INTERPRETATION OF FIELD PERMEABILITY TEST RESULTS ON FULL SCALE LINER SYSTEMS

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ABSTRACT

The evaluations of the as-compacted hydraulic conductivity of two full scale clay liner systems using the sealed double-ring infiltrometer (SDRI) are presented. Infiltration rate measurements, soil tensiometers, dye-tracing techniques, and measurements of post-test soil moisture contents were used to estimate the position of the wetting front to aid in calculating vertical hydraulic gradients and effective vertical saturated hydraulic conductivities of the liners at various times throughout the test. Laboratory permeability testing of remolded clay samples were used to establish the SDRI test liner compaction conditions to meet a specified minimum conductivity requirement. Undisturbed samples from the as-compacted liners were tested in the laboratory to provide a basis of comparison to field-determined conductivity values. The results showed that field-determined hydraulic conductivity values varied by less than one-half order of magnitude depending on the methods utilized and the assumptions made. Tensiometer measurements were shown to overpredict the position of the wetting front and the value of calculated hydraulic conductivity. Laboratory-determined hydraulic conductivities from the undisturbed liner samples slightly exceeded the range of SDRI testing results, providing a conservative estimate of the as-compacted conductivities of the liners.

INTRODUCTION

As the demands required to limit the impact of stored solid and hazardous wastes on the environment have increased over the last decade, field permeability testing methods to determine the hydraulic conductivity of compacted clay liners has received considerable attention. Laboratory testing of small diameter, undisturbed samples on several liner systems has been shown in many instances to underestimate the hydraulic conductivity of the actual earthen liners in comparison to field testing performed on much larger areas [1-3]. This has been attributed to the ability of the field tests to measure a larger, more representative volume of material and include the effect that secondary features such as fissures, macropores, and slickensides have on increasing the effective hydraulic conductivity.

A number of in-situ testing methods have been used over the years to estimate the field hydraulic conductivity of natural soils. These have been broadly grouped into borehole, porous probe, infiltrometer, and underdrain tests, and the relative advantages and disadvantages of each has been previously discussed [4].

This paper describes the application of one of the infiltration methods - the use of the sealed double-ring infiltrometer (SDRI) - to assess the as-compacted hydraulic conductivity of two full-scale test fills. The impact of the variation in the interpretation of the measurements on the estimated conductivities is discussed. Comparisons are also made between the field and laboratory-determined conductivity values.

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TABLE 1
LABORATORY PHYSICAL PROPERTIES OF CLAYS

	Test Fill 1 Gray Silty Clay				Test Fill 2 Reddish Brown Silty Clay			
Soil Characteristic[a]	No. of Tests	Mean	Standard Deviation	Range	No. of Tests	Mean	Standard Deviation	Range
Natural Moisture Content (%)	42	20.8	5.4	10.7 - 34.3	3	18.2	0.4	17.9 - 18.7
Atterberg Limits	24				3			
Liquid Limit (%)		22.3	6.0	15.4 - 37.5		19.8	3.4	17.1 - 24.6
Plasticity Index (%)		40.6	8.8	30.0 - 59.4		40.0	7.9	33.0 - 51.3
Grain Size Distribution[b]	20				6			
Clay (%)		38.0	8.0	25.0 - 49.0		25.5	11.5	19.0 - 43.0
Silt (%)		39.2	8.5	15.0 - 53.0		44.0	6.5	33.0 - 51.0
Sand (%)		22.6	12.1	4.0 - 40.0		30.0	8.5	10.0 - 43.0
Moisture Density Relationship[c]	5				5			
Maximum Dry Density (pcf)		109.1	5.0	104.2 - 114.8		107.0	1.2	105.2 - 108.1
Optimum Moisture Content (%)		15.8	2.1	12.5 - 17.8		16.2	3.0	11.5 - 19.3

[a] ASTM Test Procedures for all Characteristic Determinations
[b] Defined as in ASTM D 422
[c] Standard Proctor ASTM D 698

SEALED, DOUBLE-RING INFILTROMETER (SDRI)

The SDRI testing method evolved from the earlier standard describing double-ring infiltration testing (ASTM D 3385). Because of the equipment utilized, this standard method could not be reliably used to determine hydraulic conductivities of low permeability soils. First described by Daniel and Trautwein [5-7], the SDRI was developed to accurately measure very low infiltration rates indicative of clay liner systems so that hydraulic conductivities on the order of less than 10^{-7} cm/sec could be determined.

