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Experimental verification of roller-integrated compaction technologies

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by

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CHAPTER 1: Introduction

Overview

Roller-integrated compaction technology was introduced in Europe more than 30 years ago as a new quality acceptance method for earthwork construction when field tests confirmed that the behavior of a vibrating roller drum can be correlated to the compaction effect and bearing capacity of compacted materials (SGI 2006). Specifications for this method of "continuous compaction control" have existed since 1990 (in Austria). Based on positive European experiences since this time, the technology has more recently been incorporated into quality acceptance practices of the United States (Wilkens 2006, White *et al*. 2008). The use of such technology is anticipated to increase in upcoming years. Transportation agencies and earthwork contractors are implementing the technology with the expectation that the systems will: (1) improve construction efficiency, (2) streamline quality management programs of earthwork projects, (3) better link quality acceptance parameters and documentation with pavement design, and (4) improve the performance of compacted materials (Briaud and Seo 2003, Petersen *et al*. 2006). To realize these expectations and accelerate the implementation of roller-integrated compaction technologies into practice, detailed field studies are needed to better understand the systems.

The roller-integrated compaction systems have been studied by a number of investigators at various U.S. institutions over the past five years. These studies, many of which are summarized in Table 1.1, focus on exploring roller behavior occurring during soil compaction or validating the roller-measured parameters by comparing the measurement values with soil properties measured using alternative testing technologies.

Successful implementation of roller-integrated compaction technology requires knowledge of the compaction systems and how their measurement values are related to the properties of compacted soil (e.g. California bearing ratio, modulus, resilient modulus). The relationships between roller-integrated measurement values and soil engineering properties have previously focused on calibration equations that relate the measurement values to soil modulus measured with static plate load tests (e.g. E_{V1}, E_{V2}). Anderegg and Kaufmann (2004) and Preisig *et al*. (2003) have shown linear relationships between roller-measured stiffness and plate moduli. Regrettably, plate load tests are more frequently performed in Europe for quality acceptance than in the United States. This research, therefore, makes special effort to identify the relationships between roller-integrated measurement values and various measures of density and soil stability (e.g. DCP index, Clegg impact value).

The complexity of characterizing machine response during soil compaction operations can, in part, be attributed to the complexity of the soil compaction process. Soil type, moisture content, lift thickness, and compaction method are factors affecting soil compaction. The same factors, therefore, affect roller-integrated compaction measurements. The roller-measured values may also be influenced by roller operational parameters, including roller size, vibration amplitude, vibration frequency, and speed. This research investigates how these parameters influence the relationships between in-situ and roller-integrated compaction measurements. The approach taken for this research was to either isolate such parameters or measure the parameters during compaction and testing operations. For the latter case, the measured parameters were used as independent variables in conducting multiple linear regression analyses for predicting various soil properties.

Research Objectives and Scope

The primary objectives of this research included: (1) correlation of roller-measured parameters with the in-situ compaction measurements that are commonly used in the United States for earthwork quality assurance, (2) identification of the various factors affecting machine response during compaction and how these factors affect the roller parameters, and (3) investigation of roller-integrated compaction measurements throughout the soil compaction process. Achieving these objectives promotes more effective and appropriate use of the roller-integrated compaction technologies.

The research comprising this dissertation is a series of field studies which are part of a larger, comprehensive research program. The cogent research effort uses experimental and statistical analysis methods to validate roller-integrated compaction technology. The first field study, which is documented in Chapter 2, evaluates a vibratory-based system under project conditions. The testing and data analysis demonstrates the feasibility of having roller-integrated compaction technology indicate the properties of subgrade and granular pavement layers. The study provided prerequisite justification for more detailed study of roller-integrated compaction systems in a controlled environment.

The second and third field studies (Chapters 3 and 4, respectively) are conducted to better identify the relationships between roller-integrated and in-situ compaction measurement values. Testing for these studies was performed on carefully-constructed test strips at multiple stages of the soil compaction process. Chapter 3 focuses on the correlations observed for five granular soils in order to demonstrate the need for soil-specific roller calibration. Chapter 4, which describes research performed using static padfoot roller for compacting cohesive soils, expands upon Chapter 3 to include the influences of moisture content and lift thickness – influences which are known to affect soil behavior and machine response. Findings from these studies aid in interpreting roller-integrated compaction measurements and, ultimately, implementing the compaction technology into practice.

The fourth field study (Chapter 5) is conducted to assess how the roller calibration equations obtained from test strips are applied to larger, two-dimensional test areas. Having constructed, compacted, and tested with independent testing technologies a controlled test area with variable lift thickness and moisture content, the calibration procedure proposed in prior studies can be evaluated. Chapter 5 documents the roller calibration operation with test strips, as well as how the quality criterion from the calibration is applied to spatial data to create pass/fail maps based on roller-integrated compaction data.

The roller-integrated compaction data in Chapter 5 demonstrates how vibratory-based systems are influenced by lift thickness and the properties of compaction and underlying soil layers. Further, literature addressing vibratory-based compaction technology has noted measurement depths exceeding compaction layer thicknesses to be a significant challenge in properly interpreting roller-integrated compaction measurement values. Therefore, using data from Chapters 2 and 5 and findings from in-ground instrumentation studies, a two-layer soil system is characterized using elastic analysis and documented in Chapter 6. The primary purpose of the analytical study was to *quantify* the influence of compaction layer thickness and underlying layer stiffness on machine response at the soil surface.

Dissertation Organization

This dissertation is comprised of five scholarly papers that have been submitted to geotechnical engineering journals for publication. The technical papers, each of which appears as a separate chapter, address specific issues related to experimental validation of roller-integrated compaction technology. These chapters, therefore, include the components of a stand-alone investigation (e.g. background, data, analysis, findings). Following these chapters, the research program is summarized and the most significant research findings are highlighted.

The first paper (Chapter 2) presents results from a pilot project conducted at US 14 in Minnesota. The study was comprised of proof testing strips using an Ammann vibratory smooth drum roller. The study findings show that roller-measured stiffness can be empirically related to in-situ compaction measurements, but that the strength of correlation depends heavily on the range of values over which the measurements are taken. The intelligent compaction system also identified areas of unstable subgrade material in a manner similar to test rolling.

The second paper (Chapter 3) evaluates *compaction meter value* (CMV) and *machine drive power* (MDP) roller-integrated compaction technologies. The experimental testing of five test strips each constructed with a different granular material provided roller data and in-situ measurements for several stages of compaction that were used in performing statistical regression analyses. The research findings documented in the paper demonstrate statistical analysis techniques for which calibration procedures using roller-integrated compaction technologies may be developed.

Following the findings in Chapter 3, the third paper (Chapter 4) evaluates MDP technology for predicting the compaction parameters of cohesive soils considering the influences of soil type, moisture content, and lift thickness on machine power response. Predictions of in-situ compaction measurements from MDP were found to be highly correlated when moisture content and MDP-moisture interaction terms were incorporated into a compaction model derived from laboratory moisture-dry unit weight-compaction energy relationships.

The fourth paper (Chapter 5) investigates how roller-integrated compaction technology may be addressed in specifications for using the technology in practice. After correlating CMV and MDP to in-situ compaction measurements using data from test strips, a two-dimensional test area with variable lift thickness and moisture content was constructed and tested. The spatial distribution of the data was investigated. The paper demonstrates field calibration with both one-dimensional and two-dimensional tests areas and also introduces a new approach to generating pass/fail criteria based on roller-integrated compaction technology.

The fifth paper (Chapter 6) acknowledges how roller-integrated measurement values are affected by the upper compaction layer, as well as underlying soil layers. The analytical study attempts to characterize a two-layer soil system for better interpreting roller-integrated compaction measurement values for such conditions. Using the validated model, the paper then makes inferences about the influence of layer thickness and elastic modulus on roller-measured stiffness that are supported by both experimental and theoretical evidence.

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Table 1.1. Summary of roller-integrated compaction technology research projects conducted in the United States

Project Title	Year	Investigators	Sponsor
Exploring Vibration-Based Intelligent Soil Compaction	2003	Mooney, M., Gorman, P., Tawfik, E., Gonzalez, J., and Akanda, A.	Oklahoma DOT, FHWA
Intelligent Compaction: Overview and Research Needs	2003	Briaud, J.L. and Seo, J.	FHWA, Texas A&M
Field Evaluation of Compaction Monitoring Technology: Phase 1	2004	White, D., Jaselskis, E., Schaefer, V., Cackler, E., Drew, I., Li, L.	Iowa DOT, FHWA
Continuous Compaction Control MnROAD Demonstration	2005	Petersen, L.	Minnesota DOT, FHWA
New Technologies and Approaches to Controlling the Quality of Flexible Pavement Construction	2006	Scullion, T., Sebesta, S., Rich, D., Liu, W.	Texas DOT, FHWA
Field Evaluation of Compaction Monitoring Technology: Phase 2	2006	White, D., Thompson, M., Jovaag, K.	Iowa DOT, FHWA
Advanced Compaction Quality Control	2006	Zambrano, C., Drnevich, V., Bourdeau, P.	Indiana DOT, FHWA
Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials	2007	White, D., Thompson, M., Vennapusa, P.	Minnesota DOT, FHWA
Field Study of Compaction Monitoring Systems: Self-Propelled Non-Vibratory 825G and Vibratory Smooth Drum CS-533E Rollers	2007	White, D., Thompson, M., Vennapusa, P.	Caterpillar Inc.
CAREER: GeoWorks: Multidisciplinary Design Studio Fostering Innovation and Invention in Geo-Construction through Research, Development and Education	2007	Mooney, M.	National Science Foundation

Intelligent Soil Compaction Systems	Active	Mooney, M. and White, D.	NCHRP Project 21-09
Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material	Active	*	FHWA Pooled Fund Study TPF-5 (128)
Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrade and Structural Layers	Active	*	Wisconsin DOT
Demonstration of Intelligent Compaction Control for Embankment Construction in Kansas	Active	Hossain, M., and Romanoschi, S.	Kansas DOT
* Investigators to be determined			

CHAPTER 2: Variable Feedback Control Intelligent Compaction to Evaluate Subgrade and Granular Pavement Layers – Field Study at Minnesota US 14

A paper to be submitted to the *Transportation Research Record: Journal of the Transportation Research Board*

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Abstract

The feasibility of using variable feedback control intelligent compaction to evaluate the properties of subgrade and granular pavement layers was investigated at US 14 in Minnesota. The study was comprised of proof testing strips using an Ammann vibratory smooth drum roller. The soil of the test strips was then evaluated with the various portable testing devices commonly used for quality control and acceptance. The research findings documented in this paper focused on: (1) relationships between intelligent compaction roller-measured soil stiffness and various in-situ measurement values, (2) performance of variable feedback control of amplitude and frequency, and (3) comparison of roller-measured stiffness with rut depth from test rolling. The study findings show that roller-measured stiffness can be empirically related to in-situ compaction measurements, but that the strength of correlation depends heavily on the range of values over which the measurements are taken. The intelligent compaction system also identified areas of unstable subgrade material similar to test rolling.

Introduction

The feasibility of using roller-integrated continuous compaction control (CCC) and intelligent compaction (IC) technology to evaluate the properties of subgrade and granular pavement layers has recently been investigated in the United States for the purpose of advancing quality control and acceptance (QC/QA) methods of earthwork construction (White *et al*. 2006, Thompson and White 2007a, White *et al*. 2007a, White *et al*. 2007b). Successful implementation of the compaction technology requires knowledge of the roller-integrated compaction systems and how their measurement values relate to soil properties. In addition, the capabilities and limitations of roller-integrated systems must be disseminated to transportation agencies and earthwork contractors.

The vibratory-based compaction technologies have demonstrated a clear empirical relationship to soil stiffness. In this regard, roller measurement values (MVs) and soil properties have been linked using calibration equations that relate the MVs to soil modulus measured with static plate load tests (e.g. E_{V1}, E_{V2}). Anderegg and Kaufmann (2004) and Preisig *et al*. (2003) have shown linear relationships between roller-measured stiffness k_s and plate moduli with stronger correlation observed for E_{V1} (initial loading) than for E_{V2} (reloading). Regrettably, plate load tests are more frequently performed in Europe than in the United States, and application of these published relationships is practically limited. The relationships between roller MVs and alternative in-situ compaction measurements (e.g. DCP index) must also be identified.

In this study, test strips comprised of subgrade and granular materials were proof tested using an Ammann vibratory smooth drum roller equipped with variable feedback control intelligent compaction technology and tested with nuclear moisture-density gauge, light weight deflectometer (LWD), dynamic cone penetrometer (DCP), Clegg impact tester, and static plate load tests. The research findings documented in this paper focus on: (1) relationships between roller-measured soil stiffness and various in-situ compaction measurements, (2) performance of variable feedback control of amplitude and frequency, and (3) comparison of roller-measured stiffness with rut depth from test rolling.

Ammann Compaction Expert (ACE) System

Description of Ammann Vibratory Smooth Drum Roller

An Ammann AC 110 vibratory smooth drum roller (Fig. 2.1) was used for the field study. The 11,575-kg roller has a drum diameter of 1.50 m and a drum width of 2.16 m. The static linear load caused by the drum is about 31.9 kN/m. Vibration amplitude for the roller ranges from 0.4 to 2.0 mm, while vibration frequency ranges from 25 to 35 Hz. For this study, the roller was not fitted with a GPS system. Rather, the roller stiffness measurements were output as a list of consecutive values and assigned to locations along test strips at 0.33 m intervals (i.e. 3 pulses per meter) (Anderegg 2005).

Manual and variable control modes of operation were available with the Ammann roller. In the manual mode, the roller operator can establish fixed vibration amplitude (as percent of maximum) or frequency (absolute value). In the variable control mode, the roller operator can select one of three "compaction power" levels corresponding to the maximum soil-drum interaction force which is controlled through the closed-loop feedback control system. The higher force level is anticipated to compact deeper than the lower force levels.

Soil Stiffness (k_S) Measurement

The basis for measuring soil stiffness using the dynamics of a vibrating drum is that soil behavior can be represented with a lumped-parameter, spring-dashpot model. This soil model, which is shown Fig. 2.2, is characterized by a spring with stiffness k_S and a parallel damper with damping constant c_S. The soil-drum interaction force (F_S) is then given by

$$F_s = k_s x_d + c_s \dot{x}_d \qquad (2.1)$$

where x_d is drum displacement and $\dot{x}_d$ is drum velocity. With increasing compaction, soil stiffness increases and soil damping decreases (Anderegg and Kaufmann 2004).

If the dynamic forces within the frame suspension are neglected, the steady-state equation of motion can be written as (Anderegg and Kaufmann 2004)

$$F_S = (m_f + m_d)\, g + m_e\, r_e\, \Omega^2 \cos(\Omega t) - m_d\, \ddot{x}_d \tag{2.2}$$

where m_f is the frame mass, m_d is the drum mass, g is the acceleration of gravity, $m_e\, r_e$ is the eccentric moment of the unbalanced mass, Ω is the circular vibration frequency, and $\ddot{x}_d$ is vertical drum acceleration. Equations (2.1) and (2.2) may then be set equal to each other to calculate soil stiffness or damping constants. At the time when the drum is at its lowest position, drum velocity and damping force ($c_S\, \dot{x}_d$) equal zero. Soil stiffness is then calculated as the ratio of the soil force F_S and vibration amplitude according to

$$k_S = 4\pi^2 f^2 \left(m_d + \frac{m_e\, r_e \cos(\varphi)}{A} \right) \tag{2.3}$$

where f is the excitation frequency, φ is the phase angle, and A is vibration amplitude (Anderegg and Kaufmann 2004). Soil stiffness k_S is exactly frequency dependent. Through the range of working frequencies, however, the stiffness is relatively constant (Preisig *et al*. 2003).

Intelligent Compaction: Feedback Control of Amplitude and Frequency

Roller-integrated compaction technology is often called “intelligent compaction” when the system includes not only near-continuous assessment of soil properties through roller vibration monitoring, but also on-the-fly modification of vibration amplitude and frequency (Mooney and White 2007). Performed in parallel with soil stiffness measurement, a closed-loop feedback control algorithm may increase the vibration amplitude and reduce the vibration frequency when the roller is operated on soft material. When operated on stiff material, vibration amplitude may be reduced and frequency increased. The anticipated benefits of variable feedback control features of intelligent compaction include: (1) more efficient soil compaction, (2) improved uniformity of compacted materials, (3) prevention of over-compaction, and (4) reduced vibration amplitudes in the vicinity of sensitive structures (Briaud and Seo 2003, Adam and Kopf 2004).

Measurement of vibration amplitude, phase angle, and excitation frequency during roller operation allows for calculation of soil stiffness and also facilitates the automatic feedback control of amplitude and frequency. The ACE system employs a force-based control system to limit F_S and avoid undesirable drum behavior modes through adjustment of excitation frequency (Anderegg and Kaufmann 2004). The unbalanced mass moment is controlled to maintain a pre-selected maximum soil force F_S. The excitation frequency is then adjusted to maintain phase lag between 140 and 160 degrees. For high force levels, vibration amplitude ranges from 2 to 3 mm and frequency ranges from 23 to 25 Hz. As the force levels are reduced, vibration amplitude decreases (to as low as 0.4 mm) and frequency increases (up to 35 Hz). The control system is further detailed in Anderegg and Kaufmann (2004).

Experimental Methods

Project Soils

Field compaction was conducted using two soils, namely subgrade and Class 5 granular materials. The subgrade soil classified as CL sandy lean clay (A-6), while the Class 5 material classified as SP-SM poorly graded sand with silt and gravel (A-1-b). The classification and index properties of the soils are summarized in Table 2.1.

Moisture-density tests were performed following Standard Proctor test methods. For subgrade material, the standard Proctor maximum dry unit weight was 16.16 kN/m^3 at optimum moisture content of 18.1 percent. The maximum dry unit weight for Class 5 material was 19.58 kN/m^3 at optimum moisture content of 8.1 percent.

Field Testing Methods

A calibrated nuclear moisture-density gauge (HS-5001B122) provided a rapid measurement of soil dry unit weight and moisture content (ASTM D 2922/3017). Generally, two measurements of moisture and dry unit weight at a particular location were obtained and averaged. For measuring dry unit weight and moisture content of subgrade materials, a transmission depth of 200 mm was used. The transmission depth for measuring dry unit weight of Class 5 overlying subgrade varied with the thickness of the granular material.

The dynamic cone penetrometer (ASTM D 6951) is a testing device that provides the stability characteristics of subgrade and granular pavement layers. The test involves dropping an 8-kg hammer 575 mm (i.e. drop height) and measuring the penetration rate of a 20-mm-diameter cone. DCP index, which typically has units of mm per blow, is inversely related to penetration resistance (i.e. soil strength). For testing granular materials, DCP index values represent the compaction layer thickness divided by the number of blows to reach the bottom of the compaction layer (i.e. average DCP index for compaction layer). For testing compacted subgrade, DCP index values represent the surface/compaction layer measurements.

Clegg impact tests (ASTM D 5874) were performed for obtaining the measure of soil stability. This test has been standardized as ASTM D 5874-02 for evaluating compacted fill and pavement materials. The Clegg impact value ($CIV_{4.5\text{-kg}}$) is derived from the peak deceleration of a 4.5-kg hammer free falling 450 mm in a guide sleeve for four consecutive drops.

A lightweight deflectometer manufactured by Dynatest, Denmark, was used to determine elastic modulus ($E_{LWD\text{-}K}$). In performing the tests, a 10-kg weight is dropped on rubber buffers to produce an impact load on a plate. A load sensor measures the load pulse, and a geophone at the center of the plate measures the corresponding soil deflection. Based on elastic halfspace theory, soil modulus is then calculated as

$$E_{LWD\text{-}K} \text{ or } E_{V1} = \frac{f\,(1\text{-}v^2)\,\sigma_0\, r}{h_0} \tag{2.4}$$

where v is Poisson's ratio ($v = 0.40$), σ_0 is the peak applied stress at surface, r is the plate radius, h_0 is the peak plate deflection, and f is a shape factor that depends on the assumed plate stress distribution (Dynatest 2004).

Static plate load tests were performed for elastic modulus (E_{V1}) of compacted soil using a 300-mm plate, a 90-kN load cell, and three 50-mm linear voltage displacement transducers. E_{V1} was calculated with Equation (4) using the stiffness response taken from 0.2 to 0.4 MPa plate stress for granular soil and from 0.1 to 0.2 MPa for cohesive soil.

Relationships between k_S and In-Situ Measurements

The empirical relationships between k_S and various in-situ test results were investigated by collecting the measurements on uniform and non-uniform test strips. The subgrade test strip shown in Fig. 2.3 was established perpendicular to the highway alignment and extended 45 m in length. The roller was operated over both pavement subgrade sections, crossing the comparatively soft median. This procedure resulted in a wide range of soil stiffness to be identified by the ACE system and in-situ testing devices. The roller was operated in the variable feedback control mode at the medium force setting. Following the second roller pass, the soil characteristics were determined at 30 test points spaced at 1.5 m.

Roller-measured stiffness k_S and in-situ compaction measurements are shown in Fig. 2.4 for the subgrade test strip. Near-continuous k_S is represented with a solid line, whereas in-situ testing results (e.g. $E_{LWD\text{-}K}$, E_{V1}, $CIV_{4.5\text{-}kg}$, DCP index, moisture) are shown as discrete points connected with a dashed line. The median location is also identified in the plot (see Fig. 2.4). Mean values and coefficients of variation C_V are provided for all measurements. Along the test strip, all subgrade stability measurements follow closely the roller-measured soil stiffness. Furthest deviation from k_S is observed in the median with Clegg impact values and DCP index. Alternatively, the light weight deflectometer and static plate load tests have measurement influence depths up to two plate diameters (Abu-Farsakh 2004).

To better identify the relationships between roller-measured stiffness and in-situ testing results, the compaction measurements are plotted against spatially-nearest k_S values in Fig. 2.5. Linear relationships were observed for all measurements except for DCP index, which was highly influenced by a single observation. Measurements were collected over a range of soil characteristics (i.e. roadbed versus median), and correlation R^2 values ranged from 0.49 to 0.80. As expected, highest correlation was seen with E_{V1}. k_S was also highly correlated with moisture content, which demonstrates the moisture sensitivity of soil stability to moisture content.

The test strip shown in Fig. 2.6 was comprised of granular material and extended about 120 m in length. The Class 5 material appeared to be uniform, with C_V for all measurements less than the subgrade test strip. The C_V values are comparable to values documented in White and Thompson (2007) and Thompson and White (2007b) for uniform test strips constructed using a reclaimer. The sensitivity of roller-measured stiffness to small changes in soil conditions was thus observed. The roller was operated in the variable feedback control mode at the medium force setting. Following the third roller pass, the soil characteristics were determined at 16 test points spaced at 7.6 m.

Compaction measurements are provided in Fig. 2.7 for the test strip comprised of granular material. For this more uniform soil condition, k_S ranged only from about 25 to 40 MN/m. Scatter plots relating the in-situ compaction measurements to spatially-nearest k_S are shown in Fig. 2.8. Because measurements were collected over a comparatively-narrow range of soil characteristics, weak relationships were observed for all measurements. Also, the in-situ tests are dominated by the upper layer and the roller k_S is dominated by the lower layer.

The current Mn/DOT specification for intelligent compaction systems requires construction of control strips for determining machine target values – a process that can be time consuming, expensive and, therefore, undesirable. New methods of establishing target values are under investigation. While recognizing that a project owner runs greater risk by not incorporating calibration into the quality acceptance process, an alternative approach to obtain a target value is to simply populate a database of target machine values that can be referenced by field inspectors. The database may include different intelligent compaction systems and roller configurations, soil types, moisture conditions, and representative lift thicknesses. The contribution by this study to such a database is provided in TABLE 2, which summarizes ranges of k_S and commonly-used in-situ compaction measurements.

Evaluation of Variable Feedback Control

The benefits of variable feedback control intelligent compaction have not been thoroughly investigated and supported with quantitative compaction data. In the present study, the ability of variable feedback control systems to produce compacted material with higher uniformity than material compacted with constant amplitude and frequency was investigated.

The test strip shown in Fig. 2.9 was comprised of Class 5. The granular material at this location had been placed by the contractor solely as subgrade cover for the winter months. Thus, the material had not yet been compacted. For the study, the 90-m test strip was compacted with three roller passes in the variable feedback control operation mode at the high force setting. Even though the intelligent compaction roller used for this study did not output vibration amplitude and frequency with k_S, changing operational parameters through the automatic feedback control algorithm was apparent during roller operation.

The distribution of roller-measured stiffness was observed for three consecutive roller passes over the above test strip. Fig. 2.10 provides the k_S histograms and summary statistics for the passes. Average soil stiffness decreased slightly from the first to the second roller pass. Further, C_V for the first, second, and third roller passes were 5, 7, and 9 percent, respectively. Therefore, these admittedly limited compaction data do not support variable feedback control systems as capable of improving the uniformity of compacted materials. It is also worth noting that the Class 5 material was initially placed with relatively uniform conditions, with C_V values less than previously presented in the paper for a uniform granular test strip. Increasing compaction was unlikely to produce more uniform soil. The performance of variable feedback control features of intelligent compaction technology must be further investigated, quantified, and documented in future studies.

Comparison with Test Rolling

A two-dimensional test area was established as four adjacent test strips, each 60 m in length and the width of the roller drum. The subgrade material was compacted with three roller passes. For the first and second lanes, the roller was operated in the manual mode with amplitude set to 80 percent of maximum. The roller was operated in the third and fourth lanes in the variable feedback control mode at the high force setting. k_S data for the first and third roller passes are shown in Fig. 2.11. The change in k_S resulting from compaction is also shown. The absolute values of soil stiffness between the passes are different. The spatial distribution of soil stiffness, however, is similar. The comparatively soft areas (e.g. first and second lanes from 35 to 45 m) and stiff areas (e.g. third and fourth lanes from 25 to 50 m) are observed for both passes to demonstrate measurement repeatability.

Test rolling served as acceptance testing for the constructed subgrade at US 14 (see Mn/DOT specification 2111). For this operation, a pneumatic-tired roller with gross mass of

27.2 metric tons and tire pressure of 650 kPa is towed by tractive equipment (see Fig. 2.12). The test rolling is performed by making two passes over each test area. The roadbed is considered to be suitable if, under the operation of the roller, the surface shows yield or rutting of less than 50 mm measured from the top of the constructed grade to the rut bottom. As the subgrade material was placed without compaction by the contractor at the location of the two-dimensional test area (by request of the investigators), considerable rutting was observed following only three roller passes with the Ammann roller (see Fig. 2.12).

To evaluate whether the ACE roller-integrated compaction system might identify areas of suitable subgrade material in a manner similar to test rolling, rut depths were measured at ten test points in two adjacent lanes following the test rolling procedure. A linear relationship between roller-measured stiffness and rut depth is supported in Fig. 2.13 with similar trends observed for the two measures of soil stability. The test rolling acceptance criterion is additionally shown in Fig. 2.13 as a horizontal line, indicating that only several isolated locations of the test area are not suitable based on measured rut depth. The figures below may also be used to establish 15 MN/m as minimum soil stiffness k_S for the Ammann roller measurement system. For this criterion, nearly all of the test area would meet specification. Thus, both measurement techniques are capable of identifying subgrade stability. The principal advantages of using roller-integrated CCC and intelligent compaction technology over testing rolling, however, include: (1) more efficient construction process control and QC/QA practice, (2) documentation of subgrade stability, and (3) ability to map subgrade uniformity.

Conclusions

Based on the study findings, the following conclusions have been drawn.

1. Subgrade stability measurements from in-situ testing devices follow closely roller-measured stiffness.
2. Roller-measured stiffness is highly correlated with moisture content, which clearly show that interpretation of k_S must consider soil moisture conditions.

3. Ammann k_S is empirically related to in-situ compaction measurements through linear relationships with R^2 values ranging up to 0.80 (for this study). The relationships are heavily influence by the range of values over which the measurements are taken.
4. The intelligent compaction measurements collected during this study do not support variable feedback control systems as capable of improving the uniformity of compacted materials. Future studies should more thoroughly investigate these systems to verify the intended benefits of the technology.
5. The ACE intelligent compaction system identifies areas of unstable subgrade material similar to test rolling. Rut depth and k_S are related through a nearly-linear relationship.

