Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils

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Abstract: Hydraulic properties of soils used for water balance covers measured at the time of construction and one to four years after construction are compared to assess how the hydraulic properties of cover soils change over time as a result of exposure to field conditions. Data are evaluated from ten field sites in the United States that represent a broad range of environmental conditions. The comparison shows that the saturated hydraulic conductivity (K_s) can increase by a factor of 10,000, saturated volumetric water content (θ_s) by a factor of 2.0, van Genuchten's α parameter by a factor of 100, and van Genuchten's n parameter can decrease by a factor of 1.4. Larger changes occur for denser or more plastic fine-textured soils that have lower as-built K_s, α, and θ_s and higher as-built n, resulting in a reduction in the variation in hydraulic properties that can be attributed to compaction. After two to four years, many water balance cover soils can be assumed to have K_s between 10^{-5} and 10^{-3} cm/s, θ_s between 0.36 and 0.40, α between 0.002 and 0.2 kPa^{-1}, and n between 1.2 and 1.5. The data may be used to estimate changes in hydraulic properties for applications such as waste containment, where long-term maintenance of hydraulic properties in shallow engineered soil layers is important.

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Introduction

The hydrology of water balance covers used for waste containment systems is strongly influenced by the hydraulic properties of the cover soils, namely the saturated hydraulic conductivity (K_s), the unsaturated hydraulic conductivity (K_ψ), and the soil-water characteristic curve (SWCC) (the relationship between volumetric water content, θ, and suction, ψ). Cover soils with higher K_s, more gradually varying K_ψ, and a SWCC with higher air entry suction generally transmit less surface runoff and more percolation (drainage from the base of the cover) (Fayer and Gee 1997; Khire et al. 2000; Roesler et al. 2002; Apiwantragoon et al. 2003; Zornberg et al. 2003; Benson et al. 2005).

Hydraulic properties measured during design are often used to determine the required thickness of a water balance cover and as input to models used to predict cover hydrology (Fayer et al. 1992; Khire et al. 1997; Zornberg et al. 2003; Benson and Chen 2003; Benson et al. 2005). During design, however, hydraulic properties are typically determined on laboratory-compacted specimens and may not reflect the condition of cover soils following long-term exposure to local environmental conditions. Postconstruction processes (freezing and thawing, wetting and drying, root growth and death, and burrowing of worms and insects) often form larger pores between existing peds (Buol et al. 1997; Hillel 1998), altering the hydraulic properties of the soil and the hydrology of the cover (Suter et al. 1993; Benson and Othman 1993; Chamberlain et al. 1995; Waugh et al. 1999; Albrecht and Benson 2001; Henken-Mellies et al. 2001; Ayers et al. 2004; Meiers et al. 2006).

When long-term analyses of cover hydrology are made, temporal changes in soil properties are assumed or inferred because few data exist regarding how hydraulic properties change over time (Waugh et al. 1994, 1999; Khire et al. 2000; Zornberg et al. 2003). This paper compares hydraulic properties of cover soils measured at the time of construction and one to four years after construction, provides methods to estimate changes in the hydraulic properties over time, and provides recommendations regarding cover construction methods that will minimize the propensity for change in hydraulic properties. The data were collected from a network of final cover test sections in the Alternative Cover Assessment Program (ACAP) (Albright et al. 2004). Although this comparison spans a relatively short period of time and cannot be considered to represent "long-term" effects, the comparison does provide an indication of how the hydraulic properties of water balance cover soils may change over time and how these changes are related to the type of soil and the placement condition during construction.

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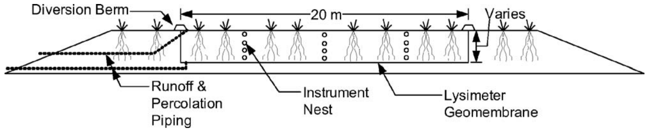

Fig. 1. Typical cross section of ACAP test section along the centerline. The lysimeter is 10 m × 20 m. The top deck of the test section is 30 m long and 20 m wide.

Background

Sample Sources

The ACAP test sections are large-scale lysimeter facilities located at sites throughout the United States that are used to monitor the water balance of prototype covers. A description of the test sections and the monitoring systems can be found in Benson et al. (2001) and Albright et al. (2004). A cross section of a typical test section is shown in Fig. 1. Each test section has a top deck that is 20 m wide and 30 m long, is sloped at 5 or 25%, depending on site-specific issues, and includes a 10 m × 20 m pan lysimeter lined with a geomembrane for monitoring the water balance (Albright et al. 2004). Instruments are included for monitoring runoff, interflow, percolation, soil-water content, soil suction, and meteorological conditions. Construction of all but one of the test sections was completed by 2000 (a test section in Apple Valley, Calif. was constructed in Summer 2002).

Cover soils were placed inside and outside the lysimeters using identical methods in lifts 300–450 mm thick. Methods planned for construction of the full-scale cover at each site were used during construction of the test sections to the greatest extent practical so that full-scale conditions would be simulated. Details of the construction methods can be found in Bolen et al. (2001). Soils were placed with light to moderate compactive effort at water contents dry of optimum with a target dry unit weight corresponding to 85% of maximum dry unit weight for standard Proctor compaction. This target dry unit weight, which is relatively low for engineered fills, was selected so that root growth would not be inhibited (Goldsmith et al. 2001).

Undisturbed samples of the cover soils were collected during construction from randomly selected locations as hand-carved blocks at the in situ water content following the methods described in ASTM D 7015. The samples were trimmed into polyvinyl chloride (PVC) rings (inside diameter and height = 200 mm, wall thickness = 8 mm) that provided lateral confinement as well as protection during transportation. All samples were collected within the boundaries of the lysimeter so that they would be directly applicable to water balance analyses and numerical water balance modeling conducted as part of ACAP. After sampling, the samples were sealed in plastic (while remaining in the PVC rings to provide protection), placed in padded boxes, and shipped to the laboratory for testing. Disturbed samples of the cover soils were also collected simultaneously for measurement of index properties.

Undisturbed samples were also collected in 2002–2004 using the same method. These samples were obtained from randomly selected locations at the near surface (upper 300 mm of the test section), where the greatest changes in properties were expected. Samples were not collected from greater depths so as to avoid disturbance of the test sections. In situ tests to determine hydraulic properties were not conducted so that no water would be added to the test sections other than that received by precipitation or irrigation.

Samples were collected from ten sites representing climatic conditions ranging from humid to arid. Locations of the test sections, climate types, year of construction, and average index properties of the soils are summarized in Table 1. The soils are designated as SM, SC, SC-CL, CL, CL-ML, and CL-CH in the Unified Soil Classification System and all but one of the soils (Apple Valley) are fine-textured. This broad range of locations and materials from test sections representing full-scale conditions is intended to capture the range of changes likely to be encountered in practice. However, because actual final cover test sections were used, a systematic evaluation of specific mechanisms affecting changes in hydraulic properties was not possible.

