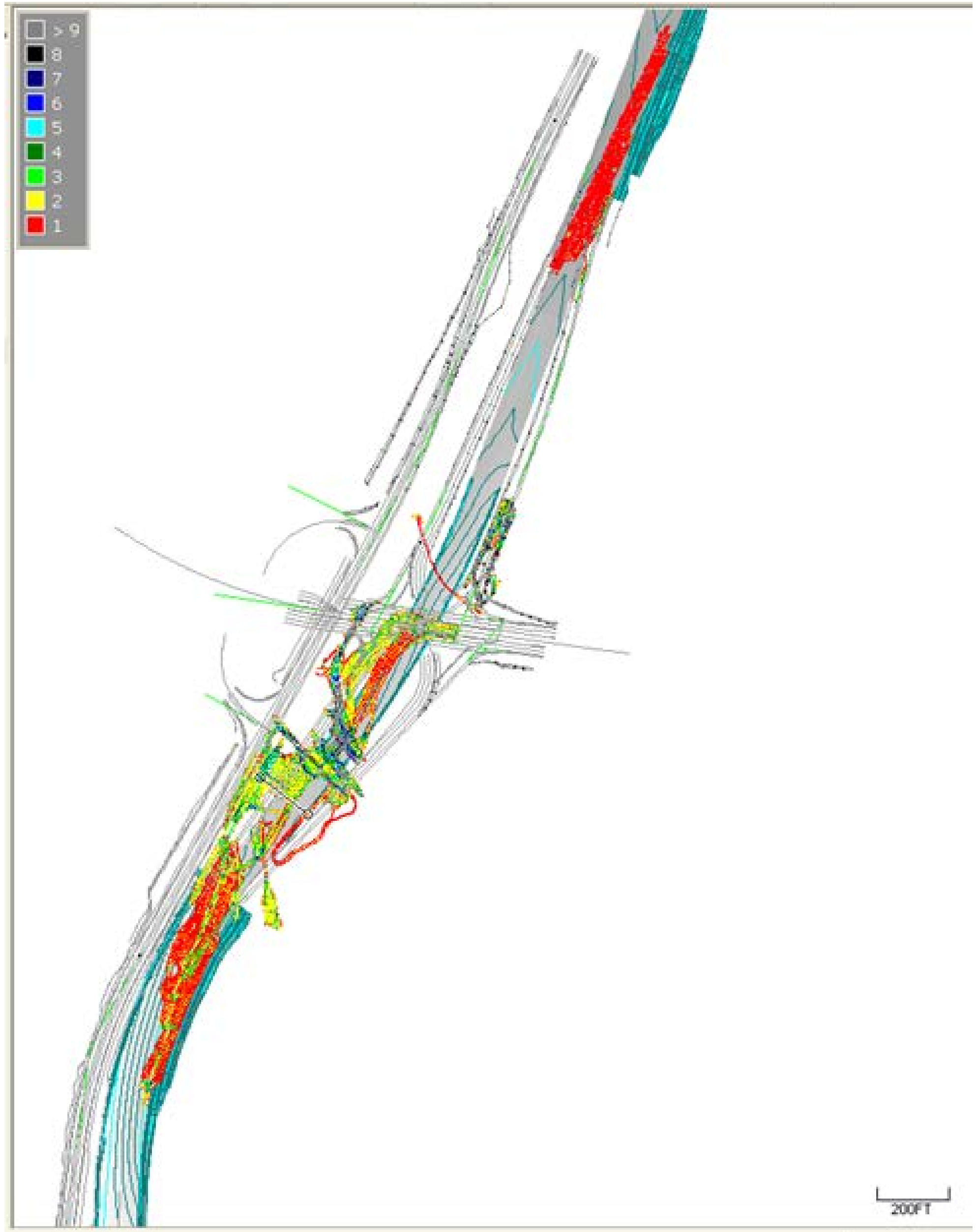
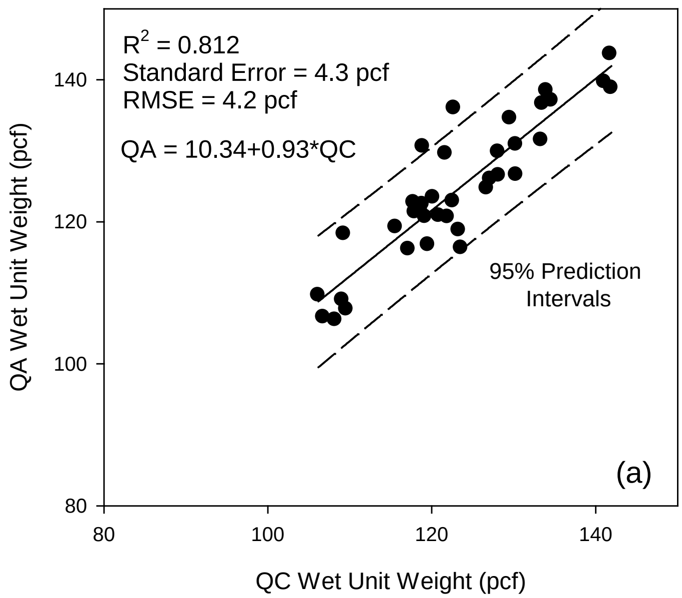
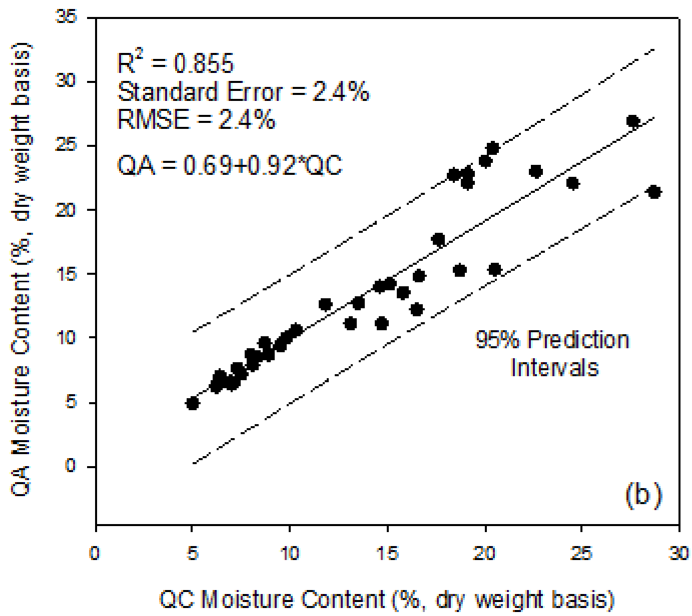


