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4/28/92

METHODS OF SOIL ANALYSIS

Part 1

Physical and Mineralogical Methods

Second Edition

Arnold Klute, *Editor*

Number 9 (Part 1) in the series
AGRONOMY

American Society of Agronomy, Inc.
Soil Science Society of America, Inc.
Publisher
Madison, Wisconsin USA

1986

EXHIBIT
tabbies
92

Reprinted in 1987, 1990 and 1994.

American Society of Agronomy, Inc.
Soil Science Society of America, Inc.
677 South Segoe Road, Madison, Wisconsin 53711 USA

Library of Congress Cataloging in Publication Data

(Revised for no. 9, pt. 1)

Methods of soil analysis.

(Agronomy; no. 9)
Includes bibliographies and indexes.
Contents: pt. 1. Physical and mineralogical methods—pt. 2. Chemical and microbiological properties.
1. Soils—Analysis—Collected works. I. Page, A.L. (Albert Lee), 1927- . II. Miller, R. H., 1933- . III. Keeney, Dennis R. IV. Series.
S593.M4453 1982 631.4'1'0287 82-22630
ISBN 0-89118-088-5 (pt. 1)
ISBN 0-89118-072-9 (pt.2)

Printed in the United States of America

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13 Bulk Density[1]

G. R. BLAKE
University of Minnesota
St. Paul, Minnesota

K. H. HARTGE
University of Hanover
Hanover, Federal Republic of Germany

13-1 GENERAL INTRODUCTION

Soil *bulk density*, ρ_b, is the ratio of the mass of dry solids to the bulk volume of the soil. The bulk volume includes the volume of the solids and of the pore space. The mass is determined after drying to constant weight at 105 °C, and the volume is that of the sample as taken in the field.

Bulk density is a widely used value. It is needed for converting water percentage by weight to content by volume, for calculating porosity and void ratio when the particle density is known, and for estimating the weight of a volume of soil too large to weigh conveniently, such as the weight of a furrow slice or an acre-foot.

Bulk density is not an invariant quantity for a given soil. It varies with structural condition of the soil, particularly that related to packing. For this reason it is often used as a measure of soil structure. In swelling soils it varies with the water content (Hartge, 1965, 1968). In such soils, the bulk density obtained should be accompanied by the water content of the soil at the time of sampling.

The determination usually consists of drying and weighing a soil sample, the volume of which is known (core method) or must be determined (clod method and excavation method). These methods differ in the way the soil sample is obtained and its volume determined. A different principle is employed with the radiation method. Transmitted or scattered gamma radiation is measured; and with suitable calibration, the density of the combined gaseous-liquid-solid components of a soil mass is determined. Correction is then necessary to remove the components of density attributable to liquid and gas that are present. The radiation method is an in situ method.

[1] Paper no. 11718 of the Scientific Journal Series, Minnesota Agricultural Experiment Station, St. Paul, MN.

Clod and core methods have been used for many years. Excavation methods were developed in recent years, chiefly by soil engineers for bituminous and gravelly material. More recently the excavation method has found use in tillage research where surface soil is often too loose to allow core sampling, or where abundant stones preclude the use of core samplers. Radiation methods have been used since the 1950s, particularly in soil engineering.

Bulk density is expressed in SI units or units derived from them. The most straightforward would be kg m^{-3}. However, derived units such as tons m^{-3}, g cm^{-3}, or Mg m^{-3}, which are numerically equal to each other, may be more convenient, as they give values for soils which vary from about 1.2 to 1.7 (rather than from 1200 to 1700, as when units of kg m^{-3} are used). Obsolete terms such as "volume weight" (weight · $volume^{-1}$) and "bulk specific gravity" or "apparent specific gravity" are sometimes found in the older literature and in some foreign language literature. Specific gravity terms are relative densities, i.e. density of a substance with respect to water at 4°C, and are nearly equal numerically to bulk density. At standard gravitation (g = 9.8 m s^{-2}), kilogram weight and kilogram mass are equal, and under this condition "volume weight" is numerically equal to bulk density. In many engineering and commercial applications, bulk density is expressed in lb ft^{-3}, which one may convert to g cm^{-3} by dividing by 62.4 (which is the mass, in pounds, of a cubic foot of a substance whose density is unity, i.e., water at 4 °C).

