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Intelligent Compaction of Soils— Data Interpretation and Role in QC/QA Specifications



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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract <p>This report describes a study of intelligent compaction (IC) technologies, within the context of actual construction projects, for its potential as a component of INDOT's QC/QA for soils. The output from an IC-equipped roller compaction equipment is a real-time area mapping of the compacted lift stiffness as captured by the IC measure. Data was collected to evaluate the correlation between each of two IC measures—compaction meter value (CMV) and machine drive power (MDP)—and in situ embankment quality test measures, the chief in situ test being the dynamic cone penetrometer (DCP) test which INDOT uses for soil embankment acceptance testing. Researchers sought to understand how well the IC measures might assess embankment quality as currently evaluated by the in situ measures. Window-averaged IC measures were compared with the in situ DCP test points. For CMV, a variable correlation was found between the average CMV and DCP values from 74 in situ locations. Also, a limited head-to-head comparison of CMV and MDP with the in situ measures provided some indication that MDP should be studied further. Lessons were learned regarding the elimination of bias in future correlation studies, critical provisions to facilitate best data quality, and important aspects of data management. IC technology holds promise for monitoring the consistency of the soil compaction effort and flagging weak areas in real time during compaction operations. However, further insight is needed regarding the correlation of the DCP measure with both types of IC measures for various soil characterizations and field moisture conditions.</p>		13. Type of Report and Period Covered Final Report	
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EXECUTIVE SUMMARY

INTELLIGENT COMPACTION OF SOILS— DATA INTERPRETATION AND ROLE IN QC/QA SPECIFICATIONS

Introduction

This report describes a study of intelligent compaction (IC) technologies, within the context of actual construction projects, for its potential as a component of INDOT's quality control (QC) and quality assurance (QA) for soils. INDOT identified two projects—U.S. 31 Kokomo and U.S. 50 North Vernon—as projects from which data could be collected to evaluate two IC technologies: compaction meter value (CMV) and machine drive power (MDP). The former is an accelerometer-based IC technology while the latter is energy based. Researchers analyzed correlations between IC values and in situ embankment quality test measures to see how well the IC measures could identify strength as already understood by the in situ measures, especially the dynamic cone penetrometer (DCP) test that INDOT employs for acceptance testing.

Findings

It was established and confirmed for both IC technologies that an averaging of the IC measure ± 5 m local to the DCP test location yielded the best correlation results. The correlation between the window-averaged CMV measures and 74 in situ DCP tests from the U.S. 31 project was observed to be quite variable, which discourages the use of CMV as a replacement for the DCP measure that is currently used by INDOT for acceptance of the constructed embankment. A limited head-to-head comparison of CMV and MDP with the in situ measures of DCP, the light weight deflectometer (LWD), and the falling weight deflectometer (FWD) revealed that while the two IC measures had a somewhat strong correlation between them, MDP had a decidedly stronger correlation with each of the in situ measures. However, the correlation between CMV and MDP was somewhat strong, indicating that the two IC measures share strong influencing factors even though they compare differently with the in situ measures. Some factors observed during the study that influenced the relationship are soil moisture and external sources of vibration that add noise to the sensor readings. It is also clearly indicated in the literature that MDP correlates better with DCP on cohesive soils than CMV does, so soil heterogeneity can also be an important factor. Reflection on the collected data revealed a bias in the samples that hindered the Research Team's opportunity to assess well the reliability of CMV for detecting weak areas that would also be evaluated as such by a failing DCP test.

Conducting data collection within the context of real construction projects confirmed that the adoption of IC introduces new challenges for data management. Four particular observations were made:

- It is necessary to establish a data management process that has been tested and corrected for errors.
- IC data might be better utilized during the construction phase by enhancing the in-cab computer display to provide

real-time analytical capabilities toward improved quality assurance.

- The enterprise GIS database, a platform that most state highway agencies (SHAs) have, is suited to incorporate IC and associated soil compaction data to support decision-making in the future.
- Users of IC data need ready access to a knowledge resource for the underlying data structure to facilitate any post-analysis using the IC data.

Furthermore, several lessons were learned regarding how to effectively conduct further investigation of IC where data is being collected and analyzed from actual construction projects:

- Data collection and transfer procedures and responsibilities should be formally established, ideally in the pre-construction meeting, and outlined in writing for everyone's reference.
- A single point of contact (not necessarily the Business Owner) should be designated with the authority to issue directives when agreed-upon arrangements for data acquisition and access are not being met.
- The Contractor must guard against any condition that introduces sources of vibration other than the roller drum-soil system.
- Random selection of locations for the in situ DCP tests must be maintained to assess whether an IC measure would agree with the acceptance that would occur based solely on the in situ test and evaluation procedure.
- Personnel conducting the DCP test must be aware to take an accurate dynamic cone penetration index (DCPI) measurement (depth of penetration per blow count) when the soil is hard, so that the measurement is precise.

Implementation

Further investigation of IC application on real projects is needed before INDOT can confidently attach engineering-based meaning to the dimensionless IC measures. However, the technology does hold promise for monitoring the consistency of the soil compaction effort and flagging weak areas in real time during compaction operations. Thus, IC is currently better poised for quality control than for quality assurance, and pilot projects aimed at QC implementation are recommended for the nearer term, while keeping QA implementation as a longer term goal. Specific objectives of further study should include the following:

- To gain further insight on the correlation of the DCP measure with both accelerator-based and energy-based IC measures for various soil characterizations and field moisture conditions,
- To gain a greater sense of the reliability of the IC measures when the embankment strength is low (i.e., confidence in the target value and procedures for setting it), and
- To facilitate broader understanding both within INDOT and among its industry partners of best practices for implementing IC on INDOT projects.

These objectives of further study may be advanced more rapidly through pooled fund studies and the attention of the ICA/INDOT Joint Cooperative Committee.

CONTENTS

1. INTRODUCTION	1
1.1 Basic Explanation of IC Technologies	1
1.2 Research Interests and Objectives	2
1.3 Survey of IC Implementation	3
1.4 Construction Projects Identified as Data Sources for the INDOT Study	4
2. METHODOLOGY AND ANALYSIS RESULTS.....	4
2.1 IC Averaging Method.....	4
2.2 Field Test Strip Investigation.....	5
2.3 Overall CMV and DCP Comparison	9
2.4 Overall MDP and DCP Comparison from U.S. 31	9
2.5 MDP and DCP Comparison from U.S. 50	9
2.6 Overall Discussion	9
3. LESSONS LEARNED	10
3.1 Field Data Collection Protocols.....	10
3.2 Data Management Protocols.....	11
4. RECOMMENDATIONS	12
5. CONCLUSIONS	12
REFERENCES	13

LIST OF TABLES

Table	Page
Table 1.1 Survey Responses on SHA Exploration and/or Adoption of IC as of Fall 2014	3
Table 2.1 R ² Values for Regressions between CMV and DCP for Various Averaging Windows	5
Table 2.2 In Situ Measurements and Averaged IC Values for the Test Points	7
Table 2.3 Results of Linear Regression of CMV on DCP and Moisture	7
Table 2.4 Correlation Matrix for IC and In Situ Measures	8

LIST OF FIGURES

Figure	Page
Figure 1.1 Intelligent compaction machine	2
Figure 2.1 The local area of a testing point	5
Figure 2.2 Quality measures collected in field test strip investigation	6
Figure 2.3 Processing of IC and in situ data	6
Figure 2.4 IC and in situ data in GIS	7
Figure 2.5 Comparison between CMV and MDP along the test strip	8

1. INTRODUCTION

Intelligent compaction (IC) refers to automated methods by which a mapping of the relative stiffness of a compacted layer is obtained in real time via sensor technology mounted on roller compaction equipment. Having participated in a pooled fund study (Chang et al., 2012), leaders at the Indiana Department of Transportation (INDOT) recognized that this technology offers the opportunity to obtain more efficient performance of related quality control and quality assurance (QC/QA) tasks for the construction of soil embankments, and therefore commissioned the study, reported herein, with the support of the Federal Highway Administration (FHWA). This study involved the analysis of IC and QA data collected in the course of construction for actual roadway projects, and as such offers valuable insight into the practical aspects of IC implementation.

