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Evaluation of Bouwer-Rice Large-Particle Correction Procedure for Soil Water Characteristic Curves

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ABSTRACT: The Bouwer-Rice correction method to account for large particles excluded during laboratory testing to measure the soil water characteristic curve (SWCC) was evaluated on samples of well-graded alluvium. A large-scale hanging column apparatus was used so that tests could be conducted on specimens containing all particle sizes. The analyses show that SWCCs measured on the fraction of alluvium finer than the No. 4 U.S. sieve (4.8 mm) can be corrected reliably to represent the SWCC of bulk soil or fractions of bulk soil corresponding to different large-particle thresholds. The method can also be used reliably to correct SWCCs measured on soils prepared with different large-particle thresholds (e.g., finer than 25 mm, 12.5 mm, or 4.8 mm). Dry density of the finer fraction being tested must be carefully controlled to match the dry density of the finer fraction in the soils containing large particles. An equation is described for computing the dry density of the finer fraction in a bulk soil. A simplified version of the Bouwer-Rice method is also proposed and evaluated. In this method, a SWCC test is conducted on the finer soil fraction with dry density matching that anticipated in the field, the van Genuchten equation is fit to the measured SWCC to define the shape parameters α and n, and then the SWCC for the field application is computed using the fitted α and n from the test on the finer fraction, saturated volumetric water content of the bulk soil in the field, and a residual water content of zero. Analyses show that this modified Bouwer-Rice method is simpler and results in an accurate representation of the SWCC of soil containing large particles.

KEYWORDS: unsaturated soil, soil water characteristic curve, matric suction, large-particle correction, moisture retention, gravel

Introduction

Flow problems in variably saturated soils are encountered frequently in near-surface environmental applications, including recharge prediction in vegetated and unvegetated areas (Gee and Hillel 1988), design and prediction of the hydrologic performance of earthen covers for waste containment (Albright et al. 2010; Benson and Bareither 2012), and environmental restoration of the vadose zone (Gee et al. 2007; Dresel et al. 2011). In each of these applications, the soil water characteristic curve (SWCC), the fundamental constitutive relationship linking matric suction (ψ) and volumetric water content (θ) in unsaturated soil (Lu and Likos 2004), is an essential component of prediction and analysis.

Standard methods for measuring the SWCC are currently available and used in practice worldwide (e.g., ASTM D6836). Most SWCC tests conducted using standard procedures are performed on relatively small specimens (≈50–75 mm diameter, ≈10 mm tall). Consequently, larger particles are typically removed (i.e., "scalped") from the soil when preparing a specimen for testing. Large particles, which make laboratory measurements cumbersome, are assumed to have negligible impact on moisture retention relative to the finer soil fraction (e.g., Baetens et al. 2009). However, they can affect the SWCC, and accounting for the effect of large particles influences predictions made during design (Somasundaram et al. 2010). In practice, however, the SWCC determined using scalped soil generally is used "as is" for design computations or as input to numerical models. Corrections to account for the effect of scalping large particles are applied infrequently.

Reinhart (1961) reports that incorporating larger particles decreases the bulk soil water content relative to the water content of the finer scalped soil because large particles typically have low intra-particle water content relative to a comparable volume of finer-textured soil. Fiès et al. (2002), Cousin et al. (2003), and Baetens et al. (2009) report similar effects of larger particles on the water content and unsaturated behavior of soils. Despite these effects, corrections to account for large particles are not common because the unsaturated hydraulic conductivity (Mehuys et al. 1975) and moisture retention (Ravina and Magier 1984) are controlled predominantly by the finer soil fraction.

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Bouwer and Rice (1984) propose a water content correction procedure for bulk soil containing larger particles as a function of the finer fraction water content and the volumetric fraction of large particles, which is often referred to as a "gravel correction" procedure. Because the definition of "gravel" varies between disciplines, the procedure is described herein as a "large-particle correction." The Bouwer-Rice methodology, although used in practice periodically, has received little validation. Khaleel and Relyea (1997) evaluated the Bouwer-Rice correction procedure experimentally by comparing SWCCs of the finer fraction (<2 mm) of gravelly sediments from the Hanford reservation using a Tempe Cell (52 mm diameter) to SWCCs of the bulk soil determined with a unit-gradient apparatus (105 mm diameter). Khaleel and Relyea (1997) do not indicate whether the bulk sample was scalped, but using a 105-mm cell would limit the largest particle size to approximately 18 mm based on the sixfold criteria stipulated in related testing methods such as ASTM D698 and ASTM D5084. Khaleel and Relyea (1997) report that the corrected SWCCs compared favorably with SWCCs obtained using the unit gradient method for the bulk soil. However, the applicability of the water-content correction procedure has not been evaluated for varying fractions of large particles or, to the authors' knowledge, for other soils.

This study had three objectives: (1) to evaluate the efficacy of the Bouwer-Rice correction procedure to predict the SWCC of a bulk soil when applied to the finer fraction (<4.8 mm) of a soil having a least 50 % larger particles that are as large as 80 mm; (2) to evaluate the efficacy of the Bouwer-Rice correction procedure to predict the SWCC of a bulk soil when applied to finer fractions corresponding to different large-particle thresholds; and (3) to assess whether the SWCC of a bulk soil can be represented satisfactorily using SWCC parameters for the finer soil along with an adjustment of the saturated volumetric water content using the Bouwer-Rice correction method. These issues were evaluated by conducting SWCC tests in a large-scale hanging column on samples of alluvium from a final cover test facility at the Cheney Disposal Site near Grand Junction, CO.

Materials and Methods

Soil Samples

Four alluvium samples referred to herein as A, B, C, and D were obtained from test sections constructed for the U.S. Department of Energy's Enhanced Cover Assessment Program (ECAP) at the Cheney Disposal Facility near Grand Junction, CO (Waugh et al. 2009; Benson et al. 2011). The alluvium serves as the bedding layer for riprap on the surface of the cover (Fig. 1). Hydraulic properties of the alluvium affect water movement into and out of the underlying frost protection layer and radon barrier layer. Four grab samples of alluvium were collected during construction of the ECAP tests sections for characterization, including particle size distribution, specific gravity, and the SWCC (Benson et al. 2010).

Particle size distributions of the alluvium determined in accordance with ASTM D422 are shown in Fig. 2. Distribution

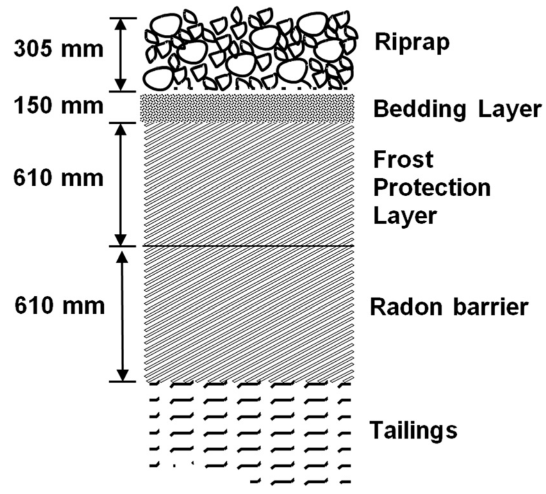

FIG. 1—*Schematic profile of earthen final cover at the Cheney Disposal Site near Grand Junction, CO.*

curves corresponding to the as-collected samples are referred to as "bulk" soils in Fig. 2 and throughout the remainder of this study. Particle size characteristics for the alluvium are summarized in Table 1. The four bulk soils have similar particle size distributions (Fig. 2), and contain approximately equal fractions of gravel and sand with negligible fines (Table 1). The bulk soils are classified as well-graded gravel with sand (GW) according to the Unified Soil Classification System (ASTM D2487). Visual inspection indicated that the larger particles were primarily igneous and slightly metamorphosed rock consisting predominantly of andesite and gabbro. The particles were crystalline and assumed to have no internal porosity.

Additional particle-size distributions curves are shown in Fig. 2 corresponding to alluvium scalped to remove particles

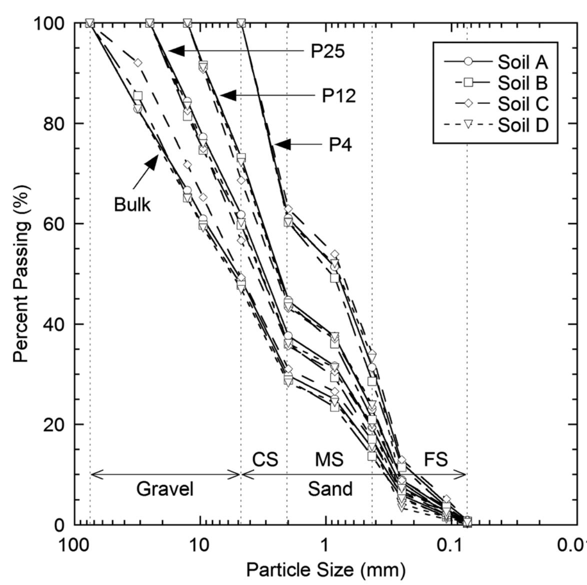

FIG. 2—*Particle size distributions for bulk soil samples as well as soils scalped on a 25.4-mm sieve (P25), 12.7-mm sieve (P12), and 4.75-mm sieve (P4). Gravel and sand particle size ranges based on ASTM D2487. CS, coarse sand; MS, medium sand; FS, fine sand.*