Notation

γ_d	=	dry unit weight
μ	=	statistical mean
φ	=	phase angle
Ω	=	circular vibration frequency
σ_0	=	peak applied stress
A	=	vibration amplitude
CIV	=	Clegg impact value
c_S	=	damping constant
C_V	=	coefficient of variation
DCPI	=	DCP index
E_{LWD}	=	elastic modulus from LWD
E_{V1}	=	elastic modulus for initial loading
E_{V2}	=	elastic modulus for reloading
f	=	excitation frequency
F_S	=	soil-drum interaction force
g	=	acceleration due to gravity
k_S	=	Ammann roller-measured soil stiffness
LL	=	liquid limit

m_d = drum mass

$m_e r_e$ = eccentric moment of the unbalanced mass

m_f = frame mass

n = number of observations

PI = plastic limit

r = plate radius

v = Poisson's ratio

w = moisture content

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Table 2.1. Schedule of testing materials

Soil Property	Subgrade	Class 5
USCS	CL	SP-SM
AASHTO	A-6 (9)	A-1-b (0)
$F_{3/4}$ (%)	100	97
$F_{3/8}$ (%)	100	82
F_4 (%)	98	73
F_{200} (%)	62	9
Percent gravel (>4.75 mm)	2	27
Percent sand (>0.075 mm)	86	64
Percent silt (>0.002 mm)	37	6
Percent clay (<0.002 mm)	25	3
LL (PI)	39 (17)	NP
$\gamma_{d, max}$ (kN/m^3) *	16.16	19.58
w_{opt} (%) *	18.1	8.1
* Standard Proctor energy		

Table 2.2. Summary of roller-measured stiffness and in-situ compaction measurements

Test Strip	Soil Type	k_S (MN/m)	Percent of w_{opt}	Percent Compaction	E_{LWD-K} (MPa)	DCPI (mm/blow)
1	CL [a]	8-40	−	−	10-140	5-100
2	CL [a]	5-45	77-122	86-111	5-110	15-70
3	CL [a]	12-35	83-117	93-105	10-80	10-55
4	SP-SM [b]	20-35	125-175	82-87	20-40	40-110
5	SP-SM [b]	25-40	88-125	92-97	10-70	25-50

a w_{opt} = 18%, $\gamma_{d,max}$ = 16.2 kN/m^3
b w_{opt} = 8%, $\gamma_{d,max}$ = 19.6 kN/m^3

Figure 2.1. Ammann vibratory smooth drum roller with integrated ACE system

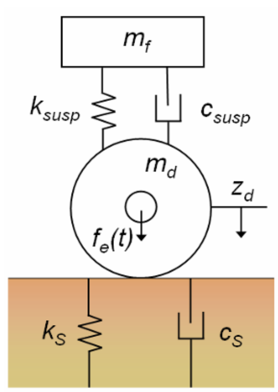

Figure 2.2. Lumped-parameter soil model for ACE estimation of k_S (adapted from Anderegg and Kaufmann 2004)

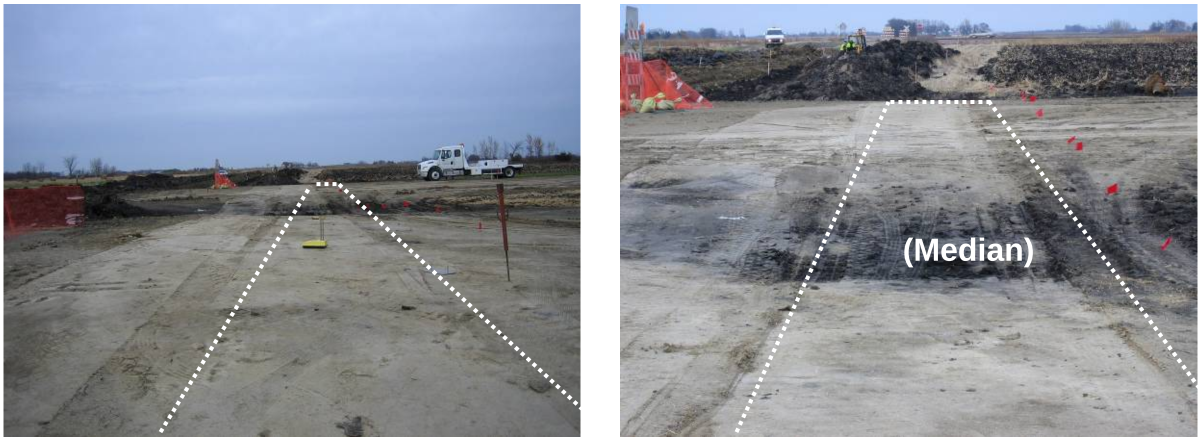

Figure 2.3. Test strip (outlined with dashed lines) comprised of subgrade material with testing locations spaced at 1.5-m intervals

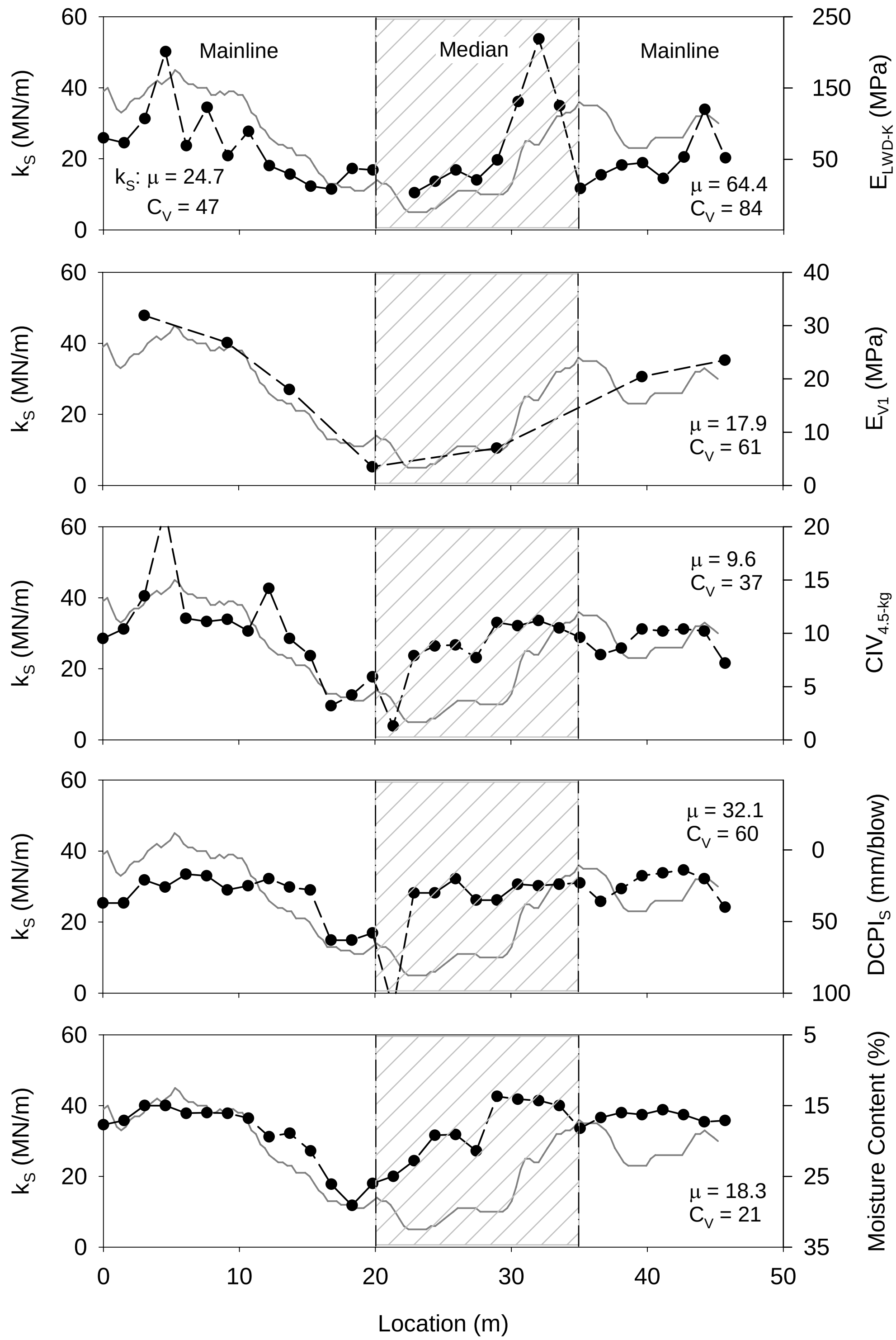

Figure 2.4. Comparison of k_S (solid line) and in-situ compaction measurements on a test strip comprised of subgrade material

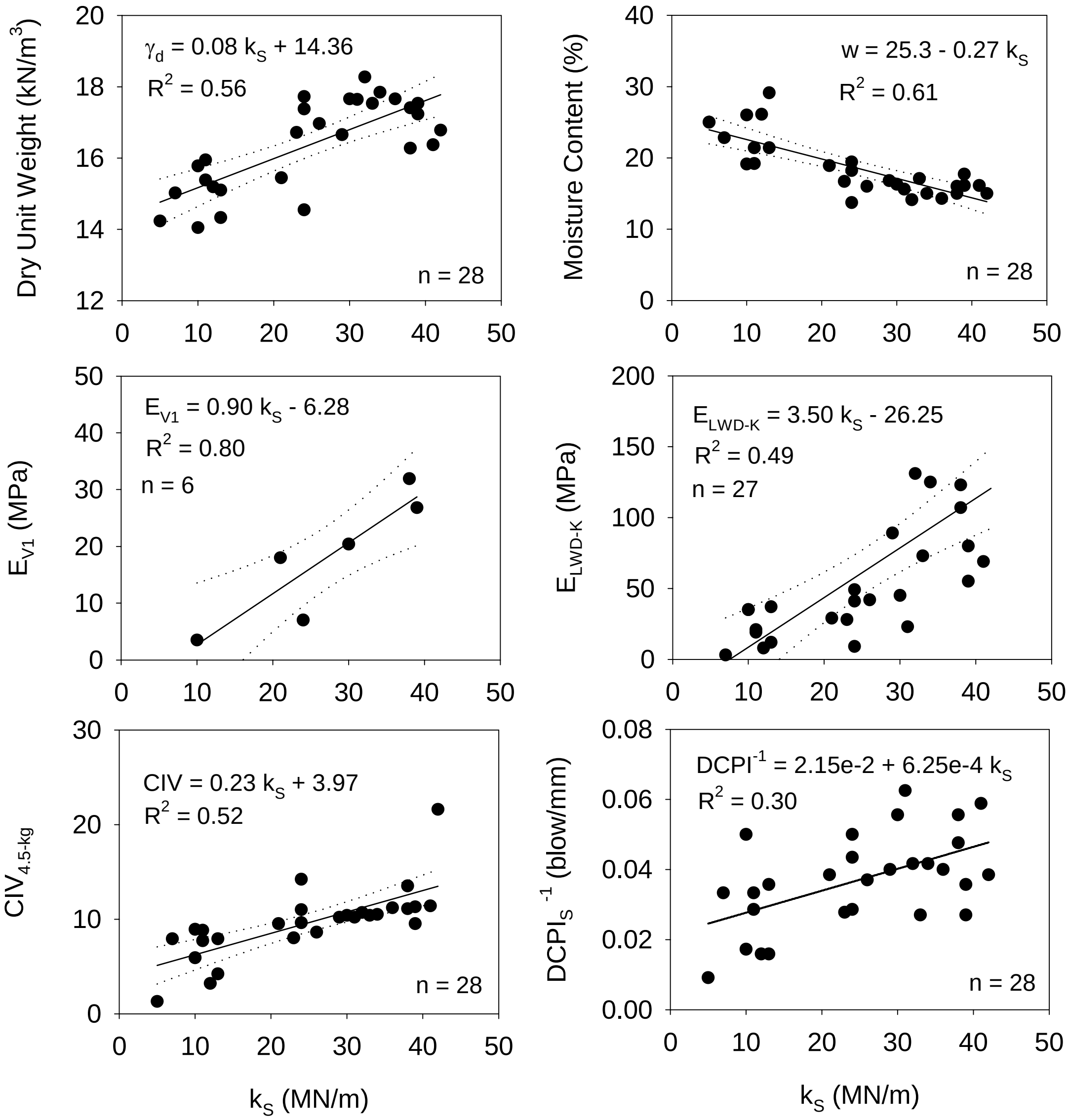

Figure 2.5. Relationships between k_S and in-situ compaction measurements for a test strip comprised of subgrade material

Figure 2.6. Test strip (outlined with dashed lines) comprised of granular material with testing locations spaced at 7.6-m intervals

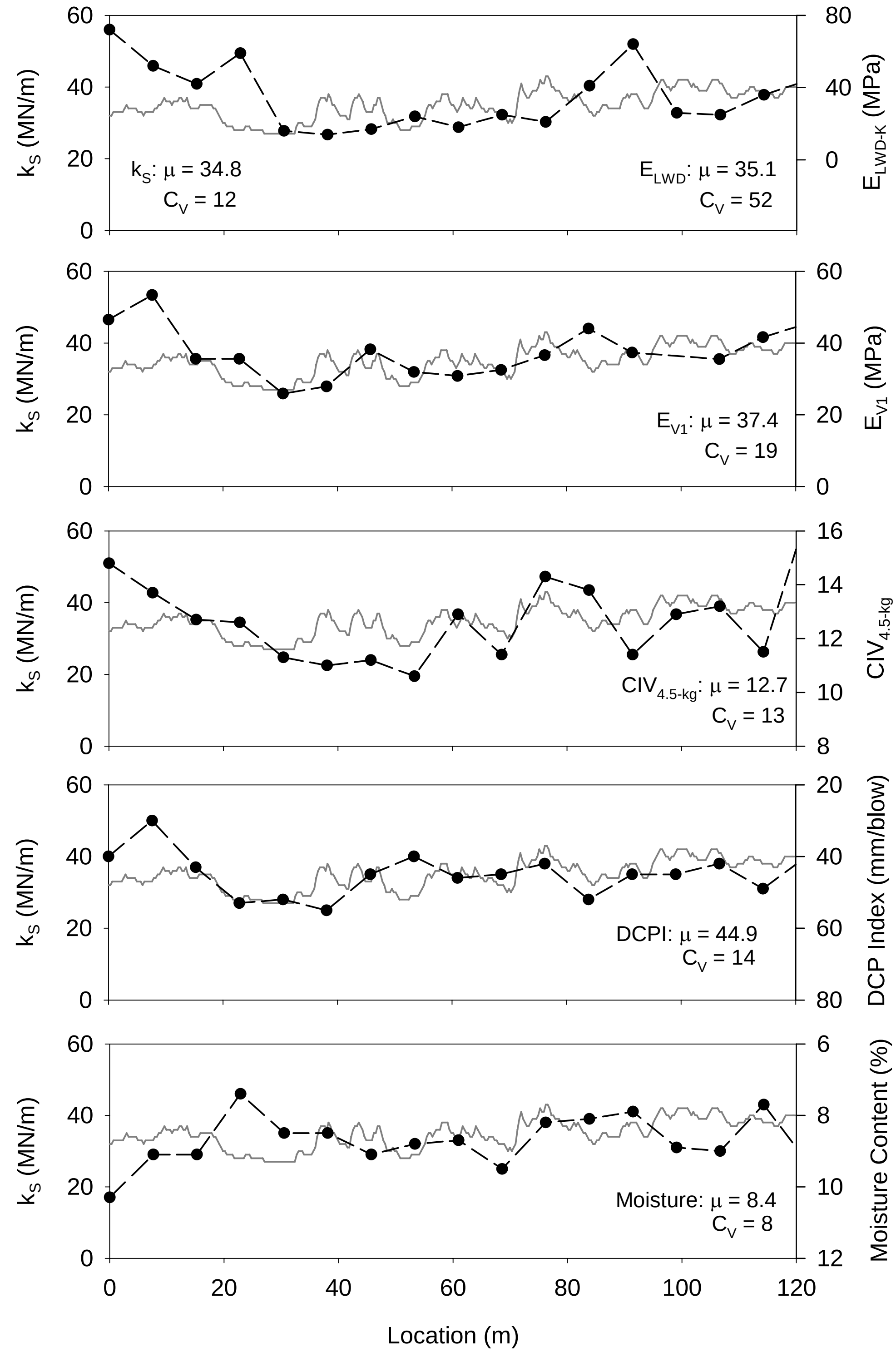

Figure 2.7. Comparison of k_S (solid line) and in-situ compaction measurements on a test strip comprised of granular material

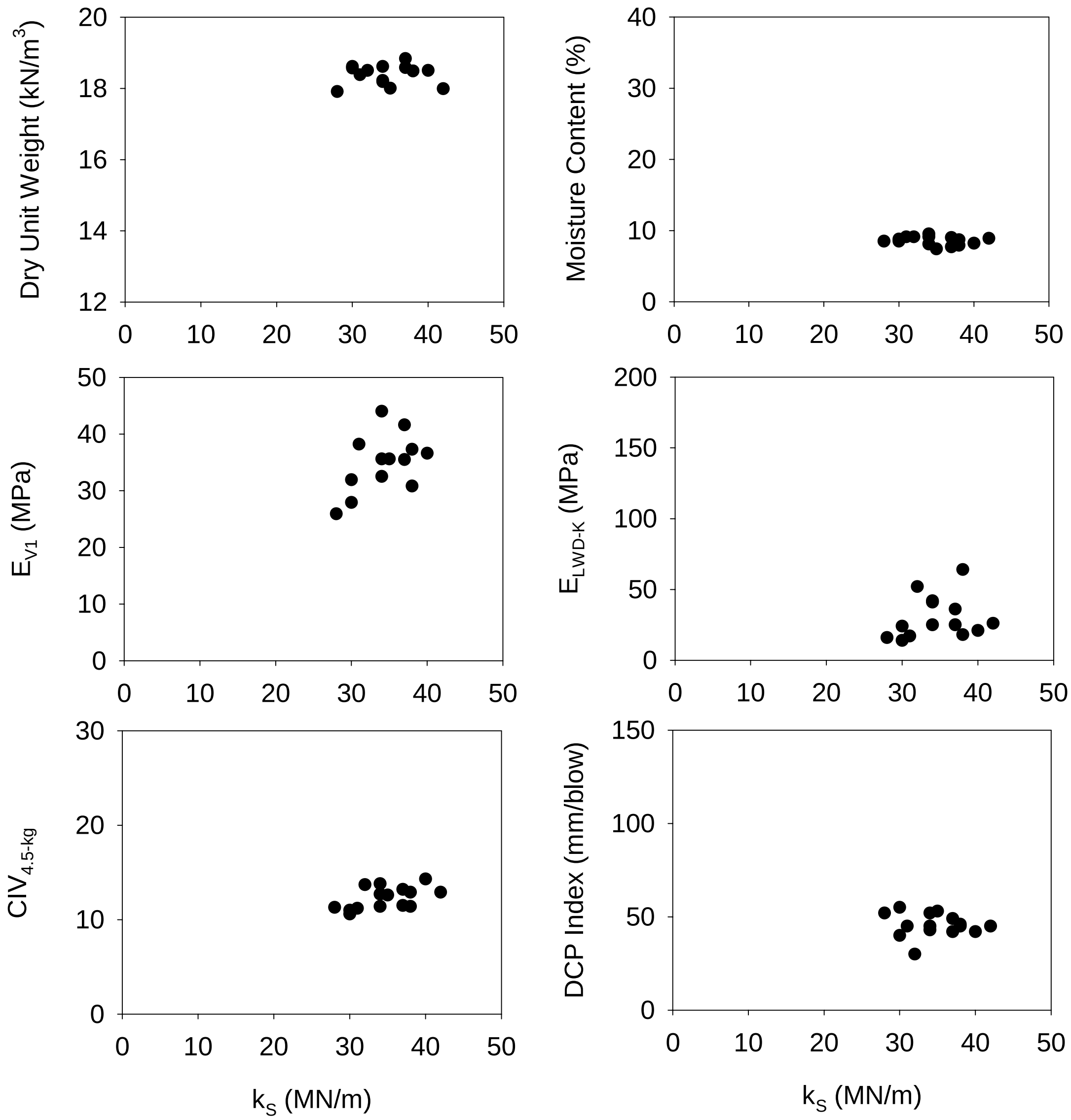

Figure 2.8. Relationships between k_S and in-situ compaction measurements for a test strip comprised of granular material

Figure 2.9. Test strip comprised of Class 5 material (outlined with dashed line) for evaluating variable feedback control operation

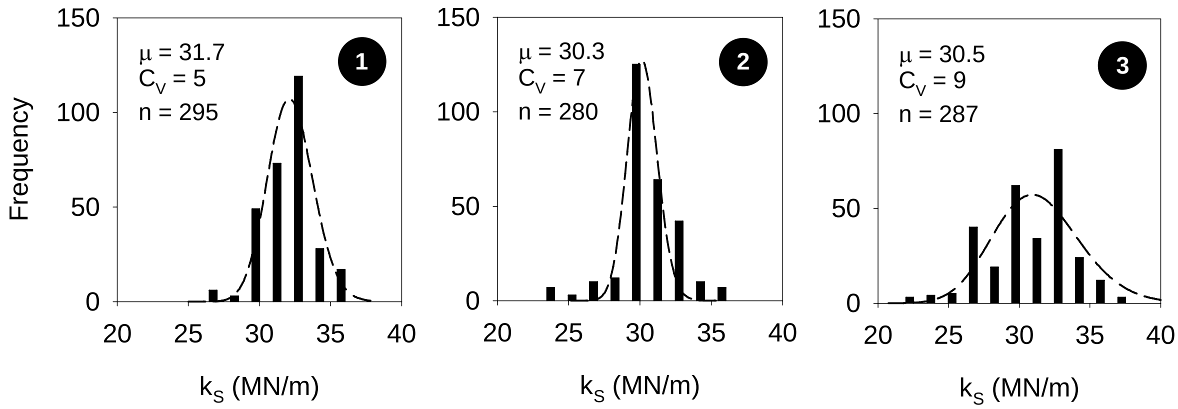

Figure 2.10. Distribution of k_S for three consecutive roller passes on Class 5 using variable feedback control operation

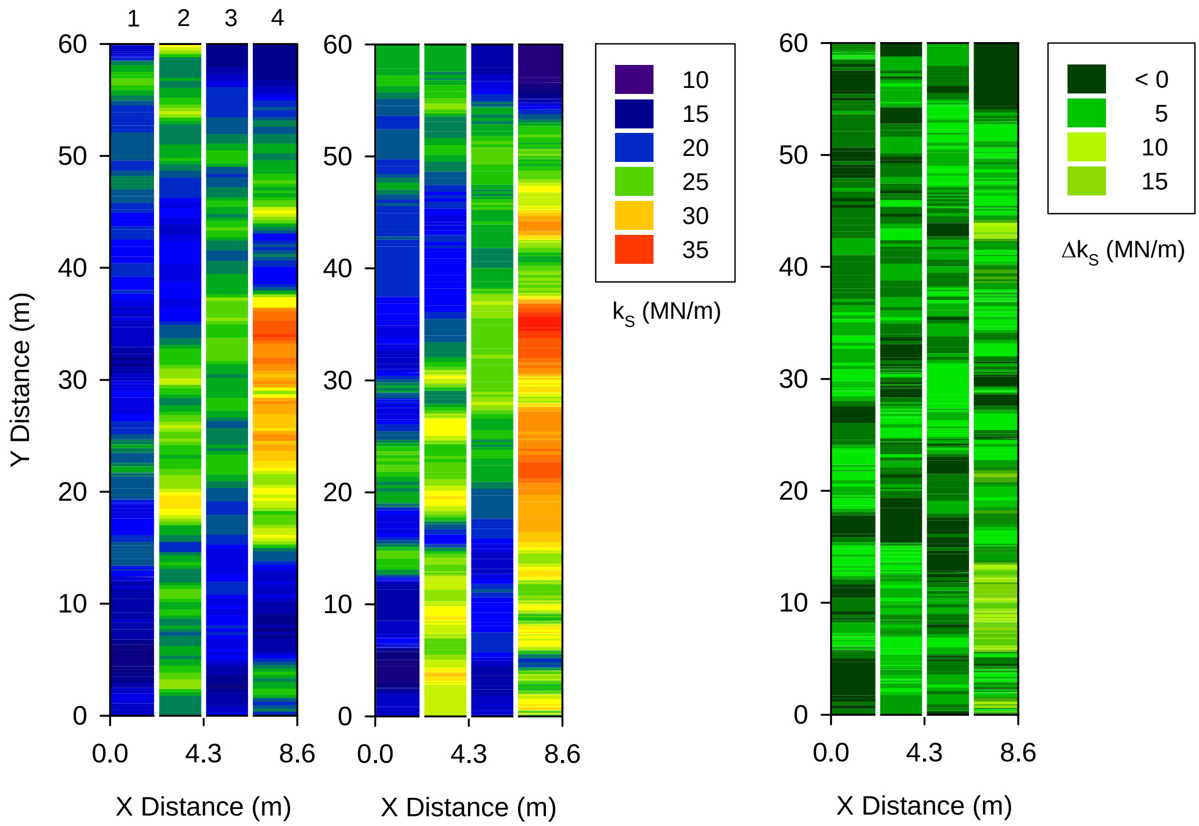

Figure 2.11. Ammann k_S (MN/m) for Pass 1 (left) and Pass 3 (middle), change in k_S (right) on test strip of subgrade material

Figure 2.12. Test roller and subgrade rutting observed following test rolling

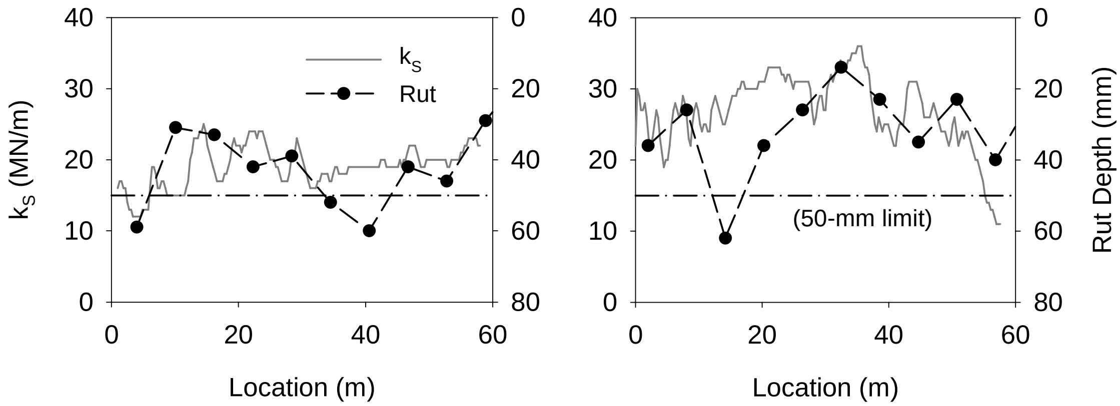

Figure 2.13. Comparison of k_S and rut depth along adjacent test strips of subgrade material

CHAPTER 3: Relationships between In-Situ and Roller-Integrated Compaction Measurements for Granular Soils

A paper submitted to *The Journal of Geotechnical and Geoenvironmental Engineering*

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Abstract

To evaluate *compaction meter value* (CMV) and *machine drive power* (MDP) roller-integrated compaction technologies, a field study was conducted with 30-m test strips using five granular materials. The test strips were compacted using a prototype CS-533E vibratory smooth drum roller and tested for various compaction parameters using in-situ test methods (e.g. nuclear moisture-density, dynamic cone penetrometer, plate load tests, etc.). To characterize the roller machine-ground interaction, soil testing focused on measuring soil compaction parameters of the compaction layer, to a depth not exceeding 300 mm. The experimental testing of five test strips provided roller data and in-situ measurements for several stages of compaction that were used in performing statistical regression analyses. The relationships between data from the roller-integrated compaction technologies were investigated with special consideration for the relative variation that was observed for each measurement system. Statistical averaging mitigated measurement variability and revealed statistically significant ($R^2 > 0.9$) relationships between in-situ and roller-integrated compaction measurements. This research demonstrates statistical analysis techniques for which calibration procedures using roller-integrated compaction technologies may be developed.

Introduction

Roller-integrated compaction technologies have recently been incorporated into quality acceptance practices of transportation earthwork projects in the United States (see White *et al*. 2007a), and the use of such technology is anticipated to increase in upcoming years. Transportation agencies and contractors are implementing the technologies with the expectation that the systems will: (1) improve construction efficiency, (2) streamline quality management programs of earthwork projects, (3) better link quality acceptance parameters and documentation with pavement design, and (4) improve the performance of compacted materials (Briaud and Seo 2003, Petersen *et al*. 2006, Thompson and White 2007). To realize these expectations and accelerate the implementation of roller-integrated compaction technologies into practice, detailed and statistically robust field studies are needed to improve the understanding of relationships between machine parameters and various in-situ compaction measurements. Machine parameters are being empirically related to soil density, as current state-of-the-practice primarily relies on control of density and moisture content to achieve acceptable performance of compacted materials. Machine parameters may also be related, however, to the deformation characteristics of soil (e.g., stiffness) to facilitate use of roller-integrated measurements for performance-based specifications (see Fleming *et al*. 2006) or input for mechanistic pavement design. The empirical relationships between roller-integrated measurements and in-situ compaction measurements, which are influenced by operating conditions of the various machines (e.g., roller size, vibration amplitude and frequency, and velocity) and soil conditions (e.g., soil type, moisture content, lift thickness, underlying layer stiffness), are identified using experimental testing and statistical analysis methods with special consideration for the nature and variability of the measurement systems.

The field study documented in this paper evaluates *compaction meter value* (CMV) and *machine drive power* (MDP) technologies for indicating in-situ compaction measurements of single layers of granular materials over well compacted subgrade. Experimental testing of five test strips, each constructed with a different granular soil, provided both machine data and in-situ compaction measurements that were used in performing statistical regression analyses. The analysis results presented in this paper provide guidance on developing prediction models from test strips and support continued implementation into earthwork practice.

Background

Compaction Meter Value (CMV)

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. The dynamic response of a roller drum on soil has been likened to dynamic plate load tests by Thurner and Sandström (1980) and Sandström and Pettersson (2004). Previous studies have found that the ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency is a reliable indicator of soil compaction. Accordingly, CMV is calculated as

$$\mathrm{CMV} = \mathrm{C} \cdot \frac{\mathrm{A}_1}{\mathrm{A}_0} \tag{3.1}$$

where C = constant (normally about 300), A_1 = acceleration of the first harmonic component of the vibration, and A_0 = acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004). CMV is a dimensionless value that depends on roller dimensions (e.g. drum diameter, weight) and roller operation parameters (e.g. frequency, amplitude, speed). According to Forssblad (1980), CMV has been noted to range from 60 to 90 for rock fill, from 40 to 70 for gravel, from 25 to 40 for sand, and from 20 to 30 for silt.