Anticipated Changes in Hydraulic Properties

In many cases, postconstruction changes in soil structure consist of the formation of larger pores and lower density. Larger pores are formed by biological process such as ingress of plant roots and burrowing of worms and insects. Volume changes caused by wet-dry cycling and frost action can reduce the density of soils and can result in formation of larger pores and a broader pore size distribution (Othman and Benson 1994; Albrecht and Benson

Table 1. Site and Soil Characteristics

					Particle size distribution				Atterberg limits	
Site Location	Climate	Year construction completed	Unified soil classification	Specific gravity	Gravel (%)	Sand (%)	Fines (%)	2 μm clay (%)	Liquid limit	Plasticity index
Apple Valley, Calif.	Arid	2002	SM	2.65	35	52	13	8	NP	NP
Albany, Ga.	Humid	2000	SC	2.65	6	65	29	23	27	12
Altamont, Calif.	Semi-arid	2000	CL-CH	2.66	2	5	93	38	48	22
Boardman, Ore.	Semi-arid	2000	CL-ML	2.70	0	16	84	12	24	4
Cedar Rapids, Iowa	Humid	2000	SC-CL	2.64	2	46	52	26	34	16
Helena, Mont.	Semi-arid	1999	SC	2.59	2	54	44	30	67	47
Marina, Calif.	Semi-arid	2000	SC	2.68	8	60	32	15	28	14
Omaha, Neb.	Humid	2000	CL	2.57	0	2	98	30	45	28
Polson, Mont.	Sub-humid	1999	SM	2.62	6	52	42	5	NP	NP
Sacramento, Calif.	Semi-arid	1999	CL	2.70	2	22	76	19	40	22

Note: Climate classifications are based on definitions described in UNESCO (1979). NP = nonplastic as defined in ASTM D 2487; particle sizes based on definitions in the Unified Soil Classification System (ASTM D 2487): gravel > 4.8 mm, 4.8 mm > sand > 75 μm, fines > 75 μm.

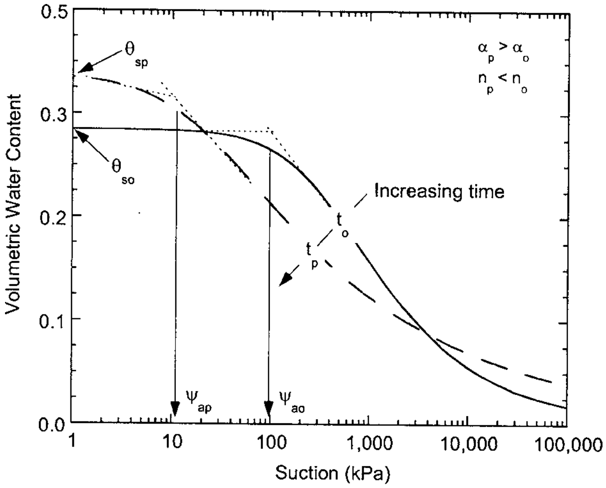

Fig. 2. Changes in SWCC between time of construction (t_0) and a later time (t_p)$>t_0$. Symbols are defined as follows: θ_{s0}=initial saturated water content; θ_{sp}=postconstruction saturated water content; ψ_{a0}=initial air entry suction; ψ_{ap}=postconstruction air entry suction; α_0=initial α parameter; α_p=postconstruction α parameter; n_0=initial n parameter; and n_p=postconstruction n parameter.

2001). Changes in hydraulic properties are anticipated in response to these changes in soil structure (Lin et al. 2006). For example, freeze-thaw and wet-dry cycling result in cracking of soil and increases in the saturated hydraulic conductivity (Benson and Othman 1993; Phifer et al. 1994; Waugh et al. 1994; Waugh and Petersen 1995; Albrecht and Benson 2001; Ayers et al. 2004).

The effect on the SWCC is hypothesized as shown in Fig. 2. The air entry suction (ψ_a) should drop due to formation of larger pores (Hillel 1998) and the saturated volumetric water content (θ_s) should increase due to the reduction in density (i.e., lower dry unit weight corresponds to higher porosity or θ_s). The slope of the SWCC for $\psi > \psi_a$ should also be shallower because of the broader distribution of pore sizes in the soil (Brooks and Corey 1966). A bimodal shape may also occur, but was not observed for any of the SWCCs measured in this study.

A variety of equations can be used to describe SWCCs parametrically (Leong and Rahardjo 1997). The most common function used to describe SWCCs is the sigmoidal van Genuchten equation (van Genuchten 1980)

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\psi)^n]^{n/n-1} \qquad (1)$$

where ψ=suction; θ=volumetric water content; θ_r=residual water content; and α and n=fitting parameters. Eq. (1) is used in this study for parametric description of the SWCCs because of its widespread use (other functions could have been used, but they are less common). The parameters α and n in Eq. (1) describe the shape of the SWCC. The parameter α is inversely related to the air entry suction and the parameter n is directly related to the slope of the SWCC (van Genuchten 1980; Leong and Rahardjo 1997; Tinjum et al. 1997). Soils with lower air entry suction have larger α and SWCCs having shallower slope have smaller n. Thus, α and θ_s should increase, and n should decrease, as larger pores and a broader pore size distribution develop in the soil.

Testing Methods

Saturated Hydraulic Conductivity

All samples were trimmed into test specimens having a diameter of 150 mm and height of 200 mm for saturated hydraulic conductivity testing. Care was taken to minimize disturbance of the soil structure. For example, root matter and other biomass was left in the specimens during testing to prevent damage to the pore structure and to represent the field condition as faithfully as practical.

The hydraulic conductivity tests were conducted in flexible-wall permeameters in general accordance with ASTM D 5084, *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter* (ASTM 2004). The falling head water-rising tail water procedure was followed (Method C). The average effective stress was 14 kPa to simulate the stress within a cover profile, the backpressure was 207 kPa, and the average hydraulic gradient was 10. All tests were conducted until the hydraulic conductivity was steady and inflow equaled outflow.

Soil-Water Characteristic Curve

SWCCs were measured using methods described in ASTM D 6836, *Standard Test Methods for Determination of the Soil-Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge* (ASTM 2004). Only drying SWCCs were measured due to the difficulties associated with measuring wetting curves for fine-textured soils (Fredlund and Rahardjo 1993; Tinjum et al. 1997). A pressure plate extractor (Method B) was used for suctions between 0 and $\approx$1 MPa; a chilled mirror hygrometer (Method D) was used for higher suctions. Data from both tests were combined to form a SWCC, even though the pressure plate extractor (PPE) applies matric suction (ψ) and the chilled mirror hygrometer (CMH) measures total suction (ψ_t). However, at higher suctions the osmotic component of suction is relatively small, rendering $\psi \approx \psi_t$ (Andraski 1996; Burger and Shackelford 2001; Wang and Benson 2004).

