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NOTE TO: Bill Ford, WMGT   24 Sep 86

FROM: Dan Goode, Mike Young, Mike Weber, Jon Forstrom, WMGT

SUBJECT: INFORMATION ON PERMEABILITY TESTING OF SOIL COVERS AND LINERS

In follow up to our meeting on 22 Sep 86, we have compiled several recommended field testing procedures and other information on the relative accuracy of field and laboratory tests for hydraulic conductivity. This information supports our position on this issue which is that field tests of hydraulic conductivity should be performed because these tests are much more reliable at predicting conservative values of field-scale saturated hydraulic conductivity. These field tests could be performed on pilot-scale field test fills. As you can see, there apparently is an ASTM standard technique for the double-ring infiltrometer test.

In addition to this information, the two papers which Steve and Joe passed out yesterday also support our position. The first paper (by Day and Daniel) clearly indicates the unreliable results often given by lab tests. The fact that the paper identifies some problems with field tests does not imply that the authors would recommend against performing field tests. Both field and lab tests are more accurate if proper procedures are used. The second paper (by Mundell and Bailey) also indicates one of the classic problems with lab tests. "One sample which exhibited a higher permeability value [almost 10 times higher than the average] was found to contain a continuous vertical silt seam and judged to be a localized condition . . ." Small localized conditions, which do affect large scale performance, are more likely to be detected by field tests. Furthermore, the permeability values predicted by lab testing were verified by taking less disturbed samples and running more lab tests. There is no field scale measure of the permeability of the liner in this study. Therefore, it is not known if the lab tests agree with the field performance.

cc: JKane
SSmykowski

A/7

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Tests for Evaluating Sites For Disposal of Low-Level Radioactive Waste

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adequate construction quality control will be provided to achieve the desired design hydraulic conductivity needed for the project. If close quality control is maintained, together with an appropriate predictive laboratory testing program (20), the writer believes that laboratory tests can be used to successfully predict the conditions necessary to achieve an as-built conductivity. Case studies documenting the performance of such closely controlled impoundments would be most valuable in further substantiating this claim.

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Discussion by Miguel Picornell-Darder,[9] M. ASCE

The author is unable to explain the difference between the permeabilities obtained from laboratory and field tests. He uses this lack of an explanation to postulate the presence of a microcrack fabric. Without an independent confirmation of their presence, but because of their existence, the author concludes that clay liners ought to be thicker than 2 ft (0.61 m).

The writer's opinion is that the observed difference in permeability can be attributed to inadequate testing procedures. The author uses the loosely defined terms "tap water" and "freshwater" for the fluids used in the laboratory tests and to fill the pond respectively. While these terms appear to indicate that the electrolyte concentration was low in both fluids, they do not give any indication concerning the presence of sodium (Na) in either fluid.

The presence of Na ions in the permeating solution has been shown (21) to decrease dramatically the permeability of soils with even minor amounts of smectites. This effect is particularly apparent at low salt concentrations. The two characteristics of the permeating fluid that determine the extent of this effect are the electrolyte concentration and the sodium absorption ratio "SAR," which is the ratio of the Na concentration over the square root of one half of the sum of the Ca and Mg concentrations.

For a series of permeating solutions of decreasing electrolyte concentration, but constant SAR, it is possible to distinguish three distinct electrolyte concentration regions from their effect on the resultant permeability. At high concentrations, the permeability is "stable" (22), i.e., independent of concentration. There is a "threshold" below which the permeability decreases with decreasing concentration. This trend continues until it reaches (21) a "critical" concentration, where the permeability becomes "essentially zero."

The most spectacular changes occur for solutions with Na as the only cation, which corresponds to a SAR of infinity. Using this fluid and a Waukema soil, McNeal and Coleman (21) obtained "stable" permeability of $5.0\ 10^{-5}$ cm s^{-1}, a "threshold" concentration of 800 meq L^{-1} (46.75 g of NaCl/L).

It is not possible to generalize, because "tap water" changes with location, and at a fixed location it changes with time. But as an example of Central Texas "tap water," that on the campus of Texas A&M University has about 0.45 g L^{-1} of dissolved solids, and typically will contain 200–250 ppm of Na, 3–5 ppm of Ca, and only traces of Mg. This cation makeup results in an extremely high SAR, that for practical purposes can be taken as infinity. Since the electrolyte concentration of this "tap water" (0.45 g L^{-1}) is less than the "critical" concentration (2.92 g L^{-1}), if it is used as the permeating fluid on a soil sample containing some smectites, which are very frequent and abundant in Central Texas soils, the laboratory results can grossly underestimate the "stable" permeability of the soil in question.

