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

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RELATIONSHIP OF LABORATORY- AND FIELD-DETERMINED HYDRAULIC CONDUCTIVITY IN COMPACTED CLAY LAYER

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The United States Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the U.S. EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the U.S. EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report documents the spatial variability of hydraulic conductivity, measured by both infiltration and seepage, throughout an area of clayey soil compacted according to engineering specifications for landfill liners. The data emphasize the need for clear design specifications and high quality construction of such earthen barriers in waste management facilities. This report will be useful to scientists, engineers, and regulatory staffs who are concerned with the actual hydraulic performance of soil liners and soil covers constructed to protect the Nation's ground water.

E. Timothy Oppelt
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ABSTRACT

A study was begun in 1983 to characterize the areal variation in hydraulic conductivity of a compacted clay liner. A field-scale research facility was constructed, consisting of a 30' x 75' area of clay soil compacted in three layers to specifications commonly used in constructing clay liners. The facility was fully instrumented to measure infiltration, drainage, and soil properties at numerous data collection points. Preliminary studies were initiated using sections of small barrels and larger caissons to verify the performance of monitoring systems. Results from these preliminary (prototype) studies have shown that any perforations of the compacted soil, such as wells, or access tubing for detectors to monitor wetting front advance, may result in preferential water movement by gravity down the walls of these perforations. To avoid this situation in the field-scale facility, access tubes were placed horizontally to accommodate the nuclear probes used to measure changes in clay density and porosity. Underdrains were imbedded in the concrete support structure to collect outflow, infiltration cylinders were installed to monitor infiltration, and metal pedestals were placed on the clay surface to assess swelling by measuring elevation changes. Quality control observations collected during the construction showed that on the average water content and dry density of the compacted clay were close to design specifications, but the spatial variability in these values was large. Measured infiltration rates and outflow rates obtained following ponding the field-scale facility were poorly predicted by the prototype data from small barrels and larger caissons. Initial data showed rapid breakthrough of percolate near the confining walls, a feature that was also observed earlier in prototype studies. The extent of clay liner integrity and observed travel times reflect the effectiveness of a field-scale clay liner in preventing possible ground water contamination. Proper evaluation of flux rates and their distribution in time and space is necessary to characterize the system.

Flux values, computed from observed infiltration and outflow measurements at 184 locations in a layer of compacted clay subsoil, were compared to effective flux values based on breakthrough time distributions for water and Br^- tracer over the same area. Results suggested that both water and tracer move at similar rates, but considerably faster than expected, on the basis of the outflow flux alone, and that only a small fraction of the total pore space is involved in active transport. The ramifications of these findings are explored against the background of effective porosity, degree of compaction, and observed changes in bulk density with time.

The experimental clay liner was ponded for 1 year. During that time inflow, outflow, and changes in density were routinely monitored at 250 locations. Results suggested that initial increase and final leveling off of the density values could be associated with water passing into the clay matrix and attainment of the steady state. Observed increases in density initially were accompanied by increases in outflow which subsequently declined and leveled off at twelve months. These changes were associated with leaching and precipitation of Fe and Mn. Tracer breakthrough times were consistently faster than water flow rates, although initial water breakthrough times following ponding were similar to tracer breakthrough times. Results suggest that water and solutes moved in the clay through only a small portion of total porosity.

Hydraulic conductivity distribution based on laboratory measurements underestimated field measured hydraulic conductivity distribution by a factor of five. However, comparisons of individual values at the same location could differ by several orders of magnitude. It was found that the distribution of water content and density in the compacted clay was adequately described by core samples and nuclear surface moisture-density probe data. However, the water content and density data appeared to have little relationship to average values of spatially distributed hydraulic conductivity.

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SECTION 1

INTRODUCTION

Installation of liners at sanitary landfills and hazardous waste sites has been one of the commonly recommended methods of containment and control. The primary function of a liner is to prevent, or limit the amount of leachate that might ultimately reach the groundwater. Thus, liners must have appropriate properties to restrict, delay or dilute leachate migration so that a given site may ideally provide an ultimate containment. Desirable properties of linear materials include (1) low permeability, (2) high adsorption capacity, and (3) resistance to chemical, biological and mechanical breakdown. These desirable attributes work to enhance several physical and chemical processes which will lessen the environmental consequences of contaminant migration. The primary mitigating factors include dilution, time delay, and retardation. The choice of liner material should be based on the extent to which these factors operate to meet the desired performance criteria.

Various treated and untreated soil mixtures have been utilized as liners for waste sites: compacted mixed clay soils, pure montmorillonite, montmorillonite mixed with concrete, bentonite with an added polymer, as well as other commercially available products. Of these, the clay liners are the most common. Typically, clay liners are constructed in one of the following ways:

(1) A commercial refined clay product is added to and mixed with the top few centimeters of native soil.

(2) A nearby deposit of clay soil is excavated, hauled to, and compacted in place at the disposal site.

(3) A native clay soil is compacted in place.

Generally, a liner is covered with a layer of sand or soil to minimize drying, and waste is placed on top of the soil varying in depth from 2 to 8 meters. For municipal waste the density varies between 297-534 kg/m^3, for many hazardous waste materials it is likely to be higher. Taking 1000 kg/m^3 as a likely number and adding to it the weight of cover cap, overburden pressures on the liner might be on the order of 5 to 10 T/m^2. Since good construction begins with adequate specifications, proper design is the single most important factor in a successful liner installation. Design procedures need to take into account the Federal and State regulations and performance standards. While State requirements must meet the minimum Federal standards, many go beyond to accommodate local conditions. For example, the Pennsylvania Department of Environmental Resources (DER) requires the following specifications be met if a native clay is to be used as a primary layer.

Permeability: < 10^{-7} cm/sec
Thickness : 60 cm
Compaction : 95% standard proctor
Clay content: greater or equal to 25%

In addition to the liners being compatible with the waste, the site must be inspected and approved by the Department. Quality testing is mandatory during and upon completion of the installation.

The least water content (by weight) at which the soil just flows under its own weight is called the liquid limit (LL), while the smallest water content (also by weight) at which the soil can still be rolled out into thin (~ 3mm) threads without crumbling is called the plastic limit (PL), the difference between the tow (LL-PL) is taken as the plasticity index (PI) and is given in units of water content by weight. In general, liners should be constructed of inorganic clays with a liquid limit greater or equal to 30 and plasticity index greater or equal to 15, and with their respective cation exchange characteristics carefully considered. The liners should be compacted wet of optimum water content using a sheepsfoot roller, and their clod size should also be controlled. Frequently inadequate installation results in clay liner failure. Thus, a strict quality control of materials, equipment and workmanship appears essential to ensure compliance with the engineering specifications.

Assuming a constant head of ponded water above a compacted clay liner the flow rate through the liner should be proportioned to its hydraulic conductivity. As far back as 1856 Darcy established experimentally that the volume of water (Q) flowing through a unit cross sectional area of a sandy formation in a unit of time, was proportional to the difference in hydraulic head (Δh) between the top and bottom of the formation. Since the head at the bottom of the formation of thickness L is ~ zero, Δh is numerically equal to the height of water ponded above the bottom, $\Delta h/L$ is referred to as the dimensionless gradient (i), and K the proportionality coefficient with units of length/time, is the hydraulic conductivity. Combining the above we get an expression $Q = Ki$, known as Darcy's Law.

OBJECTIVES AND APPROACH

The purpose of this study was to evaluate hydraulic conductivity of a field scale clay liner and to compare the field observed values of the hydraulic conductivity with the laboratory determined values of the hydraulic conductivity. Supplemental data were also to be gathered to support research into factors potentially affecting leaching of the contaminants into the groundwater.

The specific objectives of this study were:

(1) To document the present state-of-the-art for determining the *in situ* hydraulic conductivity of compacted clay soils.

(2) To construct a field-scale test plot composed of recompacted clay soil, to install appropriate monitoring devices for measuring water

flow rate in compacted clay, and to determine the in situ hydraulic conductivity using selected permeants, verifying that accurate data can be obtained.

(3) To compare the hydraulic conductivity values obtained on a field test site with those obtained in the laboratory on core samples, and if significant lack of agreement exists, to evaluate the factors responsible.

The project was to proceed in three discrete phases. The initial phase (Phase I) was to include a literature review and methods evaluation to recommend the most appropriate field scale procedure for measuring the hydraulic conductivity in a compacted clay soil liner. Particular emphasis was to be placed on available methods addressing cohesive soils, undisturbed sites, and large surface areas, as well as those that could provide data within a reasonable time frame, remembering that hydraulic conductivity of the clay liner was likely to be ~ 1×10^{-9} m/sec. The output from Phase I was to be a literature review report, with recommended approaches to construction of the field-scale hydraulic conductivity measuring facilities. In Phase II the field apparatus for measuring flow and the prototype clay liner were to be designed and tested for accuracy and performance. In Phase III field-scale facility was to be constructed and clay liner compacted and ponded according to standard industry methods and procedures. After the completion of the field phase, core samples were to be removed from the site for laboratory determinations of hydraulic conductivity. This phase was to include long-term data collection, analysis of field obtained results, and comparison with the laboratory values of determined hydraulic conductivity.

LITERATURE REVIEW (PHASE I)

It is generally assumed that the denser the clay liner the lower its permeability. When constructing clay liners for containment of water the soil material at a certain water content is compacted to a prespecified density. The amount of compaction will vary with the water content. For high values of water content a test involving a standard number of blows will eliminate the few air filled pores present. Resulting density will be low and near to the saturation density value. If, however, the soil is quite dry, no amount of compaction will substantially reduce the air filled porosity because there is not enough water to provide lubrication and allow soil particles to pack closer together. Thus, the final dry density will also be low. At some water content in between these extremes there is a point, known as optimum water content, when a compaction test such as Standard Proctor test will result in a maximum dry density for a given amount of effort (i.e., number of blows, height of fall, mass of weight) (Cooper and Cassie, 1978).

The use of Standard Proctor test as a compaction measure assumes the same aggregate size distribution for lab and field materials. This need not be necessarily so and large differences in water content between the lab and field can occur (Cox, 1978). Further modifications will take place as clay adjusts to overburden stresses imposed on it by a combined load of waste and cover cap. Thus, the equilibrium water content in the field may be different from Standard Proctor test "optimum," and may also vary sufficiently over the area to cause differences in observed flow. Although Cox (1978) investigated the behavior of clays under extreme wet or dry conditions, his work shed little light on clays compacted at or above the optimum water content. The optimum water content occurs at water contents less than saturation, with only part of the void space occupied by water and the rest by air. It is not known whether under the conditions of optimum moisture and maximum density infiltrating water moves through the still empty, connected air voids or by displacement through water-filled pores.

According to Jumikis (1965) volume of solids, volume of water, and volume of air, stabilize at the optimum water content and maximum dry density and stay constant with total void space at the minimum. Just above the optimum a 10% increase in the relative volume of water may be accompanied by as much as 50% decrease in the air voids with little change in total (< 1%) volume of voids. Considering results presented by Cary et al., (1943) and accompanying discussion by Kellog and Creager (Cary et al., 1943) large decrease in permeability can occur over the same range (just above optimum), suggesting that primary pathways of water movement may be through relatively large air filled and connected pores, while water in smaller pores of the clay matrix is more or less immobilized. This question has not been specifically addressed in literature except indirectly by Cary et al., (1943), Anderson and Low (1958), Lambe (1955) and Mitchell et al., (1965). It needs to be clarified whether the pores through which water moves following compaction are the ones which are predominantly air filled, or the ones which are predominantly water filled. Cary et al., (1943) state that optimum compaction means realignment of clay platelets, while Lambe (1955) and Cary et al., (1943) suggest that there is little or no subsequent swelling as water is applied to the surface of remolded clay. Thus, the primary water conducting pores could well be the larger pores which may initially be filled with air. In either case, the flow would be taking place only through a fraction of the total void space and in effect constitute an unsaturated flow regime. Some support for this view comes from the work of Anderson and Low (1958) who suggest that the structure of adsorbed water may also be different (i.e., less dense) from that of the free water. The concept of field capacity (Burrows and Kirkham, 1958) in agricultural soils, or nature of flow through coarse mine spoil (Rogowski and Weinrich, 1981) carries a similar connotation: only certain pores conduct water. Recent attempts to measure large pores in field soils (Clothier and White, 1981) may be a likely approach to clay liner permeability evaluation.

Generally, a quantitative knowledge of clay liner properties is required for prediction of hydrologic behavior at the hazardous waste sites. The choice of an approach may be dictated by the magnitude of spatial variability and the distribution of hydrological properties. Which properties should be measured, what sample volumes should be taken, what locations and what sampling frequency should be considered, are some of the aspects which need to be resolved in characterizing a given clay liner. Of prime importance in this context are the objectives and the desired accuracy for which hydrologic predictions are needed; this will influence the level of sophistication and detail at which a site is sampled and the data analyzed.

One source of information to evaluate the suitability of a soil as clay liner material is soil classification data. Soil classification is based on the premise that soil properties vary in space. Soil surveys are then used to identify and delineate the soil boundaries and predict extent and properties of individual horizons. But in most classification schemes these boundaries remain imprecisely defined. The soil survey classification is based on the broad morphological features of the landscape correlated to sampled profile properties such as color, horizon, depth, structure, and texture. Unfortunately, the extent and nature of variability within a soil unit and associated mapping purity are not always recorded. As a first approximation, properties of soil series may be used to select clay liner material. However, it must be realized that the criteria used in the classifying soils may not coincide with those affecting hydrologic response. Furthermore, appreciable spatial variability in soil hydrological properties has been observed within a soil series (e.g., Rogowski, 1972; Nielsen et al., 1973; Sharma et al., 1980), and this may affect the areal response of remolded material. Thus, under most conditions field characterization of an in place liner is considered important and for this, field-oriented methods are needed. These methods should be simple, rapid, and reliable so that a large number of measurements can be made. For the ease of handling and analyzing of data, grid or transect sampling schemes are preferred.

The choice of hydrological properties needed to be determined and the extent of detail of their characterization, depend largely on objectives and the choice of model to be used. For detailed prediction of water distribution within a clay liner, a physically-based deterministic model such as a three-dimensional water flow equation for swelling soils could be used. This however, would require detailed knowledge of the spatial distribution of the soil water retention $\psi(\theta)$ as a function of water ratio $æ = (1+e)\theta$, (where e is void ratio and θ is the volumetric water content); water flow function $K(æ)$ (hydraulic conductivity K as a function of $æ$) and overburden pressure distribution (Philip, 1969 a and b). On the other hand, for predicting clay liner drainage under flooded conditions, only the knowledge and the spatial distribution of effective permeability may suffice.

Clay liners are usually compacted near or above the optimum water content to attain maximum density, to minimize swelling, and to attain the lowest possible values of flow (Lambe, 1954). In general, field hydraulic conductivity will be different from the laboratory values and may be regarded as the conductivity at some effective resultant liner porosity. Hydraulic conductivity also varies depending on kind of compaction and initial water content. Cary et al., (1943) and Mitchell et al., (1956) have found that hydraulic conductivity clay soils compacted just below the optimum could be several orders of magnitude greater than in soils compacted just above the optimum.

Under natural conditions estimates of hydraulic conductivity (K) and water potential (ψ) as functions of water content (θ) are usually needed for a complete description of a flow regime. Field measurement of $\psi(\theta)$ and $K(\theta)$ is time consuming and tedious because a large number of measurements are usually required for complete field characterization. For that reason numerous attempts have been made to calculate $K(\theta)$ from laboratory measured $\psi(\theta)$ functions (e.g., Childs and Collis-George, 1950 a and b; Millington and Quirk, 1959; Brooks and Corey, 1964; Rogowski, 1971). Using the Brooks and Corey approach, Russo and Bresler (1980) computed $\psi(\theta)$ and $K(\theta)$ from field measured values of saturated hydraulic conductivity, sorptivity, air entry, and initial water content, and water content at saturation. This procedure enabled rapid determination of approximate $K(\psi)$ and $\theta(\psi)$ values for evaluation of spatial variability and estimation of redistribution of applied water in a field soil. Because K values in the compacted clay liner are expected to be very low (~ 10^{-9} m/sec), it is doubtful to what extent this approach could be used.

Considerable effort has been made in developing empirical methods to estimate hydrological properties based on particle size analysis data. Broad scale hydrological classification of agricultural soils of the USA is being attempted by estimating parameters appropriate to the Brooks and Corey model of water retention (e.g., Rawls et al., 1982) as well as parameters suitable for use in the Green and Ampt (1911) infiltration equation (Swartzendruber, 1987). In the absence of soil hydrologic data, these approaches are likely to have a wide appeal since they are usually based on readily available information. The limitations of such approaches to clay liner construction should however be realized, particularly for soils with predominant structural features.

In general, soil systems, such as a remolded clay liner, are extremely complicated and highly variable at a scale of individual aggregate, but such complexity can be bypassed by measuring hydrological properties at a larger scale. Usually the variance of a property decreases with an increase in volume of a sample. The smallest volume above which the variance no longer decreases significantly defines the representative volume for that property (Bear, 1972). This is a theoretical concept, and in real world situations, it may be difficult to define. Ideally, the representative volume should encompass components of variability at several scales, in practice, however, hydrologic properties are measured on much smaller samples and they are considered points of a continuum.

For comparative purposes and assuming normality the magnitude of variability is sometimes represented by the coefficient of variation (CV). In soils coefficient of variation is found to be highest (CV > 1.0) for transport coefficients (hydraulic conductivity and diffusivity), medium (CV ≡ 0.15-0.5) for properties such as water contents at selected water potential, and least (CV < 0.15) for properties such as bulk density and total porosity (Warrick and Nielsen, 1980). The variability of a property can also be described by a cumulative distribution function (CDF), which (if we assume a Gaussian model) contains information about the mean and other moments, and these permit estimation of confidence intervals for the property. Assuming a CDF for a parameter has important implications in computing the number of observations required to estimate the mean with a specified precision (Rogowski, 1972; Sharma, 1983), and in determining the integrated hydrologic response of an area (Sharma and Luxmoore, 1979; Warrick and Amoozegar-Fard, 1979).

In traditional parametric analysis of variability a Gaussian or normal model is usually adopted. Properties measured within an area are assumed spatially independent of one another and observations are represented by their mean, standard deviation and other moments. The assumption of spatial independence, at least for points close by, seldom holds for natural systems. Geostatistical techniques (e.g., Journel and Huijbregts, 1978) and nonparametric methods can then be employed to evaluate the degree of interdependence. The spatial dependence of neighboring observations of a property Z measured at all points x and x+h as functions of the distance vector h can be expressed by the semivariogram $\gamma(h)$,

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^{N} [Z(x_i) - Z(x_i+h)]^2 \tag{1.1}$$

where N is the number of pairs $[Z(x_i), Z(x_i+h)]$ for a particular distance (or time) increment h. Thus, a semivariogram of a property describes the average rate of change of $\gamma(h)$ with distance and shows the variance structure of observations. These observations may or may not follow any type of CDF, but should be additive (Journel and Huijbregts, 1978). An an idealized semivariogram is shown in Figure 1. The sill is an upper limit of a variogram model where it levels off, while the distance at which the variogram model begins to level off is known as the range in most applications. The sill usually approaches a priori sample variance, while the range defines a neighborhood where the variable is continuous. With increasing separation distance h, γ may increase and approach a constant value (sill) beyond some separation distance a (range). This indicates the extent of spatial dependence. If γ continues to increase with increasing h, information at larger separation distances may be required. Often γ does not pass through the origin and at

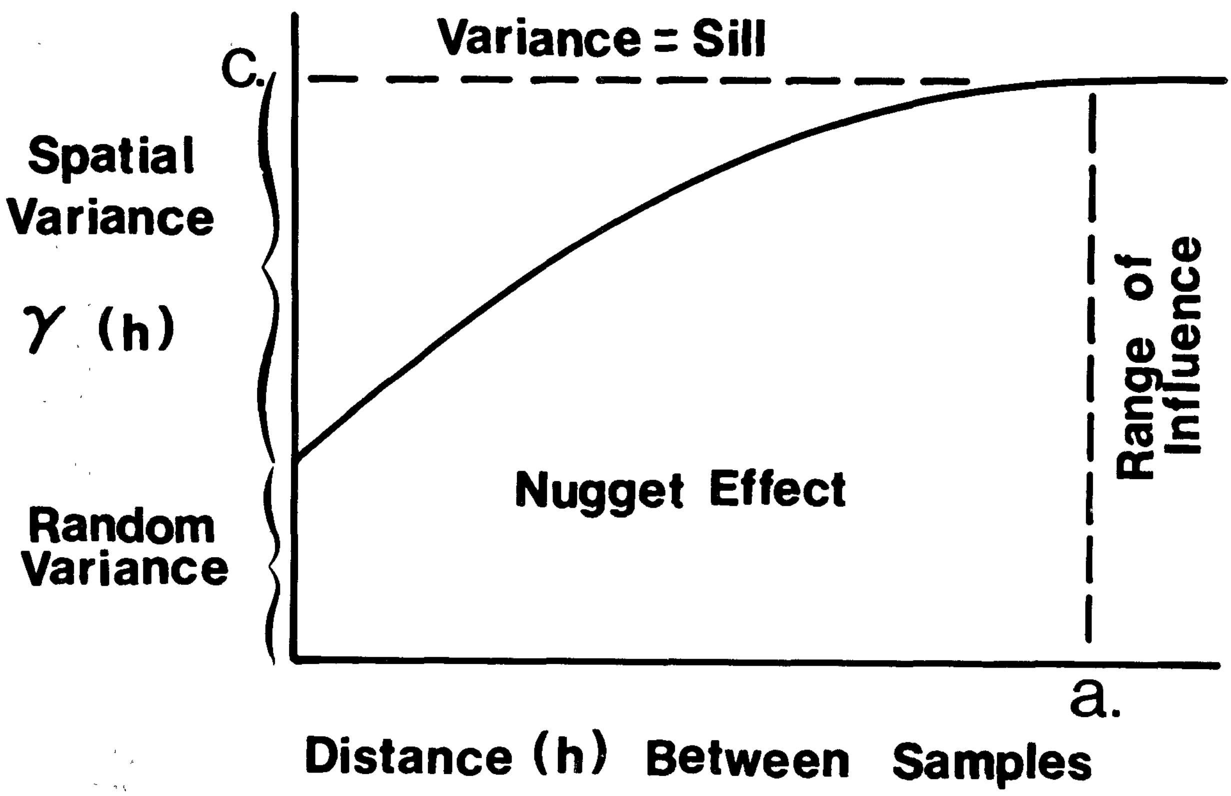

Figure 1.1. Schematic representation of a variogram $\gamma(h)$.

h=0 has some positive finite value called a nugget effect. Such a nugget effect usually suggests a spatial structure on a scale smaller than the sampling interval h. Once the spatial structure of the variable is defined by a semivariogram, the values can be kriged to interpolate the distribution of a property over an area or in space.

