A Comparison of In-Place Unit Weight and Moisture Content Measurements Made Using Nuclear Based Methods and the Drive Cylinder Method

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Abstract

The determination of in-place unit weight and moisture content is a critical component of earthwork construction quality assurance and quality control (QA/QC). Direct measurement methods such as the drive cylinder test, sand cone test, or rubber balloon test can be utilized to determine a soil’s in-place unit weight and moisture content, and have a long history of use in geotechnical engineering. However, these direct measurement methods are destructive in nature and the tests are time consuming to conduct in the field. As a result, nuclear density gauge testing has emerged as the dominant approach for QA/QC of soil compaction in the United States, as this device allows for relatively nondestructive testing (only a small hole in needed to run the test), and quicker testing, which allows for better coverage of a compacted soil area in the field. Conventional nuclear density gauges utilize radioactive sources to determine a soil’s in-place unit weight and moisture content, which can be hazardous to the user and others nearby if proper safety protocols are not followed. A new density gauge has recently been developed (the “EGauge”), which uses the same general principles as the nuclear density gauge to measure in-place unit weight and moisture content of soils, with relatively low emission radioactive sources being utilized in the device compared to more traditional devices (allowing for safer testing). This paper describes the results from a study that was carried out to examine the relative differences between in situ unit weight and moisture content measurements made with a drive cylinder, nuclear density gauge, and E.Gauge. All testing was performed on an active project site, on soil areas that had been well compacted. After calibrating the E.Gauge for moisture content, it was observed that all three test approaches were generally in good agreement with one another for the wet and dry soil unit weight and the soil moisture content. The nuclear density gauge consistently underestimated moisture content and consequently overestimated dry unit weight values relative to the drive cylinder measurements. Overall, the EGauge measurements were in better agreement with measurements made by the drive cylinder than they were with the nuclear density gauge test results.

INTRODUCTION

During earthwork construction soils are subjected to compaction-induced densification to improve their overall strength and stability, and to reduce their compressibility under load (e.g., D’Appolonia et al. 1969). “End product” specifications are utilized to ensure soils in the field are sufficiently compacted to ensure adequate engineering performance (e.g., DelDOT 2001). In situ
Spot testing plays a critical part in any end product based approach for compaction control, with periodic post-compaction measurements of soil unit weight and moisture content being common for most soil compaction projects in the field (Meehan et al. 2012, Meehan and Hertz 2013).

In conventional practice, in situ measurements of soil unit weight and moisture content are made using test approaches such as the sand cone (ASTM D1556-15), the rubber balloon (ASTM D2167-15), or the drive cylinder (ASTM D2937-17) test. These methods attempt to provide a direct measurement of a compacted soil’s unit weight and moisture content from weight and volume measurements taken in the field. Other devices such as the nuclear density gauge infer a soil’s unit weight and moisture content by measuring the amount of radiation that passes between a radioactive source and receiver through an area of compacted soil, and then using these measured radiation counts with previously established calibration relationships (ASTM D6938-17). Several comparison studies have been conducted relating the results from direct measurement devices and the nuclear density gauge. Kaderabek and Ferris (1979) made unit weight comparisons using a sand cone, drive cylinder and a nuclear density gauge on two types of sandy soils (SM and SM-SW). The authors found that the moisture content measured from the nuclear density gauge was consistently higher compared to the oven moisture contents. They also found that the nuclear density gauge measured a lower moist unit weight compared to the moist unit weight measured by the sand cone, resulting in the sand cone yielding 5% higher compaction when compared to the nuclear density gauge. For this study, drive cylinder testing was used on a limited basis since the sandy soils did not hold well in the drive cylinder, which resulted in consistently lower unit weight values relative to the sand cone. Noorany et al. (2000) performed a similar study comparing the sand cone, drive cylinder and the nuclear density gauge for tests conducted on a clayey sand (SC). In this study, the authors found that the sand cone was the most accurate. The nuclear density gauge for this study had a wide range of variability with a significant error. Inaccurate moisture content readings were made by the nuclear density gauge when compared to the oven dried moisture contents. The drive cylinder readings for this study were also consistently low; however, in this study a smaller (3 inch diameter) cylinder was used, which tended to yield gravel-induced voids along the wall of the cylinder during driving, producing lower unit weight readings.