Test specimens for the PPE tests were trimmed from the same specimens tested for saturated hydraulic conductivity using a stainless-steel ring with a sharp bevel until the soil filled the retaining ring. Excess soil on the top and bottom of the ring was removed using a spatula. The trimmed specimens had a diameter of 73 mm and a height of 25 mm, which is a typical size for SWCC tests (Topp et al. 1993; Wang and Benson 2004). The appropriate specimen size needed to represent field conditions for SWCCs has not been determined for compacted fill soils in engineered systems. However, SWCCs measured in the laboratory on specimens of this size are comparable to SWCCs determined in situ at the ACAP sites using co-located water content and suction sensors (Benson et al. 2004; Bohnhoff 2005). Li et al. (2005) also found that SWCCs measured in the laboratory on specimens having similar size to those used in this study were comparable to SWCCs measured in situ in a Hong Kong slope constructed from decomposed granite.

After trimming was complete, the gravimetric water content of the excess soil was measured and the specimen was saturated using a vacuum chamber filled with de-aired water as described in ASTM D 6836. After saturation, the test specimen was placed in the PPE and air pressure was applied in increments to obtain a set of ψ-θ measurements. Volumetric water contents were determined at equilibrium from the volume of outflow measured in a capillary

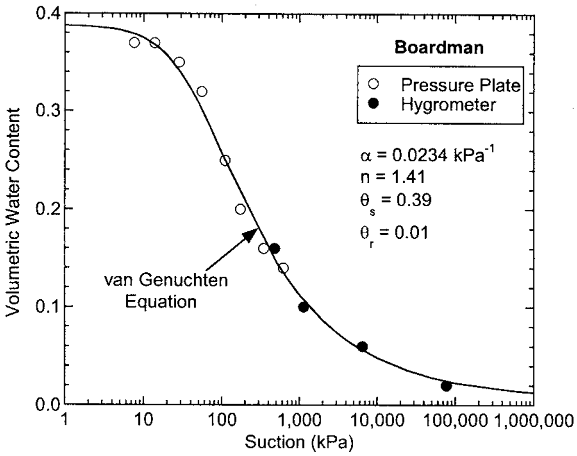

Fig. 3. Typical SWCC measured with a PPE and CMH along with fit of the van Genuchten equation [Eq. (1)] for a specimen from the ACAP site in Boardman, Ore.

tube. Typically eight to ten measurements of ψ-θ were obtained for each PPE test, requiring 1–3 months to complete depending on soil type (longer test times were required for more clayey soils). Oven-dried water contents measured at the end of the PPE tests showed that the difference in θ from the outflow and gravimetric measurements was less than 0.01.

CMH tests were conducted with a WP4 Dewpoint PotentiaMeter (Decagon Devices, Pullman, Wash.), which is similar to the CMHs described in Gee et al. (1992) and Albrecht et al. (2003). Several specimens were trimmed from the specimen used for the PPE extractor test into polyethylene cups (38 mm diameter, 5 mm tall) used in the CMH. The specimens were allowed to air dry to different water contents, and then were sealed for 24 h to promote equilibration. Afterwards, cups containing the specimens were inserted into the CMH to determine ψ_t. Once ψ_t was reported by the CMH, the specimen was removed, the gravimetric water content, mass, and volume were determined, and the corresponding volumetric water content was computed. Typically three to six measurements of ψ-θ were obtained using the CMH.

An example of a typical SWCC obtained using these methods is shown in Fig. 3. The PPE and CMH data overlap in the middle of the SWCC, indicating that $\psi \approx \psi_t$ at higher suctions, as described previously. All SWCCs were fit with van Genuchten's equation [Eq. (1)] using a least-squares optimization procedure. A typical fit is also shown in Fig. 3.

Table 3. Hydraulic Properties after One Year of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Apple Valley, Calif.	3.0×10^{-5}	0.232	1.19	0.26	0.00
	2.8×10^{-5}	0.166	1.21	0.28	0.00
	1.5×10^{-5}	0.289	1.18	0.25	0.00
	3.0×10^{-5}	0.288	1.20	0.26	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Results and Analysis

Hydraulic properties corresponding to the as-built condition are summarized in Table 2. Because a large number of tests were conducted during construction, geometric means are reported for K_s and α and arithmetic means are reported for n, θ_s, and θ_r. Geometric means are reported for K_s and α because they are log-normally distributed, whereas arithmetic means are reported for n, θ_s, and θ_r because they are normally distributed (Russo and Bouton 1992; Hills et al. 1992; Benson 1993; Gurdal et al. 2003). Standard deviations (σ) are also reported in Table 2, with standard deviations of $\ln K_s$ and $\ln \alpha$ reported for K_s and α to correspond with the geometric means. Hydraulic properties for samples collected after construction are summarized in Tables 3–6. Because fewer samples were collected during the postconstruction sampling events, K_s, α, n, θ_s, and θ_r are reported for the individual tests in Tables 3–6.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivities for the postconstruction specimens (K_{sp}) are graphed against the as-built saturated hydraulic conductivities (K_{s0}) for the same sites in Fig. 4. If there was no

Table 2. As-Built Hydraulic Properties of Cover Soils

	K_{s0} (cm/s)			α_0 (kPa^{-1})		n_0		θ_{s0}			
Site location	GM	$\sigma_{\ln_{K_s}}$	N_{K_s}	GM	$\sigma_{\ln_\alpha}$	Mean	σ_n	Mean	$\sigma_{\theta s}$	θ_{r0}	N_{SWCC}
Albany, Ga.	1.5×10^{-6}	4.11	6	0.0039	1.38	1.39	0.10	0.34	0.13	0.00	6
Altamont, Calif.	5.3×10^{-7}	2.21	8	0.0043	1.09	1.38	0.10	0.36	0.05	0.00	6
Apple Valley, Calif.	3.1×10^{-5}	0.70	6	0.278	0.08	1.42	0.02	0.26	0.05	0.00	6
Boardman, Ore.	1.2×10^{-5}	1.08	32	0.0159	0.40	1.49	0.06	0.39	0.06	0.00	27
Cedar Rapids, Iowa	9.7×10^{-7}	2.63	8	0.0016	0.55	1.61	0.15	0.33	0.05	0.00	8
Helena, Mont.	1.5×10^{-7}	0.80	16	0.0018	0.28	1.19	0.02	0.34	0.10	0.00	13
Marina, Calif.	8.6×10^{-8}	1.75	16	0.0036	0.47	1.40	0.07	0.31	0.12	0.00	12
Omaha, Neb.	1.6×10^{-7}	2.05	12	0.0014	0.86	1.50	0.18	0.39	0.06	0.00	9
Polson, Mont.	4.2×10^{-5}	0.66	8	0.0010	0.07	1.40	0.01	0.35	0.06	0.00	8
Sacramento, Calif.	3.1×10^{-7}	2.20	16	0.0048	1.21	1.34	0.07	0.29	0.02	0.00	12

Note: GM=geometric mean; σ=standard deviation; N=number of specimens that were tested; K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters, θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript 0 indicates that specimens were collected during construction.