Machine Drive Power (MDP)

The use of MDP technology as a measure of soil compaction is a new concept (see White *et al*. 2006a) originating from study of vehicle-terrain interaction (see Bekker 1969). MDP, which relates to the soil properties controlling drum sinkage, uses the concepts of rolling resistance and sinkage to determine the energy necessary to overcome the resistance to motion. The technology is comprised of sensors that monitor hydraulic pressure and flow at torque converters of the roller. The product of these machine parameters equals the gross power that propels the roller. MDP is then calculated as

$$\text{MDP} = P_g - WV\left(\sin\theta + \frac{a}{\text{g}}\right) - (mV + b) \quad (3.2)$$

where P_g = gross power needed to move the machine, W = roller weight, a = machine acceleration, g = acceleration of gravity, θ = slope angle (roller pitch from a sensor), V = roller velocity, and m and b = machine internal loss coefficients specific to a particular machine (White *et al*. 2005). The second and third terms of Eq. (3.2) account for the machine power associated with sloping grade and internal machine loss, respectively. MDP represents only the machine power associated with material properties and, therefore, can theoretically be transferred to other roller configurations.

Prior to its use, MDP technology is calibrated for θ, m and b (see Eq. (3.2)). First, the orientation of the roller pitch sensor is found by noting the pitch readings when the roller is parked on the same sloping surface facing uphill and downhill. The average of these two readings is the pitch offset applied to all later sensor readings. The internal loss coefficients m and b are then found by operating the roller on a relatively uniform, unchanging calibration surface. P_g and slope compensation (i.e. second term of Eq. (3.2)) are monitored while operating the roller in both forward and reverse directions at the range of roller speeds anticipated during construction operations, generally ranging from 3 to 8 km/hr. At each roller speed, the difference between P_g and slope compensation is taken as the internal machine loss. Plots of slope-compensated machine power versus roller speed provide linear relationships from which the internal loss coefficients m and b are calculated. By incorporating both slope compensation and internal machine loss into Eq. (3.2), MDP for roller operation on the calibration surface is approximately 0 kJ/s. MDP is a relative value referencing the material properties of the calibration surface, which is generally a well-stabilized soil. Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values would indicate material that is more compact (i.e. less roller drum sinkage).

Published Relationships

A review of the literature reveals only limited detailed studies with in-situ comparison measurements for either CMV or MDP technologies. CMV technology, which has a clear physical background, has been stated to indicate soil stiffness, with calibration of the roller output needed for quantitative evaluation (Adam 1997). In this regard, literature has focused on calibration equations that relate CMV to soil modulus determined from plate loading tests (E_{PLT}) (see Adam 1997, Brandl and Adam 1997, Forssblad 1980). The conventional post-process tests are generally performed at locations with maximum CMV values, mean values, and minimum values. Linear regressions are then fit to the data. Because the data are obtained over a wide range of soil conditions, the correlation is optimized. With CMV ranging up to 120 for predicting E_{PLT} up to about 200 MPa, E_{PLT}-CMV regression slopes have ranged from 0.57 to 4.4 MPa. The relationships were further documented by Brandl and Adam (1997) to depend on the motion behavior of the roller drum, where considerably different correlations were observed for partial uplift and double jump operational conditions.

MDP for identifying properties of cohesive soils has been documented by White *et al*. (2004, 2005, 2006b) and Thompson and White (2007). This paper is the first documented use of MDP to predict in-situ compaction measurements of granular soils.

Experimental Testing

Testing Program

The experimental testing plan, comprised of one test strip for each of five granular soils, is provided in Table 3.1. The roller used for this project was a prototype CS-533E vibratory smooth drum roller (see Fig. 3.1). The 13,570-kg roller had a drum diameter of 1.52 m, a drum width of 2.13 m and a rear wheel-to-drum length of 2.90 m. The roller was also fitted with a GPS system positioned over the center of the drum, such that roller coverage (i.e. history of the number of roller passes at a given location), CMV, and MDP were mapped and viewed in real time during compaction operations using the on-board compaction monitor shown in Fig. 3.1 (b).

Five test strips were constructed with lengths of about 30 m and widths of about 3 m — slightly wider than the roller drum. Each test strip contained a different granular subbase material, which was placed at approximately natural moisture content (4 to 8 percent) on the well-compacted subgrade layer with average CBR of 12 (σ = 5.5). Nominal loose lift thickness ranged from 280 to 360 mm (see Table 3.1), and additional material was placed at the ends of the test strips to transition from the existing ground surface to the test strip elevation. Soil was then compacted using the vibratory roller at the "high" amplitude (1.70 mm) setting. The frequency of drum vibration (31.9 Hz) and roller speed (8 km/hr) were also constant throughout the field study. During this compaction operation, CMV and MDP measurements were collected approximately every 0.2 m along the test strip and assigned GPS coordinates.

For determining the in-situ compaction measurement parameters, ten tests were performed at 3.0-m spacing along the center of the test strip between the footprint of the rear tires of the roller. Measures of soil density, moisture content, strength, and modulus were obtained following 1, 2, 4, 8, and 12 roller passes. The order in which tests were performed was: (1) nuclear moisture and density, (2) soil stiffness gauge (SSG), (3) light falling weight deflectometer (LWD), (4) Clegg impact, and (5) dynamic cone penetration (DCP). A single plate load test (PLT) was conducted using a 300-mm plate at the end of each test strip next to the tenth test point. The spatial location of each test point was obtained using a GPS rover working off the same base station as the roller GPS system. CMV, MDP, and the in-situ compaction measurements were collected for multiple roller passes.

In-Situ Compaction Measurements

The calibrated nuclear moisture-density gauge provided a rapid measurement of soil density and moisture content (ASTM 2922), each of which was determined using a transmission depth equal to the compaction layer thickness. Clegg impact value (CIV), which is empirically related to California Bearing Ratio (CBR) was determined at the surface of the compaction layer at each test point using a 4.5 kg Clegg impact tester (ASTM D 5874). Each test was comprised of two CIVs, which were averaged for use in regression analyses. DCP tests were performed at each test point to develop strength profiles with depth

(ASTM D 6951). DCP index (i.e., rate of penetration with units of mm/blow) for the compaction layer was related to CMV and MDP. Total penetration depths ranged up to about 300 mm for loose, uncompacted material and to about 100 mm for stiffer compacted material.

The SSG provided small-strain deformation properties of compacted soil with output of both soil stiffness and elastic modulus (Humboldt Mfg. Co. 2000). Soil stiffness obtained from the SSG is related to modulus (E_{SSG}) through a linear relationship, dependent on Poisson's ratio (v = 0.40) and the diameter of the annular ring of the device. Therefore, only E_{SSG} is reported. The LWD (Dynatest 2004), which is equipped with a load sensor to estimate plate stress and a geophone to determine plate deflection, was used to determine elastic modulus as

$$E_{PFWD} \text{ or } E_{PLT} = \frac{f\,(1-v^2)\cdot\sigma_0\cdot r}{h_0} \tag{3.3}$$

where E_{LWD} = elastic modulus, v = Poisson's ratio (v = 0.40), σ_0 = applied stress at surface, r = plate radius, h_0 = plate deflection, and f is a factor that depends on the stress distribution (f = 2 for a uniform plate stress, assumed for cohesive soils; $f = \pi/2$ for a rigid plate, assumed for cohesionless soils (Terzaghi *et al*. 1996). Static plate load tests were performed at the soil surface for soil modulus (E_{PLT}) using a 300-mm plate, a 90-kN load cell, and three 50-mm linear voltage displacement transducers (LVDT). Elastic modulus was calculated with Eq. (3.3).

Testing Materials

Experimental testing used five different granular materials including recycled asphalt pavement (RAP), CA6-C, CA5-C, FA6, and CA6-G (Illinois DOT classifications). The materials, obtained from local sources, were coarse grained with low plasticity. Soil classifications and particle size distribution parameters are provided in Table 3.2.

Moisture-density relations were determined using the Standard Proctor test (ASTM D 698), performed following Method C. An automated, calibrated mechanical rammer was provided for compaction. Maximum dry unit weights and optimum moisture contents were observed for all materials, while only CA6-C exhibited bulking behavior at low moisture contents (3 to 7 percent). Since the coarse-grained soils were free draining, relative density tests were performed (ASTM D 4253). Laboratory compaction measurements of the materials are summarized in Table 3.2. Maximum dry unit weights observed for Proctor tests at optimum moisture content were consistently higher than for relative density tests with oven-dried soil.

Test Data

Field compaction curves for strip-length average MDP and CMV are shown in Fig. 3.2 for each test strip. A power-function trend is observed for each measurement when presented as a function of roller pass. Decreasing MDP with each roller pass indicates that less machine energy is necessary to propel the roller over the increasingly-compact material. Similarly, increasing CMV corresponds to increasing material stiffness resulting from the compaction operation. In addition to showing the effect of soil compaction on machine response, data of Fig. 3.2 show how MDP and CMV technology may even identify decompaction. Following eight or nine roller passes, for each test strip, slight increases in MDP and decreases in CMV were observed (highlighted in Fig. 3.2 using arrows).

CMV, MDP, and in-situ compaction measurements were obtained along the entire length of the test strips. The complete test results for all test strips are reported in White *et al*. (2007b). For brevity, only the Strip 2 (CA6-C) in-situ density, DCP index, CIV and LWD modulus measurements are shown in Figs. 3.3 and 3.4 for MDP and CMV, respectively. MDP and CMV measurements are represented with solid lines, and in-situ measurements are shown as discrete points along the test strip. Comparison of roller-integrated compaction measurements shows that MDP is observed to be more locally variable than CMV; the small-scale variation is caused by the mechanical roller performance and/or the measurement variation for gross machine power. Alternatively, CMV shows greater variation over the full strip length, particularly with increasing number of roller passes. The difference in variation of MDP and CMV is of consequence to development of regression models with in-situ spot test measurements, as the two different compaction systems are influenced by machine-ground interactions differently. The MDP measurement is associated with drum sinkage and rolling resistance occurring at the soil surface, which is highly sensitive to shear strength of the soil in the compaction layer (Muro and O'Brien 2004). CMV, on the other hand, is related to dynamic interaction of the roller drum with the ground and depends on soil characteristics well below the soil surface with measurement influence depths reportedly ranging from 0.4 to 0.6 m for a 2-ton roller and from 0.8 to 1.5 m for a 12-ton roller (ISSMGE 2005). In Fig. 3.4, higher rates of compaction based on CMV measurement are observed in the regions of comparatively high stiffness following the initial roller pass (0 to 5 m). Higher stiffness of the underlying base at the beginning of the test strip, which produced an initially-higher stiffness response, promoted more efficient (i.e. more rapid) compaction of the compaction layer material. This trend is observed in the in-situ spot test dry unit weight and LWD modulus values. The effect of variable subgrade stiffness on roller response is further supported by Fig. 3.5, which shows the correlation of CMV and subgrade CBR based on DCP measurements.

Average coefficients of variation for CMV and in-situ measurements are summarized in Table 3.3 for each test strip. Standard deviation for MDP is also provided. The table of values represents the average of the calculated variation parameters for each roller pass for which there were measurements collected (i.e., roller passes 1, 2, 4, 8, and 12). MDP average standard deviation ranged from 2.39 to 4.55. Average C_V for CMV, dry density, DCP index, CIV, E_{SSG}, and E_{LWD} ranged from 19 to 36 percent, 2 to 4 percent, 10 to 28 percent, 9 to 24 percent, 13 percent, and 17 to 35 percent, respectively. Based on these results, CMV was more variable than all in-situ compaction measurements for all test strips. For each test strip, E_{LWD} was the most variable in-situ measurement. Coefficient of variation (C_V) are not used for assessing MDP variation, because absolute values of the measurement are referenced to MDP observed for the calibration surface (i.e. where MDP = 0 kJ/s)

Statistical Analysis

Analysis of CMV and MDP

Data already presented for Strip 2 (Fig. 3.2-3.5) show that CMV and MDP are both capable of qualitatively identifying the various in-situ compaction measurements of soil. The relationships between data from the independent technologies were investigated considering the nature of the respective measurements. As roller-generated measurements are averaged using moving average "window" lengths up to 30 m (i.e. full length of test strip to give one data point per roller pass), R^2 values progressively increase towards a maximum value. Statistical averaging of the data for the entire test strip clearly mitigates measurement variation, position error, and reveals underlying trends (White *et al.* 2005). Logarithmic relationships between MDP and CMV were observed, as shown in Fig. 3.6 for each soil. R^2 values for the test strips (using average MDP and CMV) ranged from 0.84 for CA5-C to 0.97 for CA6-G.

Analysis with In-Situ Measurements

The relationships between MDP and in-situ compaction measurements (using strip-length average for a given roller pass) are shown in Fig. 3.7. The effect of data variability on these relationships is discussed in Thompson and White (2006). Dry unit weight, Clegg impact value, DCP index, E_{SSG}, and E_{PLT} were all approximated by logarithmic relationships with MDP. The coefficient of determination (R^2) for each relationship is provided in Table 3.4. About 80 percent (23 of 28) of the R^2 values exceeded 0.90. Of the five values less than 0.90, four R^2 values were for estimating soil modulus. The relative difficulty in estimating soil modulus may be related to the relative complexity of deformation characteristics and also the relative variability associated with its measurement.

The relationships between CMV and in-situ compaction measurements are also shown in Fig. 3.7. The same in-situ measurements are related to CMV through linear relationships with a summary of R^2 values provided in Table 3.5. About 70 percent (20 of 28) of the R^2 values exceeded 0.90. The lowest observed coefficient of determination was 0.50 for predicting E_{PLT} (Strip 1, RAP). In this case, E_{PLT} determined by plate loading was nearly constant throughout the entire compaction process and only one test was performed for a given measurement pass.

The relationships between roller-integrated measurements and in-situ compaction measurements are limited to the five granular materials, lift thicknesses, and moisture contents of the testing program. In an attempt to estimate in-situ compaction measurements independent of these parameters, multiple regression analyses were performed using the composite dataset. Intrinsic soil properties and nominal moisture contents were used as regression parameters to quantitatively account for the influences of soil type and state, respectively. For all in-situ measurements, *one* roller-integrated compaction measurement (CMV *or* MDP) and nominal moisture content was statistically significant, based on p-test results (>0.05). Each granular material was tested at only one nominal moisture content, however, and the influence of moisture content alone on roller-generated data could not be investigated. For select in-situ measurements, various combinations of fines content, gravel fraction, sand fraction, silt fraction, and clay fraction were significant. Inclusion of these regression parameters provided weak prediction models nevertheless. A simple model for predicting the various in-situ compaction measurements using MDP or CMV technologies (independent of soil type) was not observed for data from this field study.

Summary and Conclusions

Compaction meter value (CMV) and *machine drive power* (MDP) roller-integrated compaction technologies applied to a vibratory smooth drum roller were evaluated in terms of in-situ compaction measurements for single layers of granular materials over well compacted subgrade. Experimental testing of five test strips, each comprised of a different soil, provided characteristics of the compacted soils for several stages of compaction that were used in performing statistical regression analyses. The relationships between data from the roller-integrated compaction technologies were investigated considering the nature of the measurements. MDP and CMV were then statistically related to various in-situ compaction measurements.

The following conclusions were drawn from this study.

1. The effect of soil compaction is to decrease average MDP (i.e. rolling resistance) and increase average CMV (i.e. soil stiffness). MDP was observed to be more locally variable than CMV, while CMV showed greater deviation from the mean at select locations. The variation of CMV was documented to reflect variable stiffness of the underlying subgrade, which is important for interpreting roller-integrated measurements for layered soil conditions.

2. Statistical averaging of roller-integrated measurements from the entire test strip mitigates measurement variation and reveals underlying relationships with MDP and CMV. MDP and CMV were related through logarithmic relationships that varied with soil type.
3. The in-situ compaction measurements were correlated with MDP and CMV. As a function of soil type, logarithmic relationships were observed between MDP and in-situ compaction measurements, while linear relationships were observed for CMV.
4. In-situ measurements were not correlated with MDP or CMV using the entire combined dataset and soil index properties as regression parameters. As each test strip was constructed with only one nominal moisture content, the influence of moisture content (separate from soil type) could not be identified. The dataset did not provide a simple model for predicting in-situ compaction measurement parameters using MDP or CMV technologies independent of soil type.

Notation

a	=	machine acceleration
A_0	=	acceleration of the fundamental component of vibration
A_1	=	acceleration of the first harmonic of vibration
b	=	machine internal loss coefficient
c	=	constant
C	=	CMV constant
CIV	=	Clegg impact value
CMV	=	*compaction meter value*
C_V	=	coefficient of variation
DCP	=	dynamic cone penetrometer
D_r	=	Relative density
E_{LWD}	=	modulus of soil from light falling weight deflectometer
E_{PLT}	=	modulus of soil from plate load test
E_{SSG}	=	modulus of soil from soil stiffness gauge
f	=	stress distribution factor

F	=	applied force
F_{200}	=	percent of soil passing sieve No. 200
g	=	acceleration due to gravity
G_S	=	specific gravity
γ_d	=	dry unit weight of soil
$\gamma_{d,max}$	=	maximum dry unit weight of soil
h	=	drum displacement
h_0	=	plate deflection
LL	=	liquid limit
LWD	=	light falling weight deflectometer
m	=	machine internal loss coefficient
μ	=	statistical mean
n	=	number of observations
PLT	=	plate load test
P_g	=	gross power
PI	=	plasticity index
σ	=	standard deviation
σ_0	=	plate stress
R_c	=	relative compaction
SSG	=	soil stiffness gauge
θ	=	slope angle
V	=	roller velocity
v	=	Poisson's ratio
w	=	water content
w_{opt}	=	optimum water content
W	=	roller weight
ω	=	angular frequency of vibration

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Table 3.1. Field testing plan

Soil Type	Strip No.	Nominal Loose Lift Thickness (mm)	Nominal Moisture Content (%)	Moisture Deviation from Standard [a] w_{opt} (%)
RAP	1	350	8	0
CA6-C	2	280	4	+4 [b]
CA5-C	3	300	4	— [c]
FA6	4	360	6	-2
CA6-G	5	340	8	-2

[a] Moisture deviation from optimum, based on Proctor test ($w - w_{opt}$)
[b] Within bulking moisture range
[c] Not suitable for standard Proctor test based on gradation

Table 3.2. Soil properties for field and laboratory test materials

Soil Property	**RAP**	**CA6-C**	**CA5-C**	**FA6**	**CA6-G**
USCS:	GM	SM	GP	SM	GC
AASHTO	A-1-b	A-1-a	A-1-a	A-2-4	A-2-6
G_s	2.52	2.69	2.75	2.68	2.67
F_{200} (%)	14.4	11.3	0.0	21.3	31.7
C_c	4.0	3.9	1.1	1.3	0.4
C_u	130.4	117.5	1.4	48.6	1977.0
LL (PI)	15 (NP)	14 (NP)	NP	17 (NP)	26 (12)
Standard Proctor:					
$\gamma_{d,\ max}$ (kN/m^3)	19.5	20.1	— [a]	19.8	20.0
w_{opt} (%)	8.2	0.0	— [a]	7.6	10.1
Relative Density:					
$\gamma_{d,\ max}$ (kN/m^3)	19.2	19.8	14.1	19.0	18.6
$\gamma_{d,\ min}$ (kN/m^3)	14.4	15.2	11.8	15.8	13.5

[a] Not suitable for standard Proctor test based on gradation

Table 3.3. Average variation parameters for compaction measurements

Strip No.	MDP [a]	CMV	Dry Density	DCP Index	CIV	E_{SSG}	E_{LWD}
1	4.11	36	3	26	20	— [b]	31
2	2.66	32	2	10	9	—	20
3	3.29	22	4	22	24	13	28
4	2.39	19	3	17	14	13	17
5	4.55	24	2	28	17	—	35
Average	3.40	27	3	21	17	13	26

[a] standard deviation for MDP (kJ/s) – coefficient of variation for other measurement (%)
[b] no data available

Table 3.4. Coefficients of determination (R^2) and number of observations (n) for regression analyses of granular soils with MDP as independent variable

Soil Property	**RAP**	**CA6-C**	**CA5-C**	**FA6**	**CA6-G**
CMV	0.91 (8)	0.96 (8)	0.84 (8)	0.92 (8)	0.97 (8)
γ_d	0.90 (6)	0.99 (5)	0.97 (5)	0.99 (5)	0.97 (5)
CIV	0.95 (6)	0.99 (5)	0.61 (5)	0.99 (5)	0.97 (5)
DCP Index	0.96 (6)	0.97 (5)	0.91 (5)	0.90 (5)	0.95 (5)
E_{SGG}	— [a]	—	0.96 (5)	0.99 (5)	—
E_{LWD}	0.78 (6)	0.93 (5)	0.96 (5)	0.85 (5)	0.91 (5)
E_{PLT}	0.56 (6)	0.86 (5)	0.95 (5)	0.94 (5)	0.97 (5)

[a] no data available

Table 3. 5. Coefficients of determination (R^2) and number of observations (n) for regression analyses of granular soils with CMV as independent variable

Soil Property	RAP	CA6-C	CA5-C	FA6	CA6-G
MDP	0.91 (8)	0.96 (8)	0.84 (8)	0.92 (8)	0.97 (8)
γ_d	0.82 (6)	0.99 (5)	0.96 (5)	0.94 (5)	0.95 (5)
CIV	0.98 (6)	0.98 (5)	0.59 (5)	0.99 (5)	0.98 (5)
DCP Index	0.95 (6)	0.97 (5)	0.92 (5)	0.89 (5)	0.94 (5)
E_{GG}	— [a]	—	0.96 (5)	0.98 (5)	—
E_{LWD}	0.89 (6)	0.89 (5)	0.95 (5)	0.83 (5)	0.93 (5)
E_{PLT}	0.50 (6)	0.77 (5)	0.95 (5)	0.93 (5)	0.97 (5)

[a] no data available

Figure 3.1. Prototype CS-533E vibratory smooth drum roller with roller integrated compaction monitoring technology

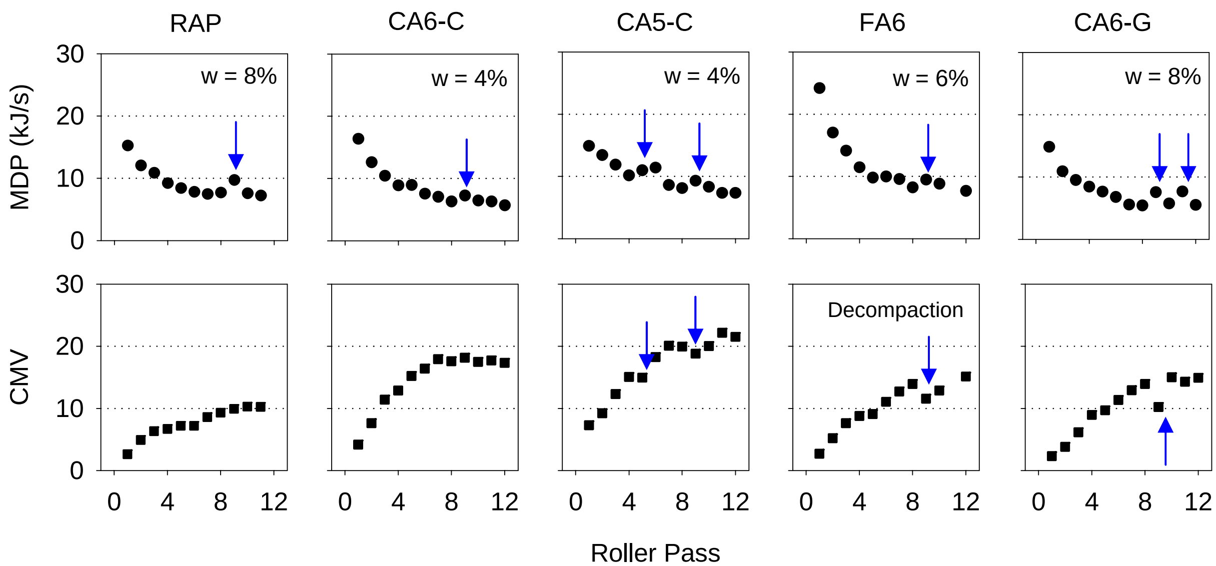

Figure 3.2. Compaction curves for average MDP and CMV (arrows indicate possible decompaction)

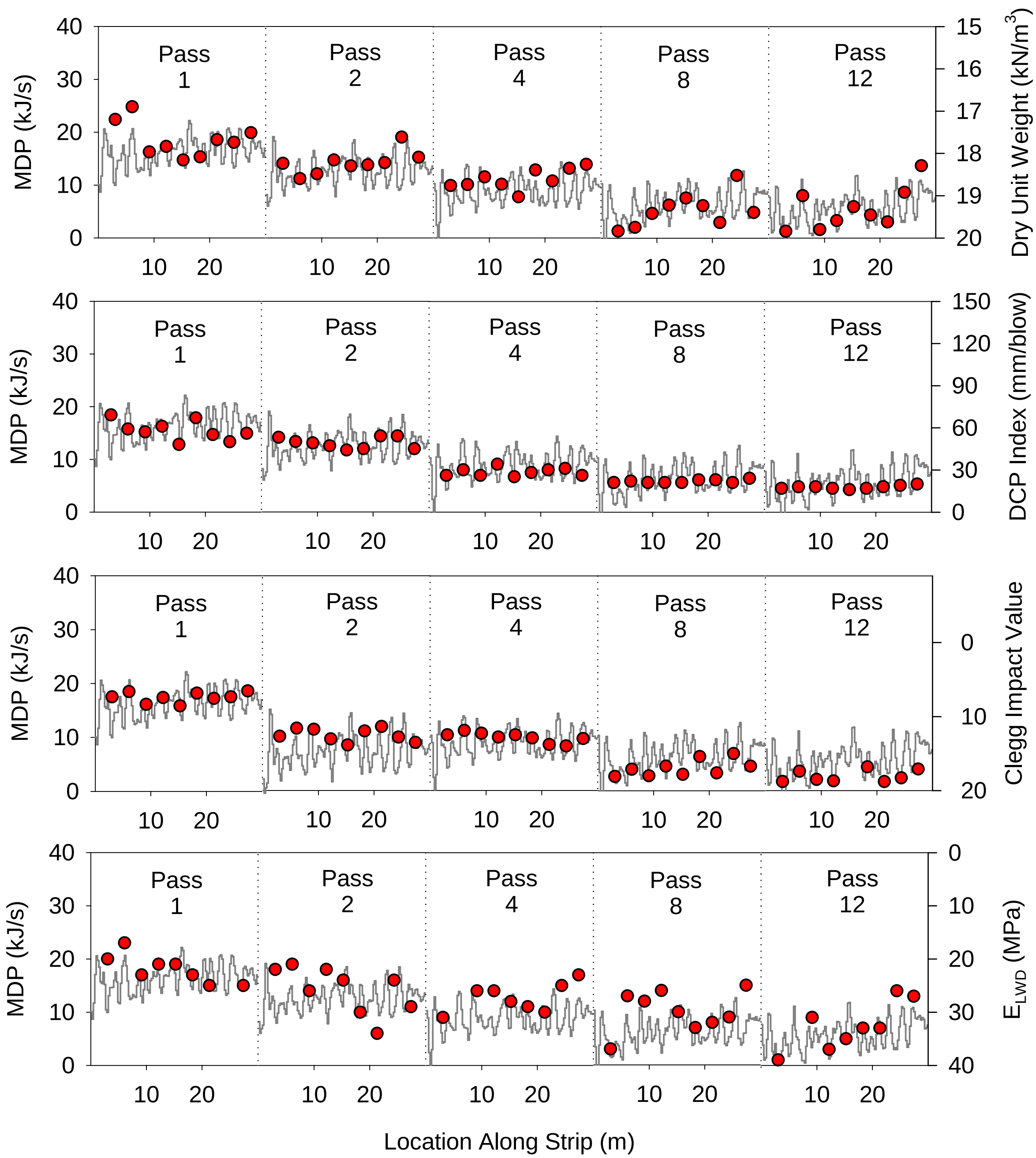

Figure 3.3. MDP, dry unit weight, DCP index, CIV, and E_{LWD} data versus CA6-C test strip location

