INTELLIGENT COMPACTION BRIEF February 2012

Minnesota TH64–Unbound Materials–Summer 2006

PROJECT DATE
Summer 2006

RESEARCH PROJECT TITLE
Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials

SPONSOR
Minnesota Department of Transportation
Federal Highway Administration

PRINCIPAL INVESTIGATOR
David J. White, Ph.D.
Assoc. Prof. and holder of Wegner Professorship, Civil, Construction, and Environmental Engineering,
Iowa State University
515-294-1463
djwhite@iastate.edu

RESEARCH TEAM
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Mark J. Thompson, Ph.D.

AUTHORS
David J. White, Ph.D.
Pavana KR. Vennapusa, Ph.D.
Department of Civil, Construction, and Environmental Engineering
Center for Earthworks Engineering Research

MINNESOTA DOT CONTACT
John Siekmeier, P.E.
Minnesota Department of Transportation
Office of Materials and Road Research,
MS 645 1400 Gervais Ave., Maplewood,
MN 55109-2044
651-366-5417
john.siekmeier@state.mn.us

MORE INFORMATION
http://www.ceer.iastate.edu/research/project/project.cfm?projectID=724838391

This document was developed as part of the Federal Highway Administration (FHWA) transportation pooled fund study TPF-5(233) – Technology Transfer for Intelligent Compaction Consortium (TTICC).

CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

IOWA STATE UNIVERSITY
Institute for Transportation

Introduction

This document summarizes the intelligent compaction (IC) specification and field results from the TH 64 reconstruction project near Akeley, Minnesota in summer 2006. Full details of this project are presented in White et al. (2007, 2008). To the authors' knowledge, this was the first earthwork project in the United States to require IC technology (White et al. 2008). In this study, in-situ point measurement values (point-MVs) of dry unit weight, moisture content, dynamic cone penetration index (DCP Index), and light weight deflectometer (LWD) modulus are compared with the roller-integrated compaction meter value (CMVs) obtained from a Caterpillar CS-563 vibratory smooth drum roller. Except for measuring soil moisture content, the IC technology applied to the roller was the principal method for quality control (QC). Test rolling on proof sections was used for final quality acceptance (QA). In the end, the IC specification was successfully implemented and all sections of the project passed the final QA test rolling criteria. Beyond the requirements for the specification, IC and point-MVs were collected and compared to assess the relationships between the various measurements and also to examine the variation observed for the measurement parameter. Further, a geodatabase using ArcGIS modules was created for demonstrating the approach of managing large quantities of IC and point-MVs. Applying geostatistical methods in the analysis of IC data was also investigated.

Project Details

The project comprised of widening and reconstructing 10 km of an existing alignment south of Akeley, MN. Compaction was performed using the CS-563 vibratory smooth drum roller with CMV technology that incorporated variable feedback amplitude control. Several in-situ tests were performed beyond that required by the specification to generate a data set for analysis. Fill material comprised of poorly graded to well-graded sand with silt (classified as A-1-b to A-3).

IC Specification Summary

The pilot specification implemented on this project was written to require use of IC technology as the primary quality control (QC) tool (Mn/DOT 2006). The contractor was required to develop and detail a QC procedure (i.e., anticipated number, pattern and speed of roller passes, potential corrective actions for non-compliant areas, etc.) that incorporated IC-MVs gathered from control (or calibration) strips. Following control strip construction, proof layers (production areas) were constructed. For proof layers, the engineer observed the final IC recording pass, reviewed and approved the QC data, performed companion and verification moisture content testing, and observed test rolling results to ensure compliance (less than 50 mm rut under wheel of 650 kPa (95 lb/in2) tire pressure). The following key attributes are included in the pilot specification: (a) equipment specifications, (b) control strip construction, (c) QC/QA requirements, (d) and documentation requirements.

