Synthesizing Bulk Density for Soils with Abundant Rock Fragments

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ABSTRACT

Bulk density is a fundamental soil property that is difficult to determine for gravelly to extremely gravelly soils because results vary significantly with sample volume. For such coarse soils, the representative volume (for whole-soil bulk density) should be large, but guidelines for selecting an appropriate sample volume do not exist. We evaluate the representative volume for a soil with abundant rock fragments, by comparing measured properties of samples ranging in volume from 0.03 to 410 liters, For whole-soil bulk density determination, the representative volume is 4 liters or larger for a soil horizon containing 34% gravel (by volume) and is between 5 and 50 liters for a soil horizon containing 54% gravel. Intact-samples of that size are prohibitively large, so an alternative approach is developed that starts with measurement of fine-earth bulk density. For fine-earth bulk density, the sample volume needed for representative results is between 0.2 liters and 1 liter for gravelly to extremely gravelly soils. The alternative approach reliably synthesizes whole-soil bulk density using 1) fine-earth bulk density from modest sized samples, 2) mass size-distribution from large (>40 kg) representative disturbed samples, and 3) rock fragment bulk densities. The mass and volume of rock fragments that “should be” in a sample are added to the mass and volume used to calculate fine-earth bulk density. The method allows integration of lateral variability in the soil without the consequence of averaging properties over a large depth range.

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The importance of accurate measurement of soil bulk density and porosity is clear — they are fundamental soil properties. Pedologists and soil geomorphologists need whole-soil bulk density to determine the volumetric content of soil constituents, such as secondary carbonate (Mach ette, 1985), or the volumetric consequence of soil weathering (Chadwick et al., 1990). Measurement of bulk density for soils containing abundant coarse fragments is problematic, however, because results vary with sample volume, and whole-soil bulk density may differ appreciably from the bulk density of fine-earth (soil with all fragments >2 mm removed, Soil Survey Staff, 1992). Although understanding of the influence of coarse fragments on the properties and processes of soils is increasing (see review by Childs and Flint, 1990) practical sampling problems remain. For example, a variety of sampling methods exist for determination of soil bulk density and porosity—each with unique strengths and weaknesses (Flint and Childs, 1984a). Most published studies compare sampling methods (Andraski, 1991; Flint and Childs, 1984a; Howard and Singer, 1981: Shipp and Matelski, 1965; and McLintock, 1959), but curiously the appropriateness of sample sizes were not evaluated. We know of no published investigations specifically designed to define the representative sample volume for determination of bulk density for soils containing abundant rock fragments.

in this paper we define the sample volume required to determine representative whole-soil bulk density for a soil containing abundant rock fragments. The resulting representative volumes arc prohibitively large and, consequently, we develop an alternative approach. We substantiate a theoretical procedure of synthesizing whole-soil bulk density using 1) fine-earth bulk density, 2) rock fragment bulk densities, and 3) representative particle-size distribution.

DEFINITIONS, OBJECTIVES and CONCEPTUAL FRAMEWORK

Several terms are used here in a broader sense than their most strict definition. The terms "gravel", "coarse fragments", and "rock fragments" are used interchangeably to indicate all particles larger than 2 mm regardless of their specific sizes and shapes. "Pebble" is used to indicate a single particle of gravel without implying a specific size class. The term "gravelly soil" is used to indicate any soil that has physical properties influenced by the presence of rounded gravel or angular rock fragments. A sample has "representative volume" if it is the smallest sample whose measured properties do not differ from that measured for larger volume samples. If a smaller volume sample was selected the measurement results would be unreliable. Its volume is also optimal, because selection of a larger volume sample would create unnecessary, extra effort.

The first objective of this study is to define the representative sample-volume required to determine bulk density for a soil with major horizons containing 34°/0, 54°/0, and 77°/0 gravel by volume. We compare the bulk densities of samples, ranging in volume from 0,03 to 410 liters, to determine graphically the minimum, optimal sample volume.

The second objective is to evaluate the possibility of reliably using intact soil samples that are smaller than a soil's representative volume. We evaluate a procedure of substituting representative-mass size distribution for representative intact volume: a procedure best explained using the following example. Consider a loam soil containing very few rock fragments larger than 2 mm. If a rare pebble is discovered inside an undisturbed soil sample after measurement of intact volume, It is acceptable to subtract the mass and volume of the pebble from that of the sample before calculating bulk density (Soil Survey Staff, 1992, p.83). Technically, the result is the bulk density of the fine-earth (<2 mm fraction) and, in this hypothetical case, the result is also representative of the whole soil because coarse fragments are so rare. Using that procedure we calculate the fine-earth bulk density and porosity for intact samples of our gravelly soil. Then we reverse the process by adding the mass and volume of gravel (determined for a disturbed sample that is large enough to adequately characterize the mass size-distribution) to the mass and volumes used in the calculations of fine-earth properties. the term "synthesized" is used to identify the results of this procedure. Synthesized whole-soil bulk densities are compared by sample volume to evaluate whether results are indeed representative of the whole soil.

Soils are composed of many volume elements each with potentially unique density. It is useful to group these elements of the whole-soil volume into two categories: first, the bulk volume of gravel (where each pebble is dominated by mineral solid, but may also contain pore space); and second, the fine-earth bulk volume (containing mineral solids, organic solids and voids). Thus, in this conceptualization, the volume of a void inside a pebble is included in the calculation of rock fragment bulk density, whereas the volume of a void bounded in part by the surface of a pebble is included in the calculation of fine-earth bulk density. In contrast, the National Cooperative Soil Survey includes the volume of voids inside gravel in the calculation of fine-earth bulk density (Soil Survey Staff, 1992).

MATERIALS AND METHODS

General Environmental and Soil Properties

The sample site is located in east central Idaho, 35 km northwest of the town of Mackay in Custer County, at an altitude of 2100 m (6900 ft), and at the center of the SW 1/4 of Section 28, T 10 N, R 22 E. The soil is located on an alluvial fan composed of well-washed gravel deposited at the end of the latest glacial (≈15 ka) and subsequently covered by a 10 to 20 cm thick blanket of loess (Pierce and Scott, 1982). Mean annual precipitation is about 25 cm and mean annual temperature is about 1.3° C. Vegetative cover is approximately 500/0 and is dominated by *Artemisia tridentata*.

