Two Non-Destructive Approaches for Assessment of Field Lift Thickness

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ABSTRACT

The placement of soil at a prescribed lift thickness during earthwork construction plays a critical role for ensuring the effectiveness of subsequent soil compaction. A majority of earthwork construction specifications consequently mandate that soils be placed and spread to a "not to exceed" target lift thickness. This approach is common for both "method-based" and "end-product-based" specification frameworks for soil compaction. To date, little research has been performed to assess the viability and relative accuracy of emerging tools that can be used to monitor soil lift thickness, either prior to or post-compaction. In the current study, two innovative pieces of survey equipment were examined: the MIT SCAN T3 nondestructive thickness scanner and a compaction roller mounted with a continuous compaction control (CCC) kit with real-time kinematic global positioning system (RTK-GPS) measurement capabilities. A compacted soil test pad was constructed, which had 82 pre-determined locations that were surveyed to measure the post-compaction lift thickness for a given compacted soil layer. Lift thickness measurements made by the MIT SCAN T3 and RTK-GPS measurements from the compaction roller were compared against physical lift thickness measurements made utilizing a caliper and steel ruler. Lift thickness measurements along the embankment ranged from 10 cm to 70 cm, with the MIT SCAN T3 measurements having an average absolute error of less than 0.5 cm, and the RTK-GPS measurements made from the compaction roller having an average absolute error of less than 2.0 cm. The results from this study illustrate the relative accuracy that can be achieved for these two approaches for assessing compacted soil lift thickness.

INTRODUCTION

Soil compaction is a critical component of earthwork construction, and as such it plays a critical role in many projects. One important aspect of the soil compaction process, which helps to ensure that the soil is being effectively compacted, is ensuring that the soil is spread into a relatively thin, uniform "lift" prior to compaction. Typically, a maximum allowable lift thickness is specified, which helps to ensure that the energy propagated by the compaction device penetrates through the entire thickness of the lift of soil that is placed.

Specification of a maximum allowable lift thickness helps to ensure that the entire lift of soil that is placed becomes compacted in a uniform fashion with respect to depth. If a given lift of soil is placed too thick, the energy induced by the compaction device during the compaction process may not penetrate through the entire lift of soil with respect to depth, causing a portion of the lift of soil to not densify sufficiently. This can lead to problems in the future, as undercompacted soil is prone to deformation problems, which causes serviceability issues for structures that bear on these soils (e.g., a pavement system experiencing premature rutting). Therefore, it is critical that during the earthwork construction phase that soil be placed in lifts adhering to the project specifications (e.g., DelDOT 2016) to ensure that the structure bearing on the embankment will adequately perform to its design specifications. On the other hand, if a given lift of soil is placed too thin, the contractor is not maximizing their productivity, ultimately adding costs to their operations and additional (unnecessary) wear and tear on their compaction equipment. Placement of soil lifts as closely to the desired lift thickness as possible is therefore beneficial to both owners and contractors.

Unfortunately, it can be extremely difficult for inspectors and field engineers to monitor the lift thickness of soil during earthwork construction without continuous surveying, which adds additional costs and delays to the project. One alternative approach that shows promise is the use of Continuous Compaction Control (CCC) technology for the monitoring of lift thickness during compaction (Meehan et al. 2013). For the past 40 years, CCC and Intelligent Compaction (IC) technologies have been developed and utilized to provide real-time monitoring of the compaction process by instrumenting compaction rollers with an accelerometer, Real-Time Kinematic Global Positioning System (RTK-GPS) receiver, and an on board computer (e.g., Thurner and Sandstrom 1980, Adam 1997, Anderegg and Kaufmann 2004). This technology allows for near continuous assessment of the compaction process by providing roller measured indicator values along with spatial location and elevation measurements in real time, allowing for nearly 100% coverage of the evaluation area during the compaction process (e.g., Mooney et al. 2010). The majority of studies conducted involving CCC/IC technology have focused their efforts on understanding dynamic roller drum-soil interaction (e.g. van Susante and Mooney 2008, Facas et al. 2010), understanding the relationship between CCC/IC roller measured indicator values and traditional in situ devices (e.g., White and Thompson 2008, Meehan et al. 2017, Cai et al. 2017) or developing and assessing the quality assurance/quality control (QA/QC) frameworks that allow for best utilization of this technology in practice (e.g. Mooney et al. 2010, Facas et al. 2011, Cacciola et al. 2013).