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TABLE 1—*Summary of gravel, sand, and fines contents. Particle sizes corresponding to 50% (d_{50}) and 10% (d_{10}) finer; coefficient of uniformity (C_u); and coefficient of curvature (C_c) of the bulk, P25, P12, and P4 fractions for the four soils used in this study.*

Soil	Fraction[a]	Gravel (%)	Sand (%)	Fines (%)	d_{50} (mm)	d_{10} (mm)	C_u	C_c
A	Bulk	51.2	48.3	0.47	5.0	0.31	29.0	1.43
	P25	38.2	61.2	0.60	3.0	0.28	16.4	0.50
	P12	26.8	72.5	0.71	2.3	0.26	11.9	0.45
	P4	0.0	99.0	0.96	0.81	0.20	9.0	0.47
B	Bulk	52.2	47.4	0.40	5.4	0.33	28.8	1.41
	P25	40.3	59.2	0.50	3.2	0.29	16.6	0.58
	P12	26.8	72.6	0.62	2.3	0.27	11.5	0.47
	P4	0.0	99.2	0.84	0.90	0.21	9.5	0.53
C	Bulk	50.7	48.9	0.47	5.9	0.30	24.7	1.46
	P25	43.3	56.2	0.55	3.6	0.28	18.6	0.51
	P12	31.3	68.0	0.66	2.6	0.26	13.8	0.38
	P4	0.0	99.0	0.96	0.74	0.18	8.9	0.53
D	Bulk	53.1	46.7	0.24	5.7	0.33	29.7	1.50
	P25	39.8	59.9	0.31	3.2	0.30	15.7	0.45
	P12	27.8	71.8	0.38	2.3	0.29	11.0	0.38
	P4	0.0	99.5	0.52	0.80	0.27	7.4	0.30

[a]Bulk soil "as-collected" from field; P25, material passing a 25.4-mm sieve; P12, material passing a 12.7-mm sieve; P4, material passing a 4.75-mm sieve.

TABLE 2—*Summary of specific gravity of large particles and the finer soil fraction as well as the saturated volumetric water content, dry density of bulk soil, mass ratio of finer soil fraction to total soil, and dry density of finer soil fraction for SWCC test specimens.*

Soil	Fraction	G_{sL}	G_{sf}	θ_s (%)	ρ_{db} (mg/m^3)	β	ρ_{df} (mg/m^3)
A	Bulk	2.655	2.646	20.8	2.10	0.49	1.72
	P25			23.3	2.03	0.62	1.78
	P12			32.4	1.79	0.73	1.60
	P4			39.3	1.61	1.00	1.61
B	Bulk	2.657	2.640	20.8	2.10	0.48	1.70
	P25			26.3	1.95	0.60	1.65
	P12			30.2	1.85	0.73	1.66
	P4			39.1	1.61	1.00	1.61
C	Bulk	2.654	2.643	21.9	2.07	0.49	1.69
	P25			24.9	1.99	0.57	1.67
	P12			27.9	1.91	0.69	1.69
	P4			39.6	1.60	1.00	1.60
D	Bulk	2.661	2.638	18.1	2.17	0.47	1.79
	P25			23.4	2.03	0.60	1.75
	P12			31.2	1.82	0.72	1.62
	P4			38.8	1.61	1.00	1.61

Note: G_{sL}, specific gravity of material retained on 4.75-mm sieve (large particles); G_{sf}, specific gravity of material passing a 4.75-mm sieve (sand and fines); θ_s, saturated volumetric water content; ρ_{db}, dry density of bulk soil; β, dry mass ratio of finer fraction to total soil; ρ_{df}, dry density of finer fraction in bulk soil.

larger than the 25.4-mm sieve (P25), 12.7-mm sieve (P12), or 4.75-mm sieve (P4). The bulk and scalped soils were used to evaluate the Bouwer-Rice correction procedure to account for large particles excluded when measuring the SWCC of soils containing larger particles.

Particle-size distribution curves for each of the scalped soils (P25, P12, and P4) are similar (Fig. 2). All scalped soils are classified as poorly graded sand (SP) based on the Unified Soil Classification System, with the P25 and P12 soils including a "with gravel" designation. As anticipated, scalping decreases the gravel fraction and increases the sand fraction as the sieve size used for scalping decreases (Table 1). The fines content for all scalped soils remains less than 1 % due to the low initial fines content of the bulk soils (Table 1). The sand fraction of all soils is primarily composed of coarse and medium sand (Fig. 2).

Specific gravities (G_s) of material retained on the 4.75-mm sieve (large particles) and material passing the 4.75-mm sieve (sand and fines) are tabulated in Table 2. Specific gravity of the combined sand and fines (G_{sf}) was measured using a water pycnometer following ASTM D854; specific gravity of the large particles (G_{sL}) was measured using the buoyant weight method following ASTM C127 and are reported herein as oven-dried specific gravity. Large-particle fractions for all four soil samples had slightly higher G_s on average (2.66) compared to G_s for the combined sand and fines fractions (2.64). Soil-specific G_s for the finer fraction (G_{sf}) and large-particle fraction (G_{sL}) as well as the bulk soil specific gravity (G_{sb}) were used in large-particle correction calculations described subsequently.

Water Content Correction Procedure

Bouwer and Rice (1984) present the following equation for computing the bulk soil volumetric water content (θ_b) from the water content of the finer fraction from which larger particles have been excluded (θ_f):

$$\theta_b = (1 - V_R)\theta_f \quad (1)$$

where θ_f is volumetric water content of the finer soil fraction and V_R is the volumetric fraction of larger particles in the total soil volume ($V_R = V_L/V_t$). The volume of the large particles (V_L) is computed as the ratio of the mass of the large-particle fraction in the bulk soil (M_{sL}) to the density of the large particles ($\rho_{sL} = \rho_w G_{sL}$), where ρ_w is the density of water; i.e., $V_L = M_{sL}/\rho_{sL}$. The total volume of the bulk soil (V_t) is computed from the total dry soil mass (M_{st}) and dry density of the bulk soil (ρ_{db}). A corrected SWCC is obtained by applying Eq 1 to each water content in a SWCC data set. An example of the SWCC correction procedure using Eq 1 is shown in Fig. 3. Using the P4 fraction for Soil B, a corrected θ_b is computed for each measured θ_f, and the corrected P4 SWCC shifts to approximately overlap the SWCC measured on the bulk soil.

The Bouwer-Rice correction procedure implicitly assumes that the large particles have neglible intra-particle moisture retention. Flint and Childs (1984) measured water retention characteristics of large particles with varying composition, and report an average intra-particle porosity of granitic particles = 0.17. For a bulk soil

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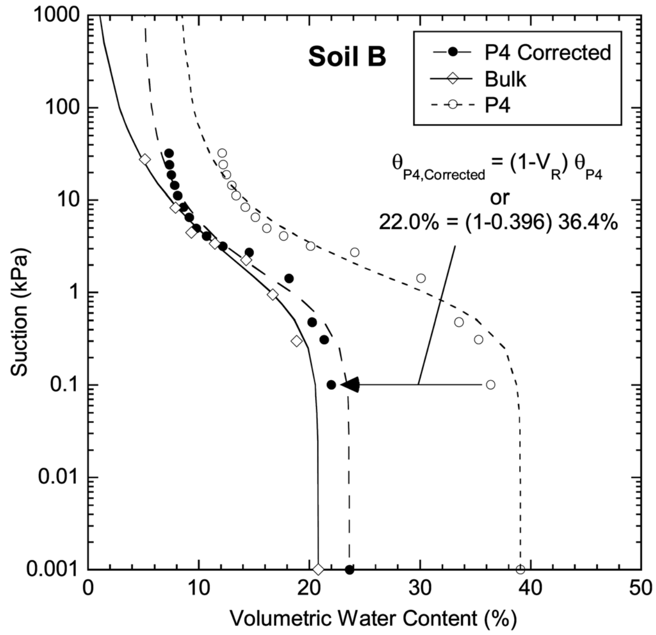

FIG. 3—*Example showing correction of the SWCC for P4 Soil B for large particles to represent the SWCC of bulk Soil B.*

sample with the large granitic particles constituting 10 % by volume, the intra-particle porosity of the granitic particles contributed approximately 4 % of the total available water. Jones and Graham (1993) report that the available water capacity (i.e., water retained between 10 and 1500 kPa matric suction) of unweathered granitic rock is approximately 1 %, and that the available water capacity increases with increasing rock weathering due to the presence of clay weathering products. Thus, for large particles derived from unweathered crystalline rocks, such as the larger particles in this study, the moisture retained within the large particles can be assumed negligible.

Applying Eq 1 to determine θ_b from θ_f requires that the dry density of the finer soil fraction (ρ_{df}) in the bulk soil and the scalped soil be the same. If the larger particles have negligible internal void volume and are assumed to act as inclusions in the finer soil matrix, then the total bulk soil volume (V_t) can be computed as

$$V_t = V_{sf} + V_{vf} + V_L \tag{2}$$

where V_{sf} is the volume of solids in the finer fraction, V_{vf} is the volume of the voids in the finer fraction, and V_L is defined previously. The dry density of the finer fraction can be expressed as

$$\rho_{df} = \frac{M_{sf}}{V_{sf} + V_{vf}} \tag{3}$$

where M_{sf} is the solid mass of the finer fraction. Alternatively, the denominator in the right-hand side of Eq 3 can be expressed as

$$\rho_{df} = \frac{M_{sf}}{V_t - V_L} \tag{4}$$

through which ρ_{db} can be incorporated via V_t, and thus, ρ_{df} and ρ_{db} can be directly related.