Extensive reviews and discussion of laboratory and field techniques of measuring permeability and related parameters are readily available in monographs (Black, 1965; Hagan et al., 1967; USGS, 1977; Nielsen et al., 1972), books (Bear et al., 1968; Childs, 1968; Baver et al., 1972; Kirkham and Powers, 1972; Hillel, 1971 and 1980), journals (Bianchi and Haskell, 1970; Ritchie et al., 1972; Alemi et al., 1976; Clothier and White, 1981). Most writings are concerned with permeability measurements in agricultural soils, and the requirement that a flow rate be less than 10^{-9} m/sec, as specified for clay liners, is of little practical interest. We have therefore, to turn to engineering literature (Olson and Daniel, 1979), particularly literature on clay cores in earth dams and embankments as well as to novel approaches in soil mechanics (Mitchell et al., 1965; Lee, 1974; Zimmie and Riggs, 1981), and to experimental and theoretical studies of shrinking and swelling systems (Kemper, 1960, 1961a,b; Sposito, 1975a,b,c) to get some idea what may be involved. These studies add new insights in a practical sense, to what has been written before by Cary et al., (1943), Lambe (1955), and Babcock (1963).

Swelling clay soils do not behave in the same manner as do nonswelling materials. Swelling soils, in addition to matric and gravitational potential flows, will be subject to overburden potential and probably varying degree of chemical potential depending on waste compatibility. This, of course, complicates the situation considerably. The effect of gravity on flow will be less and vertical moisture profiles are likely to vary depending on clay thickness, amount of swelling, and location with respect to the water table. In shallow profiles volume of water per unit volume of soil may increase, decrease, or remain constant with depth, while, for deep profiles volume of water per unit volume of soil will decrease. These developments may markedly affect profile permeability. It is well known (Philip, 1969a,b) that surface macrotopography does have a considerable influence on the equilibrium water content, but it is not known to what extent microtopography of an essentially level clay liner will affect its hydrology. Much work has been done recently to predict the behavior of swelling soils in response to water using the fluid mechanics approach (Philip, 1969a,b; Youngs and Towner, 1970; Philip, 1970; Talsma, 1974, 1977a,b; Talsma and Flint, 1958; Talsma and Lelij, 1976) or thermodynamics approach (Babcock, 1963; Sposito, 1972, 1973, 1975a,b,c; Sposito et al., 1976; Chu and Sposito, 1980. Work done by Kemper and coworkers (i.e., Kemper and Evans, 1963; Kemper and Rollins, 1966, etc.) addresses movement of water across clay membranes as a function of concentration gradients. When salt solution is forced through a compacted clay a portion of electrolyte is excluded from water films surrounding clay particles and remains behind at the high pressure side increasing the concentration of salts and possibly affecting permeability. To what extent work on swelling systems is applicable to our studies remains to be seen.

When discussing aspects of structural stability Quirk (1978) pointed out that in a soil containing illitic clay, the dominant pore peak occurred at

3.5 nm (10^{-9} m). However, volume changes during wetting usually lead to formation of planes of discontinuity and development of pores two to three orders of magnitude larger than the original peak. Recent work of Smalley (1978) suggests that compaction at moistures slightly greater than optimum leads to structural rearrangement of clay particles. Particle realignment on wetting and compaction in Leda/Champlain clays of eastern Canada was shown by Smalley (1978) to result in considerable local variations in density. Although initial open structure of these clays tended to be preserved by cementation of short range bonds, bond breakage could subsequently result in complete structural collapse.

Changes in hydraulic conductivity can be brought about by chemical and physical reactions within the clay matrix. Frenkel and Rhoades (1978) pointed out that hydraulic conductivity can increase appreciably because of dispersion, provided bulk density of the material and electrolyte level of percolate are sufficiently low, flow rates are sufficiently high, and exchangeable sodium is between 10 and 20%. Under these conditions dispersion begins to affect mechanics of transport and may lead to piping failures. On the other hand, if sufficient clay is present and exchangeable sodium is greater than 25%, swelling will most likely reduce hydraulic conductivity. At low electrolyte levels in the percolate, if the bulk density and clay content are sufficiently high, dispersion will lead to blocking of pores and reduction in hydraulic conductivity.

Thus, a system, such as a clay liner, may react in different ways and require not only the specifications depending on location, clay type, amount, and water content, but also the knowledge of the particular waste chemistry.

A basic experimental tool in field infiltration research is the ring infiltrometer. There are many different types and sizes that have been used and modifications range from a double ring infiltrometer on one end of the scale to an enclosed air entry permeameter and double tube permeameter at the other. Infiltration rate I within the rings is assumed to take place under unit gradient conditions and calculations may involve fitting the S (sorptivity) and A (coefficients) in Philip (1967) infiltration equation,

$$I = St^{1/2} + At \tag{1.2}$$

where t is the time. Straight line plot of $I/t^{1/2}$ with respect to $t^{1/2}$ gives S as a y-axis intercept and coefficient A as a slope of the line. A working estimate of hydraulic conductivity (K_s) can then be obtained as,

$$K_s = 3A \tag{1.3}$$

This relatively rapid method has been used by Talsma and Lelij (1976) to evaluate <u>in situ</u> infiltration rate and water movement on a swelling rice paddy soil during prolonged ponding. Measured values of hydraulic conductivity ranged from 5.8×10^{-7} to 1.12×10^{-5} cm/sec, certainly within the range of interest for clay liner studies. Based on their average sorptivity of ~ 25 mm/day$^{1/2}$ and average K_s value of ~ 2 mm/day (2.3×10^{-5} cm/sec) the plot of

$I/t^{1/2}$ vs $t^{1/2}$ was expected to be linear for about 3 days according to the relation,

$$t \leq 0.02\ (S/K)^2 \tag{1.4}$$

It might therefore be anticipated that a linear behavior of $I/t^{1/2}$ vs $t^{1/2}$ for a clay liner with K ~ 10^{-7} cm/sec is likely to be even longer. If a ring is large enough (> 30 cm diameter), or enclosed in a manner similar to an air entry parameter, or a falling head infiltrometer (Daniel and Trautwein, 1986) measurable infiltration rates can be readily calculated from the fall of water level in a capillary, or by weight.

Following ponding, and after the water drains a disc infiltrometer (Clothier and While, 1981) can be used to check for the presence of large pores. Disc infiltrometer will allow water movement into the profile under a known negative head and is used together with ponded values to see what proportion of the larger pores are likely to be conducting water. In agricultural soils as much as 80 or 90% of flow can take place through the larger pores. The "larger" pores in clay matrix are likely to be much smaller necessitating the use of different membrane materials with higher impedance to induce higher values of negative head.

SECTION 2

CONCLUSIONS

The initial literature review (Phase I) has raised several questions. The foremost among these was the evidence that flow through compacted clay may be very sensitive to the remolding water content and accompanying uncertainty about the representativeness and effectiveness of standard compaction techniques. Equally important was the potential existence and distribution of preferential flow pathways.

Preliminary studies (Phase II) proved useful in design of the field experiment and instrumentation. Results suggested potential for leakage along the walls of containment and sides of instruments. Some swelling was also observed; however, swelling infiltration and drainage rates from prototype studies were poor predictors of field scale facility behavior.

The large 10 x 25m, bridgelike platform facility and a compacted 0.3m thick clay line (Phase 3) provided satisfactory data about the performance of clay liners and relationship of field hydraulic conductivity to lab values.

Clay liner was constructed from a B-horizon of a typical soil meeting the EPA specifications. In the course of analysis the soil was found to contain a larger than expected number of coarse fragments. However, no evidence was found of preferential layering, or preferential distribution of these rock fragments either because of natural tendencies or mechanized compaction of the three lifts. Sand layer on top of the clay liner acted as a moisture barrier and prevented rapid drying. Spatial measurements of evaporation needed to be made to correct infiltration flux and for mass balance purposes.

The considerable variability observed in the spatially distributed infiltration, outflow and outflow chemistry on the compacted clay liner may have been affected by the presence of preferential pathways of leachate flow through the clay liner.

Higher flow rates which originated in apparently unsaturated areas suggested the presence of the preferential flow pathways. Such pathways will potentially pose a grave threat to underlying ground water quality even in the presence of a clay liner.

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. However, when the distribution of laboratory values was compared with the distribution of field values the results appeared to be linearly correlated. Laboratory distribution underestimated the field distribution by approximately a factor of 5, despite the fact that individual observations varied as much as four orders of magnitude.

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. Unfortunately, using of the ring infiltrometers is time consuming. Best estimates of clay liner performance were obtained by following the conservative tracer (Br^-) movement, and breakthrough history.

We have found little change in clay liner wet density with time suggesting a very limited movement of water into the clay matrix. Initial change, however, just after flooding could be indicative of the extent of macroporosity.

Finally, we have found a surface moisture-density probe with capability for direct transmission from shallow depths to be a quick and satisfactory method of determining field distribution of moisture and density for individual lifts during construction. Unfortunately, there appeared to be no relationship between density and water content of the clay and the observed values of hydraulic conductivity and the flow regime, as perceived by changes in wet density, did not appear to be continuous but consisted of concurrent alternating, filling and draining episodes distributed in space.

The amount of available pore space in well compacted clay was very small, and even a small change may be disproportionately large. In our case minimal swelling of ~ 2.4-mm could have accounted for ~ 20% increase in available pore space in compacted clay.

Far fewer (1/10 as many) samples were needed to characterize the compacted clay liner density and water content compared with the number of samples 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 potential distribution of the preferential flow pathways.

SECTION 3

RECOMMENDATIONS

Field constructed clay liners should have a layer of sand on the top and the bottom, because sand acts as a capillary barrier for clay water, minimizing drying and outflow components.

Specifications for liner construction should include an upper permissible level of clods, aggregates and stones to be contained in the candidate materials. Clay liner materials are often derived from deeper horizons of ordinary field soils. Such materials, particularly in the northeastern USA, contain many coarse fragments.

It is recommended that the integrity of compacted clay liners be tested using a conservative tracer, ponded conditions and an underdrain catchment system. Because, despite adequate moisture and compaction, the moisture and density readings did not appear to be correlated on a field scale with observed hydraulic conductivity or the distribution of critically important preferential flow paths. However, the nuclear surface moisture-density probe with a shallow direct transmission capacity appeared adequate for evaluating distribution of moisture and density within individual compacted lifts of clay.

In designing clay liner studies particular attention needs to be given to potential flow along the walls of the containment facility or instrumentation access ports.

Judicious selection of liner materials (specific guidelines) and extensive quality control of moisture and density (specific guidelines) during construction are recommended. At present many samples of hydraulic conductivity are needed to adequately characterize the potential flux and transport through the clay. Because far fewer samples of water content and density are required to characterize the clay liner compared with the number of samples required to characterize hydraulic conductivity with the same degree of precision, increased quality control and use of homogeneous materials at a reasonably constant water content may help decrease the number of samples needed to characterize hydraulic conductivity.

SECTION 4

PRELIMINARY STUDIES (PHASE II)

DESIGN CRITERIA

Design criteria and plans for the liner testing facility and associated instrumentation included a 10 x 25m elevated platform and a 30cm thick liner. Figure 4.1 and Plates 4.1 and 4.2 show the schematic plan and different construction stages of the platform.

Plate 4.1 shows the reinforced concrete footers, and in Plate 4.2 we show the finished (b) elevated platform. The open ramps on either side were subsequently filled with compacted soil and gravel to provide a drive on access to the platform for liner construction and removal. Plates 4.3 and 4.4 give details of drain locations and reinforcing grid. They also show the method of installation (4.3) and support (4.4) for lower access tubes. In Plate 4.5 lower access tubes protrude above the just poured concrete floor with spacers for the upper access tubes in the sidewall in the background. Plate 4.6 illustrates how density was to be measured after the clay was compacted and upper access tubes installed. The gamma source was to be placed in the lower

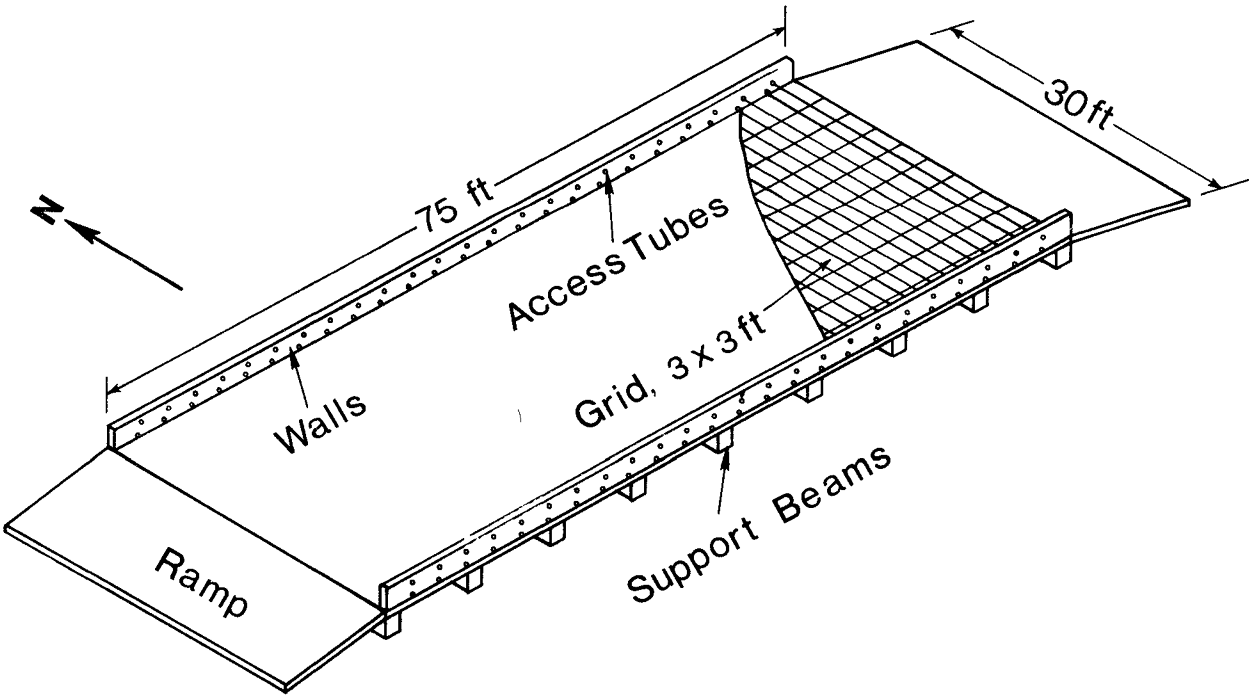

Figure 4.1. A platform for testing hydraulic properties of a 30cm thick clay liner.

access tube and the detector, connected to the scalar (foreground), was to be placed in the upper access tube. Density changes were to be computed from routine measurements at the same locations. Additional instrumentation was to include infiltration rings (Plate 4.7) and drain ports (Plate 4.8) equipped with moisture blocks to detect early arrival of breakthrough front (note wires hanging from drains), square 10 x 10cm pedestals (several can be seen in Plate 4.7) to monitor swelling, and evaporation pans (same size as infiltration rings) to correct infiltration and outflow for evaporation. The instrumentation at the site was to be installed so as not to interfere with the structural integrity of the compacted liner. The clay material was to be trucked in from an actual commercial facility. Installation and compaction were to be carried out according to the USEPA standards (i.e., USEPA, 1988) and also were to be quality tested during installation. A special effort was to be made to take many more moisture samples and make many more measurements of bulk density than may strictly be necessary, so as to establish the minimum sampling and testing criteria needed for adequate quality control.

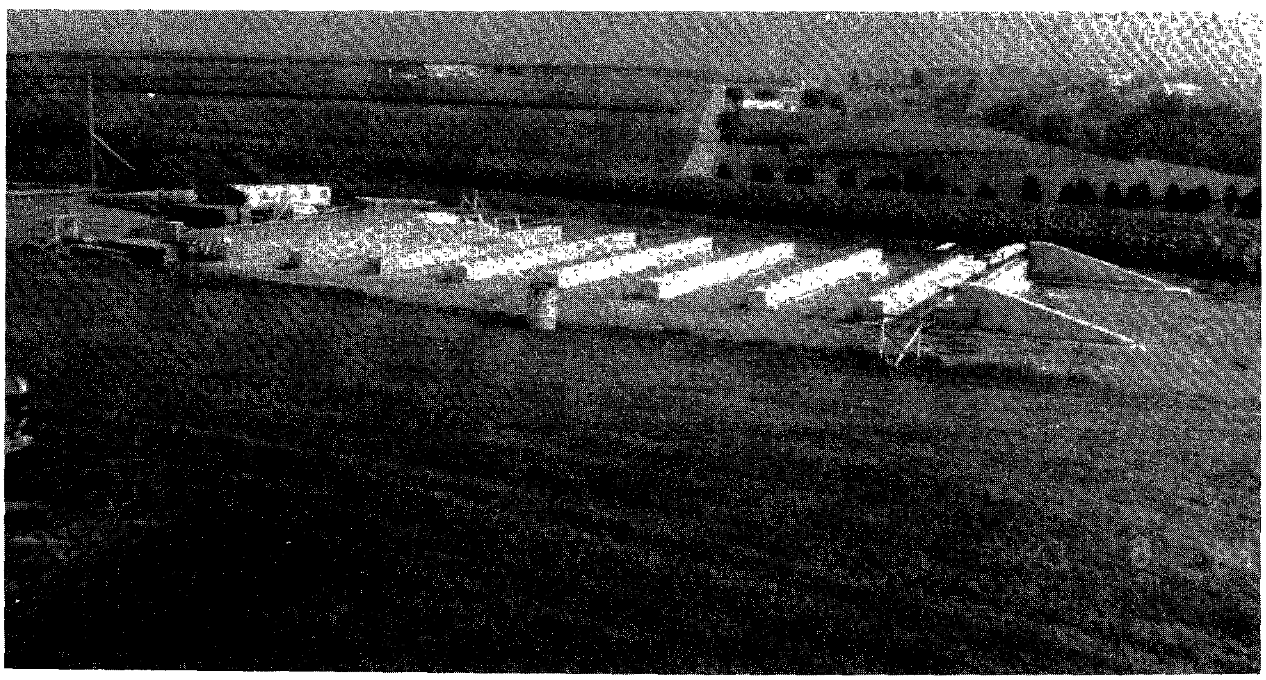

Plate 4.1. Elevated platform construction: reinforced concrete footers.

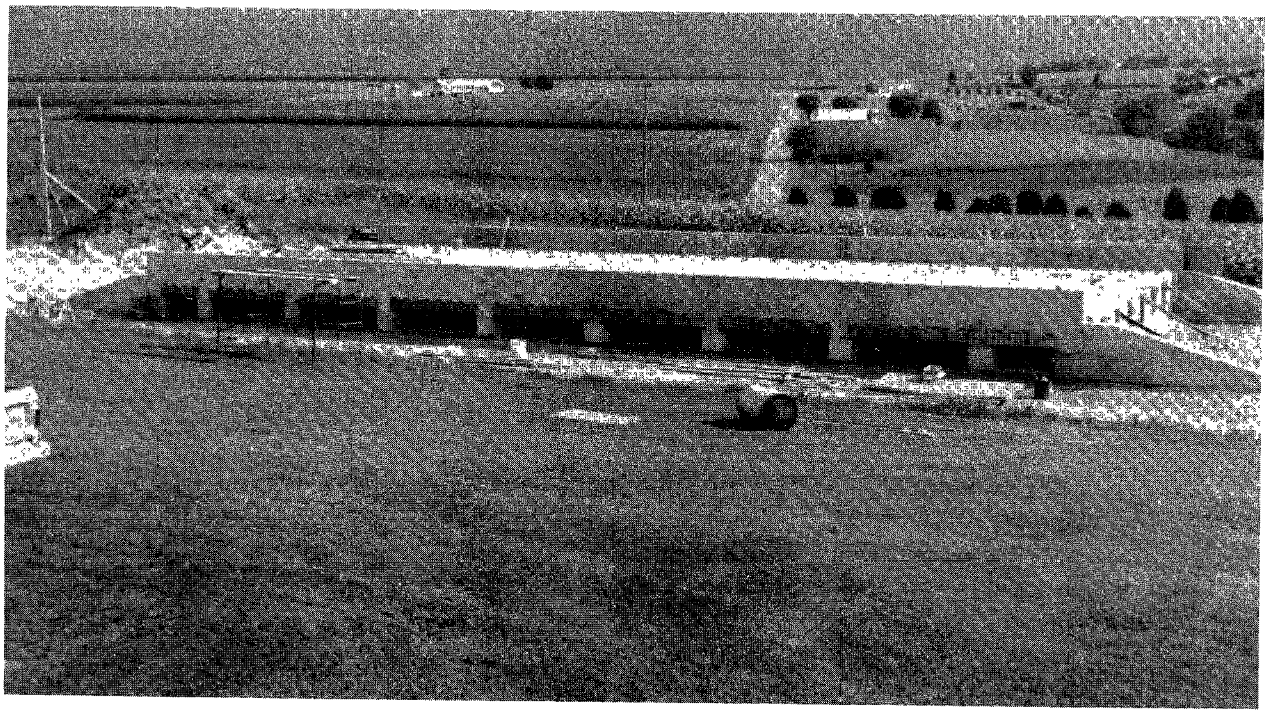

Plate 4.2. Elevated platform construction: finished platform.