To date, little research has been performed evaluating the accuracy and implementation of CCC/IC technology for lift thickness control during active earthwork construction. Meehan et al. (2013) first proposed the idea of utilizing the spatial coordinate information (e.g., Northing, Easting, and Elevation) to develop spatial maps of lift thickness. For that project, a test pad was constructed comprising 5 lifts of soil that were placed and compacted using a Caterpillar CS56B compaction roller instrumented with a CCC system. Meehan et al. (2013) compared the lift thickness measurements of each lift by utilizing two spatial interpolation techniques to develop consistent projection grids, inverse-distance weighting (IDW) and isotropic kriging (Isaaks and Srviastava 1989). The authors concluded that the use of a simpler interpolation approach such as IDW yielded results that were consistent with the results that were obtained from isotropic kriging. Ultimately, Meehan et al. (2013) proposed a framework for developing spatial maps of lift thickness from the spatial information provided by a CCC system along with geospatial interpolation techniques.

One drawback from the study conducted by Meehan et al. (2013) was that the lift thickness values determined from the CCC data were not compared against other survey measurement systems to assess the relative error in lift thickness determination that is inherent to this approach. To address this drawback, the current study focused on understanding the relative accuracy of lift thickness values determined from data obtained using a CCC system attached to a smooth drum roller that performed soil compaction during normal earthwork operations. In this study, lift thickness measurements were determined from the recorded CCC data following the approach described in Meehan et al. (2013). In parallel, a second nondestructive approach to lift thickness assessment was also explored, using the MIT SCAN T3 thickness scanner (e.g., Grove et al. 2012). Though the MIT SCAN T3 does not collect continuous data during the compaction process, it has gained much attention in the pavement industry as an accurate tool for nondestructive determination of material thickness for asphalt, concrete, and soil (Grove et al. 2012). For this study, lift thickness measurements were made at pre-determined locations utilizing both CCC technology and the MIT SCAN T3, and these measurements were validated using physical lift thickness measurements made with a caliper and steel ruler.

PROJECT DESCRIPTION

Test Pad Construction

This study took place during construction of U.S. 301, Section 3 in Middletown, DE. For this study, a test pad was constructed along a stockpile at the project site. The test pad was approximately 38.4 m long and approximately 18.5 m wide; within the test pad, two 18.4 m x 18.4 m grids were constructed with a 1.6 m space between the two grids. Within each grid 41 steel reflectors, with a nominal diameter of 30 cm, and a nominal thickness of 0.65 mm, were placed in a gridded pattern. These steel reflectors are utilized by the MIT SCAN T3 for lift thickness determination (a complete description of the methodology behind the MIT SCAN T3 will be explained in a subsequent section). The layout of the steel reflectors for each grid results in 9 columns with a nominal spacing of 2.3 m between each column. Odd numbered columns (e.g. columns 1, 3, 5, 7, and 9) had 5 steel reflectors with a nominal spacing of 4.6 m. Even numbered columns (e.g. columns 2, 4, 6, and 8) had 4 steel reflectors with a nominal spacing of 4.6 m. The spacing between adjacent steel reflectors between even and odd numbered columns was a 2.3 m offset both vertically and horizontally. Figure 1 shows the layout of the steel reflectors for each of the two test grids. For this study, the following construction sequence was used to obtain lift thickness measurements with a Caterpillar CS56B smooth drum compaction roller equipped with an aftermarket CCC kit and a MIT SCAN T3 lift thickness scanner:

