United States
Environmental Protection
Agency

Research and Development

Risk Reduction Engineering
Laboratory
Cincinnati, OH 45268

EPA/600/S2-91/022 July 1991

EPA

Project Summary

State-of-the-Art Field Hydraulic Conductivity Testing of Compacted Soils

Joseph O. Sai and David C. Anderson

The congressionally mandated performance standard for soil liners of hazardous waste management facilities is a hydraulic conductivity of 1 x 10^{-9} m/s or less. In response to this statutory requirement, the U.S. Environmental Protection Agency (EPA) has issued guidance requiring that facilities demonstrate this hydraulic conductivity in field tests.

Hydraulic conductivity test methods currently used on soil liners were evaluated for their ability to meet the minimum requirements for field tests, i.e., that the test be capable of measuring hydraulic conductivities of 1 x 10^{-9} m/s or less and that the values obtained be representative of the overall soil liner. Few methods are capable of meeting these minimum requirements, and even fewer are both practical to use and rarely give false low values. Based on the advantages of all the methods evaluated, the best and most practical currently available technologies for evaluating hydraulic conductivity are large single-ring infiltrometers and sealed double-ring infiltrometers. If correction factors are needed to bring the values obtained with single-ring devices to below 1 x 10^{-9} m/s, confirmatory tests should be conducted with sealed double-ring infiltrometers.

The size of infiltrometers used on soil liners should be at least 2 m^2. In addition, at least three separate tests should be conducted on each test fill to allow characterization of the spatial variability in the soil liner.

A long-term study is needed to allow a comparative evaluation of candidate hydraulic conductivity testing devices. A large collection lysimeter should be incorporated into the study to give the true overall hydraulic conductivity value with which other values should be compared.

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).

Introduction

In the Hazardous and Solid Waste Amendments (HSWA) of 1984, the Congress of the United States mandated that where compacted soil liners are used, their hydraulic conductivity shall be 1 x 10^{-9} m/s or less. In response to this statutory performance standard, EPA issued guidance requiring all proposed soil liners in hazardous waste management facilities to demonstrate this hydraulic conductivity in field tests. The intent of this requirement was to obtain accurate and realistic evaluations of how the compacted soil liner would perform under field conditions. Numerous studies have demonstrated that values obtained in laboratory hydraulic conductivity tests are not reliable indicators of the performance of soil liners under field conditions. No single study has been conducted, however, to document the range of field hydraulic conductivity test methods capable of adequately evaluating the field performance of a compacted soil liner.

Field hydraulic conductivity tests can damage soil liners in several ways. Damage can occur in the form of holes drilled or trenches cut in the liner to facilitate the installation of testing equipment. Also, because field hydraulic conductivity tests can take as long as several weeks to complete, both climatic events and weathering processes can substantially damage a soil liner. Consequently, the EPA has recommended that field hydraulic conductivity tests be conducted on a test fill. Both the test fill and the hydraulic conductivity tests used on the test fill should provide a sound basis for meeting the following objectives:

1) Accurately measuring hydraulic conductivities of 1×10^{-9} m/s and lower.
2) Obtaining hydraulic conductivity values that accurately represent the properties of the full-scale soil liner.

The hydraulic conductivity values obtained must be representative of the full-scale soil liner. The representative elementary volume (REV) of a soil liner is the smallest volume above which the variance no longer decreases significantly. A REV will be different for every liner and be highly dependent on the natural variability of the soil material and the level of quality assurance exercised during construction of the soil liner. At least three field hydraulic conductivity tests will be required to define the REV for a given soil liner.

The available field hydraulic conductivity test methods for soil liners discussed herein are currently used and readily available for determining the hydraulic conductivity of soils compacted in the field.

Field Hydraulic Conductivity Methods

A wide variety of field hydraulic conductivity methods have been published in the scientific and engineering literature. Many of these methods are not adequate for evaluating soil liners because they can neither measure very low hydraulic conductivities nor evaluate a large enough area to give values representative of the overall liner. Other methods are adequate to obtain representative values on low hydraulic conductivity soils, but they are complex and time consuming or require a large amount of time from skilled equipment operators.

