Field Performance of a Compacted Clay Landfill Final Cover at a Humid Site

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Abstract: A study was conducted in southern Georgia, USA, to evaluate how the hydraulic properties of the compacted clay barrier layer in a final landfill cover changed over a 4-year service life. The cover was part of a test section constructed in a large drainage lysimeter that allowed continuous monitoring of the water balance. Patterns in the drainage (i.e., flow from the bottom of the cover) record suggest that preferential flow paths developed in the clay barrier soon after construction, apparently in response to desiccation cracking. After four years, the clay barrier was excavated and examined for changes in soil structure and hydraulic conductivity. Tests were conducted in situ with a sealed double-ring infiltrometer and two-stage borehole permeameters and in the laboratory on hand-carved blocks taken during construction and after four years of service. The in situ and laboratory tests indicated that the hydraulic conductivity increased approximately three orders of magnitude (from $\approx 10^{-7}$ to $\approx 10^{-4}$ $\mathrm{cm \cdot s^{-1}}$) during the service life. A dye tracer test and soil structure analysis showed that extensive cracking and root development occurred throughout the entire depth of the barrier layer. Laboratory tests on undisturbed specimens of the clay barrier indicated that the hydraulic conductivity of damaged clay barriers can be underestimated significantly if small specimens (e.g., tube samples) are used for hydraulic conductivity assessment. The findings also indicate that clay barriers must be protected from desiccation and root intrusion if they are expected to function as intended, even at sites in warm, humid locations.

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Introduction

Conventional cover designs for waste containment facilities commonly include a hydraulic barrier layer to control drainage into the underlying waste (USEPA 1992). The barrier layer generally consists of compacted fine-textured soil and, depending on regulations, may be covered with a geomembrane. Conventional covers that rely solely on a fine-textured soil barrier layer are typically used at sites with a similar liner (a soil liner rather than a soil-geomembrane composite) beneath the waste. The soil barrier layer generally is compacted under conditions that yield low saturated hydraulic conductivity, i.e., with higher compaction water content and compactive effort (Daniel 1987). Covers that rely solely on fine-textured soil for the barrier are herein referred to as compacted clay covers. Although soils that do not classify as clay can be used for a barrier layer, the "clay" nomenclature is common in practice and therefore is used herein.

A variety of studies have suggested that the low hydraulic conductivity of the clay barrier in compacted clay covers can be compromised by wet/dry cycling, freeze/thaw cycling, differential subsidence, and/or biota intrusion (Jessberger and Stone 1991; Benson and Othman 1993; Suter et al. 1993; Smith et al. 1997; Zimmie and LaPlante 1992; Melchior 1997; Albrecht and Benson 2001). For example, laboratory studies have shown that compacted fine-grained soils crack under volumetric strain caused by desiccation (De Jong and Warkentin 1965; Boynton and Daniel 1985; Kleppe and Olson 1985; Omidi et al. 1996; Drumm et al. 1997), this can cause the saturated hydraulic conductivity to increase orders of magnitude (Albrecht and Benson 2001). Desiccation cracking of clay barrier layers has been observed in the field (Montgomery and Parsons 1989; Corser and Cranston 1992; Albrecht 1996; Benson and Khire 1997; Melchior 1997), and several studies have attributed changes in drainage from compacted clay covers to preferential flow and changes in the hydraulic conductivity of the clay barrier caused by cracking (e.g., Montgomery and Parsons 1989; Khire et al. 1997; Melchior 1997). However, to the authors' knowledge, there are no studies in which

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changes in drainage from a compacted clay cover have been related to measured changes in the hydraulic conductivity of the barrier layer from laboratory and in situ analyses and observations of preferential flow in the field.

This paper describes an investigation of a clay barrier layer in a test section located in a humid climate. The test section was intended to simulate the compacted clay cover proposed for capping a hazardous waste site in Albany, Georgia. As part of the feasibility evaluation for remediation, a test section with a large drainage lysimeter was constructed to evaluate the effectiveness of the proposed cover. When the test section was decommissioned, a field investigation was conducted to assess the hydraulic conductivity of the barrier layer as well as the structural characteristics of the barrier layer that can contribute to preferential flow. The emphasis of this paper is on the drainage record and a comparison of the clay barrier layer at the time of decommissioning to the condition at the time of construction four years earlier.

Previous Field Studies of Compacted Clay Covers

Montgomery and Parsons (1989) tested two clay covers near Milwaukee, Wisconsin, which differed only in surface layer thickness. Both covers included a 1,220-mm-thick clay barrier layer (CL in the Unified Soil Classification System, or USCS) and were overlain with an uncompacted surface layer. The surface layer of one cover was 152 mm thick, whereas the other was 457 mm thick. Precipitation ranged from 578 mm to 896 mm during the monitoring period, and freezing temperatures were recorded to a depth of 300 mm (150 mm below the interface between the surface layer and the clay in the cover with the thinner surface layer). Over four years of monitoring, drainage from both covers increased from 2–7 mm year^{-1} (<1% of precipitation) to more than 50 mm year^{-1} (7% of precipitation). Two years after construction, test pits adjacent to the test sections were excavated. Observations from the test pits showed weathering with a blocky structure in the upper 250 mm of clay in test sections, cracks 8–10 mm wide to depths of 900–1,000 mm, and dense root development in the upper 200–250 mm of the clay layer, with some roots penetrating as deep as 760 mm into the clay layer. Montgomery and Parsons (1989) concluded that cracks in the clay barrier layers were responsible for the increases in drainage rate, that the cracks persisted regardless of soil water status of the clay layer, and that the thickness of the surface layer did not affect drainage rate.

Melchior (1997) reported on eight years of field data from two test sections in Hamburg, Germany, which simulated compacted clay covers. One test section had a clay (USCS SC) barrier 400 mm thick and the other a clay barrier 600 mm thick. Both were overlain by 250 mm of sand for internal drainage and a 750-mm uncompacted surface layer. Annual precipitation at the site ranged between 740 and 1,032 mm. Drainage started to increase 20 months after construction, following a dry summer, and increased during the experiment from <10 mm the first year (<1% of precipitation) to as much as 174 mm year^{-1} (17% of precipitation) for the thicker cover and 202 mm year^{-1} (26% of precipitation) for the thinner cover. Excavation of the soil barrier layers eight years after construction revealed an extensive network of cracks, some several millimeters in width, that was attributed to desiccation. Plant roots also penetrated the entire depth of one of the test covers.