13–2 CORE METHOD

13–2.1 Introduction

With this method, a cylindrical metal sampler is pressed or driven into the soil to the desired depth and is carefully removed to preserve a known volume of sample as it existed in situ. The sample is dried to 105 °C and weighed. The core method is usually unsatisfactory if more than an occasional stone is present in the soil.

13–2.2 Method

Core samplers vary in design from a thin-walled metal cylinder to a cylindrical sleeve with removable sample cylinders that fit inside. Samplers are usually designed not only to remove a relatively undisturbed sample of soil from a profile, but also to hold the sample during transport and eventually during further measurements in the laboratory, such as pore-size distribution or hydraulic conductivity. For the latter measurement it is desirable to have core diameters not less than 75 mm and preferably 100 mm to minimize the effect of disturbed soil interfacing the cylinder wall. For the same reason it is desirable that the height of the cylinder not exceed the diameter.

A widely used and very satisfactory sampler consists of two cylinders fitted one inside the other. The outer one extends above and below the inner to accept a hammer or press at the upper end and to form a cutting edge at the lower. The inside cylinder is the sample holder. The inside diameters of the two cylinders when nested are essentially the same at the lower end, the inner being fitted against a shoulder cut on the inner surface of the outside cylinder. Figure 13–1 shows such a sampler (available in slightly different design from the Utah State University Technical Services, UMC 12, Logan, UT 84322).

Where densities at various depths in a soil profile are to be determined, one can obtain samples with a hydraulically driven probe mounted on a pickup truck, tractor, or other vehicle. The probe is forced into the soil and removed hydraulically. The probe tube has a 2- to 3-cm wide slit running most of the length of the tube, through which one can insert a rounded knife or spatula to slice off segments of the soil as desired. Segments typically 10 cm in length are cut and removed from the tube and placed in containers for transport to the laboratory. Depending on the probe model, samples can be taken to about 1-m depth, though extensions for greater depths are available for many models. Probe samplers are available from Giddings Machine Co., P.O. Drawer 2024, 401 Pine St., Fort Collins, CO 80522; A. D. Bull Enterprizes, 1904 South 21st Street, Chickasha, OK 73018; or Soiltest Inc., 2205 Lee St., Evanston, IL 60202.

Fig. 13–1. Typical double-cylinder, hammer-driven core sampler, for obtaining soil samples for bulk density.

Numerous hand-driven samplers have been described in the literature. Some of the more accessible ones are described by Lutz (1947), Jamison et al. (1950), and U.S. Department of Agriculture (1954, p. 159). McIntyre (1974) describes types of core samples and their properties and gives additional references.

13–2.2.1 PROCEDURE

The exact procedure for obtaining the samples depends on the kind of sampler used. The following steps apply when the widely known double-cylinder sampler is used.

Drive or press the sampler into either a vertical or horizontal soil surface far enough to fill the sampler, but not so far as to compress the soil in the confined space of the sampler. Carefully remove the sampler and its contents so as to preserve the natural structure and packing of the soil as nearly as possible. A shovel, alongside and under the sampler, may be needed in some soils to remove the sample without disturbance. Separate the two cylinders, retaining the undisturbed soil in the inner cylinder. Trim the soil extending beyond each end of the sample holder (inner cylinder) flush with each end with a straight-edged knife or sharp spatula. The soil sample volume is thus established to be the same as the volume of the sample holder. In some sampler designs, the cutting edge of the sampler has an inside diameter slightly less than the sample holder, so as to reduce friction as the soil enters the holder. In these cases, determine the diameter of the cutting head and use this to calculate the sample holder volume. Transfer the soil to a container, place it in an oven at 105 °C until constant weight is reached, and weigh it. The bulk density is the oven-dry mass of the sample divided by the sample volume.

