MEASURING SOIL COMPACTION ON CONSTRUCTION SITES: A REVIEW OF SURFACE NUCLEAR GAUGES AND PENETROMETERS

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Abstract. This paper reviews two techniques of determining soil compaction on construction sites. The surface nuclear gauge is found suitable for measuring soil compaction in soils with less than 5% organic matter by weight and at a depth of no more than 0.15 m (6 in.). Penetrometer readings are often unreliable on compacted soils, as well as in dry and stony soil conditions. Therefore, the penetrometer is rarely a valuable device on construction sites as a definitive measurement instrument, but it may be useful as an indicator of compacted areas. Recommendations to measure soil compaction on construction sites are given.

Key Words. Urban soils; quantification of soil compaction; soil compaction; penetrometer; surface nuclear gauge.

Soil compaction on construction sites occurs either deliberately when foundations and subgrades are prepared for construction or as an unintended result of vehicular traffic (Randrup and Dralle 1997). Soil compaction decreases porosity (e.g., Harris 1971), which results in reduced flow of air and water through the soil, as well as reduced root growth (e.g., Viehmeyer and Hendrickson 1948; Craul 1994). This ultimately increases the likelihood of secondary pest and diseases and decreases growth rates of trees (e.g., Harris et al. 1999).

To determine whether a soil is compacted or not, and thus whether a treatment is necessary for the alleviation of soil compaction, the degree of compaction needs to be quantified. However, measuring soil compaction on construction sites poses many difficulties. The high degree of variability within an urban soil (e.g., Craul 1992; Jim 1998) and the presence of human artifacts and stones make it difficult to decide where to characterize soil compaction and to find a proper measurement method. Another difficulty is characterizing soil compaction in deeper soil layers. Randrup (1997) showed that clay soils on construction sites were compacted to depths of 0.8 m (32 in.).

A bulk density measurement by the use of core sampling has been described by many (e.g., Blake and Hartge 1986). Randrup (1993), Lichter and Costello (1994), and Blake and Hartge (1986) all concluded that core sampling is a simple and relatively fast technique, but that it is not suitable for sampling in rocky, sandy, dry, or wet soils. This paper describes two alternative methods of determining soil compaction on construction sites. The use of a surface nuclear gauge (SNG) is described in detail, and the theory and use of penetrometers are presented. Also, two initial test trials were performed to test these methods against traditional core sampling.

SURFACE NUCLEAR GAUGES

Over the past 25 years, the use of SNGs has become increasingly common on construction sites. The SNG was developed for quality control of subgrade and base material compaction during road construction. Because the instrument is currently in use on construction sites, SNGs have also been used as an alternative to traditional excavation methods for determining bulk densities.

Alberty et al. (1984) used a nuclear densiometer (presumably similar to the SNG referred to in this paper) to measure bulk density on construction sites. The nuclear densiometer was easy to use and allowed rapid determination of soil bulk density with immediate readout. The limitations to its use by the landscape industry were the expense of purchase, health risks associated with nuclear radiation, and the need for a licensed operator. However, SNGs are used frequently on construction sites by road and building technicians.

When using a surface nuclear gauge, two independent measurements are determined: 1) the wet density of the soil, and 2) the soil moisture content. Wet density is measured by the suppression of gamma waves from a probe lowered from the gauge into the soil. Moisture content is measured immediately below the gauge, as the amount of reflected neutrons hitting the hydrogen in the water. By subtracting moisture content from wet density, dry bulk density is obtained. Both measurements may be derived within a minute.

The SNG is placed on the soil surface when measuring the wet density of the soil. The gamma source is lowered into the soil while the detector is located within the instrument. Gamma waves are a type of electron magnetic scattering similar to radio or light waves. They are neutral in electric charge. Unlike light, gamma waves can penetrate various materials. Several centimeters of soil can be penetrated without disruption, although gamma waves will reflect on almost everything in the soil, including water.

When a gamma source penetrates a material, the beam will either be absorbed by the material, be deflected but continue in a different direction with a lower speed (it can often be deflected several times before it absorbs or leaves the material), or the beam will penetrate the material without deflection or absorption. Although it is impossible to measure the exact reaction of a beam through a material, it is possible to calculate the percentage of a source that is absorbed, deflected, or transmitted through the material. The denser the soil, the fewer reflected waves are counted by the detector. By calibrating the detector, the number of counts can be translated into a measurement of the wet soil bulk density.