Khire et al. (1997) tested the performance of two compacted clay covers for three years, one near semi-arid Wenatchee, Washington, (600 mm compacted silty clay [USCS ML-CL] overlain by a 150-mm surface layer) and the other near humid Atlanta, Georgia, (900 mm compacted clay [USCS MH] overlain by a 150-mm surface layer). Annual precipitation during the study ranged between 1,188 and 1,721 mm at the Atlanta site and 140 and 260 mm at the Wenatchee site. They found that the barrier at Wenatchee limited drainage to approximately 3% (7.5 mm) of precipitation during the first year of observation but that annual drainage increased to as much as about 8% (22 mm) of precipitation during the third year of observation. Drainage at Atlanta was highest the first year (150 mm, 8.7% of precipitation) and lowest the second of the three years of monitoring (30 mm, 2.5% of precipitation). Test pits excavated in the covers showed no signs of cracking or intrusion of roots in the barrier layer at Atlanta. However, vertical desiccation cracks were observed in the barrier layer at Wenatchee, and these cracks were likely responsible for the increase in drainage rate and preferential flow (Benson and Khire 1995).

The National Council for Air and Stream Improvement (1997) field tested two replicates of a soil barrier cover near Kalamazoo, Michigan, consisting of a 610-mm surface layer over 610 mm of compacted clay (USCS CL). Annual precipitation during the monitoring period ranged between 795 and 1,109 mm. Drainage the first year of 16 and 26 mm (1.8% and 3.0% of precipitation) increased to as much as 70 and 56 mm (6.3% and 5.1% of precipitation) during nearly 7.5 years of observation. A dye tracer test followed by excavation of both covers eight years after construction showed interconnected vertical preferential flow paths and horizontal inter-lift flow paths (Benson and Wang 1996).

Dwyer (2003) tested a compacted clay cover (450 mm of compacted fine-textured soil overlain by a 150-mm uncompacted surface layer) near semi-arid Albuquerque, New Mexico. The soil used for the barrier layer was amended with approximately 6% bentonite to achieve the required low hydraulic conductivity. Annual precipitation during the monitoring period ranged between 144 and 300 mm. Drainage ranged between 0.0 and 3.6 mm year^{-1} (about 0.0–1.3% of precipitation) and was highest during the first 2 years of the 6-year program

Site Description

The test section evaluated in this study was constructed in March 2000 as part of the Alternative Cover Assessment Program (ACAP), a nationwide study evaluating the field hydrology of landfill covers (Albright et al. 2004). According to the classification method used by the United Nations Educational, Scientific and Cultural Organization (1979), Albany has a humid climate, with an average annual precipitation of 1,273 mm (1892–2004, Southeast Regional Climate Center, www.sercc.com) and a precipitation (P) to potential evapotranspiration (PET) ratio of 1.10. The average monthly rainfall ranges from 58 to 151 mm and is more than 100 mm for the months of January–March and June–August. Daily precipitation >100 mm has been recorded in all months. The average monthly maximum temperature ranges from 16.3° to 33.6°C, and the average monthly minimum temperature ranges from 3.6° to 21.8°C. Freezing temperatures occur intermittently during the winter months but do not persist long enough to cause soil below the immediate surface to freeze. Soil freezing was not observed during monitoring of the test section.

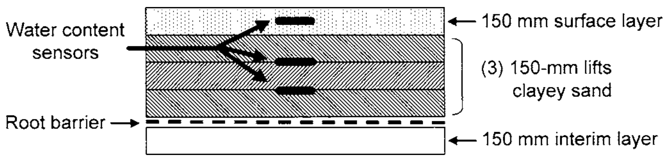

Fig. 1. Soil profile and instrument placement in soil barrier test section

Cover Design

The cover profile consisted of 450 mm of compacted clayey sand (classified as SC in the Unified Soil Classification System) overlain by 150 mm of uncompacted clayey sand (SC) (Fig. 1). This cover profile is consistent with the minimum requirements stipulated in the Resource Conservation and Recovery Act (RCRA) for unlined containment facilities and was the cover profile required for closure of the site by the Environmental Protection Division of the Georgia Department of Natural Resources. The cover was underlain by 150 mm of clayey sand (SC), which simulated the existing interim cover soil at the site.

The test section was constructed in March 2000 with methods, procedures, and equipment expected for full-scale construction at the site (Bolen et al. 2001). The soil barrier layer was placed in three 150-mm-thick lifts using a padfoot compactor having a weight of 21 Mg. Compaction control was maintained using an acceptable zone defining combinations of dry unit weight and water content corresponding to a saturated hydraulic conductivity less than 1×10^{-7} cm s^{-1} (Fig. 2). The acceptable zone was developed prior to construction using methods described in Daniel and Benson (1990). Specimens were prepared using reduced, standard, and modified Proctor compaction efforts and were permeated in rigid-wall compaction-mold permeameters with a hydraulic gradient of 10. Methods described in ASTM D 5856 (ASTM 2002b) were used to conduct the hydraulic conductivity tests.

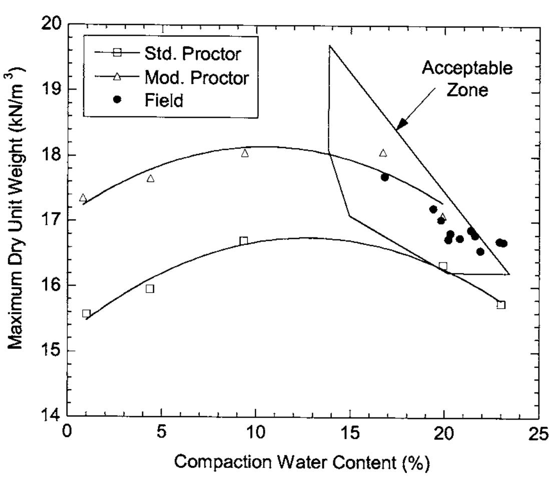

Fig. 2. Standard and modified Proctor compaction curves for clayey sand used for the barrier layer along with the acceptable zone defining combinations of water content and dry unit weight yielding hydraulic conductivity $<1 \times 10^{-7}$ cm$\cdot$s^{-1}. The acceptable zone was developed using the method described in Daniel and Benson (1990). Field measurements made with a nuclear density gauge. Two of the field data points fall directly on top of each other (water content=21.5% and dry unit weight=16.5 kN/m^3).