13–2.2.2 COMMENTS

It is not necessary that soil be kept undisturbed during transport to the laboratory and drying. A single sample cylinder can be reused if each sample is transferred to another container. It is often desired, however, to make other measurements such as pore-size distribution, conductivity, or water retention in addition to bulk density on the same samples. These require that they be kept undisturbed, each sample being transported in the sample cylinder in which it was taken. Thus one must provide for sufficient cylinders. Frequently other measurements to be made in the laboratory require that samples be kept at field water-content. In that case cylinders must be placed in containers that do not permit loss of water during transport. Waxed paper or plastic containers with lids are satisfactory for this purpose.

Core samples should be taken in soils of medium water content. In wet soils, friction along the sides of the sampler and vibrations due to hammering are likely to result in viscous flow of the soil and thus in compression of the sample. When this occurs the sample obtained is unrepresentative, being more dense than the body of the soil. Compression may occur even in dry soils if they are very loose. Whenever a sample is taken, one should carefully observe whether the soil elevation inside the sampler is the same as the undisturbed surface outside the sampler. One can only roughly estimate in this manner whether the density of the sample is changing because of sampling.

In dry or hard soils hammering the sampler into the soil often shatters the sample, and an actual loosening during sampling may occur. Pressing the sampler into the soil usually avoids the vibration that causes this shattering. Close examination of the soil sample usually allows one to estimate whether serious shattering occurs. And, as in the case of wet soils, soil level inside and outside the sampler must remain the same if the sample is to be considered satisfactory. (see also McIntyre, 1974.)

13–3 EXCAVATION METHOD

13–3.1 Introduction

Bulk density is determined in this method by excavating a quantity of soil, drying and weighing it, and determining the volume of the excavation. In the sand-funnel method, the volume is determined by filling the hole with sand, of which the volume per unit mass is known. In the rubber-balloon method, the volume is determined by inserting a balloon into the excavation and filling it with water or other fluid until the excavation is just full. The volume of the excavated soil sample is then equal to the volume of the fluid dispensed. If the excavation is carefully done it is possible simply to measure its dimensions and calculate the volume. Mensuration apparatus is described that enables one to determine the volume of an irregular excavation.

13–3.2 Method (ASTM, 1958, p. 422–441)

13–3.2.1 SPECIAL APPARATUS

13–3.2.1.1. Sand-Funnel Apparatus (see Fig. 13–2) (Soiltest, Inc., 2205 Lee Street, Evanston, IL 60202).

1. A metal funnel 15 to 18 cm at its largest diameter, fitted with a valve on the stem. Attached to the stem when the funnel is inverted is a sand container.
2. A standard sand that is clean, dry, and free-flowing. Particle size should be fairly uniform to avoid possible separation in the dispenser with consequent error in calibration. Sand particles passing a no. 20 sieve and retained on a no. 60 sieve are recommended (0.841–0.25 mm).
3. A template consisting of a thin, flat, metal plate approximately 30 cm square, with a hole 10 to 12 cm in diameter in its center.
4. Scales to weigh to 5 g.