Each control strip was at least 100 m (300 ft) x 10 m (32 ft). Thickness was equal to that of the planned granular treatment thickness being constructed (maximum 1.2 m (4.0 ft)). One control strip was constructed for each different type/source of grading material used on the construction site. Optimum compaction on control strips was reached when the engineer determined that additional compaction passes did not result in a significant increase in IC-MVs. IC target values (IC-TV) for all proof layers were obtained from a control strip representative of the proof section. All proof areas were to be compacted such that at least 90% of the IC-MVs were at least 90% of the IC-TV prior to placing the next lift. If localized areas had IC-MVs of less than 80% of the IC-TV, the areas were to be re-compacted. If a significant portion of the grade was more than 30% in excess of the selected IC-TV, the engineer re-evaluated the IC-TV. Moisture content was specified to be 65%–100% of standard Proctor optimum. Control strips constructed at moisture content extremes were allowed to be used to develop a linear IC-TV correction trend line.

Caterpillar CS563 IC System

Caterpillar used a Geodynamik compaction measurement device that measures compaction meter value (CMV) and resonance meter value (RMV). CMV technology uses accelerometers installed on the drum of a vibratory roller to measure roller drum accelerations in response to soil behavior during compaction operations. CMV can be calculated as (Sandstrom and Pettersson 2004):

where C = constant (normally about 300), A1 = acceleration of the first harmonic component of the vibration, and A0 = acceleration of the fundamental component of the vibration. The RMV gives a measurement of the degree of double jump that the vibratory drum is experiencing and provides a means for automatic feedback control (AFC) of amplitude. The RMV is calculated as (Sandstrom and Pettersson 2004):

where A0.5 = amplitude of half the fundamental vibration frequency. As a means to prevent double jump which can decompact the soil, the roller for this project was programmed by the manufacturer to decrease amplitude of the vibrating drum when roller RMVs approached 17. After the roller RMV was reduced to a sufficiently low level, the amplitude was increased until the roller RMV approached 17 at which time the amplitude was decreased. In this way, the compactor was always attempting to operate at a high amplitude. A secondary means of amplitude control was setting a maximum amplitude value and operating in the manual mode. Frequency was not changed with the amplitude.

Analysis and Comparison of IC and Point-MVs

Establishing IC-TVs from Control Strips

Prior to production soil compaction, control sections were constructed to determine target values for CMV. Separate control sections were constructed and tested for the different types of fill sections of the project (e.g. 0.25 m or 1.1 m subcut). A total of five control strips were constructed for this project with IC-TVs of 35, 42, 45, 52, and 60. For establishing the IC-TVs based on CMV data, an iterative method was adopted. Following each roller pass over the control section, the data were grouped into the following pre-defined tolerance bins: < 70%, 70 to 80%, 80 to 90%, 90 to 130%, and >130% of the trial IC-TV. The target value was adopted as quality criteria when the distribution of the data in the five bins met the specification criteria of 90% of the data exceeding 90% of the target value. An example of this process with results from a control strip constructed to establish the target value for a 1.1 m subcut section is shown in Figure 1a. The CMV compaction curve for this control section is shown as a box plot. Based on the distribution of CMV, little compaction was observed following the third roller pass. At seven roller passes, the target value was set at 42. For another control strip with a 0.25 m subcut, significantly high CMV distributions with IC-TV = 60 (Figure 1b) at 11 roller passes. It was determined that this value was unreasonably high compared to a similar section which showed IC-TV = 35 but was not subjected to the extensive off road dump truck and scraper traffic. This experience provided evidence of the benefit of managing the equipment fleet to aid in the compaction process that largely goes undocumented without the application of IC. Measurement and documentation provides a significant benefit to contractor interested in process control and optimizing fleet management.

Analysis of IC Measurement Variability and Influence of Vibration Amplitude

To understand the influence of different operating conditions on IC-MVs and to document variability over a longer distance (2.7 km) the roller was operated over several proof areas previously test rolled and accepted. The roller was operated in manual mode at nominal amplitude of 0.7 mm while heading north. The AFC mode was used from STA 178.5 to 179.7 and from STA 230.8 to 232.2. The roller was also operated in manual mode with nominal amplitude of 1.1mm while heading south along the same travel path. The AFC mode was used from STA 178.2 to 180.1 and from STA 197.9 to 198.7 and higher amplitude of 1.4 mm from STA 240 to 250. The roller data for this test section are shown in Figure 2.

