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ERROR ANALYSIS OF BULK DENSITY MEASUREMENTS FOR NEUTRON MOISTURE GAUGE CALIBRATION

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ABSTRACT
Six bulk density sampling methods were evaluated for use in neutron gauge calibration. All six methods provided estimates of bulk density which were generally within 5% of bulk density profiles measured using a gamma probe. Standard errors of estimate ranged from 3 to 7 %. When used with care, downhole, coring, and drive samplers can be used to successfully measure soil moisture and bulk density profiles for use in neutron probe calibration.

INTRODUCTION
Fixed volume or bulk density sampling of soil profiles is an integral part of neutron probe calibration. It is required to obtain volumetric soil moisture contents or to convert mass-based soil moisture percentages into volume-based soil moisture percentages. Various mechanical techniques can be used to obtain fixed volume samples of soil at various depths. Some of these techniques are described by Dickey et al. (1993) (these proceedings). This paper summarizes an error analysis of six different mechanical procedures for bulk density sampling. These procedures were applied during an ASCE Task Committee field study in Logan, Utah during July, 1992. The background of the ASCE study is described by Stone et al. (1993) (these proceedings).

The six mechanical procedures evaluated for obtaining bulk density profiles from a 2 m soil profile are listed in Table 1. Detailed descriptions for each method are given by Dickey et al. (1993) and include sample size, extraction procedure, time requirements, and resulting bulk density profiles for the ASCE

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field study. The Giddings Core sampling method used by the ARS during the study is listed twice in Table 1. The first entry represents samples taken by the coring machine while excavating a hole for installation of a neutron access tube. The second entry in Table 1 (Core3) represents an average of samples for the initial core and for two additional cores taken a few days later.

Bulk density measurements were also made using a gamma nuclear density probe. The calibration of the gamma probe for the soils used in the Logan workshop and presentation and interpretation of the gamma bulk density data is discussed by Wright et al. (1993) (these proceedings). The gamma bulk density data have been used in this analysis along with a "mean probable" bulk density profile generated from the mechanically derived bulk density data to make relative comparisons among the various mechanical bulk density sampling procedures. This paper summarizes apparent relative errors among the various sampling methods compared to the mean probable bulk density profile and to bulk densities measured using the calibrated gamma probe. It is noted that the gamma-derived bulk densities may have slightly overestimated bulk density in situations where the access tube compressed soil along the outside of the tube during installation. The majority of this bias, however, was removed during the gamma probe calibration (Wright et al., 1993).

PROCEDURE
The three soils sampled near Logan, Utah during July, 1992 were a Millville silt loam (site 1), a Nibley clay loam (site 2), and a Kidman fine sandy loam (site 3). Descriptions of typical soil profiles are included in Stone et al. (1993). Wet (W) and dry (D) profiles were sampled at each soil site. The USU and SCS Down-hole and ARS Core methods sampled to 1.5 m when possible in 0.15 m (6 in.) increments. The OSU-Core method sampled to 0.9 m (36 in.), and the SCS and ARS Drive samplers sampled to 0.6-0.7 m and 0.6 m, respectively (Table 1). The SCS and ARS Drive samplers required extraction of the sampler from each depth by excavating a trench alongside the sampler. The Down-hole and Core sampling methods were largely "non-destructive" in that they did not remove any soil in excess of that needed for installation of neutron access tubes in the sampled hole. The gamma probe was inserted into the same holes excavated by the ARS Core and the USU and SCS downhole samplers after installation of an aluminum access tube. The gamma data used in the analyses in this paper were averages of the three holes (Wright et al., 1993). Additional details of the bulk density sampling methods can be found in Stone et al. (1993), Dickey et al. (1993) and Wright et al. (1993) in these proceedings.

Standard errors of estimate (SEE) were computed for each site and sampling method as:

$$SEE = \left(\frac{\sum (\hat{Y} - Y)^2}{n - 1} \right)^{0.5} \quad (1)$$

where $\check{Y}$ was the bulk density measured using one of the mechanical methods and Y was either the bulk density represented by the mean probable profile or by the gamma probe profile. Variable n was the number of samples for a particular hole and method. Units of SEE were kg m^{-3} .

A normalized SEE was calculated by dividing the SEE from Eq. 1 by the mean reference bulk density (averaged over all depths) at each hole (or site) and multiplying by 100. This converted the SEE into a percentage SEE. The reference bulk density was either the mean probable bulk density or the gamma measured bulk density, depending on which was used in Eq. 1.

The mean probable bulk density profile was computed at each site by plotting the six nonnuclear bulk density profiles for that site on the same graph (vs. depth). Points along a profile which deviated significantly from general trend lines followed by most methods were labeled as outliers and were discarded. Only nonconforming deviations were discarded. Profiles which were systematically greater than or less than the mean bulk density profile (due to systematic sampling variation), but which followed general trends were retained. Overall, 16 outliers were identified out of 288 total samples (6 %) (Table 1).