To compare wet bulk density to dry bulk density, neutrons are used to measure the moisture content in the soil. The neutron moderation method is based on fast neutrons, which are emitted from the neutron source placed in the instrument. The neutrons then collide with hydrogen atoms in the water molecules, after which energy dissipation occurs. The fast neutrons are moderated by collision with the atoms. The greater the amount of neutrons moderated, the higher the measurement achieved. Because hydrogen in the soil primarily is bound to water, this method is favorable for measuring the moisture content of the soil.

The surface nuclear gauge is designed for use in gravel and subgrade layers, in which texture, moisture content, and compaction level are usually fairly uniform within a 0.3 to 0.4 m (15 to 20 in.) profile. While the presence of organic matter may influence the moisture content measurement (hydrogen molecules may be bound to the organic material), the SNG is not designed to measure bulk density in soils containing large amounts of organic material. However, on soils with less than 5% (by weight) of organic material, a deviation of less than 1% in water content was found, in comparison to the standardized water content (Randrup 1993). Thus, in soils that have a bulk density of 1.65 g/cm^3, the influence of organic matter is on the order of 0.02 g/cm^3.

The SNG usually measures the moisture content within a distance of 0.05 to 0.10 m (2 to 4 in.) from the instrument. The higher the moisture content, the higher the reflection of neutrons in the water molecules and the smaller the measurement depth. So, if wet density is measured deeper than 0.10 m (4 in.), the measured moisture content might not be representative of the soil from which the wet density was taken. If measurements need to be taken at greater depths, the surface gauge has to be placed in a hole. In soils with significant variability, which is easily distinguished, it may be beneficial to restrict measurements to the soil surface or top 0.10 to 0.15 m (4 to 6 in.) of the soil.

PENETROMETER

Any device forced into soil to measure its resistance to vertical penetration may be called a "penetrometer." The earliest soil penetrometers—knives, pointed sticks, or metal rods—are still used for qualitative measurements of relative density of cohesionless soils or consistency of cohesive soils. Results of such tests are commonly expressed by terms as "loose," "soft," "stiff," or "hard" (Davidson 1965).

Cone penetrometers have been used in agriculture and horticulture primarily because they attempt to measure the actual pressure a root meets when growing into a soil. They are frequently used because they are reasonably easy to operate, give an instant result, and are relatively economical.

The applied force required to press the penetrometer into a soil is an index of the shear resistance of the soil and is called the "cone index" (CI). Thus, CI gives the specifications of the actual probe and the force required to press the probe into the soil. CI can be described:

$$\mathrm{CI} = \frac{F}{\pi\left(\frac{d}{2}\right)^2}$$

where F = total pressure needed to force the penetrometer into the soil (newtons, N), the denominator is the base area of the cone, and d is the diameter of the cone. CI is measured in pascals (Pa), which is a pressure (1 Pa = 1 N/m^2). One kg is equal to a pressure at 9.8 N.

CI is dependent on soil and probe characteristics, including cone-base diameter, cone angle, and the surface roughness of the cone, as well as penetration rate and the immediate condition of the soil—primarily moisture content and texture (Bradford 1986; Perumpral 1987; Fritton 1990). However, Bengough and Mullins (1990) stated that penetration pressure is only slightly dependent on the penetration rate. In a wet soil, the penetration pressure will be dependent on the interaction between the resistance of the probe and the soil water pressure, which means that readings need to be taken at the exact same moisture content if they are to be compared. This may not be possible at a construction site due to the variations in soil moisture. This effect will be larger in less penetrable soils (e.g., those with a high content of silt and clay).

There are obvious differences between a root and a metal probe. Roots are flexible organs that will follow tortuous channels in the soil—and presumably grow in the direction with the least amount of physical impedance (Hamblin 1985; Dexter 1986). Roots absorb water from the soil, extract musigel from the root tip, and enlarge when they meet physical resistance (Russell 1977). The penetrometer is a stiff metal probe following a straight line through the soil, but because no other method is available as a direct measurement of root growth penetration, it is the best available tool for estimating root growth impedance (Bengough and Mullins 1990).