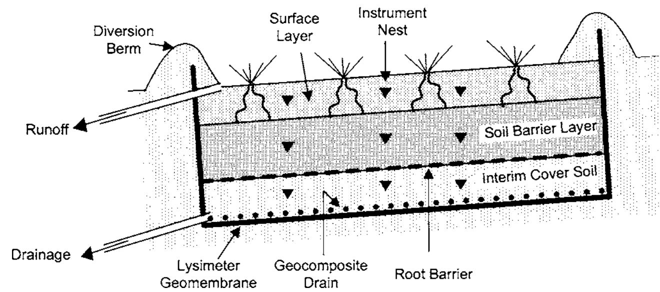

Fig. 3. Schematic of ACAP lysimeter

During construction, water content and dry unit weight were measured at four locations in each lift with a nuclear density gauge following methods described in ASTM D 2922 (ASTM 2005a). All measurements were made within the perimeter of the lysimeter. As shown in Fig. 2, all but two of the water content-dry unit weight measurements made during construction fall within the acceptable zone. The two outliers are slightly wet of the acceptable zone and are aligned with the compaction curve corresponding to modified Proctor effort.

The surface layer was placed in a single lift without compaction and had a dry unit weight of approximately 85% of maximum dry unit weight per standard Proctor. After construction, the test section was seeded with Bermuda and rye grasses. The test section was constructed on a north-facing 5% slope.

Instrumentation

A 10×20 m instrumented pan-type lysimeter (Fig. 3) constructed of 1.5-mm linear low-density polyethylene was used for direct measurement of the water balance. Methods used to install the lysimeter are described in Benson et al. (1999a) and Bolen et al. (2001). Seams in the geomembrane were tested using air pressure and vacuum box methods. A leak test was also conducted with water pooled in the lysimeter in accordance with the test procedure in Benson et al. (1999a).

The cover profile was constructed within the lysimeter and in a buffer area 3 m wide around the perimeter of the lysimeter to reduce boundary effects and to provide an area for annual sampling of soil and vegetation. A weather station was located adjacent to the lysimeter to provide measurements of precipitation, temperature, relative humidity, solar radiation, and wind speed and direction. All data were collected and recorded by a datalogger every 15 min and were normally stored on 1-h intervals.

A geocomposite drainage layer was placed on top of the lysimeter geomembrane to rapidly transmit water draining from the soil profile to the measurement system and to protect the geomembrane during placement of the cover soils. A surface berm was used to collect surface water runoff for measurement and to prevent surface water run-on. Drainage and surface runoff were conveyed through pipes to basins where flows were measured. Both collection basins were equipped with a pressure transducer and, for the drainage system, a tipping bucket gauge. The collection systems permit resolution of runoff to better than 1 mm year^{-1} and drainage to less than 0.1 mm year^{-1} (Benson et al. 2001).

Water content reflectometers (WCRs) manufactured by Campbell Scientific Inc. (Model CS 615) were installed in three nests located at the quarter points along the center line of the lysimeter for monitoring water content. Soil-specific calibration curves were developed for the WCRs, as described in Kim and Benson (2002). Each nest consisted of three probes located at depths of

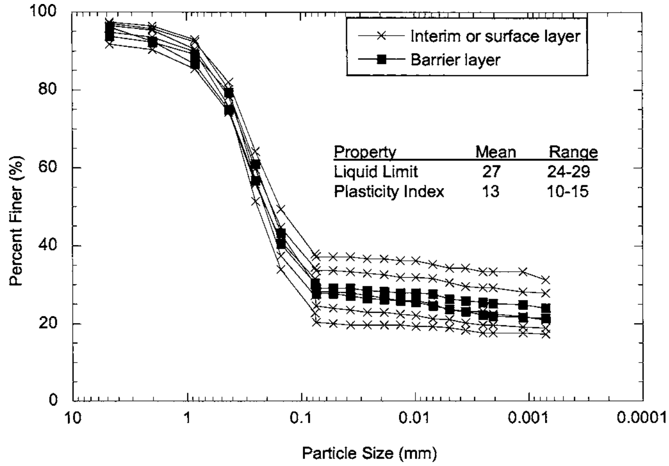

Fig. 4. Particle size distribution and Atterberg limits of soils used in the test section

75 mm (mid-depth in the surface layer), 300 mm (interface between upper and middle lifts of barrier layer), and 450 mm (interface between middle and lower lifts of barrier layer). Soil water storage was determined by integrating the point measurements of water content over the soil depth represented by individual probes.

Drainage lysimeters, like the one used in this study, form a capillary break at the interface between the cover soils and the drainage layer at the base of the lysimeter. The capillary break limits drainage into the lysimeter until soil at the soil-drainage layer interface is nearly saturated. This effect is more pronounced for coarser-textured soils with lower air entry pressure (Khire et al. 2000). The capillary barrier effect is not significant for the fine-grained soils used in this study because of their high air entry pressure (average=650 kPa) (Gurdal et al. 2003), which limits the effects of a capillary break (Khire et al. 2000). The root barrier (between the interim cover soil and the overlying layers) also prevented roots from accessing water in the interim soil adjacent to the drainage layer. Thus, the soil at the bottom of the profile remained wet, further minimizing the capillary barrier effect. Moreover, significant drainage and preferential flow occurred regularly during the study (discussed subsequently), which also indicates that the capillary break effect was insignificant. Further discussion of the importance of the capillary break effect and details of lysimeter design to minimize this effect can be found in Albright et al. (2004).

Soil Characterization

A sampling program was conducted during construction to characterize the in-place cover soils. Four disturbed samples (20-L buckets) were removed from each lift immediately after placement. The disturbed samples were analyzed for particle size distribution (ASTM D 422) (ASTM 2002c), Atterberg limits (ASTM D 4318) (ASTM 2005b) and compaction behavior (ASTM D 698) (ASTM 2000). The particle size distribution curves and Atterberg limits are shown in Fig. 4.

Two undisturbed samples for determining saturated hydraulic conductivity were taken from each lift of the soil barrier layer with thin-wall (71-mm diameter) sampling tubes and as hand-carved blocks (200 mm diameter and length). The saturated hydraulic conductivity (Table 1) was measured following the methods described in ASTM D 5084 (ASTM 2003). The hydraulic gradient was approximately 10, the effective stress was 28 kPa, and the backpressure was 207 kPa. These test conditions were selected to reasonably represent conditions within the cover while also ensuring reasonable test times and good contact between the membrane and the test specimen. Soil water characteristics curves (SWCCs) were also measured on the undisturbed specimens using pressure plate extractors. The SWCCs are not described herein, but can be found in Gurdal et al. (2003).