Nuclear-based testing devices (e.g., ASTM D6938-17, AASHTO T238-97) are currently the most commonly used tool in the United States for measuring in situ soil unit weight and moisture content; this is not surprising, given that the tests are relatively nondestructive in nature and tests can be conducted relatively quickly (Berney and Kyzar 2012, Meehan et al. 2012). However, these devices have numerous “logistical” issues which stem from the presence of a radioactive emission source in the device (Meehan and Hertz 2013). There are numerous procedures that must be followed surrounding the transportation, handling, use and storage of the device to ensure both personnel and the public are protected from the radioactive material. There are also strict regulations and reporting requirements regarding how the device must be used, stored, and transported, which are overseen by the Nuclear Regulatory Commission.

In response to these issues, a new density gauge, the EGauge, has recently been developed (Troxler 2016). This density gauge uses the same principal measurement methodology as a traditional nuclear density gauge, but with nuclear sources that have a much lower level of radioactivity. This device is consequently safer to use in the field, with fewer requirements for safety training of field personnel, and without the complexities of NRC reporting requirements. The object of this paper is to compare in situ unit weight and moisture content measurements taken from a Drive Cylinder, a traditional Nuclear Density Gauge and the EGauge on an active
project site. This data allows for comparison of the relative differences between direct in situ measurements and inferred in situ measurements for QA/QC of soil compaction.

DEVICE METHODOLOGY

The Drive Cylinder testing conducted in this study was performed in accordance with ASTM D2937-17. The testing apparatus utilized 9.7 cm (3 7/8-in.) inner diameter molds that were 12.7 cm (5-in.) in height. All Drive Cylinders used in this study had an average volume of 956 cm³. The drive hammer in this study had a sliding weight of 4.5 kg (10 lbs.) and field personnel used a target drop height of 88.5 cm (3 ft). To obtain a sample, the drive hammer apparatus was connected to the top of the Drive Cylinder mold. The driving of the cylinder was performed by raising the drop hammer and allowing it to free fall. This procedure is repeated until the top of the Drive Cylinder mold was approximately 13 mm (0.5 in) below the original ground service. Extreme care was then used to carefully undercut around the Drive Cylinder mold to obtain a representative sample. Once a sample was obtained, the sample was then weighed to obtain its moist unit weight (the volume of the mold is known). A portion of the drive cylinder sample was then weighed, oven dried, and weighed again for moisture content determination; this calculated moisture content was then used to determine the sample’s dry unit weight.

The Nuclear Density Gauge testing conducted in this study was performed in accordance with ASTM D6938-17. The Nuclear Density Gauge uses gamma-ray transmission to determine the in-place unit weight of a given soil, and thermalization of neutrons to determine the soil’s in-place moisture content. Gamma rays that are emitted are produced using a cesium isotope source. The gamma rays pass through the soil that is being tested and are measured by detectors in the gauge. Interaction with the soil particles causes the gamma rays (photons) to become scattered, reducing the number of photons the reach the detector within a given period. The number of photons that are measured by the detector over a fixed period of exposure time correlates well with the moist unit weight of the material (Troxler 2009). Neutrons that are emitted are produced using an americium-isotope/beryllium source. Neutron transmission is used to infer the amount of hydrogen that is present in the soil through a process called thermalization. During thermalization, neutrons that are emitted by the source are slowed down due to collisions with hydrogen molecules that are located between the source and the detector (i.e., in the soil that is being tested). The Nuclear Density Gauge uses detectors to measure the number of neutrons that have been thermalized over a given period, which has been shown to be proportional to the moisture content of the material (e.g., Troxler 2009).

The EGauge currently does not have a prescribed standardized test method; consequently, the testing approach that was utilized in the current study was modeled after ASTM D6938-17, as much as possible. Like the Nuclear Density Gauge, the EGauge emits photons from a cesium isotope to determine the material’s moist unit weight. For measuring moisture content, the EGauge has an attachable probe that uses a fringing field capacitance approach running at approximately 50 MHz. At this frequency, the ionic currents induced in the medium are significantly reduced (as compared to lower frequencies), which helps to reduce the changes in response that occur between tests run on different types of soil. This approach allows the moisture probe to measure the dielectric constant of the soil matrix, which indicates the amount of free water in the matrix, e.g., the soil’s moisture content (Troxler 2016, Troxler 2017 personal communication).
PROJECT AND TESTING DESCRIPTION