Table 4. Hydraulic Properties after 2 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Albany, Ga.	1.2×10^{-6}	0.0002	1.75	0.29	0.00
	5.6×10^{-5}	0.0200	1.20	0.33	0.00
	1.2×10^{-6}	0.0002	1.94	0.27	0.00
	6.2×10^{-7}	0.0200	1.30	0.23	0.00
Boardman, Ore.	1.4×10^{-5}	0.0200	1.41	0.37	0.02
	5.4×10^{-5}	0.0350	1.32	0.41	0.00
	1.6×10^{-5}	0.0400	1.30	0.38	0.00
Cedar Rapids, Iowa	3.7×10^{-5}	0.0030	1.36	0.29	0.00
	4.6×10^{-4}	0.0400	1.23	0.49	0.00
Omaha, Neb.	1.1×10^{-6}	0.0015	1.41	0.37	0.00
	3.7×10^{-5}	0.0034	1.32	0.40	0.00
Apple Valley, Calif.	1.8×10^{-5}	0.233	1.18	0.26	0.00
	1.4×10^{-5}	0.216	1.22	0.29	0.01
	1.7×10^{-5}	0.126	1.22	0.27	0.01

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Table 5. Hydraulic Properties after 3 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Altamont, Calif.	1.1×10^{-4}	0.0035	1.46	0.39	0.03
	9.9×10^{-5}	0.0044	1.27	0.34	0.00
	5.8×10^{-6}	0.0105	1.26	0.37	0.00
Boardman, Ore.	2.1×10^{-5}	0.0234	1.41	0.39	0.01
	5.4×10^{-5}	0.0340	1.84	0.43	0.00
	3.3×10^{-5}	0.0344	1.63	0.42	0.05
Cedar Rapids, Iowa	6.0×10^{-4}	0.0548	1.26	0.40	0.00
	7.4×10^{-5}	0.0359	1.21	0.31	0.00
	4.0×10^{-4}	0.0141	1.31	0.47	0.00
	3.8×10^{-4}	0.0651	1.20	0.45	0.00
	6.2×10^{-4}	0.0044	1.53	0.50	0.02
	3.5×10^{-4}	0.0137	1.28	0.48	0.00
Helena, Mont.	1.2×10^{-7}	0.1279	1.13	0.44	0.00
	4.7×10^{-8}	0.0018	1.28	0.43	0.00
Marina, Calif.	6.5×10^{-4}	0.0362	1.27	0.36	0.00
	1.7×10^{-4}	0.3288	1.27	0.61	0.00
	1.1×10^{-4}	0.0291	1.27	0.32	0.00
Omaha, Neb.	2.7×10^{-5}	0.0596	1.22	0.46	0.00
	3.2×10^{-4}	0.0090	1.29	0.45	0.00
	2.1×10^{-5}	0.0097	1.29	0.42	0.00
	9.0×10^{-6}	0.0126	1.24	0.40	0.00
	2.1×10^{-4}	0.0093	1.32	0.46	0.00
	4.8×10^{-4}	0.0050	1.45	0.47	0.03
Polson, Mont.	1.6×10^{-4}	0.1979	1.30	0.38	0.00
	9.9×10^{-5}	0.0900	1.35	0.38	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Table 6. Hydraulic Properties after 4 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Helena, Mont.	2.1×10^{-6}	0.0775	1.15	0.45	0.00
	1.1×10^{-4}	0.0451	1.24	0.53	0.00
Polson, Mont.	1.2×10^{-4}	0.0735	1.63	0.40	0.03
	2.8×10^{-4}	0.0524	1.47	0.43	0.00
	1.3×10^{-4}	0.0612	1.85	0.41	0.03
Sacramento, Calif.	3.4×10^{-5}	0.0047	1.44	0.45	0.03
	1.1×10^{-4}	0.0067	1.32	0.41	0.00
	2.6×10^{-5}	0.0129	1.20	0.44	0.00
	1.4×10^{-5}	0.0052	1.28	0.40	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

change in K_s, the postconstruction data would be scattered around the 1:1 line in Fig. 4. Data falling above the 1:1 line correspond to increases in K_s.

Some of the less permeable soils (i.e., soils with $K_s \approx 10^{-6}$ cm/s or lower) in the as-built condition retained their low hydraulic conductivity for one to three years (e.g., for the Helena site, the as-built $K_{s0}=1.5\times10^{-7}$ cm/s whereas the $K_{sp}=1.2\times10^{-7}$ or 4.7×10^{-8} cm/s after 3 years). However, K_s of other less permeable soils increased by two orders of magnitude or more (e.g., for the Omaha site, the as-built $K_{s0}=1.6\times10^{-7}$ cm/s, whereas $K_{sp}=1.1\times10^{-6}$ or 3.7×10^{-5} cm/s after two years). After 4 years, however, K_s for these soils increased by at least a factor of 10 and, in some cases, by nearly a factor of 10,000 (Fig. 4). In contrast, for those soils that were more permeable ($K_s>10^{-5}$ cm/s) in the as-built condition, K_s increased only by a factor of 1.8–6.7, and in one case (Apple Valley) K_s decreased slightly. Moreover, regardless of the as-built K_{s0}, after 3–4 years nearly all of the K_{sp} fall in a band between 10^{-5} and 10^{-3} cm/s (labeled "in-service condition" in Fig. 4), and no trend is apparent between K_{sp} and the as-built K_{s0} (Fig. 4).

