Long-Term Behavior of Water Content and Density in an Earthen Liner

Timothy E. Frank[1]; Ivan G. Krapac[2]; Timothy D. Stark[3]; and Geoffrey D. Strack[4]

Abstract: An extensively instrumented compacted earthen liner was constructed at the Illinois State Geological Survey facility in Champaign, Ill. in 1987. A pond of water 0.31 m deep was maintained on top of the 7.3 m × 14.6 m × 0.9 m thick liner for 14 years. One of the goals of the project was to evaluate the long-term performance of a compacted earthen liner by monitoring the long-term changes in water content and density. The water content of the earthen liner showed no trend with depth or time. The liner density remained essentially constant from construction through excavation in 2002. The liner did not become fully saturated. Upon excavation of the liner, the degree of saturation was 80.0±6.3% after 14 years of ponding under a hydraulic head of 0.31 m. The results imply that properly designed and constructed earthen liners may reduce the possibility of pollutants leaching from municipal solid waste containment facilities by remaining partially saturated for years and maintaining the placement density.

DOI: 10.1061/(ASCE)1090-0241(2005)131:6(800)

CE Database subject headings: Water content; Liners; Illinois; Hydrologic properties.

Introduction

A field-scale compacted earthen liner was constructed in 1987 using full-scale construction equipment at the Illinois State Geological Survey (ISGS) in Champaign, Ill. The geotechnical and hydrologic properties of the till used to construct the liner are summarized in Table 1. The practices and equipment used to construct the liner are documented in Krapac et al. (1991). Briefly, the liner was constructed in a series of six lifts using a Caterpillar 815B static load sheepsfoot compactor with an operating weight of 20,037 kg, and a 0.20 m foot length. Each lift was compacted from a loose thickness of 0.23 m to a compacted thickness of about 0.15 m, for a total liner thickness of 0.90 m. The horizontal dimensions of the liner were 7.3 m by 14.6 m. Water was ponded to a depth of 0.31 m on top of the liner in April 1988.

This technical note presents water content, density, and degree of saturation data collected during the liner construction phase in 1987, the experimental phase in 2000, and the excavation phase in 2002. These data provide a unique opportunity to evaluate the long-term performance of a compacted earthen liner and provide insights regarding boundary conditions that could be used to model contaminant transport through liners. Additional information regarding the transport and modeling of water and chemical tracer movement through the liner can be found in Toupiol et al. (2002) and Willingham et al. (2004).

Methods

During liner construction in 1987, a Siemens nuclear density meter was used to measure the postcompaction water content and density at eight locations on the surface of each lift (*ASTM D3017*). To calibrate the water content determined by the meter to conventional methods such as the gravimetric microwave oven (*ASTM D4643*) and conventional oven (*ASTM D2216*) methods, grab samples were collected at the same location as the meter measurements during construction of a prototype liner (Krapac et al. 1991).

During the experimental phase in 2000 (Toupiol et al. 2002;

Table 1. Geotechnical and Hydrologic Properties of Batestown Till (adapted from Krapac et al. 1991)

Property	ASTM standard	Value
Liquid limit	*D4318*	19.4–23.0%
Plastic limit	*D4318*	12.0–14.4%
Plasticity index	*D4318*	5.5–11.0%
Sand	*D422*	33.0–37.8%
Silt	*D422*	23.0–38.3%
Clay	*D422*	22.0–39.2%
Most abundant clay material		Illite
Hydraulic conductivity (cm/s)		7×10^{-9}–2×10^{-8}
Optimum water content, w_{opt}	*D698*	9.9–10.3%

[1]Chief of Design, US Air Force, 300 Miracle Strip Pkwy., Unit 1A, Ft. Walton Beach, FL 32548.

[2]Geochemist, Illinois State Geological Survey, 615 E. Peabody Dr., Champaign, IL 61820.

[3]Professor, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801.

[4]Graduate Engineer II, Minnesota Pollution Control Agency, 520 Lafayette Rd. North, St. Paul, MN 55155.

Note. Discussion open until November 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on September 30, 2003; approved on November 19, 2004. This technical note is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 131, No. 6, June 1, 2005. ©ASCE, ISSN 1090-0241/2005/6-800–803/$25.00.