1. The foundation of the test pad received a static proof roll from the compaction roller that consisted of the entire test pad receiving two static passes. During the proof roll of the base layer, positional and elevation data was collected utilizing the RTK-GPS receiver mounted on the roller. It should be noted that the compaction roller operated at an average speed of 6.1 km/h during the proof roll operation.
2. Upon completion of the proof roll, the coordinates of each steel reflector were staked out utilizing a Trimble SPS985 RTK-GPS rover with a Trimble TSC3 data logger. The global coordinates of each steel reflector were already uploaded in the data logger prior to staking out each location. It should be noted that the global coordinates (e.g. Northing and Easting) of the steel reflectors were transformed from their local coordinate system by utilizing the procedure outlined in Meehan et al. (2013).
3. At each staked out location the steel reflectors were secured to the foundation of the test pad by driving three 9 cm nails through them.
4. Once the steel reflectors were secured, Delaware Department of Transportation (DelDOT) survey personnel collected positional readings at each location utilizing a Lecia TS16 Total Station base station and receiver system.
5. After completion of laying out and securing the steel reflectors for both grids along the test pad, a lift of soil was placed on top of the foundation of the test pad. The northern grid received an approximate 0.33 m (12 in) loose lift and the southern grid received an approximate 0.22 m (8 in) loose lift. These two loose lift thicknesses were chosen as

these lift thicknesses are common for soil placement during active earthwork construction in the state of Delaware (DelDOT 2016). They were also chosen to illustrate measurement behavior over a range of lift thicknesses, in order to capture more generalized behavior of each measurement device utilized in this study.

6. Upon completion of the placement of fill along the test pad, the test pad received 4 low amplitude (e.g. 0.98 mm nominal amplitude) vibratory passes from the compaction roller. The test pad then received two static proof roll passes in order to collect positional and elevation data of the compacted lift from the compaction roller. During the proof roll, the compaction roller operated at an average speed of 5.8 km/h. It should be noted that the data from the final proof roll pass from both compaction operations were used for lift thickness determination purposes.
7. To collect lift thickness measurements utilizing the MIT SCAN T3, the location of each steel reflector was measured by DelDOT surveying personnel using their total station equipment. After total station surveying was completed, five measurements utilizing the MIT SCAN T3 were taken for lift thickness determination.
8. After the nondestructive measurements had been completed, a hole was dug down to the center of each reflector at each steel reflector location. Physical lift thickness measurements were then taken utilizing a 30 cm dial caliper with a tolerance of 0.025 mm for thinner lifts, or a 91 cm steel ruler with a tolerance of 1.6 mm for thicker lifts.

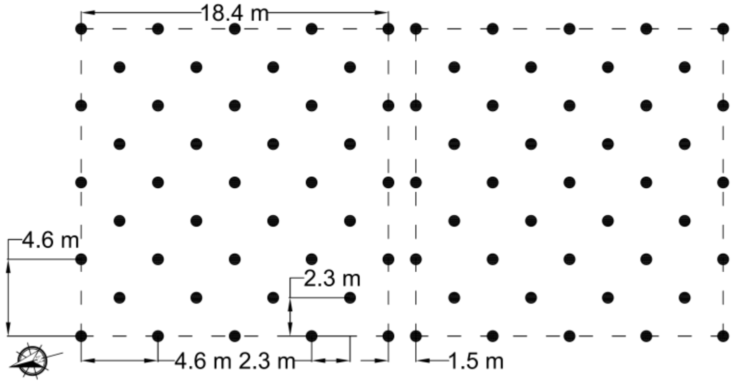

Figure 1. Nominal Steel Reflector Layout for Each Test Grid.

Device Operating Principles

The compaction roller utilized during this study was equipped with an aftermarket Trimble CCS900 Compaction Control System. One component of this system was a Trimble MS972 GPS receiver that had full Real-Time Kinematic (RTK) capabilities. RTK capabilities require a base station consisting of a GPS receiver placed at a known and fixed location on site. The base station tracks the same satellites that the GPS receiver on the compaction roller tracks, simultaneously. Errors in the positional readings that are monitored by the base station are corrected and are communicated via radio link to the GPS receiver to provide real time corrections on the compaction roller (Trimble 2003). These type of RTK adjustments allow more precise positional readings to be recorded by the compaction roller.

