Comparison of Density and Water Content Determinations Using Soil Cores and a Dual Probe Density Gauge

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ABSTRACT

Wet bulk density and water content were determined with the standard soil-core method and by using a density and moisture gauge (gamma radiation and fast neutrons). Four soils collected at different forest sites were tested in the laboratory under different degrees of compression and at various water contents. Using the count ratios of the gauge for density and water as independent variables and wet bulk density and water content determined by soil cores as dependent variables, calibration equations were developed. For the soils used, the gauge values concerning wet bulk density were in close agreement with values determined with soil cores. However, the water content readings of the gauge had to be recalculated using the equations developed. The equations were tested on soil cores collected in the field after measurements with the gauge. The dry bulk density calculated as the wet bulk density given by the gauge minus the water content recalculated using the presented equations differed by an average of -1.6 percent from the soil-core values.

Keywords: *bulk density, calibration, strata gauge, radiation method.*

INTRODUCTION

Determining the bulk density of morainic till soils in forested areas of Sweden is a difficult task. Direct methods for determining bulk density and water content involve the sampling of a known volume of soil which is then weighed in both wet and dry states. Many methods for estimating the sampled soil volume have been developed, such as the soil-core method, the rubber balloon method, the sand replacement method and the clod method [5]. In addition, a method using a frame to get larger soil samples has been developed [10]. In the soil-core method, which is considered the standard, cylinders of known volume with sharpened edges are pressed or hammered into the soil, dug out and trimmed, whereupon their contents are weighed. This method is best suited for soft, cohesive soils with a medium to high water content [5]. On sorted agricultural soils, cores are usually easy to collect, but on morainic till soils there are many difficulties involved in sampling. These problems stem mainly from the abundance of coarse roots, gravel and stones, which get in the way and disturb the soil cores.

Compaction of the soil in the cores seems to be the largest source of error during sampling under favourable conditions [16]. Håkansson reported that the bulk density was higher in soil cores than in samples obtained using the frame method [10]. Using computer tomography (CT), Matthies, *et al.* showed that compaction may occur in cylinder cores at the time of sampling [15]. Raper and Erbach concluded that "it is disturbing that a method with this many inherent errors is referred to as a standard" [16]. In addition, the core method is labour-intensive and time consuming, and since the technique is destructive, replicates at the same position cannot be obtained.

To avoid problems associated with the estimation of the sampled soil volume, a method that does not involve soil removal, i.e. an indirect method, such as the radiation method, can be used. Since no soil is removed, measurements can be repeated at the same position which has several advantages. For instance, the effects of different numbers of passes by a vehicle can be assessed, and changes from year to year can be monitored. Furthermore, readings can quickly be obtained directly in the field, and the procedures are less time and labour consuming than soil coring. One drawback is that exposure to radiation may pose a health risk.

Commercially available gauges used for determining wet bulk density (BDW) and water content based on the radiation method are calibrated at the factory. Several workers have reported that these built-in equations need to be modified to suit the conditions under which the gauge is to be used [7], [12], [22], [17] and [23]. It has also been reported that soil texture affects water content readings [13], althoughother researchers did not find any sucheffects [18], [4], [19]. Due to the described drawbacks of the soil-core method, especially in forest stands, there has been increased interest in commercially available gauges. However, before they can be used more widely, issues concerning calibration needs and accuracy must be resolved.

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The aims of this study were to
- determine the bulk density and water content of several types of Swedish forest soils under controlled laboratory conditions using a commercially available density and moisture gauge as well as the standard soil-core method
- develop equations for calibrating the gauge so that values obtained are in accordance with soil-core measurements
- test the equations on a data-set collected in the field.