The author has apparently not considered the importance of the presence of Na in the permeating fluid. However, as previously reasoned, this omission can account for the significant difference in reported permeabilities. Therefore, there is no need to resort to the hypothesized presence of a microcrack fabric. On these grounds, there is no basis for the recommendation of thicker liners. But more importantly, this illustrates the need to perform the laboratory tests with a prepared fluid of known chemical composition and not "tap water."

To avoid the interference of Na in the laboratory determination of permeability, it is necessary to use a permeating fluid with a low SAR value such as the solution of a salt of a divalent cation in distilled water. As the author is aware (10), the standard fluid used by soil physicists in permeability tests is a 0.01 N solution of calcium sulfate.

The permeability measured with this standard fluid is the "stable" permeability, which is the maximum to be expected in the field. If the fluid retained by the liner is relatively salt free, the actual field permeability could only be reasonably estimated if the laboratory permeant is *identical* to the solution flowing through the liner in the field. Central Texas soils frequently contain gypsum and carbonate nodules which, despite the fact that they are only slightly soluble, can modify noticeably the concentration and the SAR of a relatively salt-free water flowing through the liner. If a reliable estimate of the actual field permeability is needed, the changes imposed by these soluble salts on the pore solution should be considered.

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Infiltration Capacity

Field measurement

Infiltration rate can be measured in the field in accordance with the following standard method:

> ASTM D3385-75, "Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometers," Annual Book of ASTM Standards: Part 19 - Natural Building Stones; Soil and Rock, 6 pp.

When test results are plotted as infiltration rate against elapsed time from the beginning of the test, a curve commonly called the infiltration capacity is obtained. The ultimate infiltration rate after a more or less constant rate is achieved is of special importance as reflective of long-term capacit for infiltration.

The infiltration rate may also be estimated on the basis of previous experience with similar soils in the vicinity of the site. Ideally this estimation may amount to application of previous test results obtained for agricultural or other purposes, but the condition of the soil, the soil moisture, and the vegetation all must be integrated into the comparison.

Indirect measurement or estimation

Infiltration rates appropriate for longer periods can be obtained by use of site-specific stream gaging data or from the curve number method of estimating runoff (see Runoff). The runoff amount is subtracted from the site-specific precipitation amount for the appropriate time period to obtain the corresponding infiltration amount. The period under consideration is always of great importance since infiltration from storms is invariably less than that from equivalent cumulative rainfall spread over a long interval.

national handbook of recommended methods for water-data acquisition

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6.E. SOIL-WATER MOVEMENT

The entry of water into soil, movement to plant roots, flow to drains, seepage, and evaporation are a few of the processes in which the rate of water movement plays an important role. Soil water responds to differences in potential and moves from areas of high potential into areas of low potential. Movement due to temperature and osmotic gradients does occur, but it is often minor. The rate of water movement is determined by the potential gradient and the hydraulic conductivity.

With all studies of infiltration and permeability (hydraulic conductivity), at least three rules are important: (1) Carefully select representative sites or soils; (2) use exacting and well-designed techniques; and (3) repeat the tests as required by the significance level of your design. Variations are normal and the results should be averaged and the variance should be determined. Land use (grassland, forestland, pastureland, plowed ground, and so forth) may affect water movement in upper soil horizons much more than does soil type.

6.E.1. INFILTRATION

Infiltration refers to the movement of water *into* a soil as contrasted to the movement of water *through* a soil. Because the infiltration rate is influenced by the water content and surface condition of the soil, correct use of these factors is important when interpreting the results. To date, no single measuring technique that will work under all conditions has been developed. However, two general methods, flooding and rainfall simulators, are widely used.

6.E.1.a. FLOODING

The double-ring infiltrometer is probably the most widely used instrument for measuring infiltration. Infiltration can also be determined by flooding the soil and measuring the rate of water intake. A large plot bounded by a wall of soil or some impermeable material to contain the water may be used. Recommended sources for this method are Bertrand (1965, p. 202-207) and Johnson (1970, p. 187-191).

