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Implementation of ‘Smart Equipment’ in Field Construction

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16. Abstract

The goal of this study was to examine the potential benefit of Continuous Compaction Control (CCC) technology, which allows for near continuous collection of compaction effort information during the compaction process of earthwork construction operations. For this project, a CCC retrofit kit was installed on an existing smooth drum compaction roller, and CCC data was collected during active construction of US 301, Section 3 located in Middletown, DE. The focus of this study was to determine the overall benefits of collecting CCC data during active earthwork construction to determine if contractors, state agencies and other parties of interest could benefit from the use of CCC data, especially for making real time decisions regarding the compaction process. The results from this study indicated that CCC data was able to identify underlying soft soil and was sensitive to changes in material. The results also indicated that CCC data followed the same general trends of identifying poorly- and well-compacted subgrade materials when compared against traditional in situ testing methods.

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Table of Contents

List of Figures

Page

Introduction

The compaction of soil is a critical step in the process of earthwork construction. Given that soils are a frictional material by nature, compacting soil enhances the particle to particle contact within the soil matrix and ultimately improves the shear strength and bearing capacity of soils, while also reducing the potential for soils to experience significant settlement (e.g., D'Appolonia et al. 1969). Many civil engineering structures (e.g. roadways, bridges, large buildings, etc.) bear on engineered earthworks; consequently, the performance of these structures are influenced by the soil's compacted behavior. As a result, the methods and procedures utilized for quality assurance and quality control (QA/QC) during earthwork construction can play an important role in determining the in-service performance of a given structure.

Traditionally, for soil compaction during earthwork construction, QA/QC procedures rely on either 'method' or 'end-product' based specifications. 'Method' based specifications require the contractor to place the soil in uniform lifts that do not exceed a certain thickness (e.g., 20 cm (8 in) loose lifts) and compact the soil in a certain number of passes utilizing a certain type of compaction roller. 'End-product' based specifications require the contractor to achieve a certain relative compaction target at the end of the compaction process for a given lift of soil placed. Traditionally, this is done by ensuring the soil is compacted to either 90% or 95% of its maximum dry unit weight, at an in situ moisture that is within 2% of the soil's optimum moisture content (DelDOT 2016). The specified target values for a given soil are determined by conducting Proctor compaction testing of the soil in the laboratory (e.g. ASTM D698/D1557-12). In situ unit weight and moisture content values are commonly determined using field testing procedures such as the sand cone test (ASTM D1556-15) or the rubber balloon test (ASTM D2167-15). Given that these test procedures are time consuming and destructive in nature, in more recent years it has become common to utilize a Nuclear Density Gauge (NDG) to measure the soil's unit weight and moisture content during the construction process for 'end-product' based QA/QC testing (ASTM D6938-17).

Unfortunately, one of the largest drawbacks with utilizing traditional testing equipment such as the NDG for earthwork QA/QC is the lack of data collected during the construction process. Typical field testing procedures generally yield compaction test results for less than 1% of the total volume of soil fill that is placed (Mooney et al. 2010). This becomes an issue as it may lead to "problem" areas not being identified during the QA/QC process, which can ultimately cause performance issues for constructed infrastructure such as a large building experiencing excessive settlement or a roadway system experiencing a large amount of rutting prematurely.

This drawback has been the catalyst behind the development of Continuous Compaction Control (CCC), a type of earthwork machine monitoring technology. CCC allows for near continuous monitoring and collection of compaction effort data through the instrumentation of a smooth drum compaction roller. CCC systems typically utilizes three essential instrumentation components: a vibration sensor (e.g., an accelerometer) that is mounted to the drum of the roller, a global positioning system (typically a RTK-GPS receiver attached to the top of the cab of the compaction roller), and an on-board data acquisition system that is accompanied by a computer and a heads-up display for the operator in the cab of the roller. Data collected from a CCC system can be utilized to build spatial maps of the compaction process, providing real-time feedback to both the contractor and engineer during earthwork construction (e.g., Meehan et al. 2017).

The goal of this study was to examine the benefits of instrumenting an existing compaction roller with an "add-on" CCC system and to evaluate the effectiveness of this CCC system during active construction. The emphasis of this study was to determine the overarching benefits of collecting CCC data during active earthwork construction in order to determine if contractors and state agencies (e.g., the Delaware Department of Transportion) could utilize CCC data to help make real time decisions regarding the compaction process during earthwork construction.

Development of Continuous Compaction Control Measurements

The first CCC measurement was developed in the late 1970's, as researchers realized the spatial and testing-volume limitations of traditional in situ test methods such as the bulk density test, the plate load test, and various types of penetration tests. These early researchers indicated that conventional in situ tests like these are "hit and miss methods and can only provide very inaccurate, local information about the compaction results achieved" (Thurner and Sandstrom 1980). Thurner and Sandstrom (1980) realized that utilizing the compaction roller as a testing instrument was a logical step forward as it could provide both instantaneous and continuous information regarding the compaction process by monitoring the dynamic interaction between the drum and the subgrade soil.

Compactometer Value (CMV)

This early research led to the development of the CCC measurement "Compactometer value", which is commonly referred to as CMV. To measure CMV, an accelerometer is attached to the bearing of the compaction roller drum. During the compaction process the accelerometer continuously recorded the acceleration of the drum; the acceleration signal gets filtered by a bandwidth filter corresponding to the fundamental frequency (e.g. operating frequency of the drum) and the first harmonic of the drum vibrations. A Fast Fourier Transform is then performed on each two-cycle period of the acceleration to determine the frequency content of the acceleration signal. CMV is then determined from the ratio between the amplitudes of the first harmonic and the excitation frequency of the drum, which are then multiplied by a constant as shown in the following equation (Thurner and Sandstrom 1980, Mooney and Adam 2007):

$$CMV = c * \frac{A_{2\Omega}}{A_{\Omega}} \quad (1)$$

where c = constant specified by the manufacturer (typically 300), $A_{2\Omega}$ = amplitude of the first harmonic of the acceleration response signal, and A_{Ω} = amplitude of the excitation frequency. Early research showed that as soil become stiffer during the compaction process, the ratio between the amplitudes of the first harmonic and the excitation frequency of the drum increases; consequently, a higher CMV should indicate a stiffer underlying material (Mooney and Adam 2007). Figure 1 provides an illustration on how CMV is determined.

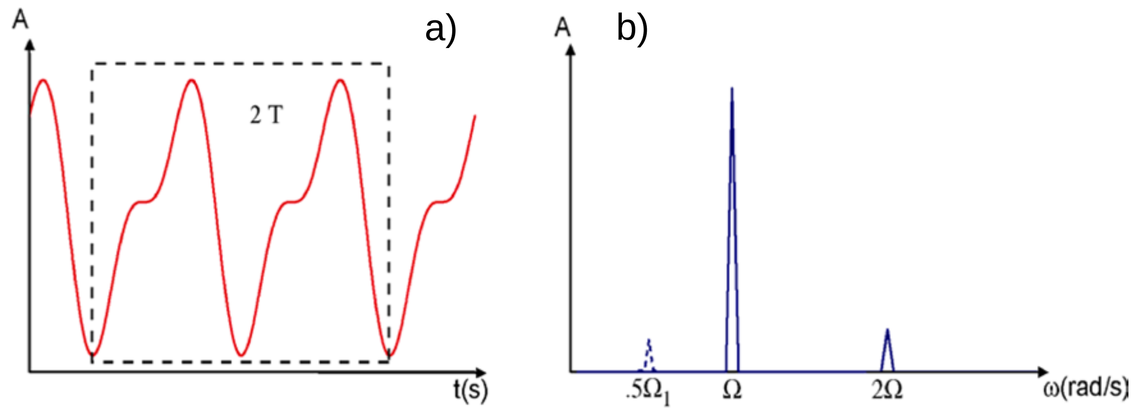

Figure 1. Conceptual visualization of CMV determination: (a) Drum acceleration amplitude with time, and (b) drum acceleration amplitude with frequency content after performing a Fast Fourier Transform of the time series data (modified after Mooney and Adam 2007).

Resonant Meter Value (RMV)

A sister CCC measurement to CMV is the Resonant Meter Value or RMV (White et al. 2008). RMV is utilized to indicate the contact mode the compaction drum is experiencing during the compaction process. Similar to CMV, RMV is calculated by conducting a Fast Fourier on each two-cycle period of the drum acceleration. RMV is calculated utilizing the following equation:

$$RMV = c * \frac{A_{0.5\Omega}}{A_{\Omega}} \quad (2)$$

where c = constant specified by the manufacturer (typically 300), $A_{0.5\Omega}$ = amplitude of the sub harmonic (e.g. half the frequency of the excitation frequency) of the acceleration response signal, and A_{Ω} = amplitude of the excitation frequency. Theoretically, a RMV = 0 indicates that the compaction drum is in continuous contact with the soil, while a RMV > 0 indicates that the compaction drum is entering into other contact modes such as “periodic loss of contact” and “double jump”. This is important because Adam (1997) showed that the CMV increases linearly with soil stiffness while the compaction drum is in continuous contact. However, for higher levels of soil stiffness, as the soil stiffness increases the compaction drum transitions into other modes of vibration such as periodic loss of contact and double jump. When this happens, RMV begins to increase and CMV begins to decrease rapidly (e.g., Adam and Kopf 2004, Vennapusa et al. 2009). Consequently, it is important to examine CMV values in conjunction with RMV values in order to evaluate the soil stiffness from these readings.