The MIT SCAN T3 utilizes pulse induction in order to determine the thickness between the sensors located on the measuring probe of the MIT SCAN T3 device and a given steel reflector that is buried beneath the material of interest at a pre-determined, discrete location; the reflectors used in the current study were circular discs, with a nominal diameter of 30 cm, and a nominal thickness of 0.65 mm. When conducting a test utilizing the MIT SCAN T3, the device generates a variant magnetic field creating an eddy current in the steel reflector. This eddy current induces a magnetic field in the steel reflector that is then measured by the sensors from the MIT SCAN T3. The intensity of the magnetic field that is measured from the MIT SCAN T3 is related to the distance between the MIT SCAN T3 and the steel reflector, allowing the MIT SCAN T3 to be utilized for nondestructive lift thickness determination of construction materials (e.g., Grove et al. 2012, AASHTO T359-16).

RESULTS

Physical lift thickness measurements utilizing a caliper or steel ruler indicated post-compaction lift thicknesses ranging from 11 cm to 66 cm. It should be noted that, prior to the placement of fill along the northern test grid (the proposed nominal 30 cm loose lift), a portion of the northern grid had a valley in its topography. This resulted in a portion of the northern grid receiving more than 30 cm of loose fill placed on top of it. This filling approach ensured that the resulting base along the width of the test pad was level after the placement of fill. Although perhaps not desirable in a production environment, this was beneficial to the current study as it yielded placement of a range of lift thicknesses, which allowed for better characterization of the relative accuracy of the CCC RTK GPS system and MIT SCAN T3 device for lift thickness determination.

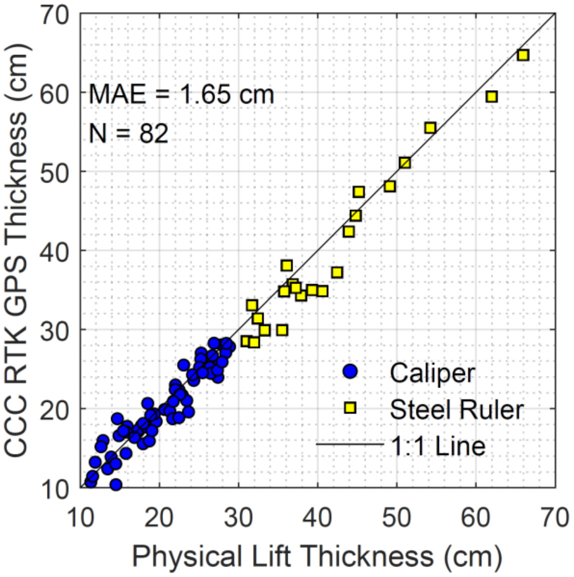

Figure 2. Lift Thickness Comparison between CCC RTK GPS Lift Thickness Measurements and Physical Lift Thickness Measurements.

CCC RTK GPS Results

Given that the elevation readings measured by the CCC RTK GPS are near continuous in nature, an interpolation technique was needed in order to estimate the elevation readings at the 82 predetermined steel reflector locations. For this study, Inverse Distance Weighting (IDW) interpolation was utilized. IDW is a deterministic, point estimation interpolation technique that utilizes the following equation to estimate unknown values at a specific location (Isaaks and Srivastava 1989).

$$\hat{v} = \sum_{i=1}^{n} \frac{\frac{1}{d_i^{p}} v_i}{\frac{1}{d_i^{p}}} \tag{1}$$

where $\hat{v}$ is the estimation point of interest, v_i is the ith sampled value used to estimate $\hat{v}$, d_i is the ith euclidean distance between the point of interest and the ith sampled value, and the exponent p is the power weighting function. Though simplistic in nature, IDW is a flexible interpolation technique that allows the end user to specify both the search radius d, and the exponent p in order to best estimate a given value at their point of interest from a known data set. In a general sense the search radius d enables the end user to control the number of sampled values that are used to estimate $\hat{v}$, while the power weighting function p controls the behavior of how sampled values within a neighborhood of search radius d are relatively weighed. Lower values of p tend to assign more equal value to sampled points, while higher values of p tend to weigh sampled points closer to the point of interest more heavily than points that are further away.