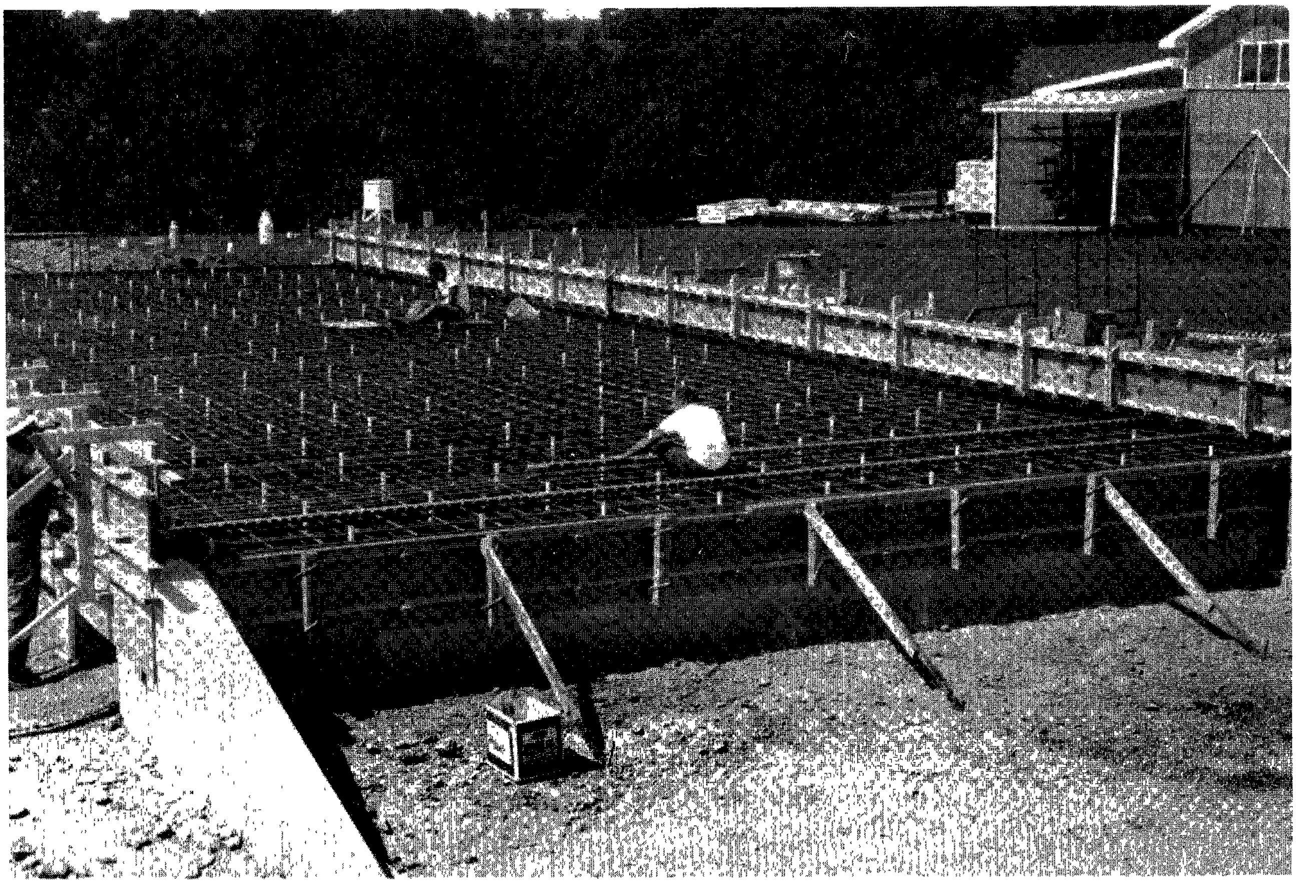

Plate 4.3. Installation of the lower access tube prior to pouring of concrete floor on the platform.

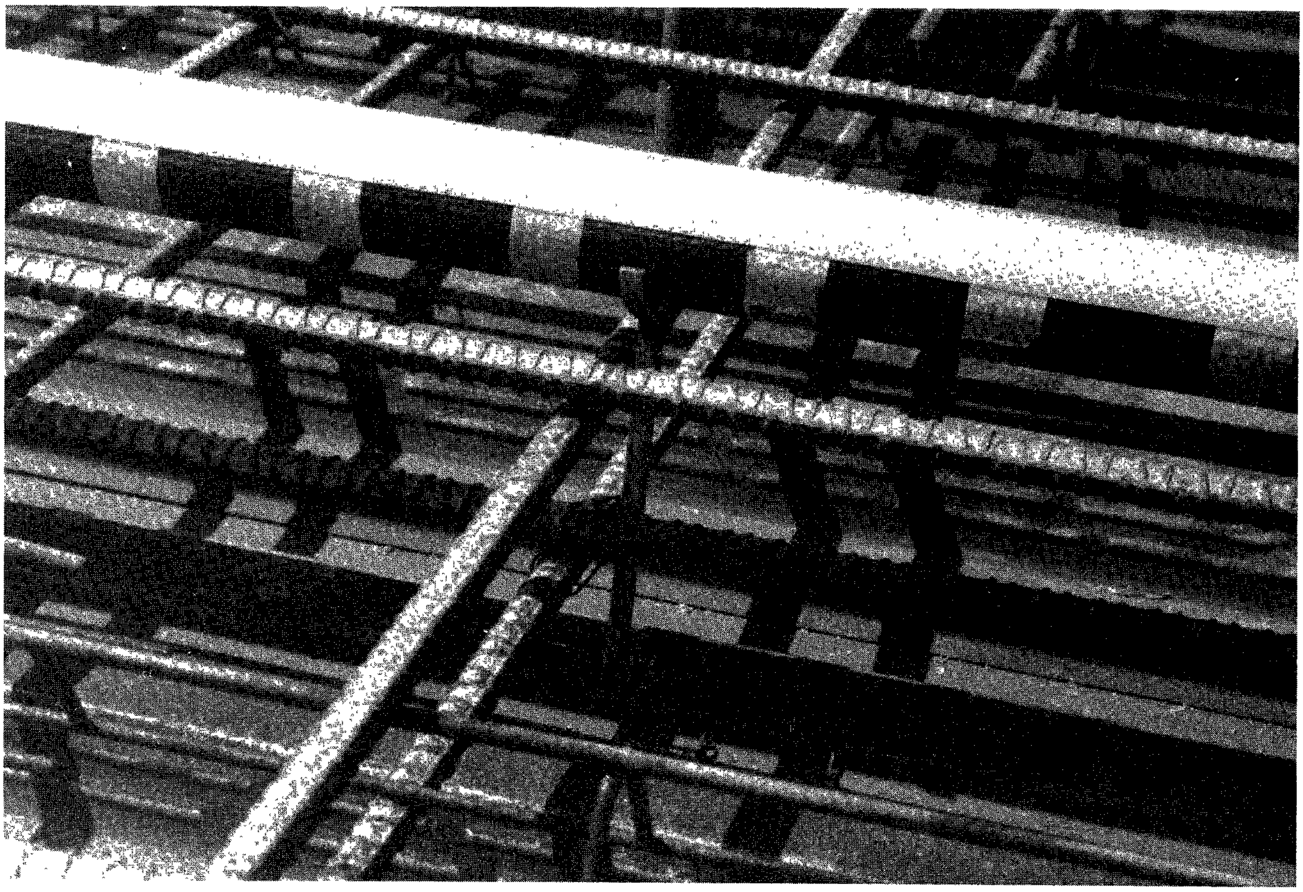

Plate 4.4. The 10m long access tubes were supported by brackets to keep them level.

Plate 4.5. Location of lower access tubes after concrete floor has been poured; spacers show where upper tubes will go after the installation of the clay liner.

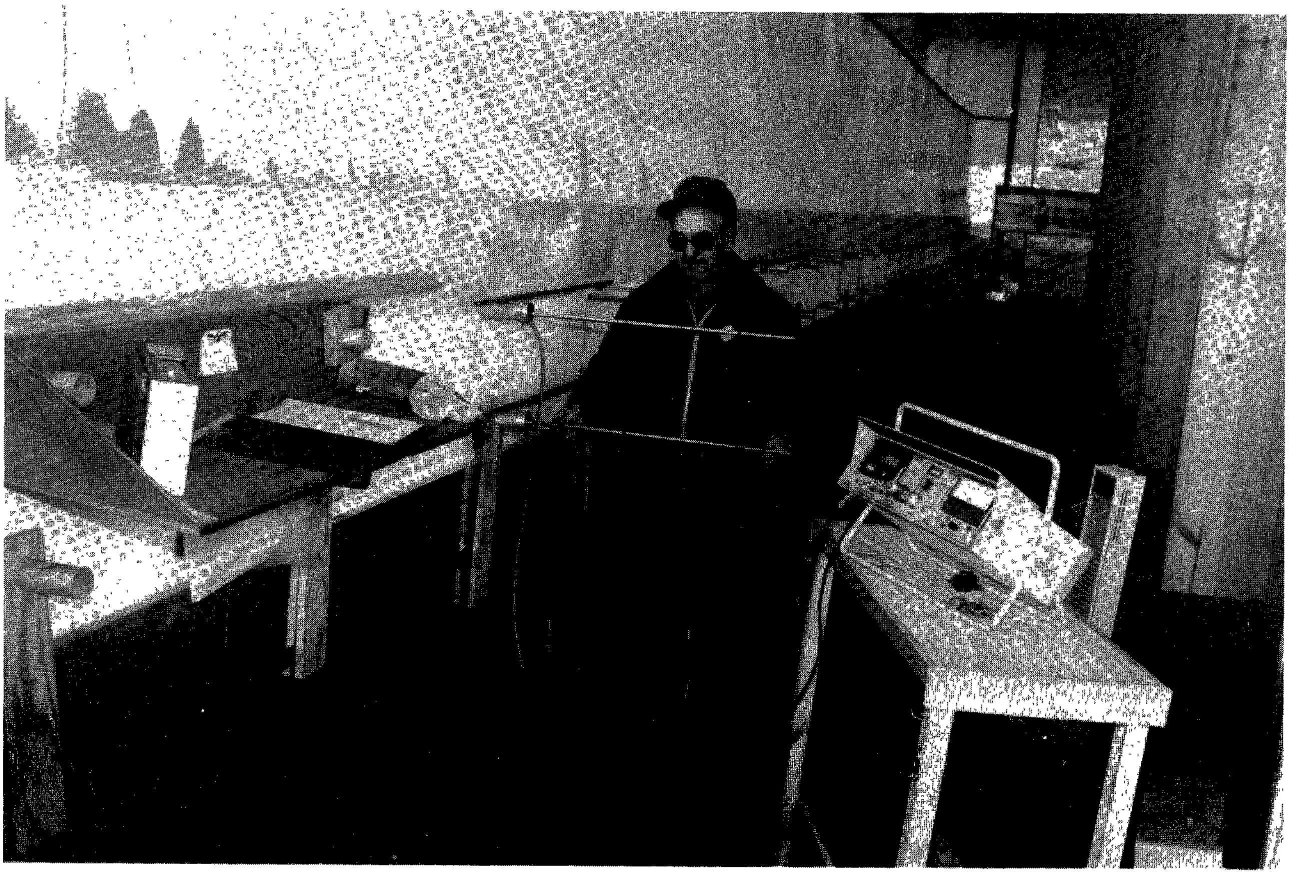

Plate 4.6. Measurement of density in horizontal access tubes with dual gamma gauge.

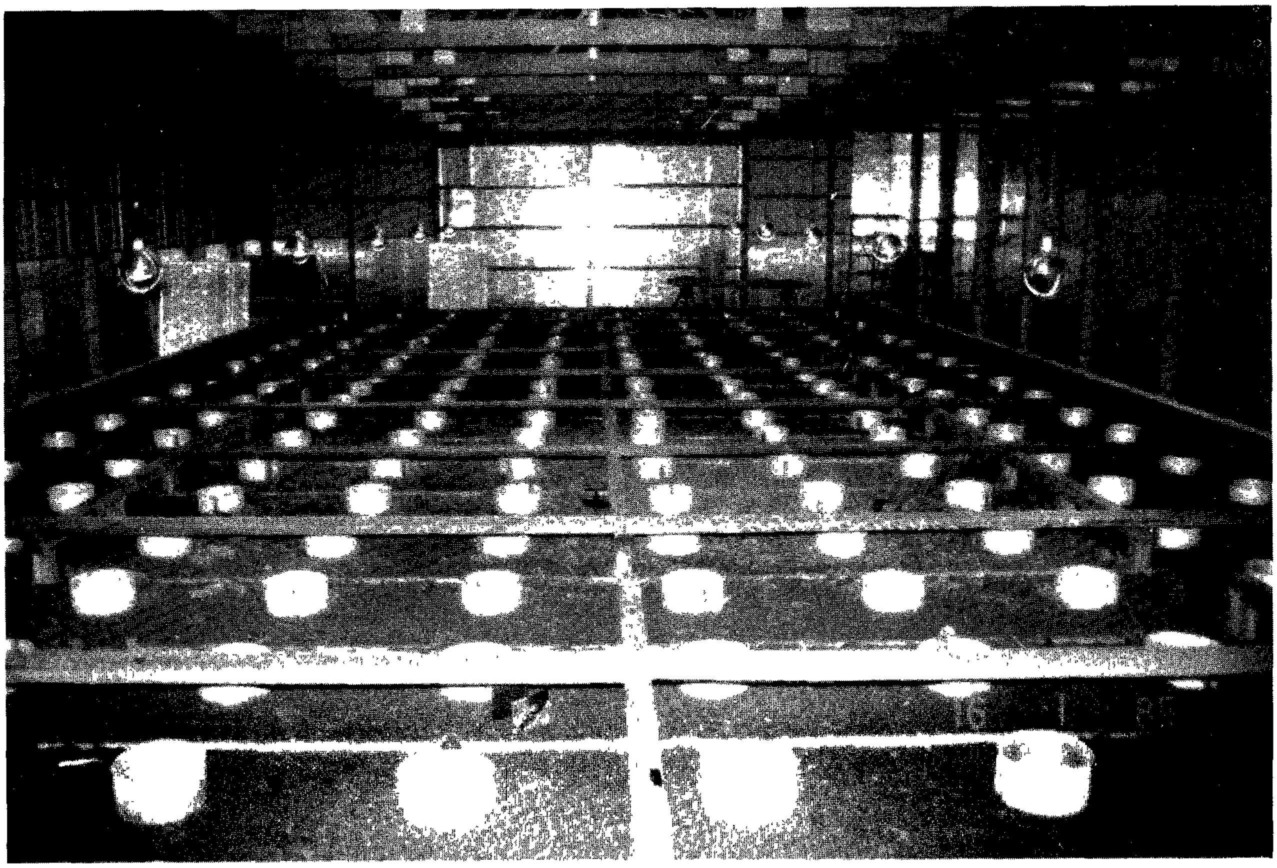

Plate 4.7. Distribution of infiltration rings on compacted clay liner, a few pedestals to monitor swelling can be seen in the background.

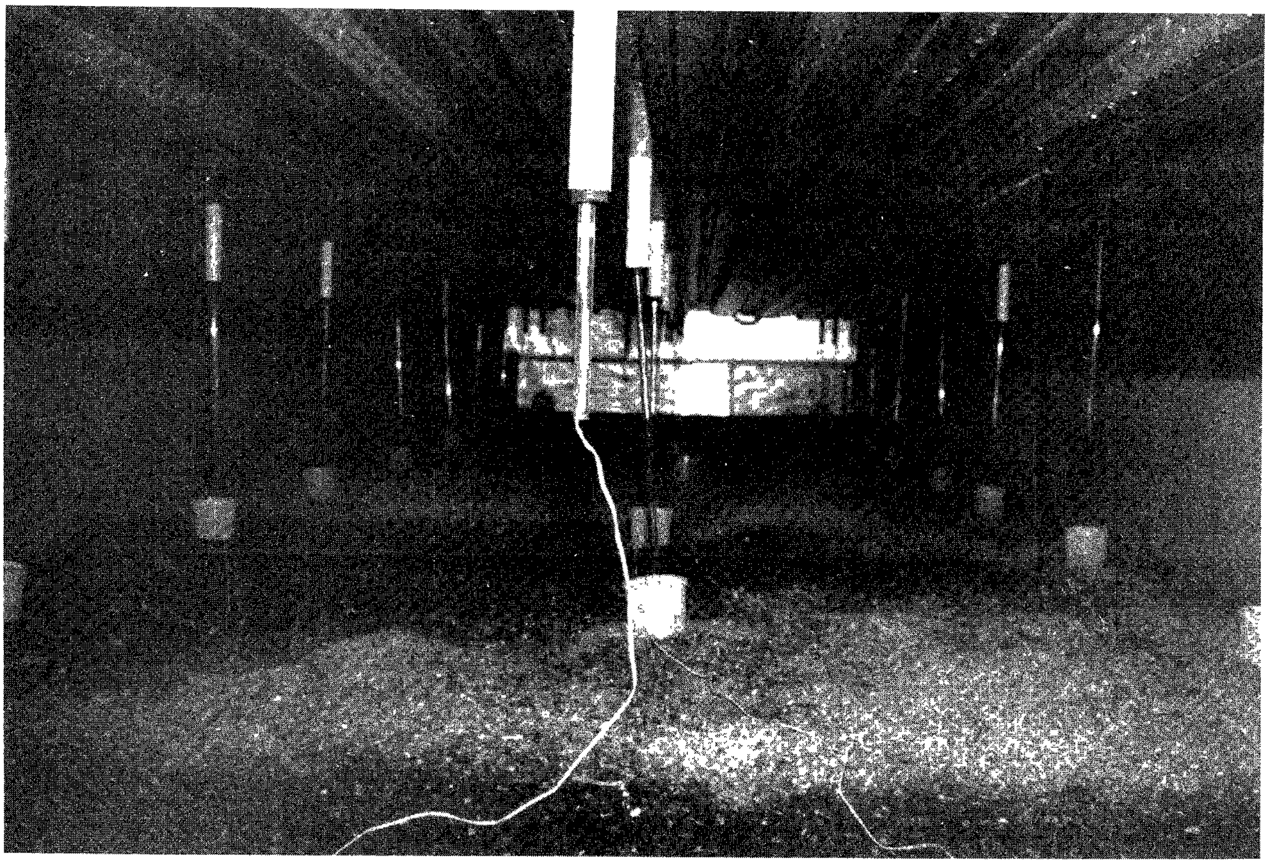

Plate 4.8. Distribution of outflow ports equipped with moisture blocks (hanging wires) to indicate early arrival of breakthrough water.

It was anticipated that 30cm diameter infiltration rings (Plate 4.7) and complementary network of outflow drains (Plates 4.3 and 4.8) will provide sufficiently rapid response to measure infiltration, compute hydraulic conductivity and estimate the distribution of macroporosity for a clay liner. Because inflow rates were anticipated to be slow, control of evaporation and maintaining of relatively constant temperature was thought to be important. Many more measurements were to be taken than are necessary, so that enough samples were available to estimate the minimum number of samples required to characterize variability. The design called for closing off both ramp ends of the liner testing platform and flooding the whole area. The final output of the study was to be a grid of inflow and outflow measurements, calculated conductivities and changes in bulk density and porosity over the area with depth, and with time. If areas of high permeability occurred a 1 x 1 m^2 grid of drains was to intercept the leachate.

Shrinkage and swelling of the liner system were to be monitored using square 10 x 10cm pedestals and a laser beam technique. Evaporation was to be measured with a class A pan and a number of smaller pans the same size as infiltration rings.

Following the ponding stage the clay liner was to be core sampled and hydraulic conductivities of cores, evaluated in the laboratory, were to be compared with those obtained from field ring and drain measurements and with overall flow rates through the liner.

Clay Liner Materials

The clay liner material consisted of commercially available B-horizon subsoil (10" to 60", 25 to 250cm) of Hubblersburg cherty silt loam found on the 3 to 8% slopes north of Roaring Springs and Highway 36 and 164 in central Pennsylvania. Typically, the subsoil extends to a depth of 60" (150cm) or more. It is yellowish red, friable cherty silty clay loam, silty clay, and cherty silty clay to a depth of 35" (90cm). At a depth of more than 35" (90cm) it is yellowish red, friable silty clay loam.