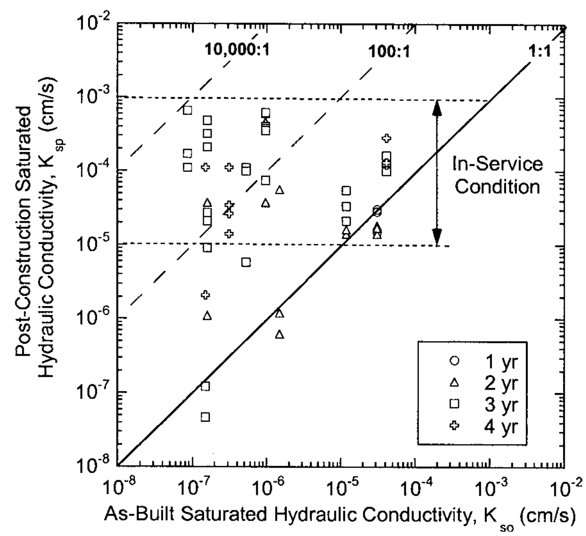

Fig. 4. Postconstruction saturated hydraulic conductivity (K_{sp}) versus as-built saturated hydraulic conductivity (K_{s0}). The band labeled "in service" indicates range for soils after 2–4 years of exposure to site environmental conditions.

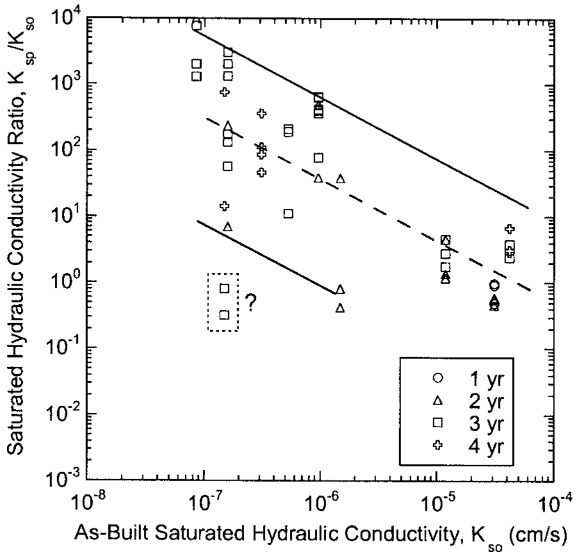

Fig. 5. Ratio of postconstruction saturated hydraulic conductivity relative to as-built saturated hydraulic conductivity (K_{sp}/K_{s0}) versus as-built saturated hydraulic conductivity (K_{s0}). Trend lines drawn by eye. Outliers ("?") are for site in Helena, Mont. (Table 5).

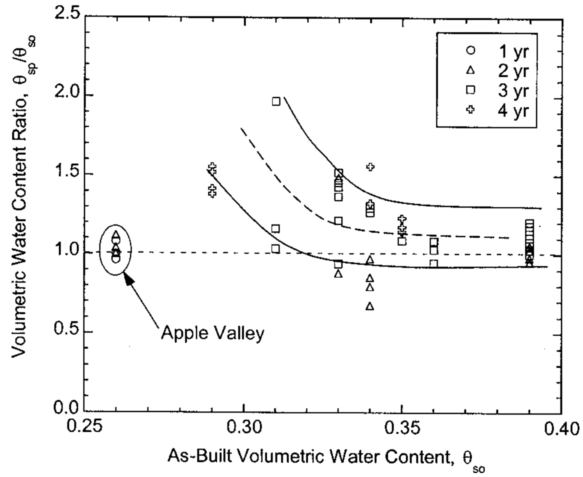

Fig. 6. Ratio of postconstruction saturated volumetric water content to as-built saturated volumetric water content (θ_{sp}/θ_{s0}) versus as-built saturated volumetric water content (θ_{s0}). Trend lines drawn by eye.

These observations suggest that differences in K_s of fine-textured soils used for water balance covers become smaller over time, with larger changes in K_s occurring for soils that have lower K_{s0} and smaller (or negligible) changes for soils that have higher K_{s0}. Location of the site appears to be less important, as similar changes in hydraulic properties occurred for sites in climates that were humid or semiarid and warm or cool (Tables 5 and 6). The importance of K_{s0} on the magnitude of change in K_s is evident in Fig. 5, where the hydraulic conductivity ratio (K_{sp}/K_{s0}) is graphed versus K_{s0}. The overall trend is decreasing K_{sp}/K_0 with increasing K_{s0}. On average, $K_{sp}/K_{s0} \approx 300$ for $K_{s0} \approx 10^{-7}$ cm/s and $K_{sp}/K_{s0} \approx 0.5$ for $K_{s0} \approx 10^{-4}$ cm/s. Soils with higher K_{s0} typically have less plastic fines or lower dry density, and therefore undergo smaller volume changes during processes such as wetting and drying (Kleppe and Olson 1985; Albrecht and Benson 2001). Consequently, smaller changes in pore structure are likely for soils with higher K_{s0}. At the other extreme, soils with high K_{s0} may also become less permeable over time due to pore filling and crusting by fines (Assouline 2004).

Statistical significance of the trend in Fig. 4 was evaluated by linearly regressing $\ln(K_{sp}/K_{s0})$ on $\ln K_{s0}$, and determining whether the slope of the regression was significant using an F-test. The significance level was 0.05, which is the significance level commonly used for hypothesis testing (Berthouex and Brown 2002). The analysis confirmed that the trend was significant, with an F-statistic of 47.0 and p value <0.0001 (i.e., $p \ll 0.05$, indicating significance).

Soil-Water Characteristic Curve

Changes in the SWCC are reflected in changes in the SWCC parameters θ_s, θ_r, α, and n, as indicated in the discussion of Fig. 2. The change in θ_s is shown in Fig. 6, where the ratio of θ_s postconstruction (θ_{sp}) to the as-built θ_s (θ_{s0}) is graphed versus θ_{s0}. Graphs are not shown for θ_r because, in nearly all cases, θ_r is approximately zero for the as-built and postconstruction conditions (Tables 2–6). Statistical significance of the trend between θ_{sp}/θ_{s0} and θ_{s0} was confirmed by regression ($F=37.1$, p value $<0.0001 \ll 0.05$).

Because θ_s is inversely proportional to dry density, θ_{sp}/θ_{s0} is a measure of the postconstruction change in dry density ($\theta_{sp}/\theta_{s0} > 1$ corresponds to a reduction in dry density). As shown in Fig. 6, $\theta_{sp}/\theta_{s0} \approx 1$ for the soils with the largest θ_{s0} (0.36–0.39) or lowest dry density in the as-built condition, and tends to increase as θ_{s0} drops below 0.35. The largest θ_{sp}/θ_{s0} (1.5–2.0) corresponds to the lowest θ_{s0} ($\approx 0.29-0.31$). The exception is the soil from Apple Valley, for which $\theta_{s0}=0.26$ and $\theta_{sp}/\theta_{s0} \approx 1.0$. The Apple Valley soil, a broadly graded alluvium, is coarse-textured (fines content=13%, Table 1) and therefore should undergo smaller changes in volume and density compared to the finer-textured soils when subjected to wet-dry cycling.