The study soil is classified as a sandy-skeletal, carbonatic, frigid Xerollic Calciorthid. Detailed soil description revealed the following horizons to a depth of 1.2 m: A, ABk, Bk1, Bk2, Bk3, BCk, and CBk (depth increments are noted on Fig, 3). For sampling purposes, we grouped the first three horizons into a major horizon designated "ABk", the next two horizons into a major horizon designated "Bk", and the bottom two horizons into a major horizon designated "CBk". Soil properties not listed In Table 1 include the following. Whole-soil mass percents are: ABk horizon — 58% coarse fragments (>2 mm), 27°/0 sand (2 to 0.043 mm), and 15°/0 silt plus clay sized particles(<0.043 mm); Bk horizon — 72% coarse fragments, 25% sand, and 3% silt plus clay; CBk horizon — 80% coarse fragments, 17% sand, and 3°/0 silt plus clay. Coarse fragment lithologies are limestone (87%), dolomite (4%), and shale, volcanic rocks and sandstone (9%). Their b-axis diameters did not exceed 15 cm, and few exceeded 10 cm.

Sample Types

Four types of samples were obtained (names are underlined) and are summarized here for clarity. 1) An entire pedon was sampled so that results would be limited by measurement imprecision, and not by lateral variability. The pedon was subdivided into three major horizons (ABk, Bk, CBk) and together these three pedon subsamples totaled 2.5 Mg of soil excavated from a pit 1.26 m^3 in volume (Tables 1 and 2). 2) Seventeen intact soil clods were sampled, at various depths from the wall of the soil pit, with sample volume ranging from 0,03 to 6.1 liters (Table 3). Bulk densities and porosities of the clod samples were determined in the laboratory and compared to that of the corresponding pedon subsamples. 3) Disturbed samples were raked from the pit wall and sieved to determine representative size-distribution of the soil mass. Three disturbed samples were obtained, with mass ranging from 32 to 43 kg, one for each of the three major horizons (Table 2). 4) Gravel samples, from each disturbed sample mentioned above, were organized by size class and each class was analyzed for rock fragment bulk density, fragment porosity, and fragment particle-density (Table 4). This information was then used to subtract (and add) the influence of gravel from (to) the properties of intact samples.

Calculations

Many equations exist for density and porosity (Brakensiek et al., 1986); all are fundamentally rooted in the laws of conservation of volume and conservation of mass, and in the definitions of density and porosity. We derived equations appropriate for our measurements and objectives. Here we use the sample worksheet in Fig. 1 as a vehicle to present a summary of all equations and measured, calculated, or synthesized variables. In addition, Fig. 1 can be used as a model format for computer spreadsheet implementation of our procedures.

The values quoted for gravel content by mass and by volume were determined for the pedon subsamples (Table 1). They are not estimates by eye. The particle mass size-distributions (Table 2) were determined by sieving and weighing, as discussed below. The percent gravel by volume was determined by converting gravel mass to bulk volume using rock fragment bulk density mentioned below. We estimate the uncertainty of these volume percent values to be about ±2 percentage points.

To determine densities and porosities for samples of variable size, we measured volumes directly, as well as masses, and no specific gravity measurements were made. Elemental volumes not measured were calculated by addition or subtraction of directly measured volumes with two exceptions. First, the volume of mineral solids <2 mm in size was calculated as the mass of fines divided by the average particle density of rock fragments, because those particle densities are quite uniform (Table 4) and clay content in the soil is minimal. Second, rock fragment properties were not measured for every pebble, rather they were determined for large sub samples. ‘1’bus, average rock fragment bulk density was used to calculate the bulk volumes of individual pebbles contained inside samples (Fig. 1). Bulk densities for individual pebbles probably differ from the average for many. In retrospect, results could be Improved by measuring the bulk volume of coarse fragments actually contained in each sample and subtracting that from sample volume to obtain fine-earth volume.

Processing of Mass

The methods for measuring volumes for each sample type, and other procedures, are discussed under the appropriate headings below. The methods for measuring soil mass and rock fragment size, however, can be discussed in general,

Soil mass was passed by hand through nested sieves with openings from 64 to 2 mm and weighed. All soil from the intact clod samples and the disturbed samples were oven dried, sieved, and weighed on an electronic balance. For the larger samples, however, only a subsample of the <4 mm fraction was sieved. The entire pedon subsamples were weighed in the field using calibrated spring scales, after all material was passed through sieves with 64 to 13.2 mm openings. Only a subsample of the < 13.2 mm fraction was passed through the smaller sieves. Field weight was corrected for moisture content which was <1% of mass for gravel and ranged from 2 to 5% for fine earth. Roots greater than one centimeter in length or one millimeter in diameter were segregated, but these macro-organics are insignificant at <0.3% of soil mass.

Pedon Subsamples

To ensure that a representative volume for the gravel soil was obtained, construction worker tactics were employed to sample an entire soil pit. A 1.26 m^3 pit was excavated by back hoe and back-filled with a known volume of water. First, a plot frame (0.92 m by 1,83 m), constructed of two-by-four lumber, was staked to the ground such that each side board was horizontal. Later the pit was excavated inside this frame. A moveable screed board was placed on the plot frame providing an elevation datum from which the vertical distance to the soil surface (and later the pit bottom) could be measured. Marks, spaced 0.1 m apart, on both the plot frame and the screed in effect created a horizontal grid. At each grid intersection point, the distance below the elevation datum was measured; thus 100 to 105 measurements were made for each computation of average elevation of the soil surface or pit bottom.

After measuring the elevation of the soil surface, the ABk horizon was excavated. The pit bottom was made roughly horizontal, loose material was removed by hand, and the excavated material was placed on a ground cloth and covered. The elevation of the base of the ABk horizon was then measured, This process was repeated for the Bk horizon and then for the CBk horizon. The pit walls were roughly vertical and did not ravel or collapse. Fine soil was unfortunately lost to the wind during excavation, and our estimates of loss ranged from 0.8%0 to 2.3% of the sample mass.

The original volume occupied by the excavated soil was determined using a variation of the compliant cavity method (Soil Survey Staff, 1992, p,101). A measured volume of water was poured into the pit after it had been lined with a doubled sheet of construction grade plastic. Water was poured into the pit using previously calibrated stainless steel buckets and the sheet was regularly inspected to make sure its loose folds conformed to the shape of the pit walls. After every 5 or 10 cm rise in water level the vertical distance of the water surface below the elevation datum was measured. Water surface elevation data was graphed against volume of water in the pit to determine the pit volumes below horizon boundaries. Filling the pit with water took about 2 hours. After the pit was full, the water level was monitored and leakage, under maximum hydraulic head, was insignificant (3.6 liters per hour). Implications of other potential errors are developed in the results and discussion section. Relevant data for the three pedon subsamples are found in Tables 1 and 2.