Figure 714: Overall coverage areas by CS-563E Smooth drum roller on south end of project


R^2 = 0.812
Standard Error = 4.3 pcf
RMSE = 4.2 pcf
QA = 10.34+0.93*QC
95% Prediction Intervals
(a)
QA Wet Unit Weight (pcf)
QC Wet Unit Weight (pcf)
80
100
120
140


R^2 = 0.855
Standard Error = 2.4%
RMSE = 2.4%
QA = 0.69+0.92*QC
95% Prediction Intervals
(b)
QA Moisture Content (%, dry weight basis)
QC Moisture Content (%, dry weight basis)
0
5
10
15
20
25
30
35

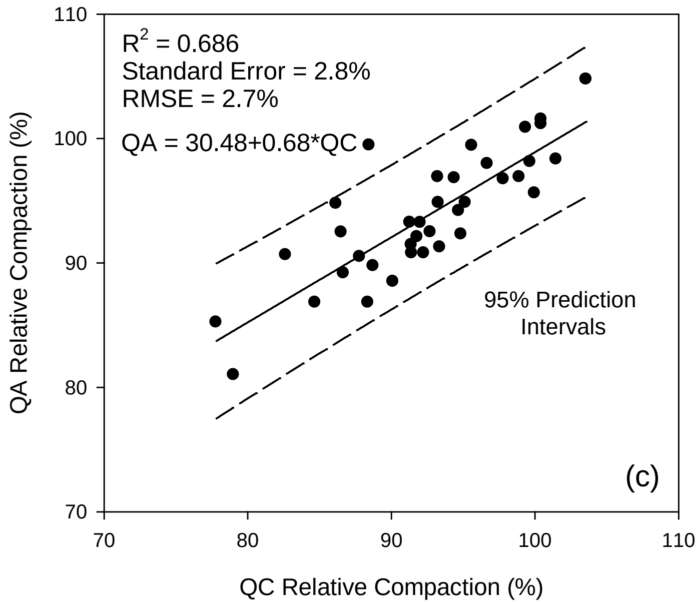


Figure 85: Comparison and calculation of standard error for QA/QC nuclear density gauge results for CS-563E test areas

Exit Interviews

On November 12, 2010, the SHRP R07 research team setup exit interviews to gain knowledge of how QC/QA field personnel and roller operators involved viewed the use of IC technology and alternative in situ testing technologies. The following captures the results of the interview.