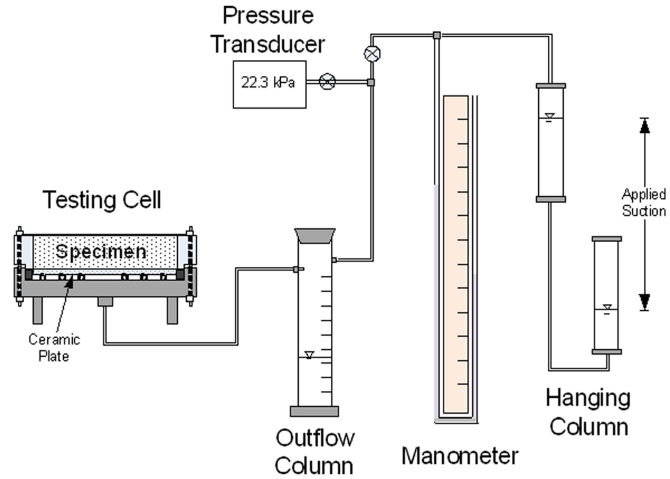

FIG. 4—*Schematic of large-scale hanging column test cell and apparatus used to test alluvium specimens with all particle sizes.*

The volume terms in the denominator of Eq 4 can be expressed as follows:

$$\rho_{df} = \frac{M_{sf}}{\frac{M_{st}}{\rho_{db}} - \frac{M_{sL}}{G_{sL} \cdot \rho_w}} \tag{5}$$

where M_{st} is the total solid mass of the bulk soil (i.e., $M_{st} = M_{sf} + M_{sL}$). The solids masses in Eq 5 can be related by the parameter $\beta = M_{sf}/M_{st}$. Substituting β into Eq 5 and simplifying yields:

$$\rho_{df} = \frac{\beta}{\frac{1}{\rho_{db}} - \frac{(1-\beta)}{G_{sL} \cdot \rho_w}} \tag{6}$$

Thus, the dry density of the finer fraction can be computed from ρ_{db}, G_{sL}, and β, where ρ_{db} can be obtained from bulk soil specimens or in situ measurements, and G_{sL} and β are obtained from conventional laboratory measurement of specific gravity of soils and the particle size distribution. Equation 6 is equivalent to the unit weight correction methodology outlined in ASTM D4718.

Soil Water Characteristic Curve

SWCCs were measured on the bulk soil with all of the particle sizes and for each of the scalped fractions (P25, P12, P4) using the hanging column procedure described in ASTM D6836 (Method A). A large-scale test cell and apparatus were used to accommodate large particles in the alluvium (see schematic in Fig. 4). The test cell can accommodate a specimen 305 mm in diameter and 76-mm thick, and is equipped with a ceramic plate having an air-entry pressure of 100 kPa. The measured SWCCs shown in Fig. 3 are examples of SWCCs measured using the test cell and associated apparatus. All specimens in this study were prepared with a diameter of 305 mm and height of 60 mm. For the bulk soil, at most, 10 % of the particles were larger than 51 mm (one-sixth of the diameter of ceramic plate).

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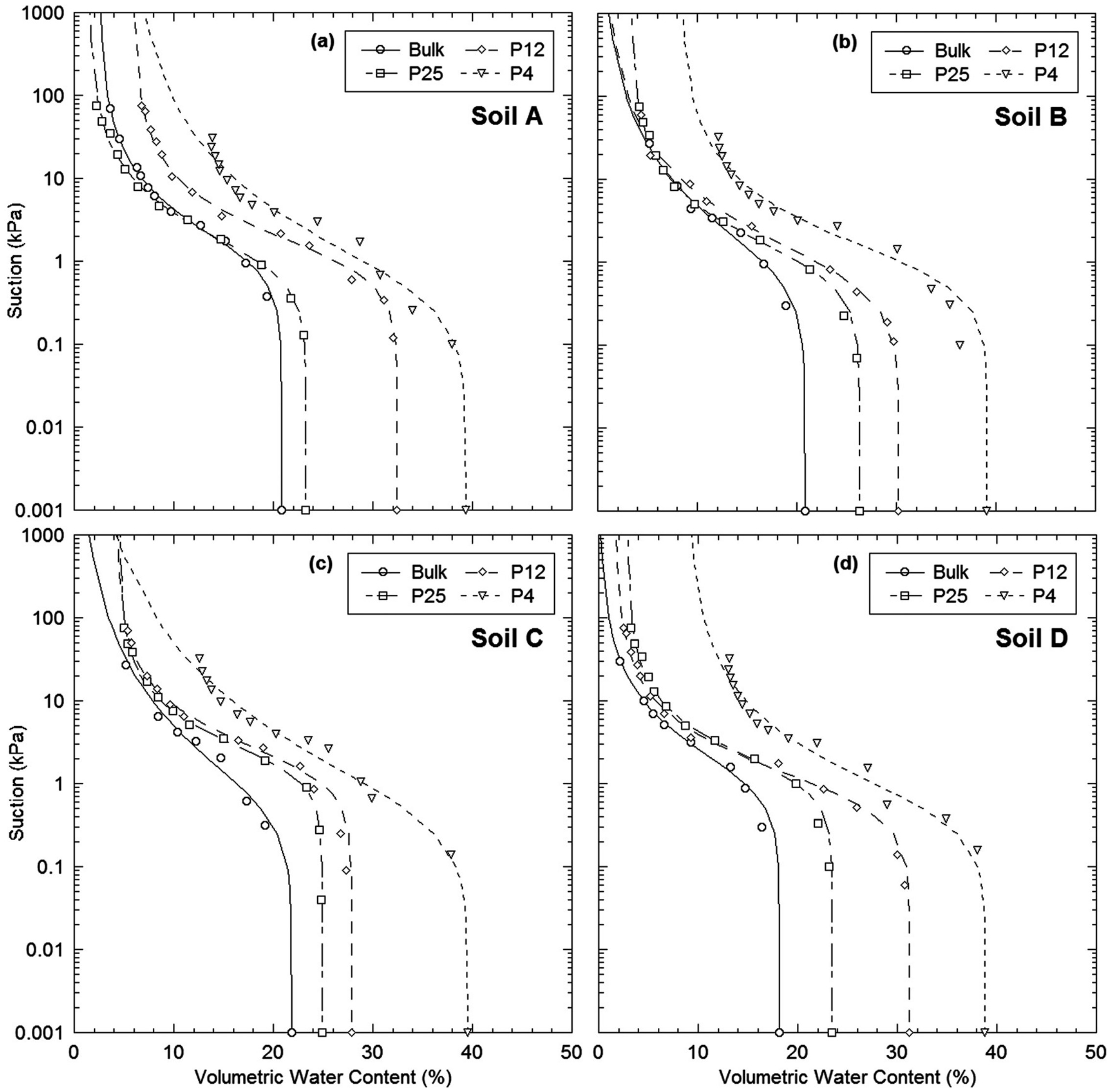

FIG. 5—*Measured suction versus volumetric water content relationships (data points) from hanging columns on bulk and scalped (P25, P12, P4) soils: (a) Soil A, (b) Soil B, (c) Soil C, and (d) Soil D. Fitted SWCCs (lines) based on Eq 7.*

All specimens were prepared with ρ_{df} as close as practical to the average ρ_{df} of the bedding layer in the ECAP test sections at the Cheney Disposal Site, which ranged from 1.41 to 1.71 mg/m^3 (average = 1.58 mg/m^3) (Benson et al. 2010). Specimens were compacted in the hanging column test cell (Fig. 4) with a wooden tamper in two lifts, with the number of blows adjusted so that the target dry density (ρ_{df}) would be achieved. For bulk specimens, particles with a diameter larger than a lift thickness (30 mm) were either included with the first compacted lift or placed within the first lift following compaction. Care was used to pack the finer soil uniformly around the very large particles with the same ρ_{df} used in the remainder of the specimen. A summary of ρ_{df} for the test specimens is in Table 2. The average dry density of the P4 specimens (i.e., all finer fraction) is 1.61 mg/m^3, which is comparable to the target $\rho_{df} = 1.58$ mg/m^3 based on the field condition. Despite the best intentions, slightly higher ρ_{df} were obtained when preparing the bulk, P25, and P12 hanging column test specimens (Table 2) relative to the target ρ_{df}. Differences in ρ_{df} between soil specimens and the influence on SWCCs are described subsequently.