6.E.1.b. RAINFALL SIMULATORS

Obtaining a satisfactory measurement of infiltration with this method requires that the artificial rain closely simulate natural rainfall and that the plot areas be large enough to represent the given soil. Infiltration equals the difference between the amount of water applied and the amount of runoff. The recommended source for this method is Bertrand (1965, p. 198-201).

6.E.2. HYDRAULIC CONDUCTIVITY

This section presents recommended methods for measuring hydraulic conductivity in both the laboratory and in the field.

6.E.2.a. SATURATED, LABORATORY

Either constant-head or falling-head methods can be used in the laboratory to measure hydraulic conductivity under saturated conditions. The constant-head system is best suited to samples with conductivities greater than approximately 0.01 cm per minute (relatively pervious soils), whereas the falling-head system is best suited to samples with conductivities lower than 0.01 cm per minute (relatively impervious soils). Laboratory measurements of saturated hydraulic conductivity are carried out using either disturbed or undisturbed soil samples that are held in metal or plastic cylinders. Recommended sources for these methods are Klute (1965a, p. 210-221) and American Society for Testing and Materials (1975, p. 298-304).

Comment: For undisturbed cores, the major disadvantages of these methods are the small sample size (which necessitates the use of a large number of samples) and the possibility of leakage along the interface of the soil core and the sample retainer.

6.E.2.b. SATURATED, FIELD

Five techniques can be used in the field to measure hydraulic conductivity under saturated conditions. Two of the techniques (auger-hole and piezometer methods) measure hydraulic conductivity below the water table, and three (double-tube, air-entry, and shallow-well pump-in methods) measure hydraulic conductivity above the water table.

6.E.2.b.1. AUGER-HOLE METHOD

The auger-hole method is based on the measurement of flow into an uncased cavity. The hydraulic conductivity calculated from the results of this test is an average value of the horizontal conductivity of primarily the layers below the water table penetrated by the hole. In stratified soil the results are dominated by more permeable horizons; hence, the method is of most value in unstratified soil. The recommended source for this method is Boersma (1965a, p. 223-229).

Comment: The auger-hole method is difficult to use in rocky soil or in coarse gravel, in soils with very high permeability rates, and under conditions in which the water table is at or above the ground surface.

6.E.2.b.2. PIEZOMETER METHOD

The piezometer method is based on the measurement of flow into an uncased cavity at the lower end of a cased hole. Because the vertical dimension of the unlined cavity is small, the method is well-suited for measuring the hydraulic conductivity of individual layers of soil. In this method the length of the cavity is generally several times its diameter, and the horizontal component of conductivity is measured. The wider the hole and the shorter the length of the cavity left unlined, the more nearly the measurement becomes the vertical conductivity. The tube method developed by Frevert and Kirkham (1948), a modification of the piezometer method, is designed to measure vertical conductivity. The recommended source for the piezometer method is Boersma (1965a, p. 229-233).

Comment: The piezometer method is difficult to use in rocky soils. Even when the tube can be installed in these soils, it is difficult to do so without leaving channels along the outside of the tube. Also, it is difficult to establish cavities of the correct dimensions. The diameter of the cavity is very important when calculating the hydraulic conductivity, making a stable cavity mandatory for reproducible results.

6.E.2.b.3. DOUBLE-TUBE METHOD

The double-tube method uses an auger hole above the water table. The hole is excavated to the depth at which a measurement of hydraulic conductivity is desired. This method can measure hydraulic conductivity of a well-defined sample area in the absence of a water table. Results from the double-tube method in the field compare favorably with hydraulic conductivity values obtained in the laboratory from soil samples taken at the bottom of the auger hole after completion of the field tests. The recommended source for this method is Boersma (1965b, p. 234-242).

Comment: The double-tube method measures hydraulic conductivity in an orientation between vertical and horizontal. It is time-consuming, requiring a day to characterize a volume about the size of a 4-inch core.

6.E.2.b.4. AIR-ENTRY METHOD

With the air-entry method, hydraulic conductivity is calculated from Darcy's equation using infiltration rates measured under high-speed conditions. The recommended source for this method is Bouwer and Jackson (1974, p. 631-633).

Comment: This method essentially gives the value of hydraulic conductivity at the air-entry value of matric suction. This value is approximately equal to half of the saturated conductivity (Bouwer, 1966).