Air-Entry Permeameters

Air-entry permeameters give rapid field measurements of vertical hydraulic conductivity in initially unsaturated soil. This method uses Darcy's fundamental law for water flow through soil to determine soil hydraulic conductivity above a water table.

The air-entry permeameters method can rapidly measure field hydraulic conductivity values as low as 1×10^{-9} m/s. One hour or less is needed to run the test, depending on the temperature of the water and the hydraulic conductivity of the soil. A major shortcoming of this method, however, is that it tests only small areas of soil (0.3 m^2) and therefore may not reflect the effect of soil macropores on hydraulic conductivity. Soil macropores that are widely spaced in a soil liner can have pronounced effect on hydraulic conductivity.

Air-entry permeameters can be used to obtain the vertical hydraulic conductivity of one lift in a compacted soil liner or the entire thickness of soil liner. The data may be inaccurate, however, either because of inadequate sealing between the cylinder and the soil or because of errors in determining the exact locations of the wetting front. Air-entry permeameters are easy to transport and to use. Also, the method is not labor-intensive (two men can set up the equipment and make the measurements).

Borehole Methods

Several borehole methods have been used to measure the hydraulic conductivity of soils. Borehole permeameters are essentially in-hole constant-head or falling-head permeameters. The methods involve measuring the steady-state infiltration rate of water into unsaturated soil from a cylindrical borehole. Two borehole methods that have been used to test the hydraulic conductivity of soil liners are Guelph and Boutwell permeameters. The Guelph permeameter uses a Mariotte siphon to maintain a constant head of water within the borehole. The Boutwell permeameter involves an evaluation of the flow into a cased borehole and an evaluation of subsequent flow after an uncased extension has been added to the hole.

Guelph permeameters have not been widely used to determine hydraulic conductivity on compacted soil liners. Studies conducted on low hydraulic conductivity soils indicated, however, that the instrument is capable of measuring values as low as 2×10^{-9} m/s. The Guelph permeameter only evaluates a small area of soil (3×10^{-4} to 2×10^{-3} m^2). For this reason, the method is unlikely to give values that are representative of the overall field hydraulic conductivity.

Boutwell permeameters can measure hydraulic conductivities of 1×10^{-9} m/s and less. The volume of soil tested in a single borehole, however, is relatively small. Because of the small size of the test area, soil macropores and other flaws in soil liner construction may be missed with this method. As a result, hydraulic conductivity determined by this method may not be representative of the actual field value.

Multiple tests could be conducted to evaluate a larger aggregate area. For several reasons, however, running many small tests may not achieve the desired test objective of obtaining a representative measure of the field hydraulic conductivity. For example, even if many tests were conducted, the small scale of each individual test would greatly increase the probability that through-going macropores would be truncated. Such truncation of through-going macropores would significantly reduce the hydraulic conductivity below the actual field value. Other problems include the large amount of potential smearing per unit volume of soil and the difficulty that may be encountered in distinguishing between defective test results and results reflecting the value of a small area of liner with a macropore.

Porous Probe Permeameters

Porous probe permeameters typically consist of a cone-shaped porous probe that is either pushed or driven into the soil. One such commercially available porous probe, the BAT permeameter,* can measure hydraulic conductivities of 1×10^{-9} m/s or less. Because of the small volume of soil tested by the BAT permeameter, the method is unlikely to yield values consistently representative of the overall hydraulic conductivity of the soil being tested.

Ring Infiltrometers

In ASTM Method D 3385, double-ring cylinders are used to determine the rate of infiltration of water into soils. This method has been widely used for more than a decade for the evaluation of both percolation rate in septic fields and infiltration rate in soils to be irrigated. Two open cylinders, one inside the other, are driven into the soil and partially filled with water. A constant water level is maintained on the soil by continuously adding water. The volume of water added in a given period is used to determine the rate of infiltration.