MATERIALS AND METHODS

Soils used in the laboratory study

Soils differing in textural composition (Table 1) were collected at different forest sites. After removal of the top layer of the soil including the A,-layer, the soil down to a depth of 30 cm was collected and hand-screened to remove roots and gravel. Soil type was determined according to the texture triangle. Water content was manipulated by wetting or drying the soils. Each soil was measured at 5 to 7 different water contents (Table 2) after compression using one of four different static pressures, i.e. 50, 100, 150 and 200 kPa.

tent determination. The count ratio (CR), i.e. the quotient obtained by dividing the amount of detected gamma radiation, which had passed between the source and the detector, by the amount determined in a standard block used as a reference, was used to calculate the BDW. The more compact the soil, the greater was the attenuation or scattering of the radiation, resulting in lower counts. Theoretical aspects of gamma-gauge operation are described in several publications, e.g. [21] and [17]. The water content was determined using the neutron method [9], in which fast neutrons (energy >1 keV) are emitted in the soil. In connection with collisions (elastic scattering) with hydrogen nuclei in the soil, energy is lost, and eventually the neutrons become thermalised (energy < 0.5 eV) and are counted by the detector. Since most of the hydrogen in the mineral fraction of a soil is present in the form of water molecules the amount of thermalised neutrons is proportional to the water content of the soil: the larger the amount of thermalised neutrons the higher the water content [9]. The counts are related to a standard count obtained in a reference block, and the quotient is used for calculating the water content. The quotient obtained by dividing the recorded count by the standard count is called the count ratio (CR).

Table 1. Particle size distributions and organic matter contents of the studied soils, $g \cdot kg^{-1}$.

Soil no.	1 (Sand)	2 (Loam)	3 (Sandy loam)	4 (Sandy loam)
Clay <0.002 mm	30	240	80	80
Silt 0.06-0.002 mm	20	490	300	180
Sand 2-0.06 mm	950	270	620	740
Organic matter	23	38	31	34

Table 2. Volumetric water contents (cm^3/cm^3) of soil cores (overall means).

Sample number	1 (Sand)	2 (Loam)	3 (Sandy loam)	4 (Sandy loam)
1	0.095	0.041	0.116	0.146
2	0.176	0.141	0.148	0.154
3	0.182	0.184	0.214	0.224
4	0.193	0.213	0.299	0.305
5	0.234	0.239	0.390	0.362
6	0.301	0.262		
7	0.357	0.400		

Density and moisture gauge

The Campbell Pacific Nuclear Dual Probe Strata gauge MC-S-24 [1] used was equipped with two radioactive sources: a Cs_{137} (370 MBq) gamma-emitter, for the determination of BDW, and an Am_{241}-Be (1900 MBq) source, emitting fast neutrons for the water con-

The gauge has two rods which can be lowered into the soil, in 5-cm intervals, down to a maximum depth of 60 cm. The rods move in guides that are rigidly attached to the instrument base. Thus a constant distance is kept between the gamma-source and the detector for any selected depth. The Cs_{137}-source is located in the tip of one probe, and the gamma ray detector (Geiger-Müller tube) is in the other one. The neutron source and the helium-3 detector, used for counting the thermalised neutrons, is located on the same probe as the gamma source. Before measurement, two parallel holes are made 30 cm apart in the soil using a sharpened rod and a special guide plate. Once the two probes have been lowered to the desired depth the measurements are started. The length of the measurement period, which can be adjusted, was 4 min. The gauge was calibrated in the calibration blocks supplied by the manufacturer before beginning the study.

BDW and water content are automatically calculated for direct read-out on the gauge display. The constants used for calculating BDW and water content with the built-in software of the gauge are varied within the uppermost 20 cm depending on the depth of measurement [1]. Dry bulk density is calculated by subtracting the water content from the BDW.

Cylinder cores

Stainless steel cylinders (height 51 mm, diameter 50 mm, volume 100 cm^3) were used. Soil cores were sampled with the help of a guide cylinder, which was placed on the soil layer and a hammering head. When necessary, a low-impact hammer was used. After sampling, the cores were sealed to avoid water loss. Fresh and dry weight after drying at 105" C to constant weight were determined, and water content was calculated.

Laboratory study

All measurements were made in a reinforced metal box (length 61 cm, width46 cm, height 36 cm, volume 100 dm^3) placed on the concrete floor in the laboratory. The box was filled with the appropriate soil following a stepwise procedure. First, the bottom third of the box was filled, whereupon the surface was carefully levelled, and the desired pressure was applied for 30 secs by using a reinforced lid and a hydraulic press. The load was measured with a load cell placed between the lid and the hydraulic piston and connected to an amplifier. Thereafter, the same amount of soil was added again, and the previous procedure was repeated. Finally the box was filled completely and the same pressure was applied once more.