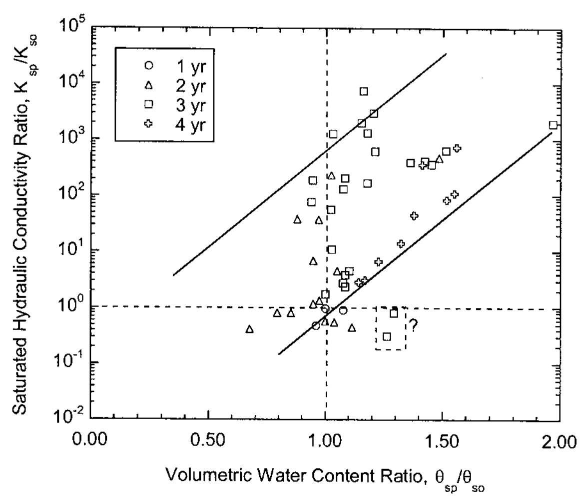

Fig. 7. Ratio of postconstruction saturated hydraulic conductivity relative to as-built saturated hydraulic conductivity (K_{sp}/K_{s0}) versus ratio of postconstruction saturated volumetric water to as-built saturated volumetric water content (θ_{sp}/θ_{s0}). Trend lines drawn by eye. Outliers ("?") are for site in Helena, Mont. (Table 5).

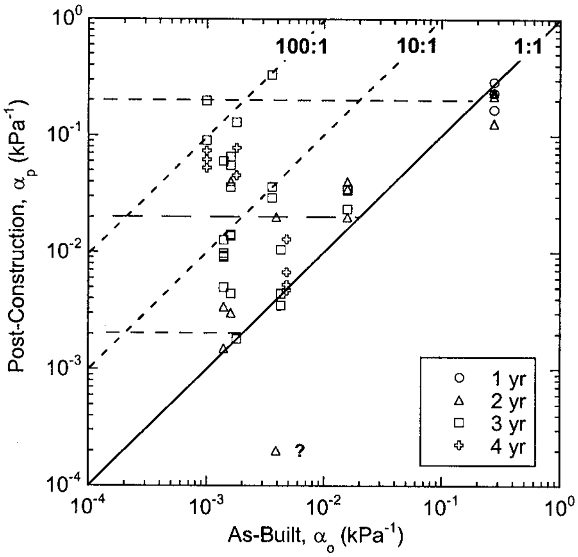

Fig. 8. Postconstruction α parameter measured in 2002–2004 (α_p) versus α in the as-built condition (α_0). Outlier ("?") for site in Albany, Ga. (Table 4).

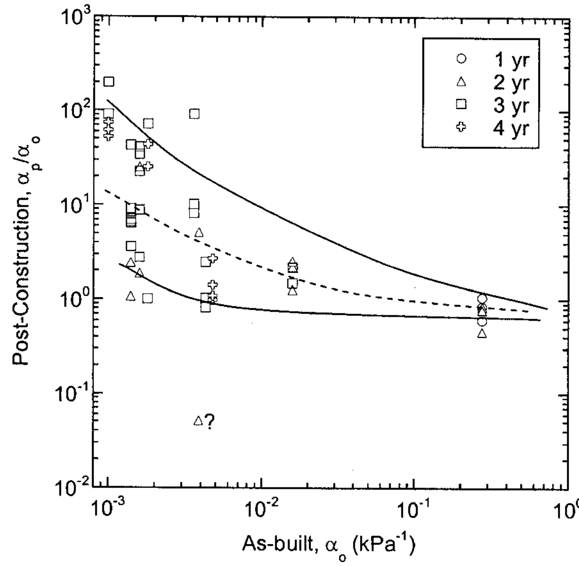

Fig. 9. Ratio of postconstruction α relative to α in as-built condition (α_p/α_0) versus α in as-built condition (α_0). Trend lines drawn by eye. Outlier ("?") for site in Albany, Ga. (Table 4).

There also is a direct correspondence between K_{sp}/K_{s0} and θ_{sp}/θ_{s0}, as shown in Fig. 7. The trend between K_{sp}/K_{s0} and θ_{sp}/θ_{s0} was also confirmed to be statistically significant using regression ($F=19.5$, p value $<0.0001 \ll 0.05$). Larger changes in K_s occur for the fine-textured soils with larger θ_{sp}/θ_{s0}. That is, K_s undergoes a greater change when the soil undergoes a larger change in θ_s (or equivalently a larger change in dry density).

The effect on α is shown in Fig. 8, where postconstruction α (α_p) is graphed versus α in the as-built condition (α_0). As was shown for K_s (Fig. 4), α increased in the four-year period after construction (many of the data points fall above the 1:1 line), with some α increasing nearly two orders of magnitude (the exception is the coarse-textured soil from Apple Valley, for which α decreased). As indicated in the discussion of Fig. 2, formation of larger pores should cause a reduction in ψ_a and an increase in α. Inspection of Fig. 8 also indicates that there is no trend between α_p and α_0 (the data fall in a horizontal band), which suggests that α becomes more similar over time and less related to α_0 (the same was found for K_s, Fig. 4). In particular, α_p ranges between approximately 0.002 and 0.2 kPa^{-1}, regardless of α_0.

Larger increases in α tended to occur for soils having lower α_0 (or, conversely, higher ψ_a), as shown in Fig. 9 in terms of the α ratio (i.e., α_p/α_0) versus α_0. Statistical significance of the trend between α_p/α_0 and α_0 was confirmed using regression ($F=22.5$, p value $<0.0001 \ll 0.05$). Although considerable scatter exists, the average factor increase in α (i.e., the trend passing through the middle of the data) is approximately 10 for $\alpha_0=0.002$ kPa^{-1}, 2 for $\alpha_0=0.02$ kPa^{-1}, and 0.8 for $\alpha_0=0.2$ kPa^{-1}. Formation of larger pores has a more dramatic effect on the network of pores in a soil that initially contains primarily small pores (low α_0) compared to a soil that initially contains both large and small pores (high α_0). In the limiting case of a soil initially dominated by large pores (large α_0), formation of additional large pores will have little effect on the network of pores controlling the initial release of water (i.e., the pores controlling ψ_a) and therefore little effect on α. However, for soils with large pores, pore filling and crusting by fines may cause α to decrease.

The effect on the n parameter is shown in Fig. 10. For many of the soils, the postconstruction n is lower than the as-built n (n_0) (i.e., n_p often falls below the 1:1 line). That is, the slope of the SWCC becomes shallower, which reflects broadening of the pore size distribution. There are a few exceptions, however, where n_p is much larger than n_0 [denoted with a question mark (?) in Fig. 10]. Examination of the SWCCs corresponding to these outlier n provided no explanation for these exceptions to the general trend.