Normally included in this soil (5 to 10%) are small areas of Opequon, Mertz, Clarksburg, Morrison, and Wharton Variant soils. Permeability in natural state is considered to be moderate and available water capacity is high. The soil is very strongly acid throughout. The unified classification of the subsoil ranges from CL to CH (10" to 60", 25 to 150cm). It contains less than 5% of fragments > 3" (76mm), with 35 to 100% passing sieve #4, 60-95% passing #10, 55-95% passing #40, and 55-85% passing #200. Liquid limit ranges from 35 to 55% and plasticity index from 12 to 30%. Clay (< 2mm) ranges from 20 to 45%, bulk density from 1200 to 1600 kg/m^3 and in place permeability from 6 to 2 inches per hour (15 to 50mm, 40 to 140 x 10^{-7} m/sec). Available water is 12 to 16% by volume with pH within 4.5 to 5.5 range. Shrink swell potential is moderate and erosion potential is quite large. In general, organic matter is low (1 to 3%). Potential for frost action is moderate and risk of corrosion for steel and concrete is high to moderate, respectively. The soil is classified as clayey, illitic, mesic Typic Hapludult (USDA, 1981), Table 4.1 shows average properties of the B-horizon.

The site where the soil came from was mined commercially for clay. Our own analyses have shown it to be a CL type clay with,

Liquid Limit:	35% of water by weight
Plastic Limit:	23% of water by weight
Plasticity Index:	12% of water by weight

which compares reasonably well with values given by supplier. The material appears to contain quartz, K-feldspar kaolinite, illite and vermiculite. It is 47% clay, 45% silt, and 8% sand as given by the sedigraph measurements. The Standard Proctor test results and 95% confidence intervals results are shown for sieved and unsieved material in Figures 4.2 and 4.3. The optimum water content (by weight) was 18% by weight for both, and the maximum density is 111.5 pcf (1786 kg/m^3) for sieved and 114.5 pcf (1834 kg/m^3) for nonsieved material, respectively. Comparison with the moisture characteristic curve of the sieved material (Figure 4.4) shows that the optimum water content (at least in loose soil) occurred between 2 and 3 bars tension. What this means is that when initially water is ponded on the surface of a clay liner a very high water content gradient will be imposed across the clay-water interface.

TABLE 4.1. AVERAGE PROPERTIES OF THE B-HORIZON OF HUBBLERSBURG CHERTY SILT LOAM (TYPIC HAPLUDULT, ILLITIC OR MIXED MESIC) DEVELOPED ON LIMESTONE, FROM PSU GP-10 FILE

Property	Unit	Mean Value	Standard deviation
Total coarse fragments	% by wt	14.0	10.7
Coarse fragments	% by vol	9.5	11.0
Less then 2 mm	% by wt	86.0	10.7
Bulk density (clod)	kg/m^3	1510.9	132.0
Bulk density (< 2 mm)	kg/m^3	1488.1	125.3
Cole	cm/cm	0.017	0.009
Uncor 1/3 bar core	% by wt	25.0	5.4
15 bar, fragment	% by wt	17.7	3.4
pH water:soil, field	-	5.1	0.4
pH KCL:soil, field	-	4.2	0.4
Organic carbon (titratin)	% by wt	0.16	0.19
Calcium	% by wt	2.1	1.9
Magnesium	% by wt	0.9	0.7
Sodium	% by wt	0.1	0.0
Potassium	% by wt	0.2	0.1
Total bases	% by wt	3.4	2.2
Aluminum	% by wt	4.8	2.1
CEC:Ex acidity	me/100 g	9.9	2.6
Base saturation	% by wt	25.5	15.7
Fe_2O_3	% by wt	5.1	1.0
Kaolinite	% by wt	24	18
Illite	% by wt	52	18
Vermiculite	% by wt	8	3
Chloride	% by wt	5	-
Int.	% by wt	5	-
Talc	% by wt	10	6

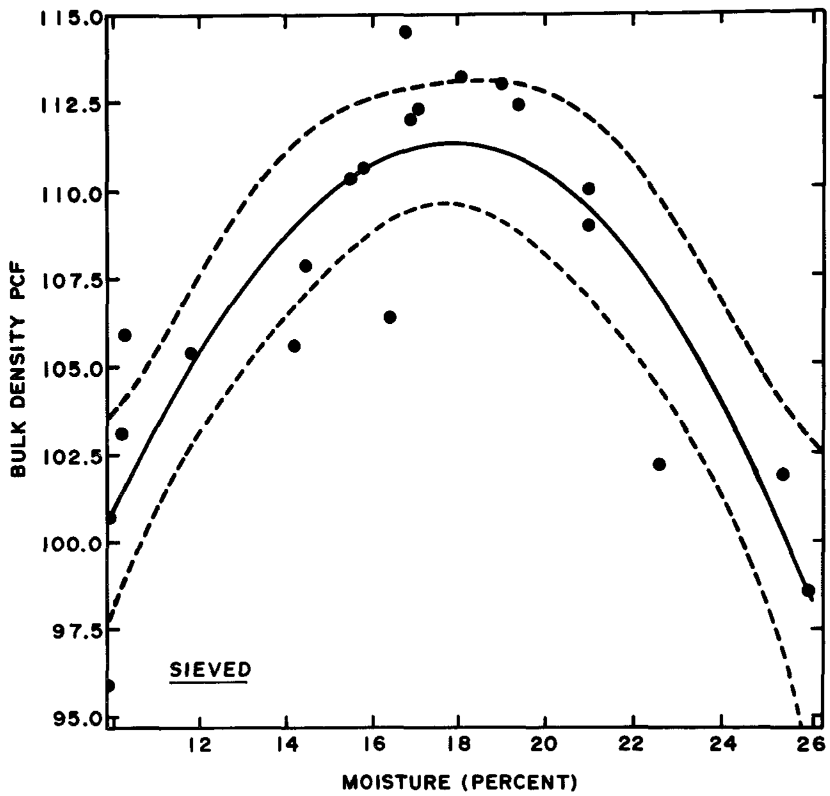

Figure 4.2. Standard Proctor test on sieved material.

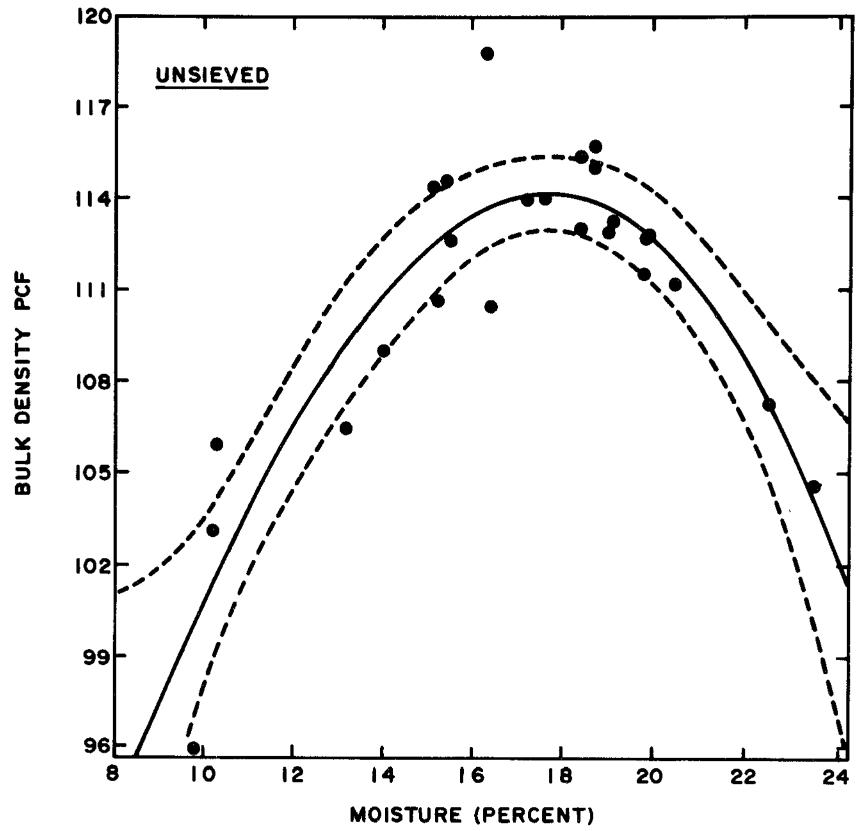

Figure 4.3. Standard Proctor test on nonsieved material.

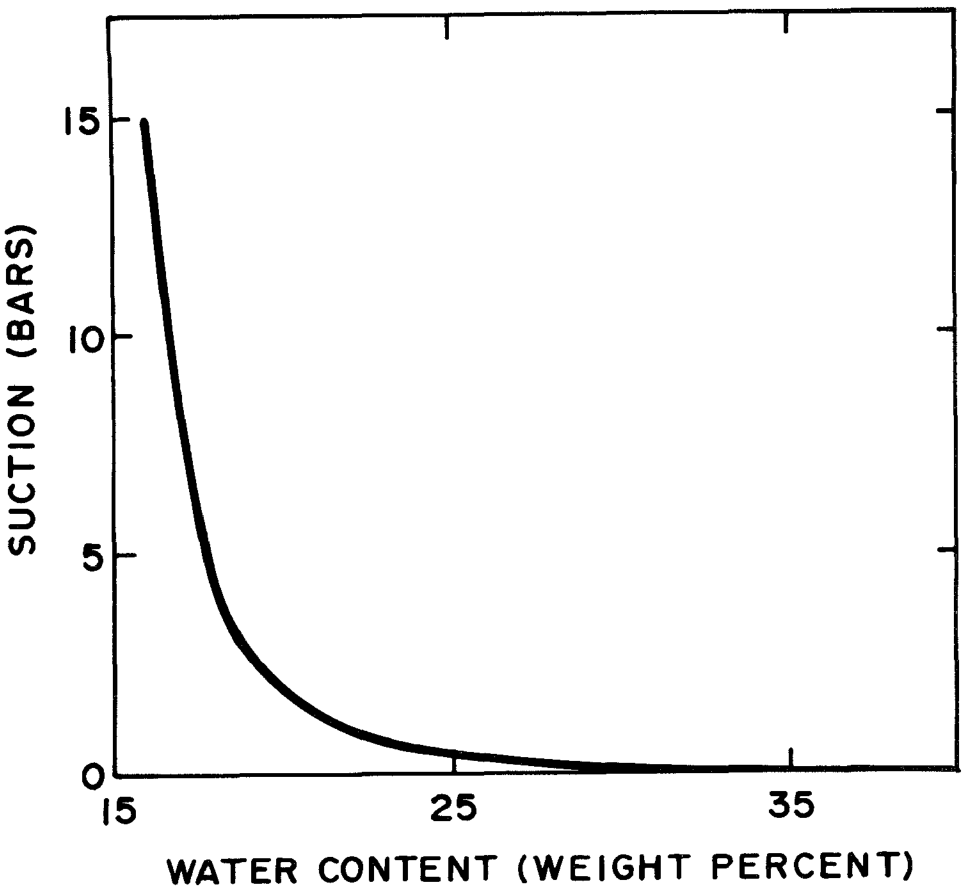

Figure 4.4. Moisture characteristic of the clay liner material.

Barrel Studies

Preliminary plans (Rogowski and Richie, 1984) called for installation of infiltration rings into the compacted clay liner and measurement of infiltration rate at 250 points over time. Since clay liner would be ponded, the procedure was to be essentially an adaptation of a double ring infiltrometer method and geometry to a large scale study. To test the procedure clay liner material was compacted in three 4" (10cm) lifts in large barrels (one-half of the 40 gallon drum) as shown in Plate 4.9. The compaction of the three 4" (10cm) lifts was accomplished using a scaled up version of a Proctor hammer (Plate 4.10). Infiltration rings (10", 25cm in diameter and 10" high) were made of galvanized 14 gauge metal with a rolled lip on top and were installed to the depth of 3" (8cm) in compacted clay by pounding a solid iron inset cover with a sledge hammer. The water was ponded over the surface to the depth of 2.5" (6cm). Plate 4.11 shows the experimental set up and Figure 4.5 gives the schematic diagram of the barrel, rings and the inner and outer constant head devices. To monitor potential wall flow effects, each barrel was equipped with a 46cm diameter inner compartment welded to the barrel bottom (Figure 4.5) which separated the outflow primarily from below the ring from the outflow percolating through the rest of material and down the walls of the barrel. The role of barrel study was two-fold. A barrel in one sense was a scaled up version of a Standard Proctor compaction mold. In another sense it was a scaled down version of a field facility.

Figure 4.6 shows the infiltration rate measured in the barrel rings by weighing the inner constant head device as a function of time. After the first 10 days the rate appeared to have settled to a steady 1×10^{-9} m/sec flow. For a scaled up version of clay liner we would expect a maximum initial rate of 100×10^{-9} m/sec would translate to a 75 ℓ/hr (400 gal/day) inflow (on a 10 x 25m area) at the beginning of experiment which would decrease to about 0.75 ℓ/hr (4 gal/day) inflow after the first 10 days assuming no high permeability zones. Figures 4.7 and 4.8 show cumulative infiltration and outflow as a function of time, respectively. While infiltration stabilized within the first 10 days, it took about 2 months for outflow to decline.

Figure 4.7 corroborates, and presents in a different way results of Figure 4.6. It appears that during the first week as much as 38mm of water was likely to infiltrate a clay liner. Thus, if we were to pond 10cm of water over the 10 x 25m liner (21,000 ℓ, 5000 gal) we would initially need an additional 8000 ℓ (1800 gal) to keep the level constant.

Figure 4.8 illustrates barrel #1 outflow during 100 days of operation. Results show no outflow during the first 13 days. Translating this to potential performance of the full scale facility we expected after the first 10 days an outflow of ~ 25 mℓ/drain/day which could drop to as little as 7 mℓ/drain/day after the first two months. Figures 4.9 and 4.10 show inflow and outflow into barrel in terms of pore volumes. After about three months of ponding only 0.8 (cm^3/cm^3) of a pore volume has moved into the compacted clay, while less than 0.1 (cm^3/cm^3) of a pore volume has moved out.

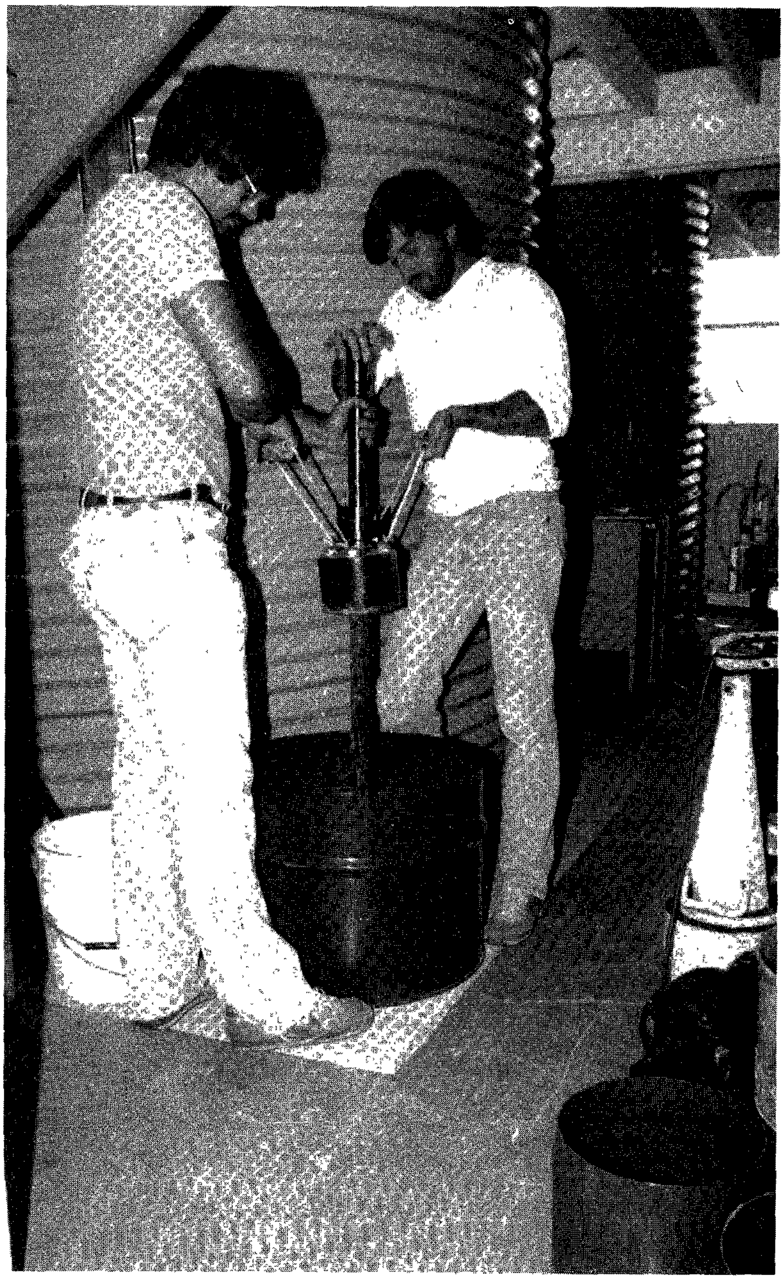

Plate 4.9. To test double ring infiltrometer geometry clay liner material was compacted in barrels (half drums).

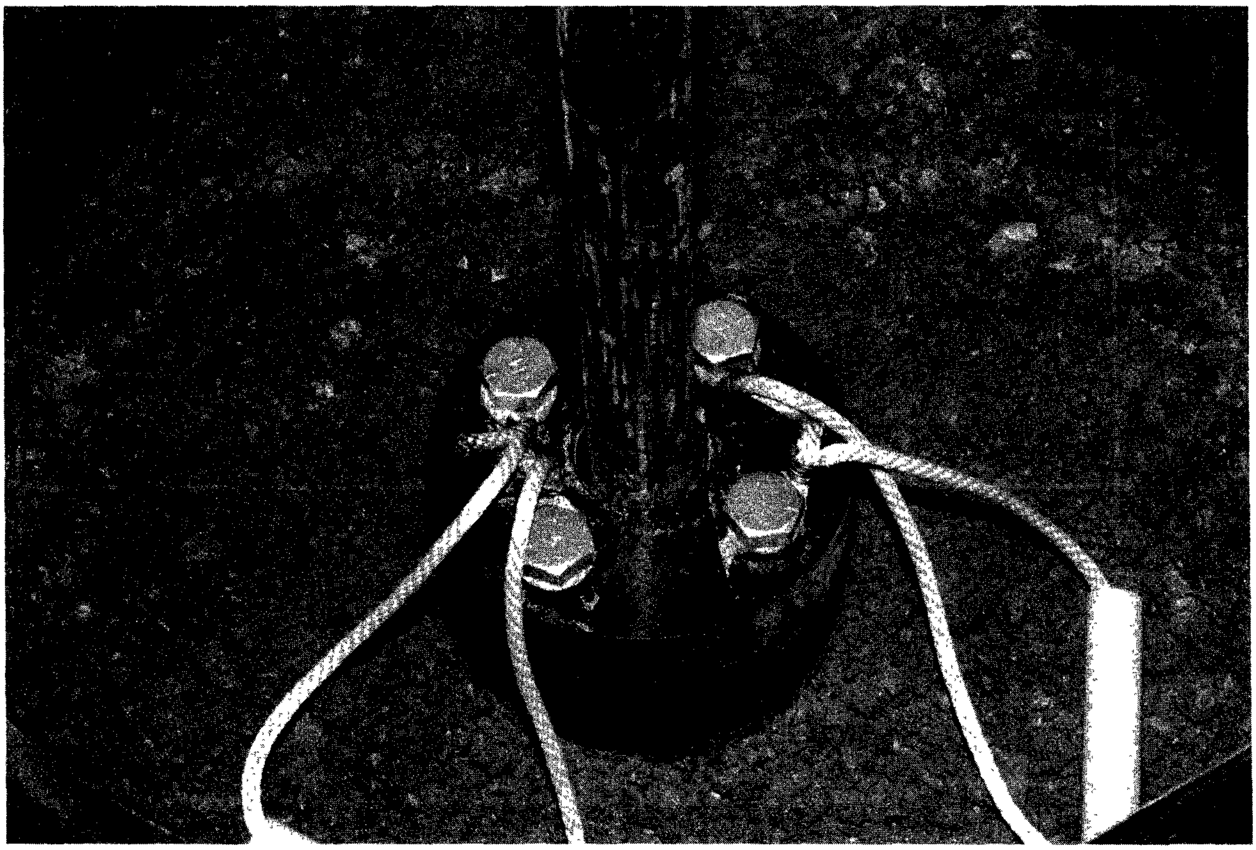

Plate 4.10. Clay liner material was compacted using a scaled up version of Proctor compaction mold and drop hammer.