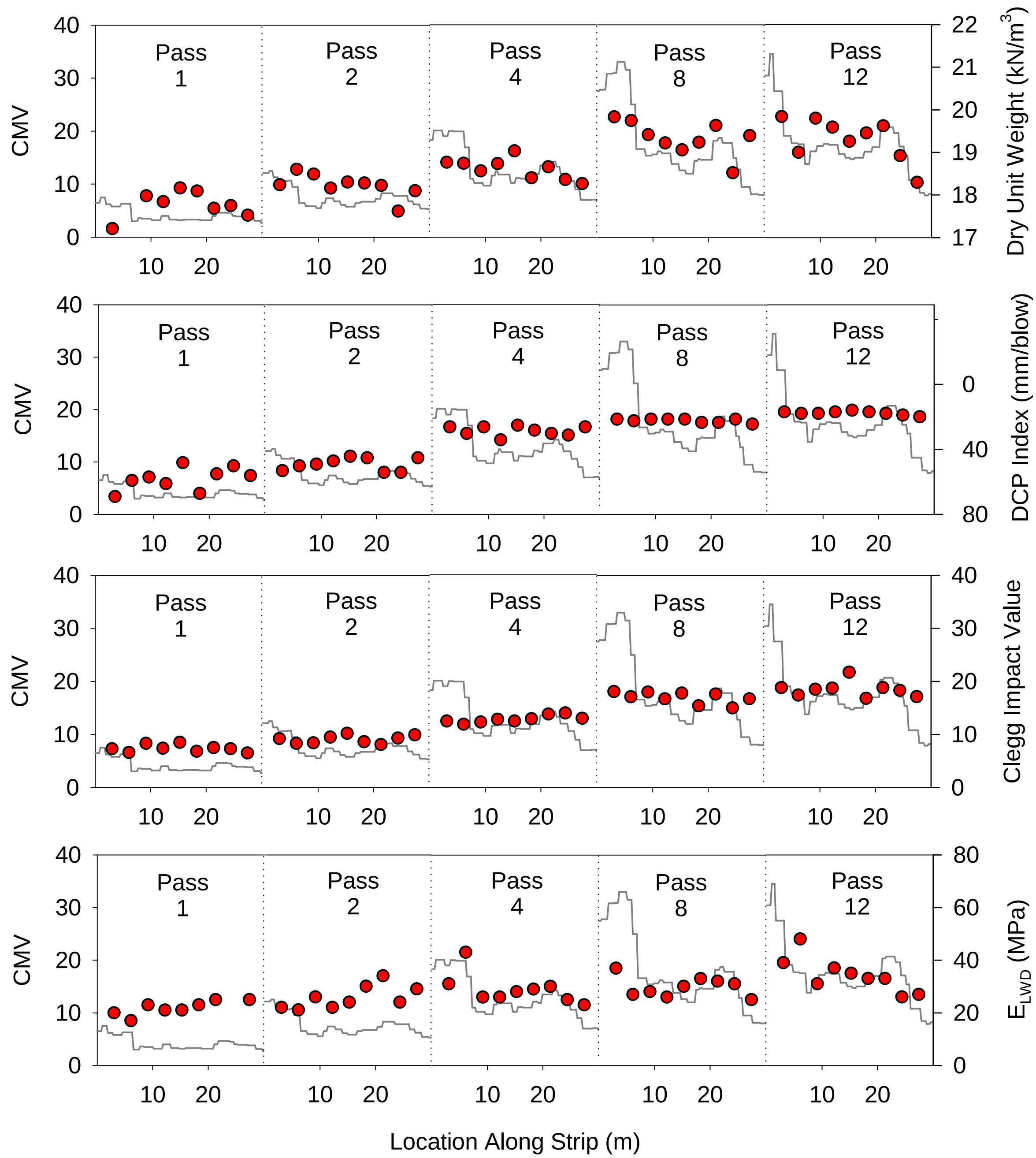

Figure 3.4. CMV, dry unit weight, DCP index, CIV, and E_{LWD} data versus CA6-C test strip location

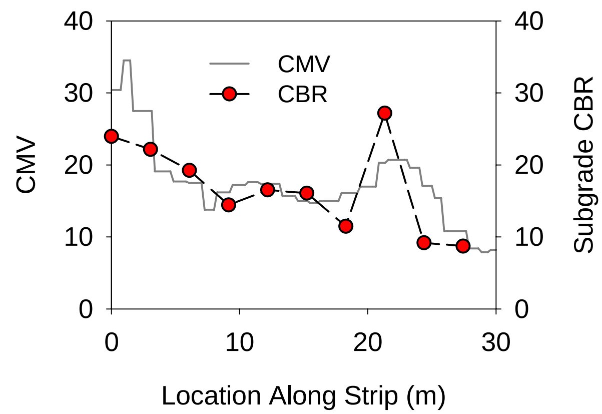

Figure 3.5. CMV (Pass 12) and subgrade CBR versus CA6-C test strip location

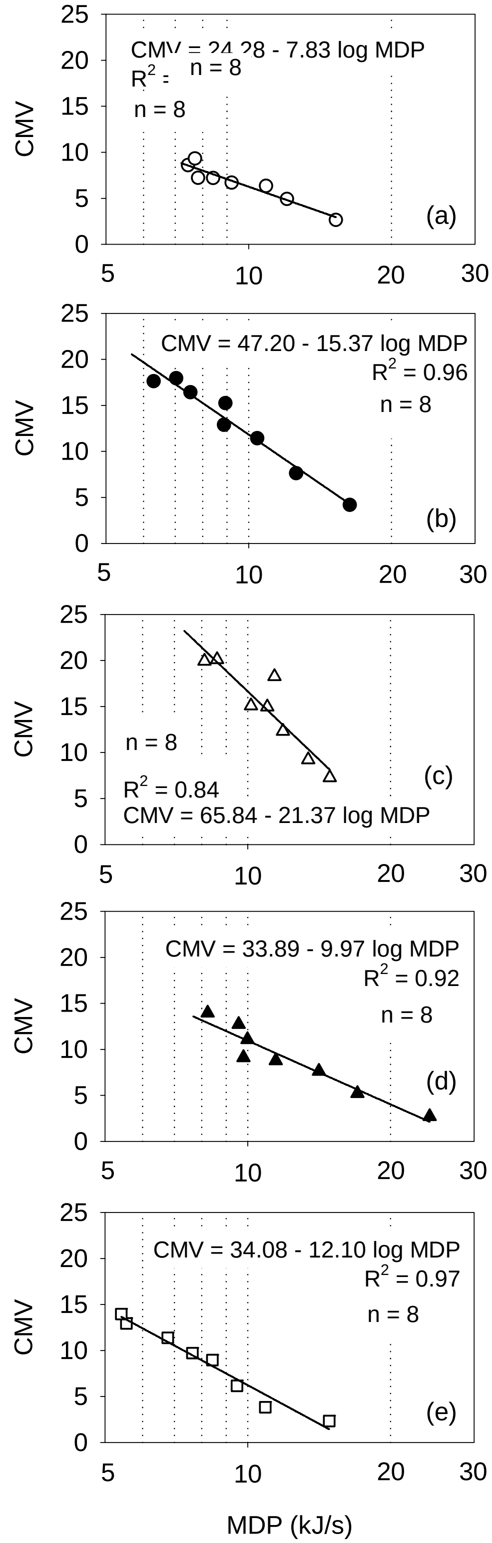

Figure 3.6. Log relationships between average MDP and CMV: (a) RAP, (b) CA6-C, (c) CA5-C, (d) FA6, (e) CA6-G

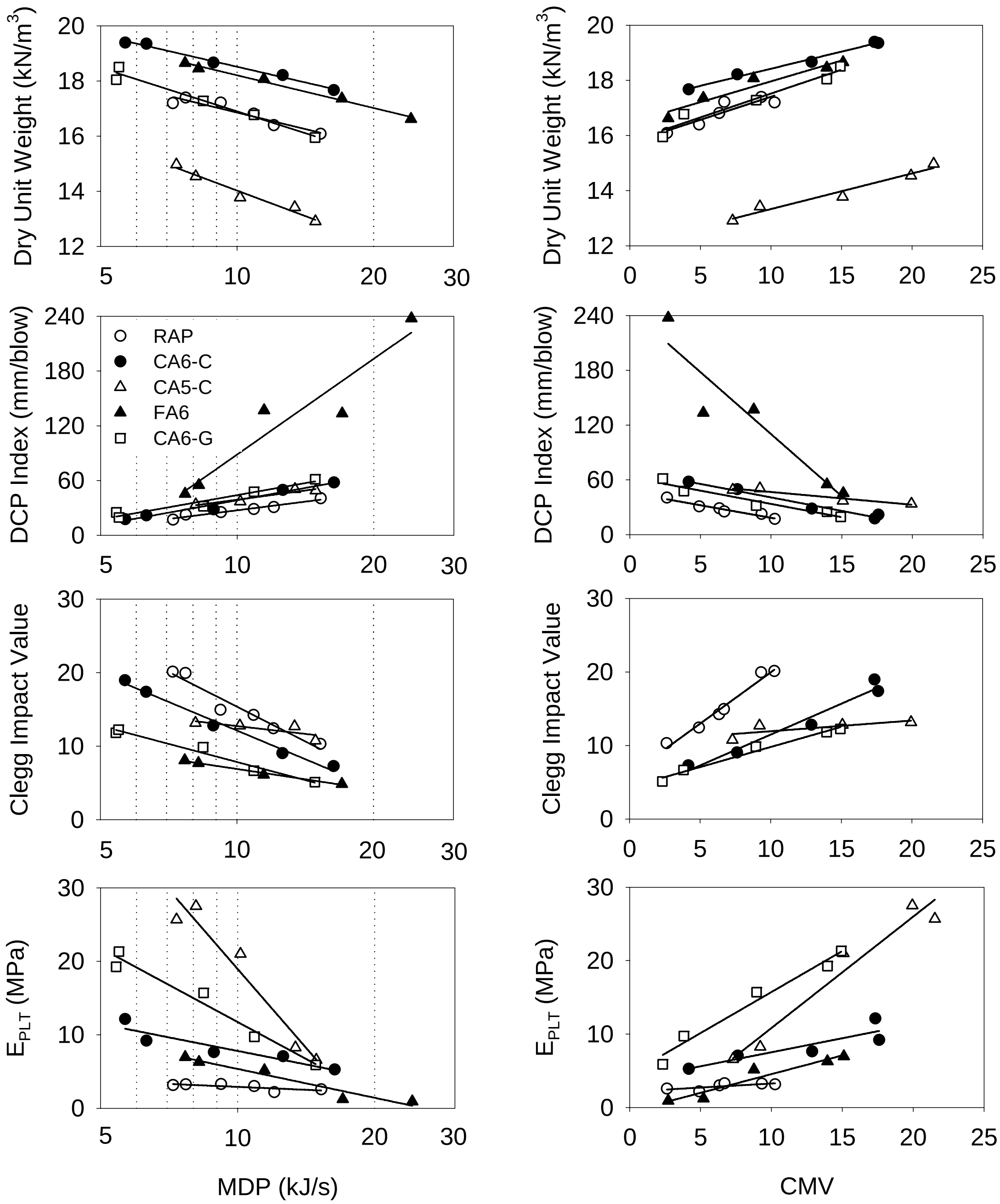

Figure 3.7. Relationships between average in-situ and roller-integrated compaction measurements

CHAPTER 4: Estimating Compaction of Cohesive Soils from Machine Drive Power

A paper submitted to *The Journal of Geotechnical and Geoenvironmental Engineering*

Mark J. Thompson and David J. White

Abstract

To evaluate roller-integrated *machine drive power* (MDP) technology for predicting the compaction parameters of cohesive soils considering the influences of soil type, moisture content, and lift thickness on machine power response, a field study was conducted with 15-m test strips using three cohesive soils and several nominal moisture contents. Test strips were compacted using a prototype CP-533 static padfoot roller with integrated MDP technology and tested using various in-situ compaction measurement devices. To characterize the roller machine-soil interaction, soil testing focused on measuring compaction parameters for the compaction layer. Variation in both MDP and in-situ measurements was observed and attributed to inherent variability of the compaction layer and measurement errors. Considering the controlled operations to create relatively uniform conditions of the test strips, measurement variability observed in this study establishes a baseline for acceptable variation in production operations using MDP technology in cohesive soils. Predictions of in-situ compaction measurements from MDP were found to be highly correlated when moisture content and MDP-moisture interaction terms were incorporated into a compaction model derived from laboratory moisture-dry unit weight-compaction energy relationships.

Introduction

A recent study by White and Thompson (2006) verified that roller-integrated *machine drive power* (MDP) compaction monitoring technology may reliably indicate soil compaction for granular soils and set the stage for additional field studies that would address the influences of other soil types and variable moisture content and lift thickness. The prediction of properties of cohesive soils using roller-integrated compaction technology is a topic which has been largely neglected, principally because roller-integrated compaction technologies have traditionally applied only to vibratory rollers. By understanding how cohesive soils influence machine behavior during compaction operations, new interpretation of MDP may be developed that offers improved predictive capabilities.

The use of roller-integrated compaction technology for cohesive soils has been acknowledged by Thurner and Sandström (1980), Adam (1997), and Brandl and Adam (1997). However, these references lack detailed data for describing the relationships between roller drum behavior and soil properties. Following the recent development of MDP technology, White *et al*. (2004 and 2005) documented real-time compaction monitoring in cohesive soils from machine-ground interactions. To the authors' best knowledge, MDP constitutes the first roller-integrated compaction technology applied to static rollers.

To evaluate MDP technology for cohesive soils, a controlled field study was conducted by means of constructing 15 test strips using three different cohesive soils, three nominal moisture contents (per soil type), and two lift thickness. Experimental testing was performed using a static padfoot roller with integrated MDP technology and also in-situ test devices to describe MDP in terms of compaction parameters. This paper documents the test program and methods for the study and then presents comprehensive data for one test strip and abbreviated statistical analysis results for the entire dataset. A complete summary of the study is provided in White *et al*. (2006).

Experimental Testing

Machine Drive Power (MDP)

The use of MDP technology as a measure of soil compaction is a concept originating from study of vehicle-terrain interaction (see Bekker 1969). MDP, which relates to the soil properties controlling drum sinkage, uses the concepts of rolling resistance and sinkage to determine the energy necessary to overcome the resistance to motion. The technology is comprised of sensors that monitor hydraulic pressure and flow at torque converters of the roller. The product of these machine parameters equals the gross power that propels the roller. MDP is then calculated as

$$\text{MDP} = P_g - WV\left(\sin\theta + \frac{a}{\text{g}}\right) - (mV + b) \tag{4.1}$$

where P_g = gross power needed to move the machine, W = roller weight, a = machine acceleration, g = acceleration of gravity, θ = slope angle (roller pitch from a sensor), V = roller velocity, and m and b = machine internal loss coefficients specific to a particular machine (White *et al*. 2005). The second and third terms of Eq. (1) account for the machine power associated with sloping grade and internal machine loss, respectively. MDP represents only the machine power associated with material properties and, therefore, can theoretically be transferred to other roller configurations.

Testing Program

This field study was conducted to evaluate MDP considering the influences of: (1) cohesive soil type, (2) lift thickness, and (3) moisture content. The experimental testing plan of this study, provided in Table 4.1, was designed to isolate and control each of these field conditions. As a result, a total of 15 relatively uniform test strips were constructed and tested using three soil types, three nominal moisture contents (per soil), and one or two lift thicknesses (per soil). The roller-integrated compaction technology used for this field study was installed on a prototype CP-533 static padfoot roller (see Fig. 4.1) to monitor changes in machine drive power output resulting from soil compaction and the corresponding changes in roller machine-soil interaction. The 10,240-kg roller has a drum diameter of 1.55 m, a drum width of 2.13 m, and a rear wheel-to-drum length of 2.90 m. Because the testing for this study was performed within an indoor demonstration arena, laser coordinates with sub-centimeter accuracy were collected by the roller concurrently with measures of mechanical performance. GPS coordinates displayed on the on-board compaction monitor were, therefore, calculated based on the initial setup of the laser measurement system.

Within the indoor facility, two parallel test beds with lengths of about 15 m were established. The existing glacial till soil of the test facility was excavated to a depth of about 250 mm, and the test bed bases were stabilized with liberal compaction. The strength of the well-compacted bases was determined using dynamic cone penetrometer (DCP). California bearing ratio (CBR) values, which were calculated using a relationship in ASTM 6951, averaged 14.0 ($\sigma = 2.6$). Testing materials (e.g. Kickapoo silt, Kickapoo clay, and Edwards till) were then placed in the test bed excavations and mixed in-situ with either a road reclaimer or tiller to achieve relatively homogeneous and uncompacted soil conditions. Achievement of the specified moisture content was established by moisture conditioning the soil and allowing the cohesive soil to mellow for periods of two to 12 hours. Water or wet soil was added to test strips containing soil too dry for testing. Soil that was too wet for testing was dried by occasionally mixing and aerating. The moisture condition was accepted for testing, provided the moisture content was within about 1 percent of the target nominal moisture for each strip. After constructing the test strip, soil was compacted using the CP-533 padfoot roller. During compaction operations, MDP data were collected approximately every 0.2 m along the test strip and assigned to coordinates calculated from the real-time laser position measurements.

For determining the various in-situ compaction parameter values, ten test points were established at 1.5-m longitudinal intervals in the center of the strip, between the paths of the rear roller tires. At these points, density and moisture content of the uncompacted material were determined using a calibrated nuclear moisture-density gauge for the full depth of the compaction layer. Following the first roller pass over the strip, in-situ test measurements were obtained at each test point. Prior to performing these tests, however, a 0.2 m by 0.2 m test pad was carefully prepared to the depth of the padfoot penetration. Further, the order in which the in-situ tests were performed was predetermined as follows: (1) nuclear moisture and density (ASTM WK218), (2) soil stiffness gauge (SSG) (Humboldt Mfg. Co. 2000), (3) light falling weight deflectometer (LWD) (Dynatest 2004), (4) Clegg impact tester (ASTM D 5874-02), and (5) DCP (ASTM D 6951-03). A single plate load test (PLT) was conducted at the end of the test strip using a 300-mm-diameter plate. Laser positioning measurements were collected at each test location to facilitate pairing of the in-situ measurements with spatially-nearest MDP data. Following subsequent passes of the CP-533 padfoot roller (typically 1, 2, 4, 8 passes), the same measurements were obtained for the increasingly-compact material. The characteristics of the compacted soil were defined with both MDP and in-situ compaction measurements for the full range of soil compaction states. The results of experimental testing provided a statistically-robust dataset to be used for evaluating MDP as an empirical indicator of various compaction parameters.

Testing Materials

Evaluating the applicability of MDP technology to various cohesive soil types was an important aspect of the current field study, particularly as all other known roller-integrated compaction technologies apply only to vibratory compaction. As a result, experimental testing involved compaction and field testing of three soils. The soils were acquired from Kickapoo and Edwards, IL and classified as ML silt, CL lean clay with sand, and CL sandy lean clay (Table 4.2). Each soil was fine-grained (fines content ranging from 68 to 92 percent) with moderate plasticity (PI ranging from 12 to 22).

Moisture-density tests were performed following Standard (ASTM 698) and Modified (ASTM 1557) Proctor compaction tests. In performing these tests, test Method A was used. An automated, calibrated mechanical rammer was provided for compaction. A wide range of maximum dry unit weight and optimum moisture content was observed between the soils. Compaction properties for each testing material are provided in Table 4.2.

Test Data

MDP and in-situ measurements are shown in Fig. 4.2 for Strip 1 (Kickapoo silt). Near-continuous MDP is represented with a solid line, whereas soil dry unit weight, DCP index, Clegg impact value (CIV), and E_{LWD} are shown as discrete points along the test strip. The variation observed for MDP data may be categorized into: (1) local variability resulting from unquantified variable mechanical performance of the roller and/or (2) inherent variability of compaction layer and to a lesser extent the properties of the underlying soil.

MDP variation for indicating inherent compaction layer variability is, in some cases, supported by the in-situ compaction measurements (e.g. Pass 2 CIVs). The high MDP values at the beginning of the test strip were observed for every pass and may indicate the influence and variability of the underlying, compacted subgrade – an influence affecting roller response more than in-situ tests of the compaction layer due to the machines greater measurement influence depth.

The implication of variable MDP data (and variable in-situ test data) on relationships between roller-integrated measurements and soil compaction parameters is demonstrated with the scatter plots shown in Fig. 4.3. Poor or non-existent correlation was observed for Strip 1 (Kickapoo silt) data using spatially-paired measurements with R^2 values ranging up to only 0.17. By averaging the data along the test strip for each roller pass, however, R^2 values for the same relationships increased up to 0.99. The experimental results reveal that a single measurement does not provide a high level of confidence in being representative of the average, particularly when addressing variable compaction parameters and roller-integrated MDP data. While strong relationships were observed between MDP and dry unit weight, comparatively poor correlation is shown between average MDP and E_{LWD} for this soil type. As is discussed below, variability of E_{LWD} measurements were the highest among the various in-situ compaction measurements evaluated in this study and is consistent with results reported by White and Thompson (2007) for granular soils.

MDP standard deviations and in-situ compaction measurement C_V for the entire dataset is summarized in Table 4.3. The table of values represents the average of the calculated variation parameters for each roller pass for which there were measurements collected (i.e., 1, 2, 4, and 8). MDP standard deviation ranged from 3.21 to 6.27 kJ/s. C_V for dry unit weight, CIV, DCP index, E_{SSG}, and E_{LWD} ranged from 2 to 6 percent, 8 to 18 percent, 12 to 34 percent, 13 to 27 percent, and 29 to 66 percent, respectively. The soil properties having a comparatively wide range of magnitude (e.g. modulus, in this case) were also generally more variable. The notably high C_V values for strength and modulus are of consequence for development of quality criteria for performance-based measurements in earthwork construction as measurements with higher C_V require relatively more test measurements to provide the same reliability as a measurement with lower C_V. Considering that test strips were constructed to be (at least) as uniform as may be expected under actual field conditions, measurement variability observed in this study establishes a baseline for acceptable variation in production compaction of cohesive soils using MDP technology. The results of Table 4.3 were also compared with average variation parameters observed for granular soil from White and Thompson (2007). Average MDP standard deviation for cohesive soil (σ = 4.60 kJ/s) was approximately 35 percent higher than for granular soil (σ = 3.40 kJ/s). Soil modulus measurements were also considerably more variable for cohesive soil with average C_V for E_{SSG} and E_{LWD} equal to 19 and 43 percent, respectively, as opposed to 13 and 26 percent, respectively, for granular soils (White and Thompson 2007). Dry unit weight, CIV, and DCP measurements showed comparable C_V values between cohesive and granular soil types.

Statistical Analysis

Description of Compaction Model

A laboratory compaction study was conducted with cohesive soils to develop a compaction model that: (1) relates dry unit weight to compaction energy and moisture content and (2) improves the prediction of in-situ compaction parameters using MDP. The compaction model, which would ideally take a simple form, would predict the dry unit weight of a soil for any combination of moisture content and compaction energy. For the study, multiple soil types, Proctor compaction energies (356, 594, 990, and 2700 kN-m/m^3), and moisture contents (varying by soil type) were controlled. The dry unit weight for each combination of soil type, energy level, and moisture content was determined using Proctor test methods. The moisture-density-energy relations for each soil type were modeled separately, however, because of the differing physical properties of the soils.

The compaction model derivation, described in detail by White *et al*. (2006) using data from White *et al*. (2004), provided the following seven-parameter model:

$$\gamma_d = b_0 + b_1 \cdot E_C + b_2 \cdot E_C^2 + b_3 \cdot w + b_4 \cdot w^2 + b_5 \cdot E_C \cdot w + b_6 \cdot E_C^2 \cdot w \qquad (4.2)$$

where γ_d = dry unit weight, E_C = compaction energy, w = moisture content, and b_0 through b_6 = regression coefficients with units that give units of density for the full term. Whether or not each of the linear or quadratic model parameters is statistically significant depends on the soil. Fig. 4.4 shows laboratory compaction data (symbols) and dry unit weight predictions (lines) for Edwards till material. The fitted model provided an R^2 value of 0.94 for 26 observations.

A separate laboratory study was performed using the same soils, moisture contents, and compaction energy levels to identify the relationships between strength and deformation parameters, compaction energy, and moisture content. Undrained shear strength and secant modulus were determined for samples prepared with each combination of compaction energy and moisture content (Drew 2005). However, a model based on quadratic relationships did not predict the measured values. The inability to use a simple, consistent model for strength and stiffness parameters may be explained as follows: (1) the relationships are complex, and simple models may not be adequate, (2) soil strength and deformation characteristics are strongly influenced by small changes in moisture (moisture variation observed within a nominal moisture range obscured a general pattern), or (3) soil strength and modulus may not be adequately predicted from compaction energy and moisture content alone (White *et al*. 2006).

Multiple Linear Regression Analysis

The laboratory compaction study showed that dry unit weight may be reasonably well modeled using compaction energy and moisture content. By substituting MDP for compaction energy in Eq. (2), the in-situ compaction parameters from the various test devices were predicted from MDP and moisture content. For the analysis, statistically non-significant (p-test value > 0.05) variables were removed from the final models, and the resulting relationships varied by the compaction parameter, soil type, and lift thickness. The final models were generally simpler than Eq. (1), usually with only three or four regression parameters including the intercept. Coefficients of determination (R^2) were used to assess the quality of the regressions.

Multiple regression analyses were performed for the cohesive soils and lift thicknesses using average MDP and in-situ compaction measurements. Scatter plots of average values for a given roller pass are shown in Fig. 4.6 for Kickapoo silt with 300-mm lift thickness (Strips 1, 3, and 5). Linear regressions of the data are provided in Fig. 4.5 as dashed lines to show a preliminary approximation of in-situ compaction measurements based on MDP. R^2 values for linear relationships ranged from 0.63 (modulus) to 0.73 (dry unit weight). By incorporating significant moisture content and MDP-moisture interaction terms into the regressions, R^2 values increased to 0.93 for dry density, 0.98 for Clegg impact value, 0.93 for DCP index, 0.96 for E_{SSG}, and 0.77 for E_{PLT}. The multiple regression model predictions for Kickapoo silt are shown in Fig. 4.5 as solid lines. The regression coefficients presented in Fig. 4.5 are applicable to Kickapoo silt material and do not necessarily fit models for other soil types.

Coefficients of determination for the entire dataset are provided in Table 4.4. 20 of 42 prediction models show a linear relationship between MDP and the in-situ measurements. The other 22 models show that moisture content and/or MDP-moisture interaction terms are significant. Since the initial model was derived from laboratory density-compaction energy-moisture data, predictions of dry unit weight were often more accurate than predictions of soil modulus. The complexity of soil modulus may require that a more complicated model be developed. With C_V ranging up to nine percent, exceptionally high variation of dry unit weight for two Edwards till test strips (Strips 12 and 15) is noted as the cause for the R^2 value of 0.00 in Table 4.4. Nevertheless, general correlation observed between MDP and in-situ compaction measurements indicates the promise of using MDP technology as a tool for predicting compaction parameters for cohesive with the advantage of real-time information.

For demonstrating the application of multiple regression analysis results to field compaction using roller-integrated compaction technology, the statistical model for dry unit weight in Fig. 4.5 (predicting dry unit weight from MDP and moisture content) is rearranged to calculate MDP for any combination of dry unit weight and moisture content. MDP contours are plotted over a moisture-density plot in Fig. 4.6. Because the original statistical model was comprised of only linear terms, MDP contours are linear and parallel lines that increase in value with increasing moisture content and decrease in value with increasing dry unit weight. Also shown in Fig. 4.6 are field moisture-density data (shown as dots) from which the model was developed and the standard Proctor moisture-density relationship. To aid the selection of target MDP values, a target area is highlighted and bounded by ±2 percent of optimum moisture content and also by 95 percent of the maximum dry unit weight. Thus, to achieve adequate compaction, MDP must be lower than 4 kJ/s for soil 2 percent dry of optimum and must be lower than about 8 kJ/s for soil 2 percent wet of optimum.

The influence of lift thickness on MDP was observed by combining all the averaged data for Kickapoo silt and Edwards till materials, thus incorporating three nominal moisture contents and two lift thicknesses. The three Kickapoo clay test strips were constructed with only one nominal lift thickness. Because lift thickness was another variable affecting the relationships, lift thickness was added to the model as a linear regression term. However, the range of lift thicknesses evaluated in this study was found to be statistically significant for only one model (DCP index in till). Comparison of R^2 values in Table 4.4 shows that coefficients of determination for thick lifts are consistently higher than for thin lifts with combined data ("Both") providing intermediate R^2 values. The relative difference in R^2 values between thin and thick lifts suggests that the depth influencing MDP exceeds the thin lift thicknesses. Characterizing measurement influence depth and the factors affecting it (e.g. roller dimensions and operational conditions, soil types and underlying layers) is still a major focus of research addressing roller-integrated compaction monitoring technologies.

Summary and Conclusions

Experimental testing was conducted using a CP-533 static padfoot roller with roller-integrated compaction technology and various in-situ test devices to evaluate *machine drive power* (MDP) in terms of compaction parameters of cohesive soil considering the influences of soil type, moisture content, and lift thickness. For each of 15 test strips prepared with a single soil type and nominal moisture content, in-situ compaction measurements were compared directly to MDP for demonstrating how the mechanical performance of a roller is related to the properties of the material it is compacting. Linear and multiple linear regression analyses of average MDP and in-situ compaction measurements were performed using a laboratory-derived compaction model that relates dry unit weight to moisture content and compaction energy. Compaction parameters (e.g. DCP index, CIV, E_{LWD}, etc.) were approximated by MDP, particularly when moisture content was included as a regression parameter.

The following conclusions were drawn from this study.

1. The results of experimental testing provided a statistically-robust dataset with sufficient variation in moisture content and lift thickness between test strips for producing meaningful correlations between MDP and compaction parameters of cohesive soils.
2. MDP measurement variation results indicate inherent variability of compaction layer and subgrade material properties and unquantified measurement errors. The variation of MDP, as well as variation of in-situ measurements, was generally higher for cohesive soil than for granular soil, based on average standard deviation and coefficient of variation values.
3. Statistical averaging of data, in which measurements from the 15 m long test strip are averaged for a given roller pass to produce single data value, mitigates data scatter and improves the prediction of compaction parameters with roller-integrated MDP results.
4. A laboratory compaction study was conducted with cohesive soils to develop a compaction model that relates dry unit weight to compaction energy and moisture content. By substituting MDP for compaction energy in the model, in-situ compaction parameters were predicted from MDP and moisture content measurements. Incorporating moisture content and MDP-moisture interaction terms into regressions, when statistically significant, improved correlation to indicate the promise of using MDP technology as a tool for predicting compaction parameters with the advantage of real-time information about the soil.
5. The influence of lift thickness on MDP was investigated. The effect of measurement influence depth on roller response and relationships between roller-integrated and in-situ compaction measurements show that the depth influencing MDP may exceed the thinner lifts (150 to 200 mm) evaluated in this study.