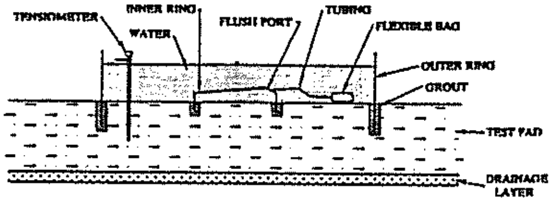

Figure 1. Schematic of the SDRI System

The SDRI system used in the two full scale tests was manufactured by the Trautwein Soil Testing Equipment Company [7] and consists of two rings: a 12 ft square aluminum outer ring and a 5 ft square sealed fiberglass inner ring (Figure 1). The rings are embedded into bentonite grout-filled trenches dug into the surface of the liner system, the outer ring to a depth of about 18 in, the inner ring to a depth of about 5 in centered within the outer ring.

When both rings are filled with water, the smaller thickness inner ring is submerged and separated from the outer ring water by its sealed cover. The outer ring water is left open to the atmosphere. The measurement of infiltration through the inner ring is made by the connection of a flexible bag filled with a known weight of water to a port on the inner ring. Weighing the loss of fluid from the bag at periodic time intervals rather than measuring a drop of elevation in the water level of the rings, as has been the practice in other ring infiltrometer methods, allows for improved resolution and accuracy of low flow measurements.

By sealing the inner ring and using a protective cover over both rings, the influences of evaporation and temperature fluctuations are also minimized. The use of the larger outer ring also provides improved confidence in the assumption of one-dimensional flow immediately beneath the inner ring.

A limited number of field tests [5,8-9] has yielded SDRI-measured hydraulic conductivity values about one order of magnitude greater than laboratory determined values. Unpublished data by Trautwein [4] on more than a dozen case histories show SDRI-measured conductivities to vary between one to ten times laboratory-measured values. Recent results on a test pad liner in Jamestown, California [10], however, showed good agreement between laboratory and SDRI-determined values.

LABORATORY PROGRAM

In order to develop stringent construction quality controls for the selection, preparation, and monitoring of appropriate soils at each site for the SDRI tests, laboratory testing programs were undertaken to fully characterize the soil properties. The test results for the soils selected as clay liner material at the two sites are presented in Table 1.

At the Test Fill 1 site, a northern Indiana glacial till clay was selected. The clay in its undisturbed natural state was described as a stiff to very stiff, mottled gray silty clay with a U.S.C.S. classification of CL. At the Test Fill 2 site, a southern Indiana residual clay was used as the liner material. The residual clay was described as a very stiff, reddish brown silty clay also with a U.S.C.S. classification of CL.

During borrow pit selection, several samples of the available clay soils were subjected to fixed-wall permeameter and triaxial permeability testing to evaluate the effectiveness of the soils as a landfill cover barrier layer. Samples were remolded and compacted in standard Proctor and Harvard miniature molds at densities varying from 90 to 110 percent of their maximum dry density (ASTM D 698) wet of the optimum moisture content. The relationships established between hydraulic conductivity and dry density were used to select the dry density and moisture ranges that would result in hydraulic conductivities that would meet the minimum U.S. EPA requirement of less than 1 x 10^{-7} cm/s for landfill cover barrier layers.

Construction specifications developed from these laboratory permeability tests required dry densities above 95 percent of the standard Proctor maximum and moisture conditions between 2 to 5 percent wet of the optimum moisture content for the Test Fill 1 site. Specifications for the Test Fill 2 site required the dry density of the soil to exceed 100 percent of the standard Proctor maximum, with moisture contents wet of optimum. If these conditions could be satisfied in the field, the testing results indicated that hydraulic conductivities of less than 5 x 10^{-8} cm/sec were possible at each test location.

TEST FILL CONSTRUCTION

The two test fill areas were prepared by removing all topsoil and vegetation and placing a one foot thick coarse sand layer at the base of the test clay liners to define the lower boundary condition for the SDRI test [5]. The clay soils in each case were placed in successive 6 to 8 in (15 to 20 cm) loose lifts and compacted with a sheepsfoot roller. A 79,000 lb Caterpillar 835 self-propelled compactor was used on Test Fill 1. At the Test Fill 2 location, a pull-behind type vibrating sheepsfoot with a rated dynamic force of approximately 15,000 lbs was used to compact the soil.