Resulting bulk density profiles for the various sampling techniques were compared with a "mean" profile and with one another, and a visual, subjective "weight" was assigned to each method and individual point measurement for computing a mean "probable" profile. The mean probable profile was then generated visually on the graph for each site. The mean probable profiles were reviewed and minor adjustments were made. The gamma probe measurements were not considered in developing the mean probable profiles. Two additional profiles were sampled at each site by the OSU Core method adjacent to the neutron access hole, similar to the procedure followed by the ARS Core method. However, these profiles were not utilized in this analysis.

Ratios of sampled bulk densities to bulk densities from the probable and gamma profiles were computed for each hole by summing measurements of bulk densities from depths were both the sampled and probable or gamma data were present. The ratios indicate average (for the hole) overmeasurement or undermeasurement of bulk density by the sampling method relative to the mean probable and gamma profiles.

RESULTS

The "mean probable" profiles are intended to represent what is considered to be the most "probable" bulk density profile at each site, based on agreement and trends among all six nonnuclear bulk density sampling methods, which were applied by experienced professionals. The mean probable profiles are not exactly correct, but were selected as a basis for comparing the various methods. Over all, the mean probable profiles averaged 1 % higher (bulk density) than gamma derived profiles. This is generally within tolerances required for volumetric moisture determination.

In general, all six methods measured bulk densities averaging within 4 percent of the mean probable and gamma profiles over all sites. Five of the methods were within 1 to 2 percent over all (Table 2). Percentage standard errors of estimate ranged from 2.7 to 5.8 % relative to the mean probable profile and from 3.3 to 7.1 % relative to the gamma measured profile. The two down-hole samplers (SCS and USU) had lowest SEE's overall (Table 2) relative to the mean probable profile. However, the generation of the mean probable profile at depths greater than 1 m were influenced by these methods. The two down-hole samplers and the average of three ARS Core samples (ARS-Core3) had the lowest SEE values relative to the gamma measured profile.

Percentage SEE's for each method are plotted in Figure 1 for each site. Relative ratios of each method to the mean probable and gamma derived profiles are given in Figure 2. In general, all methods performed similarly in terms of SEE at the silt loam site. The coring and drive methods had difficulty in the wet clay loam (site 2) (Figure 1 c). The downhole samplers experienced less difficulty at site 2 due to smaller sampler size and correspondingly less friction between the soil and the sampler. The sandy loam soil at site 3 was problematic below 1 m due to lack of structure and moisture. All methods experienced difficulty at this site. The two downhole samplers were the only methods which were able to sample below 1.1 m at site 3 (Figure 1).

The OSU and ARS core samplers were both Giddings coring machines. The ARS machine was mounted on a tractor three-point hitch and the USU Giddings machine used by OSU was mounted on a trailer. Sizes of cores taken with the two machines were different (see Dickey et al., 1993). The trailer mounted coring machine was less stable than was the tractor mounted machine and weaknesses of soil-augered anchors with the trailored machine made coring in dry soils difficult. This may explain some of the increased SEE for the OSU-Core samples. In addition, due to logistical problems, OSU sample holes were located up to 1 to 2 m from the USU-SCS-ARS holes which were generally within 0.6 m of one another in a triangular arrangement. Therefore, spatial variation in bulk density may have been a factor. SCS drive samples were taken within the USU-SCS-ARS clusters after neutron counts were completed.

The advantage of taking samples from multiple holes is demonstrated by the slight improvement (reduction) in SEE for the ARS-Core sampler when three cores were averaged and compared to the gamma profile (Table 2). An advantage of sampling from closely spaced holes is that an "internal" calculation of SEE is possible. In addition, outlying points and effects of macropores or stones are more evident. In practice, multiple samples can be made whenever multiple access tubes are installed, which is common. However, spatial variation among distant tubes can reduce the benefit of multiplicative sampling.

The USU and SCS downhole samplers and the ARS Coring sampler were somewhat disadvantaged by their greater sampling depths (to 1.5 m in most cases) relative to the other methods (usually < 1.0 m). The greater sampling depths resulting in more samples per profile would be expected to statistically decrease the mean SEE. However, difficulty in obtaining good samples at the deeper depths was encountered at all sites (gravel particles at site 1, sticky clay at site 2, and structureless sand at site 3), so that, overall, the SEE values for the three deeper methods may be larger than if only samples < 1.0 m were evaluated. It is noted that all methods were somewhat compromised during the close-quartered field study. Normally the methods would not need to accommodate one another within a 0.6 m circle and within short time periods.