MATERIALS AND METHODS

Trial I: Surface Nuclear Gauge and Core Sampling

Three test sites were selected in an urban park in the city of Ringsted, Denmark (UTM zone 32, N 6,147,000 m, E 677,000 m). At each site, the top 0.10 m of turf was removed in an area of 1.0 × 1.0 m (9 ft^2) in order to limit interference from the surrounding soil when the surface nuclear gauge measurements were carried out. At all three sites, the soil was a clay loam. The soil was leveled, and measurements with a surface nuclear gauge (model Troxler 3440) were made from the soil surface to depths of 0.3 m (12 in.), at 0.1 m (4 in.) intervals. One measurement was performed at each depth at each test site, with 12 measurements in all. A standard measurement time of 1 minute was used for each measurement. Right after the SNG measurements, a core sampler (100 cm^3, metal cores) was used to evaluate bulk density at each site. Three cores were taken at each depth, 12 cores in each hole, 36 cores at all three test sites.

Trial II: Penetrometer and Core Sampling

Three test sites were selected along a road in the city of Fredensborg-Humlebaek, Denmark (UTM zone 32, N 6,209,000 m, E 712,000 m.). Each test site consisted of three trees. Penetration resistance was measured using an ELE International computerized cone penetrometer with nine penetrations per tree, distributed in the periphery at 1.0 m (3 ft.) from each tree. Measurements were obtained every 15 mm (0.6 in.) from the soil surface to a maximum depth of 0.45 m (18 in.). Immediately after the penetrometer measurements, a core sampler (100 cm^3, metal cores) was used to evaluate bulk density at each site, at distances of 1.0 m from each tree. Three cores were taken at depths of 0.2, 0.4 and 0.6 m (8, 16, and 24 in.) for each tree. The clay content at each site was 16.6%, 12.9%, and 18.4% respectively. All measurements were carried out in early April, when the soil was believed to be at field capacity.

RESULTS

Trial I: Surface Nuclear Gauge and Core Sampling

The results and differences in bulk density measured between the SNG measurements and the core sampling are shown in Table 1 and Table 2. In general, measurements with the SNG provided a higher bulk density than found with core sampling (11 out of 12 comparisons). The difference varied between –2.4% and 18.66%, with an average of 9.18% (+/– 5.91). The difference in measured moisture content was 6.36% +/– 4.89.

Trial II: Penetrometer and Core Sampling

The results of the penetrometer measurements are shown in Table 3. At each site, 18 penetrations were performed, but at no sites were all penetrations successful. If a very high penetration resistance was experienced, the penetration was performed at shallow depths only and few results were obtained. In general, there is high variability (standard error) between the individual measurements at each site.

Table 1. Pilot test of bulk density measured with core sampling and surface nuclear gauge.

	Test site 1			Test site 2			Test site 3		
	Bulk density (g/cm^3)			Bulk density (g/cm^3)			Bulk density (g/cm^3)		
Depth (cm)	Core sampling (n = 3)	SNG (n = 1)	Difference (%)	Core sampling (n = 3)	SNG (n = 1)	Difference (%)	Core sampling (n = 3)	SNG (n = 1)	Difference (%)
10	1.38 +/– 0.09	1.35	–2.40	1.45 +/– 0.06	1.52	4.52	1.22 +/– 0.08	1.40	12.37
20	1.33 +/– 0.03	1.5	11.13	1.38 +/– 0.03	1.53	9.46	1.45 +/– 0.05	1.41	2.34
30	1.39 +/– 0.06	1.54	9.72	1.28*	1.58	18.66	1.27 +/– 0.07	1.44	12.11
40	1.42 +/– 0.16	1.52	6.50	1.31 +/– 0.04	1.58	17.11	1.37 +/– 0.03	1.50	8.51
Total			**6.24 +/– 6.07**			**12.44 +/– 6.63**			**7.66 +/– 6.90**

*Only one measurement was obtained, due to artifacts in the soil.

Table 2. Pilot test of moisture content measured with core sampling and surface gauge.