6.E.2.b.5. SHALLOW-WELL PUMP-IN METHOD

Hydraulic conductivity of soil in which no water table is present can be determined in place by measuring the rate of flow of water from a cased or uncased auger hole when a constant height of water is maintained in the hole. This method is known as the shallow-well pump-in method or the dry-auger-hole method. The shallow-well pump-in method permits the measurement of an average hydraulic conductivity for the full depth of the hole being tested. The final value, however, reflects primarily the conductivity of the more permeable layers. The recommended source for this method is Boersma (1965b, p. 242-248).

Comment: Limitations of the shallow-well pump-in method are that large quantities of water are needed, considerable equipment is required, and the procedure is time consuming. Values of hydraulic conductivity obtained with the shallow-well pump-in method are usually lower than values obtained with the auger-hole test.

6.E.2.c. UNSATURATED HYDRAULIC CONDUCTIVITY

Hydraulic conductivity declines many fold for most soil materials as tension increases from saturation to 0.1 bar. Measuring unsaturated hydraulic conductivity requires information on both the tension and the rate of water movement. The relationships and some methods are described by Klute (1965b), Bouwer and Jackson (1974), and Bouma and others (1974). The crust method for measuring unsaturated hydraulic conductivity in the field, described by Bouma and others (1974), is less time consuming and is less difficult than measuring saturated hydraulic conductivity in the field.

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6.F. QUALITY CONTROL

6.F.1. DISCUSSION

Quality control in water-data acquisition may be accomplished in three ways: (1) improving techniques and procedures to minimize potential sources of experimental errors; (2) sampling adequate representatives of a system; and (3) making a sober and realistic appraisal as to what constitutes normal field variability and, thus, what range of data values may be considered acceptable.

TABLE 6-2.—Coefficient of variation (C_v), description of data, and source for specified values of water content (θ)

Water Content, θ (cm^3/cm^3)	Coefficient of variation, C_v (percent)	Description of data	Source for specified values of water content
At saturation[1]	5- 6	between cores	Mason and others, 1957
	4-11	within series	Rogowski, 1972
	7-11	within series	Mason and others, 1957
	3-11	within series	Cassel and Bauer, 1975
	20	between soils	Rogowski, 1972
Field soil[2]	5-23	by weight	Reynolds, 1970
	3-17	by volume	Reynolds, 1970
	9-21	bare soil	Reynolds, 1970
	10-33	vegetated	Reynolds, 1970
Moisture characteristic	10-23	150-hectare field	Nielson and others, 1973
At one-third bar	10	within plots	Ike and Clutter, 1968
	16-19	within series	Ike and Clutter, 1968
At 15 bars	14-16	within plots	Ike and Clutter, 1968
	20-28	within series	Ike and Clutter, 1968
	7-35	within series	Rogowski, 1972
	25-63	between soils	Rogowski, 1972
	11-16	within series	Cassel and Bauer, 1975
	13-55	with depth	Cassel and Bauer, 1975

[1] Calculated from values given for bulk density assuming 2.65 as particle density.

[2] Calculated from values given in tables 3 and 4 of Reynolds (1970).

SOIL PROPERTIES, CLASSIFICATION, AND HYDRAULIC CONDUCTIVITY TESTING

Draft Technical Resource Document
for Public Comment

(SW-925)

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SECTION 7

SUMMARY

The conclusions that can be drawn from this study are: (1) The area of soil testing for hydraulic conductivity overlaps the professions of geology, hydrology, soil engineering, and soil science as all these disciplines have made attempts to measure the rate of liquid movement thru soil materials; (2) A high percentage of the testing methods for hydraulic conductivity determination have been developed for agricultural or engineering purposes other than the application to the feasibility and/or design of hazardous waste disposal sites; (3) All laboratory methods suffer from potential misrepresentation of actual field conditions due to small size of samples and/or disruption of samples when transported or remixed; (4) Experience with field testing techniques has generally been limited to more coarse-textured soils rather than fine-grained soils that are more appropriate for hazardous waste disposal sites; (5) It is not possible at this time to discern the degree of variation in soil testing results caused by the variation inherent in the soil testing method compared to the variation of the spatial properties of the soil itself; and (6) Determination of soil hydraulic conductivity values is the limiting factor to further development of an applicable saturated - unsaturated transport model for prediction or estimation of behavior of a proposed hazardous waste disposal site.