Intact Clod Samples

Intact soil clods were taken from the pit wall, after the pit had drained and dried, were coated with paraffin in the field and their volumes were determined in the laboratory by immersion, Samples were successfully removed intact from the ABk and Bk horizon but not from the CBk horizon. Although the CBk horizon structure is massive the bonding between particles is weak, consequently soil aggregates could not be kept intact even with wax coatings. Small clods (<300 cm^3) were placed in a hair net and dipped into molten paraffin, but large clods (1000 to 6000 cm^3) were partially excavated and coated <u>in situ</u>. The large clods were then detached so that the bottom of the sample could be sealed.

The volumes of wax-coated clods were determined by water displacement, not by weight in water (Soil Survey Staff, 1992, p.83), because a balance capable of weighing the large intact samples was not available. Water volume displaced by submerging a sample in a container was accomplished with the aid of a point-gauge: a device common to hydraulics laboratories and used for precise measurement of water level. Wax coatings were pried free of the clods and loose soil was removed from them. The volumes of (remelted) paraffin coatings were determined by volume displacement, because the coatings were thick (≈4 mm) and contained variable amounts of soil, Intact clod "sample volume", as used here, means coated-sample volume minus the volume of the coating. Loss of soil mass was minimal; thus, accuracy was primarily limited by volume precision. Relevant data for intact clods are found in Table 3.

Disturbed Samples and Gravel Samples

Large disturbed samples were raked from the pit wall and sieved to determine the size-distribution of soil mass (Table 2), A sample was obtained from the entire vertical exposure of each of the three major horizons, A "five gallon" bucket was placed in an undercut just below the sample horizon and filled. The samples were oven dried, sieved, and weighed in the laboratory.

Gravel samples, subsets of the disturbed samples, were used to" evaluate the physical properties of gravel and the dependence of those properties on particle size (Table 4). l'article size is denoted here as the opening-size of the sieve retaining the fragments. The gravel sample masses (Table 4) ranged from 500 to 2000 g for all but the smallest size classes. These sample masses were designed to contain several hundred to several thousand particles, assuring representative mix of lithologies. Only the largest size classes consisted of a few stones and, thus, could have a biased lithological mix,

Gravel properties were measured using a significant modification of ASTM method C97 (1992, p. 69) following the suggestions of Flint and Childs (1984a, p. 93). The gravel was washed to remove fine earth (secondary carbonate rinds were not removed), oven dried for 24 hours, and weighed. The gravel was then submerged under water inside a bell jar that was placed under vacuum for 40 hours. After the pores within the gravel were saturated by this procedure, the gravel was toweled to remove surface water, and then was quickly weighed and placed into a calibrated container for volume determination. Saturation of pores assured precise measurement of gravel bulk volume, and allowed calculation of pore volume as the difference in wet and dry mass divided by the density of water. The specific gravity of fragments was not measured. Rock fragment properties (bulk density, porosity, and particle-density on Table 4) were calculated using the definition of those properties.

RESULTS AND DISCUSSION

Representative Volume for Whole-Soil Density

Whole-soil bulk density increases significantly with gravel content (Table 1), It is 1.38, 1.97 and 2,38 $g\ cm^{-3}$ for the ABk, Bk and CBk pedon subsamples, respectively. These horizons are dense, the lower ones in particular, because they have gravel contents of 34%, 54% and 77?40 by volume; or 58%, 72% and 80% by mass, respectively. Whole soil porosity, acting In concert with density, decreases with increasing gravel content and ranges from 48% to 10O/O.

Our first objective was to determine the representative volume for whole-soil bulk density. This is done graphically on Fig. 2A, by plotting sample bulk density against sample volume and utilizing the lines drawn to envelop the data for each horizon. Ideally, the density data would be highly scattered for small samples, but with increasing sample size would converge to define a value no longer dependent on size. The approximate representative volume could be chosen from the graph as that minimum sample-volume yielding results similar to (within 5% of) that for larger samples. At the onset of sampling, we assumed that a large pedon subsample would provide the "best" bulk density datum, but have subsequently learned that it may not. Although the reasons for this conclusion are developed in the next section, it is important to state now that the most reliable estimate of whole-soil bulk density is 1.45 g cm^{-3} for the ABk major horizon and is about 1.9 g cm^{-3} for the Bk horizon,

Sample bulk density for gravelly soils is influenced strongly by sample volume, as shown on Fig. 2A, For both major horizons, the density of intact clod samples generally increases in magnitude with sample volume, illustrating that coarse fragments are under-represented by small samples. The scatter of density data diminishes with increasing sample volume and converge toward a uniform value. For example, all intact clod samples from the ABk horizon yield results within 20?40 of 1.45 g cm^{-3}. Samples larger than 200 cm^3, however, yield results within -8% and + 1% of 1.45 g cm^{-3}, and the two largest intact samples (≈ 6,000 cm^3) yield results within 2% of 1.45 g cm^{-3}. We infer from Fig. 2A that the representative volume (for whole-soil bulk density determination) for the ABk horizon is 4 liters or greater — substantially larger than the (100 to 300 cm^3) volume commonly sampled for bulk density measurement. Although the number of samples for the Bk horizon are limited, the representative volume is no doubt large. We infer the representative volume to be at least 5 liters and it may be as large as 50 liters. The minimum estimate, 5 liters, is two orders of magnitude larger than some intact samples retrieved from the field.

Rock Fragment Properties

In general, rock fragments in soils can contain considerable pore volume; as much as 20 to 60% porosity (Flint and Childs, 1984a). Furthermore, gravel properties may depend on particle size due to more thorough weathering of smaller particles (Childs and Flint, 1990; after Schmidt, 1988). Bulk density and porosity of gravel from the study soil vary with particle size (Table 4). Rock fragment porosity, for example, ranges from 2 or 3% for large cobbles and up to 10 or 15% for small pebbles, with the higher values for gravel from the surface horizons.

We tested the possibility that not all of the pores inside the gravel were saturated with water while under vacuum as follows. Rock fragment particle-density was formulated as dry mass divided by volume of solids (bulk volume less pore volume) and as such has larger accumulation of errors than rock fragment bulk-density or porosity. Nevertheless, rock fragment particle-densities in Table 4 are nearly identical demonstrating the reliability of the saturation method. This result also confirms that the mix of rock fragment lithologies in the samples was indeed representative.

Synthesizing Whole-Soil Density

Fine-earth bulk density is a commonly measured property, although it is not a substitute for whole-soil bulk density if the gravel content influences the physical properties significantly. Fine-earth bulk density is, specifically, the mass of mineral soil <2 mm in size plus mass of organics, divided by the cumulative volume of fine-grained mineral solids, organic solids, and voids (except, as defined here, those voids inside gravel) (Fig. 1). This density can be determined by subtracting the mass and the bulk volume of gravel inside an intact sample from the whole mass and whole volume of that sample, respectively (Soil Survey Staff, 1992, p.83). Our premise is that the reverse process should be a viable means of determining whole-soil bulk density.