Overall, the SCS down-hole ("Madera") sampler appears to have resulted in the most consistent and reproduceable bulk density samples in terms of SEE. The SCS down-hole sampler had overall SEE's of 2.7 % vs. the mean probable bulk density profiles and 3.6 % vs. the gamma-derived profiles, and averaged 2% higher than the gamma measurements. The USU down-hole sampler obtained good bulk density samples also. However, the smaller size of the USU sampler (15 cm^3) was a disadvantage in terms of precision and representative moisture samples (Allen et al., 1993). The "Madera" sampler is available from a commercial vendor[2]. The USU sampler is fabricated at Utah State University. The advantage of down-hole samplers is that they are nondestructive, if replicated profiles are not sampled, and are portable. The advantage of coring machines is the larger sampling size, reduction in muscle strain, and ability to sample multiple, adjacent holes quickly. The drive samplers had SEE's similar to other methods and represent good methods for bulk density sampling provided samples are not compressed longitudinally, the site can be destroyed, and sampling is limited to less than 1 m depth (Dickey et al., 1993).

CONCLUSIONS

All sampling methods provided estimates of bulk density which were within 5 % of a mean probable profile and a gamma-probe-measured bulk density profile in most cases, except for one coring method. Standard errors of estimate ranged from 3 to 7 %. When used with care, downhole, coring, and drive samplers can be used to successfully measure bulk density profiles.

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Table 1. Bulk Density Sampling Procedures used during the ASCE Neutron Probe Calibration Study.

		Max. Depth	No. Outliers	No. Missing[1]	Total Samples
USU-DHole:	USU (Willardson) Down Hole Sampler	>1.5 m	1	4	50
SCS-DHole:	Madera Down Hole Sampler	>1.5 m	4	3	51
OSU-Core:	Giddings Core Sampler	0.91 m	0	1	23
ARS-Core:	Giddings Core Sampler	>1.5 m	6	14	45
ARS-Core3:	Giddings Core Sampler (ave of 3 holes)	>1.5 m	8	37	53
SCS-Drive:	Large Drive Sampler (Destructive)	0.6-0.75 m	2	1	25
ARS-Drive:	'Arkansas' Drive Sampler (Destructive)	0.56 m	0	0	25

[1] Missing samples to the maximum depth shown over six holes. Missing samples for ARS-Core3 are total missing samples over three holes. Total samples for ARS-Core3 are the total number of averages of three holes when one or more samples were present.

Table 2. Normalized Standard Errors of Estimate and Ratios vs. Mean Probable and Gamma Bulk Densities for All Sites Combined (3 soil types and 2 sites, wet and dry, for each type).

Method	n	vs. Mean-Probable SEE (%)	vs. Mean-Probable Ratio	vs. Gamma SEE (%)	vs. Gamma Ratio
USU-DHole	50	3.1	0.99	3.9	1.00
SCS-DHole	51	2.7	1.01	3.6	1.02
OSU-Core	23	5.8	1.03	7.1	1.04
ARS-Core	45	3.7	0.99	3.9	0.99
ARS-Core3	53	3.8	0.99	3.3	0.99
SCS-Drive	25	5.8	0.99	5.4	1.00
ARS-Drive	25	3.9	0.98	4.0	0.99