Soil Stiffness k_s and E_{vib}

Other CCC measurements such as k_s and E_{vib} rely on utilizing the vibratory characteristics of the compaction drum to indicate soil stiffness through the calculation of a ‘force-displacement’ loop (Anderegg 1998 and Kröber et al. 2001). This force-displacement loop is determined by calculating the force transmitted from the compaction drum to the soil utilizing dynamic force equilibrium and by determining the displacement of the compaction drum with time. Both of these CCC values can be computed from the same loop, as shown in Figure 2. Mooney and Rinehart

(2009) state that the tangent stiffness value k_1 is the stiffness that is exhibited in order to calculated E_{vib} utilizing Lundberg's (1939) solution, while k_2 represents k_s which is the secant stiffness of the loop starting at the point of zero deflection (under static loading) to the point of maximum drum deflection. Given that these CCC measurements were not used during this study, interested readers are referred to Anderegg (1998) and Anderegg & Kaufmann (2004) for the theory and development of k_s and Kröber et al. (2001) for the theory and development of E_{vib}.

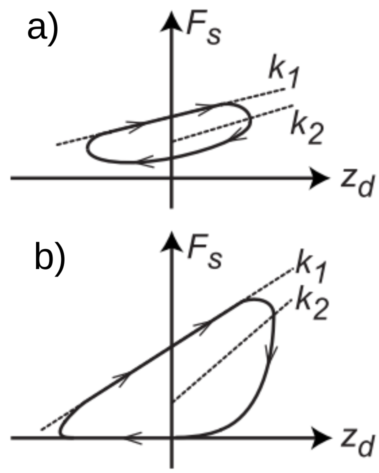

Figure 2. Force Displacement Loop: (a) During continuous contact phase, and (b) During partial up-lift phase (modified after Mooney and Rinehart 2009).

Machine Drive Power (MDP)

Unlike the CCC measurements CMV, k_s, and E_{vib} that rely on the dynamic behavior of the compaction drum, the CCC measurement Machine Drive Power (MDP) relies on the concept of vehicle-terrain interaction, by assuming that soil compaction is related to drum sinkage and the energy necessary from the compaction machine to overcome the resistance to motion while compacting soil (Thompson and White 2007). The equation for MDP is as follows:

$$MDP = P_g - WV\left(\sin\theta + \frac{a}{g}\right) - (mV + b) \tag{9}$$

Where:

P_g = gross power needed to move the machine,

W = roller weight

V = roller velocity

θ = slope angle

a = acceleration of the machine

g = acceleration of gravity

m and b = machine internal loss coefficients specific to a particular machine

A higher MDP value indicates that more energy is required from the compaction roller to overcome rolling resistance during the compaction process. This is typical when the soil is in a loose configuration. As soil becomes more compact, MDP decreases, as less energy is required from the compaction roller to overcome rolling resistance.

Project Description

The Delaware Department of Transportation (DelDOT) recently acquired a Trimble CCS900 Compaction Control System that allowed for near continuous measurements of both CMV and MDP. This system consisted of two components that were installed on an existing Caterpillar CS56B smooth drum compaction roller. The first of these was a real-time kinematic global positioning system (RTK-GPS) receiver that was mounted to the top of the cab, and the second was an on-board computer that was installed inside the cab of the roller. It should be noted that this particular compaction roller already had a manufacturer accelerometer pre-installed. A RTK-GPS base station was also required for the RTK-GPS receiver to determine its spatial location (e.g. Northing, Easting and Elevation).

For this study, CCC data was collected during active construction for U.S. 301, Section 3 location in Middletown, DE between June through October of 2017 and May through July of 2018. The main objective of this study was to examine the benefits and effectiveness of a retrofitted CCC system for collecting data during active construction. Unlike other previous studies where CCC data was collected in a controlled environment (i.e., a test pad area, Thompson and White 2007, Neff et al. 2014, Pistrol et al. 2016, Meehan et al. 2017, Wersall et al. 2017, etc.), the data collected in this project was collected in an uncontrolled environment (i.e., by the contractor, on an active site). The emphasis of this project was to determine the “big-picture” benefits of collecting CCC data during earthwork construction, which could provide valuable insight to both the contractors and owners (e.g. Department of Transportation Agencies) during the earthwork construction phase, to help both parties make real-time informed decisions regarding the compaction process.

Data collection primarily took place during the placement of subgrade soils along multiple embankments during the earthwork construction process. The material utilized for the subgrade soil generally classified as a silty sand or a poorly graded silty sand (SM, SP-SM), per a USCS classification approach (ASTM D2487-11). The subgrade material utilized for construction was obtained from an onsite borrow located along the northeast section of Section 3 for the U.S. 301 project. During the compaction process, the Caterpillar CS56B compaction roller vibrated at a nominal operating frequency of approximately 32 Hz. The compaction roller vibrated at both low and high amplitudes of vibration (0.97 mm and 2.1 mm, respectively), and the operator had the ability to manually switch between these two amplitudes. It should be emphasized that the CCC data collected during this study was collected in an “uncontrolled” environment, meaning that the CCC data collected did not influence the contractor’s decision making during the compaction process; in particular, the operator(s) utilizing the compaction roller did not directly utilize the CCC information that was available in the cab of the roller to make real-time decisions that could affect the compaction process. Along with the collection of CCC data, independent in situ QA/QC testing was performed using a Dynamic Cone Penetrometer (DCP) and a 300 mm diameter Light Weight Deflectometer (LWD) following standard operating procedures (e.g. ASTM E2583-07, and ASTM D6951-03, respectively).

Results

Spatial Coverage

For the duration of this project, CCC data was collected over nearly the entire project site, as shown in Figure 3. It should be noted that this project site consisted of the construction of approximately 3 miles of new roadway. The use of CCC technology was able to provide nearly 100% coverage of compaction effort information during the earthwork construction phase of this project. As indicated in previous studies (e.g., Mooney et al. 2010, Meehan et al. 2017), one of the major advantages of CCC technology is its ability to provide nearly 100% coverage and real time feedback regarding the compaction process. This provides a huge leap forward compared to traditional QA/QC techniques for earthwork construction that rely on spot testing techniques that provide less than 0.1% coverage of the project site.

Figure 3. Coverage of CCC data collected during Construction of US 301, Section 3.

Identification of Underlying Soft Soil

To determine the effectiveness of CCC technology, two embankment sections that were constructed during the earthwork construction phase were compared; measurements of CMV along with in situ measurements utilizing the DCP and LWD were taken along both embankments. For these two embankment sections, the collection of MDP data did not occur, as the compaction roller was unable to collect MDP data due to a machine setting. This issue will be further discussed in a later section. For both sections a single lift of subgrade material was placed and compacted. Figure 4 shows the CMV heat maps between the two sections. From the results presented in Figure 4 it is apparent that the subgrade material in Section 1 is generally stiffer compared to the subgrade material in Section 2, given that higher CMV is generally considered to be an indication of increased soil stiffness. When examining the distribution of the CMV values between the two sections, the CMV values along Section 1 ranged from 0.1 to 134.7 with an average CMV of 35.5 and standard deviation of 13.9. For Section 2, CMV values ranged from 0.1 to 95.5 with an average CMV of 13.3 and standard deviation of 8.1.

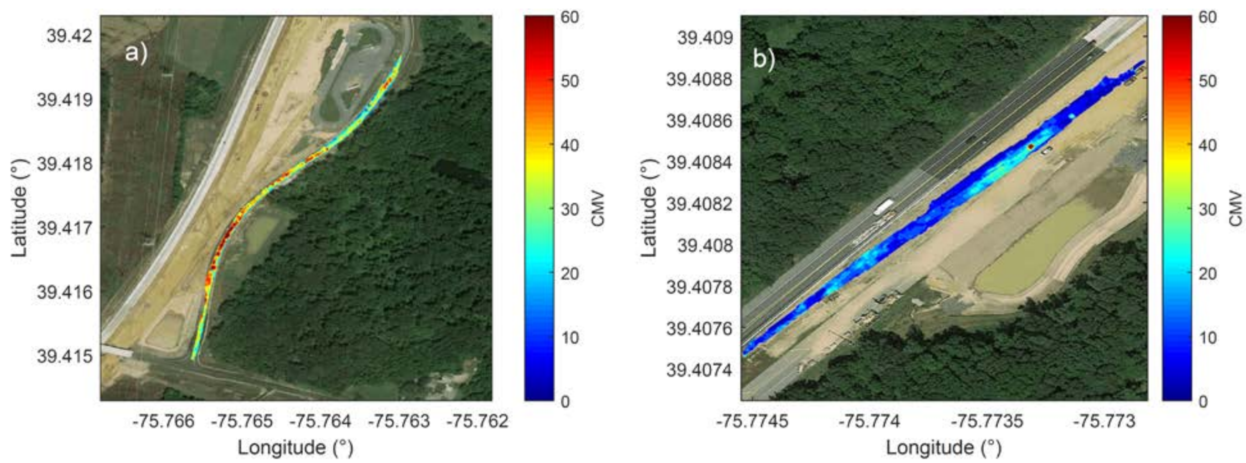

Figure 4. CMV measurements collected along both sections: (a) Section 1 CMV heat map, and (b) Section 2 CMV heat map.