One should be able to synthesize a reliable whole-soil bulk density by starting with fine-earth mass and fine-earth bulk volume, from a relatively small intact sample, and adding in an appropriate mass and volume of gravel. At the close of this project, we learned that calculations such as this have been used by the National Cooperative Soil Survey, but the method has not been published (Bob Grossman, pcrs. comm,, 1993). Here, we refer to this as "synthesized" whole-soil bulk density in contrast to sample bulk density. The mass of gravel that “should be” in the sample is calculated using equations in Fig. 1, but the calculation is described below for clarity. First, hypothetical total whole-soil mass equals fine-earth mass (in the intact sample) divided by percent of total mass that is fine grained for a large disturbed sample. The mass of gravel then equals total mass minus fine-earth mass, The volume associated with the gravel mass would equal that mass divided by measured rock fragment bulk density. The procedure is simple if gravel properties (e.g. porosity) do not vary with particle size, such as for example, the gravel dominated by quartzite from the E 12 soil on Table 4. The properties of gravel from the study soil do vary with particle size, and thus the gravel mass within each size class was treated as individual volume elements with unique properties (Fig. 1).

The premise of synthesizing a reliable whole-soil bulk density is indeed viable, as illustrated in Fig. 2. Synthesized whole-soil bulk density data (Fig. 2B) have less scatter compared to the original intact-sample bulk density data (Fig. 2A), More importantly, the data are no longer strongly dependent on intact-sample volume, which we consider a positive result. We can make a stronger case for the reliability of this method after developing two subtleties.

First, does a pedon subsample produce the "best" results? Large soil pit samples may not be the most reliable means of determining physical properties of soils because field measurements are often less precise than laboratory measurements. For example, results from previous investigations that used water to determine volumes of small pits were largely unsatisfactory (McLintock, 1959; Howard and Singer, 1981). Our field measurements are limited by problems such as loss of mass to the wind, and the need to correct for variable moisture content, but two other problems arc potentially more significant. First, it is possible that soil from the ABk horizon was dislodged from the pit wall during excavation of the Bk horizon, and erroneously ascribed to the mass of the Bk pedon subsample. The second problem is that as the pit was filled with water the increasing hydrostatic head might have forced the plastic liner more tightly against the pit wall. It is possible, therefore, that water ascribed to the volume of the ABk sample might have actually flowed down into the space of the Bk pedon subsample. These two potential problems would have the same consequence, namely to underestimate the ABk pedon subsample bulk density and, at the same time, to overestimate the Bk pedon subsample bulk density. Notice in Fig. 2B (and Fig. 3), the bulk density of the ABk pedon subsample is less than the whole-soil bulk densities synthesized from clod data; but in contrast, the bulk density of the Bk pedon subsample is greater than the whole-soil bulk densities synthesized using intact clods from that horizon. Evidently, the large soil volumes did not entirely compensate for the problems described above.

The second subtlety is caused by soil properties changing with depth in the Bk horizon. The surface horizon is discussed first for comparison. Within the ABk horizon, soil properties Including fine-earth bulk density and gravel content do not change significantly with depth. Our results for the ABk horizon indicate that synthesized whole-soil bulk density is uniform with depth (Fig. 3), and does not depend on field-sample volume (Fig. 2B). The mean of the eleven synthesized whole-soil bulk density values is 1.45 g cm^{-3}, with ranges about the mean of ±0.07 g cm^{-3} and standard deviations of ±0.04 g cm^{-3} or ±2.8%. The ABk results clearly demonstrates the utility of our method of synthesizing whole-soil bulk density. Results for the Bk horizon are affected by changing properties with depth. Below a depth of 27 cm, both fine-earth bulk density (data in Table 3) and gravel content increase with depth. On Fig. 3, synthesized whole-soil bulk density values increase with depth in the Bk horizon, and offer an explanation of the slight dependence that the data has on sample volume in Fig. 2B — smaller samples with lighter densities were taken, quite by accident, from higher in the soil profile. With this observation, we suggest that the Bk horizon data set also supports our method of synthesizing whole-soil bulk density.

One last point is that the large disturbed samples were taken from the whole depth range of the major horizons, but intact samples were only 5 to 20 cm thick, The synthesized whole-soil bulk density values for the Bk horizon in Fig. 3, therefore, are not specific to the minor horizons sampled because they were forced by the calculations (Fig. 1) to resemble the average condition of the Bk horizon. Thus the increase in estimated densities with depth in Fig. 3 is entirely the artifact of increasing fine-earth bulk density with depth, Disturbed samples should be taken from only the horizon whose average conditions are of interest, be that an entire soil profile or a thin horizon.

The discussions above lead us to conclude that knowledge of the representative volume of a soil of a given texture is not all that is required to produce accurate and useful results. The position of a sample In space, and its three dimensional shape, are also important because soil properties vary laterally as well as with depth. In pedon sampling the lateral variability of soil properties is often considered noise, whereas the changing of properties with depth is considered the information signal. A small sample (<100 cm^3) will not obscure the signal, but cannot integrate the noise. Large pit samples, such as our pedon subsamples, are inevitably about as deep as they are wide. 'l'hey absorb lateral variability, but in the process also integrate properties over a significant depth range. Bulk density synthesis can alleviate this signal/noise problem in gravely soils. For example, consider the objective of determining whole-soil bulk density for a 10 cm thick gravelly horizon, intact loaf-sized (≥1 000 cm^3) samples could easily be obtained for measurement of fine-earth bulk density, and a large (≥4 O kg,) disturbed sample could, with care, be extracted over a wide area of that thin horizon for measurement of representative mass-size distribution. The resulting synthesized whole-soil bulk density would integrate lateral variability without obscuring the horizon-specific signal.

Having established that together representative-mass size distribution, gravel properties, and fine-earth bulk densities can be used to synthesize whole-soi] bulk densities, we should know two things: 1) the minimum sample volume required to obtain reliable fine-earth bulk densities, and 2) the minimum sample mass required to obtain reliable particle size-distribution.