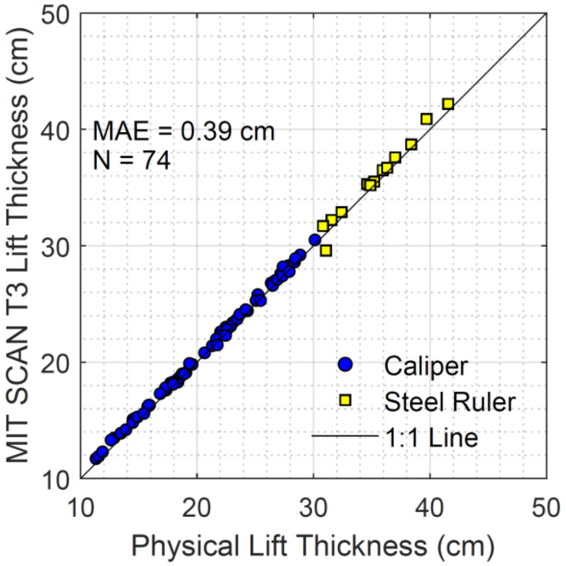

Figure 3. Lift Thickness Comparison between MIT SCAN T3 Lift Thickness Measurements and Physical Lift Thickness Measurements.

A search radius d and power weighting function p need to be assigned in order to determine the elevation readings at the 82 predetermined steel reflector locations. For the current study, a sensitivity analysis was conducted in order to determine the combination of d and p that resulted in the lowest error in thickness measurements produced by the CCC RTK-GPS receiver when compared to physical thickness measurements. To accomplish this task, a simple nested for loop was constructed in MATLAB where values of d ranged from 0 m to 5 m in 5 mm increments, and values of p ranged from 0 to 4 in .001 increments. For each unique combination of d and p, the elevation readings were estimated at the 82 predetermined steel reflector locations utilizing IDW; this analysis was performed on both sets of proof roll data collected from the compaction roller. The thickness was then determined by calculating the change in elevation between the two data sets. To determine the error between the calculated thicknesses utilizing IDW from the CCC RTK-GPS receiver and physical thickness measurements, the mean absolute error (MAE) was calculated for each unique combination of d and p. Based on the sensitivity analysis, the combination of *d* and *p* that resulted in the lowest MAE in lift thickness determination between the CCC RTK GPS receiver and physical lift thickness measurements was a *d* value of 1.75 m and a *p* value of 0.026.

Figure 2 compares lift thickness values determined using the CCC RTK GPS receiver and IDW interpolation approach (a *d* of 1.75 m and a *p* value of 0.026) with directly measured lift thickness values. The lift thickness measurements calculated ranged from 10.4 cm to 64.7 cm. The MAE calculated was 1.65 cm with the error between the two measurement devices ranging from -4.85 cm to 4.04 cm with the median error being -0.47 cm. From a statistical perspective, 43.4 % of the error values calculated ranged from ± 1 cm, 72.4 % of the error values calculated ranged from ± 2 cm, and 93.4 % of the error values calculated ranged from ± 3 cm.

Even though the MAE calculated between the CCC RTK GPS receiver and the physical lift thickness tools was 1.65 cm, the overall range in calculated error was greater than ± 4 cm. This relatively large range in error warrants the exploration of other more sophisticated interpolation techniques such as kriging for reducing the error associated with CCC RTK GPS predictions; this topic will be explored more in a future publication.

MIT SCAN T3 Results

The lift thickness measurements obtained utilizing the MIT SCAN T3 ranged from 11.7 cm to 42.2 cm. The MIT SCAN T3 was unable to measure lift thicknesses beyond a depth of 44 cm, due to limitations imposed by the operating principles of the device. It should be noted that the manufacturer indicates that the depth of influence of the MIT SCAN T3 is a function of the diameter of the reflector being utilized. For this study, the steel reflectors utilized were 30 cm in diameter (nominally), which indicates that the MIT SCAN T3's depth of influence should be 30 cm, based on the manufacturer's guidelines (MIT 2017). However the MIT SCAN T3 was able to measure lift thicknesses approximately 1.5 times the diameter of the steel reflector for this study. As previously noted, 5 measurements were taken with the MIT SCAN T3 at each of the 82 predetermined steel reflector locations. Table 1 provides summary statistics of the variation in measurements taken utilizing the MIT SCAN T3 at a given location.

