

Experimental and Numerical Investigations of the Moisture Content and Wet Density of Soils

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Abstract The objective of this study was to compare the experimental moisture content and wet density of soil, determined by the nuclear density gauge testing, with those determined by the theoretical computations. In order to serve the stated purpose, an extensive database containing 234 records of experimental moisture content and wet density of soil measured at six probe depths of thirty different holes at three different locations was utilized. A very good correlation was observed between the experimental and theoretical results of moisture content and wet density of soil. Finally, the statistical analysis were conducted to support the findings.

Keywords Wet density, Moisture content, Soils, Nuclear density gauge, Statistical analysis

1. Introduction

Many devices have been utilized to measure the in-place moisture content and density of soil to verify the appropriate soil conditions to support structures, highways, and airport runways (Rose et al. 1965; Williams 1996; Ehlers et al. 1969; IOWADOT 2004; ITEP 2009). Nuclear density gauge testing is the most versatile testing method to measure the wet density and moisture content of soil and granular construction materials (IOWADOT 2004). It is widely being used for civil construction, petroleum industry, mining and archeology purposes (Goldberg et al. 1955; Rose et al. 1965). The nuclear density gauge monitors road construction processes more accurately and quickly to assure the quality of completed asphalt work (Williams 1996; AAPA 2004). Compared to coring, nuclear gauges offer various advantages for field density testing of asphalt (AAPA 2004). Due to the non-destructive and quick procedures of nuclear gauge testing, subsequent asphalt layers can be placed immediately without delays to waiting on density test results of under layers (AAPA 2004). The nuclear density gauge offers the measurement of moisture content and density of a variety of soils or other granular materials, and is rapid and simple.

The nuclear density gauge has three main components: the

radioactive sources, the detector tubes, and the microprocessor (INDOT 2014). Fig.1 shows the components of nuclear density gauge. The microprocessor is located within the tip of the probe rod and inserted into the ground during testing, and it records the gamma radiation (Goldberg et al. 1955). The second source emits fast neutrons and is located within the gauge housing near the center of the gauge bottom.

The gauge works in two modes of operations; backscatter and direct transmission modes (Johnson 1992; Winter et al. 2002; Fratta et al. 2005). The backscatter and direct transmission modes are shown in Fig. 2. In the backscatter method, as shown in Fig. 2, the amount of radiation that is deflected by the material is measured by placing the gauge on the surface of the material. The gauge requires to be placed in contact with the surface of the material being tested. Gamma rays are emitted to just on top of the ground surface by putting down the rod handle. As a result, surface roughness affects the readings in the nuclear gauge. In that case, the length of the gauge is kept parallel to the direction of travel of the compaction equipment. The denser the material, the higher the probability that radiation will be redirected towards the detector. In the backscatter method, almost 70% and 90% of the photons are scattered back to the detector tubes in the top 2 and 3 inches of soil, respectively (Evelt 2000). Since a maximum of 10% photons left to be scattered back below the 3 inches of soil, obtaining density information is quite impossible for the soils below 3 inches from the ground.

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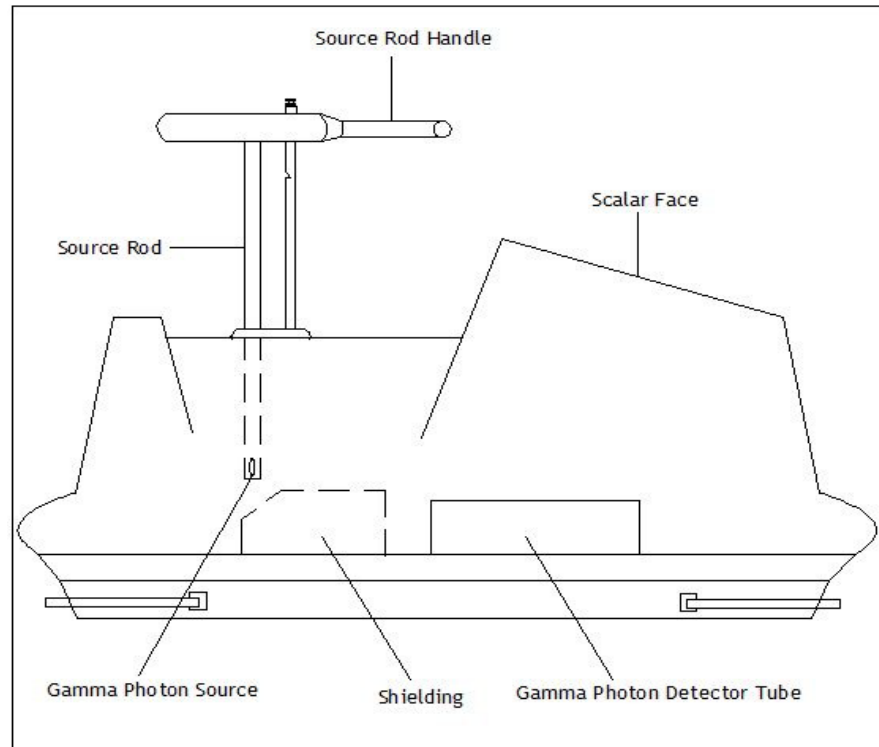