As an independent check against the CMV values collected along both sections, DCP and LWD tests were also conducted at these two locations. For Section 1, 49 test locations were organized in a 7x7 testing grid for in situ testing. The spacing between adjacent testing locations along the same row was approximately 1.5 m (5 ft) and spacing between each row of testing locations was approximately 15 m (50 ft). At each of the 49 test locations a LWD test was conducted to measure in situ dynamic soil modulus, E_{LWD}. For each row, three DCP tests were also conducted along each of the rows in the test grid to measure in situ penetration-per-blow with depth and were terminated at approximately 600 mm below grade. DCP tests were performed at the 2nd, 4th, and 6th location along each row of the test pad, resulting in a total of 21 tests being taken for Section 1. For Section 1 the test grid was laid out in the northern portion of Section 1, this was due to the contractor actively working along the southern portion of Section 1. For Section 2 a similar approach was taken to lay out the testing grid with spacing between adjacent test locations along the same row to be approximately 1.5 m while spacing between each row of tests to be 15 m with 7 rows laid out. However due to the geometry of Section 2, the first 4 rows consisted of 3 test locations. The fifth row consisted of 4 test locations and the remaining two rows consisted of 5 testing locations, resulting in a total of 26 test locations. For DCP testing along Section 2, DCP tests were conducted along the center of each row, resulting in 7 DCP tests conducted. Similar to Section 1, in situ testing along Section 2 was conducted along the northern portion of Section 2, given the contractor was actively working along the southern portion of the section.

Moisture content samples were also collected at each testing location during in situ testing along both sections. Samples collected were taken back to the laboratory for moisture content determination utilizing the general procedure outlined in ASTM D2216-10. Along Section 1 the moisture content values ranged from 8.6% to 12.4% with the average moisture content for all samples being 10.2% with a standard deviation of 0.9%. Along Section 2 the moisture content values ranged from 4.6% to 9.4% with the average moisture content for all samples being 7.6% with a standard deviation of 1.3%. Therefore, the moisture content measurements indicated that the subgrade soil along Section 2 was slightly drier than the subgrade soil along Section 1. However, in general there was not a significant difference in moisture content measurements between the sections.

Figures 5 and 6 present the results for each of the associated compaction related measurements (e.g. CMV, LWD and DCP). Figures 5a and 6a depict the testing grid layout for each section along with the associated CMV heat map underlying the test grid area. Figures 5b and 6b show the associated CMV distributions for both sections, similar to the distribution characteristics in Figure 4; within the testing grid areas, the average CMV value for Section 1 was 34.5 with a standard deviation of 13.8. For Section 2, within the testing grid areas, the average CMV value was 13.1, with a standard deviation of 9.1. These results indicate that the CMV distribution along the testing grid areas for both sections exhibited similar distribution characteristics compared to the distribution characteristics of each section in their entirety, respectfully. This indicates that the test grid areas along each section are a good representation of the overall stiffness variation of the subgrade for both sections.

Figures 5c and 6c, and 5d and 6d represent the LWD and DCP results for Section 1 and Section 2, respectfully. For Section 1, LWD readings ranged from 3.4 MPa to 68.4 MPa with an average modulus of 41.1 MPa and a standard deviation of 14.9 MPa. For Section 2, LWD readings ranged from 5.0 MPa to 37.8 MPa with an average modulus of 21.5 MPa and a standard deviation of 8.1 MPa. As shown in Figure 6c, none of the LWD tests taken along Section 2 had a recorded modulus greater than 40 MPa, while 45% of the modulus values recorded along Section 1 were greater than 40 MPa. DCP results in Figures 5d and 6d are shown in penetration index (mm/blow) versus depth profiles for both sections. Given that a series of DCP tests were conducted at each section, the associated DCP results were averaged every 25 mm to develop an average penetration index profile for each section. The solid line shows the average penetration index with depth for each section, while the shaded region indicates +/- one standard deviation of the DCP results versus depth for each section. From the figures presented, it is evident that with depth the penetration index for Section 1 generally decreases, indicating that the underlying material is generally stiff (Mooney and Rinehart 2007). The underlying material for Section 2 between depths of approximately 200 mm and approximately 550 mm showed an increase in penetration index with depth, indicating that underlying material is less stiff compared to the underlying material in Section 1. The overall average Dynamic Cone Penetration Index value (DCPI) over depth for

Section 1 was 9.4 mm/blow with a standard deviation ranging between 1.4 mm/blow to 8.5 mm/blow with depth. The average DCPI over depth for Section 2 was 23.3 mm/blow with a standard deviation ranging between 1.0 mm/blow to 16.1 mm/blow with depth.

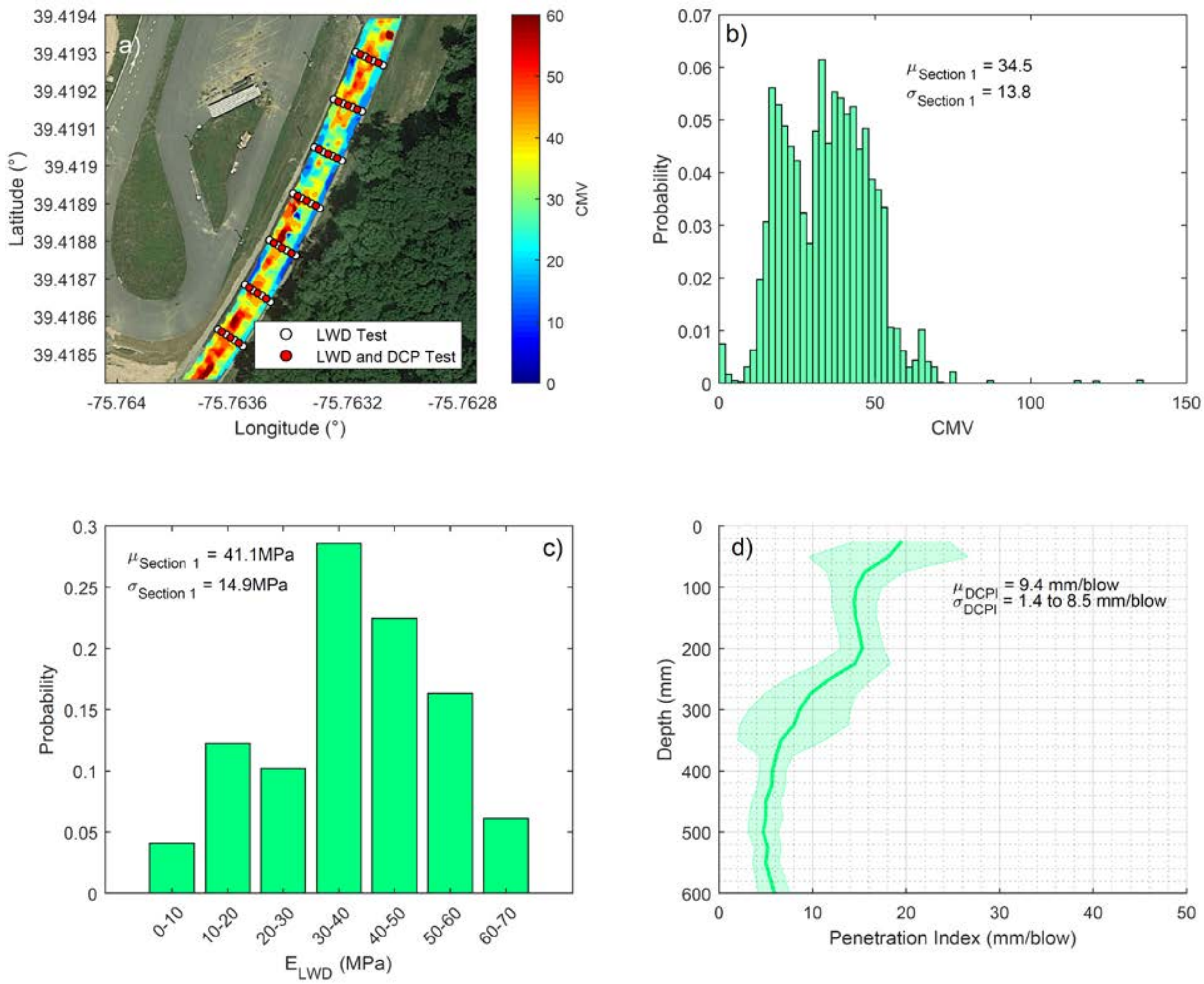

Figure 5. CMV and in situ measurements collected along Section 1: (a) CMV heatmap, (b) CMV distribution, (c) LWD modulus distribution, and (d) DCP index distribution with depth.