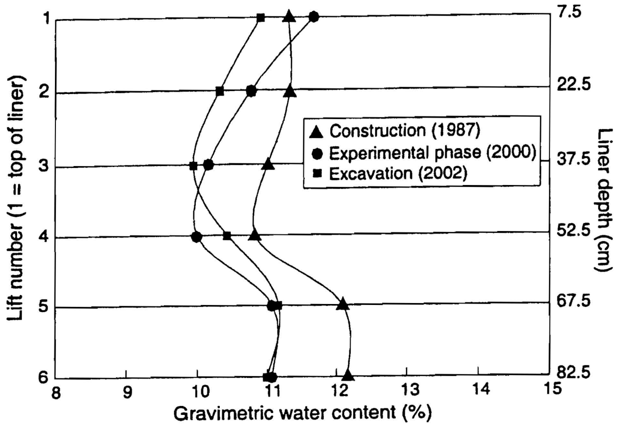

Fig. 1. Mean water contents at various depths in liner during three project phases

Willingham et al. 2004), 354 samples of liner material were collected using thin-walled sampling tubes driven into the liner with a hand-held drop hammer (*ASTM D1587*). To sample the 0.90 m liner depth, three 0.30 m core samples were taken at each location. During the excavation phase of the liner in 2002, grab samples were collected from three vertical faces that were exposed as a backhoe removed the liner. A total of 56 samples were collected at nine locations and various depths along the faces. Additional grab samples were collected during liner excavation by inscribing a 0.91 m by 0.69 m grid with 13 columns and ten rows on a vertical soil face of the liner. Soil density and water content were also determined during liner excavation using brass rings and a technique similar to the drive cylinder method (*ASTM D2937*).

Laboratory compaction tests using the reduced, standard (*ASTM D698*), and modified (*ASTM D1557*) Proctor methods were conducted to determine the relationship between the water content and dry density of the liner soil samples. These compaction tests were performed on soil material collected during liner excavation that passed a 9.5 mm (3/8 in.) sieve. The reduced, standard, and modified Proctor tests produced compactive efforts of 360, 600, and 2,700 kN m/m^3, respectively.

Results and Discussion

Water Content

During the construction phase in 1987, the mean water content for each lift ranged between 10.8±0.92 and 12.2±1.1%, and the overall mean water content of the liner was 11.4±1.0%. The mean water content for the entire liner during the experimental phase was 10.8±1.0% with individual lifts ranging from 10.0±0.70 to 11.6±1.2%. The mean water content of the liner during excavation in 2002 was 10.6±1.0% with individual lifts ranging from 10.0±0.58 to 11.2±0.76%.

The general trend in water content with respect to liner depth was similar during all phases of the project (Fig. 1). Although water infiltration has been documented (Cartwright et al. 1993), water content values among liner lifts, with the exception of lift 1, measured during construction were 0.4–1.2 percentage points greater than those measured during either the experimental or excavation phases.

The mean water content of the grid area transcribed over an exposed vertical face of the liner upon excavation was 10.5±0.78% (Fig. 2). The water contents of individual lifts in most cases were within 1.0 percentage point of the water contents measured by other methods during either the construction or experimental phases.

A comparison of the mean water contents for the various sampling times and locations at a 5% significance level indicated the differences are statistically significant; however, the data sets exhibited small variances (standard deviation <1%), which allowed the statistically significant results. Water content data were acquired using five different techniques during the course of the liner project, and it is likely that the variations in the water content data were caused by sampling techniques rather than by a change in soil characteristics over time. According to *ASTM Method D2216* (ASTM 1990), the precision of water content determinations of duplicate samples is between 7.8 and 14% depending on the equipment and inter- and intralaboratory comparisons. For all cases, the variation among the average water content values for the entire liner, regardless of sampling time and location, was less than the precision requirements, suggesting that the differences in water content were within the expected variability, and do not reflect significant differences in water content.

The soil moisture data showed that the water content of the liner did not significantly increase during the 14 years the liner was ponded even though water infiltration was documented. Values of soil tension remained small throughout the project, indicating that the liner may have been close to tension saturation from the beginning of the experiment; consequently, a distinct wetting front was not observed (Cartwright et al. 1993). Although drainage from the underdrain sytem was monitored throughout the entire project, little or no water was collected from the bottom of each quadrant of the liner (Cartwright et al. 1993). The intermittent and small volume of water discharged from some of the liner quadrants has been attributed to small changes in soil tensions in response to temperature and pressure changes in and around the liner (Cartwright et al. 1993). It is suspected that connective pores, which might have transmitted water through the liner, were saturated at liner construction, and there was not sufficient hydraulic pressure to force water into the unsaturated (less transmissible) pores (Hillel 1982). This resulted in an undetectably small change in liner soil water content over time as supported by the moisture data.

