RELATIONSHIP OF LABORATORY AND FIELD DETERMINED HYDRAULIC CONDUCTIVITY OF A COMPACTED CLAY LAYER

A field scale compacted clay layer was constructed with a number of instruments to measure infiltration, drainage and other clay properties. The field instrumentation was used to collect data from the compacted clay layer and was compared to data obtained from laboratory testing of cores obtained from the compacted clay layer.

Outflow from below the compacted clay layer was collected and measured in 250 evenly spaced drains. Data obtained showed that although the water content and the density of the compacted clay liner were close to design specifications, infiltration and drainage rates were not. Laboratory permeability testing of cored specimens underestimated the field hydraulic conductivity by a factor of 5.

Tracer testing with bromine tracer was conducted to determine breakthrough times at respective drains. Observed breakthrough timers were most likely the result of short-circuiting through macro pores as laboratory hydraulic conductivity data showed expected breakthrough to be several years. Field breakthrough test results showed that over 44% of the site, flow occurred through less than 1% of the area.

Test data has shown that although a compacted clay layer is constructed to design specifications, field performance is not always predicted from laboratory test data. Considerable variability in the compacted clay layer and preferential flow pathways may have contributed to the increased flow rates though the clay matrix.

TR-201
Revised 12/00

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Environmental Protection
Agency

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TR-201

Research and Development

EPA/600/S2-90/025 Sept. 1990

EPA

Project Summary

Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Layer

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A field-scale research facility was constructed to evaluate hydraulic conductivity of a compacted clay liner. The facility was instrumented at a number of points to measure infiltration, drainage, and properties of a clay liner. Design and instrumentation of the facility were based on results from the prototype studies. Preliminary small scale studies have shown that any perforation of the compacted clay may result in a preferential water flow pathway. To avoid this situation in the field, changes in density and porosity were monitored horizontally across the facility. Outflow from below the compacted clay was collected in 250 evenly spaced drains, and infiltration rate was measured in an equal number of buffered infiltration cylinders. Very small changes in elevation were measured with a laser beam apparatus to evaluate the extent of swelling. Data obtained during the clay liner construction showed that although the average water content and density of compacted clay were close to design specifications, spatial variability of values was large. Infiltration and drainage rates observed following ponding were poorly predicted by the prototype studies. The experimental clay liner was ponded for 1 yr. During that time inflow, outflow, and changes in density were monitored at 250 locations. Flux density values, computed from observed infiltration and outflow measurements, were compared with effective flux density values that were based on breakthrough time distributions for water and tracer. Results suggested that both water and tracer can move considerably faster than expected through only a small fraction of the total pore space. A ranked distribution of laboratory values underestimated field distribution of hydraulic conductivity by a factor of 5. However, paired values from the same location differed at times by several orders of magnitude. Although the core samples and nuclear surface moisture density probe data adequately described spatial distributions of water and density within the compacted clay, neither water content nor density appeared to be correlated in any way with the spatially distributed hydraulic conductivity. One possible reason for the above lack of correlation appeared to be a rapid breakthrough of water and tracer through a network of preferential flow pathways dominating flow and transport.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Objectives

The purpose of this study was to evaluate spatial distribution of field-observed hydraulic conductivity in a clay liner constructed to engineering specifications and to compare it with laboratory values determined on cores.

The specific objectives of this study were:

(1) to document the state-of-the-art of the in situ hydraulic conductivity determination on compacted clay soils,
(2) to construct a field-scale test plot area of recompacted clay, install permeability measuring devices, and determine the in situ hydraulic conductivity with the use of selected permeants, verifying that accurate data can be obtained, and
(3) to compare field hydraulic conductivity data with those obtained on laboratory cores to determine whether significant lack of agreement in values exists, and if so, to evaluate the factors responsible.

The initial part of this effort included a general literature survey and methods evaluation (Phase I) aimed at selecting appropriate field-scale procedures to measure the hydraulic conductivity of a compacted clay liner. Particular emphasis was placed on reports addressing cohesive soils, undisturbed sample sites, and relatively large surface areas, and on reports describing methods that could provide data within a reasonable time frame. In Phase II, field apparatus and prototype liner were designed and tested for accuracy and performance. In Phase III, which is summarized here, a field-scale facility was constructed and a clay liner was compacted according to standard procedures and ponded. After completing the field phase, core samples were removed from the site for laboratory determination of the hydraulic conductivity.