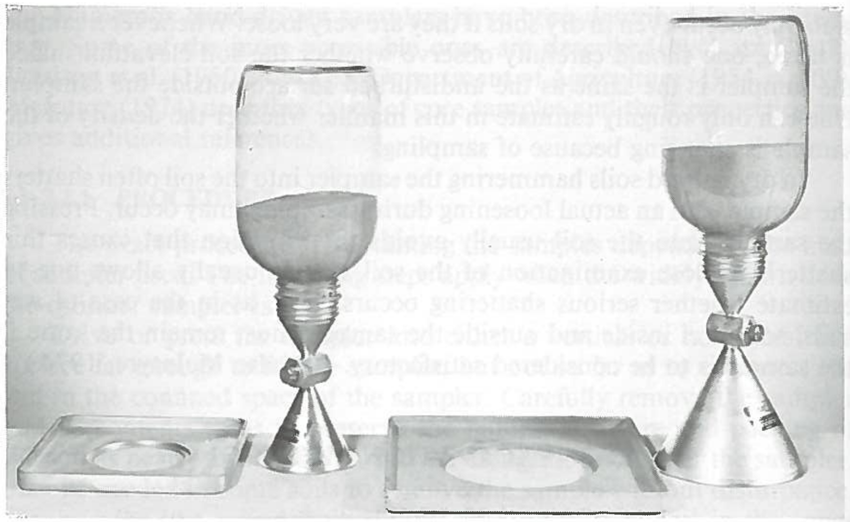

Fig. 13–2. Apparatus for sand-funnel technique of determining soil bulk density in place.

13–3.2.1.2. Rubber-Balloon Apparatus.

1. A thin-walled rubber balloon (may be purchased from Barr Inc., 1531 First Street, Sandusky, OH 44870, and the Anderson Rubber Co., 310-T N. Howard Street, P.O. Box 170 Akron, OH 44309).
2. A 1000-cm^3 graduated cylinder and a water container.
3. A template, described in section 13–3.2.1.1 (3).

Rubber-balloon density apparatus is available from several manufacturers supplying soil testing equipment. (One supplier is Soiltest, Inc., 2205 Lee Street, Evanston, IL 60202.) The apparatus made commercially has the convenience of a volumetrically calibrated water container-dispenser, with suction facilities for returning the water to the container for re-use (Fig. 13–3).

13–3.2.1.3 Mensuration Apparatus.

1. Tape measure marked in millimeters.
2. Flat metal plate approximately 50 cm square, with 30 to 40 evenly spaced holes forming a grid through which the tape measure can be inserted. Alternatively, 3 wooden beams 3 by 3 by 80 cm with 5-cm markings may be used.
3. Four wood stakes approximately 10 cm long, one end sharpened.
4. Scales to weigh to approximately 10 g.

13–3.2.2. PROCEDURE

13–3.2.2.1. Sand-Funnel Procedure. Level the soil surface and remove loose soil at the test site. Place the template on the soil. Excavate a soil sample through the center hole of the template, leaving a hole with a diameter of approximately 12 cm and a depth of approximately 12 cm,

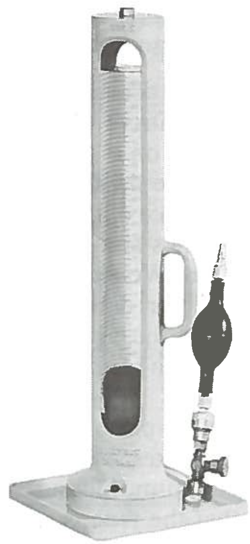

Fig. 13–3. Apparatus for determining soil bulk density in place by the rubber-balloon technique.

or other value as desired. A large spoon is convenient for excavating. Recover all evacuated soil in a container, being careful to include any loose soil that has fallen in from the sides of the excavation. Determine the oven-dry soil mass including stones by drying the soil to 105 °C and weighing it.

Determine the volume of the test hole by filling it with sand to the level of the bottom of the template. Level the sand with a spatula if necessary, but disturb it as little as possible to avoid packing the free-flowing sand. (Dispensing the sand through a funnel placed on the template, as is done with commercially available equipment, avoids the problem of leveling the sand. The excavation as well as the funnel is filled by free flow of sand, the predetermined weight required to fill the funnel being subtracted as a tare.)

Determine the weight of sand required to fill the test excavation by weighing it to the nearest 5 g. Precalibrate the mass-to-volume ratio of sand by letting sand fall from a similar height and at a similar rate of flow as in the test procedure. Using the calibration curve or values derived from it, determine the volume of the excavation from the measured mass of sand dispensed.