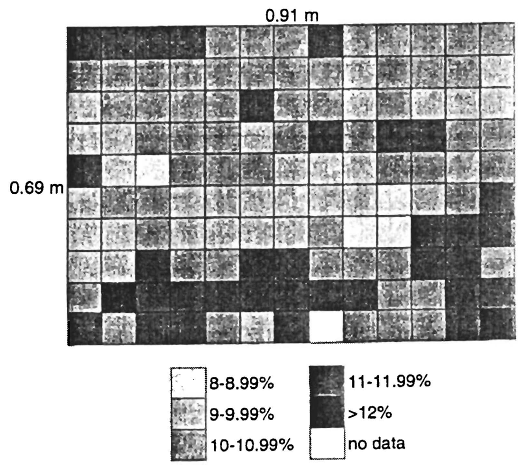

Fig. 2. Water content of grab samples collected from grid sampling of exposed vertical face of liner during excavation phase

Table 2. Mean Density Measured during Construction and Excavation Phases

Lift	Dry density at construction (kg/m³)	Dry density at excavation (kg/m³)	Change in dry density (%)	Moist density at construction (kg/m³)	Moist density at excavation (kg/m³)	Change in moist density (%)
1	1.83±0.065	1.99	8.7	2.07±0.074	2.21	6.8
2	1.88±0.039	2.00±0.044	6.4	2.09±0.040	2.20±0.039	5.3
3	1.81±0.068	2.01	11	1.97±0.062	2.20	12
4	1.77±0.041	2.05±0.034	16	2.00±0.045	2.26±0.012	13
5	1.87±0.067	2.00±0.018	7.0	2.09±0.080	2.22±0.015	6.2
6	1.85±0.095	2.02±0.037	9.2	2.04±0.11	2.24±0.048	9.8
Average	1.83±0.071	2.01±0.036	9.8	2.04±0.083	2.22±0.036	8.8

Density

The liner was constructed at a mean dry density of 1.83±0.071 kg/m^3, or about 92% of the optimum maximum dry density of 1.98 kg/m^3 based on the standard Proctor test (Krapac et al. 1991). During excavation, mean dry density for the liner was 2.01±0.35 kg/m^3, an increase of 9.8% after 14 years of ponding (see Table 2).

Since construction of the ISGS liner, Benson et al. (1999) have proposed compaction criteria that require at least 70–80% of the compaction field data lie on, or wet of, the line of optimums to ensure the construction of a low permeability compacted liner. The water content and dry density measurements of the ISGS liner determined during construction are summarized and compared to the compaction criteria based on the line of optimums and the zero air voids curve as applied to soil used for construction of the liner (Fig. 3). Compaction curves under three different compaction energies (reduced, standard, and modified Proctor) for soils obtained during liner excavation are shown in Fig. 3. The shaded area in Fig. 3 represents the acceptable zone based on the Benson et al. (1999) criteria. This zone ensures compaction at water contents wetter than optimum between the zero air voids and the line of optimums, and compacted to greater than 90% of the maximum standard Proctor density. This zone was constructed by using the zero air voids relationship and the line of optimums as the upper and lower bounds of the compaction criterion, a water content greater than optimum based on standard Proctor energy, and a dry density greater than 90% of the maximum standard Proctor density.

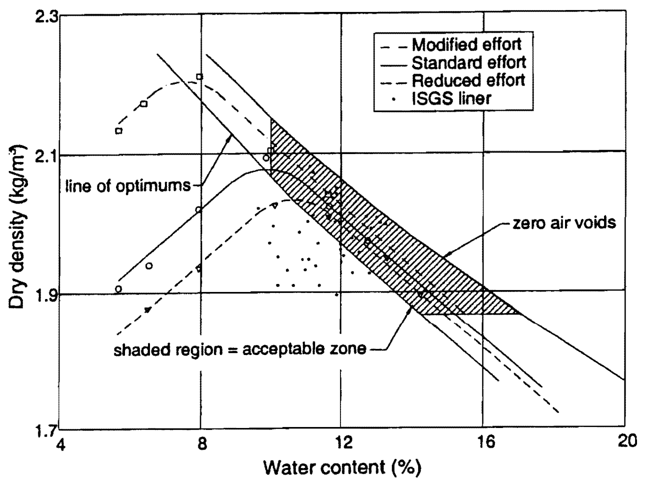

Fig. 3. Compaction criteria, compaction curves, and values of dry density and water content of liner samples

To properly represent the data and avoid discrepancies due to methods of data collection, the field data collected by the nuclear meter were adjusted by the ratio of the mean standard Proctor dry density to the mean nuclear meter dry density. When adjusted, 56% the data points measured by the nuclear meter fall within the acceptance zone. Although the percent of data points in the acceptance zone was slightly less than the suggested 70% by Benson et al. (1999), the liner was documented to have a saturated hydraulic conductivity $<10^{-9}$ cm/s (Krapac et al. 1991; Cartwright et al. 1993). In addition, all of the remaining data points met the construction specification of greater than 90% of the maximum standard Proctor density, although this is not the preferred construction criterion, because this specification does not ensure that compaction will be wet of the line of optimum.