All in situ testing was conducted during the construction of U.S. 301, Section 3 located in Middletown, Delaware, in the United States. This portion of the project consisted of the construction of approximately 3 miles of highway as part of the US 301 expansion project from the Maryland-Delaware border to DE Route 1. For the duration of this study, areas that were tested were already fully compacted. Therefore, for this data set, it is implied that the comparisons that are made for moist unit weight, moisture content, and dry unit weight are for data taken from the denser side of the compaction spectrum (i.e., “failing” compaction test points are not well represented). Initial visual manual classification testing for this project indicated that the project soil in the testing area was a silty sand (SM). More specific results from grain size analysis and soil classification via the USCS are presented in the “Results” section of this paper.

During preliminary testing with the EGauge, tests were performed using standard manufacturer calibrations to determine the soil’s in-place unit weight and moisture content. After comparing measured in situ moisture content results with oven-dried moisture content tests on samples taken from each of the in situ test locations (e.g., ASTM D2216-10), it was observed that the moisture contents measured by the EGauge were consistently lower, by up to 6%. Fortunately, the manufacturer allows the user to create a material-specific moisture probe calibration. This calibration procedure requires the user to choose 3 to 25 test locations to perform a unit weight and moisture content test with the EGauge along with collecting a sample for laboratory moisture content determination. Using the moist unit weight readings, the dielectric constant readings, and the laboratory determined moisture content readings, the EGauge’s moisture probe can be calibrated by manually entering the associated readings for each test into the gauge. Alternatively, the user can create a calibration equation utilizing a multivariate regression approach. The following multivariate regression model was used in the current study:

\[
\omega_{Lab} = \beta_0 + \beta_1 DC + \beta_2 Diff
\]  

(1)

where \(\omega_{Lab}\) is the vector of laboratory moisture content values, \(DC\) is the vector of the density counts measured by the EGauge, \(Diff\) is the vector of the dielectric constant values measured by the EGauge (in kHz), \(\beta_0\) is the intercept resulting from the regression analysis, \(\beta_1\) is the coefficient determined from the regression analysis for the moist unit weight measurements, and \(\beta_2\) is the coefficient determined from the regression analysis for the dielectric constant measurements.

To calibrate the EGauge, 30 measurements were taken using the EGauge on a separate day at various location of the project site. The laboratory moisture content for this data set ranged from 6.3% to 16.3% while the EGauge moisture content ranged from 3.8% to 9.2%. The moist unit weight measured from the Egaug ranged from 19.5 kN/m³ to 22.0 kN/m³. Utilizing Equation 1, a multivariate regression analysis was performed to develop a moisture content calibration relationship for the EGauge; for future testing, the coefficients determined from the multivariable regression analysis were used in conjunction with the measured density count and dielectric constant. Figure 1 shows both the raw and calibrated moisture contents measured from the EGauge plotted against the laboratory moisture content. For Figure 1, the laboratory moisture content is plotted as a 1:1 line.
Figure 1. EGauge moisture contents versus laboratory oven-dried moisture contents: (a) Raw measured EGauge data, and (b) Adjusted EGauge data after calibration.

From Figure 1a, it is shown that the uncalibrated moisture content measured by the EGauge exhibits the same behavior as it did during preliminary testing. For this data set, the EGauge consistently under predicted moisture content, by an average amount of 4.6% (though for individual data points the under predictions were sometimes greater, as shown in Figure 1a). After calibrating the moisture content values utilizing the multivariable regression approach outlined above, the calibrated EGauge moisture content values are in much better agreement with the laboratory-measured oven-dried moisture contents (Figure 1b), exhibiting a root-mean-square error (RMSE) of 1.8% versus 4.6%.

A similar approach was utilized to calibrate the Nuclear Density Gauge’s moisture content readings. On a separate day, 15 measurements were taken with the Nuclear Density Gauge. The laboratory moisture content for this data set ranged from 12.4% to 17.6% while moisture content measurements made by the Nuclear Density Gauge ranged from 12.4% to 16.4%, resulting in an RMSE of 1.2%. The moist unit weight for this data set ranged from 20.3 kN/m³ to 21.9 kN/m³. A simple linear regression correlating the moisture content measurements made by the Nuclear Density Gauge to the laboratory determined moisture content was utilized to calibrate the moisture content readings made by the Nuclear Density Gauge.