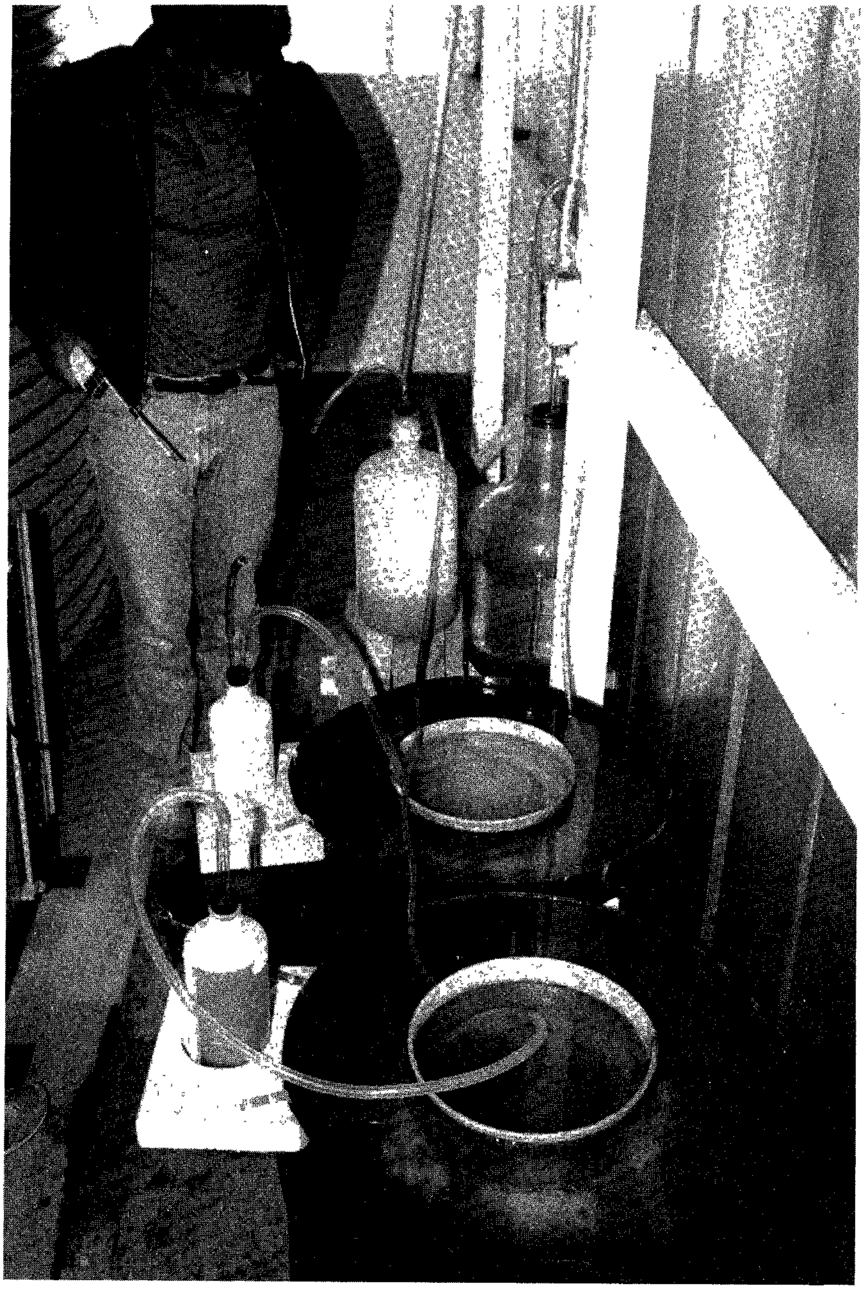

Plate 4.11. An experimental set up to measure infiltration rate on compacted clay liner material.

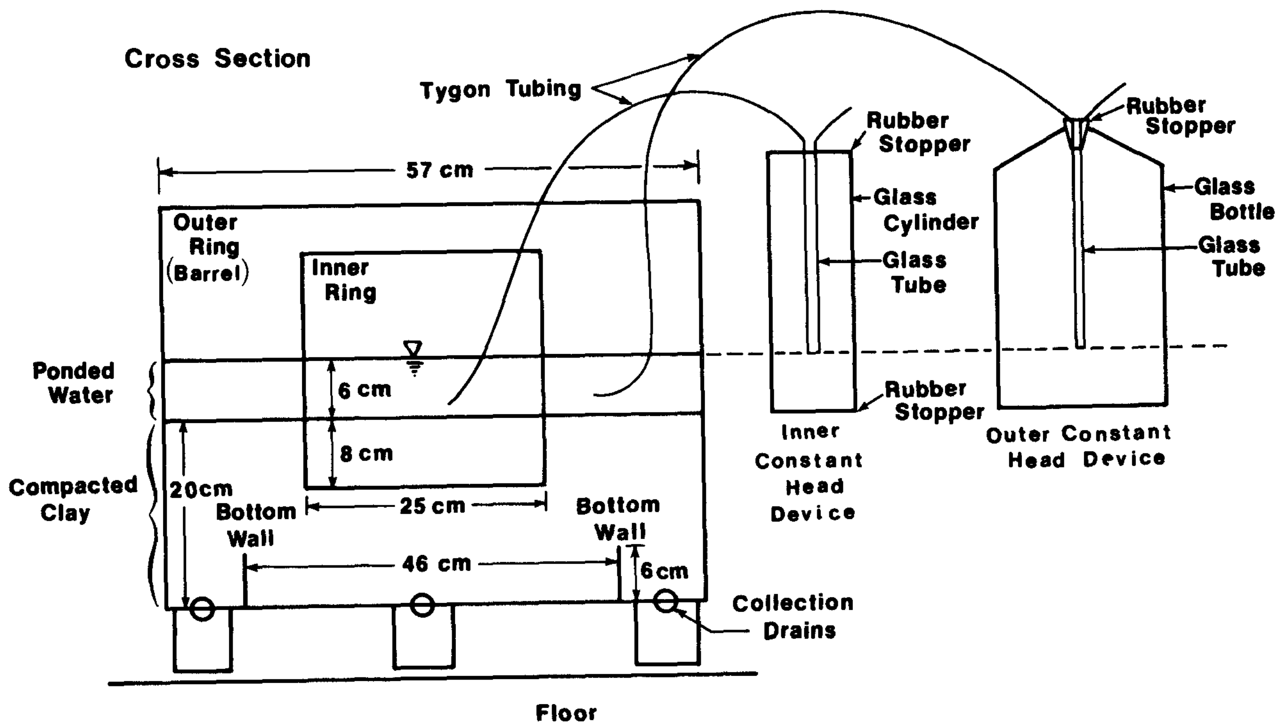

Figure 4.5. Permeability and infiltration measurement: schematic diagram of the barrel, infiltration ring, inner and outer constant head devices.

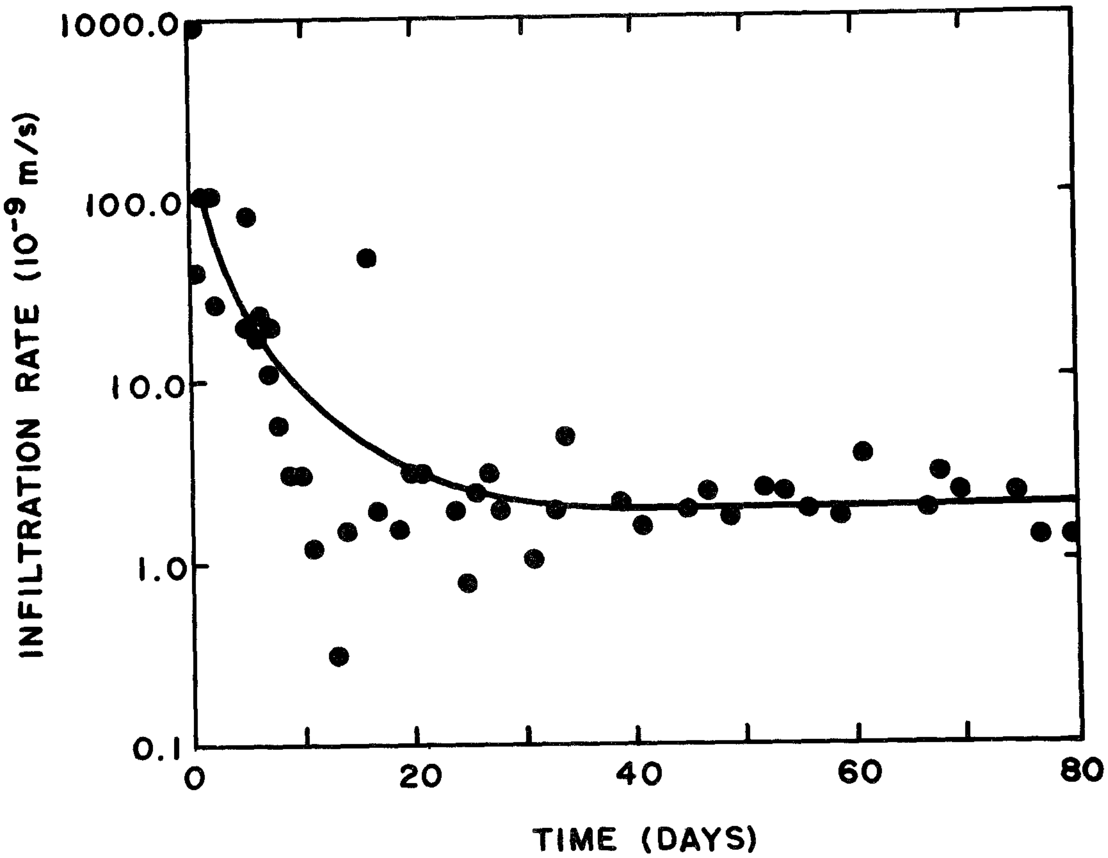

Figure 4.6. Infiltration rate x 10^{-9} (m/s) in the inner ring of barrel #1 plotted as a function of time (days).

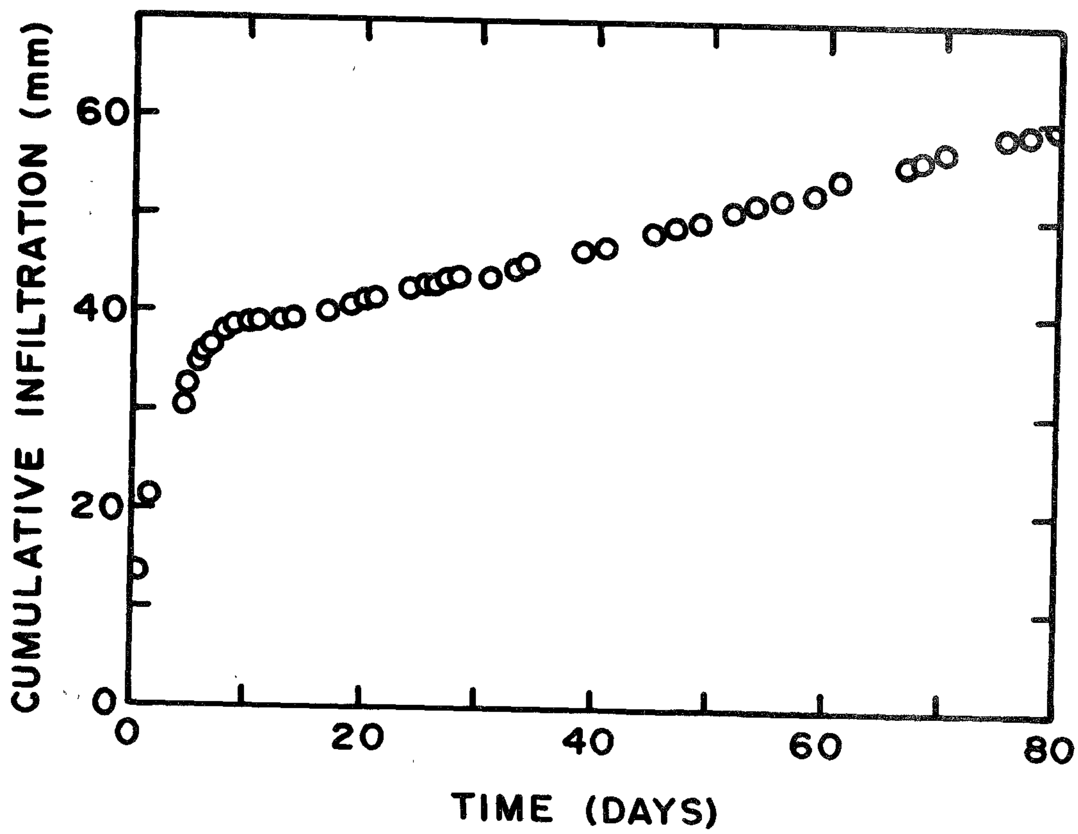

Figure 4.7. Cumulative infiltration in the inner ring of the Barrel #1 plotted as a function of time (days).

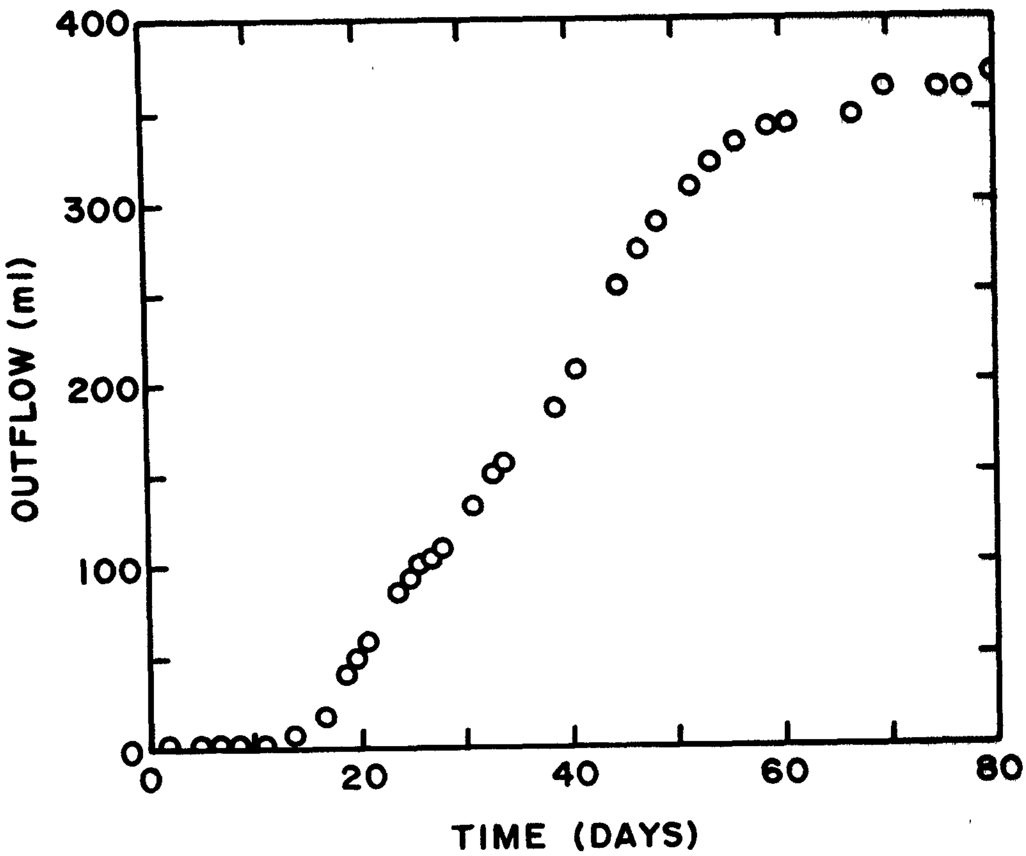

Figure 4.8. Cumulative outflow from the inner bottom compartment of the Barrel #1 plotted as a function of time (days).

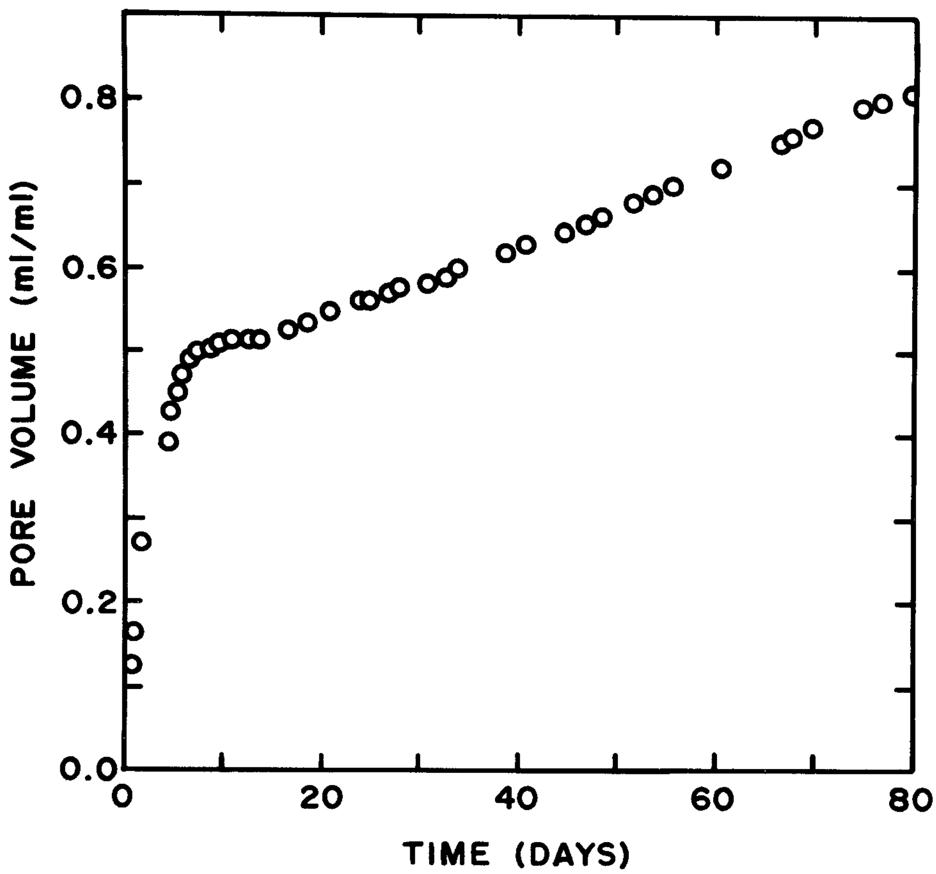

Figure 4.9. Cumulative inflow in the inner ring of Barrel #1 as a function of the total pore volume below the infiltration ring plotted as a function of time (days).

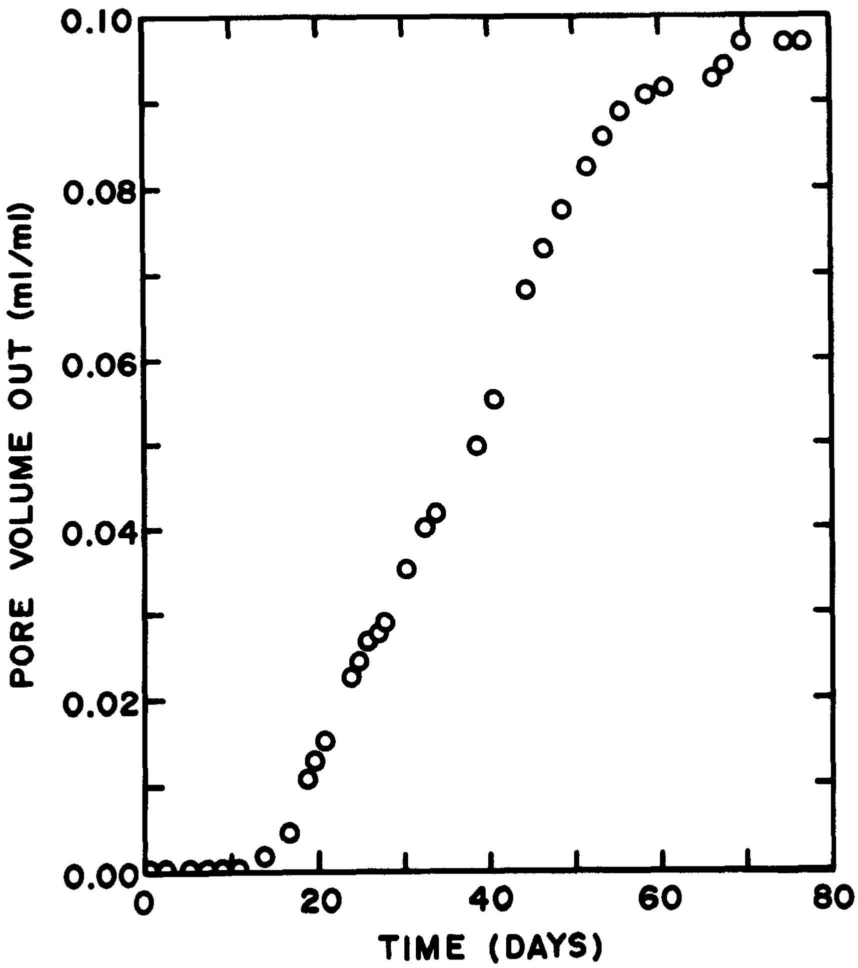

Figure 4.10. Cumulative outflow as a function of the total pore volume above the bottom inner compartment plotted as a function of time.

Caisson Prototypes

Caisson #1

Caisson studies were to test equipment and methodology. The first study initiated towards the end of summer '84, was to test a prototype liner, construction, and the experimental methods to be used in the full scale liner facility. Schematic diagram of the caisson set up is shown in Figure 4.11, Plates 4.12, 4.13 and 4.14. Four collection ports (below the liner), three sets of horizontal dual access tubes, four 1 x 1 ft banks of vertical access tubes, six infiltration rings and constant head devices, and square pedestals to measure swelling were installed in a compacted 1 ft (30cm) thick clay material. The prototype was compacted by hand in three lifts. The surface of each lift was scarified before a new lift material was applied. Table 4.2 gives average density and water content measurements for each lift obtained with surface and depth nuclear gauges.