The completed Test Fill 1 surface area measured about 30 ft by 30 ft (9 m x 9 m) and the thickness approximately 30 in (0.8 m). The liner was constructed in five lifts. Test fill 2 was constructed to an area of about 30 ft by 45 ft (9 m x 14 m) and a thickness of approximately 39 in (1 m). Six lifts were necessary to achieve the final desired thickness. Field moisture and density tests were performed on each lift to monitor adherence to the compaction condition specifications. After completion of the compaction of the top lift, the clay was covered with black plastic to prevent desiccation.

The as-compacted condition of each test fill, as determined from field measurements, indicated that the moisture and density requirements were met or exceeded at all test locations. Test Fills 1 and 2 were compacted to mean dry densities of 98.2 and 101.7 percent of the standard Proctor maximum, respectively. Fixed-wall permeameter and triaxial permeability tests were performed on undisturbed Shelby-tube samples taken from the as-compacted test fills. Mean hydraulic conductivities of 5.2 x 10^{-8} and 5.7 x 10^{-8} cm/sec were determined for Test Fills 1 and 2, respectively.

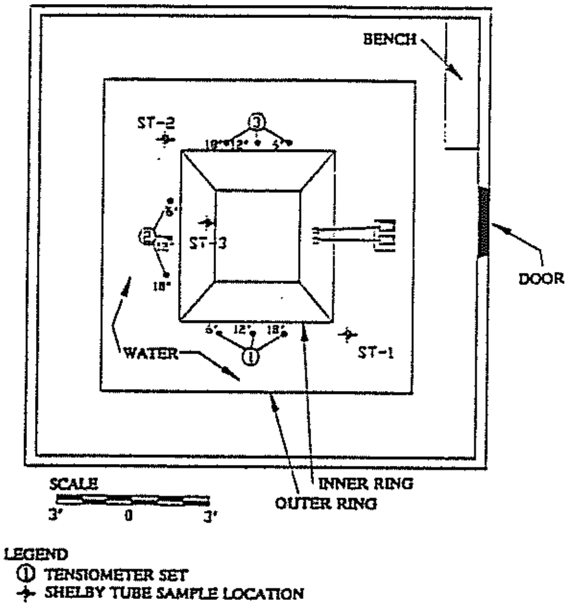

Figure 2. SDRI Set Up - Test Fill 1

SDRI INSTALLATION

The SDRI test apparatus set-up used at Test Fill 1 is shown in Figure 2. A similar arrangement was also utilized at Test Fill 2. A trenching machine was used to excavate a 4 in (10 cm) wide by 18 in (46 cm) deep trench for the outer ring placement. The outer ring was placed, leveled, and sealed with a Volclay grout. The 2 in (5 cm) wide by 5 in (13 cm) deep trench for the inner ring was hand excavated with a brick hammer, the ring positioned, leveled, and grouted into place. Complete details of the assembly and installation procedures of the SDRI may be obtained from the manufacturer [7].

As a means of providing an indication of the movement of the wetting front beneath the rings during the test, three sets of soil tensiometers were placed at depths of 6, 12, and 18 in (15, 30, 45 cm) below the surface of the liner at the locations shown on Figure 2. The tensiometers were installed by drilling a vertical pilot hole to about one-half the tensiometer depth. Once the tensiometer casing was lowered through the hole into place, another smaller diameter hole was advanced beyond the casing to the desired depth and the tensiometer lowered and sealed into place.

Protective wooden-framed housings were constructed for each SDRI installation. At Test Fill 1, the housing air temperature was controlled by a thermostat set to 80 ° F. For the Test Fill 2 location, two portable electric submersible water heaters controlled by a thermostat were used to maintain the actual water temperature at about 60 ° F. Constant ponded water levels in each SDRI were maintained by manual refilling when required.

INFILTRATION RATES

The infiltration rate of the inner ring at test duration time t, I_{ir_t}, is defined as the volume of infiltrating water per unit soil surface area per unit time, and is determined from the test measurements as the total change in the volume of water measured from the flexible bag, ΔV_{t_i}, during a specific time interval, Δt_i, per unit soil surface area of the inner ring, A_{ir}, or

$$I_{ir_t} = \frac{\Delta V_{t_i}}{\Delta t_i A_{ir}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where $\Delta V_{t_i} = V_{t_i} - V_{t_{i-1}}, \Delta t_i = t_i - t_{i-1}$.