During construction, the mean moist density of the liner was 2.04±0.083 kg/m^3. During excavation, the mean moist density was 2.22±0.036 kg/m^3, an increase of 8.8% (see Table 2). The similar trend between dry density and moist density over time further indicates that the water content did not significantly change. Earthen liner systems in landfills commonly have overburden material in the form of compacted waste and daily cover layers that provide a confining pressure on the liner material. Therefore, a liner with similar construction criteria and type of clays to the ISGS liner, but under landfill conditions, would be expected to exhibit a greater increase in density than was observed in the ISGS liner. The Batestown Till used to construct the liner contained 22% illite, a nonexpansive clay mineral. It was expected that the moist density of the ISGS liner would remain approximately constant throughout the project. The small increase in density may have resulted from compaction of the samples due to friction between the soil and the rings as the samples were collected during liner excavation.

Degree of Saturation

The degree of saturation of the liner at construction was 64.0±9.6%. Upon excavation, the degree of saturation was 80.0±6.3%, an increase of approximately 25%. The largest increase in degree of saturation occurred in the lower lifts rather than those lifts closest to the ponded water on top of the liner. This suggests that the change in the degree of saturation is likely due to the compression of air voids rather than the infiltration of air voids by water.

It was anticipated that the liner would approach saturation after being submerged for 14 years. Christiansen (1944) suggested that air becomes entrapped in soil packed columns regardless of whether water is applied from the top, bottom, or under a head. Christiansen also suggested that once a soil is wetted, as during liner construction, any air present in soil pores is completely immobilized and must be dissolved before it can be removed.

Bishop and Henkel (1962) showed that the back pressure required to dissolve entrapped air and saturate a triaxial compression specimen ranged from about 276 to 2,170 kPa for initial degrees of saturation of 95 and 70%, respectively. Because the initial degree of saturation of the ISGS liner was 64%, an applied hydraulic head of only 0.31 m (2.9 kPa) probably would not dissolve the entrapped air. Therefore, results indicating that the liner did not reach saturation after 14 years of ponding, although surprising, are not unexpected given the relatively small applied hydraulic head.

Conclusions

Excavation of the ISGS liner provided a unique opportunity to observe long-term changes in the geotechnical properties of a compacted earthen liner. Water content and density of the liner did not significantly change over time. Although the liner did not become fully saturated after 14 years of being submerged under a 0.31 m deep pond, the degree of saturation increased from 64 to 80% (a 25% increase) over that period. The increase in saturation can be attributed to a decrease in the volume of air voids.

Acknowledgments

The Illinois Office of Solid Waste Research (OSWR) and the National Science Foundation (NSF) Grant No. CMS 98-15242 provided funding for this project. The Illinois State Geological Survey provided additional support and funding. The writers would like to thank Renee J. Suarez for assisting with core sample collection and analysis. Wen June Sue provided geotechnical and liner material sampling advice. Dr. Jeffery Levengood provided statistical expertise. The writers also acknowledge the beneficial discussion with Thomas Willingham and the editorial assistance by Edwin Winzeler. Publication of this report is authorized by the Chief, Illinois State Geological Survey.

References

American Society for Testing and Materials (ASTM). (1990). "Standard test method for laboratory determination of water content of soil and rock by mass." *D2216*, Philadelphia.

Benson, C., Daniel, D., and Boutwell, G. (1999). "Field performance of compacted clay liners." *J. Geotech. Geoenviron. Eng.*, 125(5), 390–403.

Bishop, A. W., and Henkel, D. I. (1962). *The measurement of soil properties in the triaxial test*, 2nd Ed., Edward Arnold, London, 228pp.

Cartwright, K., Krapac, I. G., Panno, S. V., and Hensel, B. R. (1993). "Field study of transit time of water and tracers through a soil liner." *HWRIC RR-064*, Hazardous Water Research and Information Center, Champaign, Ill., 38pp.

Christiansen, J. E. (1944). "Effect of entrapped air upon the permeability of soils." *Soil Sci.*, 58, 355–365.

Hillel, D. (1982). *Introduction to soil physics*, Academic, Orlando, Fla., 364pp.

Krapac, I. G., Cartwright, K., Hensel, B. R., Herzog, B. L., Larson, T. H., Panno, S. V., Risatti, J. B., Su, W., and Rehfeldt, K. R. (1991). "Construction, monitoring, and performance of two soil liners." *Environmental geology 141*, Illinois State Geological Survey, Champaign, Ill., 118pp.

Toupiol, C., Willingham, T. W., Valocchi, A. J., Werth, C. J., Krapac, I. G., Stark, T. D., and Daniel, D. E. (2002). "Long-term tritium transport through a field-scale compacted soil liner." *J. Geotech. Geoenviron. Eng.*, 128(8), 640–650.

Willingham, T. W., Werth, C. J., Valocchi, A. J., Krapac, I. G., Toupiol, C., Stark, T. D., and Daniel, D. E. (2004). "Evaluation of multidimensional transport through a field-scale compacted soil liner." *J. Geotech. Geoenviron. Eng.*, 130(9), 887–895.