Comparing results of CMV (Figure 2) obtained in the manual mode at different amplitude settings shows that the CMV values were dependent on amplitude setting (CMVavg = 63 @ 0.7 mm amplitude and CMVavg = 67 @ 1.1 mm amplitude). For the section operated at 1.4 mm vibration amplitude the average CMV value dropped to 52, but in this case RMVs were variable and high indicative of double jump and rocking conditions. For the sections operated in AFC mode, the CMV measurements averaged 58 and the RMV measurements averaged 18 (close to the controller setting of 17). In-situ measurements were collected at 91 m (300 ft) intervals (every three stations) starting at STA 160. These in-situ measurements are overlain by CMV data in Figure 3.

Comparison of IC and In-situ Measurement Values

For investigating the relationships at the project scale, average CMV and point-MVs for different proof sections were compared. Scatter plots are shown in Figure 4. Average dry unit weight and DCP index are predicted from average CMV with R2 values of 0.52 and 0.79, respectively. Considerable scatter was still observed for surface light weight deflectometer elastic modulus (ELWD) with the 200 mm plate diameter measurements. Additional testing was performed to investigate the effects of performing tests at depths of 110 to 170 mm below the surface. These subsurface tests showed that the average ELWD increased by a factor of about 1.7. Future correlation studies should investigate LWD testing below the surface for fine sand materials. Relationships between coefficients of variation (Cv) for CMV and in-situ point-MVs show that Cv are similar to DCP and LWD compaction test data (Figure 4). This is of consequence as it relates to developing uniformity criteria for compaction. The Cv for density measurements is generally much less than LWD and DCP index measurements.

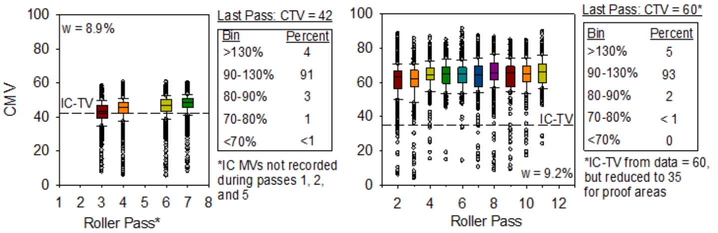


Figure 1. CMV compaction curves control strips (a) 1.1m subcut (left) and (b) 0.25m subcut (right) (from White et al. 2008)

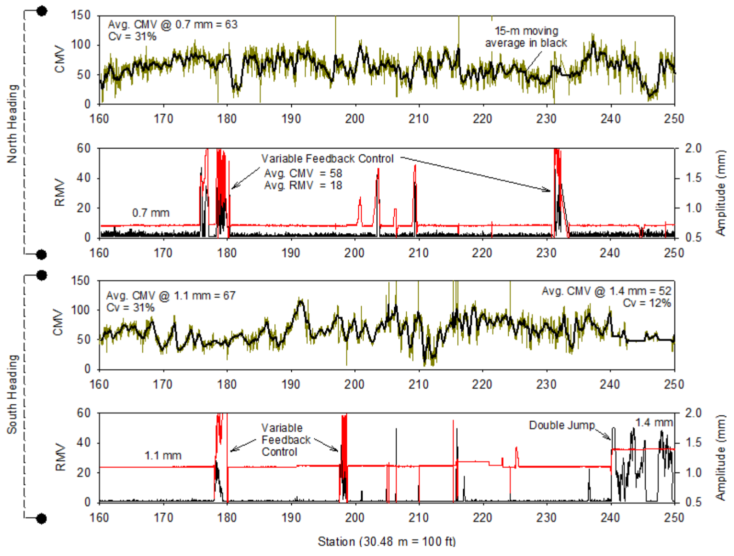


Figure 2. CMV, RMV, and amplitude data for 2.7 km test section after acceptance of all proof layers (from White et al. 2008)