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

The ASTM double-ring infiltrometers should not be used to measure infiltration rates on compacted soil liners. This method is both difficult to use and unreliable in soils with a hydraulic conductivity less than about 1 x 10^{-8} m/s. Also, loss of water due to evaporation may be higher than the quantity of water permeating the soil.

Modifications have been made to the basic ASTM double-ring infiltrometer to make it more sensitive for measuring low infiltration rates. These modifications include the use of a large outer ring and sensitive devices for measuring water level. With these modifications, the ASTM double-ring device has been used to measure infiltration rates of 9.7(± 8.1) x 10^{-10} m/s. The ability of the test to obtain representative values is questionable, however, because of the relatively small size of the inner ring (0.3 m in diameter). Macropores that can affect the infiltration rate by orders of magnitude could have a wider average spacing than the diameter of the inner ring.

Box infiltrometers use a sealed box and a relatively complex standpipe arrangement to measure infiltration into soil in a 0.36-m^2 area. They have been used to measure hydraulic conductivities as low as 5 x 10^{-10} m/s.

A single-box infiltrometer coverage (0.36 m^2) is not sufficient to determine the overall field hydraulic conductivity. One study of box infiltrometers used arrays of four to allow definition of both the overall field hydraulic conductivity and the spatial variability of the liner. The aggregate area evaluated by the infiltrometers (1.44 m^2) appeared to be sufficient to obtain representative hydraulic conductivity values. The test site was small (8 m^2), however, and it required greater effort per unit area to produce a uniform soil liner than is typical for full-scale liners. Consequently, although an aggregate area of 1.44 m^2 may have been sufficient to characterize the spatial variability of the test site, a larger area probably would have to be tested under conditions more typical of full-scale liners. The box infiltrometer is relatively difficult to use and would definitely require skilled personnel to install, monitor, and collect and analyze data.

A single-ring infiltrometer consists of a metal cylinder (20 to 60 cm in diameter), which is pressed or driven into the soil (Figure 1). Infiltration is measured by ponding water inside the cylinder and then (1) measuring the rate at which the free surface falls, or (2) measuring the rate at which water must be added to maintain a constant depth in the cylinder.

Large single-ring infiltrometers can measure hydraulic conductivity values as low as 1 x 10^{-9} m/s. If the ring is of sufficient diameter, the hydraulic conductivity values obtained should be representative of the overall soil liner. Until there is a definitive data base documenting the minimum ring diameter needed to obtain these representative values, a total area of at least 2 m^2 within the ring is recommended.

Errors can be introduced into the hydraulic conductivity values as a result of lateral flow and evaporative losses. There is no danger of falsely concluding that a soil liner meets a specific performance standard, however, as long as the uncorrected hydraulic conductivity values are less than 1 x 10^{-9} m/s. If a correction factor must be used to reduce hydraulic conductivity below 1 x 10^{-9} m/s, additional tests should be conducted with either a double-ring infiltrometer or by using measures to eliminate evaporative losses.

Single-ring infiltrometers have the advantage of being simple and inexpensive. Care should be taken, however, to make sure that thermal expansion of the water does not yield false low values. Other possible sources of false low values are the interception of rainfall by the open ring or incorrect calculation of the hydraulic gradient. These sources of error can be avoided by using a sealed ring and a free-draining layer beneath the known thickness of a soil liner, respectively.

Sealed double-ring infiltrometers (SDRI) use a sealed ring or box that measures infiltration into a relatively large area. The SDRI has a sealed inner ring that permits measurement of low infiltration rates and minimizes problems with temperature fluctuations and evaporation. It is relatively easy to operate, but as with all infiltration ring devices, it must be carefully installed to ensure that no leakage occurs around the edges.