Presently, no definitive link exists between the IC monitoring (mapped) output and quality outcomes as conventionally evaluated through a program of scattered (spot) inspection field tests. Best practice criteria regarding level of data collection and acceptance have been suggested only from a small number of experiences of state transportation agencies participating in Transportation Pooled Fund project TPF-5(128) (Chang et al., 2012). That study broadly assessed and documented the state-of-the-art in IC knowledge for agencies and the industry to advance implementation of IC technologies, citing recommendations for IC application for both soils and HMA pavement layers, and outlining an IC Road Map. The future of IC was deemed promising and the technology ready for careful adoption. INDOT thus envisioned that the potential benefits from their own further study of IC for determination of the stiffness of compacted soils would include a substantial increase in the quality of the embankment, an increased production rate and reduction of delays for the Contractor and INDOT, and a reduction of time for INDOT to determine their acceptance of embankment stiffness.

The aforementioned pooled fund study yielded recommendations for state highway agencies (SHAs) to consider, and at the initiation of this study, INDOT had crafted an approach to test them in their further investigation. Two INDOT construction projects were selected as sources of data to conduct this combined study—U.S. 31 Kokomo, and U.S. 50 North Vernon. Additionally, two brands of IC technology were considered—compaction meter value and machine drive power. The primary task for the Research Team was to investigate the correlation between the mapped IC values and those obtained from the dynamic cone penetrometer (DCP) test, INDOT's standard compaction quality measure. That analysis, combined with observations of the process, can inform recommendations for IC implementation that yield to INDOT more thorough knowledge of compaction quality. One desired result is validation or refinement of the general practice recommendations from the pooled fund study as a

complement to INDOT's use of DCP. The ultimate objective is a specification and practice for the construction and acceptance of compacted soil embankments that employs enhanced inspection capabilities in the face of limited human resources. This report describes the execution and findings of the study.

1.1 Basic Explanation of IC Technologies

IC has emerged as an automated method, by which the desired level of stiffness in an asphaltic or soil layer is achieved through monitoring and control of roller parameters to optimize the compaction effort. An intelligent compaction machine (ICM) is a self-propelled roller that is specially equipped for this task and provides, as a continuous output, the geo-referenced mechanistic response from the compacted area. With this technology, SHAs have an opportunity to obtain more efficient performance of related QC/QA tasks for the construction of soil embankments. This technology eliminates three limitations associated with traditional roller compaction inspection via in situ measurements as such: (1) the ICM automatically generates compaction measures as it rolls, (2) a complete coverage of the entire project site can be obtained, and (3) real-time control is enabled by examining the IC measurements while the roller compacts the soil and making immediate adjustments to achieve optimal compaction.

Figure 1.1 depicts ICM's equipped with the two IC measurement systems: compaction meter value (CMV) and machine drive power (MDP). IC measurements are calculated from sensor-recorded data. Coupled with roller positions acquired from an onboard real-time kinematic global positioning system (RTK GPS), the IC technologies allow the collection of real-time information regarding soil compaction to assist the QC/QA process.

The CMV technology employs a drum-mounted accelerometer to measure G-forces of the vibrating drum. During compaction, vibratory energy is imparted on the soil by the vibrating drum. The soil vibrates in response, which is detected and measured by the accelerometer. The acceleration amplitude spectrum is then obtained through spectral analysis of the measured vertical drum acceleration, upon which CMV can be calculated in Equation 1.1 as an indicator of soil stiffness (Forssblad, 1980; Thurner & Sandström, 1980). $A_{2\Omega}$ is the second harmonic of the vertical drum acceleration frequency domain amplitude, $A_{1\Omega}$ is the first harmonic of the vertical drum acceleration frequency domain amplitude, and C is a constant with typical value of 300. CMV is a dimensionless value that depends on roller dimensions and roller operation parameters (White, Thompson, & Vennapusa, 2007).

$$CMV = C(A_{2\Omega}/A_{1\Omega}) \quad (1.1)$$

The MDP technology harnesses the principle that propelling over soft soil requires more energy while propelling over stiff soil requires less energy. It measures the amount of energy required to propel through the



Figure 1.1 Intelligent compaction machine.

soil (to overcome rolling resistance) to assess the soil stiffness. Equation 1.2 illustrates the calculation of the MDP measure, where P_g is the gross power needed to move the machine; W is roller weight; V is roller velocity; θ is slope angle; a is machine acceleration; g is acceleration of gravity; m and b are machine internal loss coefficients specific to a particular machine (Mooney et al., 2010).

$$MDP = P_g - WV(\sin \theta + a/g) - (mV + b) \quad (1.2)$$

For the Contractor, timeliness of determination of the embankment lift stiffness is critical to the progress of the embankment construction. Delays in the testing process could result in delays in the completion of the contract. Identification of the lift stiffness on a real-time basis allows the Contractor to optimize the number of rollers and number of passes of the rollers to determine if the required stiffness of the lift has been achieved. The request by the Contractor for INDOT testing or evaluation of the IC stiffness printout of the embankment lift could then be made with assurances that the stiffness has been achieved and progression to the next lift could be started immediately. Also, for the IC process, INDOT might allow the lift thickness to be increased based on correlations of the Contractor's progressive IC mappings and DCP test results.

These options, if implemented, would lead to an increase in the production rate of the Contractor.

Finally, with the reduction of construction personnel available to test and approve soil embankment, the IC process would allow INDOT to reduce the amount of testing required by their staff to approve an embankment lift as well as more precisely identify sections which would require a more definitive test by the DCP method. These advantages would allow the Contractor to progress more quickly with the contract and INDOT to better utilize the time for inspection and testing by the INDOT Technician on the project.