Figure 1. Basic components of nuclear gauge (IN 2014)

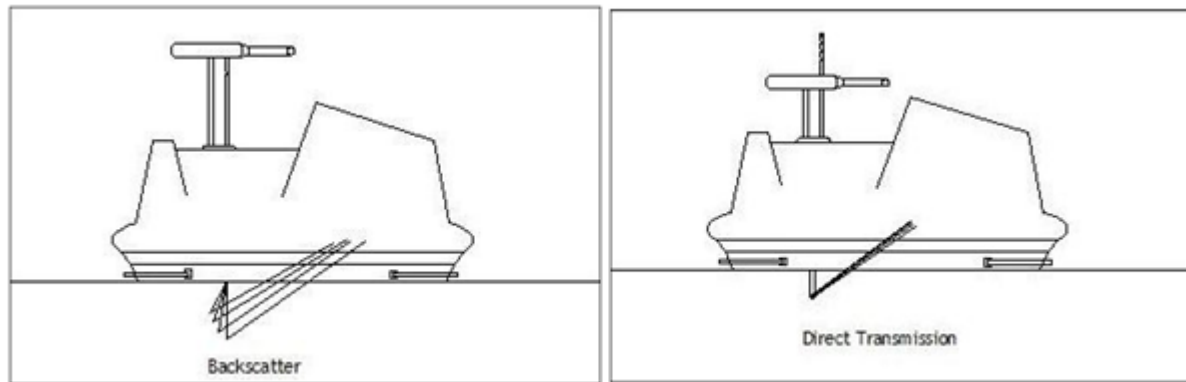


Figure 2. Backscatter and direct transmission modes of nuclear gauge machine (IN 2014)

In the direct transmission mode, as shown in Fig. 2, the detector sends the signal for the amount of radiation emitted by the sources over the specified period of time. While emitting gamma photons, a significant amounts of photons travel from the source rod through the material being tested, and is measured by drilling a hole in the material and inserting the gauge. Radiation that loses sufficient energy or is scattered away from the detector is not counted. The denser the material, the higher the probability of interaction and the lower the detector count. The direct transmission method helps to reduce errors in nuclear gauge readings caused by poor surface conditions or from unforeseen conditions below the gauge (INDOT 2014). The moisture content of soil is determined similarly as fast neutrons are slowed, absorbed, or scattered by water in the soils. Direct transmission would be used more extensively on all materials, however drilling a hole into granular material

might be difficult.

The calculated in-place moisture content and wet density of soils for the nuclear gauge testing are shown in Eq. (1.1) and Eq. (1.2), respectively. The values of A, B, and C for Eq. (1.2) at the six probe depths are presented in Table 1 (CCDPW 2003).

Table 1. The values of parameters A, B, and C at various probe depths of soil

Depth (in)	A	B	C
0.0	1.75662	74.57543	0.12959
4.0	11.31446	71.49999	-0.08874
6.0	12.68117	54.43289	-0.02946
8.0	12.44280	43.62038	0.06180
10.0	11.05279	36.55401	0.06993
12.0	11.41507	30.06259	0.07639

$$w_w (\%) = (A' * R') - B' \quad (1.1)$$

Where: w_w is the moisture content of soil, $A' = 59.79718$, $B' = 3.72034$, and R' is moisture count, which measured in-place by the nuclear gauge testing device.

$$\gamma_w (\text{lb/ft}^3) = B * \text{Ln} \frac{A}{R - C} \quad (1.2)$$

Where: γ_w is the wet density of soil, R is density count (measured in-place by nuclear gauge); A , B , and C are the parameters with respect to the probe depth.

A very few experimental research investigations had been performed on the wet density and moisture content of soils using the nuclear gauge density testing. However, none of the past studies had dealt with the comparison of the field results with those determined by the computational formulations. As such, it is a vital topic that needs to be addressed whether the nuclear density gauge offers accurate results of moisture content and density of soil.

2. Research Significance

The nuclear density gauge provides the field wet density and moisture content of soils in a quick, easy and convenient way. It is widely being used for the research, design or construction works at the private, government and non-profit organizations. As such, it is very crucial to evaluate the accuracy of the experimental results of wet density and moisture content of soils determined by nuclear density gauge. Finally, the results are compared with those obtained by theoretical computations. Statistical analysis is also presented to support the findings.

3. Experimental Procedures

The in-place wet density and moisture content of soils at three different locations in Nevada, USA were determined using the CPN MC-3 portable as per the requirements of ASTM D 2922 (1997). A total of thirty holes were dug for the testing. The experimental results of the wet density and moisture content of soil were recorded at the six probe depths of 0" (Back scattered (BS)), 4", 6", 8", 10", and 12" of 29 holes, and ten replicates were taken at the each probe depth of soil for the first hole. A total of 234 records of data measured from the testing gauge, and each record of data was consisted of density count, moisture count, wet density in lb/ft^3 and moisture content in percent.

4. Results and Discussions

A few datasets were found to be out of range, and they were discarded from the analysis purpose. The possible reasons of these erroneous records in the database might be due to the malfunctioning of the nuclear gauge, site preparation and/or the operator's typos error.