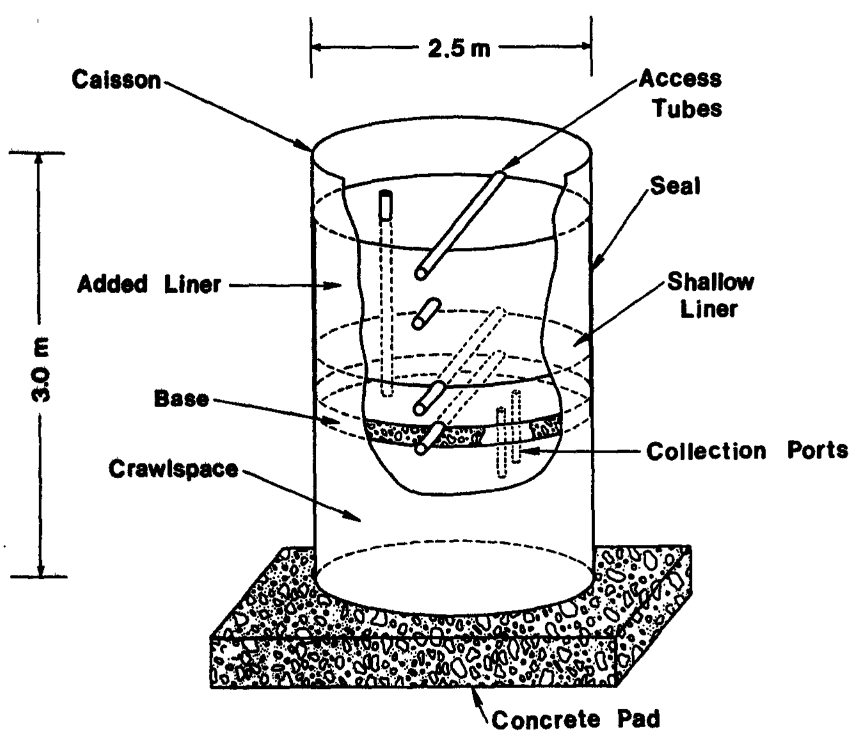

Figure 4.11. Schematic diagram of the first caisson study.

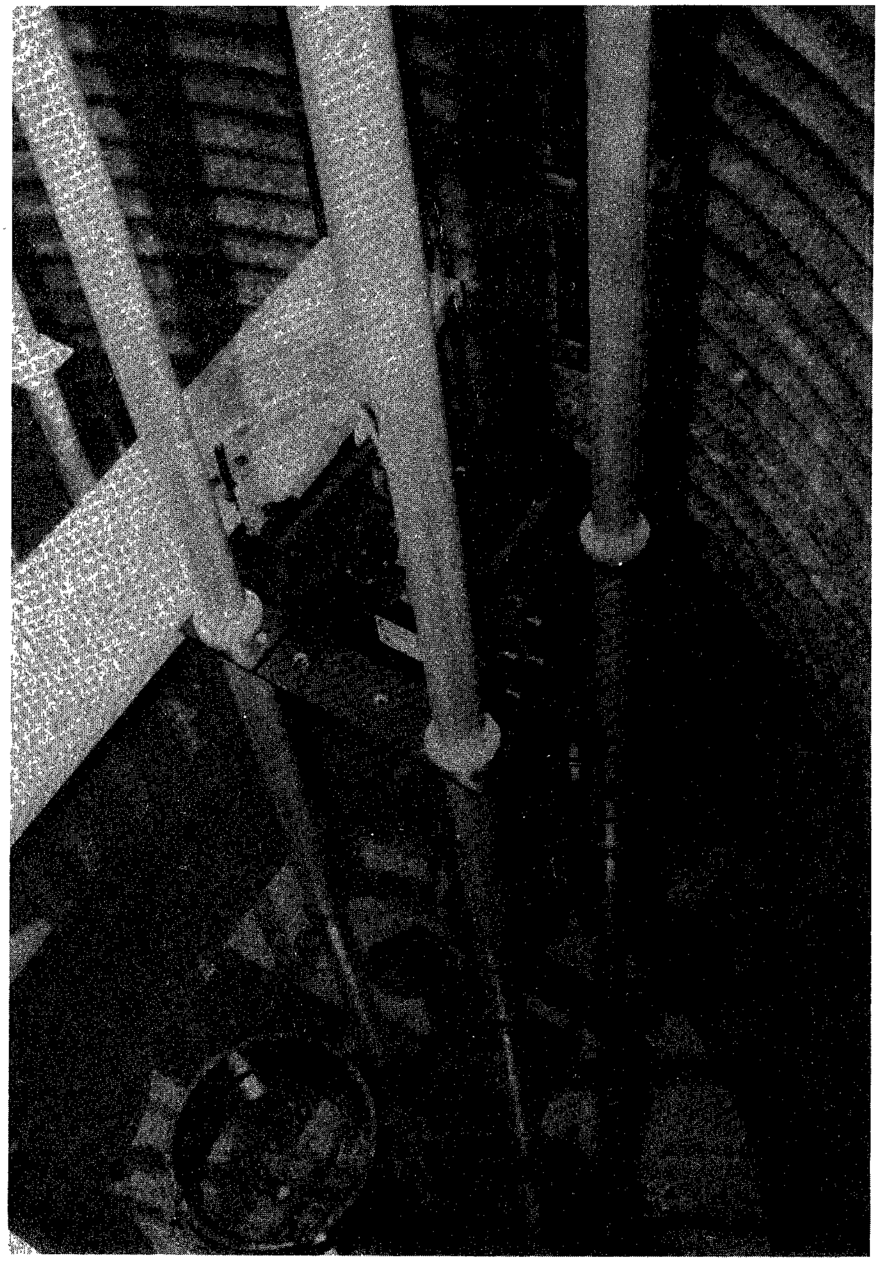

Plate 4.12. A bank of vertical access tubes for measurement of moisture and density with depth, and a ring for measuring infiltration rate in flooded caisson.

Plate 4.13. Additional details of optocator positioning and of the optocator pedestal for measurement of clay swelling, infiltration rings and access tubes shown in a flooded caisson.

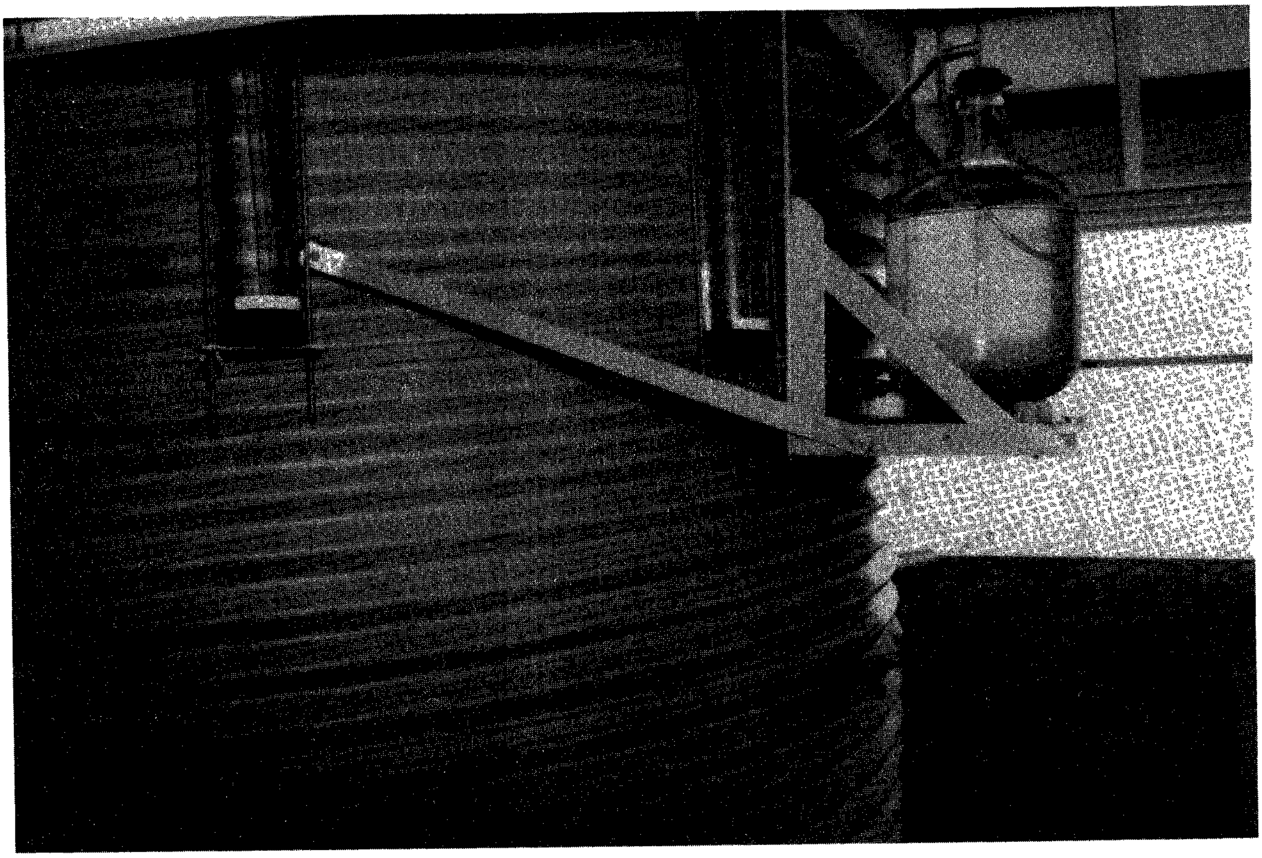

Plate 4.14. Constant head devices (cylinders) for infiltration rings and for the caisson itself (carboy) were placed on the outside of the caisson.

TABLE 4.2. AVERAGE SURFACE AND DEPTH MOISTURE AND DENSITY READINGS

Lift		Dry Density	Water Content
		kg/m^3	kg/kg
		Surface probe	
#1	5/31/84	1533 ± 85	25.5 ± 1.3
#2	6/1/84	1581 ± 39	23.7 ± 1.2
#3	6/4/84	1500 ± 42	23.7 ± 1.1
		Depth probe	
10 cm	7/13/84	1615 ± 71	14.5 ± 2.4
20 cm	7/13/84	1504 ± 81	23.8 ± 1.4

The first three readings for each one of the three lifts in Table 4.2 were obtained with a surface probe at six locations for each lift. The last two readings were made with depth moisture and density probes at 16 locations and two depths (10 and 20cm). The 20cm density readings corresponded reasonably well to the surface probe readings for lift #1, #2 and #3. Lift #3 readings on 6/4 appear considerably wetter than the 10cm reading taken with depth moisture probe on 7/13. Admittedly, the depth gage reading was taken six weeks later, however surface gauge readings for lifts #1 and #2 show results similar to depth gage readings at 20cm. Since lift #1 and #2 soil was quite wet when compacted, we have allowed lift #3 soil to dry in place with turning before compacting. It was considerably easier to compact. It may be that surface moisture gauge readings with the surface gauge are in error. One probable reasons could be that during compaction liner surface may actually be somewhat wetter than deeper layers and the neutrons from a surface gauge are more readily backscattered by this surface layer indicating higher water content and lower density than actually present. Following ponding of water over the compacted surface, underdrains began to flow almost immediately. There also appeared some leakage around the perimeter of concrete slab. The flow diminished to manageable proportion after a day as the clay begun to swell.

Liner instrumentation after the clay was compacted took a long time. Placement of access tubes, rings and optocator pedestals (swelling measurement by laser beam reflectance) as well as initial measurements before water was added was very time consuming. It also appears that some surface drying took place (i.e., water content for 10cm depth in Table 4.2). Instrumentation of a full scale clay liner will also take a long time. To minimize drying, compacted liner will need to be covered with a surface layer of sand.

Laser beam (optocator) was switched on as water was added to liner surface to measure swelling of clay in time. Figure 4.12 shows the results obtained as percent of liner thickness. Observed swelling was very rapid during the first hour following ponding amounting to about 1% change of elevation at the clay surface. The swelling forced two infiltration rings and a horizontal access tube (surface) out of the soil.

Figure 4.13 shows the comparison between cumulative infiltration rate for the rings in the caisson study and the results previously obtained for the barrels. Results suggest that the infiltration are likely to detect differences in infiltration over the surface of the full scale liner.

The results also indicated that evaporation rates as measured with class A pan will be on the order of 1×10^{-9} m/sec. Consequently, evaporation losses particularly at the lower rates of infiltration appeared to be significant and needed to be accounted for in the full scale liner.

Figure 4.14 shows the distribution of water content in time in one of the access tubes at 10 and 20cm depth following compaction. The results for other access tubes were very similar. In general, prior to ponding the drier top layer (10cm) became wetter while the bottom layer (20cm) became drier. When caisson was ponded on the 41st day after compaction water content in both layers appeared to increase very rapidly. Subsequent gravimetric sampling failed to substantiate this apparent increase of water content. The explanation however may be that water infiltrated preferentially next to the tubes

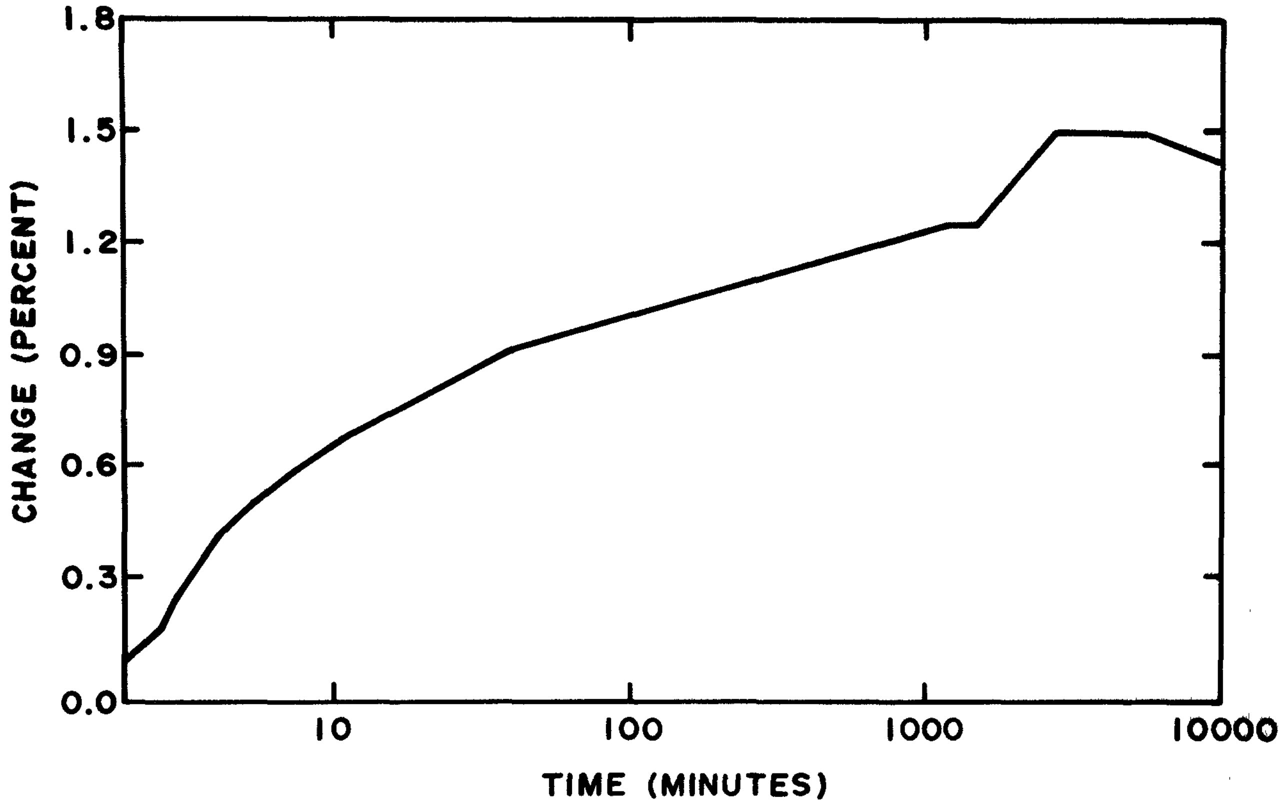

Figure 4.12. Swelling of clay liner given as percent of liner thickness and plotted as a function of time.

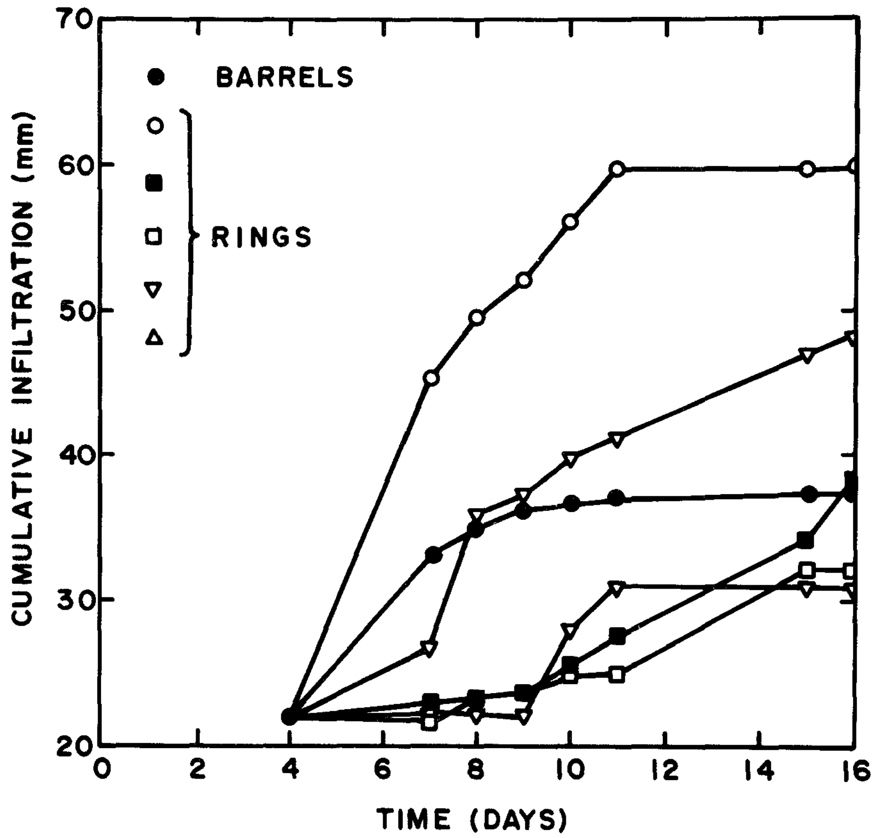

Figure 4.13. Comparison between cumulative infiltration in barrel #1 and caisson rings.

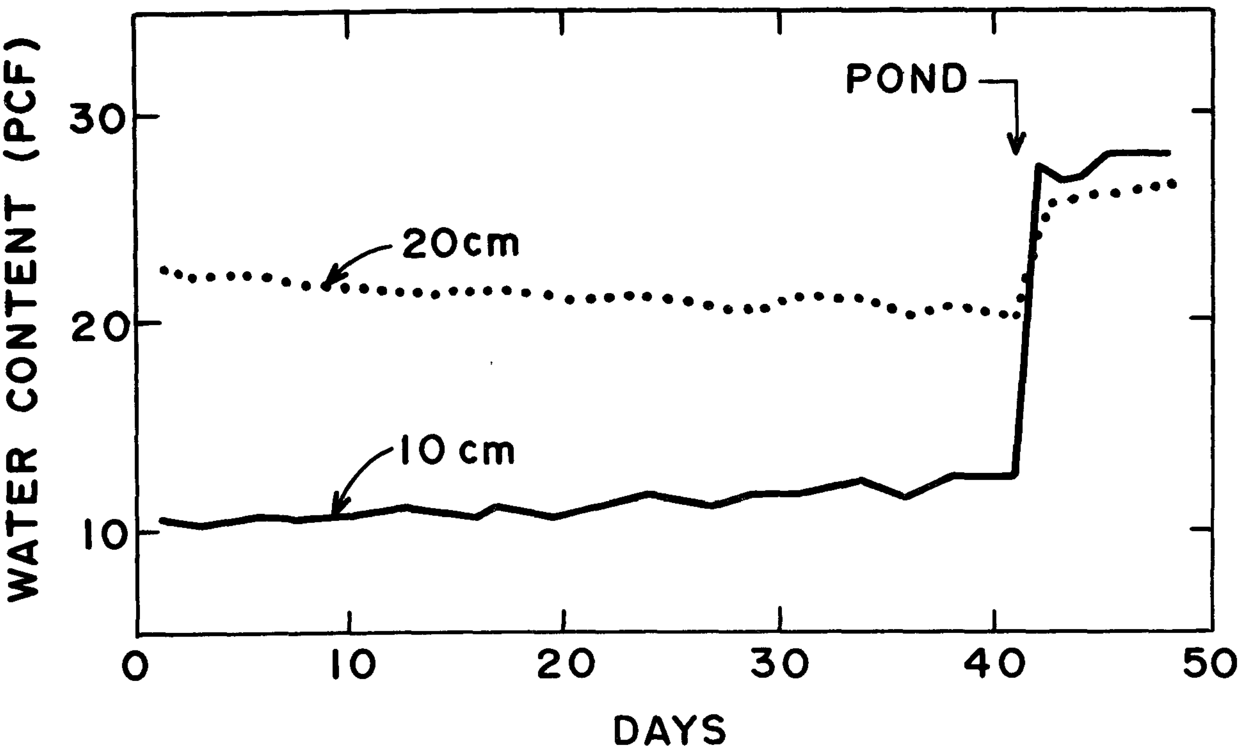

Figure 4.14. Typical water content with time (access tube #1), caisson was flooded 41 days after being compacted.

coating them with a thin sheet of water which the backscattered neutrons from the depth moisture gauge picked up as water content of that layer. We have observed that in the process of swelling two infiltration rings and one horizontal access tube were forced out of a soil. High moisture readings along the access tubes may be related to disturbance due to swelling.