Representative Volume for Fine-Earth Density

The representative intact volume for fine-earth bulk density determination is much less than that for whole-soil bulk density determination. For ABk horizon intact samples (Table 3), which range in volume from 105 to 5455 cm^3, the average fine-earth bulk density is 0.96 g cm^{-3} with standard deviation of 0.04 g cm^{-3} or 4%. More importantly, there is no dependence of fine-earth bulk density on sample size. Because no samples were smaller than 100 cm^3, we can not determine whether the representative volume is smaller than that. Therefore, in the future we will take samples with volumes larger than 200 cm^3 from horizons with 30 to 40% gravel (by volume) for determination of fine-earth bulk density. For the Bk horizon, there is a slight dependence of the data on volume due to increasing fine-earth bulk density with depth as discussed previously. Conclusions are therefore limited, thus in the future we will attempt to take samples with volumes close to 1000 cm^3 for determining fine-earth bulk density of horizons with 50-60% gravel by volume,

Representative mass for particle-size distribution

Choosing a disturbed sample mass that will yield accurate particle size distribution is important for utilizing our method of synthesizing whole-soil properties. Two citations (ASTM, 1992; sections D 75 and D 2487) provide guidance for choosing an appropriate sample mass, but their suggestions are large and may be excessive. Both methods rely on maximum or “maximum nominal” size of aggregates. Our study soil contains few rock fragments larger than 10 cm, and no rocks larger than

15 cm. Extrapolation of the ASTM linear relationship (section D 75, p. 70, Table 1) suggests we should used a sample mass of 200 or 300 kg to determine particle size distribution. This mass is large, half of themass"of our ABk pedon subsample, but admittedly, the purpose of that guideline includes sampling prospective gravel mines. For the purpose of classifying soils, ASTM (section D 2487, p. 327) provides a table of data that constitutes a semi-logarithmic relationship of suggested sample size, however their maximum particle size does not exceed 7.5 cm. Extrapolating their relationship to 10 cm indicates a mass of 200 kg should be used. Extrapolation for soils with larger rock fragments, although probably, indicates thousands of kilograms should be used.

Wc have data that are relevant to this problem. First, it should bc stated that for our synthesis method the critical information is the percent of whole soil mass that is larger than 2 mm. The distribution of mass within the various large size-classes is of secondary importance. In Fig. 4, therefore, percent of total mass that is larger than 2 mm is plotted against sample mass. Scatter in the data indicates that samples less than 10 kg are unreliable, but the more massive samples have nearly identical percent gravel values. For our gravely to cxtrcmely gravely horizons wc used ≈4 O kg samples for determining the entire mass-size distribution, the same as the compromise mass suggested by the Soil Survey Staff (1992, p. 76). Samples >400 kg are impractical and appear to be unnecessary.

CONCLUSIONS

1) The representative volume for whole-soil bulk density is large for soils with significant gravel content. For the soil horizon containing 34?40 gravel by volume it is 4 liters or larger, and for the soil horizon containing 54%

gravel by volume it is at least 5 liters and possibly as large as 50 liters. For similar soils, measurement of whole-soil bulk density may be in error if field-sample volumes are smaller than the above guidelines.

2) The representative volume for fine-earth bulk density determination is smaller than that for whole-soil bulk density determination. For the soil horizon containing 34% gravel, the representative field-sample volume may bc less than 0.1 liters. However, for gravelly to extremely gravelly soils we strongly recommend field-sample volumes between 0.2 liters and 1 liter for fine-earth bulk density determination.

3) Whole-soil bulk density and porosity can be reliably synthesized knowing: 1) fine-earth bulk density and porosity, 2) rock fragment bulk densities and porosities, and 3) representative particle-size distribution, This is a viable alternative to processing large, intact, representative volume samples; and is a positive conclusion for two reasons. First, truly representative intact samples may bc too large to handle. Second, previous studies of gravelly soil that produced unreliable bulk densities because sample volumes were too small (or where **only fine-earth properties were** calculated) need not bc discarded. The situation can be reconciled by obtaining a large (>4 O kg) disturbed sample from the original soil and following the procedure described here.

4) Our method of synthesizing whole-soil properties promises to be quite useful for detailed investigations of soils with thin horizons. The method allows integration of lateral variability in the soil without averaging properties over a large depth range.

5) Sampling entire soil pits with very large volumes (> 100,000 Liters) **arc not necessary or** even desirable for measurement of densities and porosities of gravelly soil, This conclusion is fortunate considering the

extreme effort required to obtain such samples. On a theoretical level, huge samples integrate lateral variability in the soil at the expense of averaging properties over a large depth range. This consequence may be inconsistent with research objectives. On a practical level, a huge soil volume may not entirely compensate for potential errors involving measurement of mass, and the uncertainty in measurement of large volumes in the field.

6) It is impossible to extract an intact sample from some soils. We found this to be the case for the CBk horizon of our study soil which contains 77% gravel by volume and 80% gravel by mass. In such cases, in situ volume measurement is unavoidable and we recommend a device (refined by Flint and Childs, 1984b) that measures the volume of small (<15 liters) soil pits or irregular holes using lightweight epoxy beads, Our method of synthesizing results may still be employed If 15 liters is not considered adequate or cannot be obtained.

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Figure Captions

Fig. 1. All **equations used in this study for calculations of bulk densities and porosities, and example data and results for intact soil clod** #5.

Fig. 2. Graphs of bulk densities plotted against field-sample volume. Open circles are used for the ABk horizon (34% gravel by volume) and closed circles are for the Bk horizon (54% gravel), The size of plotted symbols indicate sample type: small symbol — intact clod; large symbol — pedon subsamples.

Fig. 3. Synthesized whole soil bulk densities (closed circles) are plotted against depth, with intact-sample depth ranges shown as bars, Pedon subsamples are indicated by rectangles defined by bulk density error ranges and sarnple-depth ranges.

Fig. 4. Percent of total mass, that is larger than 2 mm, is plotted against sample mass for samples from gravely to extremely gravely horizons.