Important considerations and limitations of laboratory and field testing methods are summarized in the Soil Testing Methods Matrix which are shown in Tables 7.1 and 7.2. Table 7.1 summarizes information for laboratory and field methods for the determination of saturated hydraulic conductivity while Table 7.2 is directed at unsaturated hydraulic conductivity methods, calculation methods, and diffusivity methods.

TABLE 7-1 SOIL TESTING METHODS MATRIX/SATURATED HYDRAULIC CONDUCTIVITY

	METHOD	APPLICATION	PRECISION AND ACCURACY
SATURATED / Laboratory	PRESSURE CELL	Land treatment	Fair-many samples necessary to obtain 95% confidence limits
	COMPACTION MOLDS	Liner evaluation	Not available (new method)
	CONSOLIDATION CELL	Liner evaluation	Fair-direct measurement of consolidated sample is much more precise than K computed from consolidation and compression data
	MODIFIED TRIAXIAL APPARATUS	Liner evaluation	Good-reproducible results
SATURATED / Field	PIEZOMETERS	Land treatment	Fair-measure average of vertical and horizontal components of K in all soil layers below water table
	DOUBLE RING INFILTROMETER /PERMEAMETER	Land treatment	Good-reproducible results
	AIR-ENTRY PERMEAMETER	Land treatment	Good-reproducible results that compare favorably with other methods
	CUBE	Land treatment	Good-large size of sample more representative of in situ conditions, can measure vertical and horizontal K separately
	CRUST	Land treatment	Good-large sample size and reproducible results, can measure both saturated and unsaturated K

LIMITATIONS OF TEST	METHOD STATUS	COMMENTS
(1) Small sample may be unrepresentative of actual field conditions, (2) several days required for fine-textured soils, and (3) saturation of sample not assured	Agricultural standard	Simple and inexpensive equipment
(1) Small sample, (2) excessive gradients may cause sidewall flow, (3) interaction between metal cell and waste, (4) saturation of sample not assured, and (5) test will take 1-5 months	Experimental	Special equipment developed for use of particular waste and compacted soil
(1) Small sample, (2) falling head procedure may require many days to perform test, and (3) saturation of sample not assured	Engineering standard for consolidation data	Slight modification of common engineering laboratory equipment
(1) Small sample, and (2) recommended hydraulic gradients in range of 5-20	Engineering standard, common for clay soils with low hydraulic conductivity	Major modification of common engineering laboratory equipment
(1) Errors due to smear zones, (2) requires presence of water table, and (3) measures both vertical and horizontal hydraulic conductivity	Standard test for areas with shallow depths to water table	Many variations in equipment and and procedures
(1) Care must be taken during placement of rings into soil, (2) air trapped below wetting front will effect results, (3) a few days required for fine-textured soils, and (4) if uncovered, correction for evaporation should be made	ASTM standard, also commonly used in agriculture and irrigation	Simple and inexpensive equipment, easy method to perform
(1) Care must be taken during placement of cylinder into soil, (2) will not work well on initially wet soils, and (3) difficult on soils with gravel or stones	Relatively new method, use increasing due to ease of procedure	Moderately inexpensive equipment
(1) Method will require a few days for clay soils, (2) sample saturation cannot be assured, and (3) swelling of sample may effect measurement	Relatively new method, use increasing due to ease of procedure	Very inexpensive equipment and materials
(1) Difficult to assure good contact between soil pedestal and ring	Relatively new method, developed in connection with EPA sponsered university research	Moderately inexpensive equipment, easy to perform for saturated K

TABLE 7-2 SOIL TESTING METHODS MATRIX/UNSATURATED HYDRAULIC CONDUCTIVITY

	METHOD	APPLICATION	PRECISION AND ACCURACY
UNSATURATED / Laboratory	STEADY STATE / COLUMN	Unsaturated zone	Fair-variability decreases as length of column increases
	UNSTEADY STATE / INSTANTANEOUS PROFILE	Unsaturated zone	Fair-many variations of method, field method more accurate
	THERMOCOUPLE PSYCHROMETERS	Unsaturated zone	Good-accuracy of, and range of suction of psychrometers makes method particularly applicable to compacted arid soils
UNSATURATED / Field	CRUST	Unsaturated zone	Good-large sample size and reproducible results, can measure both saturated and unsaturated K
	INSTANTANEOUS PROFILE	Unsaturated zone	Good-probably the most accurate field method because of the large sample size
CALCU-LATION METHODS	VARIOUS PROCEDURES	Unsaturated zone	Fair-calculated values never as good as measured values
DIFFUSIVITY	PRESSURE OUTFLOW	Unsaturated zone	Fair-disagreement among authors regarding precision and accuracy
	HOT AIR	Unsaturated zone	Fair-because of dependence on the slope of the water content curve and determination of water contents gravimetrically