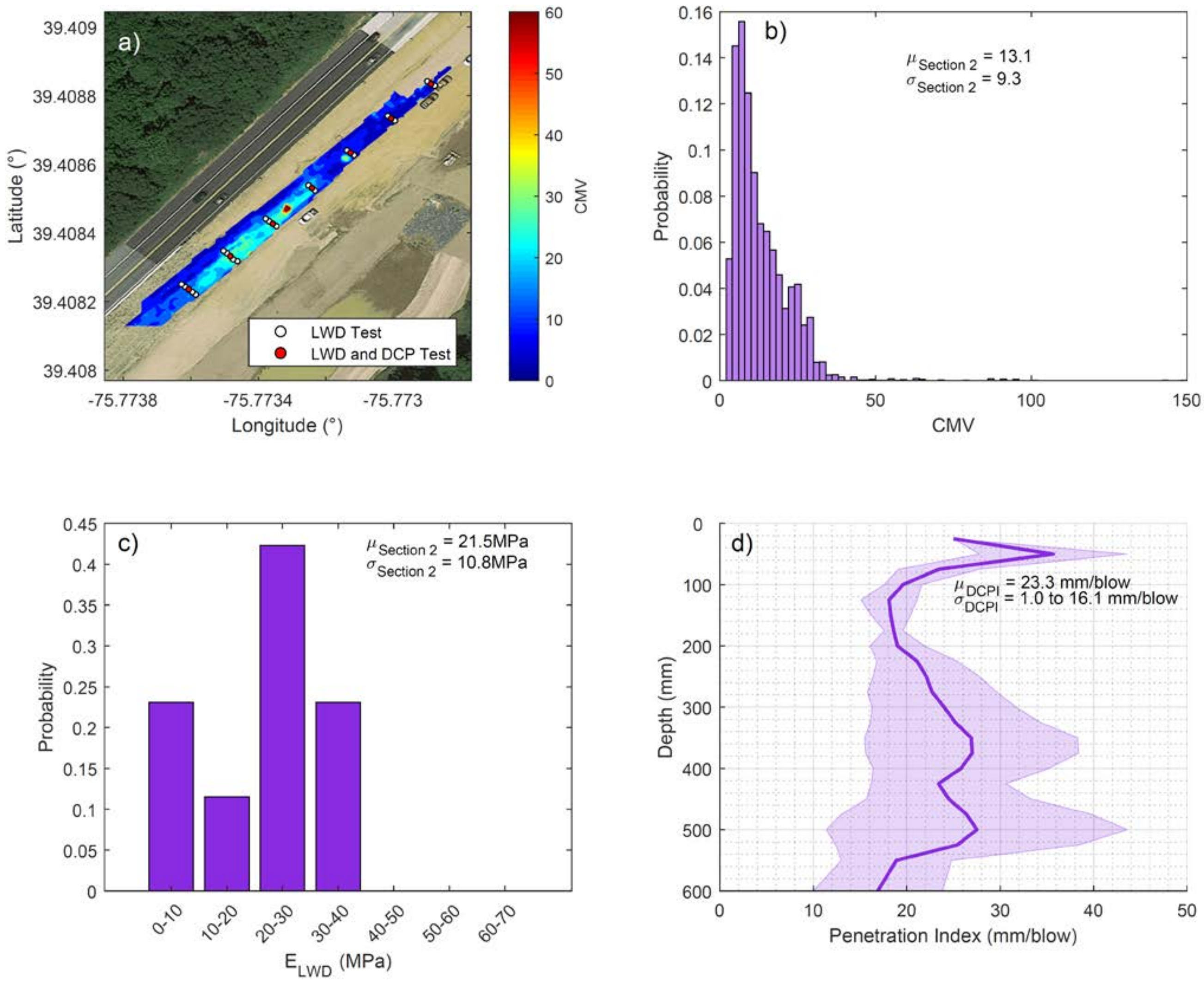

Figure 6. CMV and in situ measurements collected along Section 2: (a) CMV heatmap, (b) CMV distribution, (c) LWD modulus distribution, and (d) DCP index distribution with depth.

In an aggregate sense the three measurements, CMV, LWD and DCP all generally indicated that the subgrade soil along Section 1 was stiffer than the subgrade soil along Section 2. Figure 7 presents the relationship between CMV readings and LWD and DCP tests on a 'point-by-point' basis utilizing simple univariate regression analysis. Given that the CMV readings were not recorded at the same spatial location as the in situ tests and that CMV readings are more continuous in nature, interpolation was required in order to estimate the CMV readings at the associated in situ testing locations for both Sections 1 and 2. A simple neighbor search window was utilized, averaging the CMV readings within a 1.5 m radius for each in situ test location. Other, more sophisticated interpolation methods such as Inverse Distance Weighting (IDW) and Kriging could have been utilized, but Meehan et al. (2017) indicated that when conducting this type of analysis, simpler interpolation methods generally produce the same results as more sophisticated interpolation methods. When examining the relationship between CMV readings and LWD measurements, there is positive trend generally indicating that a higher CMV reading would correspond to a higher E_{LWD} measurement at the same spatial location. However there is a significant amount of scatter along the trend line, as indicated by the corresponding coefficient of determination (R^2) value of 0.52. When examining the relationship between CMV readings and DCP measurements there is a negative trend generally indicating that a higher CMV reading would result in a lower average penetration index calculated from a DCP test at the same spatial location. Similar to the LWD, there is scatter along the trend line. Unlike the relationship between CMV readings and LWD measurements which was modeled as a linear trend, the relationship between CMV readings and DCP measurements was modeled as an exponential trend, which yielded an R^2 value of 0.67. It should be noted that the relationship was also modeled using a linear trend, however this particular model was less accurate producing an R^2 value of 0.51. These results are similar to the results presented in White et al. (2008) and Meehan et al. (2017) where the general trends between CMV and LWD/DCP are consistent, however on a point-by-point basis there is a significant amount of scatter. It should be noted that this type of analysis was commonly performed during early studies that examined the use of CCC measurements for earthwork QA/QC in the United States, where attempts were made to 'calibrate' CCC measurements to those from known/trusted in situ measurement devices such as the LWD, DCP or NDG to determine a 'target' CCC value for acceptance. In these studies, it was deemed desirable to have a R^2 calculated during this analysis that was equal to or greater than 0.50, as a criteria for acceptance of the calibration relationship (e.g., Mooney et al. 2010).

Rinehart et al. (2012) implemented this calibration procedure to determine a 'target' CMV value by conducting a linear regression analysis between CMV data and measurements made by NDG on an active project site in Colorado. Rinehart et al. (2012) found that they were unable to meet the 'target' CMV during the construction process after performing the calibration procedure on a test-strip section. The authors realized that the underlying material along the active construction zone was much stiffer compared to their test-strip section, resulting in the authors unable to achieve the 'target' CMV value given that the CMV values along the test-strip were lower compared to the rest of the embankment. Consequently, the authors concluded that a simple goodness of fit (e.g. $R^2 > 0.50$) between CCC measurements and in situ devices may not be an acceptable approach for roller-based earthwork QA/QC, as approaches such as linear regression analysis do not account for variables such as underlying heterogeneous material and variation in moisture content across the evaluation area.

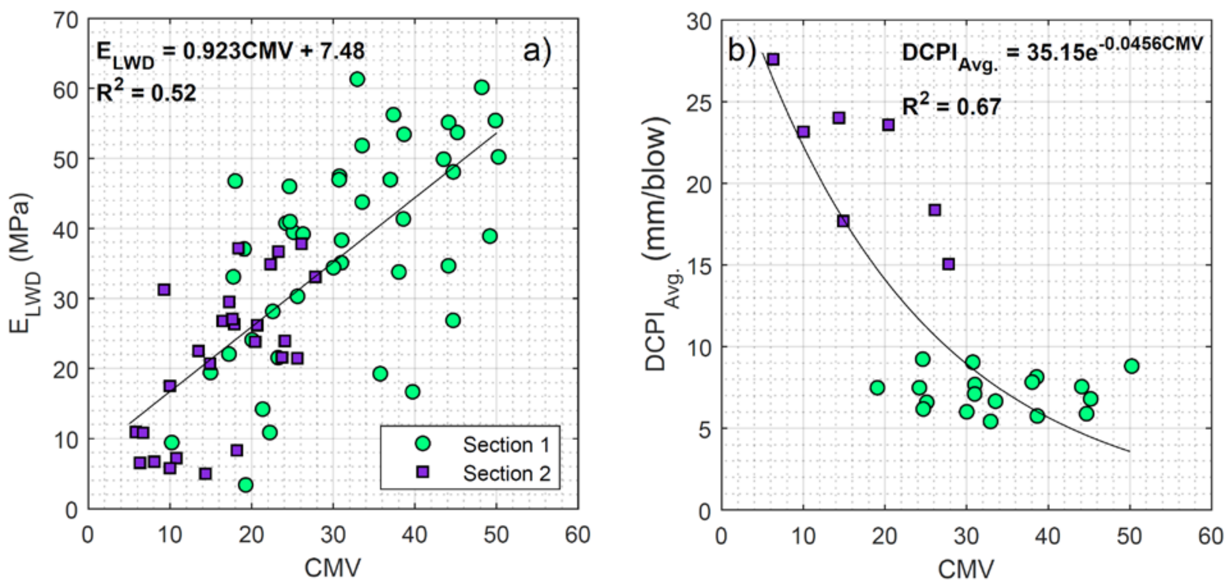

Figure 7. Univariate Regression Analysis for Sections 1 and 2: (a) CMV and E_{LWD} results, and (b) CMV and $DCPI_{Avg}$ results.