The SDRI consists of an inner ring and an outer ring (Figure 2). The fiberglass inner ring has a sloped top that extends only 12 cm above the liner surface, and the outer ring is used to pond water around the inner ring to ensure only vertical percolation is measured. Flow is measured during an infiltration test by using a flow-measurement bag attached to the infiltrometer. Any water flow out of the infiltrometer into the ground is replaced by water from the bag. Flow measurement is initiated by filling the bag with a known weight of water, connecting it to the infiltrometer, and periodically retrieving and reweighing it.

The SDRI can measure hydraulic conductivities of less than 1 x 10^{-9} m/s. The SDRI also is available commercially in a relatively large size (the inner ring covers an area of 2.3 m^2). Tests conducted with SDRI's appear to confirm that the equipment can yield values representative of the overall soil liner.

Although SDRI tests require more installation time than many methods, periodic recording of time and measuring bag weight are the only tasks performed after the equipment is installed. The SDRI appears to yield high quality data with few possibilities for yielding false low values.

Collection Lysimeters

Collection lysimeters are placed beneath the compacted soil liner to collect liquid percolating through the liner. A pipe is often installed at the low end of the lysimeter to collect and move any accumulated liquid to an access point where the liquid can be measured. Lysimeters have been used to monitor the quantity and quality of the leachate from landfills in Wisconsin and Canada.

Collection lysimeters can measure hydraulic conductivities of less than 1 x 10^{-9} m/s. If large enough, lysimeters can also yield hydraulic conductivity values that are representative of the overall soil liner. One study showed a 19.4-m^2 collection lysimeter to be large enough to yield representative values. The main drawback of this method is that it can take months to obtain steady-state hydraulic conductivity values. Unlike infiltrometers, which give initially high values that decrease to a low steady-state value, collection lysimeter values typically begin very low and gradually build up to a higher steady-state value. Consequently, the testing period may well interfere with facility construction and the adequacy of a particular soil liner design may not be known until the end of a long test period.

Tests comparing collection lysimeters and large infiltrometers have shown that values are relatively close. Therefore, if a collection lysimeter is desired, concurrent testing of the soil liner with large infiltrometers is suggested. This procedure could save months of waiting for results definitive enough to begin construction of a facility.

Constructing a collection lysimeter is time-consuming and requires skilled personnel. Special care must be taken to avoid damaging the material from which it is constructed underlying the collection field. Because such damage could result in false low hydraulic conductivity values, concurrent testing of the soil liner with large infiltrometers is recommended. Ultimately, a large collection lysimeter has

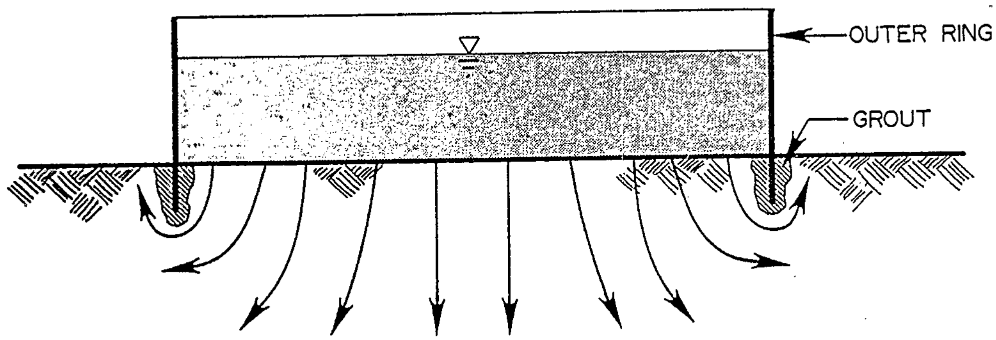

Figure 1. Open Single-Ring Infiltrometer.