Each SWCC was fit using with the van Genuchten equation (van Genuchten 1980):

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (\alpha\psi)^n} \right\}^m \qquad (7)$$

where Θ is effective saturation, θ is volumetric water content, θ_r is residual volumetric water content, θ_s is saturated volumetric water content, ψ is matric suction, and α, m, and n are fitting parameters. Equation 7 was fit to the SWCC data using a non-linear least-squares optimization allowing θ_r, α, and n to vary with the constraint $m = 1 - n^{-1}$. The saturated volumetric water

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TABLE 3—*Fitted parameters for van Genuchten's SWCC function for bulk and scalped soils.*

Soil	Fraction	θ_r (%)	θ_s (%)[a]	α (1/kPa)	n	m
A	Bulk	2.50	20.8	0.79	1.70	0.41
	P25	1.41	23.3	0.90	1.72	0.42
	P12	5.99	32.4	0.90	1.80	0.45
	P4	4.99	39.3	2.13	1.37	0.27
B	Bulk	0.00	20.8	1.11	1.42	0.30
	P25	3.26	26.3	1.04	1.74	0.42
	P12	0.60	30.2	1.41	1.50	0.33
	P4	8.23	39.1	1.16	1.66	0.40
C	Bulk	0.00	21.9	1.70	1.36	0.26
	P25	4.59	24.9	0.50	1.98	0.50
	P12	4.26	27.9	0.56	1.86	0.46
	P4	0.00	39.6	2.33	1.29	0.22
D	Bulk	0.00	18.1	0.81	1.66	0.40
	P25	2.92	23.4	0.69	1.92	0.48
	P12	1.60	31.2	1.28	1.76	0.43
	P4	8.86	38.8	1.93	1.54	0.35

Note: θ_r, residual volumetric water content; θ_s, saturated volumetric water content; α, n, and m, van Genuchten fitting parameters.
[a]Not fitted; computed from specimen preparation.

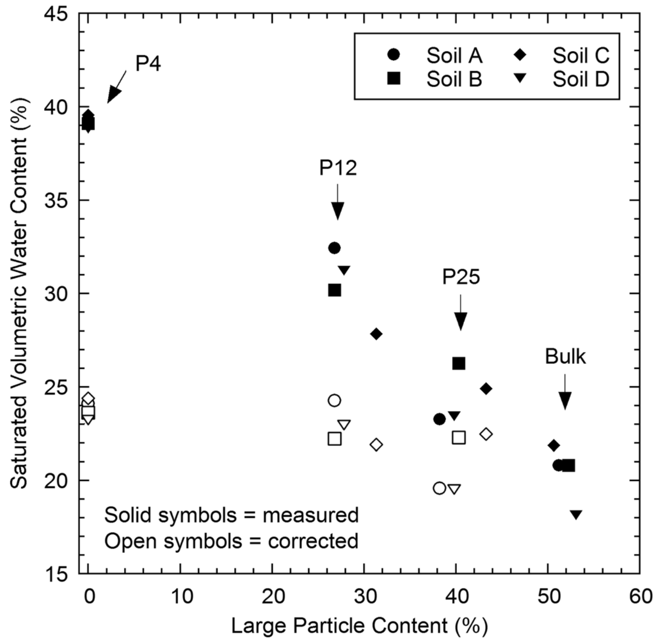

FIG. 6—*Relationship between saturated volumetric water content (θ_s) and percent gravel fraction (i.e., large particles). Measured θ_s are from as-prepared bulk and scalped soils, whereas corrected θ_s are based on Eq 1 to predict θ_s of the bulk soils.*

content was computed by weight–volume relationships and fixed during fitting of Eq 7. A summary of θ_s, ρ_{db}, β, and ρ_{df} for all bulk and scalped soils is in Table 2.

Statistical Comparison

Statistical comparisons were made between SWCCs corrected using the Bouwer-Rice method (referred to as "corrected SWCCs") and the actual SWCCs for specimens containing larger particles. Corrected SWCCs were fit with Eq 7 using the same least-squares optimization used to fit the measured SWCCs, which yielded sets of "corrected van Genuchten parameters." Volumetric water contents were then obtained from a corrected SWCC ($\hat{\theta}$) for each ψ at which a measured θ was obtained for the soil containing larger particles. The residual between the measured and corrected water contents, $\theta_i - \hat{\theta}_i$, represents the error between the measured SWCC for soil containing the larger particles and the corrected SWCC based on data from the finer soil. The subscript i represents the ith measurement point (suction, ψ) in the series of N measurement points comprising the SWCC.

The coefficient of determination (R^2), mean-square error (MSE), and average bias were computed for each set of corrected and measured SWCCs to evaluate the efficacy of the correction procedure. Procedures outlined in Berthouex and Brown (2002) were used to compute the statistics. The coefficient of determination was computed as:

$$R^2 = 1 - \frac{\mathrm{SSR}}{\mathrm{SST}} \tag{8}$$

where SSR is the sum of squared residuals and SST is the total sum of squares. The total sum of squares was computed as

$$\mathrm{SST} = \sum_{i=1}^{N} \left(\theta_i - \overline{\theta}\right)^2 \tag{9}$$

where $\overline{\theta}$ is the arithmetic mean of θ in a SWCC data set (i.e., $\overline{\theta} = (1/N)\sum \theta_i$). The sum of squared residuals is computed as

$$\mathrm{SSR} = \sum_{i=1}^{N} \left(\theta_i - \hat{\theta}_i\right)^2 \tag{10}$$

where θ_i and $\hat{\theta}_i$ correspond to the same ψ. The mean-square error is computed as the ratio between SSR and N (i.e., MSE = SSR/N). Average bias is computed as the arithmetic mean of the N residuals ($\theta_i - \hat{\theta}_i$) for a given SWCC data set. A positive average bias indicates that the actual SWCC yields a higher water content for a given suction compared to the corrected SWCC.

Results

Measured SWCCs

Soil water characteristic curves measured on the bulk soils and scalped soil fractions for Soils A, B, C, and D are shown in Fig. 5. Data points in Fig. 5 are physical measurements made on each test specimen; the lines are SWCCs fitted using Eq 7. A summary of the van Genuchten parameters for all measured SWCCs is in Table 3. All fitted SWCCs in Fig. 5 show similar shape between soil fractions analyzed (P4, P12, P25, and bulk) and between the four soils analyzed (Soils A, B, C, and D). Similar SWCCs were anticipated for Soils A, B, C, and D because the samples were

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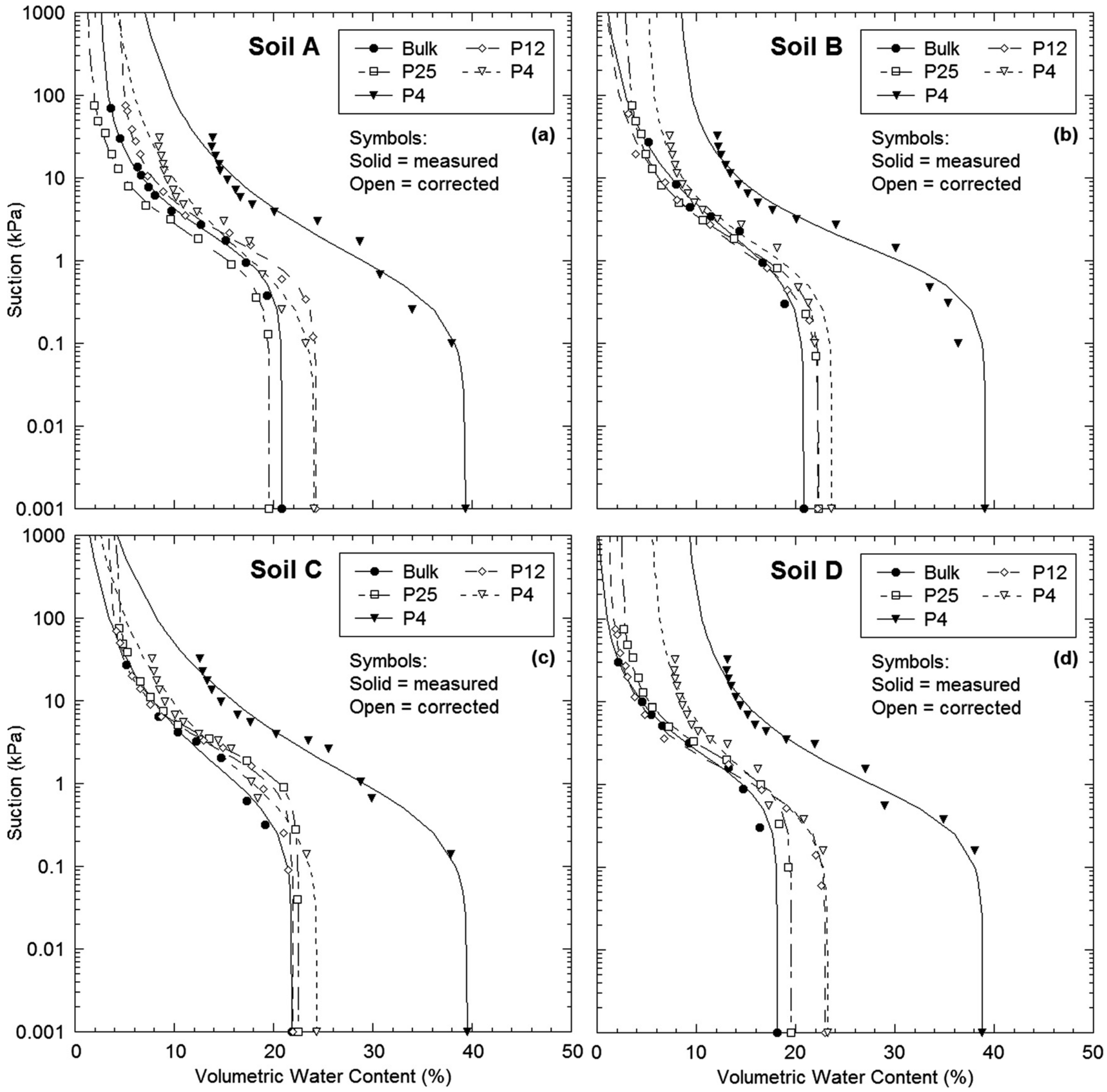

FIG. 7—*Large-particle corrected relationships of suction versus volumetric water content (open symbols) of scalped soils (P25, P12, P4) for predicting suction versus volumetric water content relationship for bulk soils (solid symbols) for all four soils: (a) Soil A, (b) Soil B, (c) Soil C, and (d) Soil D. Fitted soil water characteristic curves (lines) are based on Eq 7. Measured P4 data are included for comparison.*

from the same alluvium deposit used to construct the ECAP test sections. The shape and range of ψ and θ for the measured SWCCs are comparable to SWCCs for well-graded sands and gravels (Fredlund and Rahardjo 1993; Lu and Likos 2004).