Density and water content were measured at 5, 10, 15 and 20 cm depths. After finishing the gauge measurements, soil cores were sampled at 2.5-7.5, 7.5-12.5, 12.5-17.5, and 17.5-22.5 cm depth intervals. The soil cores were centred between the parallel holes for the gauge. The cores sampled at 2.5-7.5 and 12.5-17.5 cm depth were taken below each other near the right hole, while the cores sampled at 7.5-12.5 and 17.5-22.5 cm depth were collected below each other near the left hole. The whole procedure, i.e. filling the box and taking the measurements and the soil cores, was repeated once for each combination of water content and pressure.

Water content was varied by adding water to the soil or by letting it dry. The added water was carefully mixed into the soil which was then covered with a plastic sheet and left for a few days to allow the water content to equalise.

Second-order regression equations were developed where the BDW determined by soil coring was the dependent variable and CR was the independent variable [20]. The linear relationship between water content and CR [14] was used to establish regression equations with water content determined by soil coring as the dependent variable and the CR for the neutrons as the independent variable.

Equation tests

To test the equations developed on the basis of the laboratory analyses, a data set consisting of 30 secs measurements with the gauge and corresponding core measurement was collected in the field. The soil was a silt loam, (sand 174, silt 729, and clay 97 $g kg^{-1}$, according to the sieving analysis). In total, 45 pairs of measurements, taken at 10, 20, 30 and 40 cm depths, were included.

The relative difference (percent) between the methods was calculated as

$$R_{wet} = ((BDW_{strata} - BDW_{core}) / BDW_{core}) \times 100$$

where BDW_{strata} denotes wet bulk density determined by the strata-gauge and BDW_{core} denotes the wet bulk density determined by the core method.

The relative difference in water content was calculated in an analogous way.

Statistical treatment

Standard statistical analyses (pairwise t-test, ANOVA and linear regressions) were performed using the SAS package [2].

RESULTS

The BDW determined by the soil-core method varied between 1.24 and 2.08 gcm^{-3} among samples for study as a whole (Figure 1), whereas the corresponding range of values obtained using the density and moisture gauge was 1.29 - 1.96 gcm^{-3} (Figure 1).

The average difference between BDW means was small, 0.022 gcm^{-3} (1.4 percent) (Table 3), whereas for water content it was 0.06 cm^3/cm^3 (27 percent). Significant differences were found between methods for BDW, water content, and dry bulk density determinations ($p<0.001$, paired t-tests, not shown). High r^2-values were obtained for regression equations with BDW and water content determined using the soil-core method as dependent variables and the count ratios (CR) for density and water as independent variables (Tables 4 and 5). The ANOVA showed that differences in BDW and water content determinations between the two methods were not significantly affected by soil type. Therefore, it was possible to use the general equations on all soils. However, due to edge-effects, depth interval specific equations should be used.