The change in n is also shown in Fig. 11 in terms of the n ratio (n_p/n_0) versus n_0. Significance of the trend in Fig. 11 was confirmed using an F-test ($F=11.2$, p value $=0.002 \ll 0.05$). The change in n is larger when n_0 is larger, ranging from approximately 1 (i.e., no change) for $n_0=1.2$ to approximately 0.75 for $n_0=1.6$, on average. That is, larger changes in n occur when n_0 is larger, which reflects a greater change in pore size distribution for soils that initially have a narrower pore size distribution (i.e., larger n_0).

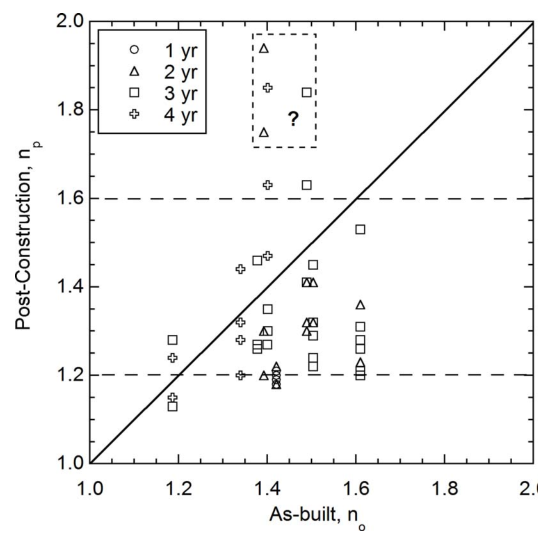

Fig. 10. Postconstruction n parameter (n_p) versus n in the as-built condition (n_0). Outliers ("?") for sites in Albany, Ga. (Table 4), Boardman, Ore. (Table 5), and Polson, Mont. (Table 6).

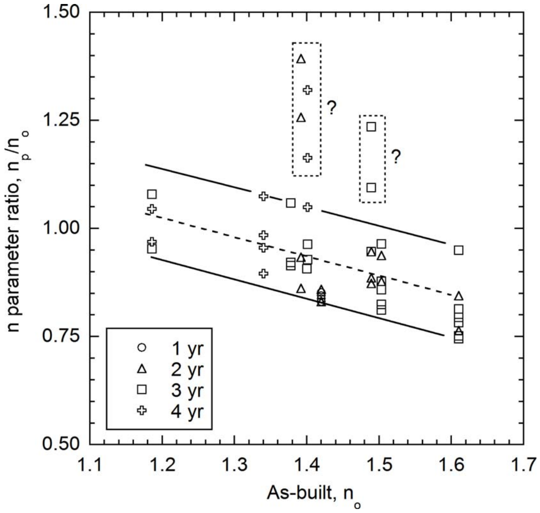

Fig. 11. Ratio of postconstruction n to as-built n (n_p/n_0) versus as-built n (n_0). Trend lines drawn by eye. Outliers ("?") for sites in Albany, Ga. (Table 4), Boardman, Ore. (Table 5), and Polson, Mont. (Table 6).

The changes in n shown in Fig. 11 are small relative to the range over which n can vary. The parameter n often falls between 1 and 2 for fine-textured soils used in covers and liners (e.g., Tinjum et al. 1997; Gurdal et al. 2003), but can be more than 10 for uniformly graded coarse-grained soils with little fines (e.g., Bradford and Abriola 2001). However, the modest change in n shown in Fig. 11 can have a significant effect on the SWCC, as shown illustratively in Fig. 12 for both high and low α (0.002 and 0.23 kPa^{-1}) and high and low n (1.2 and 1.5). Reducing n from 1.5 to 1.2 at $\psi=1{,}000$ kPa results in a change in θ of approximately 0.1 (29% of the total porosity), regardless of whether α is low or high (Fig. 12).

Influence of Plasticity

Analysis of variance (ANOVA) was conducted to determine if plasticity index of the fine-textured soils affected the changes in K_s, α, n, and θ_s. The Apple Valley soil was excluded from the analysis because of its small fines content. Plasticity index (PI) was selected because it is indicative of the potential for volume change, and therefore should be an index of the potential for change in the pore network (Albrecht and Benson 2001). Data sets for the ANOVA were compiled for K_{sp}/K_{s0}, α_p/α_0, n_p/n_0, and θ_{sp}/θ_{s0} for soils categorized as low plasticity (PI$<$10 or nonplastic), moderate plasticity ($10<\text{PI}<20$), and high plasticity (PI$>$20). For all analyses, the significance level β was set at 0.05.

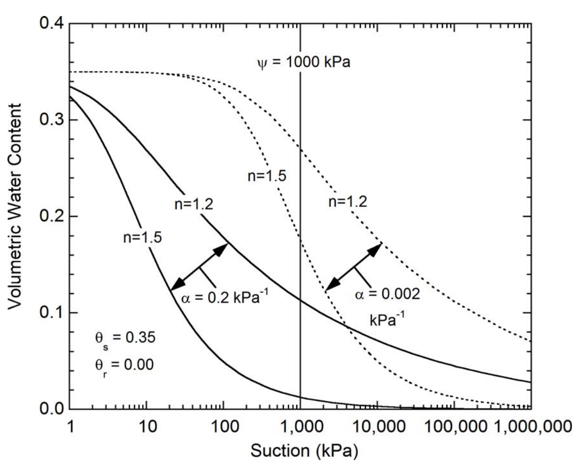

Fig. 12. Effect of n on the SWCC for $\alpha=0.003$ or 0.3 kPa^{-1} and $n=1.2$ or 1.6. For all SWCCs, $\theta_s=0.35$ and $\theta_r=0.00$.

Table 7. Summary of Statistics from ANOVAs

Hydraulic property	ANOVA p-statistic (significant?)	PLSD on plasticity effect (p-statistic; significant?)
K_{sp}/K_{s0}	<0.0001 (yes)	Low-medium: $p<0.0001$; yes Low-high: $p<0.0001$; yes Medium-high: $p=0.010$; yes
α_p/α_0	0.00340 (yes)	Low-medium: $p=0.0009$; yes Low-high: $p=0.0083$; yes Medium-high: $p=0.144$; no
n_p/n_0	0.0330 (yes, marginal)	Low-medium: $p=0.0538$; no, marginal Low-high: $p=0.947$; no Medium-high: $p=0.0122$; yes
θ_{sp}/θ_{s0}	0.0524 (no, marginal)	Low-medium: $p=0.0160$; yes Low-high: $p=0.0893$; no Medium-high: $p=0.215$; no

Fisher's protected least significant difference (PLSD) test (Box et al. 1978) was conducted after each ANOVA to provide a direct comparison of each of the data sets. The PLSD test is a t-test between the means in each data set of an ANOVA. For the PLSD, β was also set at 0.05.