To help provide context to the significance of these findings, during the construction of Section 2 an inspector requested a proof roll be conducted utilizing a dump truck, as shown in Figure 8. During the proof roll operation the inspector noticed a significant amount of wheel deflection beneath the dump truck; an excavator was then used to undercut an area within Section 2. During the undercutting process a grey clay-like material was found approximately 25-30 cm below grade, which is illustrated in Figure 9. This finding is consistent with the DCP Index results shown in Figure 6d where at approximately 250 mm the average DCP Index begins to increase with depth which typically indicates the presence of a softer material. This finding also supports why LWD measurements were lower along Section 2, as LWD measurements utilizing a plate diameter of 30 cm typically have a depth of influence of approximately 30 cm (Mooney and Miller 2009). Therefore, given that the presence of the underlying clay material was within the LWD's depth of influence, the strength characteristics of the clay material influenced the LWD measurements along Section 2. To confirm that they grey clay-like material was indeed clay, samples of both the subgrade and underlying material were taken back to the laboratory to determine each soil's USCS Classification; tests conducted for this purpose included a No. 200 wash (ASTM D1140-17), sieve analysis (ASTM D6913-17), hydrometer analysis (ASTM D7928-17), and Atterberg limits (ASTM D4318-17). The subgrade material had approximately 15-20% fines that were non plastic in nature, and it was generally classified as a silty sand (SM). The underlying softer material had approximately 80% fines, with a liquid limit of approximately 25% and a plasticity index of 7.5%, which indicated that it was a low plasticity clay (CL).

Figure 8. Inspector conducting a proof roll along Section 2.

Figure 9. Undercutting of Section 2 revealing an underlying clay material.

A similar situation occurred where CMV and MDP data were collected and exhibited similar behavior compared to LWD and DCP data. A third section (e.g. Section 3) was examined during the compaction of a single lift of subgrade material placed near Strawberry Lane Bridge located along U.S. 301, Section 3 in Middletown, DE. Figure 10 provides heat maps of both CMV and MDP data collected during the compaction process of Section 3. Figure 11 also show a zoomed in portion of the heat maps along the northern portion of Section 3. Both CMV and MDP show a distinct pattern where the CMV and MDP readings are much higher/lower respectively along the western portion of the embankment section compared to the eastern portion giving the indication that the western portion of the embankment is stiffer than the eastern portion. When examining the distribution of CMV and MDP readings the average CMV reading west of the center line was 53.7 with a standard deviation of 16.5. For MDP readings west of the center line, the average MDP value was 5.8 kJ/s with a standard deviation of 7.8 kJ/s. For CMV and MDP readings east of the center line, the average and standard deviation for CMV was 16.9 and 13.4 respectfully, along with average and standard deviation values for MDP of 11.6 kJ/s and 12.1 kJ/s, respectfully. Both of the CMV and MDP readings indicated that the soil stiffness along the western portion of Section 3 was greater than the eastern portion of Section 3. To confirm that the CMV and MDP results were valid, a 3x5 test grid was laid out, where the spacing between adjacent testing locations along the same row was approximately 10 ft and spacing between each row of testing locations was approximately 20 ft. A total of 15 LWD tests were conducted at each proposed test grid location, while 6 DCP tests were conducted in two 3 test columns with one column of test locations being located along the western portion of the test grid and the other test column being located along the eastern portion of the test grid.

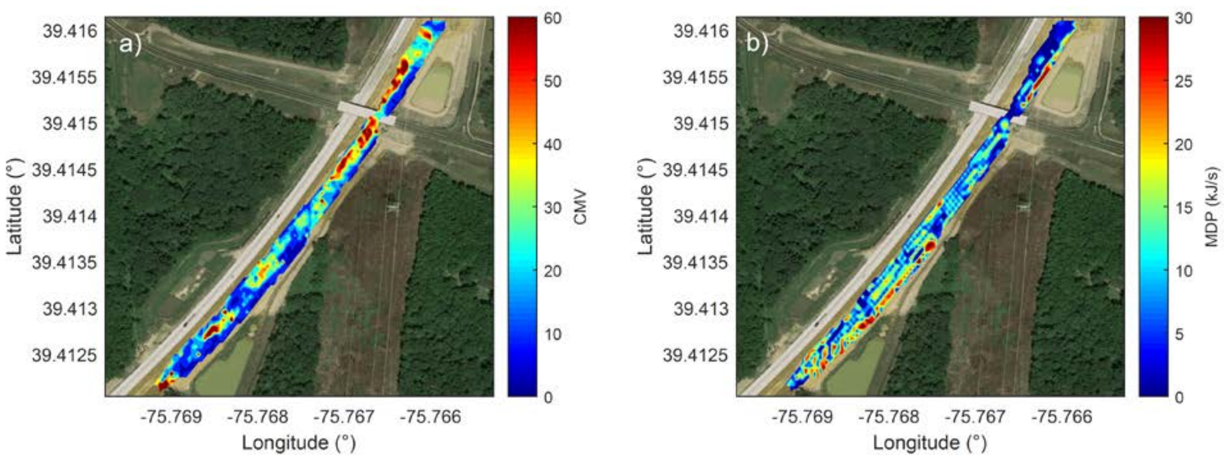

Figure 10. CMV and MDP measurements along Section 3: (a) CMV heatmap and, (b) MDP heatmap.

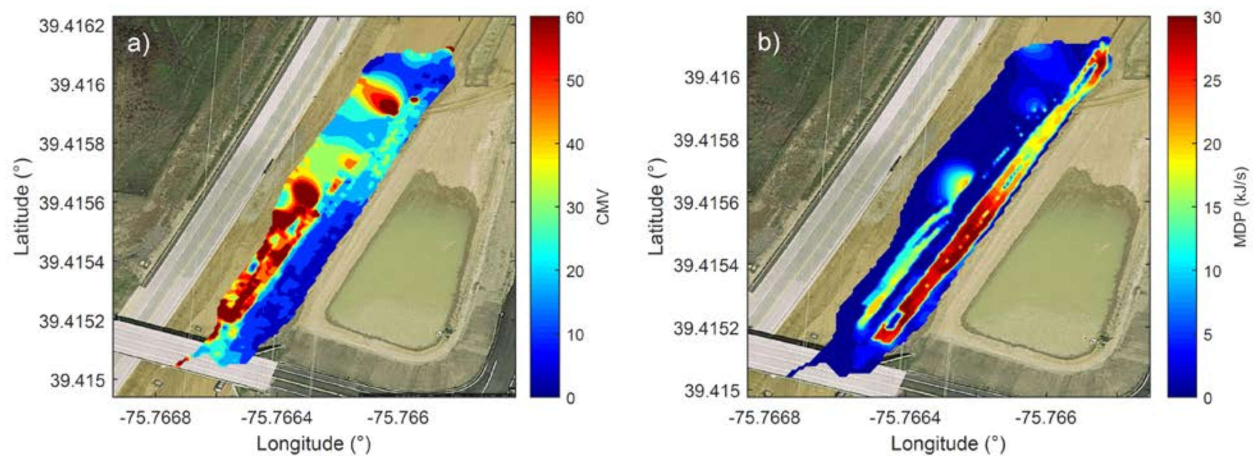

Figure 11. CMV and MDP measurements along the northern portion of Section 3: (a) CMV heatmap and, (b) MDP heatmap.

Figure 12 provides the in situ testing locations and results from Section 3. For the LWD tests, the average E_{LWD} calculated was 38.8 MPa with a standard deviation of 44.0 MPa. However, given the significant variation in apparent soil stiffness along the embankment's centerline as shown in the CMV and MDP heat maps in Figure 11, a heat map of LWD readings for Section 3 is more appropriate. As shown in Figure 12b, the western portion of the LWD heat map is significantly higher than the eastern portion, which is consistent with the results presented in Figure 11 for both the CMV and MDP heat maps. Based on the results provided by the LWD heat map, when examining the E_{LWD} values along the two most western columns of in situ test locations the average E_{LWD} calculated was 87.4 MPa with the range of values varying from 51.7 MPa to 110.3 MPa. Along the eastern portion of Section 3 the average E_{LWD} calculated along the two easternmost columns of in situ test locations was 4.1 MPa with the range of values varying from 3.7 MPa to 4.7 MPa. Figure 12c presents the DCP results along Section 3. Given that 3 DCP tests were taken along each associated testing column, the solid line in Figure 12c indicates the average DCP Index with depth while the shaded regions indicated the max-min DCP Index envelope. The same interpolation procedure that was utilized to present the DCP results from Sections 1 and 2 was also utilized for Section 3. Similar to the results presented for Sections 1 and 2, the DCP results along the western portion indicate that the penetration index was relatively consistent with depth with values ranging from 2-18 mm/blow with an average DCP index of 8.9 mm/blow with depth. The DCP results along the eastern portion of the test grid indicate similar behavior was observed for the DCP results along Section 2. From a depth of approximately 250 mm to 500 mm the DCP Index increasing with depth indicated a softer material within this zone. For the eastern portion of the test grid DCP index values ranged from 5.6-56.7 mm/blow with an average DCP index of 26.9 mm/blow with depth. Though Section 3 did not receive an independent proof roll or undergo any undercutting procedure, based on the results from Section 2, the data presented in Section 3 suggests that an underlying soft soil was present beneath a portion of Section 3. It should be emphasized that data collected during this study was utilized for research purposes only, therefore interpretation of the data was not utilized by the contractor to make field QA/QC decisions. These findings highlight the benefit of utilizing CCC for future earthwork projects, which can provide contractors another tool in their toolbox to help make better real time decisions regarding the quality of the subgrade during earthwork construction.