Table 1. Summary of Saturated Hydraulic Conductivities of Compacted Clay Soil Barrier Layer

Sample type	Test method	Number samples	Size	K ($cm\ s^{-1}$) Upper	Lower	Geometric mean
End of construction						
Undisturbed 76 mm sampling tube	Flexible wall permeameter	3	71 mm diameter	7.1×10^{-8}	1.4×10^{-8}	3.0×10^{-8}
Undisturbed hand-carved block	Flexible wall permeameter	2	152 mm diameter	1.1×10^{-8}	3.5×10^{-8}	6.2×10^{-8}
During monitoring period (first 150 day), prior to drought						
In-situ	Lysimeter	1	10×20 m	—	—	1.4×10^{-7}
During monitoring period (8 months after construction), after the drought						
In-situ	Lysimeter	1	10×20 m	—	—	3.6×10^{-5}
After four years (46 months) of service						
In-situ	SDRI[a]	1	1.5×1.5 m	NA	NA	2.0×10^{-4}
In-situ	TSB[b]	3	305 mm diameter	3.1×10^{-3}	3.2×10^{-5}	1.7×10^{-4}
Undisturbed hand-carved block	Flexible wall permeameter	2	71 mm diameter	1.8×10^{-7}	5.7×10^{-8}	1.0×10^{-7}
Undisturbed hand-carved block	Flexible wall permeameter	2	152 mm diameter	2.3×10^{-5}	3.8×10^{-6}	9.3×10^{-4}
Undisturbed hand-carved block	Flexible wall permeameter	2	305 mm diameter	6.4×10^{-5}	2.0×10^{-5}	3.6×10^{-5}

[a]SDRI—sealed double-ring infiltrometer.

[b]TSB—two-stage borehole permeameter.

Decommissioning the Test Section

The test section was decommissioned in February 2004 (46 months after construction). During decommissioning, field tests were conducted and samples were collected to determine the hydraulic conductivity of the soil barrier layer and to characterize the soil structure. Field-saturated hydraulic conductivity of the barrier layer was measured with a sealed double ring infiltrometer (SDRI) and two-stage borehole (TSB) permeameters. Large hand-carved blocks were removed so that saturated hydraulic conductivity could be measured in the laboratory. An evaluation of soil structure and a dye study were also performed to investigate whether features were present that could be responsible for the high drainage rates and apparent preferential flow. Changes in the unsaturated hydraulic conductivity could also have been assessed but were outside the scope of this study.

Field Hydraulic Conductivity Tests

The SDRI test was conducted in general accordance with ASTM D 5093 (ASTM 2002a). The inner and outer rings were square (1.5×1.5 m and 3.6×3.6 m). Both rings were placed in trenches in the barrier layer, sealed with bentonite, and filled with water. The depth of water in the outer ring was 350 mm. Flow into the inner ring was measured via a Mariotte bottle rather than a plastic bag due to the high rate of infiltration into the barrier layer. The hydraulic head in the Mariotte bottle was maintained at the water level in the outer ring. Depth of the wetting front was not measured and was assumed to be at the base of the barrier layer. Drainage was collected by the lysimeter during the SDRI test, indicating that the wetting front did reaching the bottom of the profile. Thus, the hydraulic gradient was computed as the sum of the depth of ponded water and the barrier layer thickness divided by the barrier layer thickness. Readings were taken periodically until the flow became constant. The field-saturated hydraulic conductivity was calculated as the infiltration rate divided by hydraulic gradient, as described by Daniel (1989).

Tests with the TSB permeameters were conducted at three locations in the soil barrier in general accordance with ASTM D 6391 (ASTM 2004). The casing diameter was 305 mm, the standpipe diameter was 102 mm, and the water level was typically maintained less than 0.5 m above the soil surface. For each test, the casing was set 150 mm deep in the barrier for the first stage and sealed with bentonite grout. The borehole was extended an additional 150 mm into the barrier layer for the second stage. Water level data for both stages were collected until the apparent conductivity ceased changing with time, as required in D 6391. The vertical and horizontal hydraulic conductivities were calculated following the method described in Daniel (1989). These calculations showed that the hydraulic conductivity was essentially isotropic. Thus, only vertical hydraulic conductivities are reported.

Laboratory Hydraulic Conductivity Tests

Two large (330 mm diameter) hand-carved blocks were removed from the clay barrier layer so that their saturated hydraulic conductivity could be measured in the laboratory. Flexible-wall permeameters were used following the methods described in ASTM D 5084 (ASTM 2003). The hydraulic gradient was 10, the effective stress was 28 kPa, and the backpressure was 208 kPa (i.e., the same test conditions used for the postconstruction testing).

Prior to testing, the blocks were trimmed to 305 mm in diameter and 152 mm in length. Following testing at 305 mm, the blocks were removed from the permeameters, trimmed to 152 mm in diameter, and tested again. This process was repeated one more time, with the blocks trimmed to 71 mm in diameter. The aspect ratio was the same for all analyses.

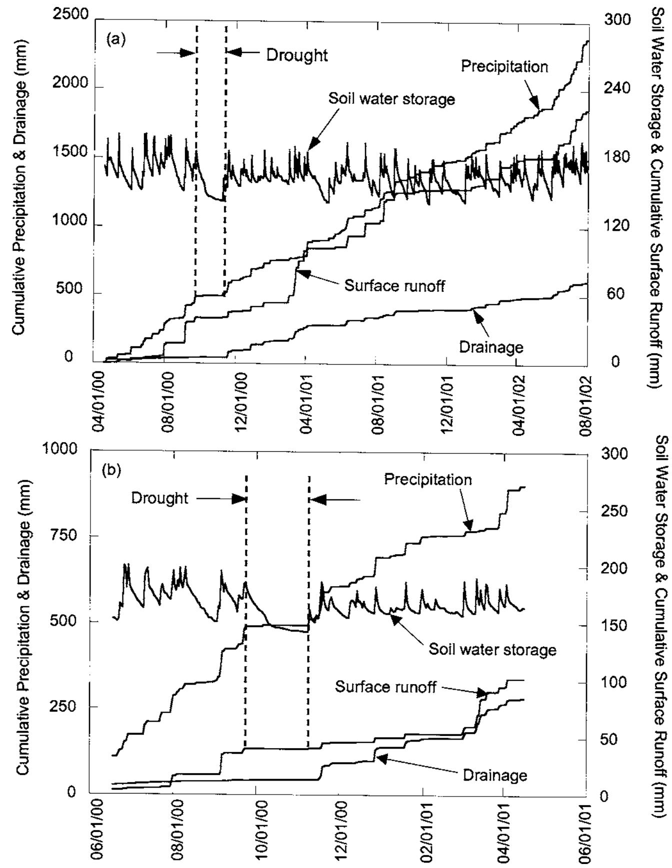

Fig. 5. Water balance components of the compacted clay cover for (a) the entire field test; (b) the period immediately prior to and following the drought in fall 2000

Soil Structure Evaluation

Soil structure was observed using a dye study and structural mapping. A solution of fluorescein dye (1:40 dilution) was ponded to an initial depth of approximately 50 mm to infiltrate a 2×4 m area of the test section. Most of the dye solution infiltrated within 18 h, and dye was observed in the lysimeter drainage collection system. A trench was excavated through the entire depth of the test cover in the dye application area with a backhoe. Soil on the face of the trench that was disturbed by excavation was removed and the exposed soil face was visually examined for the presence of the dye.