Using the depth density gauge which measures density by backscatter of photons in a sphere around the source, the average density of both the 10cm and 20cm layer was 1831 kg/m^3. After flooding the density in the 10cm layer dropped to 1487 kg/m^3 and in the 20cm layer remained about the same. The drastic decrease in density with a corresponding increase in total porosity most probably reflected the swelling of the topmost layer rather than the time passage of a wetting front.

While backscatter geometry yields an average heavily weighted by the density of material adjacent to the gauge access tube, direct transmission geometry measures the average density in a thin pyramidal wedge between the source and the detector. When density was measured using direct transmission gauge there was little or no change at 10 or 20cm depths when water was ponded on the surface. A slight drop in total pore space (TPS) and more frequent fluctuations in apparent total pore space was all that was observed.

At the close of cassion #1 study, direct transmission depth density readings were taken in all pairs of access tubes at 1" intervals. Results showed that density near the surface appeared to decrease and TPS appeared to increase suggesting swelling within the top two inches and little or no change elsewhere following 16 days of ponding.

During this preliminary test, access tubes were also placed horizontally, one at the top and one at the bottom of compacted clay material. Using dual gamma gauge, direct measurements of bulk density in 6" (15cm) intervals along each tube were made. Total pore space (TPS) values for the horizontal readings appeared higher next to the wall where it was difficult to compact the clay and lower across the middle where better compaction was achieved. Marked response to flooding (41 days) was observed, rapidly reducing the total pore-space available before ponding. Differences in density and TPS may also indicate zones of varying extent of compaction which would be more, or less permeable than the rest of the compacted area.

Computed mass balance for water in caisson #1 study showed that about 5% of water added could not be accounted for. Results suggested that the full scale research facility be scrupulously sealed along the sides and bottom before a liner was installed. It was decided first to waterproof the sidewalls at the full scale facility, and then apply the foundation coating on the inside. Commercially available panels of Vol-Clay (Wyoming Bentonite) were then to be placed between the liner and the wall to the level above the second access tube and the sand layer. In particular, the space around each horizontal access tube would have to be sealed with Vol-Clay. Vol-Clay has the property that when wetted it expands to 6 to 14 times the volume thus filling and closing any open voids at the clay wall interface.

After ponded water was drained from the caisson #1 prototype study, the caisson material was sampled on a 6" x 6" grid (15 x 15cm) with a Veihmeier tube at four depth increments 0 to 3" (8cm), 3" to 6" (15cm), 6" to 9" (23cm), and 9" to 12" (30cm) in order to verify data obtained with nuclear gauges and to substantiate hypothesis of leakage next to vertical access tubes. The samples were dried immediately in the microwave oven and gravimetric water contents were determined. In addition, samples were also taken between access tubes, to see if water contents were indeed as high as read with nuclear moisture gauge; next to access tubes to verify the hypothesis of leakage; and of the first four inches in 1" (2.5cm) increments to see how far the wetting front has progressed.

Results are given in Table 4.3 and show that there was essentially no difference in water content among the access tubes and elsewhere on a 6" x 6" grid. The surface 1" (2.5cm) appeared the wettest and most crumbly, probably because of swelling. Results for water content next to the access tubes were not conclusive. Although the bottom 6" (15cm) were wetter than soil in other areas the top six inches were not. However, during sampling the material next to the tubes appeared considerably wetter. It should be remembered that a Veihmeier tube has a bulge; consequently, a vertical sample right next to the access tube is in reality taken ~ 0.5cm away, far enough to miss the wettest zone. Gravimetric sampling thus failed to substantiate the apparent increase in water content observed in all access tubes and measured with a nuclear probe.

TABLE 4.3. RESULTS OF GRAVIMETRIC MOISTURE SAMPLING OF THE COMPACTED CLAY LINER IN CAISSON 1

Depth (inches)	Mean Water Content	Std. Dev.
	--------- % by weight ----------	
0-3	22.6	2.5
3-6	20.0	1.8
6-9	21.0	1.5
9-12	19.8	2.2
	Between access tubes	
0-3	22.3	2.4
3-6	20.1	1.4
6-9	21.8	1.5
9-12	19.6	1.6
	Next to access tubes	
1-6	22.1	1.7
6-12	23.1	0.6
	4 inch depth	
0-1	25.2	4.3
1-2	21.5	1.8
2-3	20.0	2.5
3.4	19.8	2.3

Caisson #2

Based on our experience with Caisson #1 study an improved version (Figure 4.15) of the prototype was designed and tested. The geometry was that of a concrete rectangular box contained within the caisson. The new design incorporated an inner and outer bottom compartment similar to that used in barrel studies to separate any outer wall flow from inner flow. Separate drains were installed for each area. The design incorporated inflow and outflow pipes to monitor infiltration and mechanized compaction (Plate 4.15), rather than manual compaction as in cassion 1 to achieve higher levels of compaction closer to the projected proctor maximum. The inflow pipe drained very slowly into a recording rain gauge, while the outflow pipe emptied into another recording rain gauge, the difference between the two corrected for evaporation constituted infiltration. Prior to the addition of clay, the bottom of the prototype was covered with burlap and on the sides were four removable wooden wedges (Plate 4.16). Following compaction (Plate 4.15) the wedges were lifted out and the space between the soil and the wall was filled with a 1:1 mixture of fine sand and Vol-Clay, moistened as it was packed.

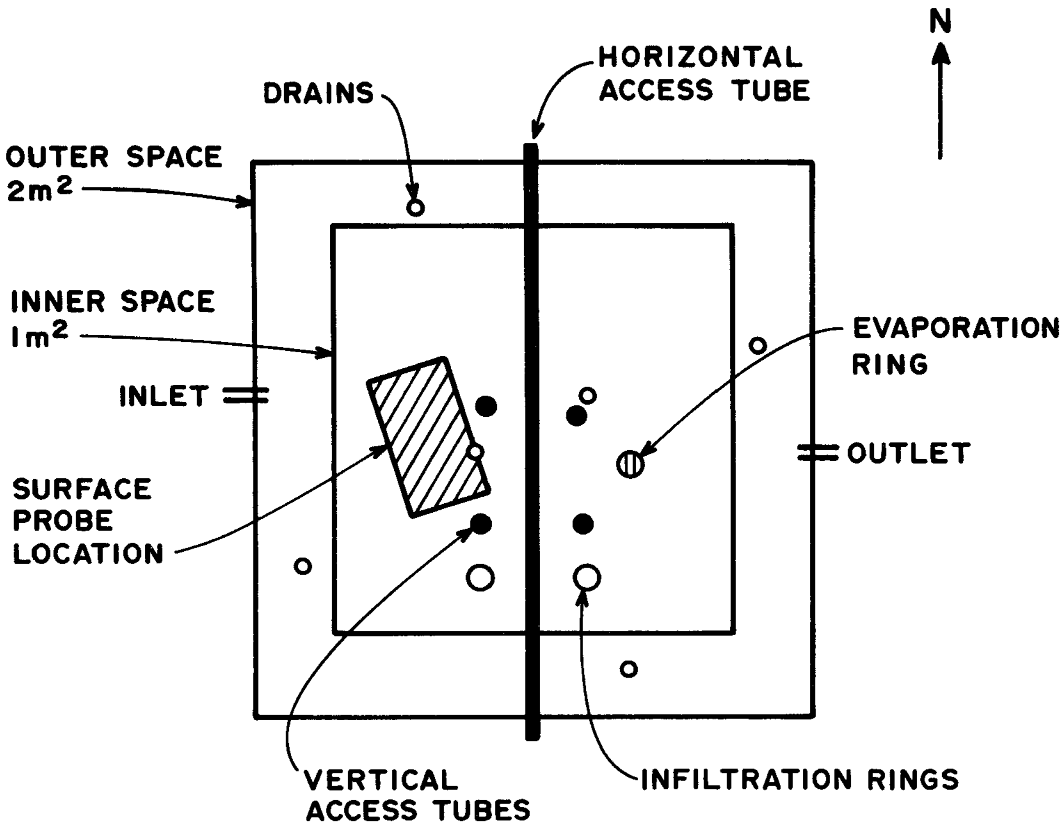

Figure 4.15. Improved version of clay liner prototype.

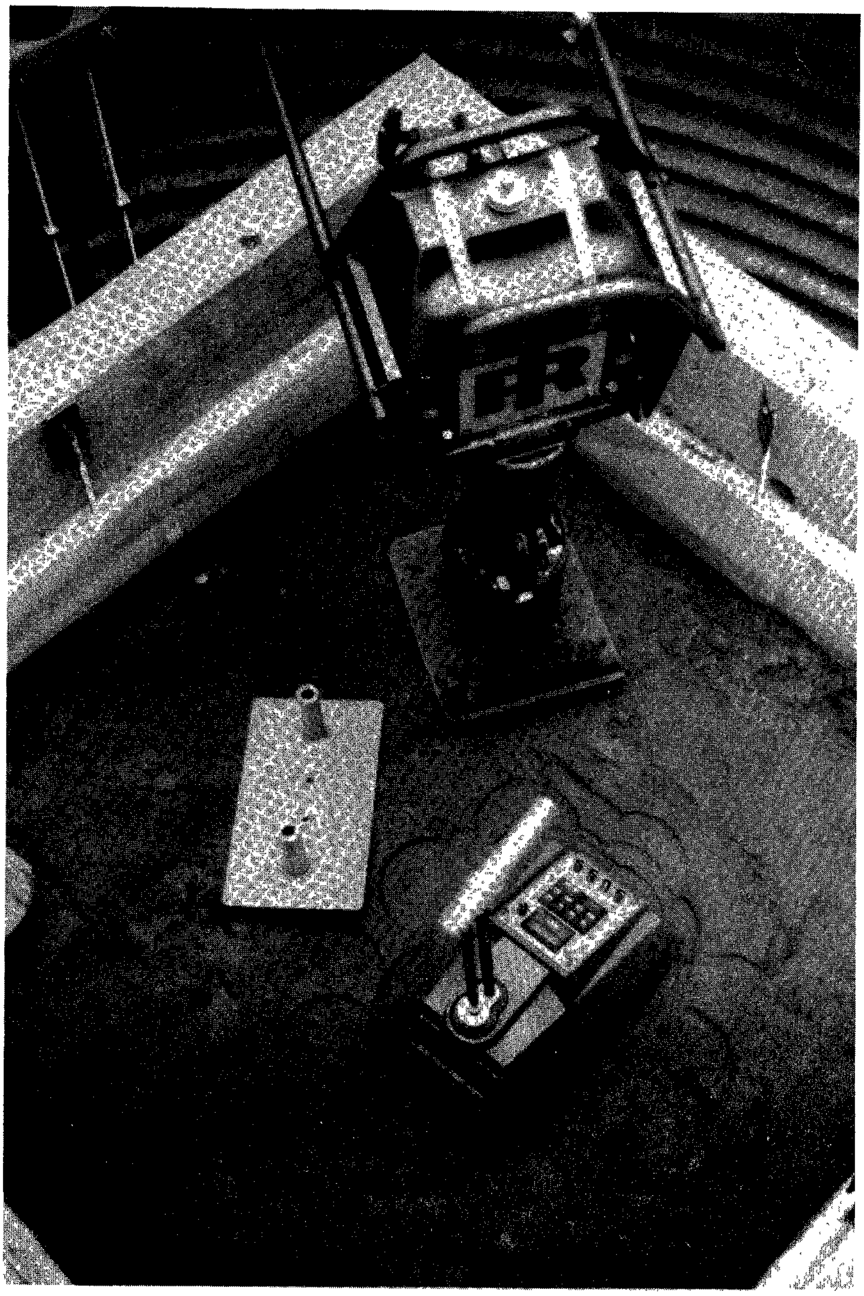

Plate 4.15. Prototype liner being installed in caisson #2 study using mechanized compaction, neutron surface moisture/density gauge was used to monitor compaction.

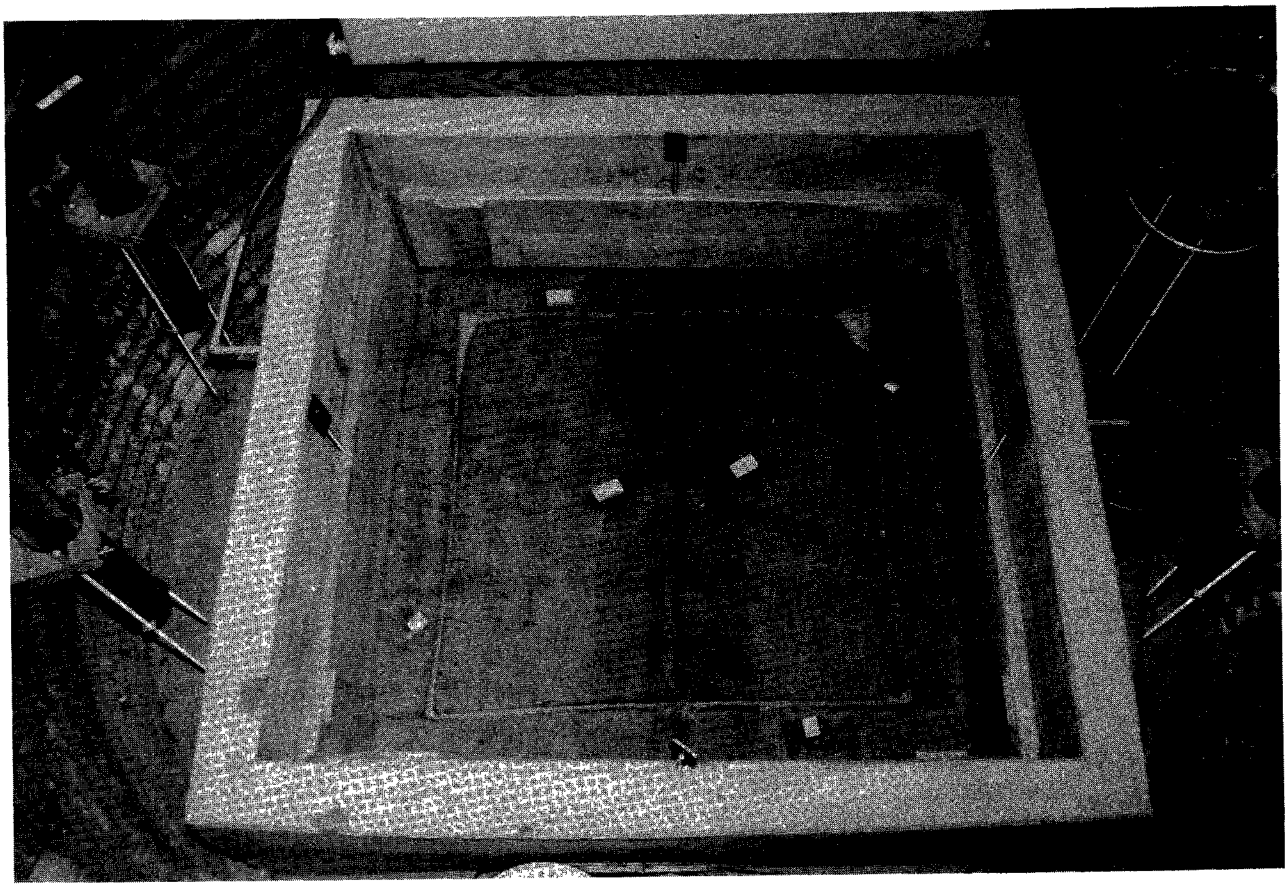

Plate 4.16. The prototype liner concrete box, just showing, burlap covered bottom, gypsum blocks located over drains and removable wooden wedges on the sides; the bottom horizontal access tube is barely visible in the center; raised metal ridge separates outer wall flow from flow in the inner compartment; constant head devices to be used with infiltration rings are shown along the walls.

Calibrated gypsum blocks were left in place below the clay (Plate 4.16) with wires exiting through underdrains. Following ponding the blocks were to provide a test of an early warning signal that conditions under the liner were getting wetter and breakthrough was imminent. One horizontal set of access tubes was installed across the box and one cluster of four vertical access tubes were placed in somewhat larger access holes which were excavated after the clay was in place. The space between the access tube and clay was then packed with dry Vol-Clay to prevent any flow along the walls of access tubes. The infiltration rings were installed after Caisson #2 was ponded. Mariotte type cylinders designed to keep water level constant were placed on the inside of the caisson to keep the facility nonfreezing during the winter.

Design of Caisson #2 was an improvement over Caisson #1 and together with the barrel studies it provided means of testing the concepts, techniques, and instrumentation to be incorporated in the full scale facility. Briefly, the principal results were as follows. In general, observed swelling (Figure 4.16) was less throughout because of better compaction. Early arrival of water at drain locations could be detected with gypsum blocks (Table 4.4). However, drain outflow was not observed until after the blocks became fully saturated. Sufficient flow existed in the clay for block electrical resistivity to begin changing very shortly (< 1 day) after ponding.

Several different ways of measuring bulk density of compacted clay were tested. They included surface and dual probe measurements and gravimetric samples with a cork borer and Eley volumeter. Water content was evaluated using grab samples, depth and surface nuclear probes as well as previously mentioned cork borer and Eley volumeter. Summarized results, given in Tables 4.5 and 4.6, show much scatter depending on the method used. Microwave drying of soil gave essentially the same results as conventional oven. Based on the results obtained dual gamma probe in the horizontal mode appeared to be a preferred method to use for extended study in a full scale research facility. Table 4.7 shows values of wet bulk density (WD) and associated changes in total available porosity in different parts of the prototype for different times following ponding. The method appeared to have sufficient sensitivity to detect small changes of water content or porosity. Finally, in Table 4.8, outflows for different portions of the prototype liner are given. Results suggest faster flows next to walls where compaction was less and in general very low outflow rates near the center. Infiltration measured with rings had to be corrected for evaporation since losses due to evaporation were of the same order of magnitude as inflow. Infiltration rate reflected outflows observed in outer drains suggesting that flow was not necessarily vertically downward. Based on the results obtained at least 35 evaporation pans, same size as the rings, were to be used in the large scale facility to provide a correction for evaporation. Tracer studies were also to be incorporated to evaluate flow pathway, and particular attention was to be focused on outflow drains to detect first sign of water breakthrough in all of the 250 drains.

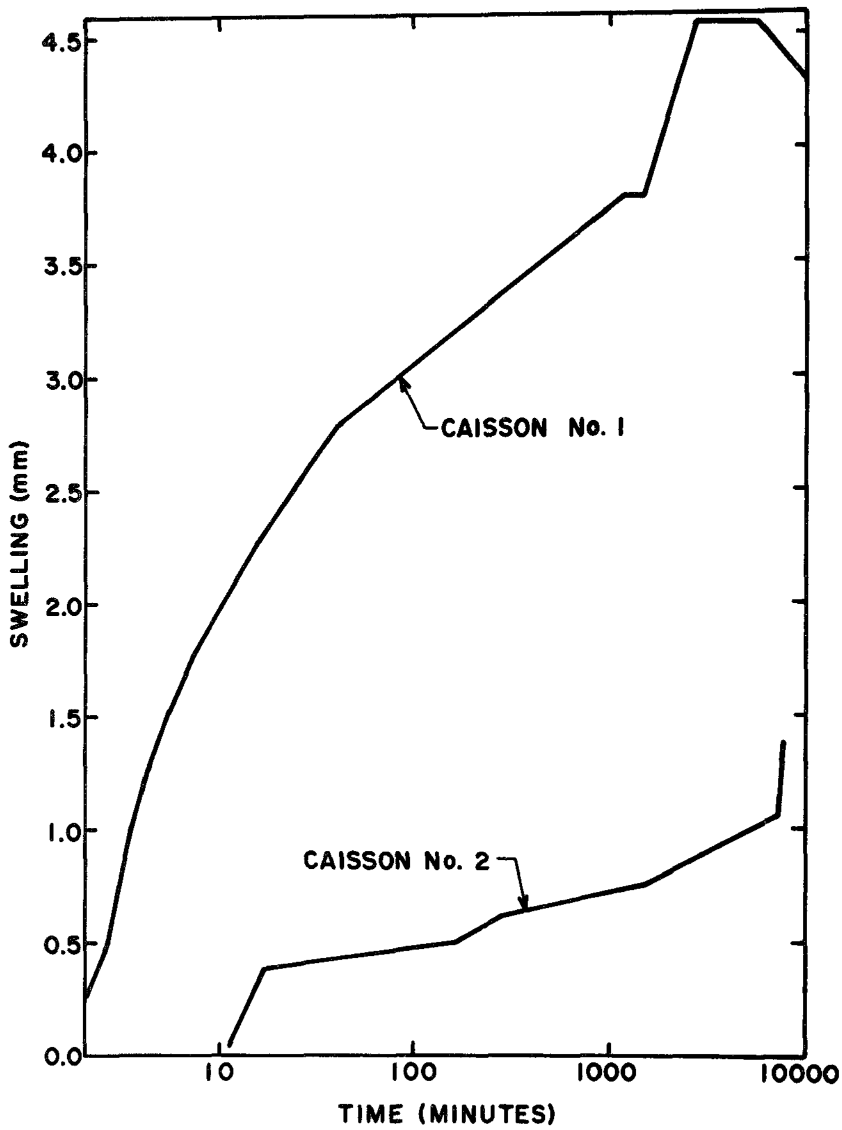

Figure 4.16. Comparison of observed swelling on prototype caisson 1 and 2 studies.