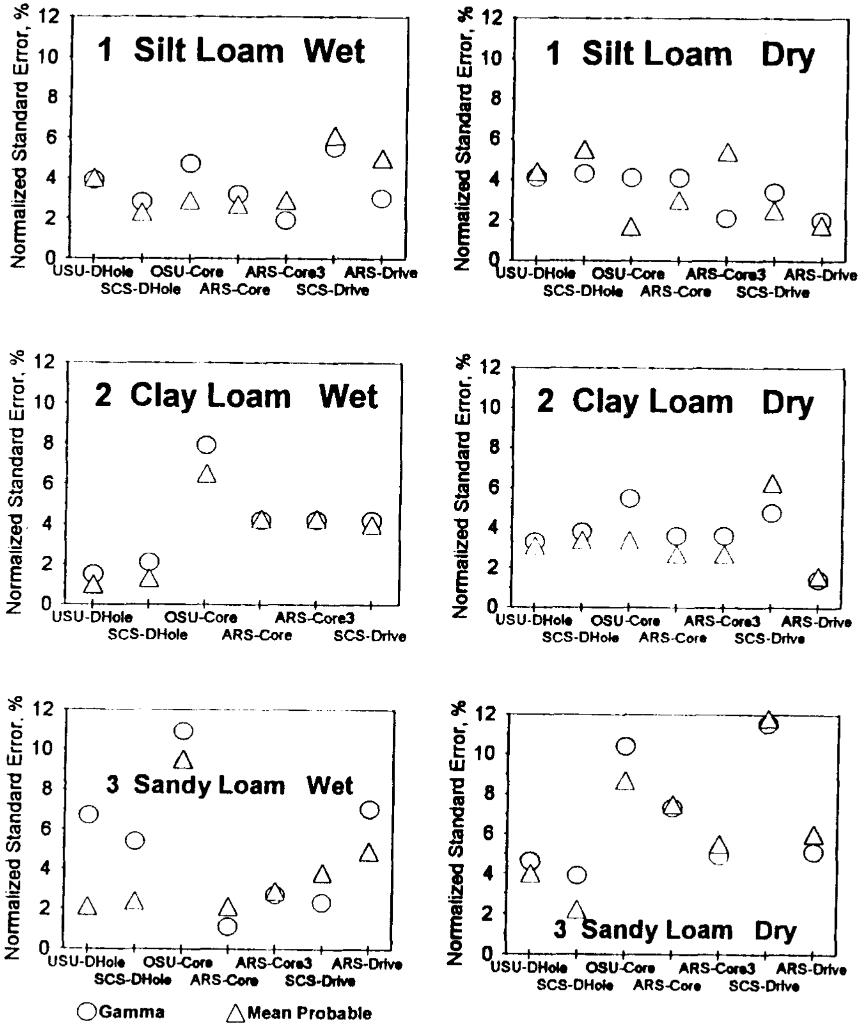

Figure 1 Normalized (percentage) standard errors of estimate for seven sampling methods relative to gamma-derived bulk density profiles an mean probable bulk density profiles at six ASCE soil-moisture sites.

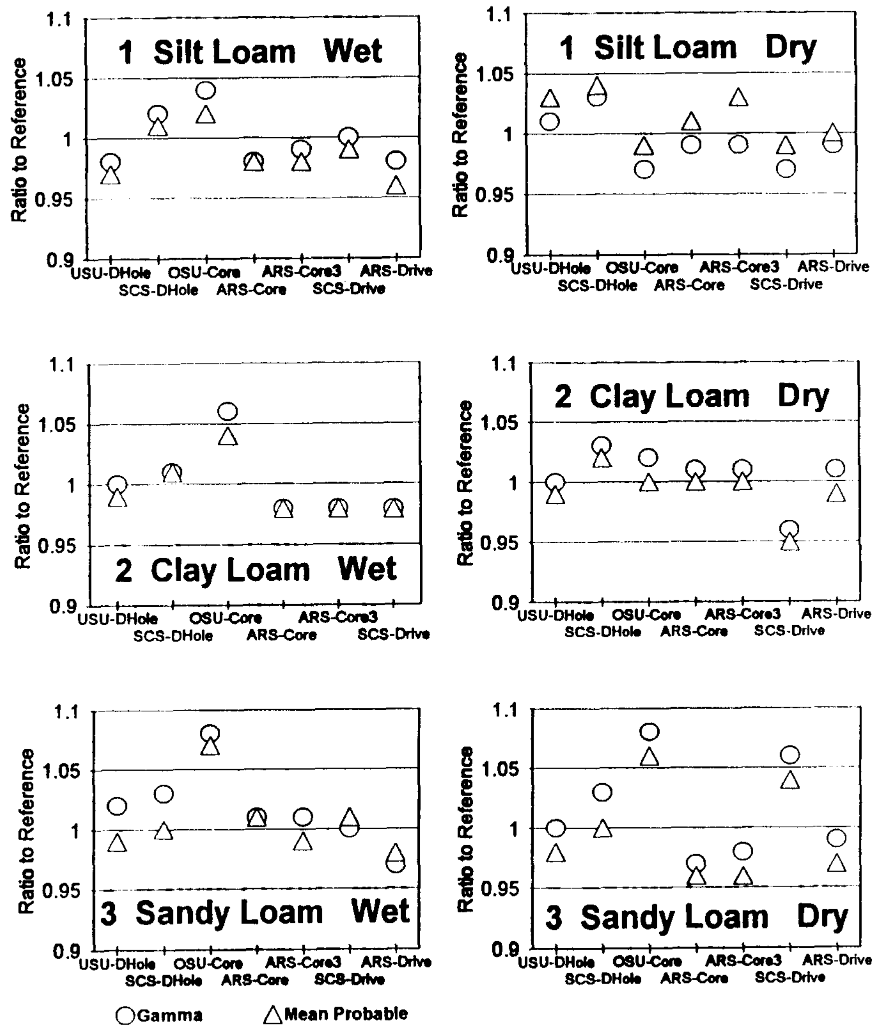

Figure 2 Mean ratios of bulk densities measured by seven sampling methods relative to gamma-derived bulk density profiles and mean probable bulk density profiles at six ASCE soil-moisture sites.