Details of soil structure on the exposed trench wall were described using standard methods for description of soil morphology (USDA-NRCS 2003) including notation of pores, fractures, and roots. Features were mapped by placing a 100 mm grid over a 1-m wide portion of the entire depth of the trench wall. Spacing in both horizontal and vertical dimensions was measured by marking the intersection of fractures in the soil with the grid. Results of the soil mapping were described in terms of average spacing of vertical cracks marked on horizontal grid elements and the spacing of horizontal cracks above and below the root barrier.

Table 2. Water Balance of Compacted Clay Cover

Time	Precipitation (mm)	Irrigation (mm)	Total applied water[a] (mm)	NOAA precipitation[b] (mm)	Surface runoff (mm)	Drainage (mm)
4/19/00–4/18/01	904	0	904	1098	102	275
4/19/00–11/15/00[c]	520	0	520	532	41	44
11/16/00–4/18/01[c]	384	0	384	566	61	230
4/19/01–4/18/02	861	48	908	829	80	211
4/19/02–8/01/02	299	265	564	285	41	115

[a]Total applied water is sum of precipitation and irrigation.

[b]National Oceanographic and Atmospheric Administration station 12 km southwest of site.

[c]The period 4/19/00–11/15/00 was pre-drought. 11/16/00–4/18/01 was post-drought.

Results and Discussion

Water Balance

The water balance of the test section (precipitation, surface runoff, drainage, and soil water storage) was monitored for 864 days immediately following construction (April 19, 2000, to August 1, 2002). The water balance quantities are shown as a function of time in Fig. 5(a) and are tabulated in Table 2. Annual precipitation during the first two complete years (April 19-April 18) of monitoring was 72% and 68% of the long-term average annual precipitation (1273 mm) recorded at the nearby Albany National Oceanographic and Atmospheric Administration (NOAA) station. Irrigation was applied after the first year of monitoring to stimulate growth of the vegetative cover. Over the monitoring period, drainage was 25.6% (608 mm) of the applied water (precipitation+irrigation) and surface runoff was 9.4% (223 mm) of the applied water.

A noticeable change in the drainage rate occurred during the fall of 2000, approximately eight months following construction [Fig. 5(b)]. The change followed a 7-week drought between September 23 and November 15, 2000, during which time the soil water storage decreased monotonically. Desiccation cracks were observed in the soil surface at the end of this period (Albright and Benson 2003). The amount of drainage, relative to precipitation, increased following the drought, and at the same time, there was a change in temporal response of drainage to individual precipitation events (Fig. 5(b)). Following the drought, drainage was often observed within 1 h of precipitation events and exhibited a "stair-step" pattern indicative of preferential flow, whereas drainage occurred at a relatively steady rate prior to the drought.

During the period prior to the drought (April 19, 2000, to September 23, 2000) drainage was 42.1 mm (8.7% of applied water), which is equivalent to an annual rate of 102 mm year^{-1}. During the same period the following year (after the drought), drainage was 2.6 times higher (111 mm), even though applied water was just 13% greater than the previous year. During the entire monitoring period following the drought (628 days), 564 mm of drainage (30.3% of applied water) was transmitted, which corresponds to an average annual drainage rate of 327 mm year^{-1}.

The influence of the 7-week drought is also evident in the quantity of drainage resulting from individual precipitation events, as shown in Fig. 6 in terms of the average daily drainage rate for precipitation events of different size before and after the drought. The precipitation events in Fig. 6 were defined as periods of precipitation separated by at least 12 h of no recorded precipitation and were grouped in increments according to size (2-mm increments for events <10 mm, 5 mm increments for events between 10 and 30 mm, and 10 mm increments for events between 30 and 50 mm). The data points in Fig. 6 relate all precipitation events in a given increment to the average total drainage resulting from those precipitation events for time periods before and after the drought.

Drainage was essentially the same before and after the drought for precipitation events <5 mm (Fig. 6). In contrast, greater drainage occurred after the drought for nearly all precipitation events and the difference between drainage before and after the drought increased with increasing size of the precipitation event. For example, precipitation events between 5 mm and 30 mm generally resulted in more drainage after the drought than before by at least a factor of 2 (with one outlier at the 25-mm precipitation increment). The sensitivity of the difference in drainage rates before and after the drought may be due to the amount of infiltration stored in the surface layer because of a precipitation event. For small (<5 mm) precipitation events, nearly all of the infiltration was stored in the surface layer, preventing flow into the barrier layer. In contrast, infiltration from larger storms was sufficient to initiate flow into to the barrier layer.

The temporal response of drainage and soil water content to precipitation is shown in Fig. 7 for conditions before [Fig. 7(a)]

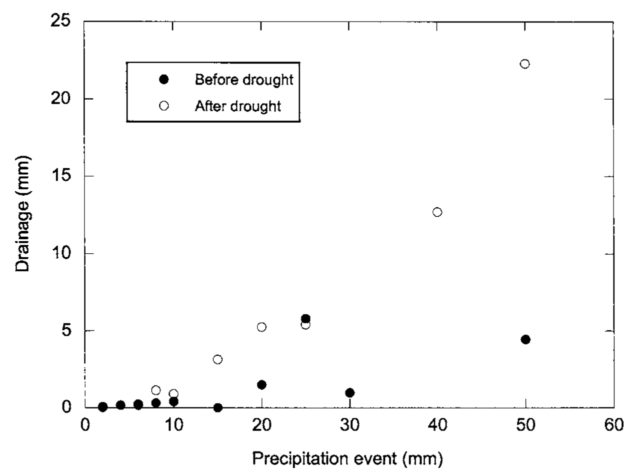

Fig. 6. Drainage before and after drought as a function of magnitude of precipitation event. Precipitation events were grouped in increments according to size (2 mm increments for events <10 mm, 5 mm increments for events 10–30 mm, 10 mm increments for events 30–50 mm). For each increment, average resulting drainage was calculated for all precipitation events in that increment.