1.2 Research Interests and Objectives

Acceptance testing of the embankment stiffness is currently determined by obtaining one random DCP test for each 1400 yd³ of each lift for each two-lane pavement. Obvious wet or weak areas determined by visual observation are required to be evaluated and/or corrected before the Contractor may proceed to the next lift. The benefits from using IC to determine the strength/stiffness of soils include the potential for a substantial increase in the quality (i.e., compaction uniformity) of embankment, an increased production rate and reduction of delays for contractors and state

highway agencies (SHAs), and a reduction in the time consumed in determining the acceptance of embankment strength/stiffness (Chang et al., 2012; Mooney et al., 2010). The IC printout might essentially replace or reduce reliance upon accepting the lift based only upon DCP tests. Given the relative newness of IC implementation, there is no standard or universally accepted best practice regarding the use of IC data to satisfy the QC/QA needs of SHAs with respect to compaction. As stated above, there is thus far no definitive link between the IC monitoring output and quality outcomes as conventionally evaluated by a program of in situ field tests. The recommendations from the Transportation Pooled Fund project (Chang et al., 2012) as best practice criteria for IC implementation (i.e., mapping 90% of the construction area and requiring 70% of the mapped area to meet the target IC value) is based on the limited experience.

The interest of INDOT was to investigate the correspondence between IC values and the values obtained from the DCP test that serves as their standard test for acceptance of compacted soils. Confirmation of a strong relationship between the two measures would encourage reliance on IC technologies and thus reduce the demand on inspection staff to perform DCP tests. Hence, the objective of this study is to conduct analysis of field data from actual construction projects to determine the relationship between IC measurements and in situ measurements, and to formulate a strategy for the practical implementation of IC as an effective QC/QA tool in earthwork projects. For INDOT, the benefit of a study of IC for determination of the stiffness of soils includes a substantial increase in the quality of the embankment, an increased production rate and reduction of delays for the Contractor and INDOT, and a reduction of INDOT time for determination of the acceptance of the embankment stiffness.

The primary tasks performed in this study consist of the following:

- Literature review and interviews of other SHAs for new insights on IC theory, technology, and implementation,
- Documentation of the QC/QA process employed on the projects, and
- Data collection and analysis to establish the relationship between the IC measure and DCP values via multivariate linear regression, including influential factors such as moisture and soil type.

1.3 Survey of IC Implementation

As an early step in this study, the Research Team conducted a survey of SHAs known to have examined IC either from participation in a Pooled Fund project or as publicized in the scholarly literature (see Table 1.1). The Research Team pursued contact with 20 states, including Indiana, and was successful in gaining an audience with 14, communicating through a combination of email and telephone conversations. Three specific questions were posed:

1. Is your agency still studying IC or actually implementing IC? Please provide details such as number of projects, soils vs pavement applications, etc.
2. If implementing IC, do you have a sample special provision that you can share with us?
3. Is your agency focused on a specific type of IC technology (e.g., CMV vs MDP from Caterpillar)?

In summary, a significant number of the states were found to have a serious interest in assessing IC and pursuing implementation on their projects. Of those states successfully contacted, respondents from a majority (10 of 14) stated that their agency was making efforts to determine how IC might be incorporated in their

TABLE 1.1
Survey Responses on SHA Exploration and/or Adoption of IC as of Fall 2014

State	Q1. Pursuing IC for soils?	Q1'. IC for HMA?	Q2. Special provisions?	Q3. Technology preference?
Colorado	NO	NO	N/A	N/A
Georgia	YES	NO	YES	CMV
Indiana	YES	YES	YES	Still determining
Iowa	YES (2009, 3 pilots)	YES (2010, 3 pilots)	YES	No
Kentucky	YES	YES	YES	See promise in MDP
Maryland	YES	YES	YES	Still determining
Missouri	YES (no pilots yet)	YES (summer 2014, 2 pilots)	NO	NO
North Dakota	YES	YES	In development	NO
New York	NO	NO	YES	NO
North Carolina	YES	(no response)	NO	NO
Ohio	NO (but have studied)	NO (but have studied)	None	N/A
Pennsylvania	YES	YES	YES	NO
Texas	YES, using for proof "marking"(rolling) Nuclear density for acceptance; doing 3-yr, 20-project implementation	NO	YES	CMV (MDP disallowed, considered not sensitive enough)
Utah	NO (bad experience)	YES	(only for HMA)	FHWA-approved; No retrofits

QC/QA practice. These efforts were at varied stages, with a handful having either accomplished or planned multiple pilot projects. Texas described, by far, the most ambitious program for testing implementation, with twenty projects planned for IC. Seven states had drafted special provisions. Although, IC for asphalt pavements was not the subject of this study, it was interesting to note that one state (Utah) was investigating only the asphalt pavement implementation subsequent to a bad experience with implementation for soils.

Comments received from the SHA respondents did not reveal a consensus of experience and opinion. States were still learning about the benefits of one type of IC technology versus another and how to effectively utilize the data obtained. While it was noted that specifications needed to avoid stipulating particular IC technologies, states have confirmed for themselves that some technologies are more effective for certain soil types. None of the states indicated a desire to replace their standard QC/QA test procedure, and one in particular stated that they would advocate it more for the contractor's QC efforts. In a couple of instances, contractors were noted to either be disinterested in the technology or to fall short in accessing the know-how to process the IC data without the SHA stepping in to facilitate.

1.4 Construction Projects Identified as Data Sources for the INDOT Study

This study is based on the data collected from INDOT's U.S. 31 Kokomo Freeway project and from the U.S. 50 North Vernon Bypass-East project. The U.S. 31 Kokomo project involved the construction of a new four-lane, limited-access divided highway around the east side of Kokomo in Howard County. The 13-mile project, which included six new interchanges, began just south of the Tipton/Howard county line and ended about one mile north of the U.S. 35 intersection. The freeway bypassed old U.S. 31, which was subsequently renamed State Road 931. The \$155 million project opened to traffic after a ribbon-cutting ceremony on Nov. 26, 2013. The U.S. North Vernon Bypass-East project involves the construction of a highway bypass around the city of North Vernon in Jennings County. Construction on the western half of the project, which consists of a new two-lane road from U.S. 50 northeast to SR 3 north of North Vernon. The approximate length of this roadway is 4.5 miles. The U.S. 31 Kokomo Freeway project and U.S. 50 North Vernon Bypass-East project provided opportunities to collect both IC and in situ measurements on an actual earthwork project and permitted the investigation of two IC technologies. IC-CMV was primarily employed on the U.S. 31 project, while IC-MDP technology was employed on the U.S. 50 project. The contractors for these projects were Fox Contractors Corp. of Ft. Wayne, Indiana and Dave O'Mara Contractor, Inc. of North Vernon, Indiana, respectively.

2. METHODOLOGY AND ANALYSIS RESULTS

The overall methodology involved a process of data collection and statistical analysis of the same from the 2012 and 2013 construction seasons for the U.S. 31 project and from the 2015 and 2016 construction seasons of the U.S. 50 project. Throughout this study, in situ DCP and moisture data was collected by construction project personnel who shared that data with the Research Team, while the IC data sets were uploaded directly from the IC machines to a cloud server where it was organized and preprocessed by SITECH Indiana for the Research Team to access and download. DCP tests were conducted according to ITM No. 509-15P with locations to be randomized, except for a special field test strip on the U.S. 31 project site, according to ITM No. 802-13P. Field moisture determination was performed by INDOT according to ITM No. 512-15T, and target IC values (i.e., minimum to flag weak areas) were established following procedures prescribed in ITM No. 513-14T. Corresponding values for each in situ DCP test (blow counts or penetration index) and field moisture, located by GPS, were compared to IC values averaged around the same location (explained in Section 2.1). One section of the U.S. 31 project was designated as a test strip to validate the IC data processing procedures, and that same test strip afforded the opportunity to compare both CMV and MDP mappings to additional in situ test methods. As it turned out, scant data was obtained from the U.S. 50 project, so ultimately, limited insight was gained to inform MDP implementation although lessons were learned.