Methods

The clay liner testing facility consisted of an elevated, bridge-like platform supported by reinforced beams resting on compacted level subgrade. In a crawl space under the platform, percolate was collected. The floor of the platform was sealed, and a bead of bentonite was placed 3 ft away from the sidewalls on the floor to separate any wall flow from the rest of the leachate. Three 6-in. thick layers of the clay material were compacted to 4-in.-thick lifts following the procedure developed on a construction test plot; the finished liner was then 12 in. thick. Construction test plot trials indicated that if a sheepsfoot roller were used on the first lift it could dent the bottom set of aluminum access tubes imbedded in the platform deck. Consequently, the first lift was spread very carefully with a backhoe, moistened with a known amount of water necessary to bring it to wet of optimum, tilled with rototillers, sampled for moisture, and compacted in place with a dozer and smoothfaced roller. Surface probe readings of water content and density at 36 locations indicated that the desired compaction had been achieved. The first lift was scarified with dozer treads, and the next lift was spread in a similar manner. Moistening, tilling, and sampling were followed by compaction with six to seven passes of the dozer and sheepsfoot roller and with a pass of the smoothfaced roller before moisture and density were sampled. After the surface was scarified, the same procedure was used for the third and final lift. During the construction phase on lifts 2 and 3, the dozer tended to compact the clay during spreading and make it difficult to rototill; compaction equipment could not approach any closer than a foot from the sidewalls. These problems were addressed by a more intensive but slower rototilling and by the use of a small vibrating roller near the sidewalls and an electric jackhammer right next to the sidewall. Although the degree of compaction near the sidewalls was judged to be near that obtained over the remainder of the area, a detailed analysis of core samples indicated considerably lower values of density next to the sidewalls. Subsequent examination of the completed liner cross section revealed no obvious flaws or planes of discontinuity among the three lifts. A grid of collection drains under the compacted clay was complemented by a grid of 11-in.-diameter buffered infiltration cylinders at the surface.

Twenty-four horizontal aluminum tubes were embedded in the floor of the platform to provide access for the transmission-gamma-probe used to measure density. After the liner was compacted, 24 upper access tubes were positioned on the clay surface exactly 1 ft above the lower ones. The density was computed from gamma attenuation made with a source (Cs^{137}) in the lower tube and the detector in the upper tube.

A wooden walkway resting on upper access tubes was constructed, and the facility was covered over with a building; heat and light were installed. To correct infiltration for evaporation, 35 11-in.-diameter evaporation pans and one large, class-A evaporation pan were placed on the clay surface. In addition, 35 square metal pedestals were also positioned on top of the liner to monitor swelling. The floor of the platform was covered with burlap and a thin layer of coarse sand. After the liner was installed, a 1-in. layer of coarse sand was placed on the surface to minimize evaporation. Clay soil used for the liner was a B-horizon of a commercially available cherty silt loam. It is classified as a CL type brown till with laboratory permeability of less than 1 x 10^{-7} cm/sec. Prototype studies suggested that some swelling was to be expected after ponding. The clay was purchased from a supplier and trucked to the site where the experimental liner was to be constructed. The clay materials were of variable quality and water content and contained some very large clods (≥ 6-in.). Standard Proctor test results at 18% water content gave a projected maximum bulk density of 110 lb/cu ft(pcf). Collection of density data began immediately after the liner was constructed and the upper set of access tubes was installed. The liner at 18% water content and compacted to 110 pcf was far from saturated (60%). Monitoring the density before and after ponding was designed to account for evaporative losses before the ponding and the rate at which the liner wetted after ponding. Highest density was observed in the central portion of the site. The dual probe density values before ponding differed by a factor of 0.9 from surface probe density values observed during the construction of individual lifts. A matrix of constantly changing, spatially distributed, dual probe density was used to compute a matrix of total available pore space and a matrix of the amount of water needed to saturate the liner before and during the different times after ponding. Observed changes were indicative of the proportion of infiltrating water either diffusing into the clay matrix or passing through the larger pores. The water level on the liner was maintained with an automatic constant head tank and the infiltration in the individual (250) rings was monitored by measuring water loss from constant head bottles. Tubing from individual drains was routed to the perimeter of testing facility platform, where percolate was collected in conveniently sized containers. Readings of water level change in evaporation pans gave the corrections to infiltration data.