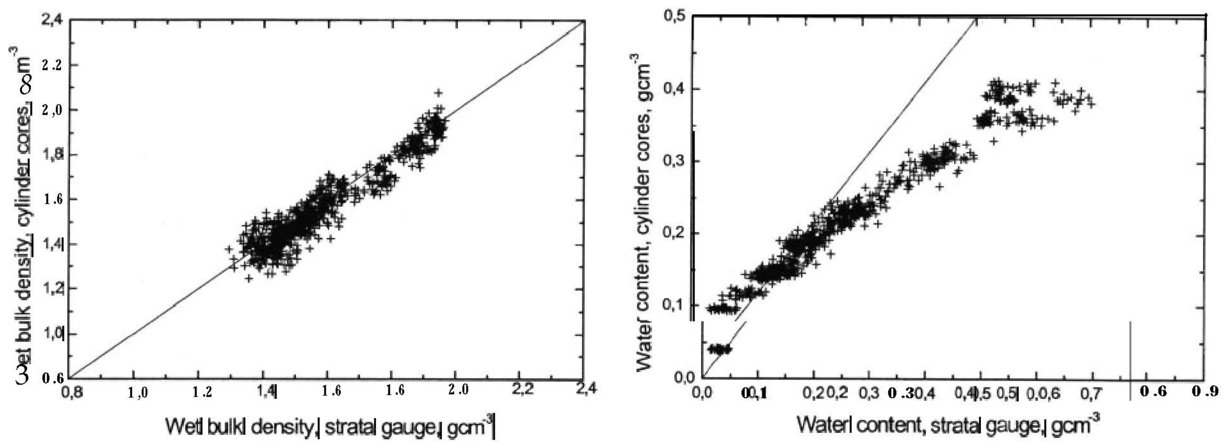

Figure 1. Relations between values of wet bulk density (left) and water content (right) obtained using the soil-core method and corresponding values registered with the strata-gauge. All data from the study are included. The straight line represents y=x.

Table 3. Overall means and coefficients of variation (C.V.) for the three variables measured. The total number of samples were 768.

Variable	Soil cores		Gauge	
	Mean	C.V., %	Mean	C.V., %
Wet bulk density, gcm^{-3}	1.578	11.9	1.600	11.5
Water content, cm^3/cm^3	0.224	41.7	0.284	58.4
Dry bulk density, gcm^{-3}	1.354	8.9	1.316	5.7

Table 4. Linear regressions relating wet bulk density, gcm^{-3} determined by the soil-core method to the corresponding count ratio. BDW = a + b CR_{wet} + c $(CR_{wet})^2$, where CR_{wet} is the density count divided by the standard count

Soil no.	Depth	n	a	Rob.	b	Rob.	c	Prob.	r^2adj
	15	56	2.5658	0.0001	-2.2524	0.0016	0.9434	0.1124	0.82
1	10	56	2.6846	0.0001	-2.6054	0.0001	1.3118	0.0033	0.83
1	15	56	2.6585	0.0001	-2.4326	0.0001	1.1605	0.0132	0.81
1	20	56	2.6486	0.0001	-2.3981	0.0001	1.0887	0.0180	0.81
2	5	56	3.0721	0.0001	-4.0069	0.0001	2.3287	0.0001	0.93
2	10	56	2.9436	0.0001	-3.2615	0.0001	1.6741	0.0001	0.94
2	15	56	2.9192	0.0001	-3.0994	0.0001	1.5133	0.0001	0.91
2	20	56	2.6849	0.0001	-2.3539	0.0001	0.9799	0.0004	0.94
3	5	40	2.7296	0.0001	-2.8889	0.0001	1.5129	0.0006	0.95
3	10	40	2.6359	0.0001	-2.3569	0.0001	1.0597	0.0134	0.95
3	15	40	2.7642	0.0001	-2.8973	0.0001	1.6022	0.0011	0.92
3	20	40	2.7085	0.0001	-2.6745	0.0001	1.4008	0.0018	0.93
4	5	40	3.0919	0.0001	-4.1228	0.0001	2.5629	0.0001	0.97
4	10	40	2.9840	0.0001	-3.4271	0.0001	1.8519	0.0001	0.96
4	15	40	2.8481	0.0001	-2.8926	0.0001	1.4426	0.0001	0.96
4	20	40	2.8718	0.0001	-3.0221	0.0001	1.5582	0.0001	0.95
Overall	5	192	2.8099	0.0001	-3.0897	0.0001	1.6154	0.0001	0.92
overall	10	192	2.7753	0.0001	-2.7837	0.0001	1.3639	0.0001	0.93
overall	15	192	2.6902	0.0001	-2.4420	0.0001	1.0921	0.0001	0.91
Overall	20	192	2.6880	0.0001	-2.4641	0.0001	1.1217	0.0001	0.92

Table 5. Linear regressions relating water content, gcm^{-3} determined by the soil-core method to the corresponding count ratio. WC = d + f CR_{H2O} where CR_{H2O} is the neutron count divided by the standard count.