Table 1. Summary Statistics of Sample Variation Utilizing the MIT SCAN T3

	5 Sample σ (mm)	5 Sample COV (%)	5 Sample Range (mm)
Minimum	0	0	0
Maximum	8	20	20
Mean	0.65	2.7	1.5
Median	0.55	2.5	1

Based on the results presented in Table 1, the measurement variation for the MIT SCAN T3 for a given location was significantly and consistently low when examining the mean and median values for both coefficient of variation (COV) and the range. It should be indicated that the location with a significantly high standard deviation, coefficient of variation, and range had a calculated averaged thickness of 40.9 cm. Therefore, this relatively large variation in thickness measurements at this location should be expected given that the measured averaged thickness is greater than the diameter of the steel reflector. Figure 3 presents the comparison in lift thickness determination between measurements utilizing the MIT SCAN T3 and physical lift thickness measurements. As shown in Figure 3, the lift thickness measurements made by the MIT SCAN T3 are nearly identical to the lift thickness measurements made utilizing the caliper or steel ruler.

The resulting MAE for the MIT SCAN T3 was 0.39 cm with the range of error varying from -1.47 cm to 1.19 cm, and with the median error being 0.36 cm. These results are consistent with the results presented in Grove et al. (2012), where the authors found that the MIT SCAN T2 (an earlier version of the MIT SCAN T3) was within 2 mm of physical concrete core thicknesses for a wide range of pavement thicknesses.

CONCLUSIONS

To date, the majority of the focus on CCC/IC equipment in the U.S. has been on understanding the dynamic behavior of these systems or developing stiffness-based QA/QC procedures for their use in the field. The ability to also monitor the lift thickness of a material during earthwork construction, both continuously and accurately, would augment the use of CCC/IC equipment and provide another benefit of this technology. This paper describes the results from a field study which was carried out examine the relative accuracy of lift thickness measurements made utilizing CCC technology and the MIT SCAN T3 relative to physical lift thickness measurements, for compacted soil lifts ranging from 11 cm to 66 cm. From this study, the following conclusions were drawn:

1. When utilizing IDW a search radius *d* of 1.75 m and power weighting function *p* value of 0.026 was found to be best combination of interpolation parameters, which produced a MAE of 1.65 cm when comparing lift thickness measurements between the CCC RTK-GPS receiver and direct measurements of lift thickness. The error between the CCC RTK-GPS receiver and physical lift thickness tools ranged from -4.85 cm to 4.04 cm, with the median error being -0.47 cm.
2. When utilizing the MIT SCAN T3 for lift thickness determination, the MAE calculated between the MIT SCAN T3 and the physical lift thickness tools was 0.39 cm. The error between the MIT SCAN T3 and physical lift thickness tools ranged from -1.47 cm to 1.19 cm, with the median error being 0.36 cm. When examining the sample variation between measurements at a given location, the average COV calculated was 2.7%, indicating that the variation between measurements at a given location utilizing the MIT SCAN T3 was low. However, the MIT SCAN T3 was unable to determine lift thicknesses beyond a depth of 44 cm. This was due to the fact that a 30 cm diameter steel reflector were used in this study, which dictated the depth of influence. It should also be noted that the MIT SCAN T3 can only obtain lift thickness measurements at pre-determined, discrete locations.

Overall, both technologies in an aggregate sense were able to produce MAE values of less than 2 cm. However, on a point by point basis, the use of IDW as the interpolation technique to determine lift thickness from the CCC RTK-GPS measurements had a range in error greater than ± 4 cm. This finding warrants the investigation of more sophisticated geospatial interpolation techniques in hopes of reducing the range of error produced by the CCC RTK-GPS receiver for lift thickness applications. The MIT SCAN T3 was found to be very accurate, with measured thicknesses being limited to the size of the reflector used; also of course, this device was only able to determine the lift thickness at discrete locations.

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