4.1. Density Count Vs. Experimental Wet Density

Fig. 3 shows the relationship between the density count and the experimental wet density of soil at the six probe depths of 0, 4, 6, 8, 10 and 12 inches. As can be seen, the wet density of soil decreased linearly with an increase in the density count. A very good correlation with R^2 values of more than 99% existed between the density count and the experimental wet density of soils at the probe depths of 0, 4, 6, 8, 10 and 12 inches. Fig. 3 also demonstrates that the density count decreased with increasing the probe depth of soil with an exception of the back scattered (0 inch), for which the density count lied between the probe depths of 8 and 10 inch.

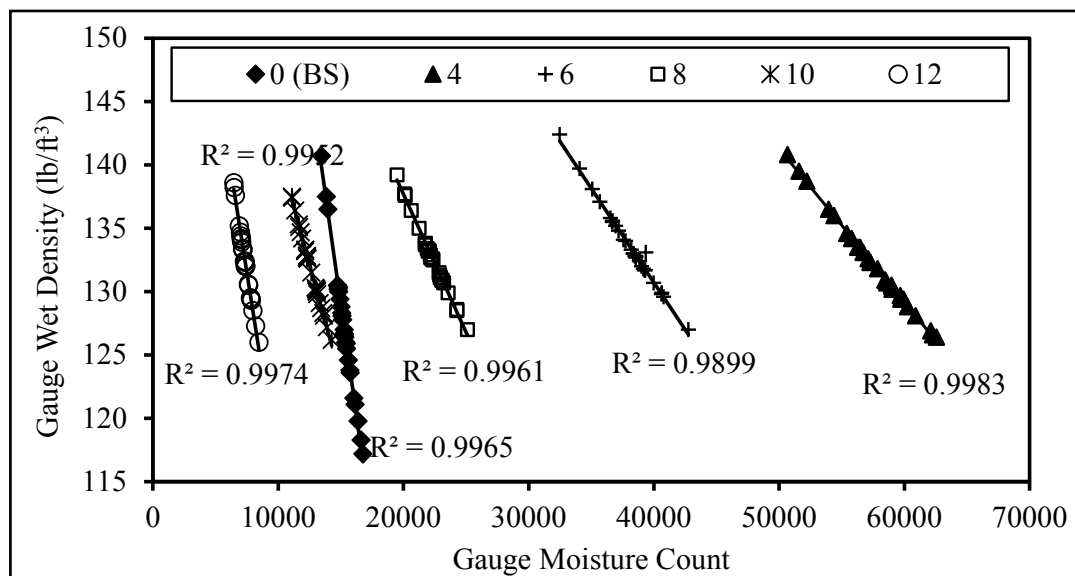


Figure 3. Density count versus experimental wet density of soil at various probe depths

4.2. Experimental Wet Density Vs. Depth of Soil

A typical plot of experimental wet density over soil depth for hole #2 is shown in Fig. 4. As can be seen, in general, the wet density of soil is minimum at the surface, and it increased with soil depth. The characteristic of the wet density of soil over the depth of soil displayed an agreement with the previous findings suggested by Chaudhari *et al.* (2013) and USDA-NRCS (2013). The reason can be stated that the subsurface layers have reduced organic matters, root penetration and pore space filled with air or water compared to the surface layer (USDA-NRCS 2013 and Chaudhari *et al.* (2013). The variation in the wet density of soil among the probe depths of 4, 6, 8, 10 and 12 inches is very low ($\leq 2\%$). The trend of the experimental wet density vs. soil depth for the remaining 29 holes was shown to be nearly identical to that obtained for the hole #2 (Fig. 4).

4.3. Experimental Wet Density Vs. Calculated Wet Density

The wet density of soil at the six probe depths of thirty different holes was calculated by Eq. (1.2), and was compared with that obtained by the experimental procedures at the corresponding probe depth. The results are shown in Fig. 5. As can be shown, a strong linear correlation existed between the experimental and calculated wet density of soil. The statistical parameters and significance of the linear relationship of the experimental wet density and calculated wet density of soil ($\gamma_{w(\text{exp})} = m \gamma_{w(\text{cal})}$; m is the slope) at various probe depths were determined, and the results are shown in Table 2. As can be shown, for each probe depth of soil, the experimental wet density of soil was well fitted with R^2 values of more than 99% with the analytical wet density at the six probe depths of soils.

As can be seen from Table 2, for each probe depth of soil,

the absolute t-ratio of the slope is much greater than 1.0, and Prob(t) of slope is equal to 0.0000, respectively. Additionally, the coefficients of determination of the regression equation were shown to be nearly unity ($\geq 99\%$), and adjusted coefficients of determination R^2_{adj} values were very close to the R^2 values. The standard errors of the estimate was found to be very minimum.

The trends of residuals of the calculated wet density of soils at six probe depths were also studied, and they are presented in Fig. 6. As can be demonstrated, the residuals were well spread around the zero line, and showed no trends or bias, which revealed that the residuals exhibited homogeneity, normality, and independence. Based on the detailed statistical analysis, it can be shown that Eq. (1.2) was able to produce the wet density of soil that perfectly aligned with the experimental wet density of soil determined by the nuclear density gauge.