13–3.2.2.2. Rubber-Balloon Procedure. Level the soil surface, place the template on the surface, and excavate a soil sample as described in the preceding section. Place the rubber balloon in the test hole and fill the balloon with water to the bottom of the template. Determine the volume of water required to the nearest 2 cm^3. (A 1000-cm^3 graduate has markings to 10 cm^3, but one can estimate to 2 cm^3 if the graduate is placed on a horizontal surface.)

Calculate bulk density from the oven-dry mass of the excavated sample and the volume of the test excavation.

13–3.2.2.3. Mensuration Procedure. Prepare the soil surface as described in previous procedures. Drive wooden stakes into the soil at four corners of a square about 40 cm on a side, allowing them to project 1 to 3 cm above the soil surface. Place the metal plate on the stakes. Measure the distance from the upper surface of the plate to the soil surface through each of the holes. Remove plates and excavate soil from an area about 30 by 30 cm to a depth of 10 cm. Weigh the soil including stones. Remove an aliquot of reasonable size for determination of water content and discard the remainder. Replace the plate on the stakes and measure the distance from the top of the plate to the excavated surface through each of the holes as before.

If wooden beams are used in place of a metal plate, place two beams parallel, each resting on two stakes. With the third beam, bridge across the other two and from this datum, measure distance to the soil surface on a 5-cm grid using care that the tape is perpendicular to the beam. As above, excavate the soil sample and again measure distance from the third beam to excavated soil surface on a 5-cm grid. Weigh the soil including stones. Remove an aliquot for water-content measurement and discard the remainder of the excavated soil.

Calculate bulk density, ρ_b, from the weight of the soil corrected to oven dryness and the volume of the excavated soil. The volume is determined by summing the volumes around each depth measurement as follows:

$$V = (\Sigma d - \Sigma d_0)A$$

where

d = depth after excavation,

d_0 = depth before excavation, and

A = area covered by each measurement of the ruler. If holes are on 5-cm centers in the plate or measurements are made at 5-cm centers with the wooden beams, A = 25 cm^2.

By subsequent excavation of deeper layers in the same holes, one can determine bulk density deeper in the profile by measurements from the same datum.

13–3.2.3 COMMENTS

Bulk density can be estimated accurately by excavation methods carried out carefully. Holes should have smooth, rounded walls. Protruding stones should be included in the sample, care being used to round and smooth the area from which stones are taken. A heavy pair of scissors can be used to cut roots at the wall surface so the surrounding soil is undisturbed.

The relatively large sample (a cylinder of 12-cm diameter and of 12-cm depth has a volume of 1357 cm^3) has the advantage that small errors

Table 13–1. Comparison of surface nuclear gauge and sand-cone method for determining soil bulk density (Mintzer, 1961).

Soil material	Number of comparisons	Mean difference	Extreme difference
		%†	
	Wet bulk density, ρ_{bw}		
Brown sand, trace silt	9	2.03	−0.25–4.28
Brown silt and clay	4	0.89	−0.64–1.87
Brown sand and gravel, some silt, trace clay	6	1.01	−2.27–7.75
Brown till	4	−1.19	−3.97–1.60
	Dry bulk density, ρ_b		
Brown sand, trace silt	9	2.05	−1.21–4.98
Brown silt and clay	4	7.21	5.51–9.27
Brown sand and gravel, some silt, trace clay	6	1.48	−1.71–8.32
Brown till	4	−0.38	−4.53–3.21

† A positive value indicates nuclear method gave higher bulk density value.

in measuring water volumes or sand weights are insignificant. The disadvantage is the lack of discrimination to a localized horizon. An error of 5 cm^3 in liquid volume will give an error of 0.005 in a sample having a bulk density of 1.36 g cm^{-3}. Though one determines the water dispensed to perhaps 2 cm^3, a much greater source of error in water measurement arises in determining when the water in the excavation is level with the bottom of the template. Extreme care and judgment are required in this. The volume of the balloon itself, being of the order of 2 cm^3, will give a considerably smaller error than the volume measurement, and can be neglected.