Notation

$b_{0\text{-}6}$	=	regression coefficients
CBR	=	California bearing ratio
CIV	=	Clegg impact value
CMV	=	Compaction Meter Value
C_V	=	coefficient of variation
DCP	=	dynamic cone penetrometer
DCPI	=	dynamic cone penetration index
E_C	=	compaction energy
E_{LWD}	=	modulus of soil from light falling weight deflectometer
E_{PLT}	=	modulus of soil from plate loading test
E_{SSG}	=	modulus of soil from soil stiffness gauge
F	=	applied force
F_{200}	=	percent of soil passing sieve No. 200
g	=	acceleration due to gravity
GPS	=	Global positioning system
G_s	=	specific gravity
γ_d	=	dry unit weight of soil
$\gamma_{d,max}$	=	maximum dry unit weight of soil from Proctor test
LL	=	liquid limit
LWD	=	light falling weight deflectometer
MDP	=	*machine drive power*
μ	=	statistical mean
n	=	number of observations
PLT	=	plate load test
PI	=	plasticity index
R^2	=	coefficient of determination
SSG	=	soil stiffness gauge
σ	=	standard deviation

w = water content

w_{opt} = optimum water content from Proctor test

ZAV = zero-air-void curve

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Table 4.1. Field testing plan

Soil Type	Strip No.	Nominal Loose Lift Thickness (mm)	Nominal Moisture Content (%)	Moisture Deviation from Standard [a] w_{opt} (%)	Moisture Deviation from Modified [a] w_{opt} (%)
Kickapoo silt	1	300	8	-12	-7
	2	200	8	-12	-7
	3	300	16	-4	+1
	4	200	16	-4	+1
	5	300	12	-8	-3
	6	200	12	-8	-3
Kickapoo clay	7	250	24	+8	+10
	8	250	16	0	+2
	9	250	20	+4	+6
Edwards till	10	150	8	-5	+1
	11	250	8	-5	+1
	12	150	16	+3	+9
	13	250	16	+3	+9
	14	250	12	-1	+5
	15	150	12	-1	+5

[a] Moisture deviation from optimum, based on respective Proctor tests ($w - w_{opt}$)

Table 4.2. Soil properties for field and laboratory test materials

Soil Property	**Kickapoo Silt**	**Kickapoo Clay**	**Edwards Till**
USCS:			
Symbol	ML	CL	CL
Name	Silt	Lean clay with sand	Sandy lean clay
AASHTO (GI):	A-6 (13)	A-7-6 (18)	A-6 (6)
G_s	2.65	2.75	2.75
F_4 (%)	100	99	97
F_{200} (%)	92	79	68
LL (PI)	38 (13)	47 (22)	29 (12)
Standard Proctor:			
$\gamma_{d,\ max}$ (kN/m^3)	15.8	17.4	18.4
w_{opt} (%)	19.9	16.0	13.8
Modified Proctor:			
$\gamma_{d,\ max}$ (kN/m^3)	17.2	18.1	19.9
w_{opt} (%)	15.0	13.5	7.9

Table 4.3. Average variation parameters for compaction measurements

Strip No.	MDP [a]	Dry Density	DCP Index	CIV	E_{SSG}	E_{LWD}
1	6.27	4	19	18	26	64
2	5.53	3	21	— [b]	27	31
3	5.24	3	22	8	19	41
4	3.30	3	21	11	16	39
5	6.00	2	22	10	15	29
6	3.33	3	29	10	20	39
7	5.41	3	17	13	20	47
8	4.29	3	32	14	21	41
9	3.28	4	18	16	13	56
10	3.21	2	15	12	21	29
11	3.58	2	19	13	21	30
12	5.01	3	12	—	13	44
13	5.41	5	23	—	—	—
14	4.09	3	34	14	13	42
15	5.12	6	24	18	22	66
Average	4.60	3	22	13	19	43

[a] standard deviation for MDP (kJ/s) – coefficient of variation for other measurements (%)
[b] no data available

Table 4.4. Coefficients of determination for multiple regression analyses of cohesive soils using average values for a given roller pass, presented as: R^2 (number of observations, number of independent variables)

Soil Type	Moisture Contents	Lift Thickness (mm)	Soil Property	R^2		
				Thin Lift	Thick Lift	Both
Kickapoo silt	8, 12, 16 %	200, 300	γ_d	0.89 (11,2)	0.93 (12,2)	0.88 (23,2)
			CIV	0.84[a] (8,1)	0.98 (12,3)	0.93 (20,3)
			DCPI	0.97[a] (11,1)	0.93 (12,2)	0.94 (23,2)
			E_{GG}	0.88[a] (9,1)	0.96 (8,2)	0.91 (17,2)
			E_{LWD}	0.89[a] (9,1)	0.63[a] (10,1)	0.73[a] (19,1)
			E_{PLT}	0.73[a] (6,1)	0.77 (10,4)	0.67[a] (16,1)
Kickapoo clay [b]	16, 20, 24 %	250	γ_d	— [c]	0.78 (11,2)	— [c]
			CIV	— [c]	0.98 (12,5)	— [c]
			DCPI	— [c]	0.93 (11,2)	— [c]
			E_{GG}	— [c]	0.74 (12,5)	— [c]
			E_{LWD}	— [c]	0.46[a] (11,1)	— [c]
			E_{PLT}	— [c]	0.48[a] (12,1)	— [c]
Edwards till	8, 12, 16 %	150, 250	γ_d	0.00[a] (11,1)	0.60 (11,2)	0.45 (22,2)
			CIV	0.52[a] (11,1)	0.84[a] (7,1)	0.73 (18,2)
			DCPI	0.55 (11,2)	0.81 (11,5)	0.70 (22,2)
			E_{GG}	0.59[a] (11,1)	0.96 (7,3)	0.75 (18,3)
			E_{LWD}	0.78[a] (9,1)	0.78[a] (7,1)	0.74[a] (16,1)
			E_{PLT}	0.46[a] (8,1)	0.44[a] (5,1)	0.55[a] (13,1)

[a] Includes MDP term only (linear relationships with intercept)
[b] Includes test strips with only 1 lift thickness
[c] No data available

Figure 4.1. Prototype CP-533 static padfoot roller with roller-integrated MDP compaction technology

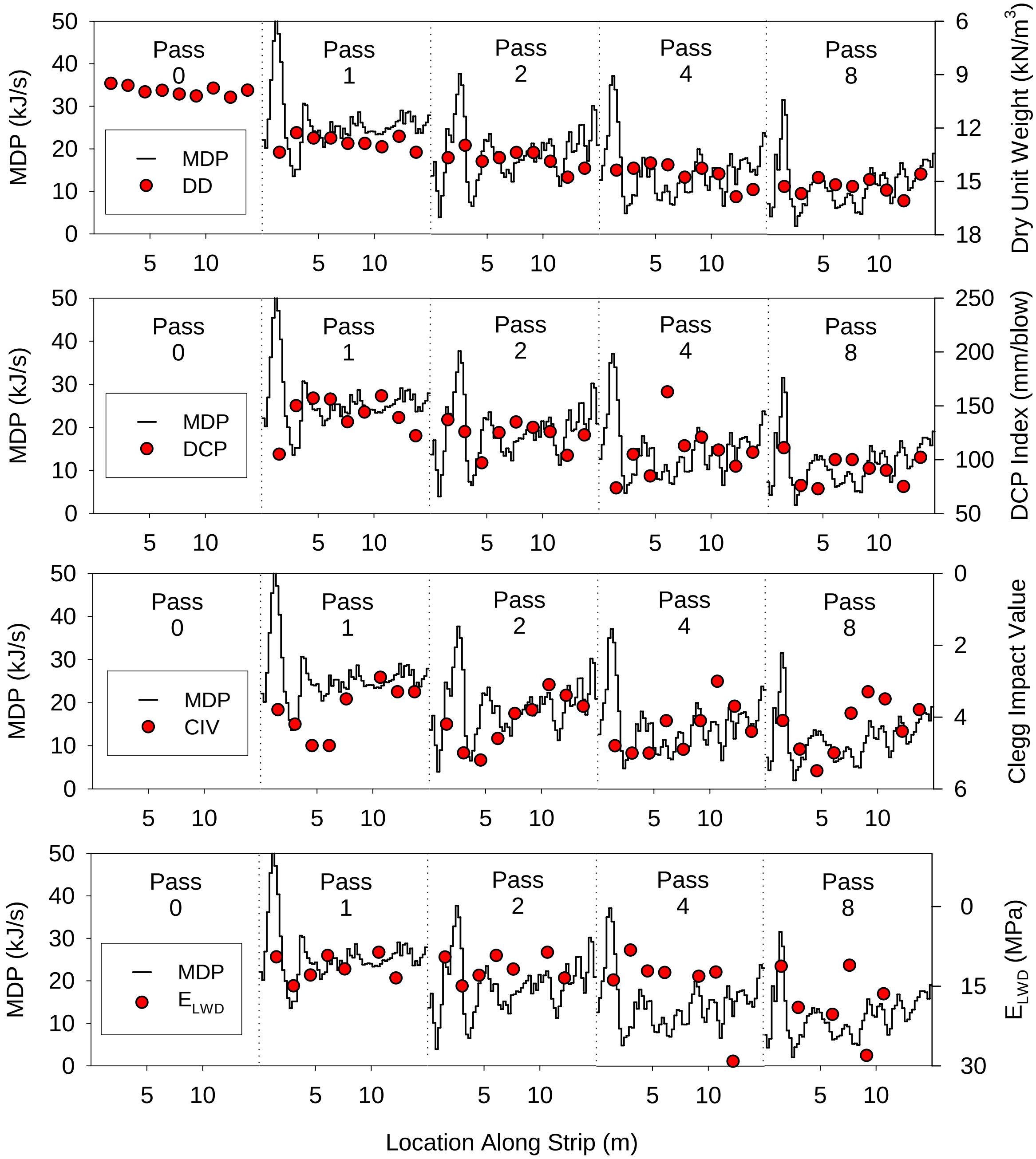

Figure 4.2. MDP, dry unit weight, DCP index, CIV, and E_{LWD} data versus test strip location

(Kickapoo silt, Strip 1)

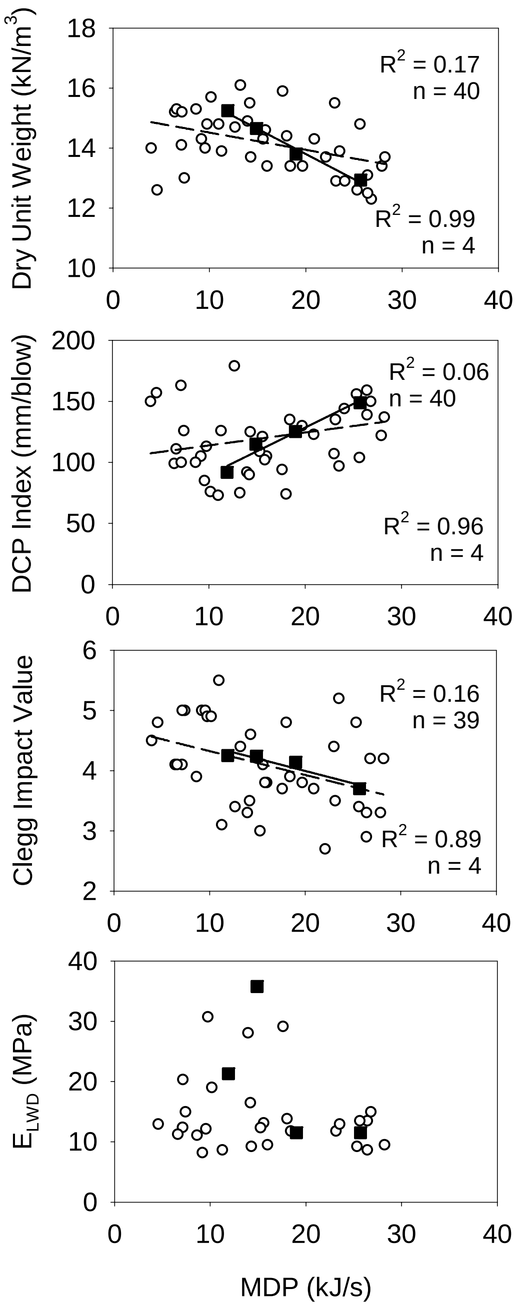

Figure 4.3. MDP correlation with in-situ compaction measurements using spatially-nearest data pairs (circles) and averaged measurements for a given roller pass (squares) (Kickapoo silt, Strip 1)

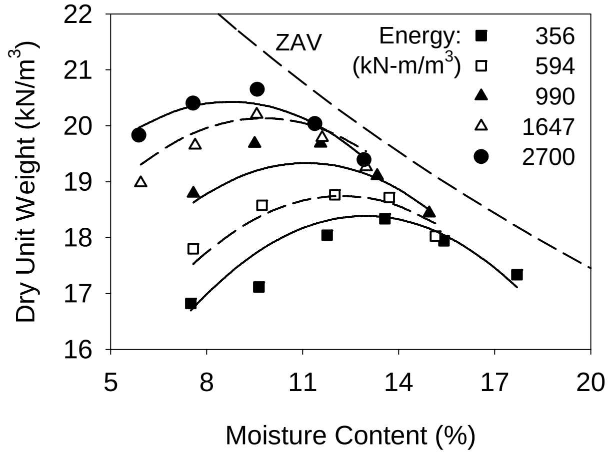

Figure 4.4. Compaction model verification for Edwards till material (R^2 = 0.94, 26 observations): dry density data (points) and predictions (lines)

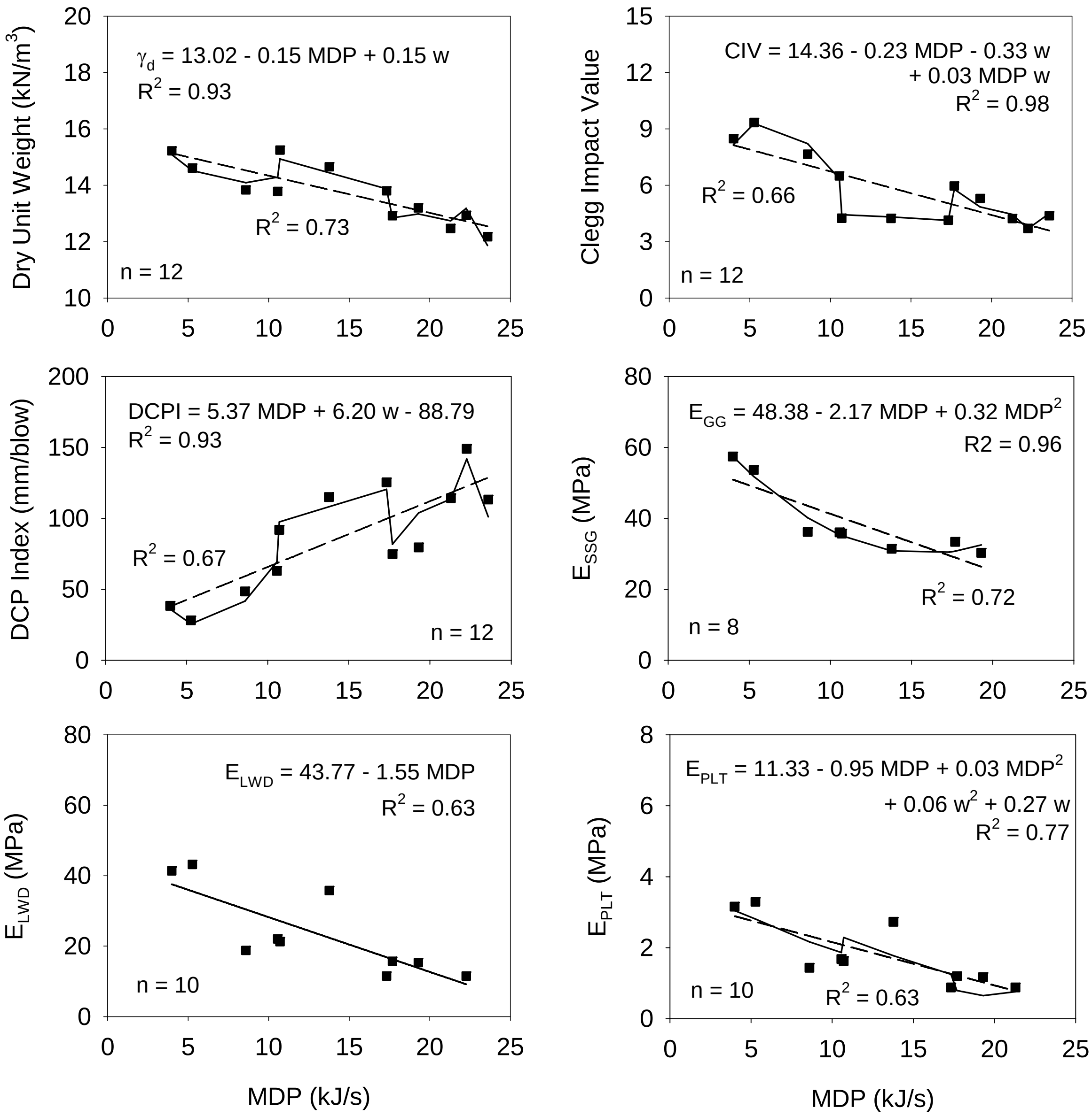

Figure 4.5. Multiple linear regressions of average MDP and in-situ compaction measurement values (Kickapoo silt, nominal 300-mm-lift test strips only)

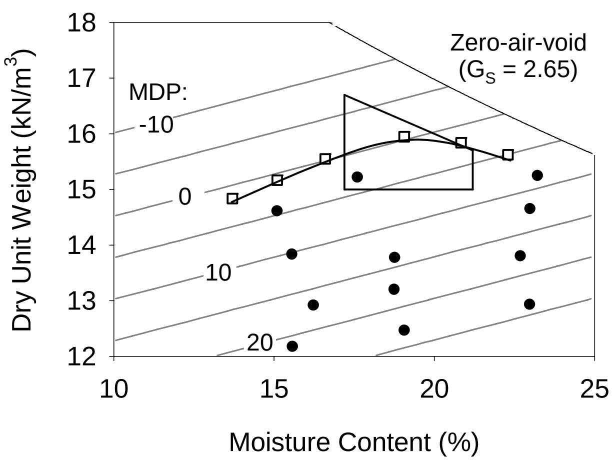

Figure 4.6. MDP contours using multiple regression model showing field compaction data (dots) and target area bounded by ±2 % w_{opt} and 95 % $\gamma_{d,max}$ (Kickapoo silt)

CHAPTER 5: Field Calibration and Spatial Analysis of Compaction Monitoring Technology Measurements

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Abstract

To implement compaction monitoring technologies (i.e., continuous compaction control and intelligent compaction), robust and versatile specifications are needed. These specifications will require field calibration of the various machine sensor outputs to in-situ soil compaction measurements. The goal of this study was to provide insights into: (1) the nature of compaction monitoring measurements, (2) how the measurements are related to soil properties determined from in-situ compaction control tests, and (3) how compaction monitoring technology may be addressed in specifications for using the technology in practice. To accomplish this goal, testing was conducted on one-dimensional test strips with several nominal moisture contents for developing statistical regression models that relate *machine drive power* (MDP) and *compaction meter value* (CMV) data to engineering and index properties of soil. Further, a two-dimensional test area with variable lift thickness and moisture content was constructed and tested using both compaction monitoring technology and in-situ devices (e.g., nuclear moisture-density gauge, portable falling weight deflectometer). The spatial distribution of the data was investigated. The significance of this research is that it represents the first documented field calibration of both one-dimensional and two-dimensional tests areas on similar soils and introduces a new approach to generating pass/fail criteria based on compaction monitoring technology.

Introduction

Compaction monitoring technologies have recently been incorporated into quality acceptance practices of transportation earthwork projects in the United States (Wilkins 2006). The use of such technology is anticipated to increase in upcoming years. Transportation agencies and contractors are implementing compaction monitoring technology with the expectation that the systems will improve construction efficiency, streamline quality management programs of earthwork projects, better link quality acceptance parameters and documentation with pavement design, and improve the performance of compacted materials. Before widespread technology implementation in the United States, it follows that research is needed to verify these potential benefits.

For validating various compaction monitoring technologies, previous research efforts have focused on field calibration testing on one-dimensional test strips with various soil conditions using compaction monitoring technology applied to various roller configurations to show that, on a relatively large scale, compaction monitoring technologies can indicate the condition of the compaction layer (White *et al*. 2004, White *et al*. 2006a, White *et al*. 2006b). Much of this research has focused on describing the variability of roller-generated data at different length scales and using both roller data and moisture content to predict in-situ soil properties, including soil density, strength, and modulus. Research findings and results from field demonstration projects (Petersen 2005, White and Thompson 2006) have supported continued compaction monitoring technology developments and technology implementation into geoconstruction operations. Continued research studies are needed for a variety of field conditions to develop comprehensive and versatile specifications for use of this technology.

In this paper, experimental testing and results are described for establishing the applicability of using averaged roller data from one-dimensional calibration test strips to assess compaction of a two-dimensional area. Such an evaluation is necessary for verifying the reliability of one-dimensional test strip calibrations as a component of specifications (see ISSMGE 2005). The specific objectives of this study included: (1) collection of compaction monitoring results over a two-dimensional area that incorporates variable lift thickness and stiffness properties, (2) documentation of how the result from two different compaction monitoring technologies are related considering spatial variability of soil properties and also measurement variability, (3) evaluation of how accurately two different compaction monitoring technologies predict soil properties compared with using in-situ compaction control tests (e.g., dynamic cone penetrometer, nuclear moisture-density gauge, portable falling weight deflectometers, etc.), and (4) evaluation of previous research findings, such as using moisture content in concert with machine compaction monitoring values to predict soil properties, for implementing the findings into quality statements or specifications.

The two compaction monitoring technologies evaluated in this paper are the vibratory-based *compaction meter value* (CMV) and the static or vibratory-based *machine drive power* (MDP). The machine parameters were statistically evaluated for both one-dimensional calibration test strips and a two-dimensional test area for demonstrating how compaction monitoring technology may be implemented on an earthwork project as a quality control/acceptance tool. The findings documented in this paper have broader implications for all compaction monitoring technologies.

Experimental Design

Compaction Monitoring Technology Description

A CS-533 vibratory smooth drum roller with capabilities for measurement and real-time output of both CMV and MDP, shown in Fig. 5.1, was used for this project. The 10,240-kg roller has a drum diameter of 1.55 m, a drum width of 2.13 m, and a rear wheel-to-drum width of 2.90 m. The roller was additionally fitted with a global positioning system (GPS) to track roller coverage and apply compaction monitoring results to discrete locations over the project area (i.e. mapping).

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. Previous studies have found that the ratio between the amplitude of the first harmonic (A_1) and the amplitude of the fundamental frequency (A_0) is a reliable indicator of soil compaction. Accordingly, CMV is defined as:

$$CMV = C \cdot \frac{A_1}{A_0} \tag{5.1}$$

where C is a constant to give a full scale reading of about 100. CMV technology is further described in (Sandstrom and Pettersson 2004) and (Thurner and Sandstrom 2000). CMV has been correlated to in-situ field compaction measurements for several soils (White *et al.* 2007a).

The use of MDP as a measure of soil compaction is a concept originating from study of vehicle-terrain interaction. MDP, which relates to the soil properties controlling drum sinkage, uses the concepts of rolling resistance and sinkage to determine the stresses acting on the drum and the energy necessary to overcome the resistance to motion (White *et al.* 2005, Komandi 1999, Muro and O'Brien 2004). Using MDP for describing soil compaction, where higher power indicates soft or weak material and lower power indicates compact or stiff material, is documented by (White *et al.* 2004), (White *et al.* 2006a), and (White *et al.* 2006b). The net MDP that is required to propel the machine over a layer of soil can be represented as:

$$MDP = P_{\mathrm{g}} - WV\left(\sin\theta + \frac{a}{\mathrm{g}}\right) - (mV + b) \qquad (5.2)$$

where P_{g} is the gross power needed to move the machine, W is the roller weight, V is the roller velocity, θ is a slope angle, a is acceleration of the machine, g is acceleration of gravity, m and b are machine internal loss coefficients specific to a particular machine (White *et al.* 2005). The second and third terms of Equation (2) account for the machine power associated with sloping grade and internal machine loss, respectively. For roller operation at this site on level ground, machine power attributed to sloping grade is generally less than than 20 percent of the gross power; internal machine loss and MDP may each range from 20 to 80 percent of gross power. Further details of the calibration process of machine internal loss coefficients are described in (White *et al.* 2006).

Project Description and Test Plan Design

For evaluating compaction monitoring output in terms of soil properties, in-situ spot tests were performed to obtain measures of the soil state and performance characteristics. Soil moisture content and dry unit weight were obtained using a nuclear moisture-density gauge with a constant transmission depth of 200 mm. Soil modulus was obtained using a portable falling weight deflectometer (PFWD) with a 200-mm plate. Modulus determination for this project followed the manufacturer's protocol of three seating drops, followed by three additional drops from which the average plate settlement was used to calculate soil modulus (Zorn 2003). Clegg impact values (CIV), a measure of soil strength, was obtained at the soil surface by Clegg Impact Tests (both 4.5 kg and 20 kg). Full-depth soil strength (about 900 mm) was measured using the dynamic cone penetrometer (DCP).

Field calibration testing of the roller was performed using four, 30-m test strips constructed at the same site, established parallel to the direction of roller travel on the two-dimensional test area. The first test strip, which was constructed using well-graded subbase material at optimum moisture content, incorporated variable lift thickness (127 to 508 mm). Roller data from this test strip indicated the effect of lift thickness on machine response. The remaining test strips were comprised of uniformly placed and moisture-conditioned material. To identify the influence of moisture content on machine response during compaction, the second test strip was compacted, tested, and then reconstructed at two additional moisture contents. For each of these test strips, five tests were conducted with each test device following 1, 2, 4, 8, and 12 roller passes. This compaction curve testing was used to develop statistical regressions relating MDP, CMV, and moisture content to the various in-situ soil properties.

The spatial testing plan was designed with dimensions of 30 m by 17.1 m with increasing x-coordinates oriented at the testing site in the North direction. The plan area, which is shown in Fig. 5.2, was subdivided into eight roller widths. The testing used only one soil type and one nominal moisture content (optimum), but incorporated variable lift thickness (either 200 or 510 mm) to artificially achieve variation in stiffness properties of the soil. The test points for determining soil density, strength, and modulus are also shown in Fig. 5.2. A stratified random testing design was used, where four random points were tested in each roller width every 5 m along the length of the test area to give a total of 192 test locations.

Soil Description

Compaction curve and spatial testing was conducted using CA6-G (Illinois DOT classification) from a local source. This non-plastic soil is coarse grained (C_u = 30, C_c = 2.7) and classifies as SW-SM well-graded sand with silt and gravel or A-1-b.

Moisture-density tests were performed following the Standard and Modified Proctor test methods. The Standard maximum dry unit weight was about 21.4 kN/m^3 with optimum moisture content at approximately 8.0 percent. The Modified maximum dry unit weight was about 21.8 kN/m^3 with optimum moisture content at approximately 5.4 percent. The minimum and maximum dry unit weights from relative density testing (ASTM D 4253-00) were approximately 14.4 and 19.8 kN/m^3, respectively, for oven dry soil.

The underlying subgrade soil – a glacial till material – classifies as CL sandy lean clay with moderate plasticity.

Construction and Testing Operations

The first calibration test strip was constructed with progressively-thicker loose lifts. The 30-m strip was divided into 5-m length sections of the following six nominal lift thicknesses: 127, 203, 279, 356, 432, and 508 mm. Variable lift thickness was achieved by first excavating the subgrade material in 76-mm steps, as shown in Fig. 5.3 (a). The second test strip (Fig. 5.3 (b)) was constructed with a single nominal lift thickness (200-mm only), but incorporated variable soil moisture content. Soil of Strip 2a was dry of standard Proctor optimum at about 5.4 percent moisture by weight, Strip 2b was moisture conditioned close to optimum moisture content (8.2 percent), and Strip 2c was wet of optimum at about 12.0 percent. For each test strip, spot testing followed 1, 2, 4, 8, and 12 roller passes.

Construction of the spatial test area began by excavating select areas of the existing subgrade material to a depth of 310 mm. The excavated plan area is shown in Fig. 5.3 (c). The subgrade material was comparatively stiff at the soil surface, but decreased in stiffness with depth. After excavating the areas of thicker lift, base material (CA6-G) was placed to

200 mm above the original grade to give either 200-mm or 510-mm loose lift. Prior to compaction, several dynamic cone penetration tests were performed to ensure low strength through the entire vertical profile of loose fill.

After construction of the test area, the base material was compacted using the CS-533 vibratory smooth drum roller. The roller was operated at the "high" amplitude (about 1.70 mm) setting, and the frequency of drum vibration was constant at about 32 Hz. Compaction of the test area is shown in Fig. 5.3 (d). For this project, the roller did not overlap its path, but rather traveled in designated "lanes". Near-continuous measurements of CMV and machine power were made approximately every 0.2 m along the length (in the y-direction) of the test area. GPS coordinates were collected with compaction monitoring measurements, such that results were mapped and viewed in real time during compaction operations.
Soil testing was performed over the two-dimensional area following only the *second* roller pass to obtain the soil density, moisture content, DCP index, CIV, and E_{PFWD} at a total of 192 test locations with the exact spatial location of these test points obtained using a mapping-grade DGPS rover working off the same base station as the roller GPS system.

Calibration of Machine Power and CMV Using Regression Analysis

Calibration of CMV and MDP was accomplished using Strips 1 and 2 by correlating the collected roller data to the measured in-situ soil properties. Coefficients of variation (C_V) for CMV, dry unit weight, DCP index, CIV, and E_{PFWD} for similar soil types and construction operations have ranged from 19 to 36 percent, 2 to 4 percent, 10 to 28 percent, 9 to 24 percent, and 17 to 35 percent, respectively (White and Thompson 2007, Thompson and White 2007). MDP standard deviation values have ranged from 2.66 to 4.55 kJ/s (White and Thompson 2007, Thompson and White 2007). Thus, considering the variability associated with the two compaction monitoring technology measurements, as well as the measurement variability of each in-situ spot measurement, data were averaged along the length of the test strips to produce a single data point for each roller pass.