Figure 13 provides the results from a univariate regression analysis comparing the relationship between CMV or MDP readings and LWD or DCP measurements. When examining the CMV results, similar trends were observed as those that are presented in Figure 7 (the results from Sections 1 and 2), where a higher CMV generally indicated a higher E_{LWD} measurement and a lower average DCP Index. The opposite trend was observed with the MDP values, where a lower MDP generally indicated a higher E_{LWD} measurement and a lower average DCP Index; this intuitively make sense, given the theory behind MDP where less machine power is required to overcome rolling resistance when working with a well-compacted soil. For the relationships between MDP and E_{LWD} and CMV and average DCP Index, an exponential model was fitted to the data while the relationships between CMV and E_{LWD} and MDP and average DCP Index were fitted utilizing a linear model. R^2 values for the models developed ranged from 0.41-0.97. However, these R^2 value should be utilized with caution due to the relatively limited number of data points that were available to develop these models (e.g., 15 LWD tests and 6 DCP tests).

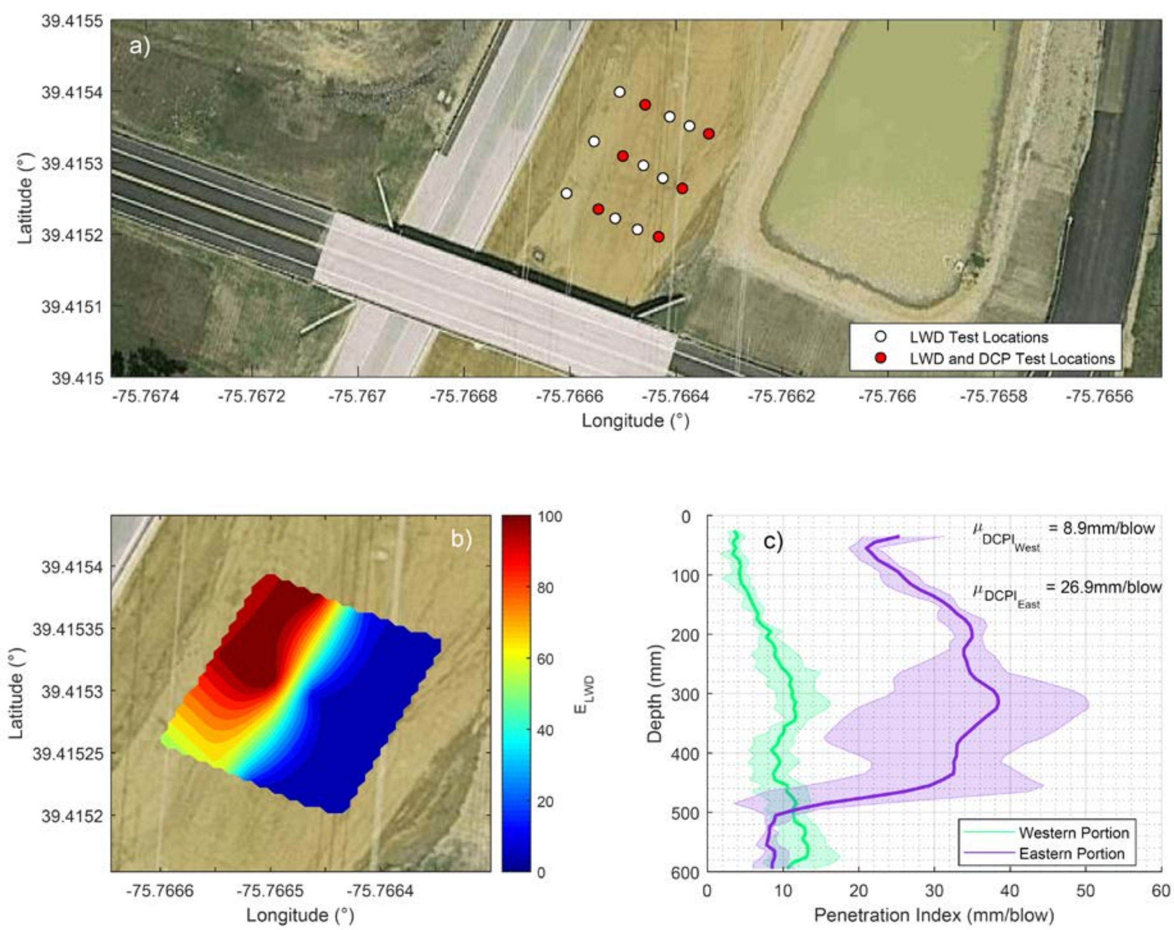

Figure 12. In situ testing location and results along northern portion of Section 3: (a) in situ testing grid layout, (b) LWD heatmap results, and (c) DCP Index Distribution with depth.

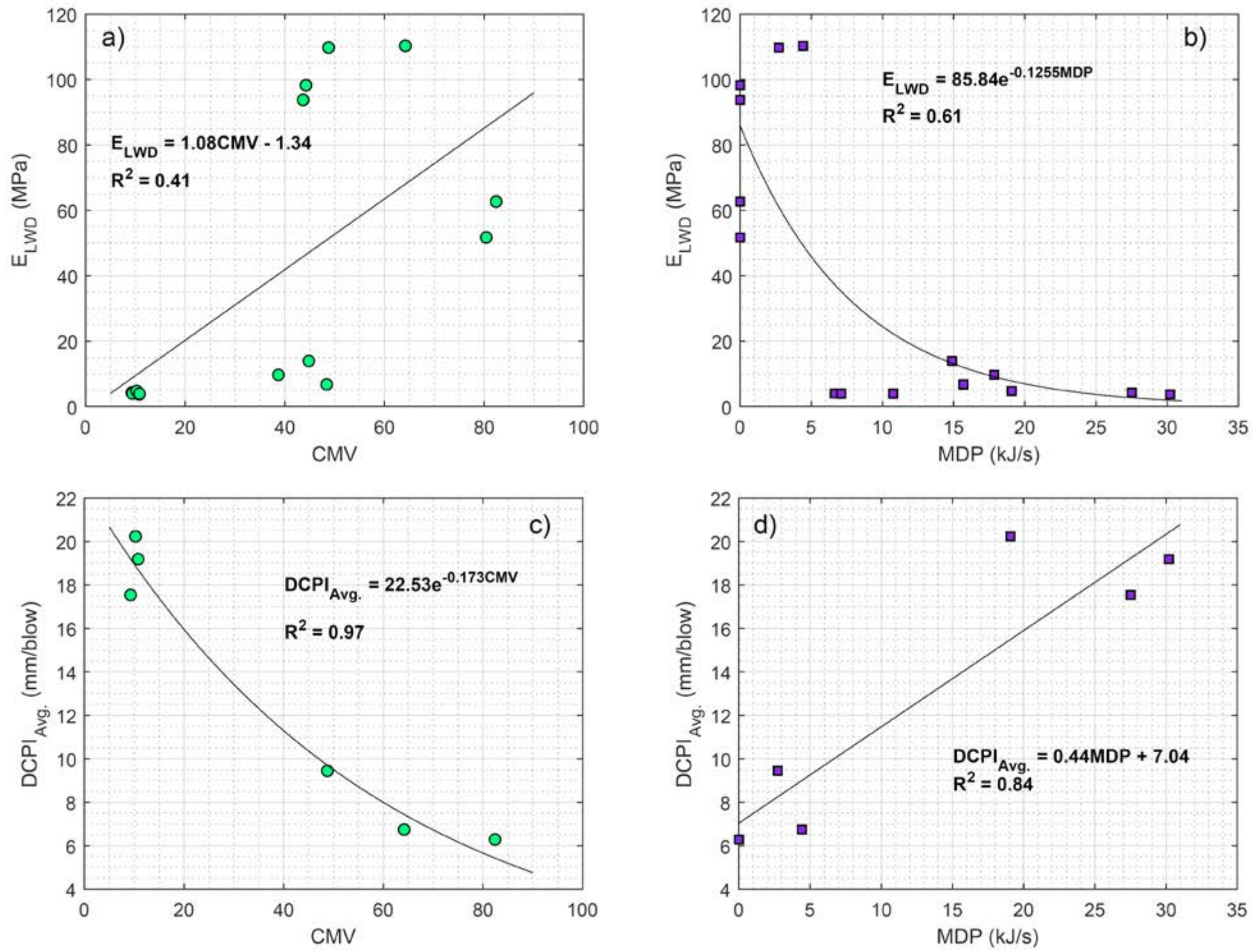

Figure 13. Univariate Regression Analysis for Section 3: (a) CMV and E_{LWD} results, (b) MDP and E_{LWD} results, (c) CMV and $DCPI_{Avg}$ results, and (d) MDP and $DCPI_{Avg}$ results.