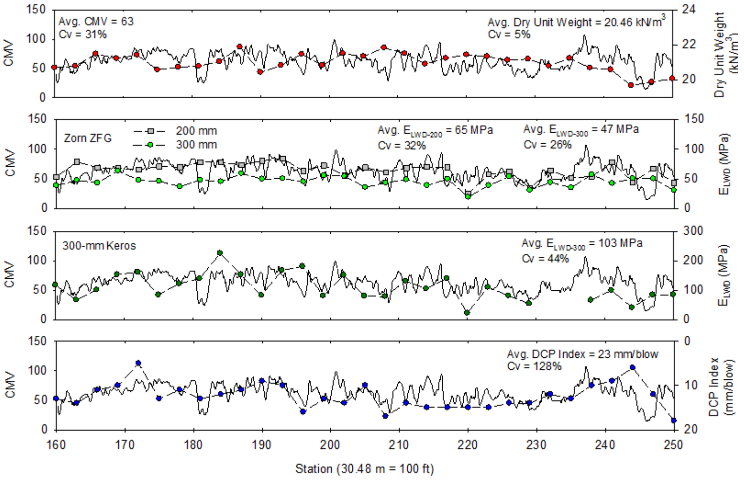


Figure 3. CMV (0.7 mm amplitude) and in-situ measurement data (from White et al. 2008)

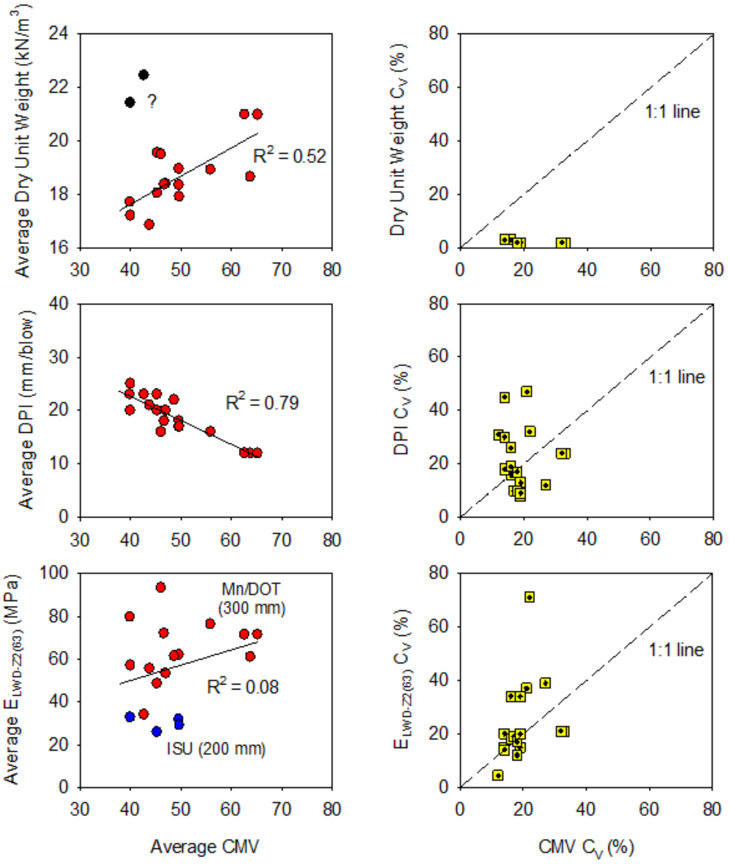


Figure 4. Correlation of average CMV and average in-situ measurements and coefficients of variation (combined proofs) (from White et al. 2008)

Data Management using GIS

IC technology provides the opportunity to collect and evaluate information for 100 percent of the project area, but it also produces large data files that create analysis, visualization, transfer, and archival challenges. As part of this project, an approach for managing the data was developed consisting of "geodatabase" using ArcGIS/ArcInfo modules. IC data archived in this manner is spatially referenced, which is useful for state agencies as it relates to data management, and mapping. IC output files usually contain unessential data (e.g. data collected when roller is reversing, etc.) which can be filtered before importing into a database. A personal geodatabase was created using ArcCatalog and ArcMap by importing tables into the geodatabase. The imported attribute tables were converted to a feature class using the Hubbard County, MN co-ordinate system projections. Data visualization and analysis such as creating histogram plots, semivariogram models, geostatistical analysis can be performed using ArcGIS. Figure 5 shows kriged CMV data obtained from a proof area overlaid with point-MVs from ArcMAP.