LIMITATIONS OF TEST	METHOD STATUS	COMMENTS
(1) Method will require longer time for clay soils, (2) small sample, (3) procedure yields K(h), not K(θ), (4) K determined from desorption rather than absorption data, and (5) suction limited to range of tensiometer measurement	Agricultural standard	Inexpensive equipment
(1) Method will require longer time for clay soils, (2) small sample, and (3) results limited to range of tensiometer measurement	Agricultural standard	Expensive and potentially dangerous equipment, detailed procedure
(1) Small sample, (2) applicable to clays with degrees of saturation between 30-90%, and sands less than 50%, (3) psychrometer corrosion in acid soils, and (4) cannot measure K near saturation	Experimental	Moderately expensive equipment, detailed procedure
(1) Several days required to achieve steady state flow under crusts of high resistance, (2) difficult to assure good contact between soil pedestal and ring, and (3) results limited to range of tensiometer measurement	Relatively new method, developed in connection with EPA sponsored university research	Moderately inexpensive equipment, repetitive procedure with crusts of different resistance
(1) Results limited to range of tensiometer measurement, (2) field plot must be level, (3) not applicable in soils with high lateral flow, and (4) plots should be larger if surrounding area is strongly evapotranspiring	Agricultural standard	Moderately expensive equipment, easy procedure once set up
(1) Limited to more coarse-textured soils, (2) matching factors must be determined, and (3) matching factors most often determined at or near saturation	Experimental	Large variety of methods
(1) Small sample, and (2) many variations of method using disturbed and undisturbed samples, inflow rather than outflow measured, or one large pressure increment used instead of several small ones	Agricultural and ASTM standard	Moderately inexpensive equipment, detailed procedure
(1) Small sample, (2) requires moisture retention curve to calculate K, (3) not very reliable near saturation, and (4) limited to soils with relatively low conductivities in the low tension range	Relatively new method, use increasing due to short time period for test	Inexpensive equipment, easy procedure

4.3 COMPACTION/HYDRAULIC CONDUCTIVITY TESTING ERRORS

The normal procedure for determination of the hydraulic conductivity of a compacted soil sample is to compact the soil in a mold and then to test for hydraulic conductivity on that sample. The samples so tested are usually cylindrical or disc-shaped with diameters between 3 and 15 centimeters. However, when trying to estimate field hydraulic conductivity from laboratory compaction and hydraulic conductivity testing, there are many sources of error possible during both laboratory compaction procedures as well as during laboratory hydraulic conductivity testing. The types and sources of these errors are discussed below.

Effect of Compaction Water Content

It has been clearly established that hydraulic conductivity of saturated samples is relatively high for samples compacted dry of optimum water content while the hydraulic conductiivity is relatively low for samples compacted wet of optimum water content. Daniel (1981) reported that the hydraulic conductivity of soils compacted dry of optimum might typically be 10 to 1000 times larger than the hydraulic conductivity of soil compacted wet of optimum. For this reason, gross errors in predicting field hydraulic conductivity from laboratory determinations may occur if the field compaction water content is not as anticipated.

Maximum Size of Soil Aggregates

During laboratory tests, the soil aggregates from the field sample are usually broken down into smaller chunks than exist in the field. Such disturbance of the natural aggregation of soils will influence hydraulic conductivity.

Daniel (1981) reported that during testing of the same soil with maximum aggregate sizes of 3/8 inches, 3/16 inches, and 1/16 inch the hydraulic conductivity of the smallest size class was nearly two orders of magnitude less than the hydraulic conductivity of the largest size class. This implies that if aggregate sizes are much smaller in the laboratory sample than exist in the field, the laboratory tests may determine hydraulic conductivities that are much lower than true field values.

Presence of Deleterious Substances

Similar to the situation with differences in soil aggregate sizes between laboratory specimens and field conditions, the presence or deleterious substances in the field such as roots or rocks or any other material not included in the 3-15 cm laboratory specimen may cause substantial discrepancies between the hydraulic conductivity measured in the laboratory and what will actually occur under field conditions.