Figure 2. Nuclear Density Gauge (NDG) moisture contents versus laboratory oven-dried moisture contents: (a) Raw measured NDG data, and (b) Adjusted NDG data after calibration.
From Figure 2a, it is shown that the uncalibrated moisture content measured by the Nuclear Density Gauge is in good agreement with associated laboratory determined moisture content, exhibiting an RMSE of 1.2%. After calibrating the NDG moisture content readings utilizing the linear regression approach outlined above, a slight improvement was made between the two measurements. Though the RMSE between the two measurements did not see much improvement, Figure 2b shows that the calibrated moisture content readings from the Nuclear Density Gauge fall closer to the 1:1 line compared to the raw measurements shown in Figure 2a. In general, the NDG probably did not require a soil specific calibration for moisture content for the soil that was tested in the same fashion that the EGauge did.

After calibrating both gauges for moisture content, a small study was performed to examine the relative differences between in situ unit weight and moisture content values measured from the EGauge, a traditional Nuclear Density Gauge and a Drive Cylinder. Within an area of compacted engineered fill at an active project site, a 3-lane test pad was laid out for testing purposes, with 5 test locations defined for each lane. Sampling points within each lane were spaced approximately 12.2 m apart while the test locations from lane to lane were spaced approximately 6.1 m from one another. At each testing location, 3 Nuclear Density Gauge and 3 EGauge tests were performed. Each test consisted of a 1-minute count performed at a depth of 6 inches. This testing approach was chosen following the typical testing protocol that is utilized by DelDOT technicians when performing QC/QA for earthwork construction (DelDOT 2001). After testing was complete for each of the gauges, a sample was obtained using the Drive Cylinder (DC). A portion of each DC sample was weighed and taken back to the University of Delaware laboratory, where oven-dried moisture content testing was performed.

**ANALYSIS & RESULTS**

Sieve Analysis (ASTM D6913-17) tests were conducted for the 15 samples that were collected; Atterberg Limit testing (ASTM D4318-17) was also conducted to classify the fine portion of the material. The soils that were tested classified as either silty sand (SM) or poorly graded sand with silt fines (SP-SM), with the fine portion of the material being non-plastic in nature (ASTM 2487-11). For comparison purposes, the 3 tests at each testing location for both the Nuclear Density Gauge and EGauge unit weight and moisture content values were averaged. Table 1 provides descriptive statistics (min, max, average) for each of the devices. It can be seen in Table 1 that all three devices are in close agreement with one another. For dry unit weight and moisture content, the measurements made by the EGauge were in better agreement with the measurements made by the Drive Cylinder compared to the measurements made by the Nuclear Density Gauge.

**Table 1 – Moist Unit Weight, Dry Unit Weight and Moisture Content Results from Nuclear Density Gauge (NDG), EGauge (EG) and Drive Cylinder (DC)**

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<td>Min</td>
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<td>10.2</td>
<td>19.7</td>
<td>17.5</td>
<td>9.7</td>
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<tr>
<td>Avg.</td>
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<td>18.4</td>
<td>11</td>
<td>20.2</td>
<td>18</td>
<td>12.5</td>
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<td>Max</td>
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<td>19</td>
<td>12.2</td>
<td>21.1</td>
<td>18.5</td>
<td>13.9</td>
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Figures 3 through 5 present results comparing moist unit weight, dry unit weight and moisture content from all three devices. Each set of figures compares an inferred in situ measurement on the y-axis (e.g., Nuclear Density Gauge and EGauge results) against a direct in situ measurement on the x-axis (e.g., Drive Cylinder results). For comparison purposes, a 1:1 line is also shown, and the corresponding RMSE value between the two data sets shown in each figure is presented. Complete agreement (i.e., 100%) between the two data sets that are plotted corresponds to an RMSE value of zero – in this case, the plotted points will all fall directly on the 1:1 line that is shown.