	Test site 1				Test site 2				Test site 3			
Depth (cm)	Core sampling (n=3) ϖ	Core sampling (n=3) θ	SNG (n = 1) θ	Diff. (θ^*) (%)	Core sampling (n=3) ϖ	Core sampling (n=3) θ	SNG (n = 1) θ	Diff. (θ^*) (%)	Core sampling (n=3) ϖ	Core sampling (n=3) θ	SNG (n = 1) θ	Diff. (θ^*) (%)
10	0.192 +/– 0.022	26.6	27.8	4.4	0.180 +/– 0.009	25.5	23.1	10.2	0.180 +/– 0.013	22.0	20.3	8.5
20	0.172 +/– 0.014	22.9	24.3	5.6	0.166 +/– 0.004	23.0	23.3	1.4	0.136 +/– 0.06	19.7	19.2	2.5
30	0.184 +/– 0.005	25.6	23.5	8.9	0.141*	18.1	22.1	18.1	0.165 +/– 0.010	20.9	19.2	9.1
40	0.171 +/– 0.032	24.4	24.6	0.8	0.170 +/– 0.013	22.3	23.2	3.8	0.142 +/– 0.210	19.4	18.9	2.8
Total				**4.9 +/–3.3**				**8.4 +/–7.5**				**5.7 +/–3.6**

*Volumetric moisture content (θ) is calculated by multiplying the gravimetric moisture content (ϖ) with the bulk density (ρ_j) (see Table 1) and dividing by the density of water (ρ_w): $\theta = (\varpi \times \rho_j)/\rho_w$.

Table 3. Penetrometer resistance measurements along a roadside in Denmark.

	Test site 4			Test site 5			Test site 6		
Depth (mm)	n	Average (kPa)	SD (kPa)	n	Average (kPa)	SD (kPa)	n	Average (kPa)	SD (kPa)
15	17	311	162	16	330	139	17	540	288
30	17	483	226	16	546	140	17	980	406
45	17	508	150	16	620	162	17	973	293
60	17	570	144	16	659	164	17	1,035	262
75	17	661	183	16	715	197	17	1,172	297
90	17	732	175	16	779	198	17	1,357	385
105	17	811	229	16	830	150	17	1,515	404
120	17	928	252	16	913	169	17	1,707	477
135	17	1,082	261	16	1,054	231	17	1,944	723
150	17	1,240	325	15	1,157	290	17	2,193	933
165	17	1,404	406	15	1,212	378	17	2,332	1,057
180	17	1,604	397	15	1,363	474	16	2,287	768
195	17	1,729	370	14	1,551	556	14	2,428	1,068
210	17	1,818	314	14	1,688	601	13	2,112	1,123
225	17	1,979	371	13	1,658	571	13	2,259	933
240	17	2,184	578	13	1,818	618	12	2,173	1,041
255	16	2,402	806	11	1,862	775	10	1,928	858
270	16	2,647	903	11	1,981	828	10	2,043	786
285	16	2,856	975	11	2,147	987	10	2,130	861
300	15	3,270	1,028	11	2,396	1,081	10	2,256	887
315	14	3,169	994	9	2,355	869	10	2,325	948
330	13	3,135	1,105	8	2,607	870	9	2,303	1,032
345	12	3,080	1,094	7	2,725	843	9	2,336	1,077
360	12	3,191	1,184	6	2,875	886	9	2,458	1,079
375	12	3,039	1,181	5	2,912	970	9	2,517	1,013
390	12	3,333	1,208	2	1,969	609	9	2,336	1,198
405	12	3,240	1,130	2	2,078	381	8	2,299	1,301
420	12	3,325	1,165	2	2,292	95	7	2,621	1,132
435	11	2,933	1,142	2	2,285	675	8	2,109	1,088
450	10	3,096	1,063	2	2,037	554	8	2,493	903

Table 4. Bulk density measurements along a roadside in Denmark.

	Test site 4		Test site 5		Test site 6	
Depth (mm)	n	BD	n	BD	n	BD
200	9	1.65 +/– 0.07	9	1.68 +/– 0.10	9	1.56 +/– 0.14
400	9	1.62 +/– 0.08	9	1.79 +/– 0.12	9	1.61 +/– 0.22
600	9	1.62 +/– 0.09	9	1.79 +/– 0.18	9	1.78 +/– 0.07

As shown in Table 4, the bulk density measurements showed relatively high variability at each depth at each site (standard errors of 0.07 to 0.22 g/cm^3).