The primary difference between SWCCs for the bulk and scalped soils is in θ_s. An increase in the large-particle content from P4 to bulk causes a corresponding decrease in θ_s, shifting the SWCC to a lower range of θ. The relationship between θ_s and large-particle content is shown in Fig. 6. Adding large particles reduces the volume of the finer fraction (P4) per total volume of soil, which results in a reduction in the volume of voids and volume of water in the bulk soil, and a corresponding decrease in bulk soil water content. Reinhart (1961), Fiès et al. (2002), and Baetens et al. (2009) show a similar effect of large-particle content. Soil water characteristics curves of the P4 materials are also steeper at the dry end of each curve, which may indicate that the time between increments in suction was insufficient to reach equilibrium at the dry end of these SWCCs (Gee et al. 2002).

No systematic relationships were observed between the van Genuchten parameters α and n and soil composition or particle size characteristics. For example, the α parameter, which is related to the air entry suction of the soil (i.e., suction at which the largest pores begin to drain), varied by less than 2 kPa^{-1} between any combination of bulk and scalped soils for a given soil (Table 3). The absence of any influence of soil composition or particle size characteristics reflects the relatively consistent finer fraction in the bulk and scalped soils, as the finer soil fraction controls moisture retention (Ravina and Magier 1984). The modest differences that exist in the computed ρ_{df} between the bulk and scalped soils (Table 2) appear to have negligible influence on the SWCC

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TABLE 4—*Summary of van Genuchten's SWCC parameters from corrected volumetric water contents for scalped soils (P25, P12, and P4) used to predict volumetric water contents of bulk soils.*

Soil	Fraction Used to Predict Bulk SWCC	$V_R = V_L/V_t$	θ_r (%)	θ_s (%)[a]	α (1/kPa)	n	m	R^2	MSE	Average Bias
A	P25	0.159	1.19	19.6	0.90	1.72	0.42	0.90	3.23	1.73
	P12	0.252	4.48	24.3	0.90	1.80	0.45	0.88	3.83	−1.69
	P4	0.387	3.06	24.1	2.13	1.37	0.27	0.80	6.48	−2.34
B	P25	0.152	2.76	22.3	1.04	1.74	0.42	0.92	2.07	0.15
	P12	0.264	0.44	22.2	1.41	1.50	0.33	0.93	1.90	0.46
	P4	0.396	4.98	23.6	1.16	1.66	0.40	0.85	4.05	−1.68
C	P25	0.098	4.14	22.5	0.50	1.98	0.50	0.82	5.10	−1.90
	P12	0.213	3.35	21.9	0.56	1.86	0.46	0.90	2.80	−1.25
	P4	0.383	0.00	24.4	2.33	1.29	0.22	0.84	4.55	−2.00
D	P25	0.167	2.43	19.5	0.69	1.92	0.48	0.92	2.26	−1.34
	P12	0.265	1.17	23.0	1.28	1.76	0.43	0.80	5.91	−1.07
	P4	0.402	5.29	23.2	1.93	1.54	0.35	0.48	15.4	−3.72

Note: Statistical parameters describe comparisons between predictions made with corrected SWCCs and SWCCs measured on bulk soils. V_R, volumetric fraction of large particles; θ_r, residual volumetric water content; θ_s, saturated volumetric water content; α, n, and m, van Genuchten fitting parameters; R^2, coefficient of determination; MSE, mean-square error.

[a]Not fitted; computed from initial specimen preparation with subsequent correction via Eq 1.

parameters fit to the SWCC data for the bulk and scalped soils tested in this study.

Corrected SWCCs

Volumetric water contents measured with the hanging column at each ψ on the scalped soils (P4, P12, and P25) were corrected using Eq 1 to obtain volumetric water contents corresponding to soil with the larger particles present. Corrections were made using two methods: (1) sets of θ for each scalped soil (P4, P12, and P25) were adjusted to represent the bulk soil (Method 1), and (2) sets of θ for the finer fraction (P4) of each soil were used to predict sets of θ for the P12 and P25 fractions as well as the bulk soil (Method 2). Correcting θ measured on the P4 fraction to represent the bulk soil is the same in Methods 1 and 2.

Method 1: Using Scalped Soils to Predict Bulk SWCC—Corrected SWCCs for all scalped soils are shown in Fig. 7 for Soils A, B, C, and D. Although some variability exists between the measured SWCCs for the bulk soils and the corrected SWCCs, the corrected SWCCs generally converge to a single ψ-θ relationship that is comparable to the measurements made on bulk soil.

The volumetric fraction of large particles (V_R) used in Eq 1, fitted van Genuchten parameters for the corrected SWCCs, and statistics computed for each of the corrected SWCCs are tabulated in Table 4. When fitting the corrected SWCC with Eq 7, θ_r, α, and n were allowed to vary in the least-squares optimization, whereas θ_s was fixed based on the calculation made with Eq 1. Each correction included the systematic application of Eq 1 to each measured θ comprising the SWCC of a scalped soil using V_R specific to the soil (Table 4). Thus, all corrected SWCCs retain a similar shape as the measured SWCC. Additionally, the van Genuchten parameters (α and n) fitted to the corrected SWCCs are the same as those obtained from the SWCC on which the corrections were made. For example, the measured SWCC for the P4 fraction of Soil A has $\alpha = 2.13$ kPa^{-1} and $n = 1.37$ (Table 3); the same α and n were obtained when Eq. 7 was fitted to the corrected SWCC (Table 4). This similarity in measured and corrected SWCCs is expected, because the correction cancels out when the volumetric water content is interpreted in terms of effective saturation $[\Theta = (\theta - \theta_s)/(\theta_s - \theta_r)]$. The residual volumetric water content also consistently decreased from the measured to corrected SWCCs, with the exception of P4 Soil C, where $\theta_r = 0$. The decrease in θ_r agrees with a systematic decrease in θ based on the applied large-particle correction equation.

The coefficients of determination compiled in Table 4 suggest that the corrected SWCCs provide an adequate representation of the measured SWCC for the bulk soils. Except for P4 of Soil D, the R^2 is at least 0.80 when the corrected SWCCs are used to predict the SWCCs of the bulk soils. These R^2 indicate that more than 80 % of the variance in the bulk soil ψ-θ relationships can be explained by correcting the SWCC of a scalped soil for the large particles that were excluded. The average bias generally is negative, indicating that the corrected SWCCs typically yield larger θ than the SWCCs measured on the bulk soils. One of the main reasons for the negative average bias is that the corrected θ_s is generally larger than the measured θ_s (Fig. 6), yielding a corrected SWCC that is to the right of the measured SWCC when plotted on a ψ-θ relationship (Fig. 7). Differences

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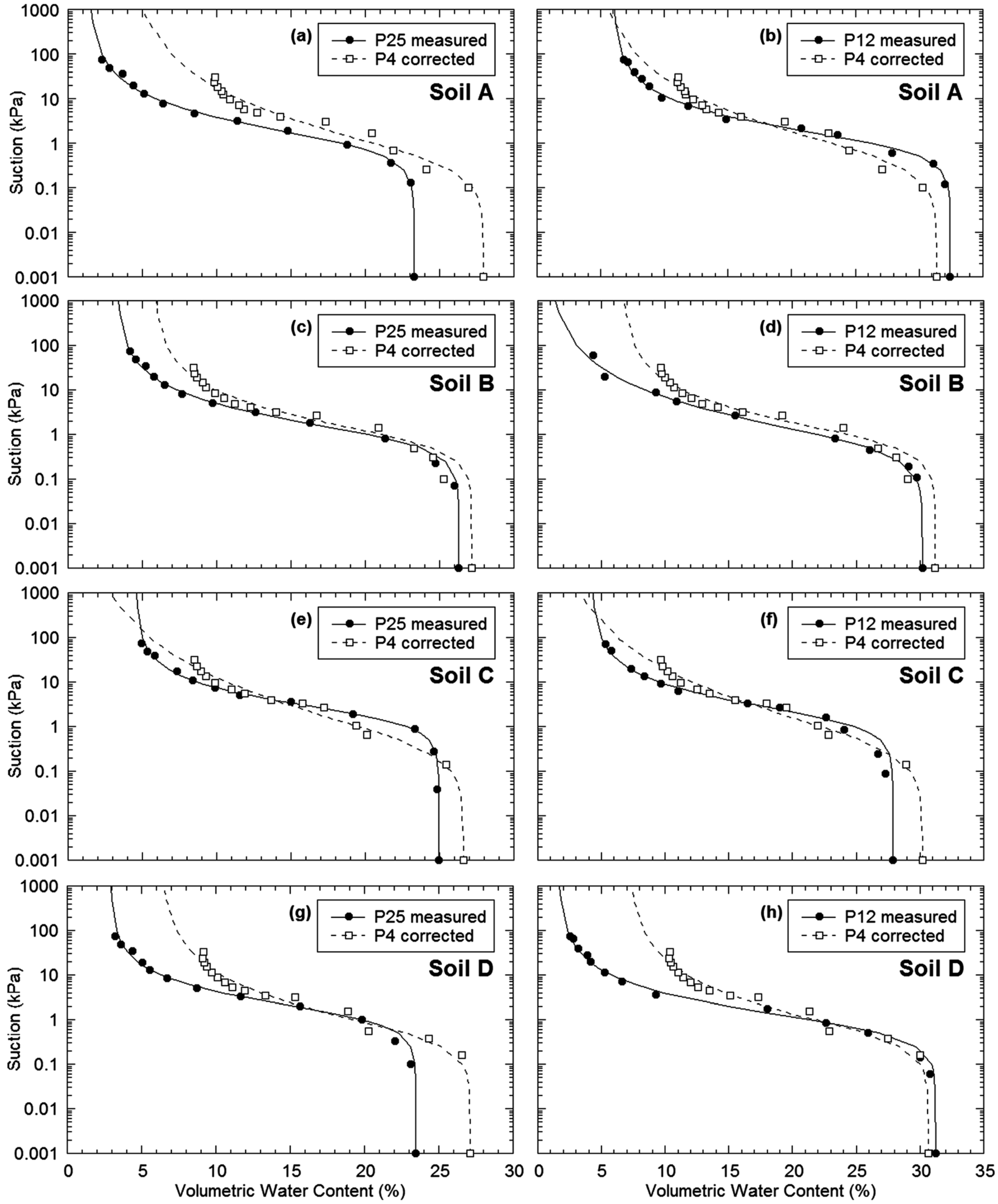