Measured infiltration rates versus time for the inner ring for the two test fills are shown in Figure 3. During the 143 day and 161 day test durations for Test Fills 1 and 2, respectively, both tests showed initially higher infiltration rates in the 10^{-6} cm/sec range steadily decreasing at a higher rate within the first 10 to 20 days and then more slowly after that. Observed fluctuations in infiltration rates were most likely caused by changes in the viscosity and density of the water due to temperature fluctuations, barometric pressure variations, or small differences in the manner of weighing the flexible bag by the field technicians that occurred during the long duration of testing.

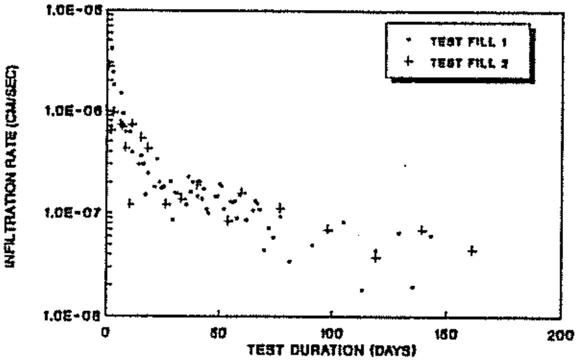

Figure 3. Infiltration Rate Versus Time

Cumulative infiltration through the inner ring, I_{irc_t}, was determined as the total change in the volume of water measured from the flexible bag at test duration time t per unit area of the inner ring soil surface area, or

$$I_{irc_t} = \frac{\sum_{i=1}^{m} \Delta V_{t_i}}{A_{ir}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where $m\Delta t_i = t$.

The cumulative infiltration was calculated to be 1.6 cm and 2.2 cm for Test Fills 1 and 2, respectively.

WETTING FRONT POSITION

Several methods were employed during the SDRI tests to estimate the position of the wetting front. A theoretical approach based on the sharp wetting-front Green-Ampt model [11] assumes that as infiltration occurs, the soil profile is uniformly wetted to a constant, saturated, final volumetric moisture content, θ_f, above the wetting front, and at the front a step-like change in moisture content back to the initial constant volumetric soil moisture content, θ_i, occurs. Using this approximation, the wetting front position, L_{f_t}, below the inner ring after an elapsed test duration time t, may be determined as

$$L_{f_t} = I_{irc_t}/\Delta\theta \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where $\Delta\theta = \theta_f - \theta_i$. If complete saturation of the soil is assumed above the wetting front [12], then the final volumetric moisture content can be taken to be equal to the porosity, n, of the compacted soil, or

$$\theta_f = \eta = 1-(\rho_b/\rho_s) \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where ρ_b is the bulk dry density of the soil and ρ_s is the mean soil solid density. The mean dry density and moisture content of the as-compacted fills determined from the field testing programs were utilized in the porosity value and wetting front calculations.

The estimated theoretical wetting front position during the SDRI test on Test Fill 1 based on these equations is shown in Figure 4. Wetting front locations at the end of each test were calculated by the Green-Ampt model to be 9.5 and 14.1 cm for Test Fills 1 and 2, respectively.

Measured soil suction head values from the three sets of tensiometers were also used to calculate the wetting front location. It was assumed that as the wetting front arrived at the depth of a tensiometer, the soil suction head value recorded by the tensiometer would be zero. Interpretation of the averaged readings from the various depths of the tensiometer sets at Test Fill 1 results in the wetting front prediction shown in Figure 4. Constant velocity movement of the front was assumed between the tensiometer depths. From the tensiometer readings, the wetting front positions at the end of the tests were estimated to be at 45.7 and 43.7 cm for Test Fills 1 and 2, respectively.

Rhodamine dye was initially added to the outer SDRI ring at the Test Fill 2 location to determine the

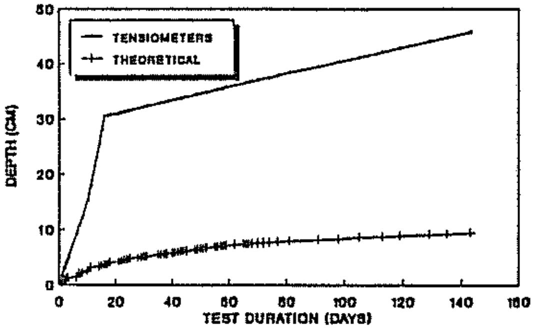

Figure 4. Wetting Front Position Versus Time for Test Fill 1

wetting front location at the end of the test. A sharp dye front was observed at a depth of about 16.0 cm at 161 days.

The results of soil moisture content measurements from undisturbed Shelby tube samples taken at the end of the tests were used to estimate the final position of the wetting front. Moisture variations indicate wetting front positions at 7.6 and 15.2 cm for Test Fills 1 and 2, respectively.