The remainder of this chapter describes the data collected and the analysis performed. First the unique averaging method is explained for processing IC measures to establish the one-to-one spatial correspondence with in situ measures. Then the field experiment with the dedicated test strip is described, and the statistical analyses performed on the preprocessed data is elaborated. Finally, the overall results, mostly from the U.S. 31 project are explained.

2.1 IC Averaging Method

On the U.S. 31 project, initial comparisons between DCP values and average CMV values from the areas the DCP test was deemed to represent revealed a poor correlation; the best coefficient of determination (R^2) values, a statistical indicator of correlation strength, was barely above 0.2. Inspection of the CMV control charts revealed high variability in the stream of CMV values, which appeared to explain the weak correlation. The Research Team hypothesized that a better one-to-one spatial correspondence between IC and in situ measurements would be achieved from a more localized average IC value to represent the soil stiffness in the area of the point in situ measurement. Therefore, they investigated the use of more localized averages of the CMV measure, testing windows of plus/minus 0, 1, 3, 5, 7, 10, and 15 m before and after the DCP test location.

The Research Team limited the investigation to no more than a ± 15 m window based on reference to highly controlled tests of CMV and MDP conducted by White and Thompson (2008).

Figure 2.1 illustrates the application of this window-averaging approach for the test strip comparison that was mentioned above. The strip of parallel, spaced lines reveal the roller path and represent the locations of each IC measurement. The rectangle indicates the limits of the local area over which the IC measure is averaged. For each test point, its corresponding local area was defined as the area of the IC strip that contains the point and is longitudinally centered at the test point. The distance d , preceding and following the test point location, determines the size of the local area.

Table 2.1 shows the R^2 values that were obtained from correlating test point DCP values to the corresponding window averages from some of the U.S. 31 data collected during the first construction season. The strongest correlations were obtained for the ± 3 m and ± 5 m windows, and the Research Team chose to employ the latter for analysis going forward. Subsequent reexaminations of this approach, both for the CMV and MDP data, confirmed the choice of ± 5 m for the size of the averaging window.

2.2 Field Test Strip Investigation

The Research Team recognized issues with inaccurate geo-correlation of the DCP and IC measures for the 2012 construction season data from U.S. 31, and therefore, INDOT construction engineers selected a field test site for verifying the data management procedures for the study (see Figure 2.2). The Study Advisory Committee (SAC) recommended additional in situ measures to be included in the test strip study so that IC measures could be compared to them as well. Besides the

comparison of the various measures of embankment construction quality, this field test revealed an error in correlating GPS coordinates with local project coordinates and confirmed that the IC data was otherwise being processed and managed properly. This section, therefore, describes that field test while also clarifying the data management and analysis procedures that were employed throughout this study.

2.2.1 Field Data Collection

The field test was conducted on May 30, 2013, on the U.S. 31 project. INDOT construction engineers collected DCP, LWD, GPS coordinates, and soil moisture at nineteen points along the section of the project designated as the test strip (roughly between stations 1673+00 and 1679+00); and personnel from the INDOT Research Division collected FWD deflection results and GPS coordinates at these nineteen points. These three in situ tests (DCP, LWD, and FWD) were employed because DCP is the standardized acceptance test used by INDOT, LWD is being used by other SHAs, and as a more robust technique, FWD can serve as the ground truth of the soil stiffness under compaction. The ICMs were a Caterpillar CS56 vibratory soil compactor equipped with CMV technology and a Caterpillar CP74B vibratory soil compactor equipped with MDP technology. The IC technologies were not used for monitoring the progression of compaction but for mapping the end result. Specifically, IC measures were recorded every 0.2 seconds as the compactors rolled over the test strip that contained the nineteen points. Each IC measure was associated with the GPS coordinates of the left end and right end of the roller drum. As implied by Figure 2.1, the left and right end points can be connected to form a line to represent the position where the drum touched the soil surface when an IC measure was taken.

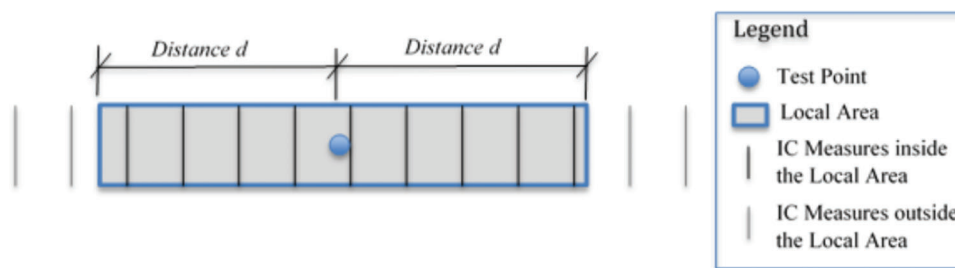


Figure 2.1 The local area of a testing point.

TABLE 2.1
 R^2 Values for Regressions between CMV and DCP for Various Averaging Windows

Distance in Meters Before and After DCP Test Location	0 m	1 m	3 m	5 m	7 m	10 m	15 m
R^2	.593	.583	.669	.668	.613	.539	.445
Adjusted R^2	.564	.553	.645	.644	.585	.506	.411



Figure 2.2 Quality measures collected in field test strip investigation.

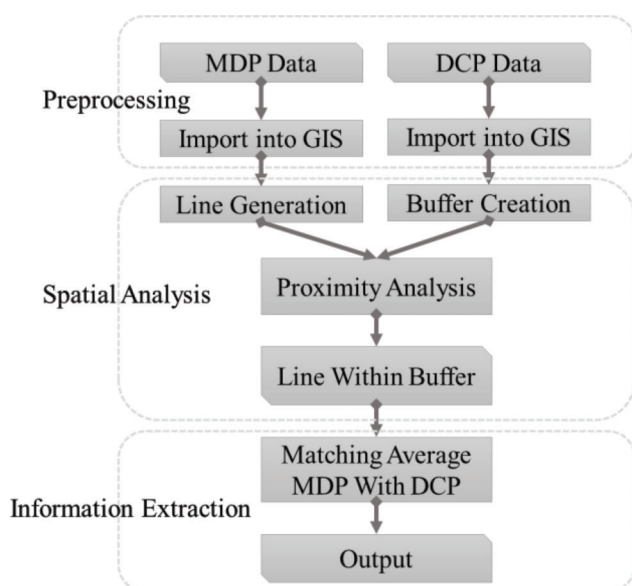


Figure 2.3 Processing of IC and in situ data.

2.2.2 Data Processing

The purpose of processing IC and in situ data is to convert both data into a GIS format and match them based on their location such that statistical correlation analysis can be performed. Figure 2.3 illustrates the steps for data processing: preprocessing, spatial analysis, and information extraction. First, IC data such as MDP are converted into line features and in situ data such as DCP data are converted into point features in GIS according to their GPS coordinates. All relevant data items are conserved as attributes. Importing MDP and DCP into GIS forms the prerequisite for correlating DCP with MDP values based on the proximity information.