Results of the ANOVAs and PLSD tests are summarized in Table 7. The ratios $K_{sp}/K_{s0}$and α_p/α_0 are significantly affected by plasticity (Table 6). Plasticity also has a significant effect on n_p/n_0 and an insignificant effect on θ_{sp}/θ_{s0}, although in both cases the inference is marginal ($p\approx0.05$). The PLSD indicates that both K_{sp}/K_{s0} and α_p/α_0 are significantly different for low plasticity soils relative to other soils, and that K_{sp}/K_{s0} is significantly different for soils categorized as low, moderate, or high plasticity. In contrast, n_p/n_0 is significantly different only for the medium and high plasticity soils and θ_{sp}/θ_{s0} is significantly different only for the low and moderately plastic soils. The more plastic soils typically exhibited larger changes in K_s, α, n, and θ_s (Tables 1–6), which is consistent with the results of the ANOVAs and PLSD tests in Table 7.

Practical Implications

The data presented illustrate that the hydraulic properties of soils used for water balance covers can change over time, and that the magnitude of the change is related to the as-built condition. The ranges of hydraulic properties shown in Figs. 4, 8, and 10 can be used as a starting point for assessing how changes in hydraulic properties may affect the hydrology of water balance covers constructed with fine-textured soils. In particular, after a relatively short period ($<$5 years), fine-textured cover soils are likely to have K_s between 10^{-5} and 10^{-3} cm/s, α between 0.002 and 0.2 kPa^{-1}, and n between 1.2 and 1.5, regardless of the initial properties. Different combinations of these parameters can be used in design to evaluate potential long-term conditions and to make predictions.

Estimates of typical K_{sp}, α_p, n_p, and θ_{sp} can be obtained using the central (dashed) trend lines in Figs. 5, 6, 9, and 11 using values of K_{s0}, α_0, n_0, and θ_{s0} measured during design or construction. For example, consider a soil with the following as-built hydraulic properties: $K_{s0}=10^{-6}$ cm/s, $\alpha_0=0.003$ kPa^{-1}, $n_0=1.5$, and $\theta_{s0}=0.32$. Based on the central trend lines in Figs. 5, 6, 9, and 11, $K_{sp}/K_{s0}=40$, $\alpha_p/\alpha_0=5.5$, $n_p/n_0=0.9$, and $\theta_{sp}/\theta_{s0}=1.2$. Applying these factors yields $K_{sp}=4.0\times10^{-5}$ cm/s, $\alpha_p=0.016$ kPa^{-1}, $n_p=1.35$, and $\theta_{sp}=0.38$. Because the specimens tested in this study were obtained at a shallow depth (upper 300 mm), such estimates probably represent maximum effects. Smaller changes in hydraulic properties may occur at deeper depths. However, more study is needed to assess how changes in hydraulic properties vary with depth.

Inspection of the data suggests that the hydraulic properties of cover soils converge to common values over time, eliminating many of the differences that exist in the as-built condition due to compaction and differences in soil composition. Consequently, for applications where long-term maintenance of hydraulic properties is important, designers should consider designing and constructing covers in a manner that mimics the long-term condition. Soils that are less prone to volume change in response to wetting and drying or freezing and thawing (and therefore less susceptible to changes in pores size) should be selected if possible (e.g., coarse-textured soils with low plasticity fines or less plastic fine-textured soils). Compaction specifications should ensure that the soil is not overly compacted and will have a dry density close to that expected in the long term. One approach to determine a realistic long-term dry density is to measure the dry density of natural vegetated surficial soils of a similar type in the vicinity of the site. The data in Fig. 6 also suggest that θ_s will be in the range of 0.36–0.40 in the long term, which corresponds to a dry density between 1.6 and 1.7 Mg/m^3 for a specific gravity of solids of 2.65. Water content should also be controlled during construction to ensure that cover soils are placed under conditions that minimize remolding of clods and formation of soil with hydraulic properties dominated by microstructure [i.e., compaction should be dry of optimum water content, Benson and Daniel (1990)].

Water balance covers designed and constructed using these principles are less likely to exhibit large changes in hydraulic properties, at least in the short term (<5 years). In addition, vegetation is more readily established and maintained when cover soils are placed with less compaction and a more open pore structure (Goldsmith et al. 2001). Nevertheless, the long-term persistence of conditions similar to those reported in this study remains unknown. For example, the effects of loosening in the short term could be compensated by processes that tend to fill pores (e.g., siltation or calcification). Moreover, for soils that are not processed during construction (e.g., clod size reduction, moisture conditioning), structure remaining in the borrow source may persist in the cover profile. An indication of conditions expected in the long term can be obtained by inspecting existing natural soil profiles having similar composition and layering, such as the profile in the borrow source (Waugh et al. 1994). Other factors besides hydraulic properties may also have an important effect on the long-term performance of water balance covers, such as erosion or eolian deposition, differential settlement, fire, and climate change. Dealing with each of these issues, and the related effects on hydraulic properties, is beyond the scope of this study. A discussion of these factors can be found in Gee and Ward (2004).

Summary and Conclusions

Data collected from ten field sites in the Alternative Cover Assessment Program have been presented to illustrate how the hydraulic properties of soils used in water balance covers can change over time. Comparison of the data collected at the time of construction and 2–4 years hence indicated that the saturated hydraulic conductivity (K_s) can increase as much as 10,000 times, the van Genuchten parameter α as much as 1,000 times, the saturated volumetric water content (θ_s) as much as 2.0 times, and the van Genuchten parameter n to decrease as much as 1.3 times. Larger changes occur for fine-textured soils that have lower K_s, α, and θ_s and higher n in the as-built condition (i.e., denser fine-textured soils with more uniform pores). In addition, at least in the near term, cover soils appear to become more similar over time, eliminating many of the differences that exist in the as-built condition. Changes in hydraulic properties can be limited by using soils less prone to volume change (coarse-textured soils or soils with less plastic fines) and by placing the soil with methods that result in soil structure having less propensity for change (i.e., with lower compactive effort and at water contents dry of optimum). Placement conditions that result in soil having similar characteristics as observed in existing analog soil profiles are likely to result in covers that are less prone to changes in hydraulic performance over time.

The data presented in this paper can also be used to estimate hydraulic properties input to water balance models for assessing the hydrology of water balance covers over time. Ranges of the hydraulic properties identified in this study can be selected for sensitivity analyses and the trend lines that are presented can be used to estimate changes in the hydraulic properties of cover soils based on the hydraulic properties measured at the time of construction.

Acknowledgments

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