The differences in the sample means of the experimental wet density of soil among at the six probe depths were conducted by using t-test. The results are documented in Table 3. As it can be seen from Table 3, the t-calculated (t-critical) is greater than the absolute t-statistics at each probe depth of soil. That proved that there is no difference of the mean of the wet density of soil among the six probe depths of 0, 4, 6, 8, 10 and 12 inches.

4.4. Gauge Moisture Count Vs. Experimental Moisture Content

Fig.7 shows the correlation between the moisture count and the moisture content of soil at the six probe depths of 0, 4, 6, 8, 10 and 12 inches. As can be shown, an identical regression line was observed for the six probe depths of soil. It was shown that a linear correlation with an R^2 value of 0.99 existed between the independent variable and the response variable.

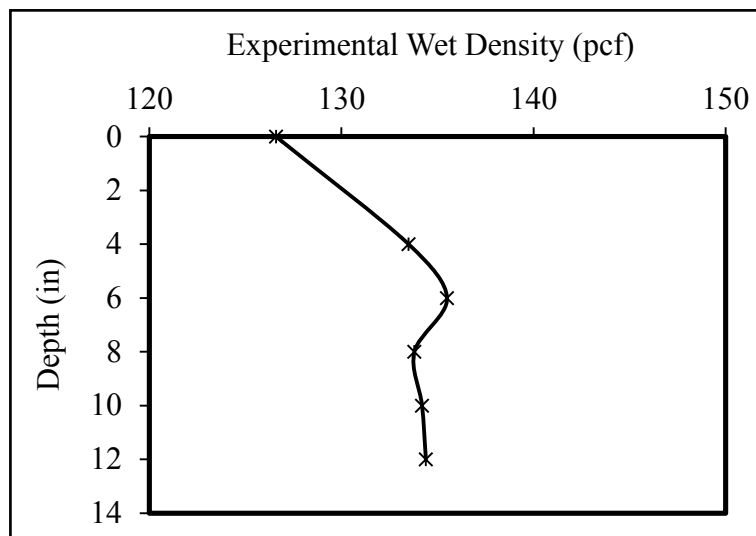


Figure 4. Experimental wet density of soil vs. depth of soil at hole #2

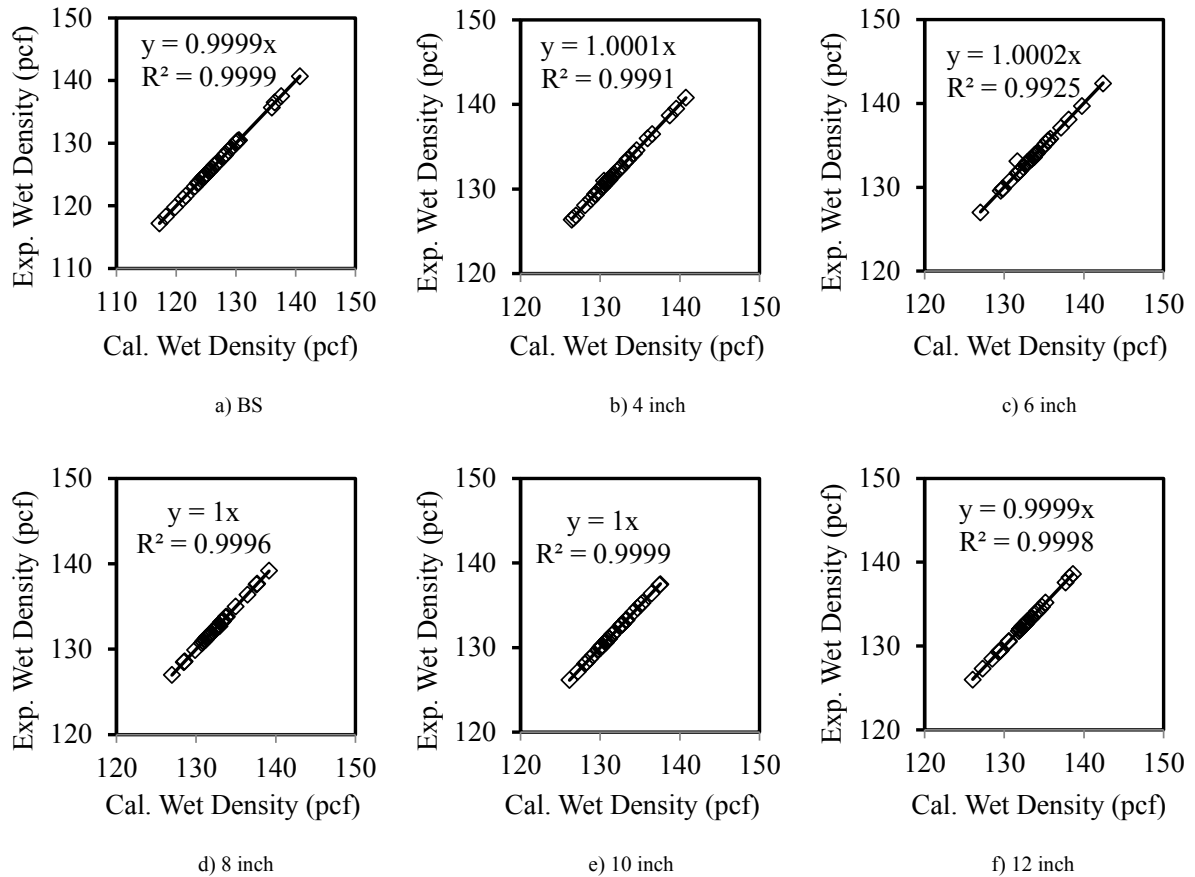


Figure 5. Relation of experimental wet density and calculated wet density of soil at different probe depth