Figure 2.4 presents a GIS spatial display of the field test strip with the locations of the DCP test points. The two boxes to the right are close-up views of the overlay

of the IC line measures and the in situ DCP test points. The GIS environment enabled the isolation of the IC averaging window that was described in Section 2.1. With this one-to-one spatial correspondence between IC and in situ measurements established, the correlation analysis can be conducted.

2.2.3 Statistical Analysis

As explained in Section 2.1, the averaging windows of ± 3 m and ± 5 m (and sometimes ± 7 m) were found to provide a similarly good fit between the DCP and average CMV measures, reinforcing the choice of a ± 5 m averaging window for the statistical comparison of IC to all the strength/stiffness measures in the field test strip analysis. For consistency, this averaging window was also confirmed as appropriate and used for analyzing relationships with the MDP measure.

Table 2.2 presents the nineteen in situ measurements and the averaged IC values, which were used for correlation analysis. Table 2.3 presents the results of regression of CMV on DCP and moisture content, showing that moisture content is a statistically significant variable in the regression (p -value ≤ 0.05). The R^2 and adjusted R^2 for this linear regression are 0.40 and 0.32. Table 2.4 summarizes the correlation coefficients for all possible pairs of measures. High CMV and MDP values implies high soil stiffness. Since FWD and LWD are measures of deflection as an impulse response to a falling weight, high FWD and LWD values indicate low soil stiffness. DCP penetration index is the rate of penetration of the cone of DCP per blow. A high DCP penetration index indicates a rapid penetration or low soil stiffness. Hence, DCP penetration index should be positively correlated with FWD and LWD, but negatively correlated with CMV and MDP. FWD tended to have the highest correlation with the other measures. This result is expected from a statistical standpoint if FWD measured the stiffness of soils with the least error.

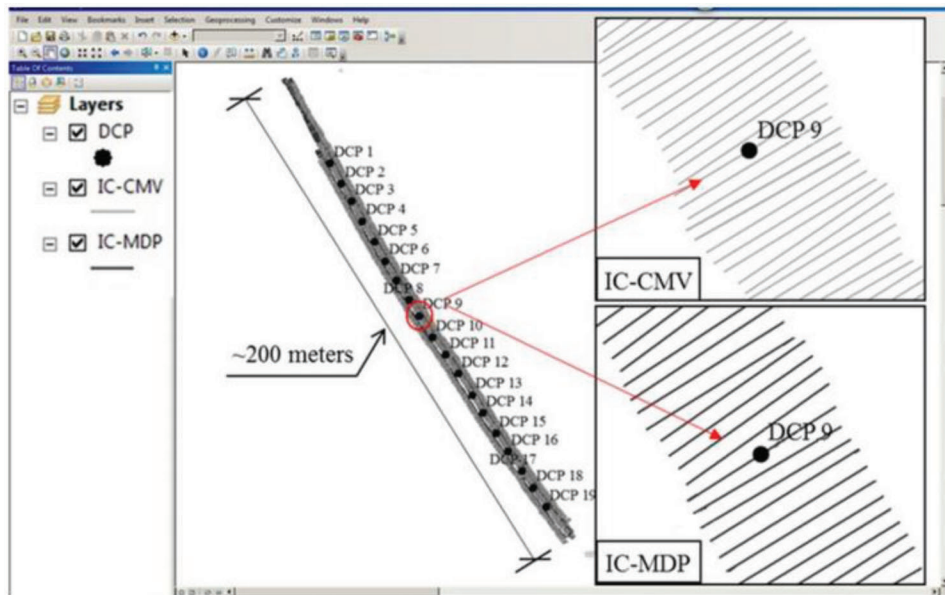


Figure 2.4 IC and in situ data in GIS.

TABLE 2.2
In Situ Measurements and Averaged IC Values for the Test Points

Point ID	MDP	CMV	DCP	LWD	FWD	Moisture (%)
1	126.21	25.54	0.41	0.79	145.58	6.40
2	123.34	16.79	0.25	1.25	283.74	10.20
3	122.11	6.65	0.32	0.90	285.47	11.70
4	119.04	9.86	0.32	1.27	326.23	11.10
5	118.33	6.12	0.38	1.82	415.69	11.50
6	122.41	6.75	0.32	0.72	209.80	13.80
7	125.30	8.80	0.32	0.67	187.18	11.00
8	130.49	25.32	0.36	0.54	94.54	12.10
9	127.13	19.19	0.40	0.98	189.90	11.00
10	123.19	10.05	0.32	1.13	222.78	13.80
11	122.72	9.17	0.32	0.85	300.17	13.40
12	120.16	6.40	0.32	0.68	205.96	13.10
13	117.49	5.78	0.60	1.29	457.41	12.10
14	113.50	7.94	0.71	3.53	553.61	12.70
15	116.20	7.91	0.40	0.95	376.19	13.80
16	115.56	7.53	0.50	1.32	272.93	11.50
17	117.28	8.99	0.48	1.22	315.84	11.00
18	115.00	6.66	0.80	2.16	506.80	11.10
19	116.98	6.49	0.57	3.47	546.63	10.80

TABLE 2.3
Results of Linear Regression of CMV on DCP and Moisture

Term	Coefficients	Standard Error	t Stat	P-value
Intercept	41.039	9.400	4.366	0.000
DCP	-13.401	8.229	-1.629	0.123
Moisture_Percent	-2.113	0.712	-2.967	0.009

CMV had the lowest correlation with the other measures on this test strip including DCP penetration index. This is likely, in part, due to mechanical issues observed with that CMV machine resulting in a much higher degree of

variability than another CMV-equipped machine observed on the site that day. Contrary to the generally low correlation with other measures, CMV did exhibit a relatively high correlation with MDP. Figure 2.5 shows a

TABLE 2.4
Correlation Matrix for IC and In Situ Measures

Variable	MDP	CMV	DCP	LWD	FWD
MDP	1.000				
CMV	0.752	1.000			
DCP	-0.647	-0.264	1.000		
LWD	-0.649	-0.343	0.709	1.000	
FWD	-0.842	-0.611	0.732	0.853	1.000

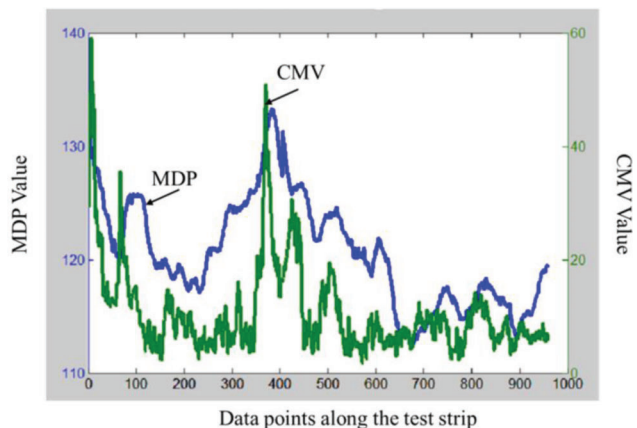


Figure 2.5 Comparison between CMV and MDP along the test strip.

comparison of the corresponding data streams of CMV and MDP along the test strip, which did seem to explain this particular result. There is apparently some significant parameter that causes both of these stiffness measuring techniques to trend in similar fashion despite the fact that they do not correlate equally well with the DCP, LWD, and FWD in situ measures.