In summary, the results from Sections 1-3 indicate that the CCC measurements CMV and MDP were able to identify soft underlying material that was also identified utilizing location specific in situ tests such as LWD and DCP testing. These findings are consistent with the findings from Pristrol et al. (2016) who used field demonstrations where two mattresses were buried approximately 1.5 feet below a gravel pit to simulate uncompacted, weak spots. Their study concluded that CMV measurements were able to identify these underlying soft zones. CMV and MDP measurements also generally followed the same trends as LWD and DCP tests collected along the same embankment sections, providing support for the idea that implementing CCC technology as part as the QA/QC protocol for earthwork construction can provide useful information to all parties involved during the construction process.

Sensitivity to Changes in Material Stiffness

The previous section concluded that CCC measurements such as CMV were able to identify an underlying clay material during the active construction of an embankment. This observation was validated by the undercutting and backfilling work that was performed in Section 2. Along with backfilling Section 2 with subgrade material, 3/4 inch "crusher run" aggregate was also placed and compacted. Both CMV and LWD data was collected during this process. Figure 14 provides the results comparing the CMV readings prior to Section 2 being undercut due to underlying soft clay material and after aggregate was placed and compacted along the section. Figures 14a and 14b show that the corresponding CMV values increased along the majority of the section due to the placement of the aggregate material, which was expected. Figures 14c and 14d also show the change in CMV distributions between these two different subsurface soil conditions, which yielded an increase in average CMV from 13.3 to 35.9. Figure 15 provides the relative change in CMV readings along Section 2 during this construction sequence. The results indicate that the majority of Section 2 did experience an increase in CMV and that on average CMV readings increased by approximately 200% after the placement of aggregate along Section 2. Sixty (60) LWD measurements were taken after the compaction of the aggregate material was completed. Figure 16 provides the results comparing the 26 LWD measurements taken prior to the undercutting of Section 2 to the 60 LWD measurements taken after the compaction of the aggregate material. Similar to the CMV results, the average LWD measurement increased from 21.5 MPa to 53.2 MPa.

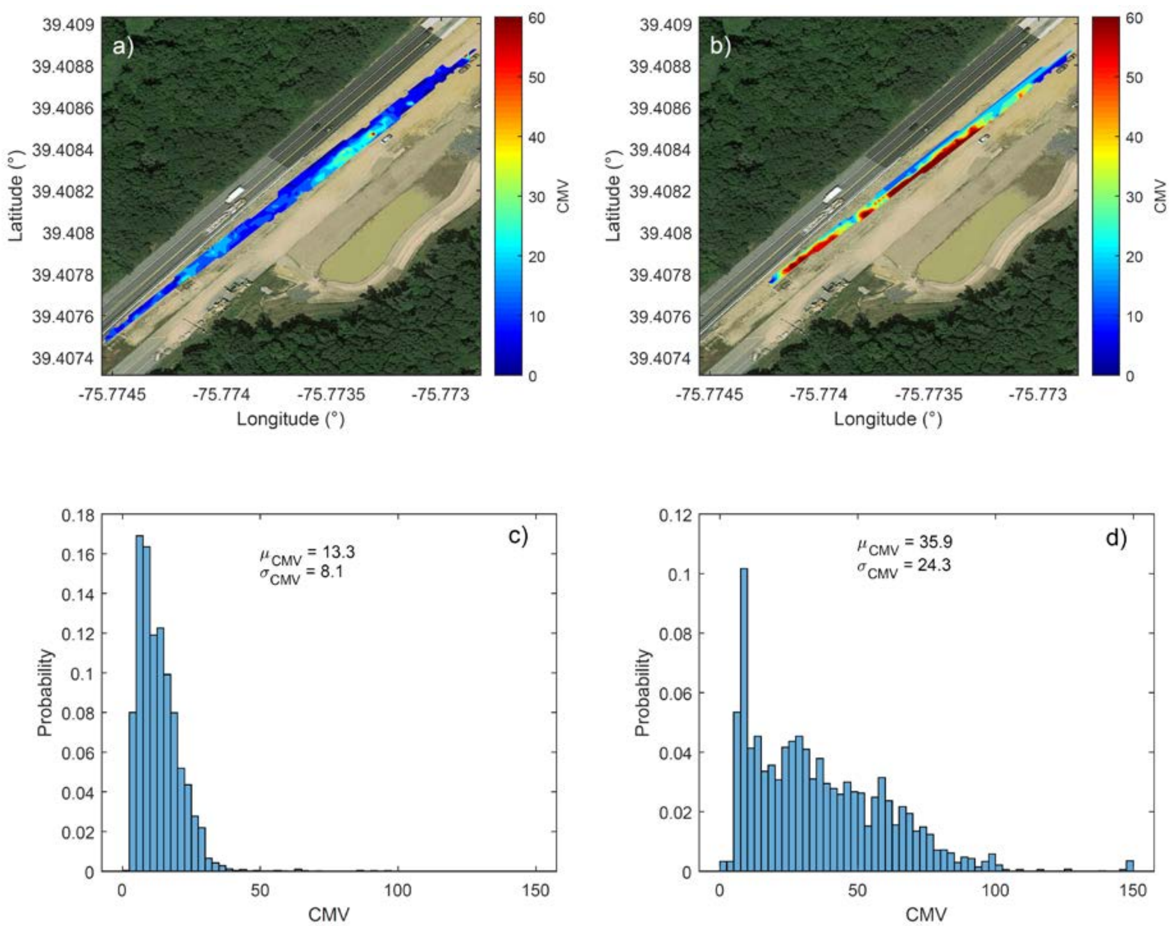

Figure 14. Variation in CMV measurements along Section 2 during construction: (a) CMV heatmap prior to undercutting, (b) CMV heatmap after placement of aggregate, (c) CMV distribution prior to undercutting, and (d) CMV distribution after placement of aggregate.

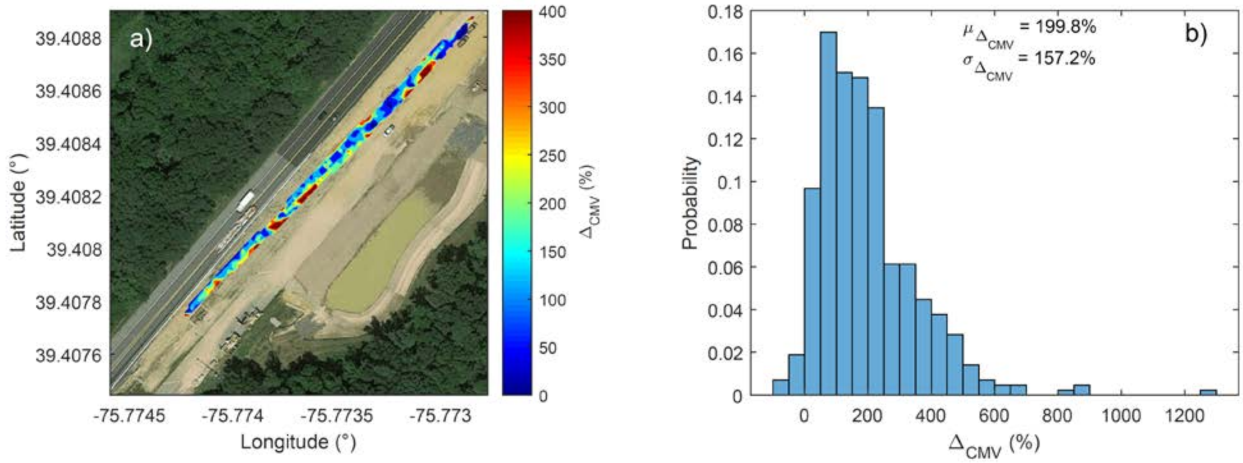

Figure 15. Change in CMV measurements along Section 2 during construction: (a) heatmap of change of CMV values, and (b) distribution of change in CMV values.

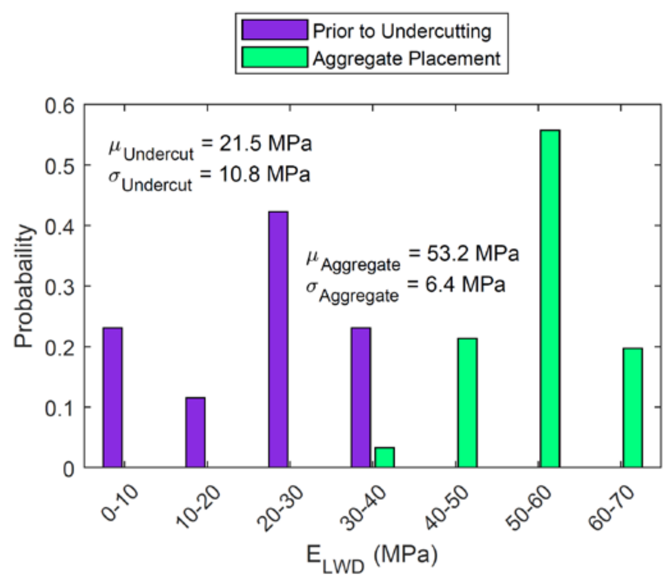

Figure 16. LWD measurement results prior to undercutting and after placement of aggregate along Section 2.