HYDRAULIC CONDUCTIVITY

The apparent saturated vertical hydraulic conductivities (k_s) of the two clay liners during the SDRI tests were calculated from the infiltration data and the estimates of the wetting front position using both the theoretical Green-Ampt model and the tensiometer readings previously discussed. Conductivities were calculated using the following equation:

$$k_{s_t} = \frac{I_{ir_t}}{i_t} = I_{ir_t}[1 + \frac{H + \psi_f}{L_{f_t}}]^{-1} \cdots\cdots\cdots\cdots (5)$$

where i_t is the hydraulic gradient at test duration time t, H is the depth of the ponded water on the surface of the liner, and ψ_f is the wetting-front suction head, taken as zero in the absence of direct measurements (this is a conservative assumption that results in smaller calculated hydraulic gradients and thus larger hydraulic conductivities).

The calculated hydraulic conductivities for Test Fills 1 and 2 are shown in Figure 5. Initially higher infiltration rates in the first 10 to 20 days resulted in conductivities about one order of magnitude higher in the early stages of the tests than calculated near the end of the tests. In each case, the use of the tensiometer readings resulted in estimated conductivity values greater than the theoretical predictions.

Test Fill 1 exhibited hydraulic conductivities near the end of the test in the range of 8×10^{-9} cm/sec using the Green-Ampt approximation, and 3×10^{-8} cm/sec based on the tensiometer data. Hydraulic conductivities for Test Fill 2 near the end of the test were calculated to be about 2×10^{-8} and 4×10^{-8} cm/sec using the Green-Ampt model and tensiometer data, respectively.

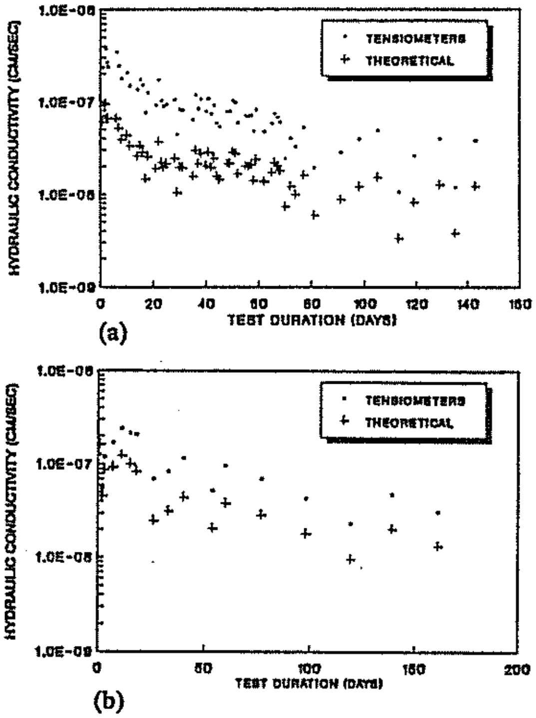

Figure 5. Hydraulic Conductivity Versus Time for (a) Test Fill 1 and (b) Test Fill 2

DISCUSSION OF RESULTS

Reductions in infiltration rates and thus hydraulic conductivity were observed during each SDRI test. Prior studies have also noted this phenomenon [5, 9-10] and have explained that it may result from higher initial soil suction [5] or swelling of the soils tested [10]. Inadequate preparation and protection of the surface of the liner prior to the initiation of the test could also result in surficial drying, lower initial moisture contents, and an apparent high conductivity. This behavior may also be produced by dry density variations within the upper lift (e.g. a lower dry density in the upper few inches) resulting from typical effective compactive effort differences within the liner system.

Despite the long duration of the two tests, the wetting front movement occurred only within the upper lift of the multi-lift liners. Similar flow behavior within the lower lifts may not be extrapolated from the test results.

A comparison of laboratory permeability test results on both remolded and as-compacted liner soils to the field-determined values indicates that the laboratory testing accurately predicted the observed field behavior of the liner systems. Hydraulic conductivities of less than 5×10^{-8} cm/sec were predicted and observed in the field. Test durations of greater than 10 to 20 days were necessary to reach this conclusion.

Good agreement in the predicted wetting front position was observed using the Green-Ampt model, post-test soil moisture content measurements, and the dye tracing observations. Although it has been suggested that the use of tensiometers may be desirable for measuring the wetting front position and hydraulic gradient above the front [6,7], this study suggests that the readings produced by carefully installed tensiometers consistently tend to overpredict the movement of the front position. New enhancements in tensiometer installation and sealing techniques are apparently required before reliable readings may be obtained.