Method of Compaction

While most laboratory hydraulic conductivity tests on soils are performed on samples prepared with impact compaction using a drop hammer, such equipment bears no resemblance to any pieces of field compaction machinery.

Figure 4.10 presents a comparison of field and laboratory compaction on the same soil. The figure illustrates the difficulty of choosing a laboratory test that reproduces a given field compaction procedure. The laboratory curves generally yield a somewnat lower optimum water content than the actual field optimum.

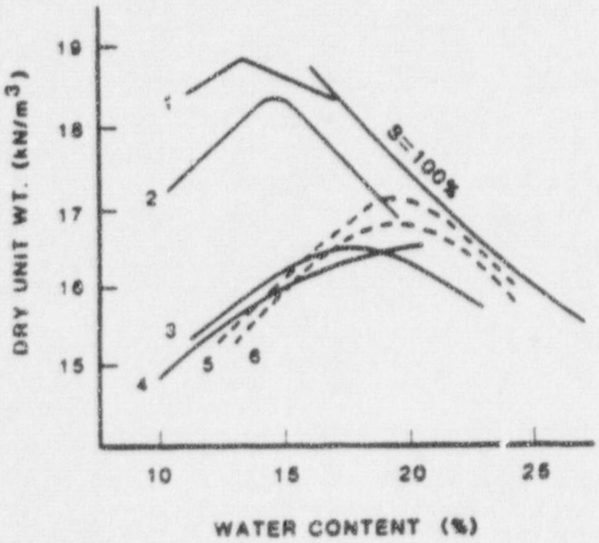

Figure 4.10 Comparison of field and laboratory compaction. (1) Laboratory static compaction, 13.8 MN/m^2 (2) Modified AASHO (3) Standard AASHO (4) Laboratory static compaction 1.38 MN/m^2 (5) Field compaction, rubber-tired load, 6 coverages (6) Field compaction, sheeps-foot roller, 6 passes. Note: Static compaction from top and bottom of soil sample (Lambe and Whitman, 1979).

Additionally, Mitchell et al. (1965) compared static compaction and kneading compaction and reported that similar hydraulic conductivities were found on samples compacted dry of optimum while kneading compaction produced hydraulic conductivities nearly five times less than static compaction when samples were compacted wet of optimum.

Compactive Effort

Many researchers have found that hydraulic conductivity of compacted soils is very sensitive to compactive effort. Mitchell et al. (1965) reported that in studies on compacted silty clay soil that the hydraulic conductivity may decrease by two orders of magnitude, with no change in density or moisture content, simply by changing the compactive effort. Therefore, it is very important to make certain that the compactive effort used in the laboratory is reasonably close to the compactive effort that will be used in the field.

Air in the Sample

I. testing compacted samples, it is often assumed that soaking the samples from the bottom, with the top open to the atmosphere, will yield saturated samples. However, Jackson (1963) reported that for loam soils, only 79-91% of the total porosity was fillable by water. Because water cannot pass through air pockets, such pockets will effectively reduce the pore space that can be occupied by water and thus reduce hydraulic conductivity. This phenomena is one of the main reasons why laboratory hydraulic conductivity results are generally lower than hydraulic conductivities under actual field conditions.

Excessive Hydraulic Gradients

It is virtually impossible to duplicate field hydraulic gradients (usually less than 1) in the laboratory as testing time becomes excessive as well as it is difficult to obtain accurate measurements of the low flows and heads associated with very low hydraulic gradients.

Since Darcy's Law indicates a linear relationship between flow rate and hydraulic gradient, many workers have used elevated hydraulic gradients to reduce testing time. However, if hydraulic gradients become excessive, piping or particle migration may occur and adversely affect hydraulic conductivity measurements.

Criteria for selecting an appropriate hydraulic gradient depends on the soil type and the proposed use of the hydraulic conductivity study. In comparative studies where qualitative, rather than quantitative analyses are needed, larger gradients may be used. Wardell and Doynow (1980) used hydraulic gradients of 48 and 67 in a triaxial cell, while Brown and Anderson (1982) utilized hydraulic gradients of 61.1 and 361.6 in a rigid-wall permeameter. In both studies, no piping, particle migration, or non-Darcy behavior was observed.

However, where the objective is to quantitatively estimate field hydraulic conductivity values from laboratory results, Olson and Daniel (1981) have suggested use of hydraulic gradients as close to those encountered in the field as is economically feasible. Likewise, Zimmie et al. (1981) have recommended use of hydraulic gradients of 5-20 (with gradients nearer the lower end of the range to be preferred) for laboratory studies attempting to duplicate field conditions.