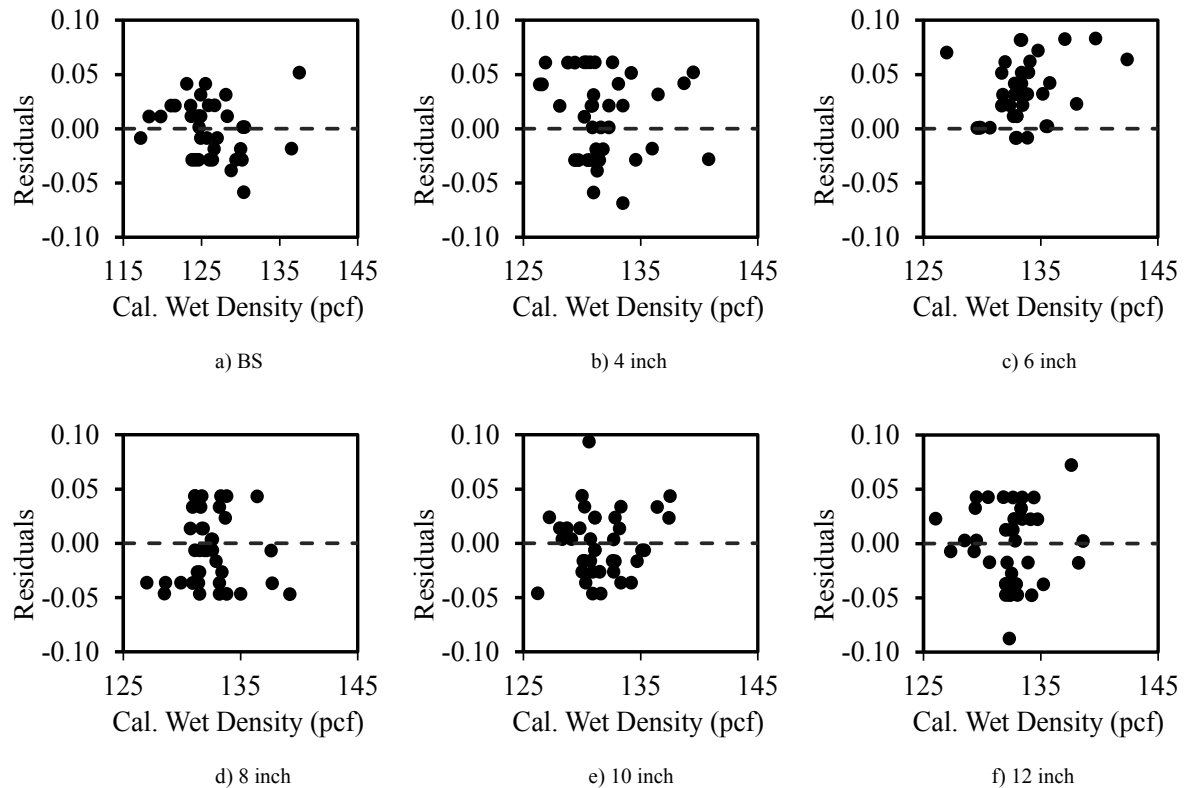


Figure 6. Residual plots of the calculated wet density of soils at various probe depths

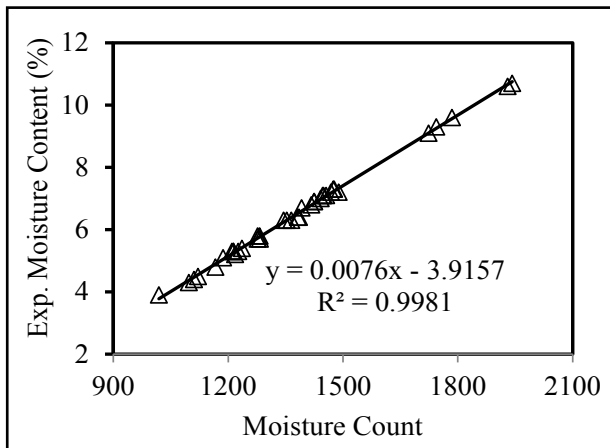
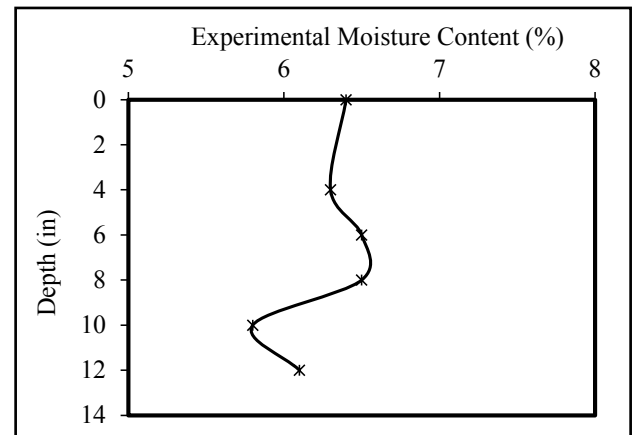
Table 2. Statistical parameters of experimental and calculated wet density