Table 1: Data and Properties of Pedon Subsamples

Description	Label	Units	ABk Horizon	Bk Horizon	CBk Horizon
Depth Range		cm	O-27	27-62	62-109
Mass of gravel, (>2 mm)	$M_{>2}$	kg	254	584	1008
Estimate of fines lost		kg	20	10	20
Mass of all fines (<2 mm)	$M_{<2}$	kg	183	226	251
Mass Total	MT	kg	437	810	1259
Mass Error	M±	kg	10	10	10
Volume of sample	VT	L	317	410	528
Volume Error	v *	L	10	10	10
% of VT as bulk gravel	$\%Vbk_{>2}$	%	34	54	77
Vol. of voids in gravel	$\sum Vv_{>2}$	L	10	17	27
Bulk Density of sample	BD	$g\ cm^{-3}$	1.38	1.97	2.38
Compounded BD Error	BD±	$g\ cm^{-3}$	0.07	0.07	0.06
Porosity of sample	P	‘/0	47.6	29.4	10.2
Bulk Density of fines	$BD_{<2}$	$g\ cm^{-3}$	0.87	1.19	2.07
Porosity of fines	$P_{<2}$	‘/0	66.9	54.8	21.8

Table 2: **Particle Size Distributions for Pedon Subsamples and Disturbed Samples.**

Size Class	ABk Horizon Pedon Subsample	ABk Horizon Disturbed Sample	Bk Horizon Pedon Subsampe	Bk Horizon Disturbed Sample	CBk Horizon Pedon Subsample	CBk Horizon Disturbed Sample
mm	%	%	%	%	%	%
64	2.1	2.0	8.8	14.0	6.0	10.6
45	2.8	1.8	10.4	11.2	7.2	7.4
32	3.7	2.4	9.3	7.8	7.7	9.7
22.4	5.3	4.6	9.2	8.2	10.7	12.4
16	6.0	6.7	8.0	6.5	10.0	10.5
13.2	3.7	4.2	4.0	2.9	5.1	4.7
11.2	5.4	5.5	2.9	2.9	5.5	4.6
8	8.7	8.9	5.0	4.9	7.9	6.6
5.7	7.2	7.4	4.6	4.5	6.8	5.7
4	5.3	5.5	3.2	3.1	4.8	4.0
2.8	4.2	4.3	3.4	3.4	4.4	3.7
2	3.6	3.7	3.3	3.2	4.0	3.4
< 2	42.0	43.0	27.9	27.4	19.9	16.7
Mass, g	437,000	32,580	809,000	42,660	1,259,000	69,860

Table 3: Data and Results for Intact Soil Clods by Sample Number.

			ABk Horizon											Bk Horizon					
			#1	#2	#3	#4	#1P1	# fP2	# 1P3	#1P4	#3Pt	#3P2	#3P3	#5	#6	#7	#bP1	#bP2	#bP3
Measured for Sample																			
Depth of Sample		cm	5-17	5-20	1 2-27	17-27	10	10	10	10	20	2 0	m	40-50	35-60	3545	32	32	32
Mass of gravel (.2 mm)	M>2	g	1579	4430	889	4525	36	7s	141	144	61	202	676	2050	7118	1676	14	128	192
Mass of fines (<2 mm)	M<2	9	1365	4230	1051	3446	67	126	1?2	203	62	181	654	1431	3495	617	2s	74	159
% of Total mass <2 mm	%M<2	%	47	49	54	43	71	63	u	59	57	47	49	41	33	27	65	37	45
Macro-organics	Mo	g	10	2	1	4	o	0	0	0	0	0	0	0	0	0	0	0	0
Mass Total	MT	9	2974	6662	1940	7975	122	201	253	347	144	384	1332	3461	10613	2295	39	202	351
Mass Error	M±	g	6	5	3	5	1	1	1	1	1	1	3	3	5	3	1	1	1
Volume of sample	VT	cm^3	2?90	61Ol	1463	545s	105	173	176	259	116	273	646	20%?	5791	1236	31	117	223
Volume Error	v*	cm^3	18	46	18	56	9	9	7	7	7	7	13	33	40	23	6	7	7
Calculated for Sample																			
Bulk Density of sample	BD	g cm^{-3}	1.36	1 .42	1.33	1.46	1.16	1.16	1.44	?.34	124	1.41	1.41	1.66	1 .s3	1.65	127	1.73	1.57
Compounded BD Error	BD±	g cm^{-3}	0.01	0.01	0.02	0.02	0.10	0.06	0.06	0.04	0.08	0.04	0.02	0.03	0.01	0.04	0.23	0.11	0.05
Porosity of sample	P	%	46.5	46.0	49.6	44.4	55.7	5s.8	45.4	49.0	52.6	46.6	46.5	36.3	30.s	29.9	52.0	34A	40.3
Bulk Density of fines	BD<2	g cm^{-3}	0.91	1.00	0.97	0.97	0.67	0.90	0.96	1.03	0.92	0.97	0.99	1.16	1 22	1.12	1.02	1.17	1.12
Porosity of fines <2 mm	P<2	%	65.4	62.0	63.2	63.0	63.2	65.9	63.5	60.9	65.0	63.2	622	55.3	53.6	57.6	61.5	55,6	57.5
Synthesized for whole soil (•)																			
Mass Total "	MT*	g	3215	9818	2440	7999	201	293	261	472	191	421	1517	5227127672252			e2	271	580
Bulk Volume of gravel •	ΣVbk>2*	cm^3	774	2363	567	1925	46	71	63	114	46	101	365	1546	3776	666	27	60	172
Bulk Density*	BD*	g cm^{-3}	1 .40	1.49	1.46	1 .46	1.46	1.39	1.45	?.52	1.41	1.46	1.48	1.90	7.93	1.65	1.77	1.69	1 .6s
Porosity "	P*	%	46.7	43.3	445	44.4	44.6	47.2	44.6	42.4	46.3	44.6	43.6	26.3	27.2	30.0	33.0	26.6	29.9

Table 4: Densities, and Porosity of Rock Fragments.