FIG. 8—*Large-particle corrected relationships of suction (ψ) versus volumetric water content (θ) of P4 soil for predicting ψ versus θ relationship for P25 and P12 soils: (a) P25 Soil A, (b) P12 Soil A, (c) P25 Soil B, (d) P12 Soil A, (e) P25 Soil C, (f) P12 Soil C, (g) P25 Soil D, and (h) P12 Soil D. Fitted SWCCs are based on Eq 7.*

between the measured and corrected θ_s are attributed to the differences in ρ_{df} between the soil specimens (described subsequently).

Method 2: Using the Finer Fraction to Predict SWCCs for Different Large-Particle Fractions—Corrected SWCCs obtained by correcting the P4 SWCC data for the presence of large particles in the P25 and P12 soils are shown for Soils A, B, C, and D in Fig. 8. For all analyses except P25 for Soil A (Fig. 8(*a*)), the corrected SWCCs overlap with the measured SWCCs. Similar to the analysis for Method 1, the corrected SWCCs for Method 2 shift to a lower range of θ due to the large-particle correction procedure, but retain the same shape of the SWCC. That is, the finer fraction of the soil is controlling retention of water, whereas the large particles influence the total volume of pores available for water to occupy.

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TABLE 5—*Summary of van Genuchten's SWCC parameters from corrected volumetric water contents for P4 soil used to predict the volumetric water contents of bulk, P25, and P12 soils.*

Soil	Predicted Soil Based on P4 SWCC	$V_R = V_L/V_t$	θ_r (%)	θ_s (%)[a]	α (1/kPa)	n	m	R^2	MSE	Average Bias
A	Bulk[b]	0.387	3.06	24.1	2.13	1.37	0.27	0.80	6.48	−2.34
	P25	0.289	3.55	28.0	2.13	1.37	0.27	0.65	21.1	−4.46
	P12	0.202	3.98	31.4	2.13	1.37	0.27	0.95	4.40	−0.21
B	Bulk[b]	0.396	4.98	23.6	1.16	1.66	0.40	0.85	4.05	−1.68
	P25	0.305	5.72	27.2	1.16	1.66	0.40	0.94	4.48	−1.98
	P12	0.203	6.56	31.2	1.16	1.66	0.40	0.93	6.55	−2.34
C	Bulk[b]	0.383	0.00	24.4	2.33	1.29	0.22	0.84	4.55	−2.00
	P25	0.328	0.00	26.6	2.33	1.29	0.22	0.95	3.06	−0.52
	P12	0.237	0.00	30.2	2.33	1.29	0.22	0.94	4.44	−1.08
D	Bulk[b]	0.402	5.29	23.2	1.93	1.54	0.35	0.48	15.4	−3.72
	P25	0.302	6.18	27.1	1.93	1.54	0.35	0.80	11.6	−3.03
	P12	0.211	6.99	30.6	1.93	1.54	0.35	0.84	20.7	−3.36

Note: Statistical parameters describe comparison between predictions made with the corrected P4 SWCCs and measured bulk, P25, and P12 SWCCs. V_R, volumetric fraction of large particles; θ_r, residual volumetric water content; θ_s, saturated volumetric water content; α, n, and m, van Genuchten fitting parameters; R^2, coefficient of determination; MSE, mean-square error.

[a]Not fitted; computed from initial specimen preparation with subsequent correction via Eq 1.

[b]Same analysis as P4 in Table 4—use gravel corrected P4 data to predict bulk soil SWCC.

The volumetric fraction of large particles (V_R) used in Eq 1, fitted van Genuchten parameters based on the corrected SWCCs, and statistics computed on each of the corrected SWCCs in Method 2 are tabulated in Table 5. The θ_r for the corrected SWCCs decreases relative to the θ_r determined for the measured P4 SWCC (Table 3) coincident with a shift to a lower range of θ. However, as was obtained with Method 1, the van Genuchten parameters α and n for the corrected SWCCs (Table 5) are the same as those obtained by fitting Eq 7 to the measured SWCC for the P4 fraction (Table 3). The similarity in all α and n parameters for corrected SWCC with varying amounts of large particles (P12, P25, and bulk) indicates that applying Eq 1 to measured ψ-θ data only shifts and compresses the corrected SWCC to a lower and narrower θ range, but does not change the shape of the SWCC.

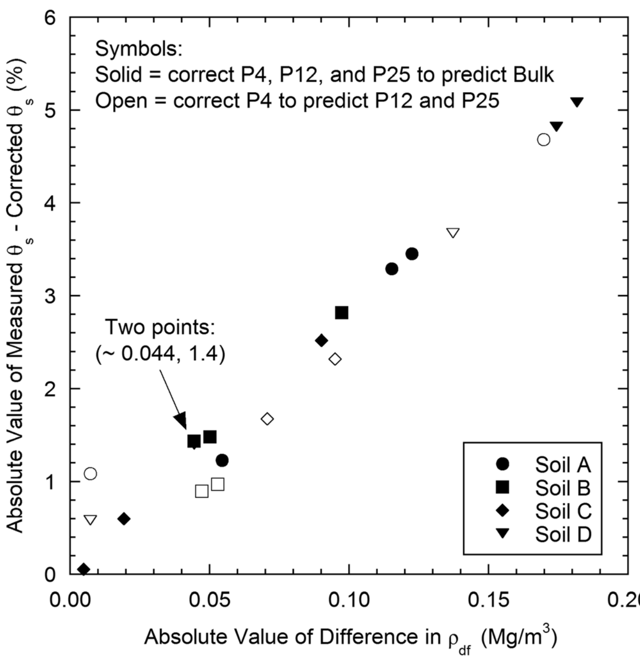

FIG. 9—*Comparison between the absolute value of the difference between measured and corrected saturated volumetric water content (θ_s) versus the absolute value of the difference between the dry density of the finer fraction (ρ_{df}) of soil containing large particles and scalped soil used to create the corrected soil water characteristic curves.*

The coefficients of determination for the corrected SWCCs for P25 and P12 soils are greater than 0.80, except for P25 of Soil A. Mean-square errors for P25 of Soil A and P12 of Soil D are the largest computed for all Method 2 analyses. The large MSE and low R^2 for P25 of Soil A is attributed to a 4.7 % absolute difference between the corrected and actual θ_s (Fig. 6(*a*)), which prevents the corrected SWCC from adequately overlapping the measured SWCC. For P12 of Soil D, θ_s is the same for the corrected and measured SWCC (Fig. 6(*h*)); however, θ_r for the corrected SWCC is considerably larger than θ_r for the measured SWCC for P12 of Soil D, which leads to a poor prediction of moisture retention as ψ increases (Fig. 6(*h*)). A combination of these two deviations in the corrected SWCC (i.e., variation in θ_s and θ_r) is shown for P25 of Soil D (Fig. 8(*g*)), which has high MSE but $R^2 = 0.80$. Similar to the analysis presented in Method 1, the average bias is predominantly negative, indicating that water contents for the corrected SWCCs at a given suction are larger, on average, than water contents for the actual SWCC of the soil.