Preliminary target compaction monitoring values were selected from the 203-mm lift thickness section of Strip 1. The compaction curves are shown in Fig. 5.4 for MDP, CMV, and dry density. The compaction curves for the 508-mm lift thickness section are additionally provided to show the influence of this parameter on machine response, which is to increase MDP and decrease CMV. At 95 percent of the maximum dry unit weight (based on standard Proctor compaction energy), observed after four roller passes, the average MDP equaled 8.3 kJ/s and the average CMV equaled 8.0. This relatively simple method for determining quality criteria, while not providing a unified correlation that accounts for all variables affecting machine response, also does not require detailed statistical analyses.

Since the second test strip (2a, 2b, and 2c) was tested following 1, 2, 4, 8, and 12 roller passes; five data points were obtained per test strip to provide a total of 15 data points from which a correlation was developed to account for variable moisture content. The averaging and regression model development procedure is described in (White *et al*. 2006a). Multiple regression analysis results are presented in Fig. 5.5 with MDP shown on a log scale and CMV shown on a linear scale. The data points are the average measured values; the solid lines are not functions for any one particular moisture content, but rather connect soil property predictions at average MDP and CMV values. For predicting DCP index, CIV, and E_{PFWD} from compaction monitoring results, the addition of moisture content as a second regression parameter yielded correlation coefficients (R^2) that ranged from 0.85 to 0.95 with both MDP and CMV providing reliable results. For predicting soil density, the compaction monitoring technologies differed in that the regression model using MDP yielded a higher correlation coefficient (0.92) than CMV (0.68).

Compaction Results from Spatial Area

Distribution of Soil Property Measurements

The variation of soil property measurement results are shown with distribution plots in Fig. 5.6. To provide some indication of whether after the second roller pass the compaction monitoring technologies and the in-situ spot tests consistently identified variable lift thickness, the distributions of test results are separated into results performed on a 200-mm or 510-mm lift. Mean values, C_V (%), and number of tests (n) are additionally provided in Fig. 5.6 for each measurement and for the two nominal lift thicknesses. CMV and full-depth DCP index clearly show the influence of variable lift thickness on the measurements, evidenced by two different distributions of data. MDP and the other compaction control test results, however, provide only a slight indication of a different soil condition. The ability of the measurements to identify regions of different lift thickness is controlled by the measurement influence depths of the measurement system. Future research should investigate similar data comparisons for multiple roller passes and lift thicknesses.

Dry density and moisture content were within a relatively narrow range for the spatial test area. Moisture content of the test area ranged from 7 to 9 percent. Dry density varied from about 19.2 to 21.1 kN/m^3 (90 to 99 percent of the maximum dry unit weight). Soil modulus and strength measurements were generally more variable with E_{PFWD} ranging from 6 to 30 MPa, mean DCP index ranging from 10 to 50 mm/blow, and CIV ranging from 2 to about 8.

Compaction Monitoring Output

Roller data are shown in Fig. 5.7 for the second roller pass over the test area. The data at a particular location within a given roller path is assumed to be constant along the entire width of the roller drum, as no method has yet to account for variation of soil properties along the width of the roller. Further, dashed lines are provided in the figure to demarcate areas of 200-mm and 510-mm lift thickness (see Fig. 5.2).

MDP results are shown in Fig. 5.7 (a) to be locally variable, ranging from nearly 0 kJ/s (stiff material) to greater than 20 kJ/s (soft material) in distance of less than 1 m. Still, the global trend of the data is that high MDP values are observed in regions of 510-mm lift thickness and lower MDP values are observed in regions of 200-mm lift thickness. Recognizing that rolling resistance and sinkage are affected by surficial soil characteristics, MDP measurements provide only a subtle indication of differential lift thickness over the test region at two roller passes.

CMV – a measure of roller drum behavior – depends on soil characteristics well below the soil surface with measurement influence depths reportedly ranging from 0.4 to 0.6 m for a 2-ton roller to 0.8 to 1.5 m for a 12-ton roller (7). CMV compaction monitoring technology identified the regions of 510-mm lift thickness, as shown in Fig. 5.7 (b). In these areas, CMV ranged from 0 to about 6 (red to green). In regions of 200-mm lift thickness, CMV ranged from about 5 to about 15 (green to violet). CMV measurements even identified localized areas of thick lift on the south (left) side of the test area – every area except those from 2 to 12 m in the y-direction in the first roller path (x ranging from 0 to 2.16 m). At these locations, the excavated areas have dimensions smaller than the drum width, such that the drum can bridge the comparatively soft area. Still, CMV provides accurate *mapping* capabilities for areas nearly as wide as the roller drum and with lengths greater than about 1 m.

Spatial Analysis of Field Measurement Results

The semivariogram remains as a standard method to quantify spatial structure of soil properties (Pozdnyakova *et al*. 2005). Spatial variability of each soil measurement was thus described by an experimental variogram derived from measurements taken on the spatial test area. The semivariograms did not fluctuate around a constant value, indicating that field measurements were correlated at the scale of the sampling plan. The ability to observe spatial structure of the data is the principal prerequisite for performing reliable geostatistical analyses; many gridding methods requiring only that a continuous function (or model) be used to express the semivariance as a function of lag distance. The semivariogram models that produced the cross-validation results of the highest accuracy were retained for further geostatistical analysis. Either exponential or spherical models were fitted to the experimental semivariograms for each soil measurement system of this project.

Kriging is an interpolation method of geostatistics that uses spatial dependence and spatial structure of a measured property to predict values of that property at unsampled locations (Warrick 2002). As the method was originally developed for the mining industry, kriging is particularly common in geosciences including geotechnical engineering. Further, kriging provides the least bias in predictions from all linear interpolation methods, because the interpolated or kriged values are computed from equations that minimize the variance of the estimated value. Kriging is an exact interpolation method, where the measured values will always be returned when interpolating to measurement locations. For this project, spatial data from 192 test points (see Fig. 5.2) were analyzed using kriging operations and spatial modeling results.

Single, nominal moisture content (optimum) was intended for the test area. The contour plot of moisture content (Fig. 5.8) shows that, in fact, moisture content was within 1 percent of optimum moisture content (8 percent). Inherent variation in moisture content with strong spatial structure resulting from construction operations was present, however, and impacted measurements of soil stability. The soil moisture content approached 9 percent in the southeast (lower-left), center, and northwest (upper-right) regions of the test area. The moisture content was as low as 7 percent in the southern portion of the test area. Moisture variability on large-scale production areas is generally unavoidable. The moisture variation observed for this project, which was relatively uniform, clearly affect the compaction results as discussed later.

Contours of in-situ soil properties (e.g., dry density, modulus, DCP index, Clegg impact value) are provided in Fig. 5.9. Dashed lines are again provided for the boundaries of 200 and 510-mm lifts. Dry unit weight ranged from about 19 to 21 kN/m^3, but was relatively uniform over the test area. The contour plot (Fig. 5.9 (a)) appears “spotty”, which is a result of kriging procedures necessarily producing measured values at measurement locations. From a uniformity standpoint, the spatial variation observed in dry density is preferred over variation that contains more global trends.

Soil strength and modulus measurements have previously been documented to rapidly decrease with increasing moisture content (White *et al*. 2005). Soil modulus determined using a PFWD and soil strength determined using a 20-kg Clegg Impact Tester, in particular, show the influence of moisture content. The comparatively high moisture observed in the southeast, center, and northwest regions of the test area are mirrored by lower modulus (less than 8 MPa) and Clegg impact value (less than 4) results, as shown in Figs. 5.9 (b) and (d).

Mean DCP index results from full-penetration tests, presented in Fig. 5.9 (c), are affected by both moisture content and lift thickness. DCP index over the western (upper) portion of the test area (y greater than 15 m) strongly reflects the observed moisture content with higher moisture content producing higher DCP index (lower strength). DCP index over the eastern (lower) portion of the test area (y from 0 to 15 m) reflects the artificially-imposed variation in lift thickness. In regions of 200-mm lift thickness, the DCP index begins to decrease at a depth of 200 mm – the depth of a stiff subgrade layer. In a similar trend, the regions of 510-mm lift thickness also show higher DCP index values for the full depth of the compaction layer. The DCP index contour very clearly identifies regions of variable lift thickness, as the measurement interpretation is essentially a measurement of lift thickness. Even localized regions of thick loose lifts (second roller path from 0 to 5 m and from 10 to 15 m) are identified.

Applying Compaction Monitoring Technology to Earthwork Quality Assessment

Quality Assessment Using Compaction Monitoring Technology

The capabilities of a roller in identifying the in-situ characteristics of unbound materials can be separated into three levels of compaction monitoring technology use (White *et al*. 2007). The most basic of these levels (Level 1) may be the mapping of an area to obtain some compaction value which relates to the density, strength, or stiffness of the area. This capability was demonstrated in Fig. 5.7, where MDP and CMV measurements showed differential stiffness over a two-dimensional area. By specifying a target compaction value for a particular compaction monitoring technology, the next level of compaction monitoring technology use (Level 2) may be achieved. In this case, the areas that fail to meet the prescribed specification can easily be identified and differentiated from areas that do meet the quality criterion. Spatial plots that show pass/fail regions of the test area based on quality criteria from Fig. 5.4 are provided in Fig.5.10 for MDP and CMV. This presentation of pass/fail regions of a spatial area demonstrates the use of compaction monitoring technology as a quality control and acceptance tool. In Fig. 5.10 (a), the test area with MDP exceeding 8.3 kJ/s is shaded black to indicate a failing condition. This is done for CMV in Fig. 5.10 (b) with 8.0 as the quality criterion. Figs. 5.10 (a) and (b) coincidentally show failing soil conditions in many of the same regions, including those of 510-mm lift thickness. Recognizing that MDP is more locally variable and that this system is more sensitive to surficial characteristics, the failing regions of Fig. 5.10 (a) appear to be more scattered. For the maps of Fig. 5.10, only 35 and 30 percent of the test area achieved a passing condition according to MDP and CMV, respectively. 47 percent of the test area achieved 95 percent compaction, which was the quality criterion for which the technologies were calibrated.

The ultimate use of compaction monitoring technology, which is to precisely convert roller-generated data to either soil density or modulus possibly for pavement design inputs, is described in the following section.

Application of Findings to Technology Verification and Specification Development

Evaluation of pass/fail maps. For evaluating the previously-described calibration procedure, the fraction of the test area that fails based on results from traditional testing techniques (e.g., density, modulus) can be compared to the fraction of the test area that fails based on compaction monitoring results. Ideally, compaction monitoring results would indicate the same failing regions as field measurements. By using the regression analysis results from strip testing (i.e. calibration of Figs. 5.4 and 5.5), however, the same pass/fail regions could not be created for density, modulus, Clegg impact value, or DCP index. The inability to quantifiably link soil properties with roller measurements for the spatial area, despite achieving very high correlation for test strip results, is attributed to: (1) the different factors affecting compaction monitoring and in-situ compaction control measurements – factors of which many have already been identified, and (2) the relatively high variation observed for the compaction monitoring measurements.

The limited measurement influence depths of in-situ compaction control tests resulted in the inability of these devices to differentiate between regions of variable lift thickness. Rather, variation in soil modulus and surface strength measurements resulted only from variable moisture content. Alternatively, the measurement influence depth for the roller was much deeper, particularly since the roller was operated at the “high” amplitude setting. For this reason, CMV accurately identified regions of 510-mm lift thickness. Characterizing measurement influence depths and the effect of underlying layers on machine response is an area of ongoing study.

Machine Calibration Design Considerations. The empirical relationships between soil properties and compaction monitoring output are influenced by roller size, vibration amplitude and frequency, operating velocity, soil type, and stratigraphy underlying the compaction layer. Machine calibration procedures must therefore be conducted under the same conditions as may be expected during earthwork production. Considering the variation of construction operations and environmental conditions on a project site, however, calibration for every condition is likely not feasible. The implications of this reality are that current calibration procedures may need revision prior implementation in the United States. For example, the influence of stiffness of underlying layers (and how it varies) must be addressed. Instead of 30-m or 60-m control strips, 300-m strips or calibration *areas* may be used in an attempt to incorporate more variation into the calibration operation – a measure which would likely reduce correlation precision, but increase the robustness and statistical validity of the calibration.

For now, as compaction monitoring technologies continue to be implemented, the technologies must simply be used with special consideration for what the results may actually be measuring and indicating about the soil.

Summary

The ability of two compaction monitoring technologies to identify soil properties over a spatial test area was investigated with particular emphasis on demonstrating how the technology may implemented as a quality control/acceptance tool. The following statements summarize the study.

1. Testing conducted on test strips with multiple nominal moisture contents produced regression equations that relate machine data to soil properties. The use of moisture content as a regression parameter yielded correlation coefficients ranging from 0.85 to 0.95 for predicting soil strength and modulus from either MDP or CMV.
2. A two-dimensional test area with variable lift thickness and moisture content was constructed and tested using both compaction monitoring technology and in-situ test devices. MDP, shown to be locally variable, provided some indication of differential lift thickness and variable moisture content. CMV identified the regions of thick compaction layer. In-situ tests for soil engineering properties showed only the influence of moisture content on soil stability.

3. Differences between the spatial distribution of CMV and MDP with that of in-situ test results was attributed to different measurement influence depths and measurement variation of compaction monitoring technology and compaction control tests.
4. Pass/fail maps were generated using machine parameters and calibration results to demonstrate the use of compaction monitoring technology as a quality control and acceptance tool.

Notation

θ	=	slope angle
μ	=	statistical mean
a	=	machine acceleration
A_0	=	acceleration of the fundamental component of vibration
A_1	=	acceleration of the first harmonic of vibration
b	=	machine internal loss coefficient
C	=	CMV constant
CIV	=	Clegg impact value
CMV	=	*compaction meter value*
C_V	=	coefficient of variation
DCP	=	dynamic cone penetrometer
E_{PFWD}	=	modulus of soil from portable falling weight deflectometer
g	=	acceleration due to gravity
m	=	machine internal loss coefficient
MDP	=	*machine drive power*
n	=	number of observations
P_g	=	gross power
V	=	roller velocity
W	=	roller weight

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Figure 5.1. Caterpillar CS-533 vibratory smooth drum roller with compaction monitoring technology

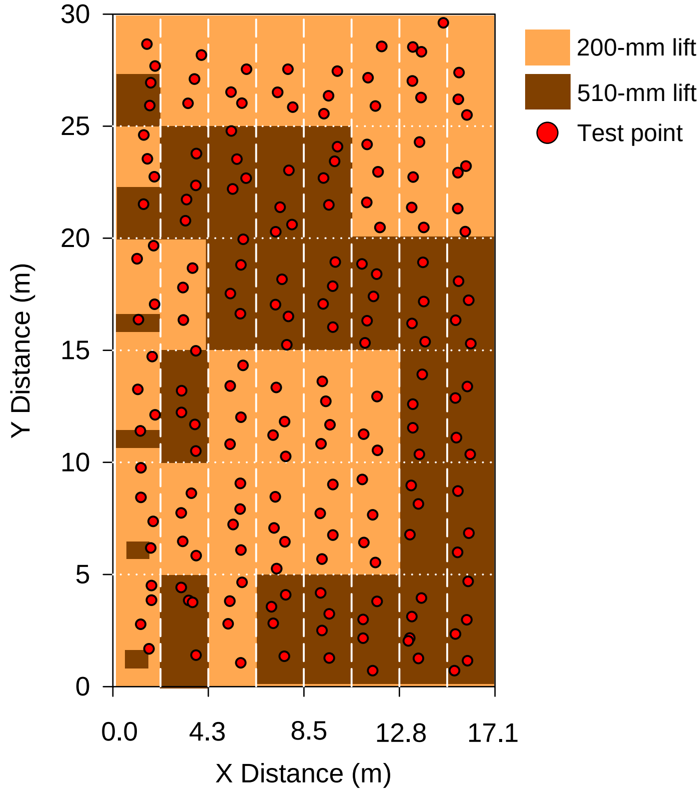

Figure 5.2. Testing plan for two-dimensional area

Figure 5.3. Construction and testing processes: (a) constructed test strip, (b) test Strip 1 excavations for variable lift thickness, (c) excavations for 510-mm lifts in spatial area, (d) compaction of spatial area

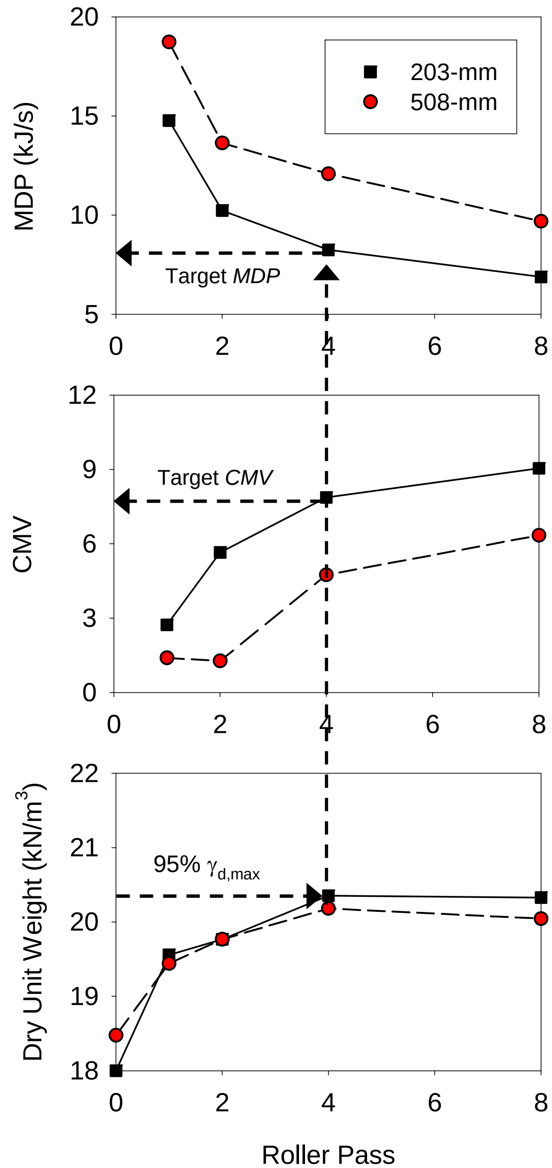

Figure 5.4. Compaction data for Strip 1 at 203-mm and 508-mm lift thickness

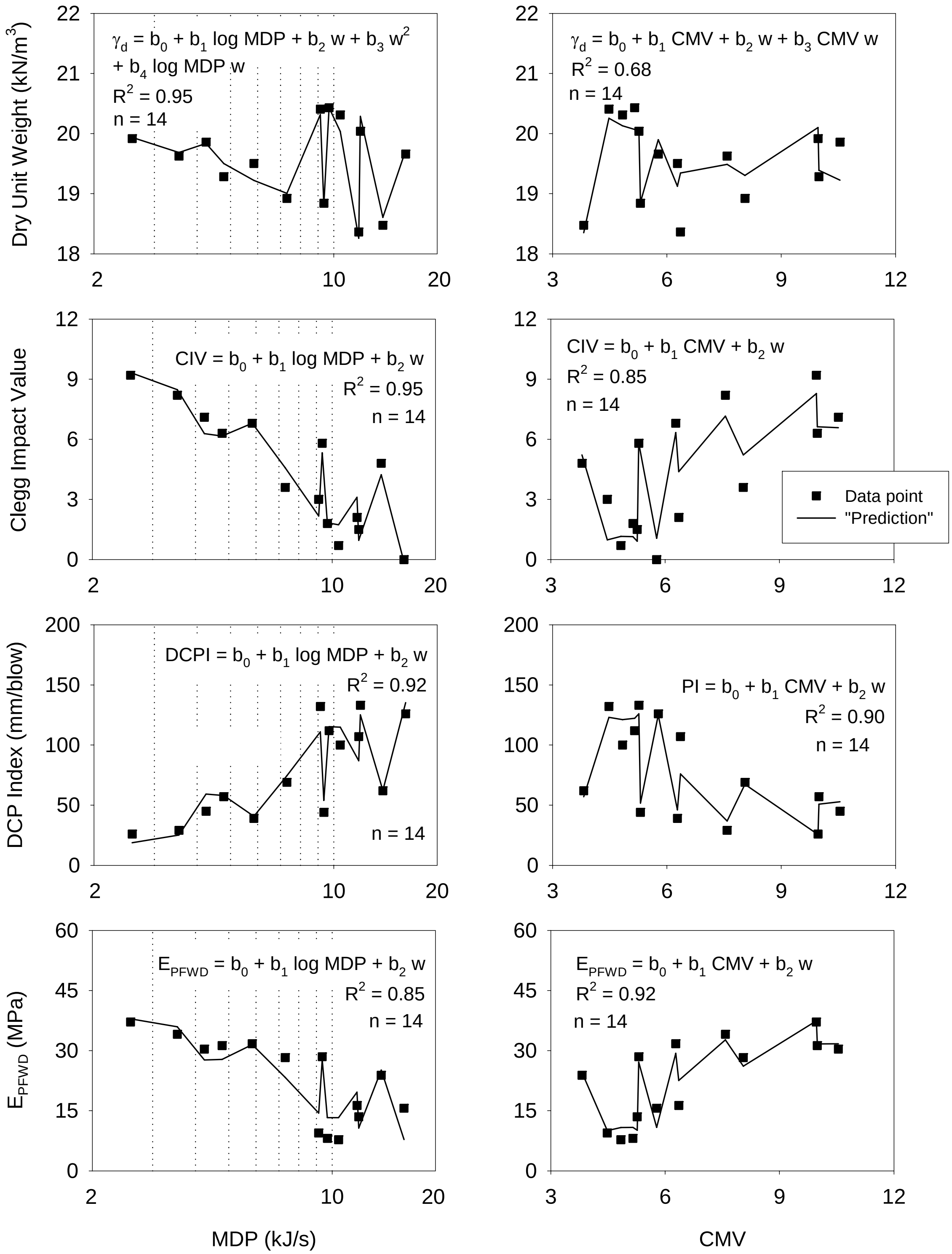

Figure 5.5. Multiple regression analysis results with highlighted data points obtained from test strip at optimum moisture content