For illustrative purposes, the placement and compaction of the aggregate along Section 2 are presented in Figures 17 and 18, respectfully.

Figure 17. Placement of aggregate stone along Section 2.

Figure 18. Compaction of aggregate stone along Section 2.

Challenges

During this study a limited amount of MDP data was collected during the compaction process. After 3 months of communication with the manufacturer, the manufacturer realized that the compaction roller had to be operating in 'low' gear in order to collect both CMV and MDP data. For the majority of the days prior to this realization, the compaction roller was operating in 'high' gear, consequently little MDP data was collected during this period.

Another challenge during this study was the effect of machine parameters on CMV readings. Figure 19 provides results comparing CMV and RMV readings from the same embankment section during active construction. For this given embankment section the operator operated in both 'low' and 'high' amplitude vibrations (e.g. 0.97 mm and 2.1 mm). When examining the CMV and RMV results for 'low' amplitude vibrations there is no apparent relationship between CMV and RMV. The majority of RMV values range from 0-10 with an average of value of 1.16. For 'low' amplitude vibrations CMV values ranged from 0.1 to 134.7 with an average CMV reading of 35.5. The results for 'high' amplitude vibrations (e.g. Figure 19b) reveal that CMV has a linear dependence for RMV values ranging from 5-45. The range in RMV values increased with the minimum RMV value being 0 and the maximum RMV value being 48.9 with the average RMV value increase to 3.87 along with the average CMV reading also increasing to 47.8. The results here illustrated the importance of keeping machine parameters consistent during the CCC measurement process during active construction. Due to increasing the vibratory amplitude of the compaction roller, both the operation behavior of the compaction roller became more 'chaotic', (e.g. increase in RMV readings) along with CMV readings increasing for the same subgrade material compacted along the same embankment section. Therefore machine parameters such as vibratory amplitude can influence the interpretation on how stiff the soil is upon completion of the compaction process which can influence the inspector's decision making during the QA/QC process. For the CCC data presented along Sections 1-3, the operator was operating in 'low' amplitude vibration.

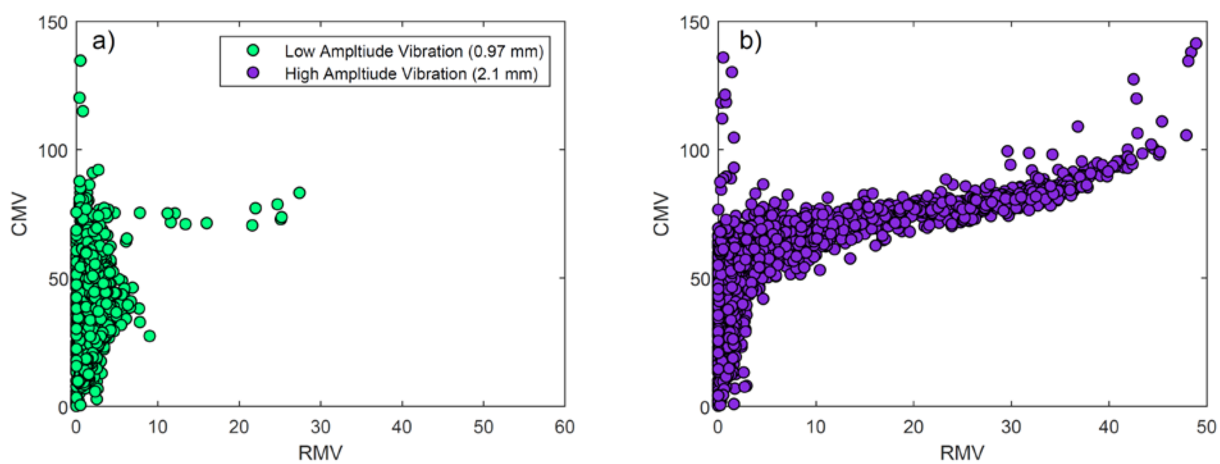

Figure 19. Variation of RMV and CMV measurements due to operating parameters: (a) CMV and RMV results for low amplitude vibrations, and (b) CMV and RMV results for high amplitude vibrations.

The final challenge with interpreting CCC measurements such as CMV is to consider the 'depth of influence' that are associated with these measurements. Based on experimental studies Rinehart and Mooney (2009) indicated that vibratory CCC measurements have a depth of influence of approximately 1 m (≈3 ft). Therefore, a given vibratory CCC measurement represents a composite soil stiffness for multiple layers of soil that may correspond to a varying stratigraphy.

Traditional earthwork construction practices and QA/QC protocols utilize placing, compacting and testing a given lift of soil that is usually placed in 8-12 inch loose lifts. Therefore, the interpretation of CCC measurements by themselves may be difficult to use for QA/QC protocol given that the depth of influence is greater compared to what is required for traditional testing. This depth of influence issue is also one of the reasons why fair to poor R^2 values were determined when comparing CMV to LWD and DCP measurements. For example, the LWD with a 30 cm plate diameter in particular has a depth of influence of approximately 30 cm. Therefore a given CMV reading and a given LWD measurement at the same spatial location will be influenced by a different volume of soil, which affects the relationship between the two measurements. Ultimately when examining CCC measurements on their own, this depth of influence phenomena needs to be accounted for when interpreting results.

Conclusions

The Delaware Department of Transportation has recently acquired a Continuous Compaction Control system that was utilized during active construction on U.S. 301, Section 3 in Middletown, DE. During this study the following conclusions were made:

1. When utilizing CCC during active construction, nearly 100% spatial coverage of compaction effort data was obtained for a site that was 3 miles long. This provides an abundance of information to both the contractor and inspector regarding the quality of the compaction process compared to traditional spot testing techniques.

2. When comparing the CMV, LWD, and DCP data collected along Section 1 and Section 2 CMV readings were generally higher along Section 1 with an average CMV of 35.5 while Section 2 had an average CMV of 13.3. LWD and DCP measurements generally indicated the same trend where the average E_{LWD} measurement was 41.1 MPa and the average DCP Index with depth was 9.4 mm/blow along Section 1. Along Section 2 the average E_{LWD} measurement was 21.5 MPa and the average DCP Index with depth was 23.3 mm/blow indicating that the soil was stiffer along Section 1 compared to Section 2. Ultimately the reason for this was due to an underlying clay material that was present along Section 2. This was discovered through an independent proof roll and undercutting procedure conducted by the inspector and contractor. Therefore, CCC has the potential be utilized as a proof rolling tool to help make real time decisions regarding the condition of the subgrade during the compaction process, instead of a traditional proof roll assessment with a heavily loaded truck, which tends to delay further site compaction activities.

3. Similar behavior was observed along Section 3 where both CMV and MDP readings were able to identify a drastic change in soil stiffness that varied transversely along the embankment. Along the western portion of the embankment the average CMV, MDP, E_{LWD}, and $DCPI_{Avg}$ were 53.7, 5.8 kJ/s, 87.4 MPa, and 8.9 mm/blow, respectfully. Along the eastern portion of the embankment the average CMV, MDP, E_{LWD}, and $DCPI_{Avg}$ were 16.9, 11.6 kJ/s, 4.1 MPa and 26.9 mm/blow, respectfully. The results from Section 3 further support the results from Section 1 and 2 indicating that CCC measurements such as CMV

and MDP are able to distinguish between soft and stiff soil conditions during the compaction process and provide the same general indications about behavior when compared to traditional in situ testing such as LWD and DCP.

4. Upon completion of the undercutting process along Section 2, aggregate stone was placed above the subgrade material. During the compaction process, CMV readings generally increased by 200% indicating that CMV was sensitive to changes in material stiffness.

5. When comparing CMV and MDP readings to LWD and DCP measurements on a 'point-by-point' basis, generally trends were observed where a higher CMV reading would indicate a higher E_{LWD} and lower $DCPI_{Avg}$ measurement, and a lower MDP reading would indicate a higher E_{LWD} and lower $DCPI_{Avg}$ measurement. However, the majority of the R^2 values ranged from 0.41 to 0.67, indicating significant scatter between the CCC measurements and in situ measurements. One of the contributions to these fair to poor correlations is the difference in the volume of soil that is tested for each of the different tests. Previous research has shown that CCC measurements have a depth of influence of approximately 1 m (≈3 ft) while traditional in situ testing devices such as the LWD have a depth of influence of approximately 0.3 m (≈1 ft).

Overall, the results from this study illustrate that CCC technology can be an effective tool for use during earthwork construction by providing contractors, inspectors, and state agencies with more real-time information regarding the compaction process.

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