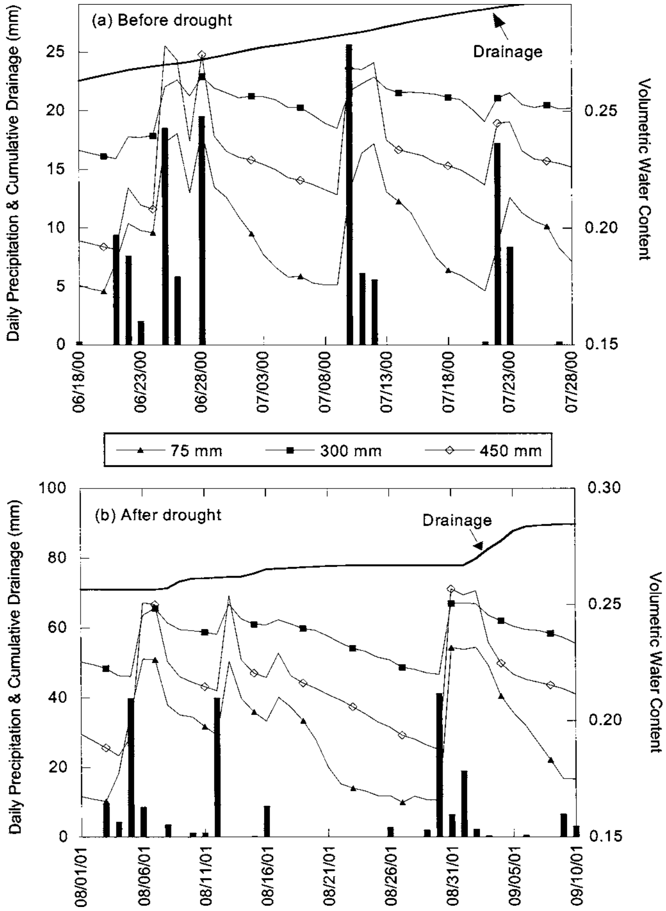

Fig. 7. Water content of cover soils, daily precipitation, and cumulative drainage (a) before; (b) after the drought. Legend indicates depth of probe placement. Precipitation shown as vertical bars.

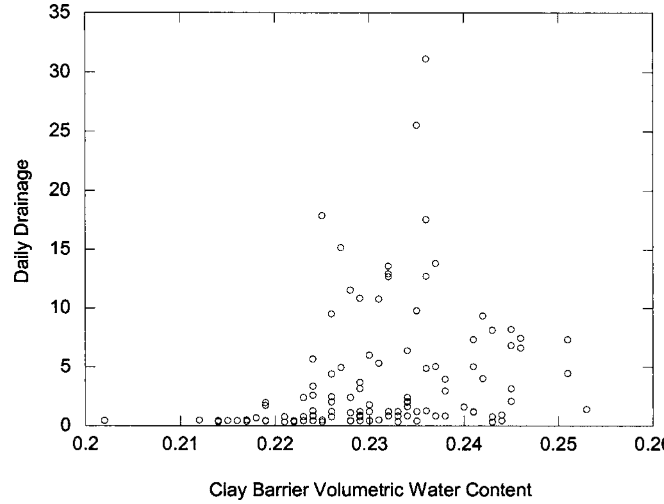

Fig. 8. Preferential flow after the drought as a function of water content of the clay barrier. For each day with recorded precipitation, daily drainage was plotted against volumetric water content of the clay barrier just prior to the precipitation event.

and after [Fig. 7(b)] the drought. Daily precipitation is shown as vertical bars. The lines correspond to cumulative drainage and spatially averaged water content at three depths in the soil profile (75, 300, and 450 mm). Water content at the 300 and 450 mm depths typically varied <0.05 between the three sensors at each depth whereas water contents reported by the surface sensors varied by as much as 0.15. During the summer of 2000 (the first few months after construction and before the drought), drainage occurred at a relatively steady rate and showed little variation in response to daily precipitation events, even those in excess of 25 mm day^{-1}, indicating that there was little or no preferential flow. In contrast, during the following summer (after the drought), the drainage rate increased rapidly following most precipitation events, and most of the drainage occurred within 24 h of a precipitation event. Following the drought, drainage rates typically returned to near-zero within 1–2 days of precipitation events.

Drainage rates, though different before and following the drought, displayed little sensitivity to soil water content. For example, the predrought precipitation events on June 27–28, 2000 (when water content was relatively high), and July 11–12, 2000 (when the water content at all depths was somewhat lower), produced little discernable increase in drainage rate even though the water content of the soil barrier increased in response to the precipitation [Fig. 7(a)]. The absence of a change in drainage rate, despite the presence of heavy precipitation and difference in water content of the barrier layer, suggests that the barrier layer was intact and had low hydraulic conductivity. In contrast, large precipitation events approximately one year later (August 4–7, 13, and 31, 2001) and after the drought resulted in immediate increases in the drainage rate at times when the soil water content was both relatively low (August 4–7 and 31, 2001) and high (August 13, 2001). Fig. 8 shows that the average water content of the barrier soils after the drought was usually between 0.21 and 0.25 and that significant drainage occurred when the barrier layer was both relatively wet and dry at the onset of precipitation. In Fig. 8, drainage on days for which precipitation was recorded is graphed versus volumetric water content of the clay barrier for the previous day. These postdrought observations suggest that preferential flow occurred through the barrier layer, regardless of soil water content.

The temporal variation in water content in response to precipitation was more rapid after the drought [Fig. 7(b)] than before the drought [Fig. 7(a)]. Postdrought precipitation typically resulted in an abrupt increase in water content at all depths (e.g., August 31, 2001), whereas pre-drought changes in water content were more gradual (e.g., July 11, 2000). The rapid propagation of water throughout the soil profile after the drought suggests that the hydraulic conductivity of the barrier layer increased appreciably postdrought. Moreover, the relatively rapid response of the sensors at all depths and at all instrument nests suggests that the change in hydraulic conductivity was caused by a relatively dense network of cracks. If a limited number of large and widely spaced cracks were responsible, drainage would have been observed with little change in water content (i.e., flow would probably have bypassed the soil containing the water content sensors if the cracks were widely spaced). Soil structure observations, described subsequently, confirmed that a dense network of cracks did exist in the barrier layer.

Patterns in surface runoff suggest that changes in the soil barrier layer had little effect on the occurrence or quantity of surface flow. Surface flow prior to the drought was 8.1% of precipitation and 9.9% following the drought (Table 2). Similarly, the number of days with both precipitation and surface flow was 26% prior the drought and 27% following the drought.

Saturated Hydraulic Conductivity

A summary of hydraulic conductivities of the soil barrier layer measured using various methods (laboratory tests, SDRI, TSB permeameters) is in Table 1. These hydraulic conductivities correspond to conditions at the end of construction and after four years of service. Table 1 also includes estimates of the effective field hydraulic conductivity computed from drainage rates recorded with the lysimeter prior to and after the drought. Effective field hydraulic conductivity was computed using the peak daily drainage rate from the lysimeter assuming steady flow and a unit downward hydraulic gradient in the barrier layer. These assumptions are simplistic, but the K_{ef} obtained in this manner indicates the in-service hydraulic conductivity of the barrier layer. Specifically, in the absence of ponded conditions, the saturated hydraulic conductivity must be $>10^{-7}$ cm s^{-1} if $K_{ef}>10^{-7}$ cm s^{-1}.