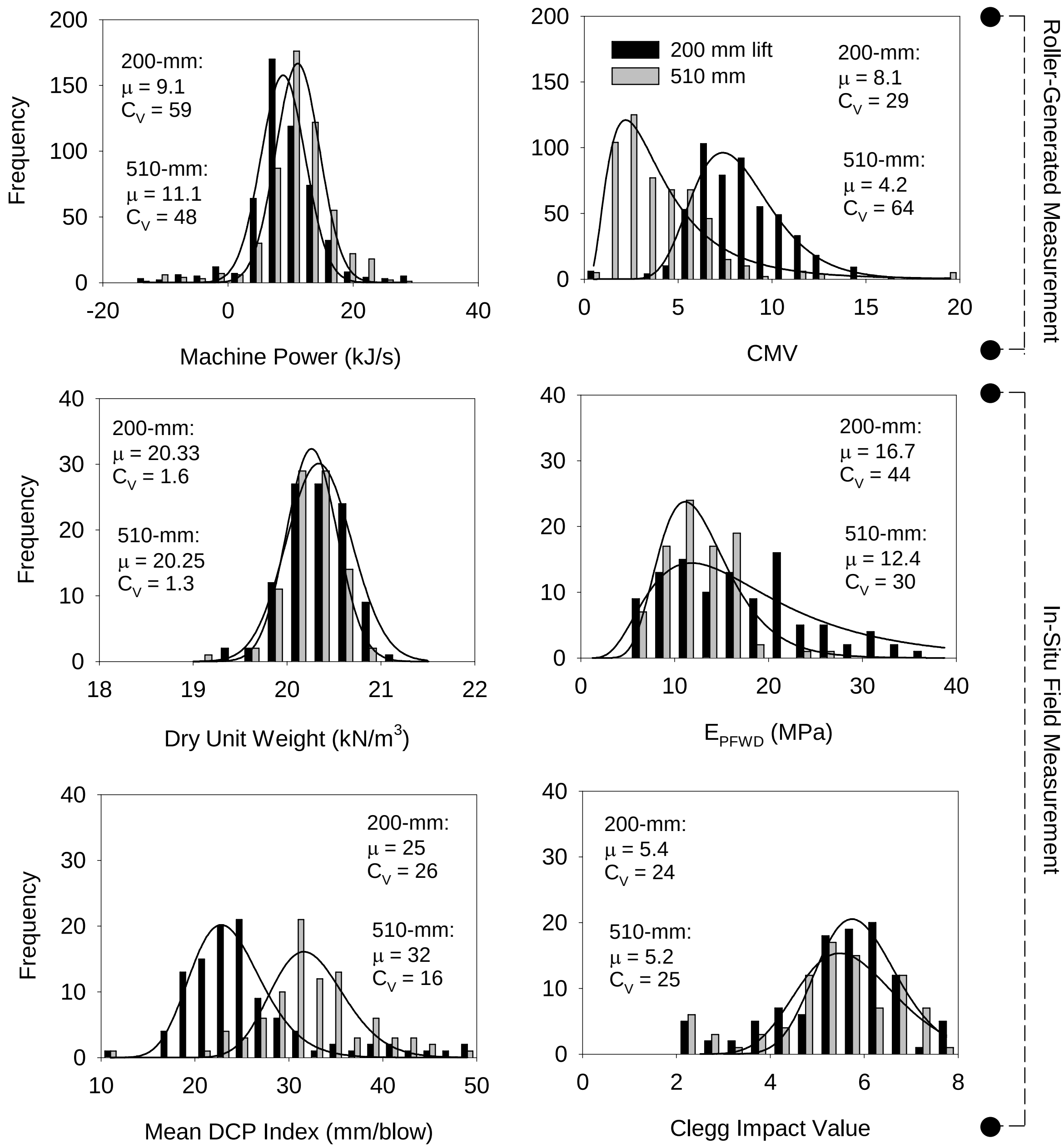

Figure 5.6. Distribution plots for measurement of 200 and 510-mm lift thickness

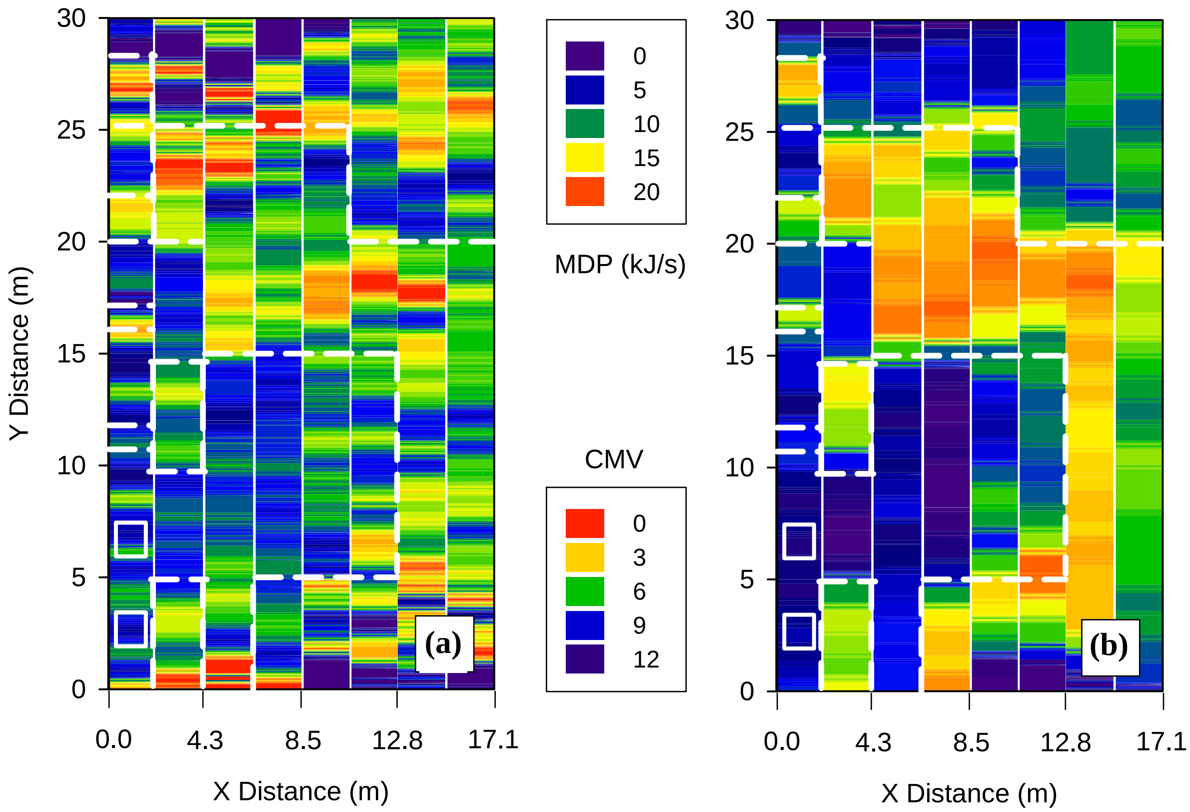

Figure 5.7. Compaction monitoring data: (a) MDP and (b) CMV

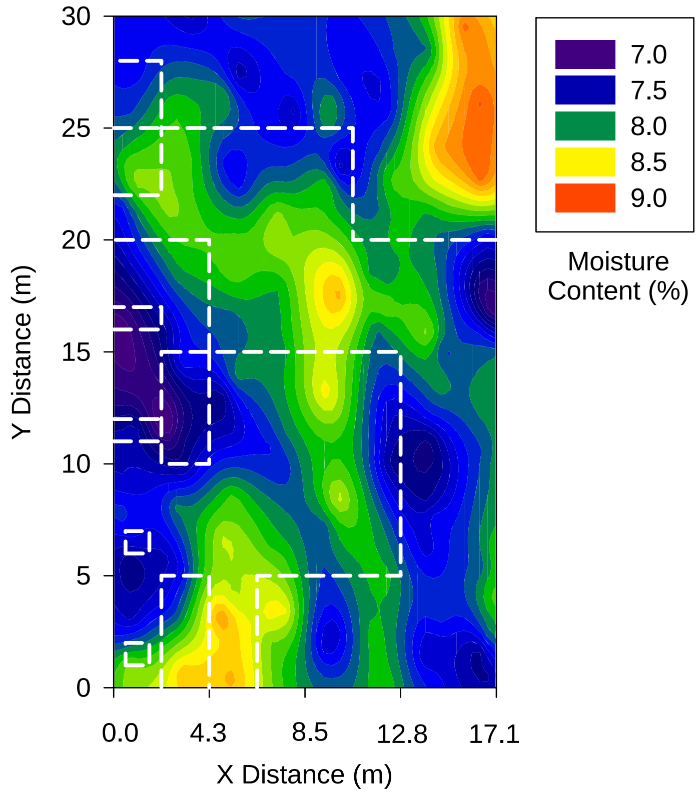

Figure 5.8. Moisture content

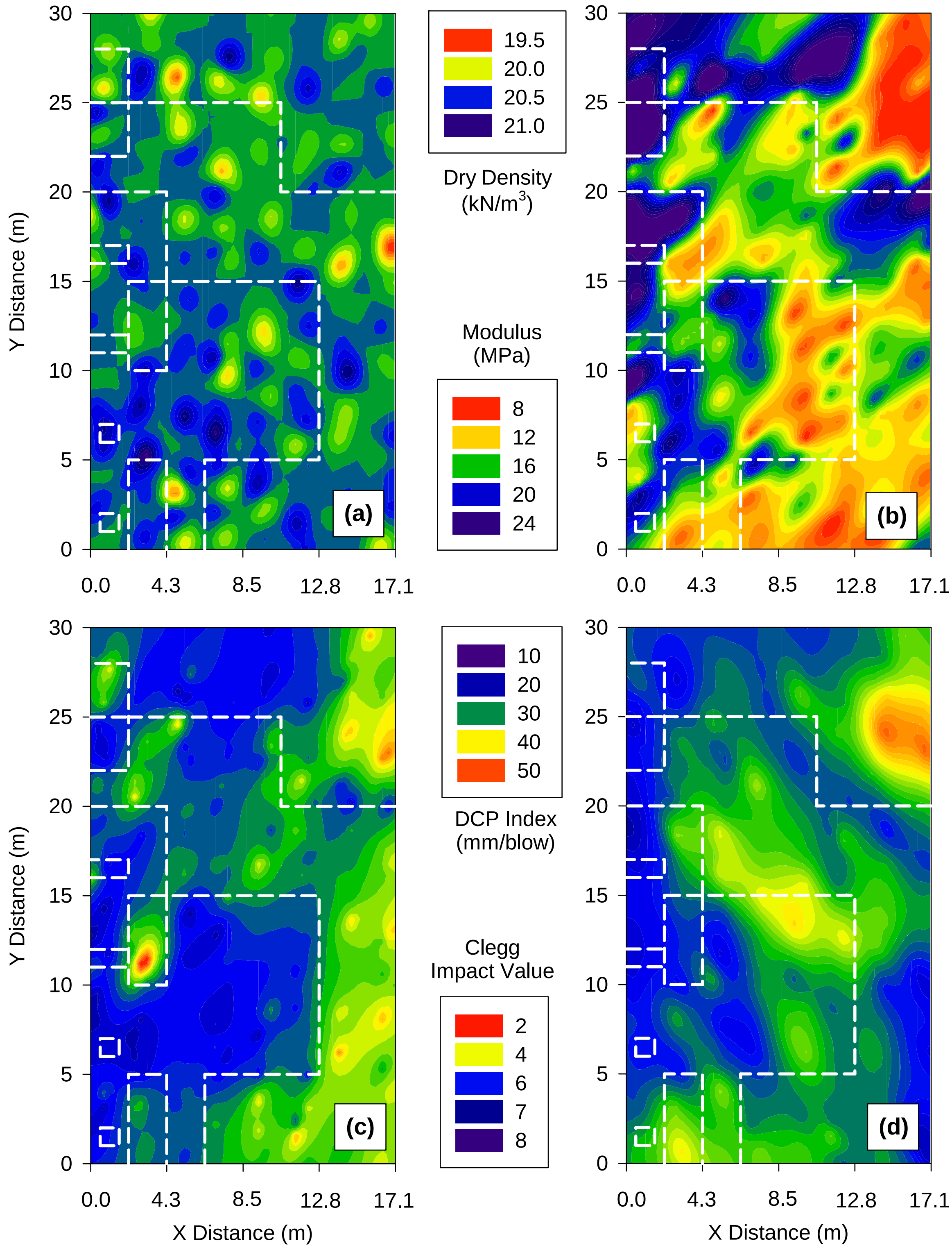

Figure 5. 9. Soil properties: (a) dry unit weight, (b) PFWD modulus, (c) DCP index, and (d) Clegg impact value (20-kg)

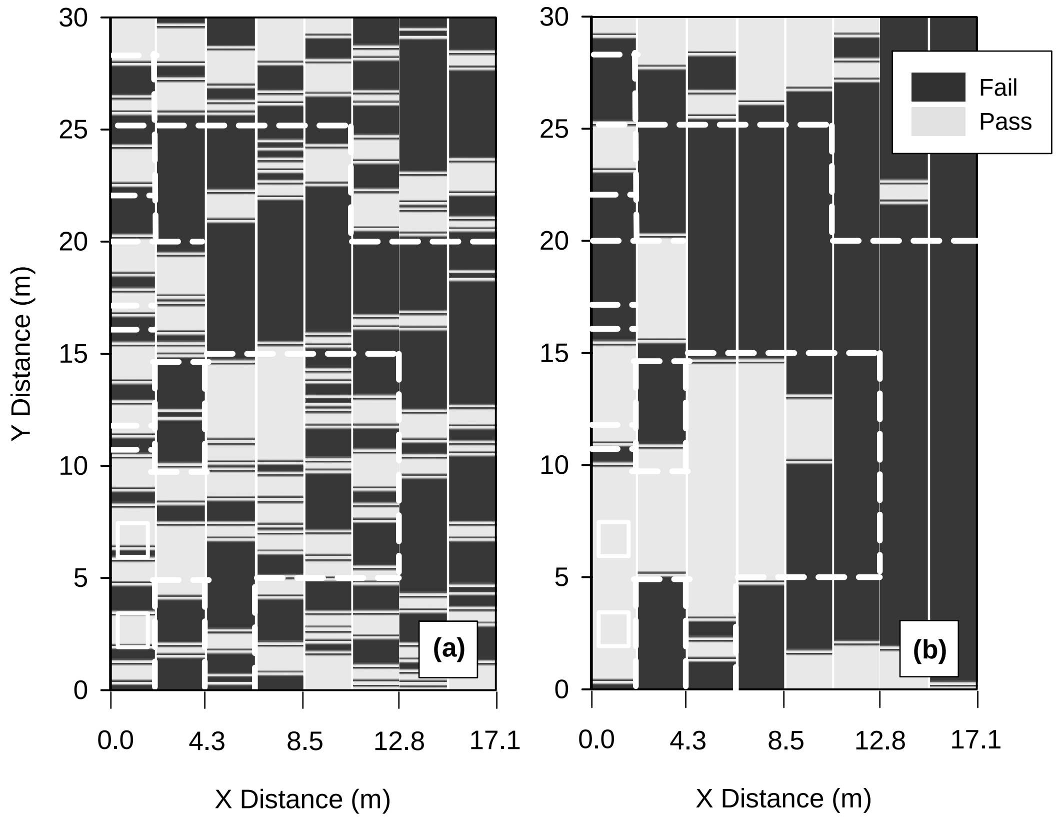

Figure 5.10. Pass/fail regions as assessed by: (a) MDP (>8.3 kJ/s), (b) CMV (<8.0)

CHAPTER 6: Elastic Analysis of Roller-Integrated Compaction Measurement Values for a Two-Layer Soil Condition

A paper to be submitted to the *Geotechnical Testing Journal*

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Abstract

Measurement depths for roller-integrated compaction systems exceed representative lift thicknesses, such that the measurement values reflect not only the properties of the compaction layer, but also underlying layers. Roller-integrated measurement values from roller operation on two-layer soil systems were investigated using a proposed method of equivalent stiffness. Experimental testing was first conducted using roller-integrated compaction technologies and dynamic cone penetration (DCP) on test strips with two distinct soil layers. DCP index was then empirically correlated to elastic modulus from static plate load tests. Using elastic modulus, Poisson's ratio, and layer thickness as analysis inputs, equivalent stiffness representing the deformation behavior of the layered-soil system was calculated and compared with roller-measured stiffness values to support the proposed analysis method. Equivalent stiffness was more strongly correlated with roller-integrated measurement values than upper layer modulus alone. The validated elastic model was used to make inferences regarding the effect of layer thickness and layer modulus on roller response and measurement values.

Introduction

Roller-integrated compaction technology that monitors drum behavior during soil compaction enables the continuous monitoring of soil properties (Forssblad 1980, Thurner and Sandström 1980, Briaud and Seo 2003, Mooney *et al*. 2006). The feasibility of using vibratory-based compaction technologies for earthwork quality control and acceptance has recently been studied in the United States. The research has focused on characterizing roller vibrations during compaction operations (e.g. Mooney *et al*. 2006, Mooney and Rinehart 2007), as well as investigating the relationships between roller-integrated measurement values and the properties of compacted materials (e.g. White *et al*. 2007a, White *et al*. 2007b, White and Thompson 2007). These studies have led to improved understanding of the systems and have identified many of the factors influencing roller response, which include roller operational parameters, soil type, and moisture content.

The roller measurement depth is the depth of soil that influences roller behavior and the roller-integrated measurement values. Measurement depths reported in the ISSMGE 2005 specification are 0.4 to 0.6 m for a 2-ton roller, 0.6 to 1 m for a 10-ton roller, and greater than 1 m for a 17-ton roller. Anderegg and Kaufmann (2004) report a rule-of-thumb which states that 0.1 mm of vertical vibration amplitude equates to 0.1 m of measurement depth (e.g. 2.0 mm amplitude gives 2.0 m measurement depth). Notwithstanding the widespread use of these guidelines, little evidence has been published to support the assertions. Mooney and White (2007) used in-ground instrumentation to measure stress and strain beneath static and vibratory rollers. The findings from instrumentation studies indicate that Boussinesq stress profiles for strip footings approximate roller-induced compaction stresses.

The impetus of this study is that measurement depths exceed representative lift thicknesses and that roller-integrated measurement values reflect not only the properties of the (upper) compaction layer, but also underlying soil layers (White and Thompson 2007). The layered-soil system must be characterized for interpreting roller-integrated measurement values for layered soil conditions. The preliminary objective of the study is to validate the proposed method of equivalent stiffness using field compaction data. The second study objective is to use the validated model to make inferences about the influence of layer thickness and elastic modulus on roller-measured stiffness that are supported by both experimental evidence and the theoretical model. While this paper evaluates Ammann roller-measured stiffness k_S and Geodynamik *compaction meter value* (CMV), the findings may also apply to other roller-integrated compaction technologies.

Experimental Methods

Testing Program

Experimental testing was conducted using the roller-integrated compaction technologies and dynamic cone penetration (DCP) on test strips with two distinct soil layers (soft overlying stiff in all cases). The test strips were designed to enable collection of both roller-integrated measurement values and DCP index for the purpose of verifying the analysis method for layered soils.

Testing was first conducted on a 120-m test strip (herein Strip 1) comprised of granular material 80 to 140 mm in thickness overlying compacted subgrade (see Fig. 6.1). The "Class 5" subbase soil classifies as SP-SM poorly graded sand with silt and gravel (A-1-b), and the subgrade soil classifies as CL sandy lean clay (A-6 (9)). An Ammann vibratory smooth drum roller was operated in the forward direction at constant speed in the variable feedback control mode, in which the roller vibration amplitude and frequency parameters were automatically adjusted based on the roller measurement value (see Anderegg and Kaufmann 2004). Vibration amplitude for the roller can range from 0.4 to 2.0 mm, while vibration frequency ranges from 25 to 35 Hz. Roller-measured stiffness was provided at 0.33 m intervals (Anderegg 2005). The roller operational parameters were not provided with the stiffness measurements. Following the third roller pass, DCP tests were conducted at 17 test points spaced at about 7.6 m.

Testing was also conducted on a 30-m test strip (herein Strip 2) designed with six nominal lift thicknesses to identify the effect of layer thickness on roller response. At the site, the natural subgrade material, which classified as CL sandy lean clay (A-6 (6)), was excavated in 75-mm steps, each 5 m in length (see Fig. 6.2). "CA6" granular material classifying as SW-SM well graded sand with silt (A-1-b) was then placed to give final lift thickness ranging from 125 to 510 mm. A Caterpillar vibratory smooth drum roller monitored CMV for each of 16 roller passes over the test strip with measurement values provided about every 0.2 m. The roller was operated in the forward direction at constant speed of 7.5 km/hr in the "high" amplitude (1.4 to 2.0 mm) setting. The frequency of drum vibration ranged from 27 to 28 Hz. Full-depth DCP tests were conducted in each nominal lift section following 1, 2, 4, and 16 passes (total of 24 tests).

Roller-Integrated Compaction Technologies

Ammann k_S. An Ammann AC 110 vibratory smooth drum roller (Fig. 6.3) was used for the field study. The 11,575-kg roller has a drum diameter of 1.50 m and a drum width of 2.16 m.

Fundamental research has shown that roller and soil dynamics occurring during vibratory compaction can be modeled with a lumped-parameter, spring-dashpot system having two degrees-of-freedom (Yoo and Selig 1979). This simple model of soil behavior provides the basis for measuring soil stiffness using the dynamics of a vibrating drum. The soil model, illustrated in Fig. 6.4, is characterized by a spring with stiffness k_S and a parallel damper with damping constant c_S. The soil-drum interaction force (F_S) is then given by

$$F_s = k_s x_d + c_s \dot{x}_d \tag{6.1}$$

where x_d is drum displacement and $\dot{x}_d$ is drum velocity. With increasing compaction, soil stiffness increases and soil damping decreases (Anderegg and Kaufmann 2004).

If the dynamic forces within the frame suspension are neglected, the steady-state equation of motion can be written as (Anderegg and Kaufmann 2004)

$$F_s = (m_f + m_d)\, g + m_e r_e \Omega^2 \cos(\Omega t) - m_d \ddot{x}_d \tag{6.2}$$

where m_f is the frame mass, m_d is the drum mass, g is the acceleration of gravity, $m_e r_e$ is the eccentric moment of the unbalanced mass, Ω is the circular vibration frequency, and $\ddot{x}_d$ is vertical drum acceleration. Equations (1) and (2) may then be set equal to each other to calculate soil stiffness or damping constants. At the time when the drum is at its lowest position, drum velocity and damping force ($c_s\,\dot{x}_d$) equal zero. Soil stiffness is then calculated as the ratio of the soil force F_S and vibration amplitude according to

$$k_s = 4\pi^2 f^2 \left(m_d + \frac{m_e\, r_e\, \cos(\varphi)}{A} \right) \tag{6.3}$$

where f is the excitation frequency, φ is the phase angle, and A is vibration amplitude (Anderegg and Kaufmann 2004). Soil stiffness k_S is exactly frequency dependent. Through the range of working frequencies, however, the stiffness is relatively constant (Preisig *et al*. 2003).

Compaction Meter Value. A Caterpillar CS-533 vibratory smooth drum roller (Fig. 6.5) was also used for the field study. The 10,240-kg roller has a drum diameter of 1.55 m and a drum length of 2.13 m. This roller was additionally fitted with a global positioning system (GPS) to track roller coverage and apply measurement values to locations along the test strip.

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 (Thurner and Sandström 1980, Sandström and Pettersson 2004). Previous studies have found that the ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency is a reliable indicator of soil compaction. Accordingly, CMV is calculated as:

$$\mathrm{CMV} = \mathrm{C} \cdot \frac{\mathrm{A_1}}{\mathrm{A_0}} \tag{6.4}$$

where C is a constant (normally about 300), A_1 equals acceleration of the first harmonic component of the vibration, and A_0 equals acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004). CMV is a dimensionless value that depends on roller dimensions (e.g. drum diameter, weight) and roller operation parameters (e.g. frequency, amplitude, speed).

CMV is fundamentally a measure of the degree of nonlinearity in the roller-soil system (Mooney and White 2007) with the ratio of A_1 to A_0 equaling unity for a linear system. As this ratio (and thus CMV) increases during the soil compaction process, the system nonlinearity decreases with the soil approaching a more linear-elastic condition. CMV has been empirically related to soil stiffness through a linear relationship (White *et al*. 2007a, White and Thompson 2007). For the purpose of the analysis presented in this paper, CMV is treated as a stiffness parameter.

Dynamic Cone Penetration

The dynamic cone penetrometer is a testing device that provides a profile (with depth) of the stability characteristics of embankment and pavement layers. The test (see ASTM D 6951) involves dropping an 8-kg hammer 575 mm and measuring the penetration rate of a 20-mm diameter cone. The penetration index, which typically has units of mm per blow, is inversely related to penetration resistance (i.e. soil strength). DCP testing is discussed in literature (Konrad and Lachance 2001, Abu-Farsakh *et al*. 2004, Chen *et al*. 2005) with a focus of correlating DCP index to other soil properties including elastic modulus (E) and California bearing ratio (CBR).

The use of DCP testing to identify a layered soil condition and to provide properties of the soil layers is shown in Fig. 6.6. The five profiles of DCP index at five stages of compaction (0, 1, 2, 4, and 8 roller passes) have been adjusted vertically to account for changing surface elevation, such that the location of the underlying layer is constant. Fig. 6.6 shows two distinct soil layers. The (upper) compaction layer shows decreasing DCP index with increasing roller passes to indicate increasing soil compaction and the resulting increase in strength/modulus. The underlying layer is approximately uniform with depth and does not change significantly during compaction.

The nonlinear relationship between DCP index and elastic modulus takes the following form.

$$\text{Log}\,(\text{DCPI}) = a + b\,\text{Log}\,(\text{E}) \qquad (6.5)$$

Recognizing that the coefficients *a* and *b* may depend on soil type and soil moisture conditions, soil-specific correlations of DCP index and elastic modulus from static plate load tests were developed for the subgrade and granular materials of the two test strips. The relationships are provided in Figs. 6.7 and 6.8 for materials of Strips 1 and 2, respectively. For the correlations, E_{PLT} is defined as the secant modulus taken from 0.2 to 0.4 MPa plate stress of the initial plate loading. If the 0.4-MPa stress level was not achieved during loading, the modulus was calculated using the linear portion of the load-deflection curve up to the plate stress that was achieved. The average DCP index for the compaction layer – calculated as layer thickness divided by the cumulative blows to the reach bottom of the layer – was used for correlation with modulus. Based on the available data for each test strip material, the subgrade and granular materials show similar relationships between modulus and DCP index. Thus, the regression coefficients were used for obtaining modulus of upper and underlying layers.

Method of Equivalent Stiffness

Overview of Method

The method of equivalent stiffness was initially proposed by Baidya *et al*. (2006) to describe the dynamic response of foundations resting on a layered soil. Predicted behavior obtained by an equivalent spring-mass-dashpot model matched well with experimental results for all cases of differing layer thickness and layer properties. Extension of the method of equivalent stiffness to the analysis of roller-integrated measurement values for layered soil conditions involves estimating composite stiffness of the layered-soil system based on the deformation response of individual layers.

Model Representation for Equivalent Stiffness

The response of individual soil layers having elastic modulus E_i and Poisson's ratio v_i are represented as springs which are connected in series. The springs in Fig. 6.9 with stiffness coefficients k_1, $k_2 \ldots k_n$ can be modeled as a single spring with equivalent stiffness k_{eq}. The equivalent stiffness of springs in series is obtained from elastic theory as follows:

$$k_{eq} = \frac{1}{1/k_1 + 1/k_2 + \ldots + 1/k_n} \tag{6.6}$$

Eq. 6.6 produces the same equivalent stiffness value irrespective of the thickness of individual layers and the order in which individual springs are connected in series.

Layer Stiffness

The deformation of a soil layer resulting from a surface load can be partially characterized by vertical strain. The vertical strain ε_z of an elastic medium is defined as

$$\frac{\partial w}{\partial z} = \varepsilon_z = \frac{1}{\mathrm{E}}[\sigma_z - v\,(\sigma_x + \sigma_y)] \tag{6.7}$$

where *w* is vertical deflection; E is elastic modulus; *v* is Poisson's ratio; σ_z, σ_x, and σ_y are stress components in a Cartesian coordinate system. The total vertical deflection w_i of the *i*th soil layer can then be obtained through strain integration with depth over the limits of the layer as follows:

$$w_i = \int \varepsilon_z \, dz = \int_{z_{i-1}}^{z_i} \frac{1}{\mathrm{E_i}}[\sigma_z - v\,(\sigma_x + \sigma_y)]\, dz \tag{6.8}$$

By defining stiffness as the ratio of load to deflection, the stiffness of the *i*th layer can be obtained as

$$k_i = \frac{\mathrm{Q}}{w_i} = \frac{\mathrm{Q}}{\int_{z_{i-1}}^{z_i} \frac{1}{\mathrm{E_i}}[\sigma_z - v\,(\sigma_x + \sigma_y)]\, dz} \tag{6.9}$$

The deflection of a soil layer depends on the state of stress within the layer and the elastic modulus of the material. Elastic modulus is an input for the analysis which is obtained through empirical correlation with DCP index. The stress underneath the roller is obtained by modeling the roller drum as a uniformly-loaded strip footing with width B. From elastic halfspace theory, the three stress components in a Cartesian coordinate system are as follows:

$$\sigma_z = \frac{q}{\pi}[\alpha + \sin\alpha \cos(\alpha + 2\delta)] \tag{6.10}$$

$$\sigma_x = \frac{q}{\pi}[\alpha - \sin\alpha \cos(\alpha + 2\delta)] \tag{6.11}$$

$$\sigma_y = \frac{q}{\pi}[2\mu(\alpha)] \tag{6.12}$$

where q is the footing pressure and the α and δ terms define the location at which stress is calculated. Under the centerline of the footing,

$$\alpha = -2\delta = 2\tan^{-1}\left(\frac{B}{2z}\right) \tag{6.13}$$

The stress components, which are functions of depth, are substituted into Eq. 6.9. The expression is simplified by calculating an intermediate term as

$$[F_z]_{z_{i-1}}^{z_i} = \left[\left(\frac{B}{2}\right)\ln(4z^2 + B^2) + 2\tan^{-1}\left(\frac{B}{2z}\right)z\right]_{z_{i-1}}^{z_i} \tag{6.14}$$

The simplified expression for layer stiffness k_i then is

$$k_i = \frac{\pi \, E \, B}{(1 - \nu - 2\nu^2)\,[Fz]_{z_{i-1}}^{z_i} + (\nu - 1)\cos\left([Fz]_{z_{i-1}}^{z_i}\right)} \tag{6.15}$$

The subject of soil damping becomes complicated with soil layering, and a simple method for estimating the damping has not yet been developed. Fortunately, roller-measured stiffness is generally calculated when the drum is in its lowest-most position and drum velocity equals zero. In this case, the calculation of roller-measured stiffness does not necessitate the damping constant.

Layer Thickness Transformation

The formulation of layer stiffness outlined in the previous section is valid for the case of homogeneous subsoil, where the stress distribution underneath a surface loading depends only on depth. In the case of multi-layer soil systems, however, the individual layers having differing elastic modulus affect stress dissipation. Vertical stress generally concentrates in the layers of higher modulus.

The Odemark (1949) method of equivalent thickness is used to transform an elastic two-layer system into an equivalent halfspace for which Boussinesq equations for stress distribution beneath a surface loading are applicable. For calculating the components of stress in the upper layer, the layered-soil system is treated as an elastic halfspace with properties of the upper layer. For calculating the stress in the lower layer, the upper layer is replaced by a layer with properties of the lower layer and an equivalent thickness h_e as:

$$h_e = f \cdot \mathrm{h}_1 \sqrt[3]{\frac{\mathrm{E}_1 (1 - v_1)}{\mathrm{E}_2 (1 - v_2)}} \tag{6.16}$$

where f is about 0.9 for a two-layer system and 1.0 for three or more layers (Abu-Farsakh *et al*. 2004).

Method Verification

Test Data

The calculation of equivalent stiffness used elastic modulus for upper and lower layers (obtained through empirical relation to DCP index) and layer thickness obtained from DCP index profiles. The roller contact width B and Poisson's ratio v were adjusted to maximize the correlation between k_{eq} and the roller measurement values. The fitted parameters equaled 0.10 m and 0.35, respectively. This roller contact width was less than estimated by a Mooney and White (2007) study, in which the parameter ranged from 0.18 to 0.49 m based on measured vertical stress profiles from in-ground instrumentation. To support the fitted value of 0.10 m, a still image of the soil-drum interaction during compaction was examined. Fig. 6.10 illustrates this estimation of the roller contact width. The scaled B value equaled 0.12 m, which agrees reasonably well with the fitted value. The authors further recognize that the roller contact width changes through the compaction process; estimating or measuring this parameter is the subject of ongoing research.

Roller-measured stiffness k_S and calculated equivalent stiffness are shown in Fig. 6.11 for Strip 1 following the third pass. k_S is represented with a solid line, whereas calculated k_{eq} values are shown as discrete points connected with a dotted line. The scale for k_{eq} in Fig. 6.11 was adjusted to provide preliminary indication of the correlation between the measured and calculated stiffness parameters. The mean value of k_S equaled 34.8 MN/m with coefficient of variation (C_V) equal to 12 percent. The mean value of k_{eq} equaled 77 MN/m with C_V equal to 28 percent. The C_V is comparable to values documented in White and Thompson (2007) and Thompson and White (2007) for relatively uniform test strips constructed under controlled conditions.

CMV and calculated equivalent stiffness are shown in Fig. 6.12 for Strip 2, which incorporated variable nominal lift thickness. The loose lift thicknesses along the length of the test strip are provided as a dashed line, with layer thickness increasing with strip location. Mean CMV increased from 2.6 for Pass 1 to 7.2 for Pass 16; C_V for CMV ranged from 47 to 118 percent for the different roller passes. Mean k_{eq} increased from 33.2 MN/m for Pass 1 to 55.1 MN/m for Pass 16; C_V for k_{eq} ranged only from 24 to 34 percent. Because the underlying subgrade layer was more stable than the compaction layer, both CMV and equivalent stiffness are highest for the test strip section with the thinnest upper soil layer. The measured and calculated stiffness parameters decrease with increasing lift thickness through a nonlinear relationship.

Comparison of Equivalent Stiffness with Roller Measurement Values

The relationships between roller-measured stiffness parameters, calculated equivalent stiffness, and compaction layer modulus are provided in Fig. 6.13. E_1 represents the compaction layer modulus, obtained using average DCP index values and the correlations provided in Figs. 6.7 and 6.8. Ammann k_S and CMV were more strongly correlated with k_{eq} (R^2 ranging up to 0.81 for 24 data points) than E_1. The method of equivalent stiffness unfortunately did not provide slope coefficients equal to unity (i.e. true prediction of roller measured stiffness). The challenge of relating roller-measured stiffness and equivalent stiffness through a 1:1 relationship is attributed to the conversion of DCP index to elastic modulus and is further discussed as a limitation of the analysis method at the end of this paper.

The general correlation between roller measurement values and equivalent stiffness support the use of elastic theory to study roller-integrated measurement values for layered soil conditions. The next section uses the method of equivalent stiffness to investigate the influences of layer thickness and modulus on roller response and measurement values.

Influence of Layer Thickness and Modulus on Stiffness

The method of equivalent stiffness enables investigation of the influence of both layer thickness and modulus on equivalent stiffness of the layered soil system (which is proportional to roller measurement values). Fig. 6.14 provides equivalent stiffness normalized with roller contact width and the modulus of the underlying layer as a function of the modulus ratio of the upper and lower layers. The roller contact width for Fig. 6.14 is a constant (0.10 m), and is used to normalize equivalent stiffness for the sole purpose of calculating a parameter without units. Doubling the roller contact width, for example, would decrease the normalized stiffness parameter to half of the original value. A first check of the results is that equivalent stiffness is independent of layer thickness for a homogeneous halfspace (i.e. $E_1 = E_2$). The second check of the results is that, for high layer thickness, equivalent stiffness is proportional to E_1 through a linear relationship, indicating that the underlying layer has negligible effect on the surface response to loading.

The results of Fig. 6.14 show that, for a soft layer overlying a hard layer (i.e. $E_1/E_2 < 1$), decreasing lift thickness increases the roller-measured stiffness. The condition of a hard layer overlying a soft layer shows the opposite effect. Fig. 6.14 illustrates how roller measurement values overestimate soil stiffness of the upper compaction layer for the range of lift thicknesses used on production grading projects (h_1/B from 1 to about 5), because the stiffer underlying layer increases the stiffness response observed at the soil surface. The results further indicate that the relationships between roller-measured stiffness and in-situ modulus measurements from portable testing devices (which are primarily influenced by the upper compaction layer) may be slightly nonlinear.