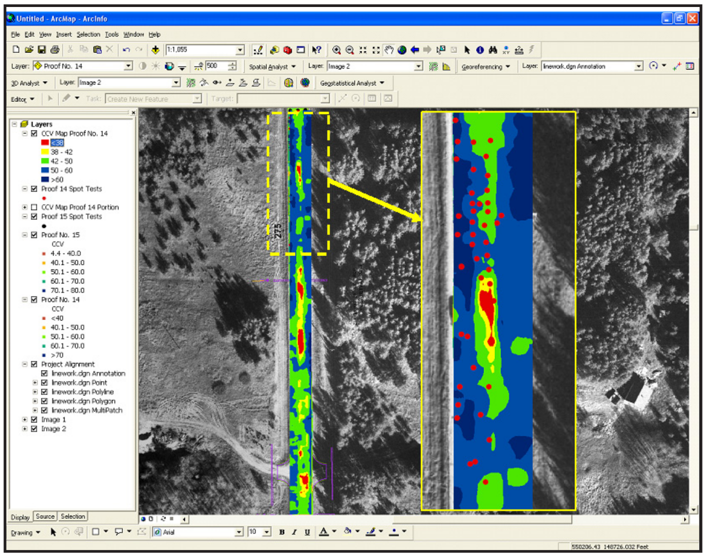


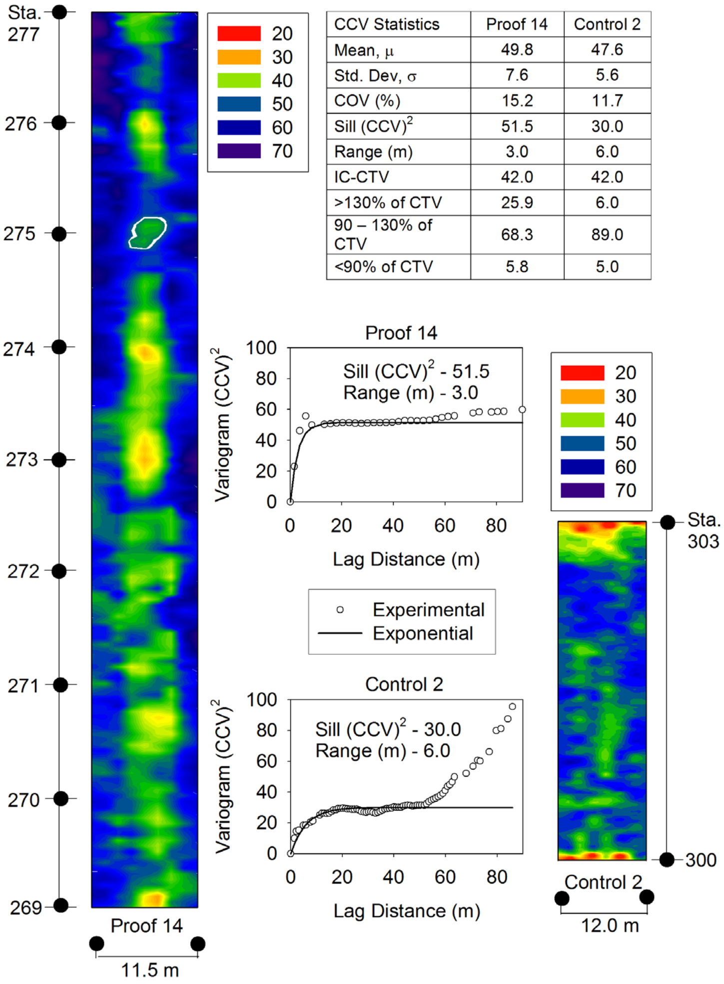
Figure 5. Kriged surface map of CMV from a proof area overlaid with point-MVs (in red circles)–created using ArcMap (from White et al. 2008)

Geostatistical Analysis

Univariate statistics of IC measurements alone do not characterize the spatial variability and specifically do not address the issue of uniformity from a spatial viewpoint. Mn/DOT implemented a tolerance acceptance criterion for the TH 64 project such that a proof area should meet at least 90% of the target value established from a calibration strip for 90% of the area. This approach has the advantage of being relatively simple and easy to implement. However, it should be emphasized that the proof areas may have identical distributions of the data as control strip, but may not be spatially similar. A semi-variogram model in combination with univariate statistics could potentially be utilized to effectively address the issue of uniformity. From a semi-variogram model, a low "sill" and longer "range of influence" can represent best conditions for uniformity, while the opposite represent poor conditions for uniformity.