Probe Depth (in)	For the slope of the regression line			Standard Error of Estimate	R^2	R^2_{adj}	Prob(F)
	Value	Prob(t)	t-ratio				
BS	0.9999	0.0000	29390	0.0258	0.9999	0.9999	0
4	0.9999	0.0000	8807	0.0935	0.9991	0.9991	0
6	0.9998	0.0000	3463	0.2380	0.9926	0.9924	0
8	1.0000	0.0000	16519	0.0500	0.9996	0.9996	0
10	1.0000	0.0000	27291	0.0301	0.9998	0.9998	0
12	1.0000	0.0000	23052	0.0359	0.9998	0.9998	0

Table 3. t-test for the differences in wet density of soil among different probe depths

Probe Depth (in)	0 (BS)	4	6	8	10	12
0 (BS)		$t_s = 0.98$ $t_c = 2.05$	$t_s = 0.99$ $t_c = 2.05$	$t_s = 1.00$ $t_c = 2.05$	$t_s = 1.00$ $t_c = 2.05$	$t_s = 1.00$ $t_c = 2.05$
4	$t_s = 1.06$ $t_c = 2.05$		$t_s = -1.12$ $t_c = 2.04$	$t_s = -1.12$ $t_c = 2.04$	$t_s = -0.40$ $t_c = 2.00$	$t_s = -0.10$ $t_c = 2.00$
6	$t_s = 0.98$ $t_c = 2.05$	$t_s = -1.12$ $t_c = 2.04$		$t_s = 0.50$ $t_c = 2.02$	$t_s = 1.06$ $t_c = 2.05$	$t_s = 1.11$ $t_c = 2.05$
8	$t_s = 0.99$ $t_c = 2.05$	$t_s = -1.12$ $t_c = 2.04$	$t_s = 0.50$ $t_c = 2.02$		$t_s = 1.00$ $t_c = 2.04$	$t_s = 1.08$ $t_c = 2.04$
10	$t_s = 1.00$ $t_c = 2.05$	$t_s = -0.40$ $t_c = 2.00$	$t_s = 1.06$ $t_c = 2.05$	$t_s = 1.00$ $t_c = 2.04$		$t_s = 0.29$ $t_c = 2.01$
12	$t_s = 1.00$ $t_c = 2.05$	$t_s = -0.10$ $t_c = 2.00$	$t_s = 1.11$ $t_c = 2.05$	$t_s = 1.08$ $t_c = 2.04$	$t_s = 0.29$ $t_c = 2.01$	

t_s : t-statistics; t_c : t-calculated

**Figure 7.** Experimental moisture content vs. the moisture count**Figure 8.** Experimental moisture content over depth of soil at hole #2

4.5. Experimental Moisture Content Vs. Depth of Soil

A typical experimental moisture content over the depth of soil is shown in Fig. 8. As can be shown, the moisture content over the depth of soil was not consistent. The moisture content at surface was maximum, and it varied over the depth of soil. However, the variation in the moisture content of soils among the depth is very limited. The reasons can be stated that the surface layer often has contact with water than the subsurface layers (Rose *et al.* 1965).

4.6. Experimental Moisture Content Vs. Calculated Moisture Content

The calculated moisture content of soil at the six probe depths of thirty different holes were determined by using Eq. (1.1), and was compared with the experimental moisture content of soils determined by nuclear density gauge. The results are shown in Fig. 9. As can be shown, a nearly perfect linear relationship existed between the experimental moisture content and calculated moisture content of soil at

the above-mentioned probe depths of soil.

Table 4 shows the statistical parameter and significance of the linear relationship between the experimental moisture content and calculated moisture content of soil [$w_{w(\text{exp})} = m w_{w(\text{cal})}$; where m is slope] at the six probe depths. As can be stated that, an excellent correlation with R^2 values of more than 99% was observed between the experimental and calculated moisture content of soils at the six probe depths of 0, 4, 6, 8, 10 and 12 inches. The adjusted coefficient of determinations, R^2_{adj} values, were shown to be very close to the R^2 values. The slope of the each linear regression line

was shown to be nearly unity. The standard error of the estimate varied from 0.0291 to 0.2140. The prob(t) and t-ratio of the regression line showed that the regression parameter (slope) was a very good fit to the linear equation.

Fig. 10 show the residual plots of the calculated moisture content of soils at various probe depths. As can be shown, the data points were randomly presented around the zero line, and did not follow any trends. This indicated that the moisture content of soil, calculated by Eq. (1.1) nicely aligned with the experimental moisture content of soil at the six probe depths.