2.2.4 Findings from Statistical Analysis of Field Test Strip

Four points may be made from the statistical analyses. First, there is the necessity of window-averaging the IC data and the matter of how the window-averaged IC measures relate to other measures of strength/stiffness. The high short-term variability in the CMV measure around an in situ point test indicates that an average CMV value in a window is an appropriate representation of local area strength/stiffness. The high short-term variability may be explained by the undulating nature of the compacted soil the roller drum travels over (i.e., the impulse response of the CMV is not taken in strips over a uniformly smooth sheet but an irregular ground surface). When point measures of strength/stiffness are compared to IC data, the best relationship was obtained by using an average IC value computed over a window of ± 5 meters centered at the point measure location, though we note that three and seven meters were also consistently close in fit. This result was derived empirically on this project but makes sense given that the zone of influence of the in situ point

measure tests extends outward from the surface point of impact.

Second, in general, the more similar the measurement system, the stronger the relationship observed in the correlation values. The measurement systems which were compared statistically are either used or proposed for use in QC/QA. FWD and LWD are designed to measure an impulse response at a localized area around a point, while CMV measures an impulse response on a narrow strip. MDP is a dynamic measure of resistance to motion. DCP measures resistance to penetration, or shear strength, in a localized area under a point. As should be expected from these distinctions, the FWD and LWD are the most strongly related. The main exception seemed to be the CMV data, which did not correlate highly with other measures. After the data collection it was determined that that machine had a much higher coefficient of variation and a video recording of the data collection revealed a loose scraper blade on the steel drum roller, which likely distorted the sensor readings. This apparent signal interference emphasizes the need for considering sensor data quality in the regular maintenance of machines equipped with this system. The DCP penetration index was reasonably well correlated with the LWD, both commonly used QA measures.

Third, the relationship observed between CMV and DCP was quite weak. This observed relationship was perhaps influenced negatively by the noted shortcoming in the operating condition of the smooth drum roller. A subsequent comparison of data available from another CMV-equipped roller working in the same area with both the original CMV roller data and the MDP roller data seemed to confirm this conclusion because the data from the other CMV roller exhibited less variability and a stronger correlation with the MDP data. However, there was no data from this machine to correlate with the point measures employed in the controlled test area. The low correlation with the standard acceptance measure, in this case DCP, indicates CMV to be more suitable for flagging significantly weaker areas rather than for replacing DCP for acceptance testing. Consideration of the other data on the overall project would inform the final conclusion regarding this question.

Fourth, there is a seemingly contradictory result of a strong relationship of CMV to MDP and a weak relationship of CMV to the in situ measures. The strong relationship between CMV and MDP also gives hint to the existence of a common variable influencing the two

measures that does not affect the in situ measures. The researchers hypothesize that ground surface characteristics (i.e., shape or smoothness) or mechanical characteristics of the ICMs may be culprits.

2.3 Overall CMV and DCP Comparison

Following the field test strip investigation, the Research Team continued its efforts to analyze the relationship between IC-CMV and DCP for the U.S. 31 project. Employing the same methodology as that outlined for the field test strip investigation, correlation analysis was conducted for all matches of the DCP test points and associated field moisture with the window-averaged CMV values extracted from the IC mapping.

Inherent variability emerged as a key influencer in the correlation analysis. For the first 17 points from the project, an R^2 of 0.705 (and adjusted R^2 of 0.659) was obtained, indicating a reasonably strong correlation. However, from analysis of all 74 matching test points, R^2 of 0.461 (and adjusted R^2 of 0.446) was obtained, considered a weak correlation. In this latter result, it was recognized that field moisture was more variable and thus yielded more predictive power, while counter to that benefit, it was noted that the CMV values were also more variable. These two observations denote the greater heterogeneity of project conditions through the larger scale and duration of embankment construction and raise questions regarding other possible influencing factors. The Research Team was able to investigate a few additional questions and concluded as follows:

- Statistically, there was no apparent machine-by-machine contribution to the variation in the larger data set (notwithstanding the ICM maintenance issue discovered with the field test strip).
- Taking the DCP measurement just prior or after CMV mapping did not seem to matter.
- There were no significant time trends on the error terms, indicating that the variability was randomly distributed over the duration of the project.

The Research Team inspected the distributions of CMV, DCP, and percent moisture and was able to make some observations regarding the extreme CMV values:

- The largest CMV values were associated with medium high DCP values but very high moisture levels. On the other hand, the lowest CMV values tended to be associated with lower DCP and lower moisture levels, although this relationship was not strong. This latter outcome cast some doubt on how well low CMV values could predict low DCP values.
- A sampling bias exists in the data set which diminished the opportunity to be conclusive about the relationship between low CMV and low DCP values. In practical terms, the sampling bias stemmed from an absence of data when weak areas were flagged by IC mapping. When the roller operator flagged an area as weak (by CMV mapping criteria), that area was reworked before a DCP measurement was made and recorded. The DCP measurement should have been taken first and thus made available

for analysis. If immediate DCP measurements had been taken for all such flagged areas, the results could look very different.

2.4 Overall MDP and DCP Comparison from U.S. 31

The May 2013 field test afforded the Research Team's first opportunity to examine the relationship between MDP and DCP. Following that investigation, additional mapping was performed on the U.S. 31 project using the MDP-equipped machine, for a total of 25 points that could be analyzed. The small size and circumstances of this combined data set dictate that the results be taken as preliminary.

Consistent with the earlier analysis, the total data set of 25 DCP measurements had a better fit with the MDP average values than observed with the CMV-DCP pairings. A reasonable R^2 of 0.66 (adjusted R^2 0.63) was obtained. Inspection of MDP, DCP, and percent moisture distributions revealed that the highest MDP values tended to correspond to high DCP values and somewhat higher percent moisture, and the lowest MDP values tended to correspond to low DCP and low percent moisture values. An additional complicating factor, however, is that the handful of points from which data was collected after the field test strip investigation were distinctly different from the former set, having lower MDP averages, lower soil moisture and somewhat lower DCP values, than those from the test section. Therefore, regarding the data set for MDP from the U.S. 31 project, although MDP values appeared to correlate better than CMV with DCP, considerably more data, obtained from various conditions, should be analyzed before strong conclusions can be put forward for IC-MDP implementation.

2.5 MDP and DCP Comparison from U.S. 50

Although identified as an appropriate opportunity to collect additional data for the analysis of correlation between MDP and DCP, the U.S. 50 project ran into numerous issues resulting in an insufficient quantity of data becoming available to provide any new insights into effective implementation of IC-MDP. The experience, however, did highlight important lessons for further study and implementation of IC on transportation construction projects which will be elaborated in the next chapter.