Questions:

1. What is your experience/impression of using the IC equipment to date?
2. How do you see the IC information being used in a Q/C plan?

Dave Dwiggins: 815 operator for Fred Weber Inc.

1. I like the technology. It helps me know where to focus where more compaction work is needed as well as knowing when it is good.
2. It could speed up operations by not having to guess on what is going to pass.

Ross Adams: Roadway Superintendent for Fred Weber Inc.

1. I like the concept if the results correlate with the acceptance criteria.
2. It could eliminate nuclear tests on the contractors Q/C plan.

Nancy Leroney: Project inspector for MoDOT

1. Neat thing to be involved with new tests. I find it very interesting.
2. It could save time and money by knowing when the soil passes. I would love to eliminate the nuclear testing.

Lashonda Neal: ABNA Engineering-QC Inspector

1. Great learning experience with the new technology and approaches. I liked being part of the whole experience.
2. It could save time. With the nuclear test you actually test a very small area versus the larger area with the new tests being demonstrated.

Dan Gruen: 563 operator for Weber Fred Weber Inc.

1. Good experience. Good to know what compaction results are as you roll. A nuclear test could pass and a short distance away could fail.
2. The IC roller could replace Q/C nuclear testing. Also with the IC roller you can test the rock backfill at the MSE walls which is not tested now.

SUMMARY AND CONCLUSIONS

Results from a field study conducted on the Hwy 141 project in Chesterfield, MO in 2010 and 2011 are presented in this report. The project involved evaluating a Caterpillar CS-563E smooth drum and a Caterpillar 815F impact roller. Several test areas were evaluated using the intelligent compaction systems in materials including silty clay embankment fill and, type 5 aggregate subbase, and MSE wall backfill. Test areas involving calibration and production operations were constructed by obtaining IC-MVs in conjunction with various in-situ point-MVs. IC-MVs maps on the on-board computer display unit were utilized in selecting field QA test locations in production areas.

Results obtained from various test beds contributed to developing empirical relationships between IC-MVs and various in-situ point-MVs. Empirical correlations between IC-MVs and different point-MVs sometimes showed weak correlations when evaluated independently for each test bed, because of the narrow measurement range. The correlations improved when data are combined for site-wide correlations with a wide measurement range. IC-MVs generally correlated better with modulus based in-situ point-MVs (i.e., E_{LWD-Z3}, E_{FWD-K3}, E_{V1}, and E_{V2}) and CBR point MVs than with dry density point-MVs. Correlations between IC-MVs and E_{FWD-K3}, and IC-MVs and E_{V1} showed strongest correlation coefficients.

The results for the IC-MV mapping operations were as follows:

- RICM Target Value (MDP) = 123. MDP = 123 is correlated to CBR = 10 based on 800 mm (32 inch) weighted average. Correlations to rut depth and modulus of subgrade reaction confirmed the target value.
- Based on the project conditions, it IC criteria was changed from 90% of coverage area ≥ RICM-TV to 80% ≥ RICM-TV in the specifications.
- The CS-563E IC system setup with RTK-GPS provided useful information to determine lift thicknesses and pass coverage.
- Lift thickness and pass coverage are generally highly variable for earthwork construction operations, without using IC measurement systems.
- Allowing the operators to use the on-board display improved the uniformity of pass coverage.

- The IC-MVs can be correlated to rut depth from proof rolling, modulus of subgrade reaction from plate load testing, and CBR profiles from DCP testing. The k-values determined from plate load test provide highest degree of correlation to RICM-MVs ($R^2 = 0.93$). RICM-TV analysis for plate load testing and actual rut depth measurements produced similar results.

- Areas of non-compliance based on the IC maps were primarily areas of high moisture content.

- The RICM-MVs are not well correlated to percent relative compaction or moisture content, particularly compared to percent compaction from nuclear moisture-density gauge testing.

- Comparison between QC/QA nuclear moisture-density test results were used to quantify the reproducibility measurement error.

- The results from this study provided new information with application of IC-MVs in conjunction with various QA test devices on cement treated subgrade and base materials, which to the authors' knowledge, has not been previously documented in the United States. The study demonstrated several potential advantages of implementing IC roller operations and various in-situ testing methods into earthwork construction QC/QA practice.

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