Sample Size

The measurement of hydraulic conductivity in small cores offers many practical problems as such cores may not be representative of in situ conditions where root holes, cracks, and fissures are present. Thus, the size of the sample used to test hydraulic conductivity is important if such information is used to predict field behavior.

Anderson and Bouma (1973) experimented with a series of cores of different lengths to determine the effect on hydraulic conductivity. They found that 17 cm long cores had hydraulic conductivities that were half a magnitude less than 5 cm long.

Daniel (1981) measured the hydraulic conductivity of a compacted clay liner on samples of various sizes in the laboratory with one very much larger sample tested in the field. The results were: 3.8 cm diameter core, 1×10^{-7} cm sec^{-1}; 6.4 cm diameter core, 8×10^{-9} cm sec^{-1}; and 243.8 cm diameter core, 3×10^{-5} cm sec^{-1}. Additionally, the average hydraulic conductivity of the liner was back-calculated from measured leakage rates and found to be 1×10^{-5} cm sec^{-1}. Such results demonstrate the significance of sample size in predicting field hydraulic conductivity values.

Table 4-2 is a summary of testing errors possible when testing for the hydraulic conductivity of compacted soils (Daniel, 1981). It also shows estimates of the possible magnitude of error associated with each problem and an indication of whether the laboratory hydraulic conductivity is likely to be higher or lower than the field value. The estimates of error are based on available data and are intended to show trends rather than precise values.

TABLE 4-2 SUMMARY OF SOURCES OF ERROR IN ESTIMATING FIELD HYDRAULIC CONDUCTIVITY OF COMPACTED CLAY LINERS FROM LABORATORY TESTS

Potential sources of error	Laboratory K Too High or Low?	Possible Number of Orders of Magnitude of Error
Compaction at a higher water content in laboratory than field	Low	1 to 3
Maximum size of clay chunks smaller in laboratory than field	Low	1 to 2
Deleterious substances present in the field but not in laboratory samples	Low	1 to 3
Use of static or impact compaction rather than kneading compaction to prepare laboratory specimens	High	0 to 1
Use of more compactive effort in the laboratory than in the field	Low	1 to 3
Air in laboratory samples	Low	0 to 1
Use of excessive hydraulic gradients	Low	0 to 1
Sample size	Low	0 to 3

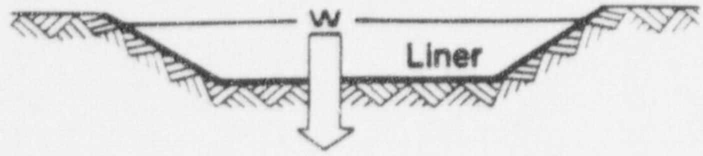

Figure 5.2 Water and waste movement through a soil liner.

Because soil liners are constructed from disturbed or admixed materials, there is no simple and reliable way to test them in situ. Accordingly, hydraulic conductivity must be performed on compacted laboratory specimens that will be used in the field. Therefore, as the facility is constructed, the field density should be checked to ascertain that density and associated hydraulic conductivities are related to the laboratory model.

Laboratory methods for determining saturated hydraulic conductivity on compacted specimens are:

1. Compaction Molds (Section 6, pp. 60)
2. Consolidation Cells (Section 6, pp. 64)
3. Triaxial Apparatus (Section 6, pp. 66)
4. Thermocouple Psychrometers (Section 6, 97)

5.3 THE UNSATURATED ZONE

Another type of liquid movement that is relevant in all types of land disposal facilities is movement in the unsaturated zone between the root zone or liner and ground water table or bedrock as depicted in Figure 5.3.

As described in Section 3, unsaturated hydraulic conductivity is more difficult to measure than saturated hydraulic conductivity due to the fact that the unsaturated hydraulic conductivity varies with both moisture content and pressure head and therefore must be determined over a range of values while saturated hydraulic conductivity will be a constant value.

Also, it can be noted that testing of the unsaturated zone during feasibility and design stages will be of benefit later as for most systems there will be the requirement for monitoring of the unsaturated zone after construction of the facility. Good decisions made during feasibility and design stages for types and locations of unsaturated hydraulic conductivity tests will facilitate the unsaturated zone monitoring requirements.