An error of 7 g in weighing the sand gives an error of 0.005 if the bulk density is 1.36 g cm^{-3}. As in the balloon technique, greater error is likely to result in the precision with which one can determine the sand level at the bottom of the template. An error of 1 mm in this level will result in an error of 0.01 in the bulk density. Extreme care is therefore required to assure that the sand level is at the template bottom. The need for the dispensing funnel in reducing this error is obvious.

If one assumes an excavation of 30 by 30 by 10 cm in the mensuration method and measures depth 36 times on a 5-cm grid, assuming a cumulative error of 1 mm in each of the depth measurements the error in volume measurement is 1%.

A comparison of the sand-funnel and radiation methods was made by Mintzer (1961), and the results are summarized in Table 13–1.

13–4 CLOD METHOD

13–4.1 Introduction

The bulk density of clods, or coarse peds, can be calculated from their mass and volume. The volume may be determined by coating a clod of known weight with a water-repellent substance and by weighing it first in air, then again while immersed in a liquid of known density, making use of Archimedes' principle. The clod or ped must be sufficiently stable to cohere during coating, weighing and handling.

13–4.2 Method

13–4.2.1 SPECIAL APPARATUS

1. A balance, modified to accept the clod suspended below the balance arm by means of a nylon thread or thin wire, to allow weighing the clod when it is suspended in a container of liquid.
2. A fine nylon thread or 28 to 30 gauge wire, to attach the clod to the balance. A fine nylon hairnet makes a good container for the clod.
3. Saran solution. Dissolve 1 part by weight of Saran resin (Dow Saran F-310; Dow Chemical Co., Suite 500/ Tower No. 2, 1701 West Golf Road, Rolling Meadows, IL 60008) in 7 parts by weight of methylethyl ketone in a 1-gallon container in sufficient quantities to fill the container about three-quarters full. Manufacturer's instructions for safe handling of solvents should be carefully followed. Dissolution requires about an hour, with vigorous stirring. Since the solvent is flammable and explosive when its vapors are mixed with air, either hand-stirring or use of an air-driven stirrer should be employed in a well ventilated hood. The solution can be stored for long periods if kept in a tightly closed container to prevent evaporation of the solvent.

13–4.2.2 PROCEDURE

Secure the clod with two loops of the thread or wire, loops being at right angles to one another, leaving sufficient thread or wire to connect to the balance arm. Weigh the clod and thread. Holding it by the thread, dip the clod into the saran solution. Suspend it in air under a hood for 15 to 30 min to allow the solvent to evaporate. Repeat dipping and drying one or more times as needed, to waterproof the clod. Weigh the clod, with its coating and the thread. Weigh it again when it is suspended in water and note the water temperature. Determine the tare weight of the thread or wire. To obtain a correction for water content of the soil, break open the clod, remove an aliquot of soil, and weigh the aliquot before and after oven-drying it at 105 °C.

Calculate the oven-dry mass of the soil sample W_{ods} as follows, from the water content of the aliquot removed from the clod after other weights are taken:

$$W_{ods} = W_{sa}/(1 + \theta_w)$$

where θ = water content of the subsample in g/g and W_{sa} = net weight of clod or ped in air at its original water content.

Calculate bulk density as follows:

$$\rho_b = \rho_w W_{ods}/[W_{sa} - W_{spw} + W_{pa} - (W_{pa}\rho_w/\rho_p)]$$

where

ρ_w = density of water at temperature of determination,
W_{ods} = oven-dry weight of soil sample (clod or ped),
W_{sa} = net weight of clod or ped in air,
W_{spw} = net weight of soil sample plus saran in water,
W_{pa} = weight of saran coating in air, and
ρ_p = density of saran.

13–4.2.3 COMMENTS

The clod method usually gives higher bulk-density values than do other methods (Tisdall, 1951). One reason is that the clod method does not take the interclod spaces into account.

Extreme care should be exercised to get naturally occurring masses of soil. Clods on or near the soil surface are likely to be unrepresentative, for these are often formed by packing with tillage implements. Natural soil masses, or coarse peds, that are more representative should be sought.