Figure 3 shows that for moist unit weight measurements, the Nuclear Density Gauge and EGauge are in good agreement with one another, on a point-by-point basis. This observation is further supported by comparing the RMSE values between the two devices, as the Nuclear Density Gauge has an RMSE of 0.41 kN/m³ while the EGauge has an RMSE of 0.40 kN/m³. Similar behavior can be observed in Figure 4 for dry unit weight measurements made by both the Nuclear Density Gauge and EGauge, with measurements plotting above and below the 1:1 line. The Nuclear Density Gauge showed slightly more deviation from the 1:1 line on a point-by-point basis when compared to the EGauge, resulting in an RMSE of 0.44 kN/m³ while the EGauge had an RMSE of 0.33 kN/m³. When comparing moisture content measurements made by both gauges (Figure 5), again both gauges were in good agreement when compared to the laboratory determined moisture content. The Nuclear Density Gauge showed slightly better results with an RMSE of 0.93% while the EGauge had an RMSE of 1.2%, however it should be noted that the Nuclear Density Gauge moisture content measurements consistently plotted below the 1:1 line while EGauge moisture content were more evenly distributed above and below the 1:1 line.

These results indicate that the EGauge and Nuclear Density Gauge moist unit weight measurements are nearly identical. This makes sense since both devices use the same general methodology (e.g., gamma ray transmission) to measure a material’s total unit weight, although different strength sources and radiation shielding are employed by the two devices. Generally similar measurements in terms of overall total accuracy were observed for both the dry unit weight and moisture content measurements made by both gauges. One important caveat here is that for this observation to be true, both devices should be calibrated to increase the relative accuracy of the measured moisture content values (particularly the EGauge).

![Figure 3. Comparison of measured moist unit weight values: (a) NDG vs DC, and (b) EG vs DC.](image-url)
CONCLUSIONS

An experimental study was carried out to examine the relative differences between the Nuclear Density Gauge, the EGauge and the Drive Cylinder, for both unit weight and moisture content measurements. This study was carried out on an active project site, where the areas of soil that were tested had already been fully compacted. The material that was tested during the course of this study was a silty sand (SM) and samples obtained during the calibration and validation/comparison portion of this study exhibited little change from one another. The following conclusions were drawn from this study:

1. The measured moisture content from the EGauge prior to calibration consistently measured in situ moisture content values that were up to 6% lower compared to the physical moisture contents. A multivariate regression analysis approach was utilized to calibrate the EGauge’s Moisture Probe. After the calibration procedure, the EGauge showed good agreement with laboratory determined moisture content, with an RMSE decreasing from 4.6% to 1.8%. The measured moisture content from the Nuclear Density Gauge exhibited fairly accurate results compared to physical moisture content.
measurements with an RMSE of 1.2%. After calibrating the Nuclear Density Gauge’s moisture content readings utilizing a linear regression approach, results were slightly more accurate with an RMSE of 1.1%.

2. When comparing the moist unit weight measurements from the Nuclear Density Gauge and the EGauge, both gauges reported very similar point-by-point results, with similar overall RMSE values of 0.41 kN/m$^3$ and 0.4 kN/m$^3$ respectively when compared to the Drive Cylinder. This make sense as both gauges use the same methodology to determine a soil’s moist unit weight.

3. When comparing dry unit weight measurements from the Nuclear Density Gauge and the EGauge, both gauges exhibited consistent behavior, plotting in a relatively similar fashion around the 1:1 line when compared to the Drive Cylinder measurements. The Nuclear Density Gauge exhibited slightly more variation for dry unit weight than the EGauge, relative to the Drive Cylinder measurements. This resulted in the Nuclear Density Gauge having an RMSE of 0.44 kN/m$^3$ for dry unit weight measurements versus the DC, while the EGauge had an RMSE of 0.33 kN/m$^3$. Similar results were observed when comparing moisture content readings from both gauges. The Nuclear Density Gauge exhibited slightly better agreement with the Drive Cylinder (laboratory determined) moisture content, with an RMSE of 0.93% versus an RMSE of 1.2%. However, the majority of the Nuclear Density Gauge’s moisture content measurements plotted slightly below the 1:1 line while the moisture content measurements made by the EGauge were evenly distributed above and below the 1:1 line.

Overall, after calibration for moisture content, all three in situ QA/QC devices exhibited results that were in relatively good agreement with one another. The EGauge after calibration did exhibit similar or slightly better performance relative to the Nuclear Density Gauge. This is advantageous for DOTs and consultants who are looking for a new gauge that performs just as well as the Nuclear Density Gauge but does not carry a heavy regulatory compliance burden to use the gauge. Further testing is required to validate the preliminary findings that are presented in the current study, as testing was only conducted on a single soil type and at one compaction state (i.e., the soil that was tested was all generally well-compacted).

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