The effective field hydraulic conductivity was computed for the as-built conditions using the fairly constant rate of drainage during the first 150 days following construction. The total drainage during that period was 42.1 mm, which corresponds to an effective hydraulic conductivity of 3.2×10^{-7} cm s^{-1}. This effective hydraulic conductivity is 5.2 times higher than the geometric mean saturated hydraulic conductivity (6.2×10^{-8} cm s^{-1}) from the 305-mm undisturbed blocks taken during construction, 10.7 times higher than the geometric mean saturated hydraulic conductivity (3.0×10^{-8} cm s^{-1}) of specimens collected in 71-mm sampling tubes, and more than three times higher than the design specification (1.0×10^{-7} cm s^{-1}) for the barrier layer. The difference between the effective hydraulic conductivity from the lysimeter data and the saturated hydraulic conductivity measured in the laboratory may be the result of scale effects (i.e., the hydraulic conductivity depends on the volume of soil permeated) caused by the presence of macroscopic features in the larger measurement (e.g., Daniel 1984; Day and Daniel 1985; Benson et al. 1994, 1999b) or differences between the effective stress applied in the laboratory (28 kPa) and that in the field (≈6 kPa) (Manuel et al. 1987; Trast and Benson 1995).

The highest daily drainage during the postdrought period was 31.1 mm (December 28, 2000), which corresponds to an effective hydraulic conductivity of 3.6×10^{-5} cm s^{-1}. This hydraulic conductivity is more than two orders of magnitude higher than the design specification and the as-built condition. The effective hydraulic conductivity is about 5 times lower than the hydraulic conductivity measured with the SDRI (2.0×10^{-4} cm s^{-1}) and the geometric mean hydraulic conductivity measured with the TSBs (1.7×10^{-4} cm s^{-1}) but is identical to the geometric mean saturated hydraulic conductivity of the blocks tested at a diameter of 305 mm (3.6×10^{-5} cm s^{-1}). The higher hydraulic conductivity measured with the SDRI and TSBs may reflect the tests being conducted in particularly permeable regions of the soil barrier. As indicated in the range of hydraulic conductivities measured with the TSBs (3.1×10^{-3}–3.2×10^{-5} cm s^{-1}), the postdrought hydraulic conductivity of the soil barrier was highly variable. Also, two of the three hydraulic conductivities measured with the TSBs were similar to the effective hydraulic conductivity computed from the drainage rate.

The saturated hydraulic conductivity after four years was also scale dependent, as shown in Fig. 9 as a function of the permeated cross-sectional area. The geometric mean hydraulic conductivity increases nearly two orders of magnitude as the permeated cross-sectional area of soil that was permeated increases from 0.04 m^2 to 0.73 m^2. For larger areas, the hydraulic conductivity appears scale independent. The scale dependence at Albany is consistent with previous studies by Daniel (1984), Day and Daniel (1985), and Benson et al. (1994), which have shown that the hydraulic conductivity of small-scale laboratory specimens can be orders of magnitude lower than the field-scale hydraulic conductivity when clay barriers contain macroscopic defects. Similar results were noted in a study of a field soil by Sisson and Wierenga (1981), who found that small-scale (50 mm) measurements did not adequately represent field-scale (6.35 m) infiltration and that measurements at 250 mm and 1270 mm were much more representative.

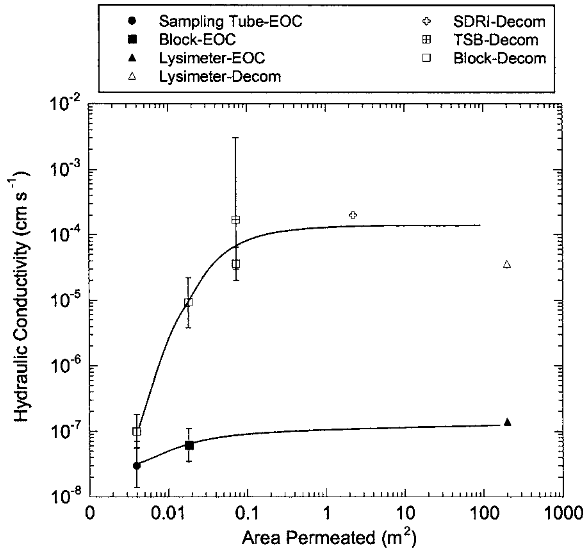

Fig. 9. Hydraulic conductivity of barrier layer as a function of area permeated for conditions at the end of construction after four years of service. EOC=end of construction. Decom=at the time of decommissioning.

Effective Porosity

Cracks and other macroscopic features responsible for preferential flow generally make up a small fraction of the total porosity and are often referred to as the effective porosity. Booltink and Bouma (1991) and Lin et al. (1996, 1997) described preferential flow through macropores in undisturbed fine-textured, structured soils, and all noted that preferential flow can constitute more than half of total flow even though, as noted by Lin et al. (1996), effective porosity can represent a small fraction of total porosity.

The effective porosity (n_e) of the soil barrier was estimated using the lag time between precipitation and drainage events for postdrought conditions when the preferential flow was observed. The effective porosity was computed as the ratio of the Darcy velocity (q) to the seepage velocity (v_s)

$$n_e = \frac{q}{v_s} = \frac{K_e i}{L/t} \tag{1}$$

The Darcy velocity was estimated from the effective field hydraulic conductivity ($K_e=3.6\times10^{-5}$ cm s^{-1}) for the postdrought period, assuming that the hydraulic gradient was unit. The seepage velocity was computed as the thickness of the cover (L) divided by the lag time (t) between high-intensity precipitation events and peak drainage rates (i.e., the same conditions used to define K_e), which ranged between 2 and 8 h. The calculated n_e (0.004 to 0.014) is considerably less than the total porosity (0.37) and indicates that the macropores responsible for the observed prefer-