Results

Collection of infiltration, leachate, and evaporation data began immediately after ponding (3/85). Initially, the data expressed as flux were collected on a daily basis, later on a weekly or longer-interval basis. Soon after the start it became apparent that the infiltration cylinders and leachate drains situated next to the sidewalls in the lower density zones were responsible for a large portion of the infiltration and drainage. The leachate from all drains near the sidewalls was therefore isolated, combined into one, and measured separately from the central matrix of 184 individual rings and drains that represented the area compacted with sheepsfoot roller.

A rapid increase in density after ponding followed by a more gradual rise over the next 9 mo was indicative of progressive saturation. Although at the time of ponding, the average water content was 18.1% by eight, the water content after the liner was drained and covered with plastic averaged 18.5%. A gradual increase in density continued through the first 9 mo, and about the time the drains were vented, the readings stabilized.

Infiltration rings were activated in stages. Changes in infiltration were first measured with a form of a hook gage and Mariotte constant head bottles—first by volume and ultimately, as the infiltration rates became slower, by weighing. Faster infiltration rates were observed near the side walls in lower density material. Before the liner was drained, fluorescein was introduced into all the rings to check for leaks, and nontoxic daylight fluorescent water color was added to mark potential flow pathways when rings were excavated or when the surrounding area was cored.

The assumption under which the results were analyzed was that a distribution of infiltration rates was represented by individual ring inflow rates, and the distribution of outflow flux was given by the individual drain outflow. The observed variability was assumed to be a function of soil properties as well as spatial distribution of the preferential flow pathways. Hydraulic conductivities based on inflow and outflow data were not significantly different from one another; both, however, were significantly lower than hydraulic conductivity based on the initial infiltration values. The outflow flux appeared to be the best description of clay liner performance. Tracer tests with Br- were carried out towards the end of the study, whereas water breakthrough times, given as first arrival of water at the respective drains, were recorded immediately following ponding. Bromine was chosen as a tracer because of its conservative behavior and low background concentrations.

Tracer breakthrough, given as the first arrival of tracer at the principal drain or one of the surrounding drains, originated from a centrally positioned infiltration ring. Water breakthrough, however, was a result of ponding the entire facility, and outflow was from a much larger area surrounding each drain. In either case, the clay was not fully saturated. Initial water content distribution corresponded to a 100 Pa tension, and water content after the water was drained was no more than 3% higher throughout. Under these conditions, observed breakthrough times would most likely be a result of short-circuiting flow through the macropores since breakthrough times based on laboratory hydraulic conductivity values for a 1-ft thick clay liner would be expected to be several years.

The considerably shorter breakthrough times observed for water and tracer suggest relatively low effective porosity. Results showed that over 44% of the site, flow took place through less than 1% of the area. At a few locations, however, flow may have occurred through 10% or more of the local cross sectional area despite the assumed uniform compaction and water content of the clay liner material. Results suggest that a seemingly uniform clay liner is, in fact, a highly variable one with an effective porosity that can range from a low of 0.1% to more than 5%.

Subsequent coring (with a Veihmeier tube*) of the tracer application area and surrounding sites on the 0.3-m grid and qualitative tests for the tracer corroborated preliminary observations. On sites where little tracer was lost as leachate, strong evidence of tracer showed in corings as a tight, well-defined "plume" surrounding the infiltration ring to which tracer had been added. For sites where much tracer was lost, however, the distribution plume was quite extensive but rather diffuse throughout the area of nine drains. Percolate quality appeared somewhat related to hydraulic conductivity, degree of saturation, and number of pore volumes of percolate.

One possible source of fluctuations in inflow, outflow, and bulk density as well as tracer concentration could be the swelling of randomly distributed montmorillonite clay minerals within the liner matrix on wetting and possibly moderate shrinkage as a result of consolidation and piping in zones of lower compaction. The mineral composition of the clay liner material was primarily illite and kaolinite with some montmorillonite. Thus, although swelling could not be ruled out, little was expected.