If bubbles appear on the saran when the sample is weighed in water or if the weight in water increases with time, water is penetrating the clod, and the sample must be discarded.

Brasher et al. (1966) first proposed use of saran coating. They suggested that for clods with large pores, a more viscous saran solution of 1 part resin to as little as 4 parts methylethyl ketone could be used. They gave the density of saran to be 1.3 g cm^{-3}.

Precision in calculating the bulk density would require a correction for the difference of the weight of the wire in air and in water. However, the error is negligible with thread or a 28-gauge wire.

Using clods as small as 40 g oven-dry weight and weighing to 10 mg gives a standard deviation in the bulk density with 25 replications of a single measurement of 0.07 g cm^{-3} (Hartge, 1965). This can be reduced by using larger clods or by weighing to 1 mg or both. Obviously, using a greater number of samples for a determination would also reduce the standard deviation.

Several other substances have been used to seal the clod against water, including paraffin, rubber, wax mixtures, and oils.

13–5 RADIATION METHODS

13–5.1 Introduction

The transmission of gamma radiation through soil or scattering within soil varies with soil properties, including bulk density. By suitable calibration, measurements of either transmission or scattering of gamma radiation can be used to estimate bulk density.

In the transmission technique, two probes at a fixed spacing are lowered into previously prepared openings in the soil. One probe contains a Geiger tube, which detects the radiation transmitted through the soil from the gamma source located in the second probe. The scattering technique employs a single probe containing both gamma source and detector separated by shielding in the probe. It can be used either at the soil surface or placed in a hole, depending on design of the equipment.

Radiation methods have several advantages, among which are minimum disturbance of the soil, short time required for sampling, accessibility to subsoil measurement with minimum excavation, and the possibility of continuous or repeated measurements at the same point.

Both transmission and scattering techniques measure the bulk density of all components combined. The densities of gaseous components are insignificant in comparison to those of the solid or liquid components, and can therefore be ignored. It is necessary, however, to determine the water content of the soil at sampling time and to apply a correction to obtain bulk density on a dry soil basis.

13–5.2 Methods

13–5.2.1 SPECIAL APPARATUS

Transmission apparatus is supplied by Troxler Electronics Laboratories, P.O. Box 12057, Cornwallis Road, Research Triangle Park, NC 27709, following a design by Vomocil (1954). A design, including a discussion of the theory of the method, calibration, and methods of making measurements was included in the first edition of *Methods of Soil Analysis*, Part 1 (Blake, 1965).

Scattering apparatus is supplied by Troxler Electronic Laboratories, P.O. Box 12057, Cornwallis Road, Research Triangle Park, NC 27709 and by Soiltest Inc., 2205 Lee Street, Evanston, IL 60202.

13–5.2.2 PROCEDURE

It is recommended that the instructions supplied with the commercial apparatus be followed. One may also wish to refer to the first edition of *Methods of Soil Analysis,* Part 1 (Blake, 1965).

13–5.2.3 COMMENTS

There is some radiation hazard with these methods. Gamma photons are high-energy radiation. Some will pass through several centimeters of lead shielding. Commercially available equipment, as well as designs described in the literature, reduce the hazard to safe levels. But it is important to adhere strictly to time limits, distances, and other conditions described by the manufacturers. One should be equipped for and knowledgeable in means of checking the equipment for radiation levels ac-

cording to the way it is handled in actual sampling. If there is doubt, the equipment should be checked for safety by a competent testing laboratory.

Since radiation transmitted from a source to a detector is dependent on probe spacing or sample thickness, care must be exercised with the two-probe sampler to assure that access holes are parallel and spaced exactly as in the calibration.

Mintzer (1961) reported comparisons of the surface-density probe and the sand-cone method on four engineering projects. He reported his comparisons on both the wet and dry bulk-density bases. He used a surface neutron meter for water content where the surface-density probe was used. His results are summarized in Table 13–1.

13–6 REFERENCES

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