To demonstrate this application, IC-TV's established from a control section was used as reference for QA in a proof section.

Comparison of the univariate statistics of CMV measurements and acceptance criteria is presented in Figure 6. Results indicate that this proof area "passed" the quality acceptance criterion of achieving 90% of IC-TV in 90% of the evaluated area. However, if spatial statistics between the proof and the calibration strip are compared, the proof area failed to achieve the "sill" and "range" values achieved in the referenced calibration strip. The production area consisted of localized areas of soft ground conditions or "hot spots" that have CMV < 30, especially along the centerline of the alignment. These locations generally match with the locations of grade stakes in the field and were not subjected to construction traffic like the outside lines. Although the proof area meets the acceptance criteria specified for the project based on average values, geostatistical spatial analysis reveals localized areas that perhaps could benefit from additional compaction to improve spatial uniformity.



CCV Statistics	Proof 14	Control 2
Mean, μ	49.8	47.6
Std. Dev, σ	7.6	5.6
COV (%)	15.2	11.7
Sill (CCV)^2	51.5	30.0
Range (m)	3.0	6.0
IC-CTV	42.0	42.0
>130% of CTV	25.9	6.0
90 – 130% of CTV	68.3	89.0
<90% of CTV	5.8	5.0

Figure 6. Comparison of a proof section with a control section using CMV surface maps, semi-variograms, and univariate statistics (from White et al. 2007)

Figure 7 illustrates a mathematical exercise to select localized areas within the proof area to target for additional compaction or other treatment that would contribute to improved uniformity. Ideally, any given portion of the production area with dimensions equal to that of the calibration area (94 m) should meet the spatial statistics established from the calibration. This means that the sill values in the production area should be equal to or lower than the sill values achieved in the calibration area and likewise the range values in the production area should be equal to or higher than the range values achieved in the calibration area. Kriged surface maps of the original and mathematically adjusted CMV data are presented in Figure 7. For this exercise, CMV data was adjusted to one of the following:

CMV < 45 = 45, CMV < 48 = 48, or CMV > 52 = 52. The semivariograms associated with each adjusted CMV data set are presented in Figure 7 along with the semivariogram of the calibration strip. Comparatively, the semivariogram for the CMV < 48 = 48 adjusted dataset with sill = 29 closely follows the semivariogram of the target calibration strip with sill = 30. The semivariogram of the CMV < 52 = 52 adjusted dataset shows greater uniformity with a lower sill value, relative to the calibration strip, which would exceed the baseline uniformity criteria established from the calibration strip. This approach provides an optimized solution to target areas that need additional compaction. It also provides quantitative parameters to establish uniformity based on spatial statistics criteria.

Summary and Key Findings

- IC technology was successfully used as the principal QC tool on a grading project on TH 64 in MN.
- Control sections were constructed and tested to establish appropriate quality criteria, which were then applied to production areas. Compaction curves observed with control section CMV data showed that little compaction occurred after the initial roller passes. This highlights the importance of GPS location and pass information provided to the operator. Target values were selected form the control sections to be applied to proof sections.
- Roller and in-situ measurements values were collected on proof sections and analyzed with the objectives of correlating CMV with measures of dry unit weight, DCP index, and LWD modulus. Variation parameters were also investigated, as intelligent compaction technology may be effective in indicating uniformity of compacted materials. CMV and in-situ test results are correlated at the project scale using average values for different proof sections. Dry unit weight and DCP index were predicted from CMV with R2 values of 0.52 and 0.79, respectively. Scatter was still observed for ELWD and attributed to different measurement influence depths of this compaction control device and the roller.
- IC technology provides opportunity to collect and evaluate information for 100%of the project area, but it also produces large data files that create analysis, visualization, transfer, and archival challenges. An approach for managing large quantities of data is to create a "geodatabase" using ArcGIS modules. A geodatabase of the TH 64 project IC data and in-situ spot test measurements was briefly described to demonstrate this application.
- Applying geostatistical methods in the analysis of IC data has the advantage of quantifying spatial variability, which is not possible with univariate statistical analysis. A semi-variogram model can be used to characterize uniformity of the IC data.
- To demonstrate the application of geostatistics, IC data collected for a proof section and a reference control section were analyzed and compared with the specification quality control criteria. The proof section "passed" the specification acceptance criteria but failed to meet an alternatively proposed "sill" criterion that establishes a uniformity criterion.