The relationship between the relevant bulk densities and respective average penetrometer resistance measurements are shown in Figure 1. No correlation was found between core sampling (bulk densities) and penetrometer resistance (kPa).

DISCUSSION

Trial I: Surface Nuclear Gauge and Core Sampling

The high variability between core sampling and SNG measurements may be due to high differences between the three core samples that were used to describe each depth. It was difficult to obtain three valid core samples in each depth due to rocks and artifacts in the soil (primarily bricks). In some cases, five or more samples were taken before three valid samples could be obtained. Rocks did not seem to cause practical problems for the SNG measurements. The core sampling technique was far more time consuming than the SNG technique.

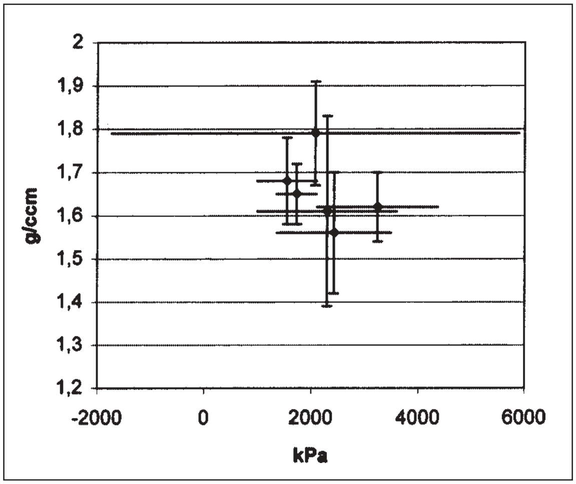

Figure 1. Relationship between core sampling and penetrometer readings, at depths of 200 mm and 400 mm, shown in Table 3 and Table 4.

Trial II: Penetrometer and Core Sampling

The variation among core sample results and penetrometer resistance may be caused by the same reason as described in Trial I. In some cases, the lack of penetration results is due to the presence of rocks in the soil, which would stop the penetrometer from further penetration. However, a relation between higher resistance and fewer results per site is indicated. The core sampling technique was far more time consuming than the penetration technique.

General Discussion

In general, there is a high variability in an urban soil profile. Randrup (1997) found several soil textures and organic matter contents represented within the same soil profile in a study of 17 construction sites in Denmark. Short et al. (1986) found buried A horizons in 42 of 100 profiles of the Mall in Washington D.C., and Jim (1998) described urban soils in Hong Kong as diverse and having a densely packed surface layer. Thus, the high variability in bulk density related to the core sampling results might be an indication of the high variability of the soil.

In Trial I, the tendency of lower bulk densities with core sampling than with the SNG may be because a number of cores were rejected as being invalid (e.g., if a rock disturbed the sample). The presence of a stone or a rock may cause a higher bulk density in the sample, and if samples with rocks or stones are not obtained, a lower bulk density than actual could be expected. Therefore, this trial might indicate that the SNG will provide a higher bulk density than what would be obtained with traditional core sampling in stony soils (urban soils), simply because stony core samples are rejected.

In theory, the high variability in urban soils may provide a limitation in the use of the SNG because the different texture and compaction layers may cause an uneven reflection of radiation beams. Despite this, a qualitative evaluation of the results of the SNG measurements shows a more steady flow through the soil profile than do the results obtained with core sampling. In general, both theory and the practical testing of the three methods indicate that on urban sites, the SNG has advantages in comparison to traditional core sampling and penetrometer resistance as an indication of soil compaction. Both core sampling and penetrometers may be regarded as unreliable for measuring soil compaction on urban sites, if the soil is stony.

Suggestions for use of surface nuclear gauges and penetrometers on construction sites are presented in Table 5. The preferred method will depend on the purpose of the measurement and the degree of accuracy needed. Randrup (1996) recommended dividing soil compaction measurement schedules into three periods: 1) prior to construction, 2) prior to planting, and 3) after planting.

Prior to construction, measurements should be carried out to detect the original soil density from which the recommendations and requirements regarding soil compaction will be derived. There are two reasons for carrying out these measurements: 1) to be able to distinguish what the “natural” soil compaction level is for a particular soil and 2) to be able to compare the data to determine if an area has been compacted during the construction period.