2.6 Overall Discussion

Perhaps, the most noteworthy result is the varying degree of correlation, as measured by the correlation coefficient, R^2 . Although all the CMV data came from the U.S. 31 project, the R^2 values varied substantially between (1) the first 17 data points, (2) the 19 points from the May 2013 test strip study, and (3) the full data set of 74 points. As hinted in Section 2.3, there may be significant influencing factors other than moisture that introduce significant variations in the correlation

between DCP and IC-CMV values. One of those may be variation in the soil type. White et al. (2007) concluded that MDP is more effective than CMV for cohesive soils, so the CMV measure is more appropriately applied to mapping non-cohesive soils. However, soils are generally heterogeneous, resulting in varying degrees of cohesiveness. Even if a scale for this parameter were developed, the changes that are typical within fill material (borrow) sources are such that this influencer cannot be practically controlled, so the kind of variation observed on the U.S. 31 project is probably indicative of what can be expected under normal project conditions and indicates that attention to the setting and adjustment of target IC values is appropriate.

The data bias that was also noted in Section 2.3 should be addressed in further study so that confidence in the target CMV can be increased. Accordingly, false identifications of weak areas can be minimized through the understanding that would be obtained from further investigating the correlation between lower DCP and CMV values.

The rather variable correlation between CMV and DCP measures points toward the aim of IC implementation being to reduce the DCP testing requirement to the evaluation of areas flagged by the IC measure rather than replacing the DCP test. Thus, the IC mapping would be aimed at assuring consistency in surpassing some predetermined minimum “strength” in the embankment. For this objective to be met, however, further investigation is necessary, particularly to arrive at the level of confidence alluded to above in the IC values that correspond to the lower DCP values.

Another element to be considered in developing effective practices toward implementation is the use of IC for monitoring compaction progressively rather than simply mapping the lift after the final pass. It remains to be seen whether this approach would provide knowledge that would reduce the number of passes performed, but it would certainly help operators to be more efficient by showing in real time when an area needs no further compaction. It was noted during one of the U.S. 50 project meetings that the compaction equipment models used in this study, while suitable for the mapping task, were not the models suited for production but that the manufacturer (Caterpillar) had near term plans to equip production machines so that compaction of each lift can be monitored from start to finish.

3. LESSONS LEARNED

While verification of the relationship between IC measures and the standard DCP field measure was a central component of this study, just as important is what could be learned regarding best practices for successful future study of IC and for future implementation of IC as a part of the QC/QA procedures for INDOT projects. Both projects revealed important issues that are now enumerated, in which communications are identified as the key to the success of IC implementation.

3.1 Field Data Collection Protocols

In a situation where a research team’s activities are ancillary to the execution of a construction project, it becomes important that mechanisms exist to assure that the research team is able to acquire the data necessary for analysis. Otherwise, an “out of sight, out of mind” mentality can easily set in during the day-to-day progress of the construction project. An unfortunate outcome from the U.S. 50 project was insufficient data for correlation analysis, specifically GPS coordinates did not accompany most of the DCP tests that were performed. For the standard practice of relying solely on an in situ test method such as DCP for QC/QA, documenting location by station and offset would be satisfactory, but as presented in Section 2.1, correlating a local average value for the IC measure to an in situ measure calls for greater precision in locating the in situ test point. There was an apparent lack of understanding of data needs by the persons collecting the DCP and moisture data, perhaps due to the organizational separation of field personnel from those who made the commitments and perhaps due to the number of hand-offs involved in the data collection and management process. High-level commitments were made to provide data as requested, but field personnel defaulted repeatedly to the simpler practice of documenting locations without GPS, not being mindful of the correlation analysis the Research Team was poised to conduct.

Therefore, it seems necessary that data collection responsibilities should be (1) formally established and (2) outlined in writing. Not to be confused with the special provisions that were provided to inform the Contractor of expectations regarding methods for employing IC technology, the lesson learned here is the need to give named parties written instructions once their role has been determined, preferably, during a pre-construction meeting. Specific individuals need to be given roles regarding data, and for their role, there must be clearly documented instructions, ideally in the form of a checklist of what is to be done for the data collection that requires sign-off by the data collector. Among other things, this checklist must require that in situ tests are located and documented by GPS coordinates. Creating and maintaining such a document would also salvage such occurrences as the reassignment and replacement of key staff involved with the data collection and management process, something that actually happened on the U.S. 50 project. A practice of this fashion as a project deliverable should be a high priority in future studies and projects and should be prescribed in special provisions.

In addition to identifying and securing the attention of field personnel to the data needs of the researcher(s), the execution of the research would be aided by also designating a single point of contact who has the authority to issue directives when agreed-upon arrangements for data acquisition are not being met. Ideally, this individual would also be someone who assumes the role during the pre-construction (or other organizing)

meeting and may be someone other than the Business Owner for the research study.

As noted in Section 2.2.4, the CMV parameter being based in the vibratory mode of the IC machine means that the Contractor must guard against any condition that introduces sources of vibration other than the roller drum-soil system. It is apparent that the sensor system does not distinguish between the vibratory response from the soil and vibrations from other sources. In this instance, a loose scraper bar banging against the roller drum was the source of an additional vibration, but the Contractor should be on guard generally against any such sources of vibratory noise so that the cleanest practical IC measure is obtained, which again speaks to the measure of confidence that can be placed in the IC measure.

Finally with respect to DCP and field moisture data collection in the further investigation of IC technologies, there are a couple of items that are important to maintain: (1) the random selection of locations for the in situ DCP tests, and (2) being aware to take an accurate dynamic cone penetration index (DCPI) measurement (depth of penetration per blow count) when the soil is hard. Regarding the former, the standard procedures call for randomization of the locations so that construction engineers can have confidence that the tests are representative of the overall quality of the embankment. Ultimately, one would like to use an IC mapping technique to assure minimum uniform “strength” as calibrated by the relevant “gold standard” measure. If an IC measure is to be validated as a reliable alternative, it should be based upon correlations that are established against a properly representative set of DCP values. A satisfactory correlation from such a comparison inspires confidence that the IC measure would most probably assure acceptance of at least the same level of quality as would be obtained by the DCP measure. Regarding the DCPI, the individual doing the DCP tests should have a measuring tape on hand to accurately measure the penetration achieved when the maximum of 25 blows is achieved with less than the standard 12 inches of penetration. Because a measuring tape was not on hand during the May 2013 field test strip, the DCPI measurements had to be estimated and were therefore less precise than desired.

3.2 Data Management Protocols

Data management protocols emerged as a key consideration for effective implementation of IC for QC/QA. IC allows a complete measurement of soil strength/stiffness for practically the entire project site, generating huge amounts of data. In the near and mid future, IC and in situ measures for soils are expected to co-exist, leading to the heterogeneity of soil compaction quality data. How to effectively process, analyze, and manage the heterogeneous and large volume of soil compaction quality data will remain a challenge for SHAs. A number of data management lessons learned through this

study will inform the establishment of best practices in the data management aspect.

First, it is extremely important to have a data management process that has been tested and corrected for errors. For the U.S. 31 project, raw GPS coordinates for IC measures were recorded using a local coordinate system and then converted to Universal Transverse Mercator (UTM) coordinates while the location of DCP tests was recorded directly using UTM coordinates. The plan for the test section reported here was initially prompted by evidence of an error—a discrepancy between US Survey Foot and International Foot, as it turned out—in the conversion equations causing the misalignment of DCP points to IC measures and leading to incorrect observations regarding the correlation between DCP measures and IC measures. Had this error not been identified and corrected, any future analyses using this group of data would have been invalid. Ideally, a common coordinate system for both DCP and IC data should be chosen at the beginning of the project, so that translation errors are not introduced.