Assessment—The relationship between the absolute value of the difference between actual and corrected θ_s, i.e., $|\theta_s - \hat{\theta}_s|$ versus the absolute value of the difference between ρ_{df} of soil containing large particles and scalped soil used to create the

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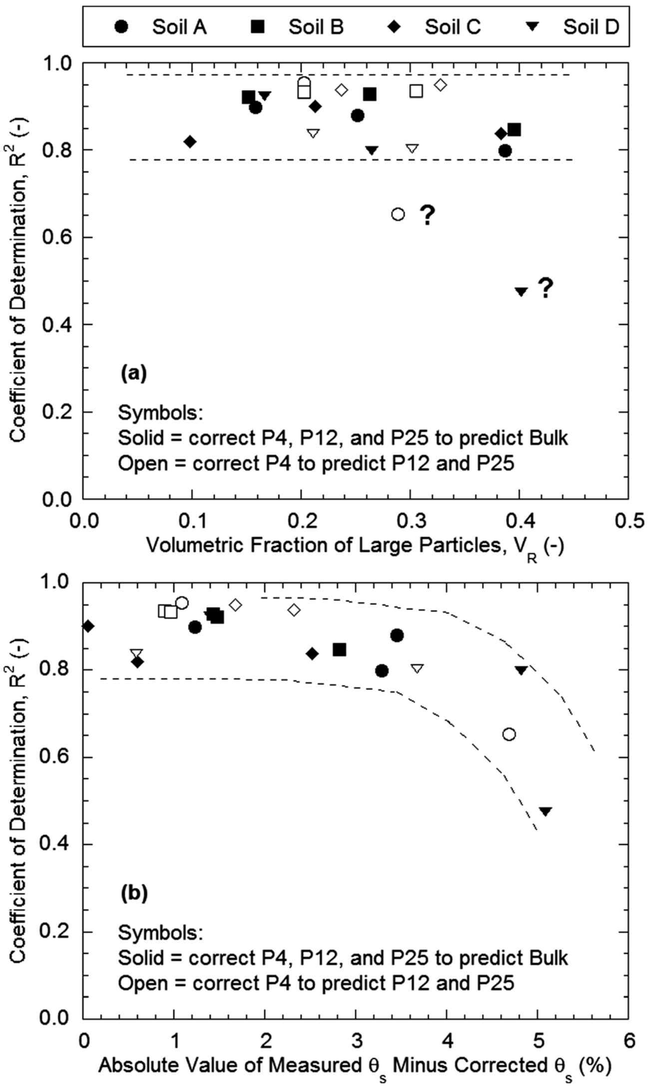

FIG. 10—*Comparison between coefficient of determination and (a) volumetric fraction of large particles (V_R), and (b) absolute value of the difference between measured and corrected saturated volumetric water content (θ_s). Dashed lines capture general data trends.*

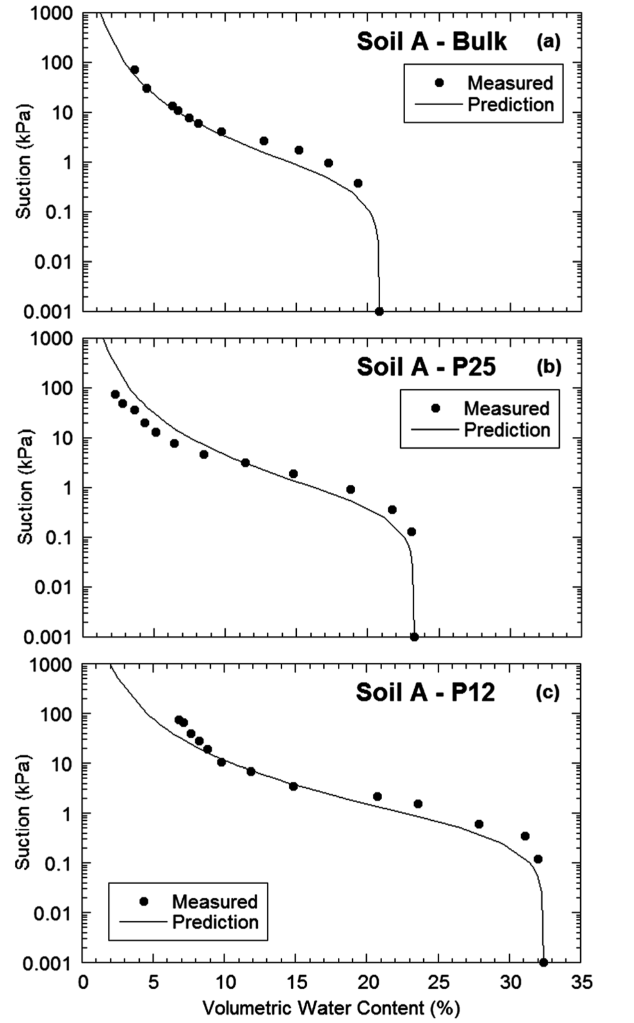

FIG. 11—*Predicted soil water characteristic curves for Soil A based on modified Bouwer-Rice correction: (a) bulk, (b) P25, and (c) P12. Predicted curves include van Genuchten parameters α and n from P4 fraction, saturated volumetric water content measured on soil analyzed, and residual volumetric water content assumed equal to zero.*

corrected SWCCs is shown in Fig. 9 for Methods 1 and 2. These differences in ρ_{df} occurred as a result of experimental error despite the intention of maintaining identical ρ_{df} in all test specimens. As the absolute difference in ρ_{df} increases, there is a corresponding increase in the absolute difference in θ_s. Greater consistency between ρ_{df} of the scalped soil used to create a corrected SWCC and ρ_{df} of a soil containing large particles would have resulted in more accurate estimates of θ_s (and SWCCs) corrected for the presence of large particles.

The coefficient of determination for Methods 1 and 2 are shown versus V_R in Fig. 10(*a*) and versus the absolute value of the difference between the actual and corrected θ_s (i.e., $|\theta_s - \theta_s|$) in Fig. 10(*b*). Except for two outliers, R^2 is essentially independent of V_R (Fig. 10(*a*)), suggesting that the correction procedure has similar efficacy for a broad range of large-particle contents. A more definitive relationship exists between R^2 and $|\theta_s - \theta_s|$ (Fig. 10(*b*)); R^2 diminishes as $|\theta_s - \theta_s|$ increases. The relationship in Fig. 10(*b*) suggests that properly controlling the dry density of the finer fraction to properly represent θ_s (as shown in Fig. 9) is particularly important for developing an accurate SWCC correction.

Practical Implications

There are three important practical observations from this assessment of the Bouwer-Rice correction method: (1) the van Genuchten shape parameters α and n for the SWCC obtained from a conventional test on the finer soil fraction are directly applicable to the bulk soil or other scalped fractions of the bulk soil that contain larger particles than those included in the test specimen; (2) application of Eq 1 to create corrected SWCCs systematically decreases θ for a given ψ, and in particular, shifts θ_s to a lower water content and θ_r closer to zero; and (3) the correction for

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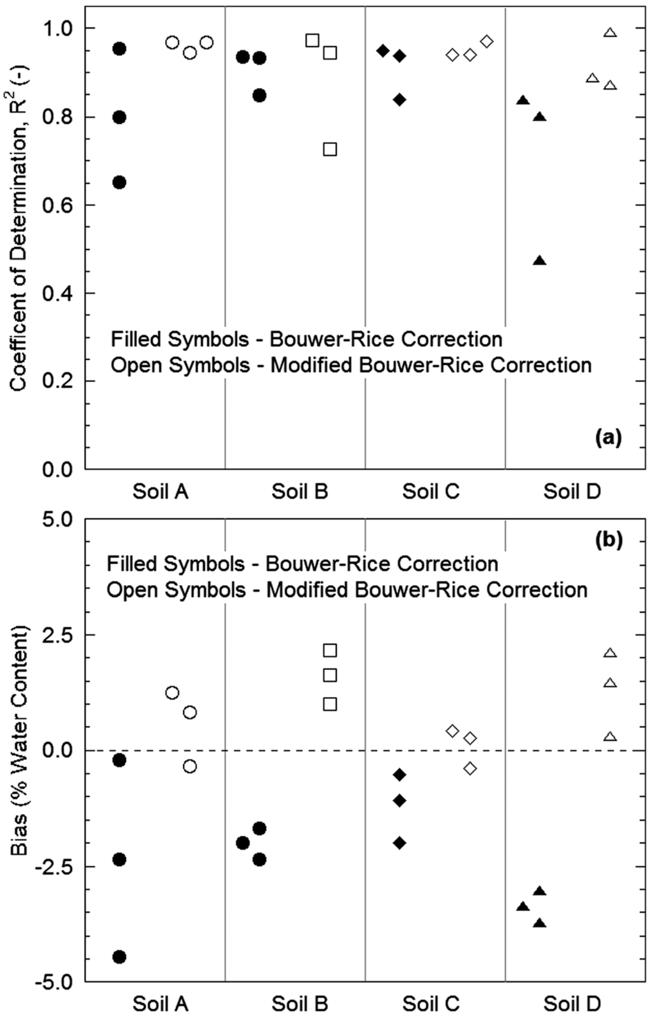

FIG. 12—*Comparison of (a) coefficient of determination, and (b) average bias between actual soil water characteristic curves (SWCC) for bulk soils and SWCCs corrected from scalped soils (P25, P12, P4) with corrections made using conventional Bouwer-Rice correction procedure and recommended modified Bouwer-Rice correction procedure.*

θ_s has a large impact on the efficacy of the corrected SWCC. The third practical observation is directly related to maintaining consistent ρ_{df} between scalped soils and soils containing large particles (Fig. 9).