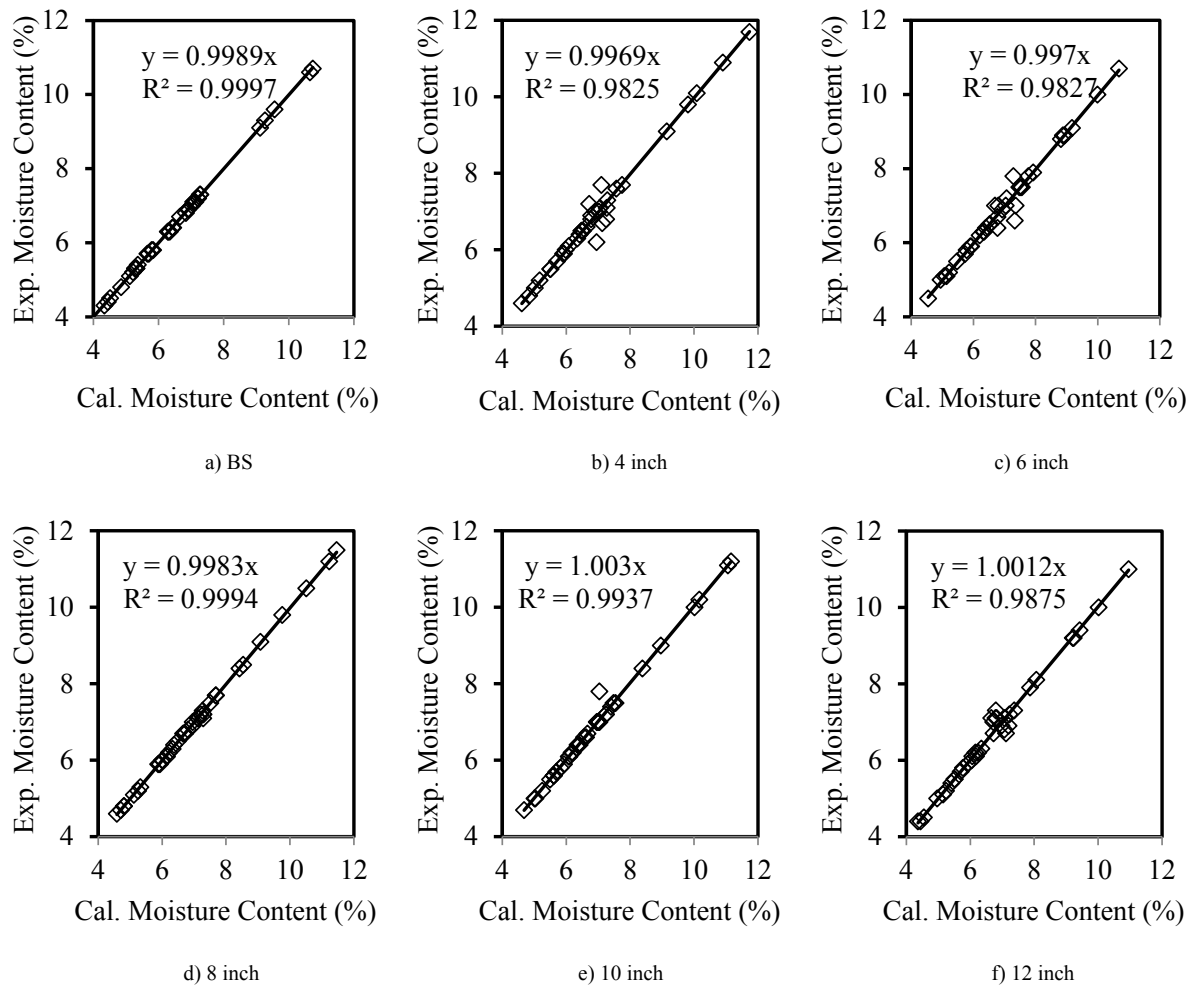
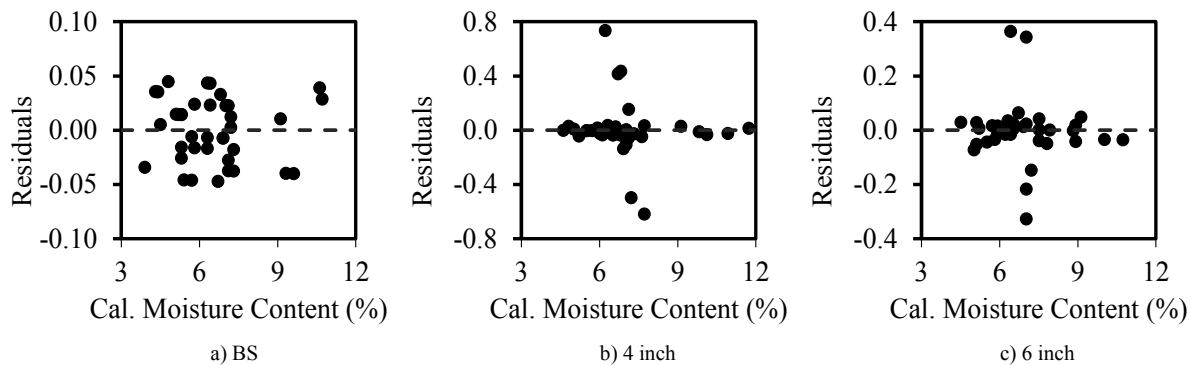


Figure 9. Relation of the experimental moisture content and calculated moisture content of soils at different probe depths