Penetrometers may be useful for preliminary evaluation of soil compaction. If more exact measurements are needed, the SNG may be used. The preferred measurement depths will depend of the planned amount of grading and fill for the area.

Prior to planting, Randrup (1996) recommended evaluating bulk density to determine if the soil bulk density is in accordance with the specified bulk density determined on the basis of the earlier measurements and the design of the site. If trees are to be planted, the specifications are likely to be more detailed than if the design is without trees. If the soil is compacted to levels above those specified, this is the time to alleviate

Table 5. Use of surface nuclear gauges and penetrometer ovens on construction sites. Partially from Randrup (1996).

	Prior to construction	Prior to planting/After planting
Purpose of measurement	detection of existing conditions	control of compaction
Preferred method	penetrometer or surface nuclear gauge	surface nuclear gauge
Measurement depth	depends of amount of fill or excavation proposed;	depends on site conditions
	subsoil must be quantified	min. top 0.3 m of subsoil and preferably the total compacted layer should be ascertained*

*See Randrup (1997) and Randrup and Dralle (1997).

compacted soil or to exchange whole soil volumes. After planting, it will often be advisable to carry out another measurement to quantify the soil conditions before the actual work is handed over from the contractor to the owner. For both measurements, the SNG may be used.

In many cases, the geo-technician will carry out quality control of foundations and subgrades for buildings, sidewalks, and roads. Because the geo-technician already is on the site, she or he could be asked to determine density of the soil that is going to be used for planting. Before and after planting, the soil bulk density may again be measured by a geo-technician.

CONCLUSION

SNGs may be used to measure bulk densities of soil on construction sites if the content of organic material is less than 5% (by weight). If the measured depths are more than 0.15 m (6 in.) from the gauge, caution should be taken to ensure that the soil profile is homogeneous, because significant changes in texture could cause unreliable readings. Further research is needed to develop a nuclear gauge that is inexpensive, easy to use, and that can measure bulk density at depth. The penetrometer may be a useful instrument for identifying areas with compacted soil, but it should not be used to evaluate the severity of soil compaction at construction sites.

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Résumé. Cet article fait la revue de deux techniques différentes de détermination du degré de tassement du sol sur des sites de construction. La jauge à surface nucléaire s'est avérée adéquate pour mesurer le tassement du sol dans les sols ayant moins de 5% en masse de matière organique et à une profondeur ne dépassant pas 0,15 m. Les lectures du pénétromètre sont souvent peu fiables avec les sols compactés, tout comme avec des sols aux conditions sèches et pierreuses. De ce fait, le pénétromètre est rarement un instrument efficace pour donner des mesures précises sur les sites de construction, mais il peut être utile pour identifier les zones compactées. Des recommandations sont données sur le mesurage du tassement du sol dans les sites de construction.

Zusammenfassung. Diese Studie gibt eine Überblick über 2 verschiedene Techniken, um Bodenverdichtung auf Baustellen zu bestimmen. Die Nuklearoberflächenmessung ist geeignet, um Bodenverdichtung in Böden mit weniger als 55 org. Substanz und einer Tiefe von nicht mehr als 0,15 m zu messen. Die Messungen mit einem Penetrometer sind bei verdichtetem Boden und auch bei trocknen und steinigen Bodenbedingungen nicht vertrauenswürdig. Daher ist das Penetrometer auf der Baustelle selten ein verlässliches Messinstrument, aber es kann hilfreich sein beim Erkennen von verdichteten Bereichen. Es werden einige Empfehlungen zum Messen von Bodenverdichtungen gegeben.

Resumen. Este reporte revisa dos diferentes técnicas para la determinación de la compactación del suelo en sitios de construcción. El barreno de muestreo superficial se ha encontrado aceptable para mediciones de suelo compactado con menos de 5% de materia orgánica por unidad de peso y una profundidad no mayor de 0.15 m (6 in.). Las lecturas con penetrómetro resultan imprácticas en suelos compactados, pero aún más en lugares secos y pedregosos. De ahí que, el penetrómetro raramente sea un aparato confiable en sitios de construcción como un instrumento de medición, pero podría ser útil como indicador en áreas compactadas. Se dan recomendaciones para la medición de la compactación en sitios de construcción.