Sieve Size	Sample Masa	Fragment Bulk Density	BD± †	Fragment Porosity	P i t	Fragment Particle Density	PD± †
mm	9	g cm-3	g cm^{-3}	%	%	g cm-3	g cm^{-3}
ABk Horizon							
64	.						
45		.		.			
32	350	2.49	0.07	5.0	1.5	2.62	0.11
22.4	902	2.49	0.03	6.3	0.6	2.65	0.04
16	1018	2.47	0.02	6.5	0.5	2.54	0.04
13.2	526	2.39	0.04	9.1	1.0	2.63	0.08
11.2	929	2.41	0.02	8.8	0.6	2.65	0.04
8	715	2.34	0.03	11.1	0.8	2.63	0.05
5.66	844	2,31	0.02	11.8	0.6	2.62	0.05
4	115.1	2.25	0.02	14.1	0.5	2.62	0.03
2.8	90.8	2.20	0.02	14.8	0.6	2.58	0.04
2	76.7	2.27	0.03	13.6	0.7	2,63	0.05
						2.63 ‡	
Bk Horizon							
64	1753	2.59	0.01	3.5	0.3	2.69	0,02
45	.	.	.	.	.	.	.
32	1205	2.52	0.02	4,4	0.4	2.63	0.03
22.4	1099	2.49	0.02	5.9	0,5	2.64	0.04
16	1029	2.42	0.02	7.8	0.5	2.63	0.04
13.2	535	2.41	0.04	8,6	1.0	2,63	0.07
11.2	593	2.38	0.04	9.6	0.9	2.63	0.07
8	965	2.35	0.02	11.0	0.6	2.64	0.04
5.66	865	2.32	0.02	12.6	0.6	2.65	0.05
4	86.9	2.30	0.04	13.0	0.7	2.54	0.09
2.8	91.7	2.30	0.22	13.0	6.0	2.64	0.45
2	86.8	2.29	0.24	10.8	6.2	2.57	0.45
						2.64$	
CBk Horizon							
64	836	2.71	0.03	1.6	0.7	2.75	0.05
45	1256	2.58	0.02	2.9	0,4	2.66	0.03
32	1243	2.56	0.02	4.5	0.4	2.68	0.03
22.4	1142	2.51	0.02	6.2	0.5	2,68	0.04
16	959	2.49	0.02	6.2	0.6	2.66	0,04
13.2	838	2.48	0.03	6.5	0.6	2.65	0.05
11.2	923	2,44	0.02	7.4	0.6	2.64	0.04
8	765	2.42	0.03	7.9	0.7	2.63	0.05
5.66	712	2.40	0.03	9.5	0,8	2.65	0.06
4	106.3	2.34	0,02	9.9	0.5	2.60	0,04
2.8	99.1	2.36	0.02	10.5	0.6	2.63	0.04
2	90	2.32	0.02	10,3	0.6	2.59	0.04
						2.65 ‡	
E12 Soil §							
64	2079	2.69	0,01	1.8	0.3	2,74	0.02
45	1687	2.63	0,02	3.3	0.3	2.72	0,03
32	1870	2.68	0.01	2.4	0.3	2.74	0.02
22.4	894	2.60	0.03	2.9	0.6	2.68	0.05
16	760	2.65	0.03	2.8	0,7	2.73	0.06
13.2	317	2.62	0.08	3.3	1.7	2.71	0.13
						2.72 ‡	

† Compounded, worst case error due to imprecision

‡ Average particle density for all rock fragment size classes

§ Data for nearby soil E12 dominated by quartzite for comparison

Example Worksheet for Intact Soil Clod Data and Calculations

"Gravel" (>2 mm) Properties by Size Class

	M	BD>2	P*2	Vbk>2	Vv>2	%M2	M'	Vbk>2*	Vv>2*
Size Class, Retaining Sieve	Mass Dry	Gravel Bulk Density	Gravel Porosity	Bulk Vol. of Gravel	Pora Vol. in Gravel	Pit Wall % of M2T	Estimated Dry Mass	Bulk Vol. of Gravel	Pore Vol. in Gravel
mm	9	g cm-3	%	cm³	cm³	%	g	cm³	cm³
	Note: #1	#2	#3	#4	#5	#6	#7	#8	#9
64	0	2.59	3.55	0	0	14.10	736.89	284.39	10.09
45	114	2.54	4.00	44.88	1,80	11.16	563.18	229.60	9.18
32	67.8	2.52	4.38	26.95	1.18	7.84	409.75	162.88	7.14
22,4	324.1	2,49	5.88	130.34	7.67	8.17	427.05	171.74	10.10
16	282.1	2.42	7.77	116.43	9.05	6.47	338.41	139.67	10.85
13.2	168.1	2.41	8.55	69.82	5.97	2.90	151.72	63.02	5.39
11.2	128.9	2.38	9.62	54.21	5.22	2.86	149.25	62.76	6.04
8	210.9	2.35	10.98	89.58	9.83	4.88	255.02	108.32	11.89
5.66	210.8	2.32	12.61	90.86	11.45	4.52	236.45	101.92	12,85
4	182.9	2.30	12.97	79.53	10.31	3.15	164.46	71.51	9.27
2.8	184	2.30	13.03	80.10	10.43	3.36	175.80	76.53	9.97
2	176	2.29	10.81	76.86	8.31	3.22	168.24	73.52	7.95
<2 mm	1431	.	.			27.38			

Measured for Whole Sample

Mass of all gravel	M>2	2049.5	g
Mass of fines (<2 mm)	M<2	1431	g
% of Total mass <2 mm	%M<2	41.11	%
Macro. organics	Mo	0.2	g
Mass Total	MT	3480	g
Mass Error	M±	3	g
Volume of sample	VT	2072	cm³
Volume Error	V±	33	cm³
Particle Density <2 mm	PD<2	2,64	g cm⁻³

Notes for above:

- #1 Measure for intact sample
- #2 & #3 Measured for gravel taken from sample or appropriate horizon
- #4 Vbk>2 = M / BD>2
- #5 VV>2 = (Vbk>2) • (P/1 00)
- #6 Measured for pit wall sample M2
- #7 M' = (MT*) •(%M2)
- #8 Vbk>2* = (M*)/ B D>2
- #9 Vv>2* = (Vbk>2*)•(P>2/1 00)

Calculated for Sample

Bulk Volume of gravel	ΣVbk>2	859.6	cm³, Sum for all sieve sizes ≥2 mm
% of VT as bulk gravel	%Vbk>2	41.5	% = (ΣVbk>2 / VT)•100
Vol. of voids in gravel	ΣVv>2	81.2	cm³, Sum for all sieve sizes ≥2 mm
Bulk Density of sample	BD	1.68	g cm⁻³ = MT / VT
Compounded BD Error	BD±	0.03	g cm-a= BD . ((MT-M±) / (VT+V±))
Porosity of sample	P	36.28	% = [(Vv>2 + (Vbk<2-Vs<2)) / Vt]•1 00
Bulk Volume of fines	Vbk<2	1212.4	cm3 = VT - Vbk>2
Volume of solid fines	Vs<2	542	cm³ = M<2 / PD<2
Bulk Density of fines	BD<2	1,18	g cm⁻³ = M<2 / Vbk<2
Porosity of bulk fines	P<2	55.3	% = [(Vbk<2 - Vs<2) / Vbk<2] *1OO

Synthesized for whole soil (*)

Mass Total	MT*	5227.3	g = M<2 / (%M2<2 / 100)
Bulk Volume of gravel	ΣVbk>2*	1545.9	cm3, Sum for all sieve sizes ≥ 2 mm
Vol. of pores in gravel	ΣVv>2*	110.7	cm³, Sum for all sieve sizes ≥ 2 mm
Bulk Density	BD*	1.90	g cm-a= MT'/ (Vbk<2 + ΣVbk>2*)
Porosity	P'	28.3	% = [(ΣVv>2* + (Vbk<2 - Vs<2)) / (ΣVbk>2* + Vbk<2)] • 100