Based on these observations, the following simplified procedure is recommend for making large-particle corrections to SWCCs determined on the finer fraction:

1. Measure the SWCC for the finer soil fraction on a specimen prepared with the dry density computed using Eq 6.
2. Fit van Genuchten's equation (Eq 7) to the measured SWCC using θ_s computed based on the dry density from Eq 6 by adjusting shape parameters α and n as well as θ_r to obtain an optimal fit using a non-linear least-squares fitting algorithm.
3. Determine θ_s of the bulk soil containing large particles via laboratory-prepared bulk specimens or mass-volume calculations from in situ water content and density measurements.
4. Create a corrected SWCC for the bulk soil using θ_s for the bulk soil (from Step 3), the fitted van Genuchten shape parameters α and n for the finer soil fraction (from Step 2), and assuming $\theta_r = 0$.

SWCCs for the P12, P25, and bulk soil for Soil A created using this procedure are shown in Fig. 11. The SWCCs predicted with van Genuchten's equation using the recommended procedure agree well with the data in each case, and explain more than 95 % of the variance in the data sets (i.e., $R^2 \geq 0.95$). Similar graphs for Soils B, C, and D are reported in Benson and Bareither (2013).

The R^2 and average bias associated with the conventional Bouwer-Rice correction procedure and the recommended simplified method are shown in Fig. 12. Data used to populate Fig. 12 correspond to SWCCs measured using the P4 fraction and corrected to represent the P12, P25, and bulk soils for Soils A–D. In all but one case (Soil B bulk), the recommended SWCC correction method yields comparable or greater R^2 than the conventional method (Fig. 12(*a*)) and an average bias closer to zero (Fig. 12(*b*)).

A unified perspective on the modified Bouwer-Rice correction method is shown in Fig. 13, with the SWCCs depicted in terms of effective saturation (Θ). Effective saturations in Fig. 13 for each soil (A–D) and each soil fraction (bulk, P25, P12, and P4) are computed using measured θ_s (Table 3) and θ_r assumed equal to zero. The SWCC data for the bulk and scalped fractions converge to a single relationship for each soil. The corrected SWCCs in Fig. 13 (solid lines) correspond to α and n from the P4 soil fractions and $\theta_r = 0$. These corrected SWCCs capture the majority of the data and further demonstrate that the finer soil fraction controls moisture retention behavior of soils containing larger particles that have negligible moisture retention.

The best fit to all SWCC data using a single corrected SWCC based on the modified Bouwer-Rice method is for Soil C (Fig. 13(*c*)). The dry density of the finer soil fraction between the four soil fractions of Soil C (bulk, P25, P12, and P4) were the most comparable for any of the soils analyzed in this study (Table 2). This comparison reinforces that accurate control of ρ_{df} between a scalped soil used for laboratory testing and the soil containing large particles in the field is important for direct application of a corrected SWCC. The uniqueness of the corrected SWCC for Soil C (Fig. 13(*c*)) also suggests that a single corrected SWCC based on the recommend method outlined above is applicable for varying fractions of large particles as long as ρ_{df} is maintained the same. However, an upper-bound limit on the percent contribution of large particles for which the recommended SWCC correction method is applicable cannot be identified from the data obtained from this study; subsequent analyses are required to evaluate an upper-bound threshold for large particles.

The soils analyzed in this study had a finer fraction comprised primarily of sand-sized particles. The recommended SWCC correction methodology needs to be evaluated for soils containing a significant silt and/or clay fraction, particularly silts and clays that are plastic. The finer fraction also had small θ_r, and therefore assuming $\theta_r = 0$ for the simplified correction method is reasonable. This assumption will have greater impact for situations where θ_r of the finer fraction is larger.

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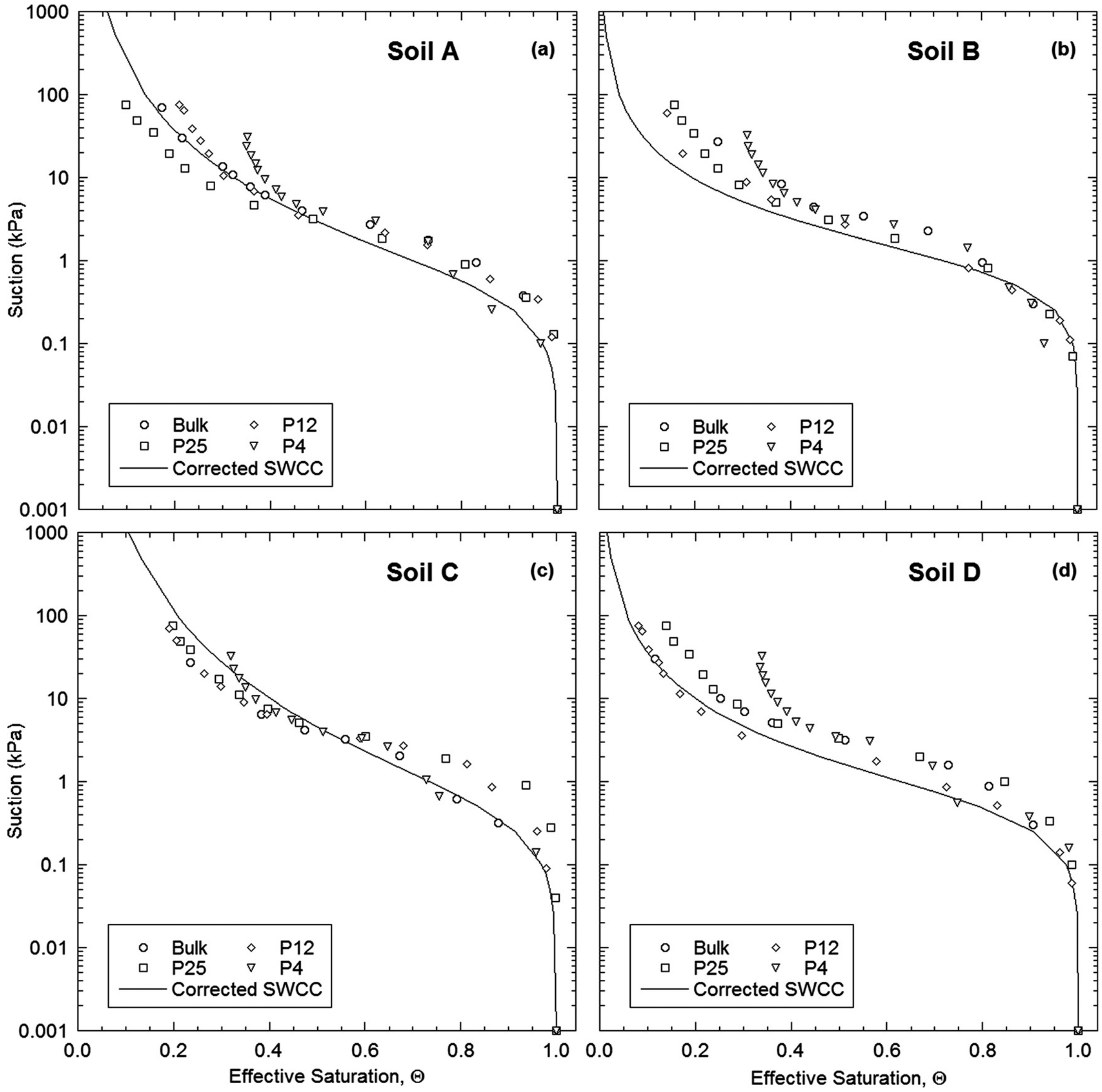

FIG. 13—*Soil water characteristic curves for (SWCC) bulk, P25, P12, and P4 fractions of Soils A, B, C, and D presented in terms of effective saturation using* θ_s *measured on each soil and* θ_r *assumed equal to zero. The corrected SWCC is obtained using the modified Bouwer-Rice correction method.*

Conclusions

The Bouwer-Rice correction method to account for large particles excluded during laboratory testing to measure the soil water characteristic curve (SWCC) was evaluated in this study. Data were obtained from large-scale hanging column tests on samples of well-graded alluvium from which large particles of varying size had been removed. A large-scale hanging column apparatus was used so that tests could be conducted on specimens prepared using all of the particle sizes in the alluvium.

The evaluation has shown that the Bouwer-Rice method works well for the alluvium that was tested in this study. SWCCs measured on the fraction of alluvium finer than the No. 4 U.S. sieve (4.8 mm) were corrected reliably to represent the SWCC of the bulk soil or fractions of the bulk soil corresponding to removal of different large-particle fractions. The correction method worked equally well when used to correct SWCCs measured on soils containing particles finer than 25 mm and 12.5 mm.

The SWCC correction method requires that the dry density of the finer fraction used to measure the SWCC match the dry density of the finer fraction in the soil containing large particles. Errors in the dry density of the finer fraction affect the saturated volumetric water content (θ_s), resulting in a shift of the entire SWCC. An equation for computing the dry density to be used for the test on the finer fraction is included in this paper. Care must be used to ensure that the dry density of the finer fraction matches the field condition as closely as practical.

A simplified version of the Bouwer-Rice method was also evaluated. In this method, an SWCC test is conducted on the finer fraction of the bulk soil with the dry density of the finer fraction matching that anticipated in the field. The van Genuchten equation is then fit to the measured SWCC to define the shape parameters α

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and n. The SWCC for the field application is then computed using the fitted α and n, θ_s of the bulk soil in the field, and a residual water content of zero. Analyses suggest that this simplified Bouwer-Rice method results in a more accurate representation of the SWCC of soil containing large particles as defined by an increase in the coefficient of determination and reduction in average bias.

Acknowledgments

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