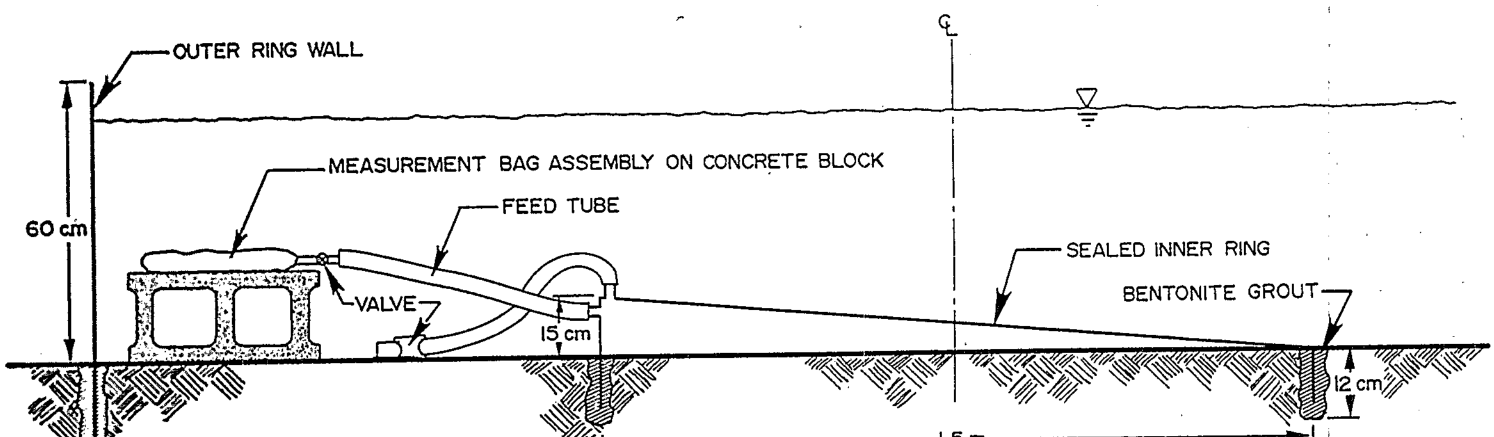

Figure 2. Schematic of a Sealed Double-Ring Infiltrometer. (Modified from Elsbury et al. 1988).

the potential for yielding the most accurate values for quantification of the volume and rate of liquid that moves through a compacted soil liner. In practice, however, the response time of a lysimeter limits its utility for short-term tests.

Other Apparatus

The applicability of both velocity permeameters and porous plate infiltrometers for measuring the hydraulic conductivity of compacted soils is being studied. Current data are not sufficient to determine the adequacy of either method, but both methods show promise.

Various methods are also available for obtaining the hydraulic conductivity of soil cores in the laboratory. Laboratory methods generally do not provide a reliable indicator of field performance of clay liners.

Laboratory hydraulic conductivity tests can measure very low hydraulic conductivity values; however, using these values to represent field conditions presents several problems. Because laboratory samples used to determine hydraulic conductivities are typically too small to have a representative distribution of the macropores present in the field, the values derived are one to three orders of magnitude lower than the actual field values.

Conclusions

Widely varying methods are currently being used to evaluate the field hydraulic conductivity of soil liners. Only a few of these methods, however, can reliably meet the following requirements for evaluating soil liners:

1) A method should be capable of accurately measuring hydraulic conductivities of 1×10^{-9} m/s and lower.

2) The values obtained should be representative of the overall hydraulic conductivity of a soil liner.

Of the few methods capable of meeting these requirements, even fewer are relatively simple to use, rarely give false low values, and provide definitive results in a reasonable time frame. Key findings of each method evaluated are summarized here.

Air-entry permeameters, velocity permeameters, porous plate infiltrometers, borehole methods, and porous probe methods, can give rapid field measurements of vertical hydraulic conductivity, but they may not test a large enough area to give values representative of the overall soil liner. The ASTM double-ring infiltrometers use an outer ring to ensure that the inner ring measures only the vertical hydraulic conductivity of a soil. This method cannot measure hydraulic conductivity values of less than 1×10^{-8} m/s or obtain values representative of an overall soil liner. The primary disadvantages of box infiltrometers are that they are difficult to use and that skilled personnel would definitely be required for installing, monitoring, and collecting and analyzing data.