Fig 1- Vincent

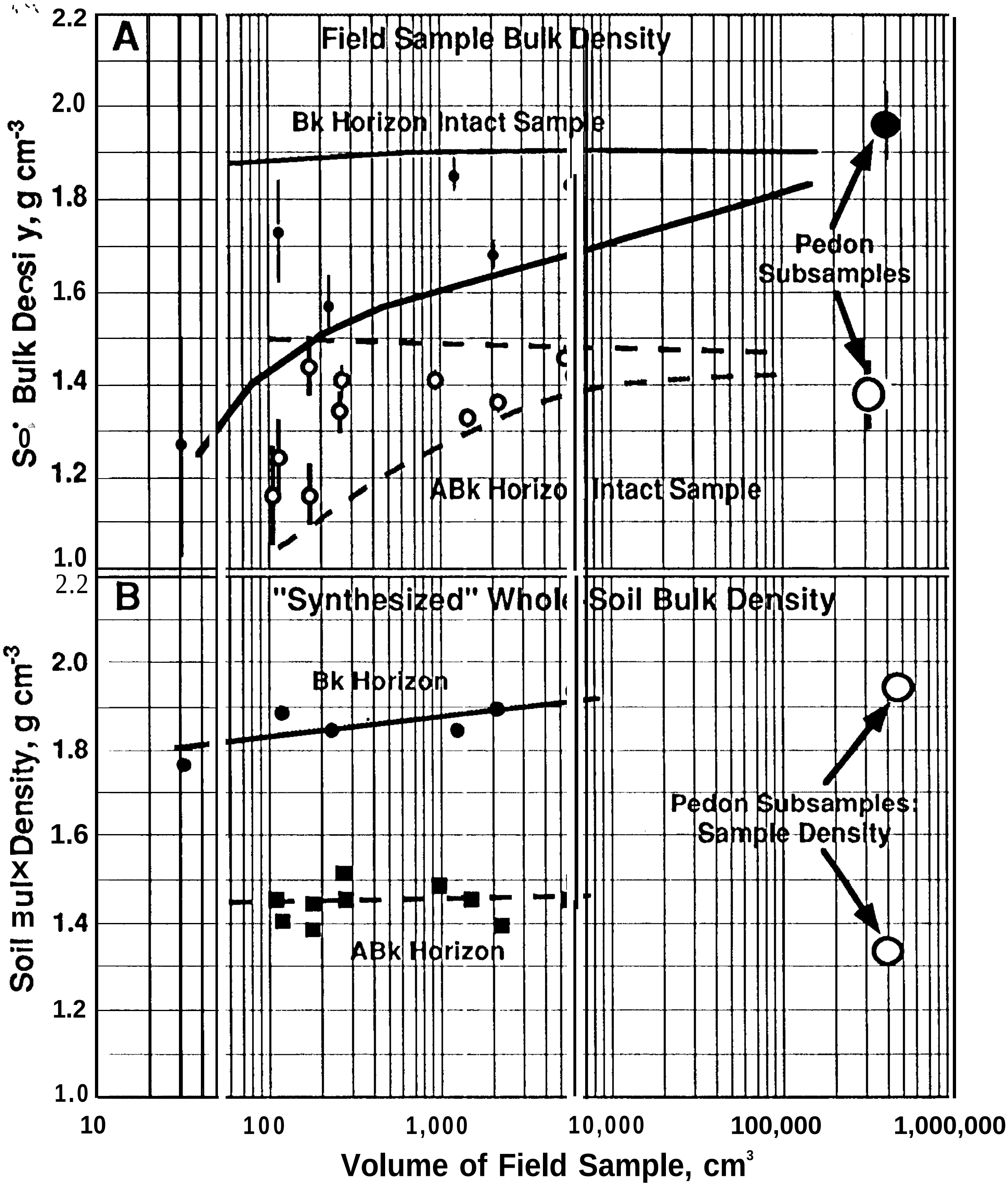

Fig 2- Vincent

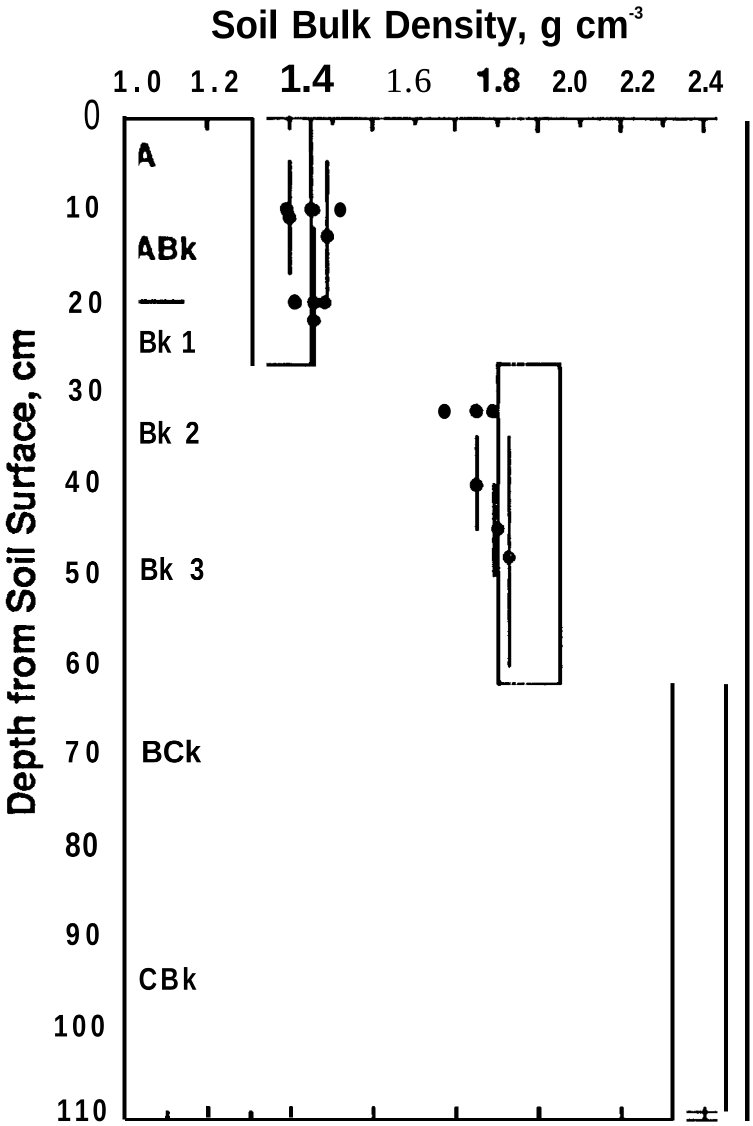

Fig 3- Vincent