CONCLUSIONS

The SDRI is currently the most reliable apparatus available to determine the as-compacted hydraulic conductivity of low permeability clays. Increased confidence in predictions may be gained by using multiple methods of tracking the wetting front as was done in the testing reported herein. It is apparent from the results of the two tests reported, however, that there are limits to its accuracy at low infiltration rates. Considerably more scatter in the data was observed at the lower infiltration rates observed near the end of the tests, most probably due to the greater influence of small variations in external factors such as temperature.

Although the SDRI has the advantage of testing larger areas that are presumably more horizontally representative of the actual liner than smaller laboratory samples, the wetting front during the test may only infiltrate the top few inches of the upper compacted liner lift even after long test time durations. As a result of this, the SDRI test does not examine the representative flow behavior of the entire liner system vertical cross section.

Finally, the results of this study indicate that contrary to past findings on some earlier liners, a comprehensive laboratory permeability testing program [13] on undisturbed liner samples taken from well-controlled, multiple-lift clay liners may yield as reliable on indicator of the as-compacted hydraulic conductivity as more cumbersome, more expensive, longer-term field tests. Additional well-documented case histories are required to further support this assertion.

REFERENCES

[1] Olson, R. E., and Daniel, D.E., "Measurement of the Hydraulic Conductivity of Fine-Grained Soils," ASTM STP 746, pp. 18-64, 1981.

[2] Daniel, D. E., "Predicting the Hydraulic Conductivity of Compacted Clay Liners," Journal of Geotechnical Engineering, ASCE, Vol. 110, No. 2, pp. 285-300, February, 1984.

[3] Day, S. R., and Daniel, D. E., "Hydraulic Conductivity of Two Prototype Clay Liners," Journal of Geotechnical Engineering, Vol. 111, No. 8, pp. 957-970, August, 1985.

[4] Daniel, D. E., "In Situ Hydraulic Conductivity Tests for Compacted Clay," Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 9, pp. 1205-1226, September, 1989.

[5] Daniel, D. E., and Trautwein, S. J., "Field Permeability Test for Earthen Liners," Proc., In Situ '86, ASCE, Blacksburg, Virginia, pp. 146-160, June 23-25, 1986.

[6] Daniel, D. E., "Hydraulic Conductivity Tests for Clay Liners," Proc. Ninth Annual Symposium on Geotechnical and Geohydrological Aspects of Waste Management, Fort Collins, Colorado, February 1-6, 1987.

[7] Trautwein Soil Testing Equipment Company, Installation and Operating Instructions for the Sealed Double Ring Infiltrometer, Trautwein Soil Testing Equipment Company, Houston, Texas, 1987.

[8] Chen, H. W., and Yamamoto, L. O., "Permeability Tests for Hazardous Waste Management Unit Clay Liners," Geotechnical and Geohydrological Aspects of Waste Management, Proc. of the 9th Annual Symposium on Geo-Aspects of Waste Management, D.J.A., van Zyl et al., eds., Lewis Publishing, Inc., Chelsea, Michigan, pp. 229-243, 1987.

[9] Albrecht, K. A., and Cartwright, K., "Infiltration and Hydraulic Conductivity of a Compacted Earthen Liner," Groundwater, Vol. 27, No. 1, pp. 14-19, Jan.-Feb., 1989.

[10] Fernuik, N. and Haug, M., "Evaluation of In Situ Permeability Testing Methods," Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 2, pp. 297-311, February, 1990.

[11] Green, W. H., and Ampt, G. A., "Studies on Soil Physics Part I--The Flow of Air and Water Through Soils," Journal of Agricultural Science, Vol. 4, pp. 1-24, 1911.

[12] Goldman, L. J., Truesdale, R. S., Kingsbury, C. M., and Damle, A. S., "Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities," Draft Technical Resource Document, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, D.C., EPA/530-SW-86-007, 1986.

[13] Mundell, J. A., and Bailey, B., "The Design and Testing of a Compacted Clay Barrier Layer to Limit Percolation Through Landfill Covers," Hydraulic Barriers in Soil and Rock, ASTM STP 874, A. I. Johnson, R. K. Frobe, J. J. Cavalli, and C. B. Pettersson, Eds., American Society for Testing and Materials, Philadelphia, pp. 246-262, 1985.