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 distin-
guished, it may be beneficial to restrict measure-
ments 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 "penetro-
meter." The earliest soil penetrometers—knives,
pointed sticks, or metal rods—are still used for
qualitative measurements of relative density of co-
hesionless soils or consistency of cohesive soils. Re-
sults of such tests are commonly expressed by terms
as "loose," "soft," "stiff," or "hard" (Davidson 1965).

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

The applied force required to press the pen-
etrometer into a soil is an index of the shear
resistance of the soil and is called the "cone in-
dex" (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:

\[
CI = \frac{F}{\pi \left( \frac{d}{2} \right)}
\]

where \( F \) = total pressure needed to force the
penetrometer into the soil (newtons, N), the de-
ominator is the base area of the cone, and \( d \) is
the diameter of the cone. CI is measured in pas-
cals (Pa), which is a pressure (1 Pa = 1 N/m²).
One kg is equal to a pressure at 9.8 N.

CI is dependent on soil and probe character-
istics, 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 depen-
dent 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 be-
cause 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 ft²) 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 per-
formed at each depth at each test site, with 12
measurements in all. A standard measurement
time of 1 minute was used for each measure-
ment. Right after the SNG measurements, a core
sampler (100 cm³, 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.

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

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Test Site 1</th>
<th></th>
<th>Test Site 2</th>
<th></th>
<th>Test Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core sampling (n = 3)</td>
<td>SNG (n = 1)</td>
<td>Difference (%)</td>
<td>Core sampling (n = 3)</td>
<td>SNG (n = 1)</td>
</tr>
<tr>
<td>10</td>
<td>1.38 +/- 0.09</td>
<td>1.35</td>
<td>-2.40</td>
<td>1.45 +/- 0.06</td>
<td>1.52</td>
</tr>
<tr>
<td>20</td>
<td>1.33 +/- 0.03</td>
<td>1.5</td>
<td>11.13</td>
<td>1.38 +/- 0.03</td>
<td>1.53</td>
</tr>
<tr>
<td>30</td>
<td>1.39 +/- 0.06</td>
<td>1.54</td>
<td>9.72</td>
<td>1.28*</td>
<td>1.58</td>
</tr>
<tr>
<td>40</td>
<td>1.42 +/- 0.16</td>
<td>1.52</td>
<td>6.50</td>
<td>1.51 +/- 0.04</td>
<td>1.58</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.24 +/- 6.07</strong></td>
<td><strong>12.44 +/- 6.63</strong></td>
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<td></td>
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</tbody>
</table>

*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.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Test site 1</th>
<th>Test site 2</th>
<th>Test site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core sampling (n=3)</td>
<td>SNG (n = 1) Diff. (θ*)</td>
<td>Core sampling (n=3)</td>
</tr>
<tr>
<td>10</td>
<td>0.192 +/- 0.022</td>
<td>26.6 27.8 4.4</td>
<td>0.180 +/- 0.009</td>
</tr>
<tr>
<td>20</td>
<td>0.172 +/- 0.014</td>
<td>22.9 24.3 5.6</td>
<td>0.166 +/- 0.004</td>
</tr>
<tr>
<td>30</td>
<td>0.184 +/- 0.005</td>
<td>25.6 23.5 8.9</td>
<td>0.141* 18.1 22.1 18.1</td>
</tr>
<tr>
<td>40</td>
<td>0.171 +/- 0.032</td>
<td>24.4 24.6 0.8</td>
<td>0.170 +/- 0.013</td>
</tr>
</tbody>
</table>

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 (ω) with the bulk density (ρ) (see Table 1) and dividing by the density of water (ρw): θ = (ω × ρ)/ρw.

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

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Test site 4</th>
<th>Test site 5</th>
<th>Test site 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (kPa) SD (kPa)</td>
<td>Average (kPa) SD (kPa)</td>
<td>Average (kPa) SD (kPa)</td>
</tr>
<tr>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>15</td>
<td>17</td>
<td>17</td>
<td>17</td>
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<tr>
<td>30</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>45</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>60</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>75</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>90</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>105</td>
<td>17</td>
<td>16</td>
<td>17</td>
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<tr>
<td>120</td>
<td>17</td>
<td>16</td>
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<tr>
<td>135</td>
<td>17</td>
<td>16</td>
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<tr>
<td>150</td>
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<td>16</td>
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<tr>
<td>165</td>
<td>17</td>
<td>15</td>
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<tr>
<td>180</td>
<td>17</td>
<td>15</td>
<td>17</td>
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<tr>
<td>195</td>
<td>17</td>
<td>14</td>
<td>17</td>
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<tr>
<td>210</td>
<td>17</td>
<td>14</td>
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<tr>
<td>225</td>
<td>17</td>
<td>13</td>
<td>17</td>
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<tr>
<td>240</td>
<td>17</td>
<td>13</td>
<td>17</td>
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<tr>
<td>255</td>
<td>16</td>
<td>11</td>
<td>17</td>
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<tr>
<td>270</td>
<td>16</td>
<td>11</td>
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<tr>
<td>285</td>
<td>16</td>
<td>11</td>
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<tr>
<td>300</td>
<td>15</td>
<td>11</td>
<td>17</td>
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<tr>
<td>315</td>
<td>14</td>
<td>9</td>
<td>17</td>
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<tr>
<td>330</td>
<td>13</td>
<td>8</td>
<td>17</td>
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<tr>
<td>345</td>
<td>12</td>
<td>7</td>
<td>17</td>
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<tr>
<td>360</td>
<td>12</td>
<td>6</td>
<td>17</td>
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<tr>
<td>375</td>
<td>12</td>
<td>5</td>
<td>17</td>
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<tr>
<td>390</td>
<td>12</td>
<td>2</td>
<td>17</td>
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<tr>
<td>405</td>
<td>12</td>
<td>2</td>
<td>17</td>
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<tr>
<td>420</td>
<td>12</td>
<td>2</td>
<td>17</td>
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<tr>
<td>435</td>
<td>11</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>450</td>
<td>10</td>
<td>2</td>
<td>17</td>
</tr>
</tbody>
</table>
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/cm³).

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.

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).

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

*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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