Single-ring infiltrometers should cover an area of at least 2 m^2 and care should be taken not to rely on correction factors to reduce the hydraulic conductivity values below 1×10^{-9} m/s. Sealed double-ring infiltrometers have received substantial field testing and have a demonstrated capability of measuring hydraulic conductivity values below 1×10^{-9} m/s and of obtaining values representative of the overall soil liner. The method requires more installation time than many methods, but it has the advantages of few ambiguities in the experimental method and few possibilities for yielding false low values. Collection lysimeters can be time-consuming and may require skilled personnel. Ultimately, this method has the potential for yielding the most accurate values for hydraulic conductivity of a soil liner.

Recommendations

To maximize the probability of obtaining a hydraulic conductivity value that is representative of the overall soil liner, a test method should have the following qualities:

1) The ability to measure hydraulic conductivities of less than 1×10^{-9} m/s.

2) Minimal requirements for skilled personnel during installation, operation, data acquisition, data reduction, and interpretation of results.

3) Few ambiguities in the experimental method and few possibilities for yielding false low values.

4) Inexpensive enough to allow at least three replicate tests to determine spatial variability of field hydraulic conductivity.

5) Sufficient area of coverage for each replicate test to ensure that a statistically sound average number of macropores per unit area is covered.

6) Sufficiently short time required to conduct each test to ensure that it is practical for use.

Not all of these qualities are quantifiable, given the current state of knowledge on hydraulic conductivity test methods and soil liners. It is possible, however, to pinpoint where additional study is needed and to suggest the best currently available methods.

For a better definition of the test methods that would maximize the probability of obtaining representative hydraulic conductivity values for soil liners, a long-term soil-liner study is recommended that would incorporate a large collection lysimeter (to give true overall hydraulic conductivity) and arrays of candidate hydraulic conductivity testing devices. The results could be used to define the reliability of the testing devices and to characterize their sensitivity to spatial variability within the soil liner. Ideally, several sized versions of each test method should be used in each array to obtain a better understanding of the minimum size requirement for the test devices.

Based on the advantages and disadvantages of the methods reviewed in this document, the following are recommended as the best and most practical currently available technologies for evaluating field hydraulic conductivity:

1) A single-ring infiltrometer covering an area greater than 2 m^2.

2) A sealed double-ring infiltrometer with an inner ring covering an area greater than 2 m^2.

Until conclusive studies are completed, correction factors (such as those commonly used with single-ring devices) should not be relied on to reduce hydraulic conductivity values below 1×10^{-9} m/s. Also, correction factors for evaporative losses should be avoided. If the uncorrected hydraulic conductivity values are higher that the maximum allowable value (1×10^{-9} m/s), confirmatory tests should be conducted with sealed double-ring infiltrometers.

Spatial variability of the soil liner must be characterized to ensure that the hydraulic conductivity values obtained are representative. At least three field hydraulic conductivity tests should be conducted, and the values obtained from each of the three should be 1×10^{-9} m/s or less.

The full report was submitted in fulfillment of Contract No. 68-03-3413 by PEI Associates, Inc., under the sponsorship of the U.S. Environmental Protection Agency.

☆U.S. GOVERNMENT PRINTING OFFICE: 1991 - 548-028/40049

Joseph O. Sai and David C. Anderson are with K.W. Brown & Associates, Inc., College Station, TX 77840.
Walter E. Grube, Jr., *is the EPA Project Officer (see below).*
The complete report, entitled "State-of-the-Art Field Hydraulic Conductivity Testing of Compacted Soils," (Order No. PB91-206 243/AS; Cost: $17.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

United States Environmental Protection Agency

Center for Environmental Research Information
Cincinnati, OH 45268

BULK RATE
POSTAGE & FEES PAID
EPA PERMIT NO. G-35

Official Business
Penalty for Private Use $300

EPA/600/S2-91/022