After the excess ponded water was removed and the clay liner drained, several studies were initiated to check or corroborate observations made during the ponded stage. To complement detailed inflow/outflow data for all ring/drain combinations, 3-in.-diameter cores were removed from the center of each ring infiltrometer by using a standard, split-tube sampler. The central portion, or the most homogeneous portion, of each was trimmed for use in laboratory analysis of saturated hydraulic conductivity.

In addition, a large number of 2-, 3-, and 6-in.-diameter cores were taken for comparison with and calibration of the dual gamma measurements of density, for evaluation of changes in density with depth, and for the assessment of the extent and distribution of coarse fragments within the clay liner. With the use of nuclear surface probe, a set of surface moisture measurements, as well as surface and direct transmission density measurements at 2, 4, 6, and 8 in. were made to be compared with the initial surface probe readings made during the construction. When the water had drained from the liner, vertical access tubes were installed at 45 locations from which 2-in. cores had been previously removed, and 45 gypsum moisture blocks were placed 3 in. below the clay surface. Monitoring change of the liner water content began and continued on a regular basis for about 18 mo until the liner was broken up, inspected, and removed from the site.

The laboratory hydraulic conductivity analysis was carried out on 3-in.-diameter cores varying in length from 2-7/8 to 6 in. depending on the number of sections the original core was divided into and on how well a refrigerated core segment could be trimmed to fit in the apparatus. Because of stones imbedded in the clay matrix, this was, at times, difficult. Initially, only the most homogeneous portions of the original core were selected for analysis.

Conclusions and Recommendations

A clay liner was constructed from the B-horizon of a typical soil that met normal engineering specifications. In the course of analysis, the soil was found to contain a larger than expected number of coarse fragments.

The considerable variability, which existed in the spatially distributed flow in the compacted clay matrix, may have affected the rate, quality, and pathway of leachate flow through the clay liner.

A sand layer on top of the clay liner acted as a moisture barrier and prevented rapid drying.

Higher flow rates, which originated in apparently unsaturated areas, suggested the presence of the preferential flow pathways.

There was no correlation between laboratory and field-derived values of hydraulic conductivity on the point-to-point basis when values from the same locations were compared. When, however, the distribution of laboratory values was compared with the distribution of field values, the results appeared to be linearly correlated.

Laboratory hydraulic conductivity values were not a good indicator of the clay liner behavior. Ring infiltrometers, despite problems, appeared to provide better estimates of potential outflow from below the compacted clay. Best estimates of clay

* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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liner performance were obtained by following the conservative tracer (Br-) movement and by breakthrough history.

Little or no change in clay liner density with time suggested a very limited movement of water into the clay matrix after the clay was compacted. The largest amount of change, which occurred just after flooding, could be indicative of the extent of macroporosity. A surface moisture-density probe in a direct transmission mode was found to be a quick and satisfactory method of determining field distribution of moisture and density in shallow lifts. No relationship was observed between density and water content of the clay and the values of hydraulic conductivity.

The flow regime consisted of concurrent alternating, filling, and draining episodes distributed throughout the space occupied by the compacted soil mass.

Results from preliminary studies have shown that any perforations of the compacted clay can result in preferential water movement along these access points. Infiltration and drainage rates from field scale facility were poorly predicted by the small-scale studies.

Because the amount of available pore space in well compacted clay is very small, even a small change may have disproportionately large effects, i.e., minimal swelling of about 2.4 mm could account for as much as a 20% increase in available pore space.

About one-tenth as many samples were needed to characterize the compacted clay liner density and water content as were needed to characterize hydraulic conductivity with the same degree of precision. Considering that hydraulic conductivity per se did not appear to be the primary controlling factor in the flow and breakthrough of water and tracers in the compacted clay liner, more effort is needed to characterize possible distribution of preferential flow pathways.

The full report was submitted in fulfillment of Interagency Agreement No. DW 12930303 between the Agricultural Research Service, U.S. Department of Agriculture and the U.S. Environmental Protec-

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The complete report, entitled "Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Layer," (Order No. PB 90-257 775: Cost $31.00, subject to change) will be available only from:
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