Fig. 6.15 provides normalized equivalent stiffness for any two-layer soil system in which the roller contact width is 0.10 m and v equals 0.35. The contours of normalized stiffness show that the influence of lift thickness on roller-measured stiffness is greatest for lift thickness less than the contact width (i.e. $h_1/B < 1$), particularly when the upper layer modulus is less than for the lower layer. For thicker soil layers, equivalent stiffness is more heavily influenced by the modulus of the soil layers.

The contours of equivalent stiffness in Fig. 6.15 may provide theoretical support for specifying target roller measurement values. Selecting target values based on elastic theory may be particularly useful for transportation agencies finding current roller calibration procedures to be inefficient and/or uneconomical. To demonstrate the approach, normalized equivalent stiffness for a fully-compacted upper layer (i.e. E_1 equaling E_2) of any reasonable thickness is about 19 for roller contact width of 0.1 m (see Fig. 6.15). The normalized equivalent stiffness is then 3.8 for roller contact width of 0.5 m, which is upper bound of the parameter reported in Mooney and White (2007). After multiplying these values by the respective roller contact widths, the expected roller-measured stiffness becomes 1.9 multiplied by the modulus of the bottom layer. Elastic modulus of 20 MPa produces a stiffness value of 38 MN/m (i.e. target k_S). And because roller-integrated measurement values produced when the roller is operated over near-surface bedrock, box culverts, or very soft subsoil can be particularly difficult to interpret, contour plots of stiffness may also be used during production grading by inspectors as a diagnostic tool to explain measurements deviating considerably from specified values.

Limitations of Analysis Method

The principal limitation of interpreting roller measurement values using DCP index profiles is that the relationship between DCP index and elastic modulus often lacks calibration for different cohesive and granular soils. For example, even though statistically significant correlation was observed between roller measurement values and calculated equivalent stiffness, the slope of the correlation does not equal unity. A wide range of regression coefficients (see Eq. 6.5) has been published. The coefficients significantly affect the magnitude of estimated elastic modulus. The use of different testing technologies (e.g. plate load test, light falling weight deflectometer, seismic surface wave) further complicates elastic modulus estimation for interpreting roller-integrated compaction measurement values, because each testing technology measures modulus within a different strain range (normally less than roller-induced strain). And, as with interpretation of all in-situ tests, the variation associated with each measurement and the uncertainty in correlation equations must be considered.

The method of equivalent stiffness presented in this paper is based on static analysis and does not account for the effect of vibratory surface loading on stiffness response. Accounting for dynamic soil behavior during the soil compaction process may enhance the proposed analysis method.

Summary and Conclusions

Roller-integrated measurement values from roller operation on two-layer soils were investigated using a proposed analysis method. DCP index profiles provided the layering of the subsoil and also properties of the upper and lower layers, which were converted to elastic modulus through an empirical relationship. Using modulus, Poisson's ratio, and layer thickness as analysis inputs, equivalent stiffness was calculated and compared with roller-measured stiffness values. The validated method was then used to make inferences regarding the effect of layer thickness and modulus on roller response and measurement values.

The following conclusions were drawn from this study.

1. The method of equivalent stiffness uses a simple model of soil behavior that enables

relatively easy computation of a spring stiffness that represents composite behavior of the layered-soil system.

2. Roller-integrated measurement values are more strongly correlated with equivalent stiffness (R^2 values as high as 0.81) than with compaction layer modulus alone. Equivalent stiffness accounts for layer thickness, as well as the properties of the underlying layer.
3. The general correlation between roller measurement values and equivalent stiffness support the use of elastic theory to study roller-integrated compaction technologies for operation of layered soils.
4. The fitted roller contact width equaled 0.10 m, which agrees reasonably well with a scaled dimension from a still image of drum-soil interaction taken during roller operation.
5. The influence of underlying layers on roller-measured stiffness is greatest for lift thickness less than the contact width.
6. The method of equivalent stiffness provides theoretical support for specifying target measurement values (for production operations) that are not based on roller calibration procedures, but on target elastic modulus values.

Notation

φ	=	phase angle
ε_z	=	vertical strain
$\sigma_{x, y, z}$	=	stress components of Cartesian coordinate system
Ω	=	circular vibration frequency
a	=	DCP index-modulus regression coefficient
A	=	vibration amplitude
b	=	DCP index-modulus regression coefficient
B	=	roller contact width
CMV	=	*compaction meter value*
c_S	=	damping constant
C_V	=	coefficient of variation

DCPI	=	DCP index
E	=	elastic modulus
E_1	=	elastic modulus for upper soil layer
E_2	=	elastic modulus for lower soil layer
F_S	=	soil-drum interaction force
g	=	acceleration due to gravity
h_1	=	thickness of upper soil layer
h_e	=	Odemark equivalent thickness
k_{eq}	=	equivalent stiffness
k_i	=	stiffness of individual soil layer
k_S	=	Ammann roller-measured soil stiffness
m_d	=	drum mass
$m_e r_e$	=	eccentric moment of the unbalanced mass
m_f	=	frame mass
v	=	Poisson's ratio
w	=	deflection

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Figure 6.1. Strip 1, comprised of Class 5 subbase material overlying compacted subgrade

Figure 6.2. Excavation of natural subgrade for construction of Strip 2 with variable lift thickness

Figure 6.3. Ammann AC-110 vibratory smooth drum roller

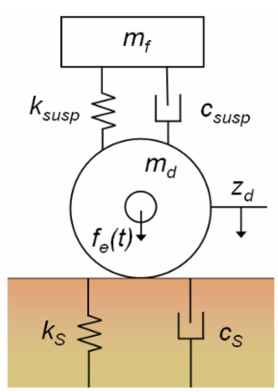

Figure 6.4. Lumped-parameter model for roller estimation of soil stiffness (from Thompson *et al*. 2008)

Figure 6.5. Caterpillar CS-533 vibratory smooth drum roller

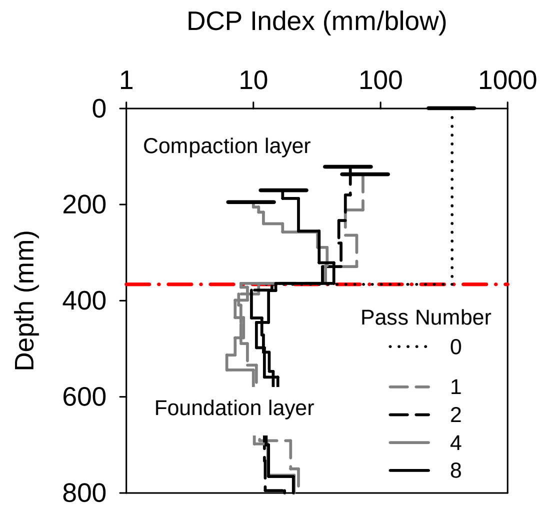

Figure 6.6. DCP index at five stages of compaction showing two-layer soil system

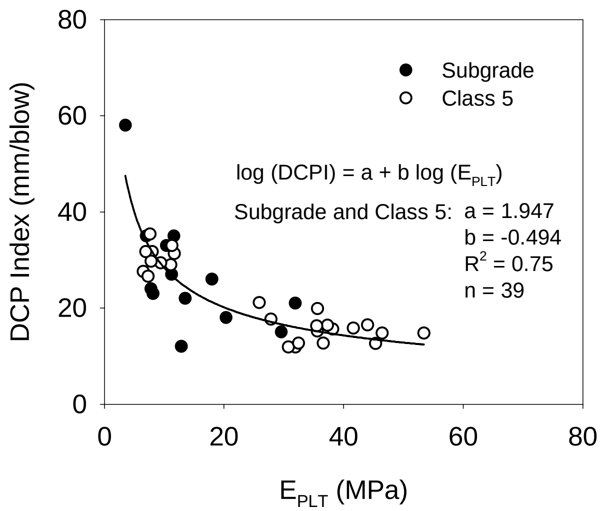

Figure 6.7. Relationship between DCP index and elastic modulus from static plate load tests for materials of Strip 1

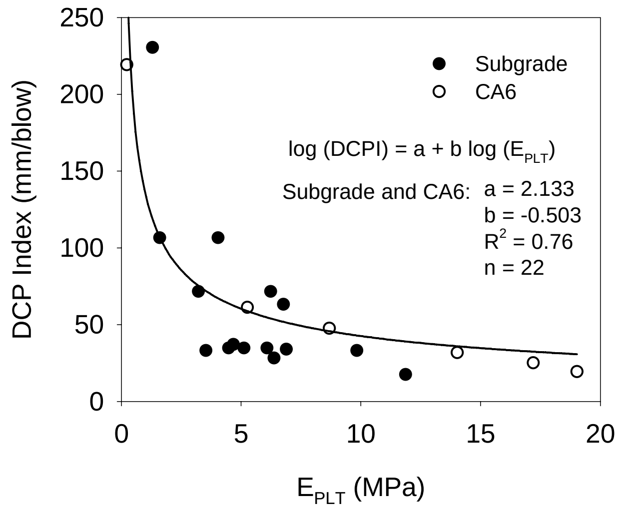

Figure 6.8. Relationship between DCP index and elastic modulus from static plate load tests for materials of Strip 2

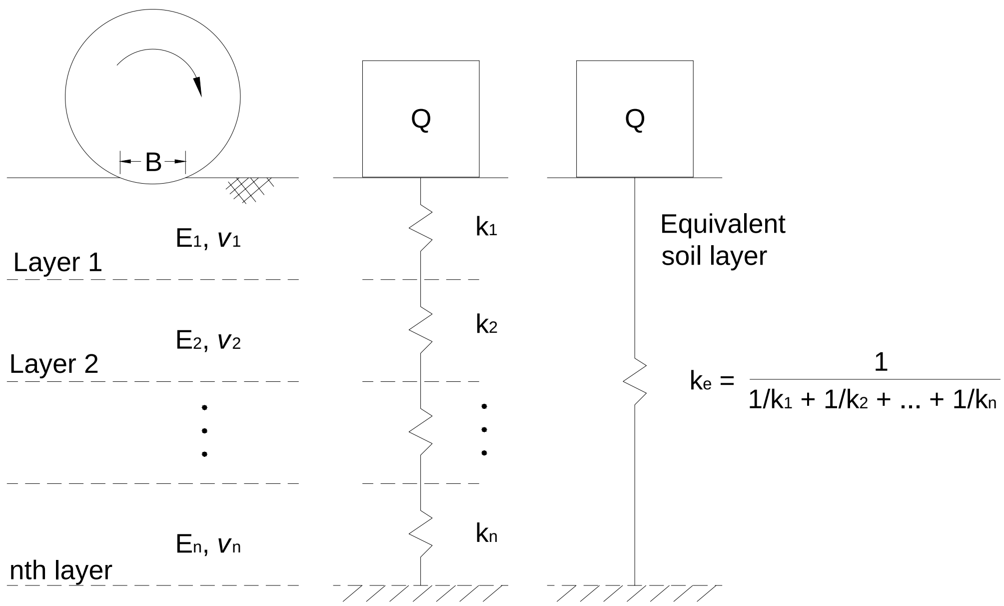

Figure 6.9. Model representation for equivalent stiffness

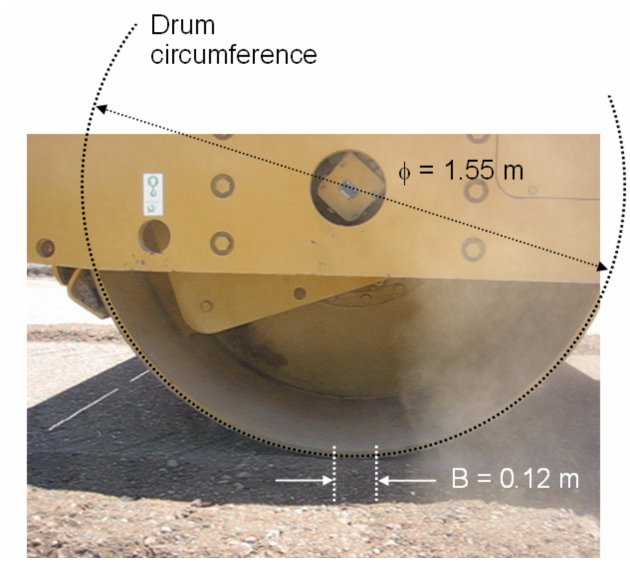

Figure 6.10. Roller contact width for operation on CA6 material

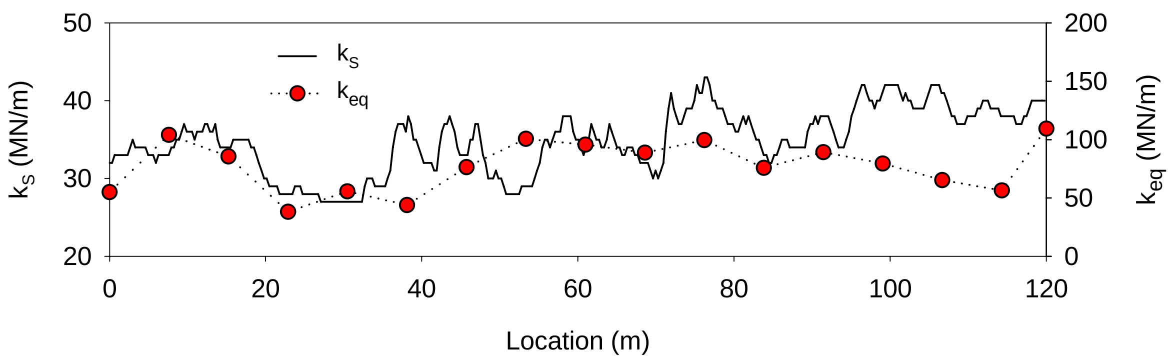

Figure 6.11. k_S and calculated equivalent stiffness for Strip 1 at Pass 3

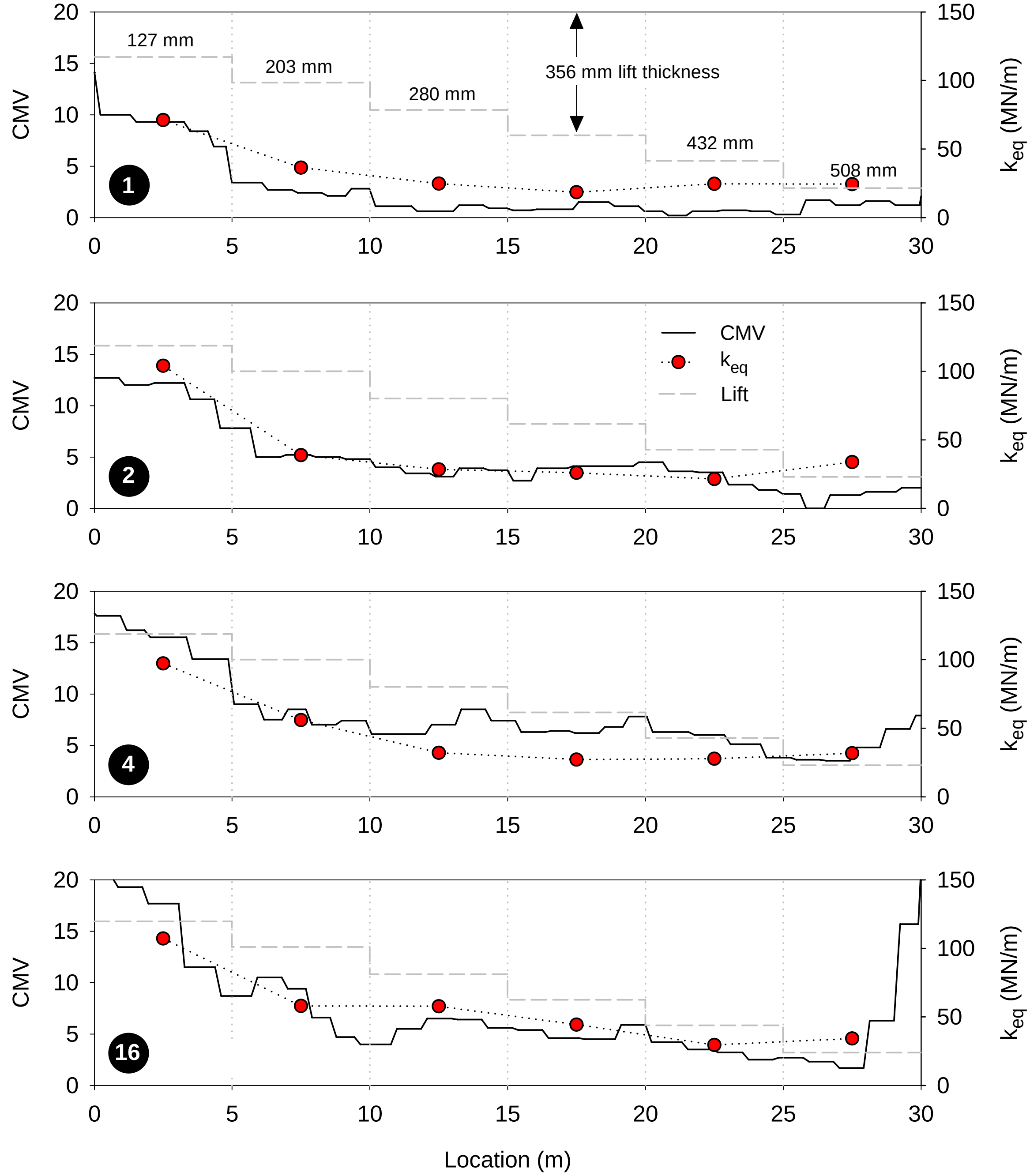

Figure 6.12. CMV and calculated equivalent stiffness for Strip 2 at Passes 1, 2, 4, and 16

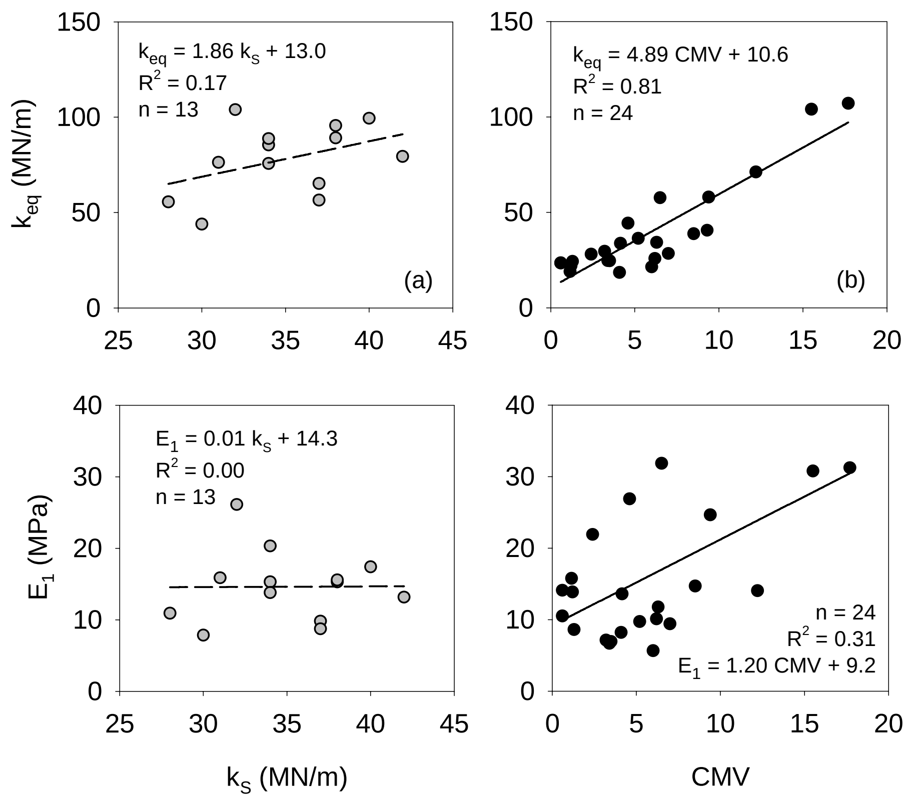

Figure 6.13. Relationships between roller-measured parameters, equivalent stiffness, and upper layer modulus for: (a) Strip 1, (b) Strip 2

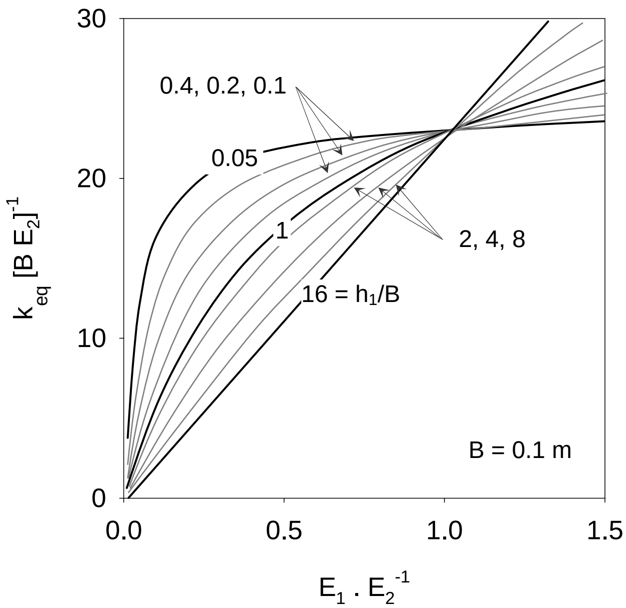

Figure 6.14. Role of relative modulus and lift thickness on normalized roller-measured stiffness

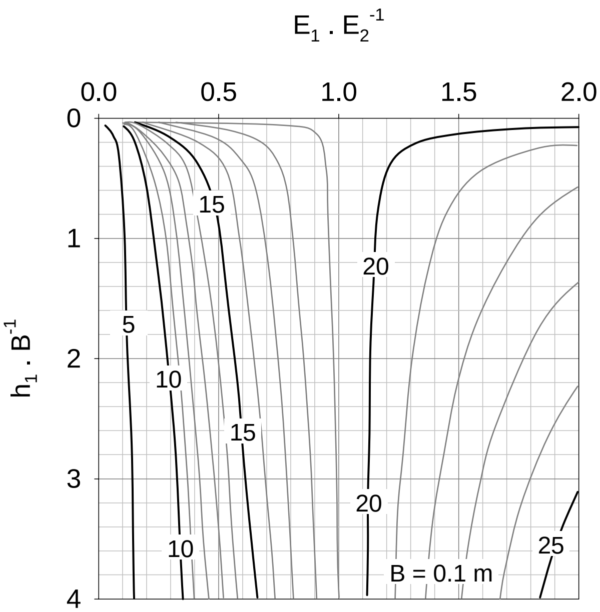

Figure 6.15. Contour plot of normalized equivalent stiffness (k_{eq} [B E_2]$^{-1}$)

CHAPTER 7: Conclusions and Recommendations

Summary

Roller-integrated compaction technology that monitors roller behavior in response to machine-ground interaction was shown to indicate the characteristics of compacted soil. To support the development of specifications for roller-integrated compaction systems and accelerate implementation of the technology into practice, this research identified the relationships between roller-integrated measurement values and the in-situ compaction measurements that are commonly used in the United States for earthwork quality assurance.

The experimental study evaluated the following roller-integrated compaction systems: (1) Ammann soil stiffness k_S, (2) Geodynamik compaction meter value, and (3) Caterpillar machine drive power. Roller data for these studies were obtained by compacting a wide range of cohesive and granular soils using static padfoot and vibratory smooth drum rollers. The soil at different states of compaction was also tested for properties using other in-situ testing technologies. The experimental testing methods provided both roller-measured parameters and material characteristics that were used in performing statistical analyses.

Linear regression analyses using compaction data from test strips showed that soil properties measured using in-situ test devices can be predicted from roller-integrated measurement values, provided that measurement variability is mitigated with spatial averaging techniques. The in-situ soil properties are particularly well correlated when moisture content and interaction terms are incorporated into a compaction model initially derived from laboratory moisture-density-energy relationships. Multiple linear regression analysis results helped to identify and quantify the factors affecting roller response, in particular soil moisture content.

Roller-integrated compaction technology was also investigated for layered soil conditions, with the measurement values affected by the upper compaction layer and the underlying soil layers. The individual soil layers were represented as elastic springs connected in series, and equivalent stiffness for the layered-soil system was formulated using principles of elastic theory. Experimental compaction data supported the new model. The validated model was then used to make inferences regarding the influence of layer thickness and elastic modulus on roller-measured stiffness. The assertions were supported by both experimental and theoretical evidence.

Conclusions

Correlating Roller-Integrated and In-Situ Measurements

The following conclusions address the semi-empirical relationships between in-situ and roller-integrated compaction measurement values.

1. Each roller-measured parameter (e.g. k_S, CMV, MDP) can be empirically related to in-situ compaction measurements. Correlation strength is heavily influenced by the range of values over which the measurements are taken. The relationships additionally depend on soil type and soil moisture conditions.
2. Ammann roller-measured soil stiffness identifies areas of unstable subgrade material similar to test rolling. Rut depth and k_S are related through a nearly-linear relationship.
3. The effect of soil compaction is to decrease MDP and increase CMV and k_S. MDP is observed to be more locally variable than vibration-based system output, while CMV and k_S often show greater deviation from the mean at select locations of a test area. The variation of vibration-based system output is documented to reflect variable stiffness of the underlying subgrade, which is important for interpreting roller-integrated measurements for layered soil conditions.
4. Statistical averaging of roller-integrated measurements mitigates measurement variation and reveals underlying relationships between in-situ and roller-integrated compaction measurement values.
5. Using a laboratory-derived compaction model that relates dry unit weight to compaction energy and moisture content, in-situ compaction parameters were predicted from MDP and moisture content measurements. Incorporating moisture content and MDP-moisture interaction terms into regressions, when statistically significant, improved correlation to indicate the promise of using MDP technology as a tool for predicting compaction parameters.

6. MDP provides some indication of differential lift thickness and variable moisture content. CMV may identify regions of different compaction layer thickness.
7. Differences between the spatial distribution of roller-integrated measurement values with that of in-situ test results for a controlled two-dimensional test area is attributed to different measurement depths and measurement variation of roller-integrated compaction technology and compaction control tests.

Addressing Roller Measurement Depth

The following conclusions address roller measurement depth and the analytical investigation of roller-integrated measurement values for layered soil conditions.

1. The method of equivalent stiffness uses a simple model of soil behavior that enables relatively easy computation of a spring stiffness that represents composite behavior of a layered-soil system.
2. Roller-integrated measurement values are more strongly correlated with equivalent stiffness than with DCP index alone. Equivalent stiffness accounts for layer thickness, as well as the properties of the underlying layer.
3. The general correlation between roller measurement values and equivalent stiffness support the use of elastic theory to study roller-integrated compaction technologies for operation of layered soils.
4. The method of equivalent stiffness provides theoretical support for specifying target measurement values (for production operations) that are not based on roller calibration procedures.

Recommendations for Future Research

The following recommendations address future research which may be conducted to build upon the findings documented in this dissertation.

1. Develop relationships between roller-integrated compaction data and pavement design parameters, such as resilient modulus. The mechanistic parameters may be linked directly or indirectly through in-situ testing of compacted materials.
2. Investigate the mechanical performance of compaction machines for identifying and

quantifying the factors affecting internal power losses (e.g. speed). Improving upon the MDP calibration process and correction for internal losses may improve the output of the MDP system.

3. Investigate the feasibility of using the MDP compaction technology applied to alternative roller configurations. The research of this dissertation showed that the technology may be applied to vibratory smooth drum (Chapter 3) and static padfoot (Chapter 4) rollers. To expand upon the role roller-integrated compaction technology may play during earthwork construction, the MDP system may be installed on larger rollers or earthmoving equipment that serves functions other than soil compaction.
4. Document that using roller-integrated compaction technology results in a higher quality product than using earthwork equipment without such technology. Such documentation should investigate as-compacted material properties, as well as the long-term performance of the pavement and/or earth structure.
5. Evaluate variable feedback control features of intelligent compaction systems with respect to the intended benefits. The data in Chapter 2 did not confirm that variable control systems improve uniformity or result in more efficient compaction.
6. Develop data management and analysis tools for the purpose of aiding transportation agencies in working with very large quantities of roller-integrated compaction data. These tools should be flexible and allow for use with output from any roller-integrated compaction system.
7. Investigate the use of geostatistics for interpreting roller-integrated compaction data. In addition to the Kriging interpolation method documented in Chapter 5, other methods for representing spatial data should be investigated. Special consideration should be given to the likelihood that soil properties under field conditions reflect non-stationary conditions (i.e. trends in data resulting from different processes must be eliminated prior to interpolation methods).
8. Correlate the non/uniformity and spatial distribution of soil properties, based on roller-integrated compaction data, with the long-term performance of pavement structures. Findings may be compared with predictions from numerical/analytical pavement performance models to support the use of roller-integrated compaction

technology as an opportunity for improved uniformity and, ultimately, improved pavement performance. Special consideration should be given to spatial scale.

9. Compare compaction curves observed for field compaction with those for laboratory compaction using existing compaction methods (e.g. impact, vibratory, gyratory) or new methods.
10. Conduct laboratory studies to evaluate the relationships between the strength and stiffness of compacted materials with dry unit weight, moisture content, compaction energy, and compaction method. Findings from such a study may provide insight into machine-ground behavior and the link between roller-integrated measurements and in-situ soil properties.
11. Use in-ground instrumentation to investigate in-situ stress/strain resulting from compaction machines operated at different speeds, vibration amplitudes, and frequencies.
12. Model field compaction processes using analytical and/or numerical methods. The data presented in this dissertation and also from in-ground instrumentation may be used to calibrate and validate possible models.
13. Study roller behavior and roller-integrated compaction systems for compaction of hot mix asphalt.