Soil no.	Depth	n	d	Prob.	f	Prob.	r^2adj
1	5	56	0.0942	0.0001	0.6065	0.0001	0.95
1	10	56	0.0882	0.0001	0,1359	0.0001	0.96
1	15	56	0.0729	0.0001	0.0760	0.0001	0.98
1	20	56	0.0514	0.0001	0.0710	0.0001	0.99
2	5	56	0.0491	0.0001	0.8142	0.0001	0.98
2	10	56	0.0461	0.0001	0.1789	0.0001	0.98
2	15	56	0.0311	0.0001	0.0950	0.0001	0.98
2	20	56	0.0143	0.0001	0.0869	0.0001	0.99
3	5	40	0.0837	0.0001	0.6432	0.0001	0.99
3	10	40	0.0783	0.0001	0.1398	0.0001	0.99
3	15	40	0.0631	0.0001	0.0770	0.0001	0.99
3	20	40	0.0365	0.0001	0.0738	0.0001	0.99
4	5	40	0.0972	0.0001	0.5730	0.0001	0.97
4	10	40	0.0779	0,0001	0.1408	0.0001	0.99
4	15	40	0.0632	0.0001	0.0785	0.0001	0.99
4	20	40	0.0392	0.0001	0.0754	0.0001	0.99
Overall	5	192	0.0820	0.0001	0.6504	0.0001	0.95
Overall	10	192	0.0729	0.0001	0.1482	0.0001	0.97
overall	15	192	0.0569	0.0001	0.0818	0.0001	0.98
Overall	20	192	0.0351	0.0001	0.0769	0.0001	0.98

The relative difference in water content determinations between methods was negative for water contents below approximately 0.15 cm^3/cm^3 and positive for higher water contents (Figure 2). In other words, using the strata-gauge and the original equations to determine the water content of a dry soil will result in underestimates, whereas the same procedures used on a moist soil would result in an overestimate.

Tests on field-collected soil

In the comparisons, the original equations and the overall equations (from hereon referred to as "adjusted equations") presented in Tables 4 and 5 were used. The wet bulk density for the cores collected varied between 1.5 and 2.1 gcm^{-3}, while the water content ranged from 0.26 to 0.44 cm^3/cm^3. The average deviation in the determination of BDW between the gauge (using the original equations) and the cores was -1.5 percent (non-significant). Use of the adjusted equations increased the deviation to -5.3 percent. The corresponding deviation in the determination of the water content was 60.3 percent (original equations) and 8.2 percent (adjusted equations). Use of the dry bulk density calculated by subtracting the water content (adjusted equations) from the original gauge values resulted in an average difference of -1.6 percent compared with soil core values. The dry bulk density calculated using the original wet density equations and water content (adjusted equations) differed significantly from the corresponding value obtained using the soil-core method (paired t-tests, $p<0.018$). In addition, water content determinations made with the adjusted gauge values differed significantly from those obtained with the cylinder values ($p<0.030$).

DISCUSSION

Although the two methods differed significantly in terms of their BDW determinations (paired t-tests), the absolute difference was so small that the original equations can be used. However, there were large differences between water contents determined with the gauge and those determined using the soil-core method, and the magnitude of the differences varied with the water content. Therefore, it is necessary to correct the water content readings before calculating the dry bulk density. In the factory calibration for the water content determination plastic blocks are used. The hydrogen in this material is supposed to correspond to a certain volumetric water content. In this work, however, it was shown that, at least for the investigated soils, this was not a good calibration. On the other hand, there was a strong relationship between CR and gravimetrically determined water content, thus it was easy to correct the gauge water readings.