Second, presently IC data is underutilized during the construction phase. IC rollers are typically equipped with an in-cab screen display to geospatially visualize IC measures as the roller moves. Analytical capabilities such as calculating variance, a critical factor to the long-term pavement performance, in user-specified sections and correlating in situ measures to IC measures in real time are lacking. Without such real time analytical capabilities, a huge opportunity for improved quality assurance is lost.

Third, a platform is needed to manage heterogeneous data. This study adopted a GIS platform that greatly facilitated the data management and analysis tasks. Almost all SHAs have enterprise GIS databases and thus, soil compaction data, after being brought into a GIS format, are compatible with existing organizational data structure. They can be readily incorporated into the enterprise GIS databases to support decision-making in the future.

Fourth, an unforeseen change in the IC technology underscored the necessity of having a representative of the IC technology manufacturer involved with the project. In this instance, the MDP technology manufacturer (i.e., Trimble) made a change in the underlying data structure before the start of the U.S. 50 project, something not readily apparent to an IC user because the presentation of the mapping information to the roller equipment operator was not changed. The Research Team noted discrepancies upon inspection of the data downloaded from the cloud site and needed SITECH, a Trimble dealer, to delve into the new data structure and reformat the IC data to suit the Research Team’s predetermined analysis methodology. It is not difficult to see, therefore, that ready access to a knowledge resource for the underlying data structure is desirable to facilitate any post analysis using the IC data.

4. RECOMMENDATIONS

Following are the recommendations of the Research Team regarding the prospects of IC technology as a component of INDOT's QC/QA for soils. Further study is needed, however, so some points regarding future study of IC are also cited.

Based on the results that have been obtained, the Research Team recommends that INDOT continue to pursue the incorporation of IC mapping as part of QC/QA for soils. The primary aim should be to employ IC to confirm minimum uniform "strength" in the embankment as calibrated by the relevant "gold standard" of DCP. IC mapping also should serve the needs of the Contractor for obtaining more immediate feedback and permitting work to proceed with fewer interruptions for in situ tests. In that regard, IC is suitable for QC and might be implemented as such in the nearer term. Greater confidence in the target (threshold) IC value must be achieved for its use in QA, which necessitates even further study.

Because of the heterogeneity of soils, further study of IC should include both of the two primary categories of IC technologies, accelerometer-based and the energy-based techniques, because the latter is known to be more effective for cohesive soils. For this study, Caterpillar's proprietary version of CMV was studied, but there are at least six other manufacturer versions available in the U.S. This means that more important than the manufacturer is the procedure for setting the IC target value for each project. Furthermore, implementation on pilot projects is recommended before fully adopting IC for QC in all INDOT's projects.

The Research Team's study of MDP correlation to DCP from the U.S. 31 project was limited but showed a considerably stronger relationship with DCP than was revealed for CMV. This observation is consistent with the conclusion by White et al. (2007) that MDP is more effective than CMV for cohesive soils. Thus far, the data available to the Research Team is inadequate for actionable conclusions, and further study of MDP should be conducted on a future construction project on a large scale.

The implementation of a new technology for monitoring quality, especially an automated technique like IC, has important implications for the standard of practice and expectations an SHA can maintain of contractors who construct their projects. The implementation of IC requires that not only INDOT, but its project partners also, become knowledgeable and proficient in the application of IC technologies. If INDOT determines to pursue the implementation of IC, the industry statewide will need to be educated and encouraged to develop capability and proficiency in implementing IC. Such adoption of IC should be advanced by INDOT in collaboration with its project partners. The ICA/INDOT Joint Cooperative Committee is a standing partnership that might deliberate stakeholder interests and facilitate education regarding IC across the state. Therefore, as new projects come on line,

project stakeholders will have already been primed to participate in a successful implementation.

A final recommendation is that INDOT consider advocating a new Pooled Fund study with interested State DOTs in the region as a relatively inexpensive way to answer questions of IC correlation with a variety of in situ tests and to share best practices for data collection and management. Given the array of influencing variables noted in this study and the "gold standards" that exist for QA, a pooled fund study to collect IC data from broad range of soil types may be the most efficient way to confirm the efficacy of IC for soils QC/QA. This study would involve a collection of studies like that conducted for U.S. 31 where data is obtained from selected construction projects among which some employ brands of accelerator-based IC and MDP technologies.

5. CONCLUSIONS

This study has had as its objective to evaluate the extent to which INDOT might rely upon IC mapping if the agency were to incorporate the technology in their program of QC/QA for soils. Using data obtained during the execution of actual construction projects, the Research Team has studied two IC technologies—CMV and MDP—the former an accelerometer-based method and the latter constituting an energy-based method. The Research Team performed analyses of the correlation between each IC measure and INDOT's standard DCP test measure by using ± 5 m window averaging of the respective IC measure matched against each corresponding geo-located DCP test value. While two INDOT construction projects were designated as data sources, only one of the two projects, U.S. 31 Kokomo, yielded sufficient data for the Research Team to gain some of the insight that was sought. While this project primarily employed CMV, a designated field test strip provided the opportunity to obtain some MDP data and to compare the CMV and MDP measures against three different types of in situ test methods—DCP, LWD, and FWD.

In summary, the correlation between CMV and in situ tests was quite variable, discouraging notions of CMV as a total replacement for DCP testing. However, insights on the influence of soil moisture, recognition of unintended but preventable sources of noise in the sensor readings, and a recognition that the accelerometer-based CMV technique does not perform as well on cohesive soils leads the Research Team to the present conclusion that CMV should be investigated further for non-cohesive soils in the context of actual construction projects. Due to data collection bias that was noted, the appropriate reliability on lower range values of CMV also remains unanswered. Although the data for MDP was much less, the correlations were observed to be strong and consistent enough to inspire the conclusion that it should also be investigated further, especially in light of the fact that MDP performs better on cohesive soils than CMV with respect to correlation with the DCP measure. Overall, indications are that IC might be effectively applied to at least

reduce the number of DCP tests required for QC/QA, but more knowledge and experience should be gained by both INDOT and the contractors who would employ the technology.

Equipment manufacturers appear to be committed to making IC technology available to the construction market. The Research Team, based upon their conviction that more must be learned about the reliability of IC measures, recommends that INDOT pursue implementation of IC through further pilot projects with the initial aim of establishing its use by contractors as a QC tool. Studied experience gained through this adoption for QC can also facilitate further evaluation of IC for QA by more comparisons of IC mappings of compacted soils with the agency's standard acceptance test measurements on actual construction projects. In both efforts, if IC continues to show promise, the investigation should be complemented with an industry dialogue to prepare project stakeholders to maximize the benefits of IC. Well-considered protocols for data collection, analysis, and communications commitments between stakeholders should be designed to the mutual benefit of both parties. The long-term goal is to implement specifications and corresponding practices that accommodate various IC measures, thus enabling contractors' effective technology adoption, and to alleviate at least some of the necessity for in situ DCP measurements while assuring INDOT of quality in the constructed embankment.

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