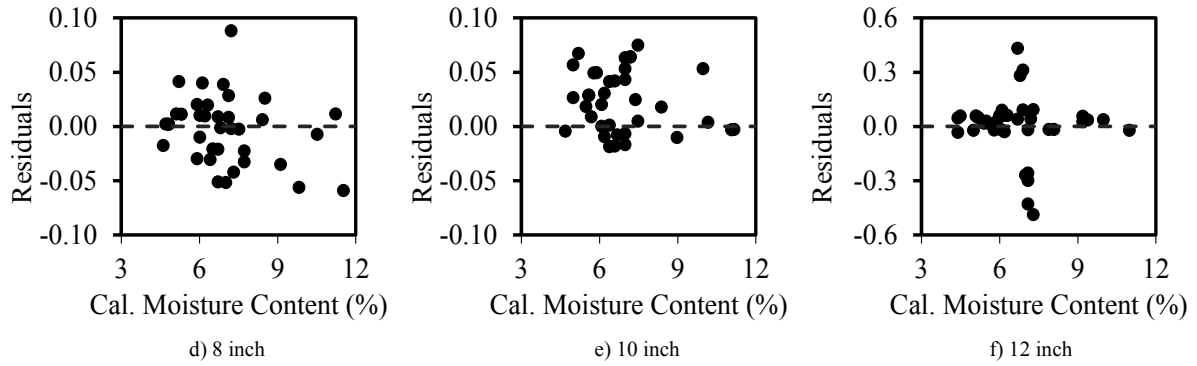


Figure 10. Residual plots of the calculated wet density of soils at various probe depths

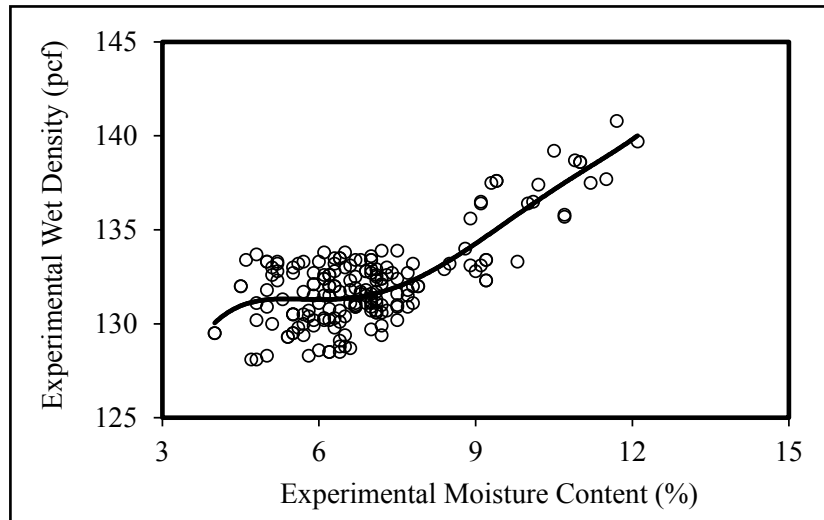


Figure 11. Relationship between the experimental wet density and moisture content of soil

Table 4. Statistical parameters of experimental and calculated moisture content

Probe Depth (in)	For the slope of the regression line			Standard Error of Estimate	R^2	R^2_{adj}	Prob(F)
	Value	Prob(t)	t-ratio				
BS	1.0010	0.0000	1424	0.0291	0.9997	0.9997	0
4	1.0022	0.0000	200	0.2140	0.9823	0.9818	0
6	1.0024	0.0000	231	0.1860	0.9825	0.9820	0
8	1.0016	0.0000	1042	0.0426	0.9994	0.9993	0
10	0.9967	0.0000	346	0.1260	0.9936	0.9935	0
12	0.9982	0.0000	249	0.1704	0.9874	0.9870	0

4.7. Experimental Moisture Content Vs. Wet Density of Soil

Fig. 11 shows the experimental moisture content vs. the wet density of soils at the six probe depths of soil. As can be shown, the wet density increased with an increase in moisture content. The rate of increase in the wet density of soil was low until the moisture content of soil had reached at 7.5%, and the rate increased progressively thereafter. The study revealed an agreement with the previous findings; the density of soil increased with an increase in the moisture

content until the moisture content of soil had reached at more than 14% (Siddiqui et al. 1995, ATT-23 1996, Vanapalli et al. 1999, Abadi et al. 2010).

5. Conclusions

A few records in the dataset behaved inconsistently, unpredictably, and out of range, and they were discarded for analysis purpose. The possible reasons of having those erroneous records may be due to the malfunctioning of the

nuclear gauge. For the entire dataset, a very good correlation with R^2 value of more than 99% existed between the experimental wet density and calculated wet density of soils at the six probe depths of 0, 4, 6, 8, 10 and 12 inches. Likewise, the experimental moisture content of soil showed a nearly perfect correlation with the calculated moisture content of soil at the six investigated probe depths of soil. As expected, for each probe depth, the moisture content and wet density of soil were proportional to the moisture count and density count, respectively. Nuclear density gauge testing is the most versatile non-destructive method to measure the experimental wet density and moisture content of soils and granular construction materials. As expected from the previous research study (Ehlers et al. 1969), the wet density and moisture content of soil changes with the depth. The wet density of soil increased with an increase in soil probe depth. The moisture content at surface was maximum, and it varied over the depth of soil. However, the variation in the moisture content of soils among the depth is very limited.

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