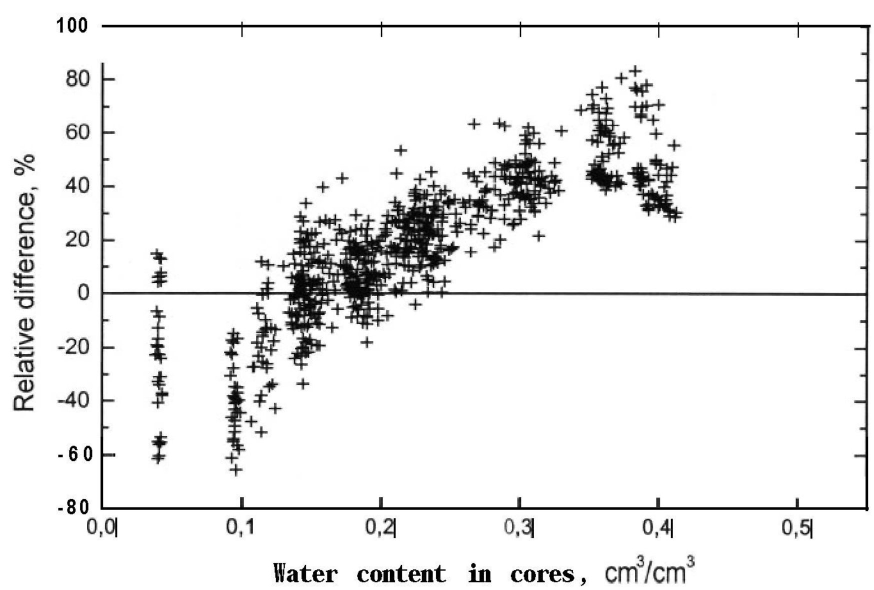

Figure 2. Relative deviation between water content determined using the soil-core method and the value obtained with the strata-gauge, percent.

The development of calibration equations in this study was based on the assumption that the core sampling results were accurate. An important factor influencing accuracy is the relationship between the length of the core and its diameter [5]. To restrict wall-friction effects. Koolen recommended length/diameter values of 0.59 to 0.33 for compression tests [11], whereas others recommend a length not more than three times the diameter [5]. The cylinders used had a relatively large length/diameter ratio, so it is likely that the soil was slightly compacted during sampling. On the other hand, the laboratory soils in this study were easy to sample, and no disturbing factors, such as roots or stones, were present. Thus measurement accuracy should have been higher in the laboratory than during field sampling.

When using an indirect method, such as the gamma radiation method, the soil volume influencing the readings is not known. The thickness of the gamma beam is inversely proportional to the density of the soil and varies in thickness from 5.1 to 10.2 cm in the centre of the beam [3]. Hence, the floor on which the box was placed during the measurements should not have influenced the results. The use of push rods to prepare holes for the gauge may disturb the soil and thereby affect the readings. However, no sign of any such disturbance was found by [3].

Similarly, the soil volume influencing the water content readings is unknown. The drier the soil the larger is the sphere within which thermalisation of the neutrons can occur. The sphere of influence for the neutrons is reported to have a radius of 7.5 cm to 25 cm [6]. Gardner, et *al.* reported a radius of 15 cm to 50 cm as the sphere of importance [8]. Edge effects may have influenced the values obtained in the present study since the closest distance from the source/detector to the box wall was 15 cm. Problems may also arise in cases where steep gradients in water content are present in a soil. In this study the soil in the box had a uniform water content, therefore minimising problems of this kind.

Kremer developed calibration equations based on soil cores and field measurements made using the same model of density and moisture gauge that was used in the present study [12]. Using those equations to calculate water contents based on CR readings from the field data, and comparing the values obtained with water contents calculated by using the adjusted equations from this study resulted in an average difference of -0.035 cm^3/cm^3 (9 percent). This indicates that the effects of the box walls were minor at most.

The use of field data to validate the equations yielded satisfactory results. The average difference in dry bulk density determination was -1.6 percent compared with soil cores. For the wet bulk density there was good agreement between values obtained with the original equation and those determined with the soil-core method. As in the laboratory study the correspondence between core-determined water content and the gauge readings was poor. Since the water content was rather high the gauge overestimated the real water content (Figure 2).

In conclusion, the density and moisture gauge is a useful tool for determining soil bulk density and water content. For the soils investigated in this study there was no need to correct the wet bulk density given by the gauge. By contrast, the water content readings had to be corrected before calculating the dry bulk density. Good correspondence was found between the soil-core measurements of the dry bulk density of soil collected in the field and gauge readings after correcting the water content values.

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