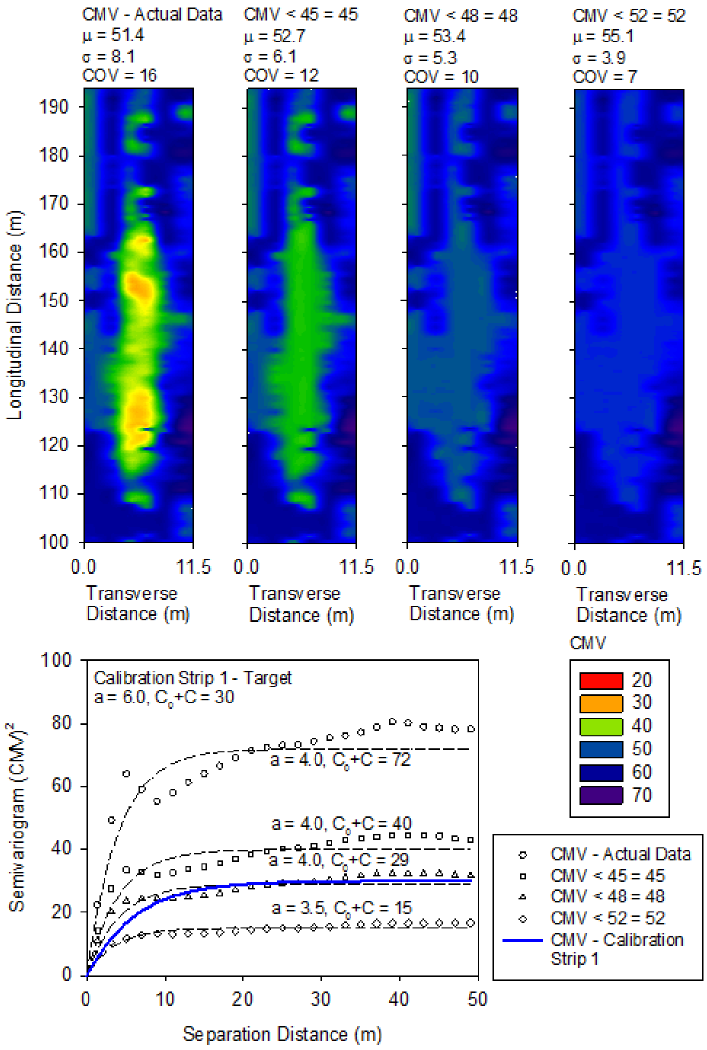


Figure 7. Kriged surface maps and semivariograms of a selected portion of the proof showing variations with modifications in the actual CMV data (from Vennapusa et al. 2010)

- The approach of using geostatistics provided an optimized solution to target areas that need additional compaction along with quantitative parameters to establish uniformity based on spatial statistics criteria. Geostatistical analysis and spatially referenced roller-integrated compaction monitoring represent a paradigm shift in how compaction analysis and specifications could be implemented in the future.

References

Mn/DOT. (2006). Excavation and embankment – (QC/QA) IC quality compaction (2105) pilot specification. Minnesota Department of Transportation, St. Paul, Mn.

Sandström Å., and Pettersson, C. B., (2004). "Intelligent systems for QA/QC in soil compaction", Proc. TRB 2004 Annual Meeting (CD-ROM), Transportation Research Board, Washington, D. C.

Vennapusa, P., White, D.J., Morris, M. (2010). "Geostatistical analysis for spatially referenced roller-integrated compaction measurements, J. of Geotech. and Geoenv. Engrg., ASCE, 136 (6), 813-822.

White, D., Thompson, M., and Vennapusa, P. (2007). Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials. Final report 2007-10, Mn/DOT, St. Paul, Minnesota.

White, D., Thopmson, M., Vennapusa, P., and Siekmeier, J. (2008). "Implementing intelligent compaction specifications on Minnesota TH 64: Synopsis of measurement values, data management, and geostatistical analysis." Transp. Res. Rec., 2045, 1-9.