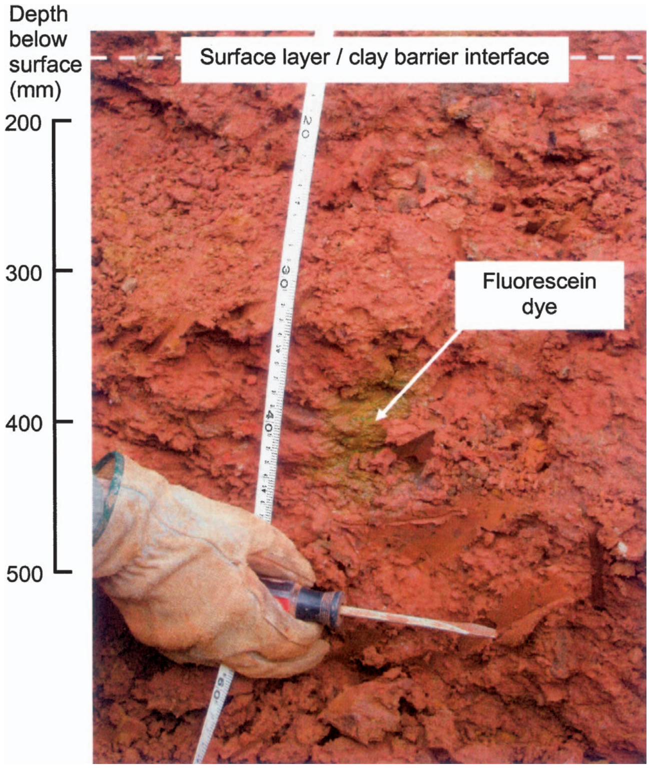

Fig. 10. (Color) Photograph of wall of trench in clay barrier showing presence of green fluorescein dye flowing through a preferential flow path. The depth of the dye is 400 mm, which is below 150 mm of surface layer and 250 mm of clay barrier.

ential flow involved a small fraction of the total porosity. Lin et al. (1996) reported that n_e for undisturbed samples of clay soils ranged between 0 and 30% of the total porosity depending on the degree of structural development.

Soil Structure

Examination of the trench walls in the regions where dye was pooled showed that dye was flowing from numerous cracks throughout the depth of the barrier layer. Fluorescein does not stain the soil to leave a visual record. Therefore, the presence of dye flowing from these cracks was strong evidence that preferential flow was occurring. Dye was also clearly visible in water draining from the lysimeter, indicating that the dyed water pooled on the surface passed through the soil barrier quickly. A typical example of dyed water flowing from a crack in a trench wall is shown in Fig. 10. Green dye is flowing from a crack at a depth of 400 mm (250 mm below the interface between the surface and barrier layers).

Inspection of the exposed trench wall also revealed numerous cracks in the soil barrier layer with the density of cracks generally decreasing with depth (Fig. 11). The cracks were spaced at intervals of approximately 100–300 mm. Roots were also observed throughout the barrier layer and typically existed in cracks. Soil structure formed in the clay barrier consisted of platy and blocky types. Platy structure was most common and best developed between the surface and about 400 mm depth, with the strongest development between about 50 and 260 mm depth. Blocky structure was most common between 50 and 600 mm depth (to the top of the root barrier) with the strongest development between 50 and 140 mm depth. Most of the cracks found in the soil barrier

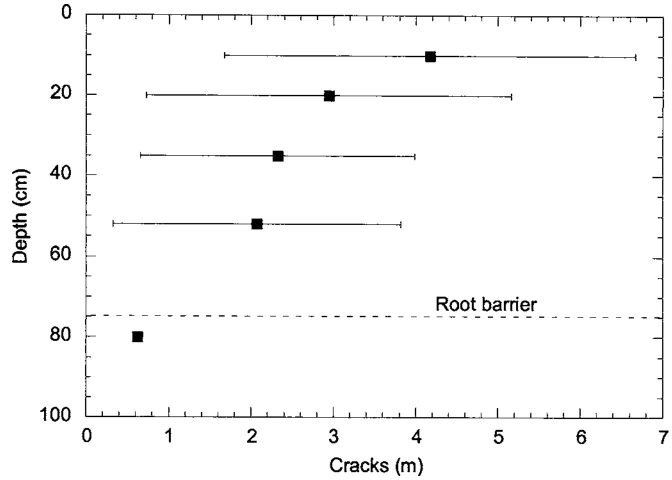

Fig. 11. Spacing of vertical cracks in the compacted clay cover after four years of service. Horizontal bars indicate one standard deviation. Below the root barrier, only one crack was recorded.

represented the incipient development of pedologic structure. The abundance and degree of soil structure development diminished considerably below the root barrier relative to the soil above the barrier.

Summary and Conclusions

Data describing the water balance from a 10×20 m test section simulating a compacted clay landfill cover have been presented along with a comparison of the hydraulic conductivity of the soil barrier layer at the time of construction and during decommissioning after four years of service. The hydraulic conductivity was measured in the laboratory and field over a broad range of scales (0.004 to 200 m^2). Structure of the soil barrier was also observed during decommissioning using a dye study and by conducting a soil structural analysis.

Drainage from the cover, expressed as a fraction of precipitation, increased by nearly a factor of four following a drought. In addition, the pattern of drainage changed from a steady flow, relatively independent of the timing of precipitation prior to the drought, to rapid and intermittent flows closely related to precipitation events (in particular those events during which more than 5 mm of precipitation was recorded) after the drought. Rapid movement of water through the barrier layer after the drought was also reflected in a more immediate response of soil water content to precipitation events. The increased rate of drainage following the drought was independent of the water content of the barrier layer. All of these changes in behavior indicate that desiccation during the drought caused cracks to form that acted as preferential flow paths. The presence of cracks was confirmed by the dye tracer test and soil structure analysis. Both showed the existence of a connected network of cracks in the barrier layer. Roots were commonly found in these cracks.

Hydraulic conductivities from laboratory tests, field tests, and from drainage rates recorded before and after the drought showed that the hydraulic conductivity of the barrier layer increased by more about three orders of magnitude over the service life of the test section, most likely because of the network of cracks in the soil barrier. Moreover, laboratory tests conducted on specimens of various sizes showed that the hydraulic conductivity of the barrier layer at the time of decommissioning was scale dependent and that tests on small specimens tended to underestimate the field hydraulic conductivity by two to three orders of magnitude. These results support earlier studies of the scale dependency of hydraulic conductivity tests and the conclusion that assessments of hydraulic conductivity of in-service clay barriers based on laboratory tests on small specimens or small-scale field tests probably can be misleading.

Comparison of the findings in this study with those reported by others has shown that desiccation, or weathering in general, causes relatively rapid degradation of soil barriers, and that the effectiveness of soil barrier covers as hydraulic barriers can be compromised over a relatively short period of time. Thus, in applications where clay layers are used as hydraulic barrier layers in landfill covers, the design should include features (e.g., an overlying geomembrane) to ensure that the barrier layer will not be adversely affected by weathering. The results of this study also demonstrate the important role of pedogenic processes on the effectiveness of compacted clay covers. The formation of extensive soil structure within only four years indicates that common surface processes (wetting and drying, propagation of roots, etc.) can degrade covers relatively rapidly, resulting in much higher drainage rates than often expected during design.

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