TABLE 4.4. ELECTRICAL RESISTIVITY OF GYMSIUM BLOCKS BURIED BY RESPECTIVE DRAINS (1 TO 6) UNDER THE COMPACTED CLAY PONDED (TIME 0) ON 10/9/84

Drain	Saturated Value	Time after ponding (days)						
		0	1	2	3	6	14	17
		electrical resistivity (ohms)						
1	400	4300	3200	800	440*	450†	380°	360△
2	420	4300	4000	2600	1850	460†	390°	380△
3	390	4100	2700	1900	1500	420†	350°	360△
4	300	3000	2700	1800	400*	400†	340°	360△
5	420	5400	3600	2450	1950	1000	400	360△
6	400	4300	3700	2250	1625	620	320°	360△

*Outflow (mℓ) #1(180), #4(130).

†Outflow (mℓ) #1(2000), #2(25), #3(130), #4(2100).

°Outflow (mℓ) #1(940), #2(220), #3(360), #4(30), #5(0), #6(120).

△Outflow (mℓ) #1(910), #2(270), #3(130), #4(30), #5(10), #6(70).

TABLE 4.5. WET AND DRY BULK DENSITY (WD AND DD) OF COMPACTED CLAY BEFORE PONDING, MEASURED WITH NUCLEAR PROBES AND GRAVIMETRICALLY

Lift	Surface probe		Dual probe		Cork borer	
	WD	DD	WD	DD	WD	DD
	kg/m³					
1	1910	1538	2063		1770	1433
2	1984	1580	2033	1630	1728	1523
3	1973 1507*	1588 1507	2025	1622	1633 2195**	1413 1817

*Surface probe direct transmission from 2" depth.

**Sampled with Eley Volumeter.

TABLE 4.6. WATER CONTENT MEASURED GRAVIMETRICALLY AND WITH NUCLEAR PROBES ON COMPACTED CLAY PRIOR TO PONDING

Lift	Cork borer	Volumeter	Grab samples[1]	Depth probe	Surface probe
	% by wt				
1	17.8	-	20.7	14.7	24.2
2	14.8	-	18.1	19.8	25.6
3	15.0	20.9	20.8	-	24.2

[1]Conventional oven dried.

TABLE 4.7. WET BULK DENSITY (WD) OF COMPACTED CLAY AS MEASURED WITH HORIZONTAL ACCESS TUBES AND COMPUTED VALUES OF TOTAL AVAILABLE PORE SPACE (TAPS)[1] BEFORE (0) AND FOLLOWING (1, 3, 14 DAYS) PONDING

Distance from side[2]	Days after ponding							
	0		1		3		14	
	WD	TAPS	WD	TAPS	WD	TAPS	WD	TAPS
inches	kg/m3	-	kg/m3	-	kg/m3	-	kg/m3	-
2	1993	0.2479	2066	0.2204	2075	0.2170	2089	0.2116
8	1956	0.2619	2087	0.2125	2054	0.2249	2097	0.2086
20	1930	0.2717	1971	0.2562	1989	0.2493	1994	0.2475
20	2021	0.2374	2075	0.2170	2086	0.2128	2109	0.2042
8	1984	0.2513	2090	0.2113	2086	0.2128	2106	0.2053
2	1872	0.2936	1969	0.2570	1970	0.2560	2060	0.2264

[1] $TAPS = \frac{WD}{2650}$

[2] South to North across the prototype (Figure 4.15).

TABLE 4.8. OUTFLOW RATES MEASURED IN INNER (#5 AND #6) AND OUTER (#1, #2, #3 AND #4) COMPARTMENT[1] DRAINS

Days[2]	Outer compartment				Inner Compartment	
	#1	#2	#3	#4	#5	#6
	x 10^{-7} cm/sec					
3	3	-	-	2	-	-
14	41	10	16	1	-	0.22
17	39	12	8	1	0.02	1.40
200	35	3	7	<1	0.05	0.13
560	27	2	2	≪1	0.001	0.002

[1] See Figure 4.15.

[2] After ponding.

SECTION 5

FIELD SCALE STUDIES

TESTING FACILITY

Based on the design and preliminary studies in Phase II a field scale facility was constructed and a clay liner was installed. After the site was instrumented inflow, and outflow evaporation changes in density and surface elevation were continuously monitored for a year. This constituted Phase III of the study. Figure 5.1 shows the field scale facility. The facility consisted of an elevated bridge-like platform (Plate 4.2) supported by reinforced concrete beams (Plate 4.1) which rested on compacted level subgrade. This arrangement allowed a crawl space under the platform (Plate 4.8) for collection of percolate which passed through the liner. A 3' x 3' (0.9 x 0.9m) grid of collection drains (Plate 4.3) was complemented by a similar grid of 11" (28cm) diameter buffered infiltration cylinders (Plate 4.7) at the surface.

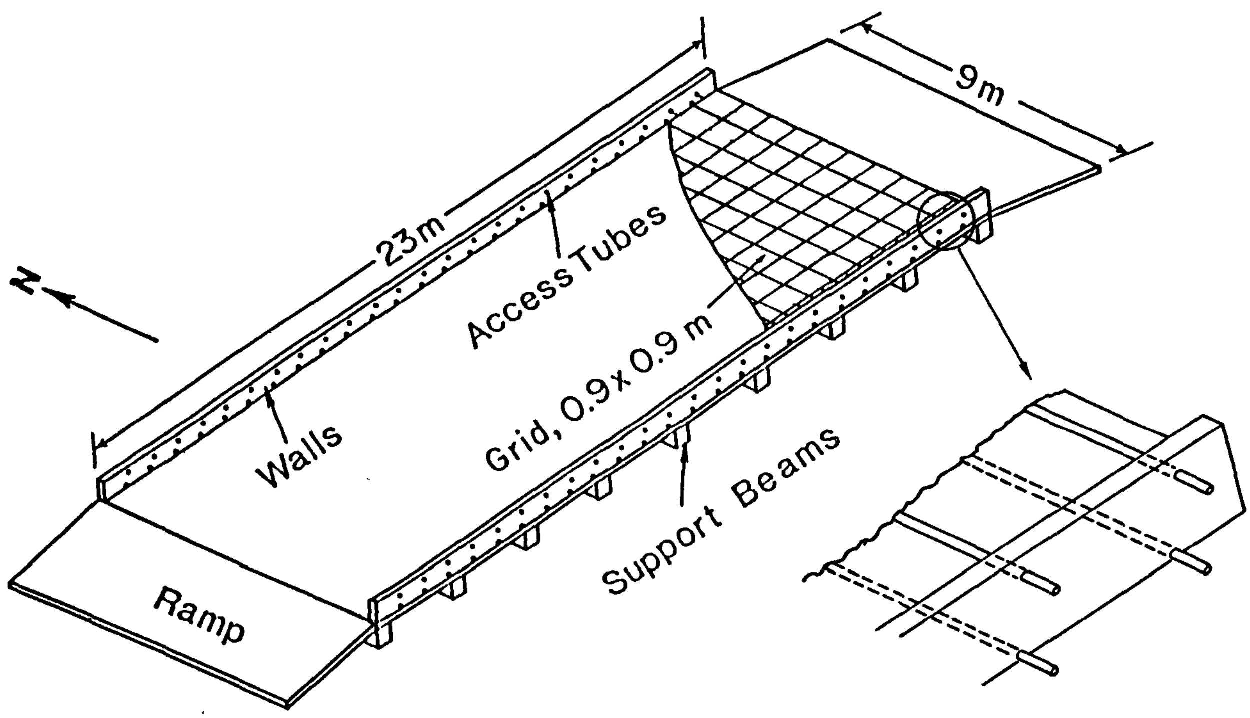

Figure 5.1. Clay liner testing facility, similar to Figure 4.1 but in SI units showing additional detail on horizontal access tubes.

Embedded in the floor of the platform, horizontally across the facility were the lower of the 24 access tubes (Plate 4.5) for the measurement of density using the Troxler[1] dual gamma probe, their tops protruding 0.25" (0.60cm) above the level of the floor. Positioned on top of the clay and situated exactly 1' (0.3m) above the lower ones were the upper access tubes. The attenuation measurements were made with a gamma source (Cs^{137}) in the lower tube and the detector in the upper tube (Plate 4.6).

Figure 5.2 shows the measuring grids used in the study. Their origin (0,0) was in the southwest corner of the platform shown in Figure 5.1. After the liner was compacted the facility was covered with a building, and heat and light systems were installed. To account for evaporation from infiltration rings 35 small evaporation pans, same size as the rings, were installed (Figure 5.2c) in addition to one large class A evaporation pan, to correct for evaporation from water ponded on the liner surface. In addition, 35 metal pedestals and a wooden walkway supported by access tubes (Plate 5.1) were placed on the clay surface (Figure 5.2c) to monitor potential swelling, to keep access tubes from being forced up, and to provide access to instrumentation.

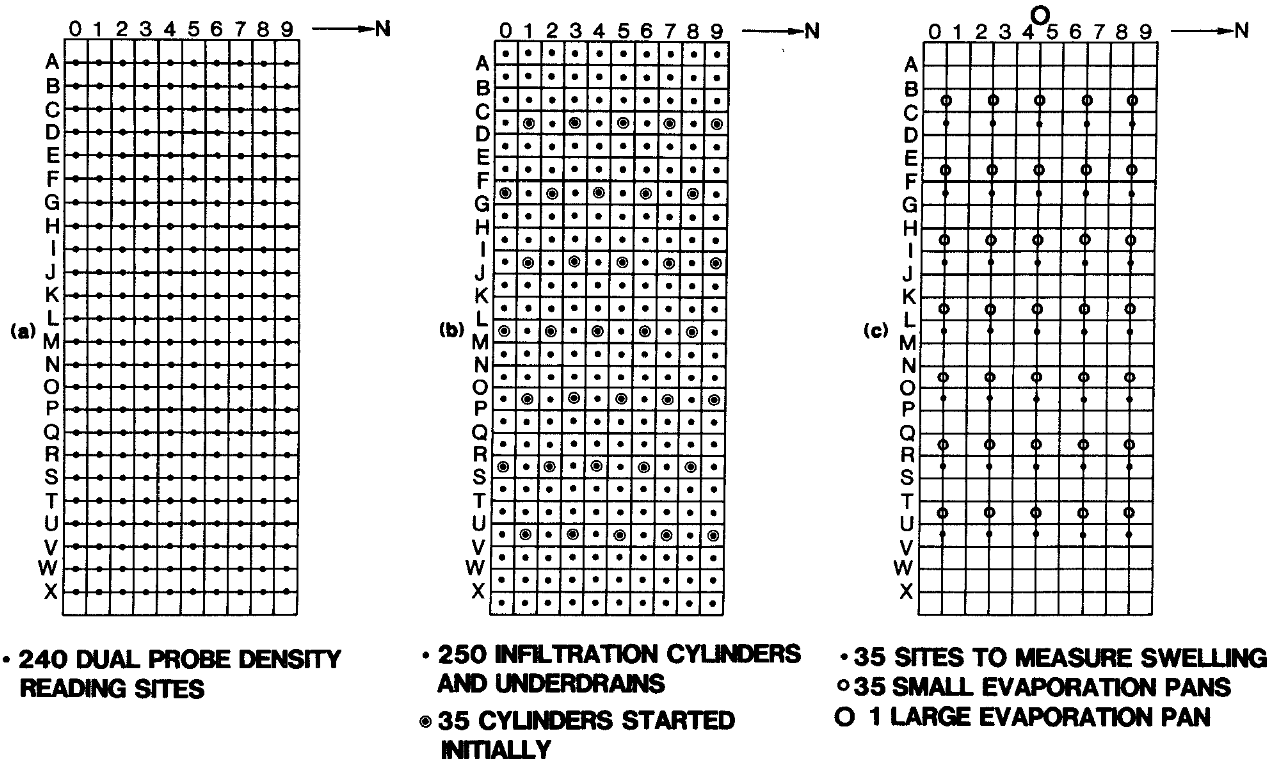

Figure 5.2. Experimental measuring grid for (a) bulk density, (b) infiltration and drainage, (c) swelling and evaporation.

Plate 5.1. Infiltration rings, a pedestal and a wooden walkway supported by access tubes were installed in compacted clay liner.

Prior to installation of clay, the floor of the platform was sealed with B/C Cure-Seal[1], and a bead of Vol-Clay[1] (Wyoming bentonite) was placed 3' away from the sidewalls (Plate 5.2) on the floor to separate any potential wall flow from the rest of the leachate. To minimize wall flow Vol-Clay[1] panels were also placed against sidewalls (Plate 5.3), which were previously sealed on the inside and on the outside with Bondex[1] waterproof seal, and another bead of Vol-Clay[1] was placed at the junction of sidewall and main deck. Since Vol-Clay[1] swells on contact with water, pressure build up between the liner clay and Vol-Clay[1] should have created a leak-proof contact. The floor of the platform was first covered with burlap and then a thin layer of coarse sand was placed on top to just cover the bottom access tubes. After the liner was installed another layer of coarse sand was placed on clay surface to minimize evaporation prior to ponding.

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[1]The mention of trade names in this publication does not constitute an endorsement of the product by the U.S. Department of Agriculture over other products not mentioned.

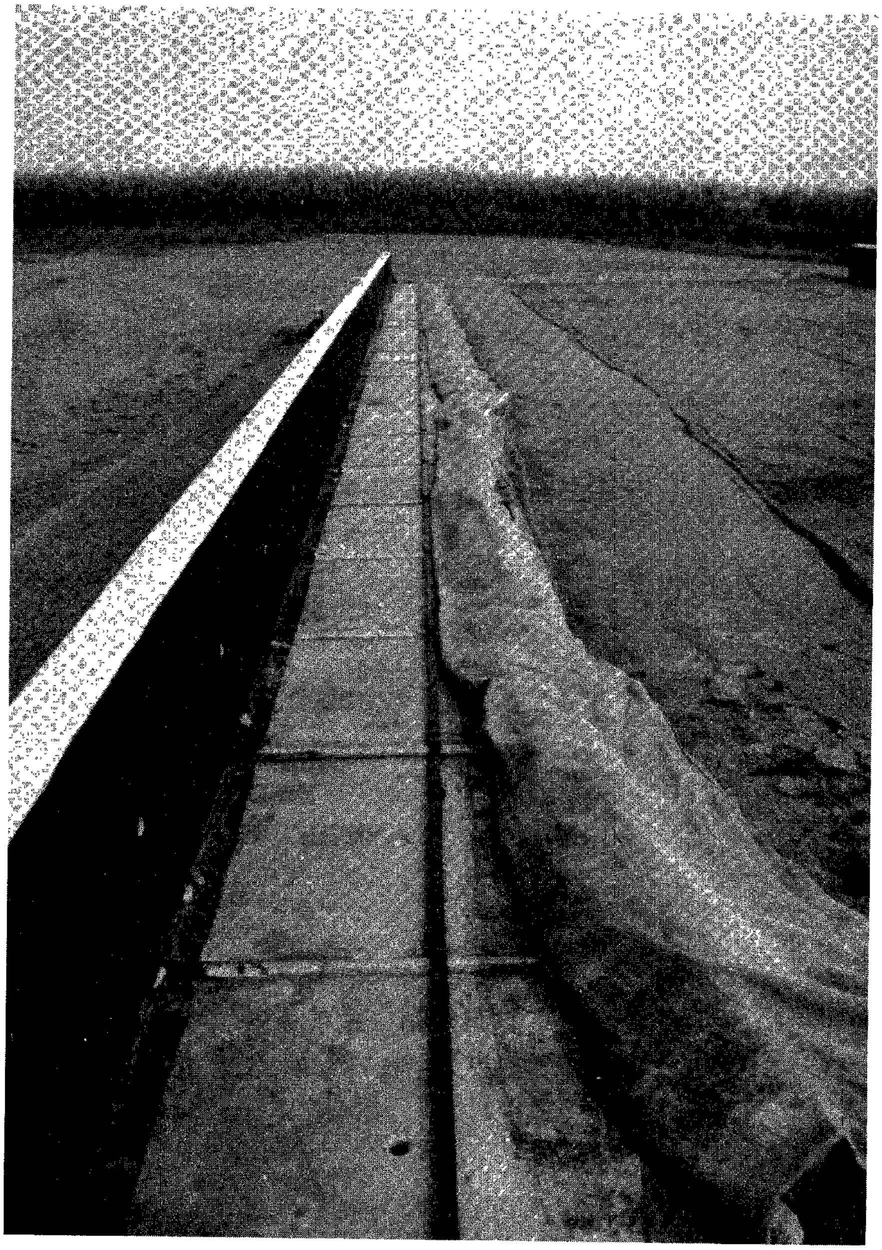


Plate 5.2. The floor of the platform was sealed, and the bead of the bentonite was placed 3' away from the sidewalls, subsequently the floor was covered with burlap and a thin layer of sand.

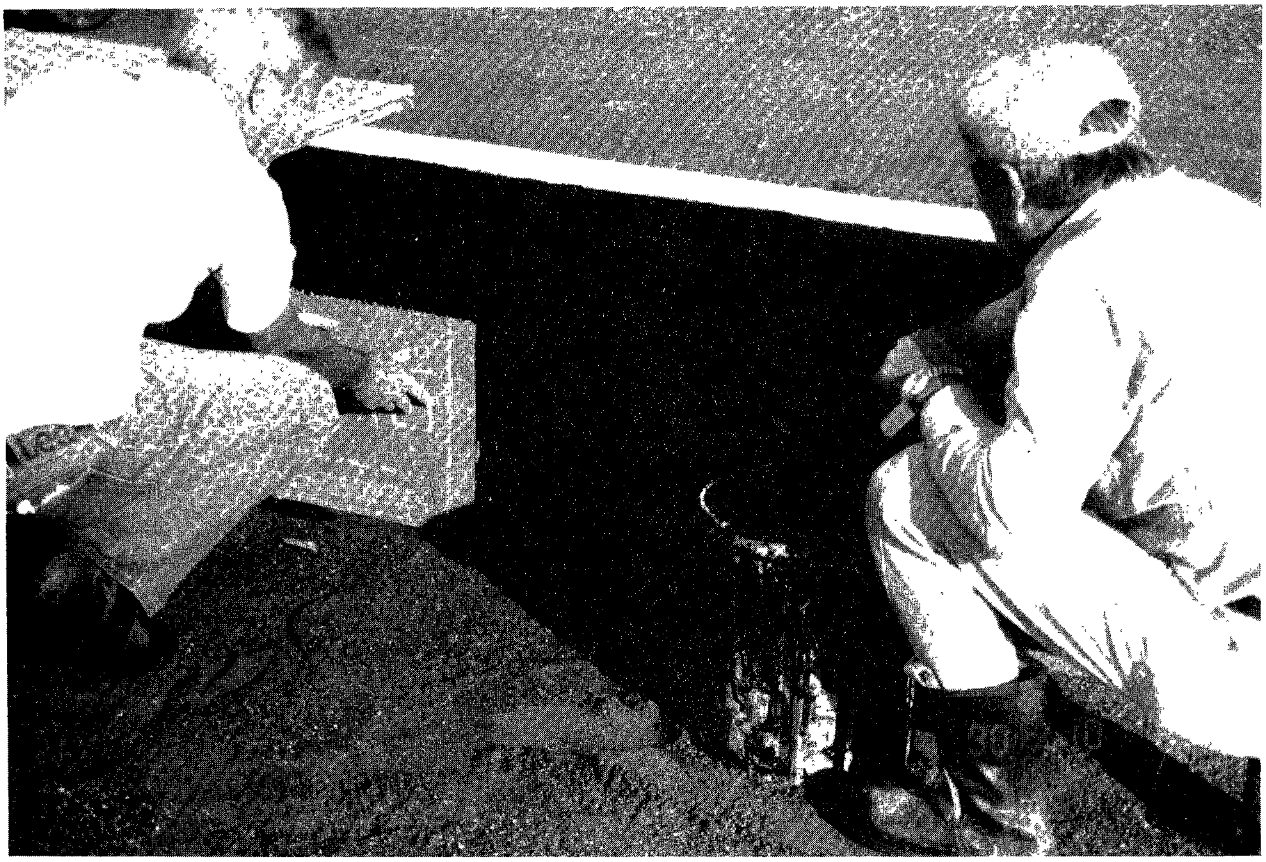


Plate 5.3. Bentonite panels are being placed against sealed platform sidewalls, to minimize wall effects.

Clay soil materials used for the experimental liner was a B-horizon of a commercially available cherty silt loam (Typic Hapludult) from central Pennsylvania. Table 5.1 shows some properties of this material as furnished by the supplier, as measured by HWERL, and as determined by us (NWRC). The soil is classified as a CL type brown till with laboratory permeability ≪ 1 x 10^{-7} cm/sec. Based on x-ray diffraction procedure the till was found to be a mixture of kaolinite and illite with some smectite. Prototype studies suggested that some swelling was to be expected after ponding mainly through enlargement of capillary films in nonexpanding lattice illite and kaolinite as well as osmotic imbibition by the expanding lattice smectite. Since the proportion of smectite was very low, swelling and dispersion were expected to be minimal. The till material was purchased from the supplier and trucked to the site where the liner was to be constructed.

Soil Materials

The 180 tons of till brought by truck (23T/load) to Klingerstown, were of variable quality. It contained some very large clods (> 6"). Most seemed dry (14-16% water content by weight), while some got wet (22%) in transit since tarps covering it were not fastened well enough. The till was brought in and deposited in large piles. These were subsequently sampled for moisture with a Veihmeyer tube, split into several (5-6) subsamples dried, and weighed. In addition, two large samples were also taken for clod size analysis. The results are given in Table 5.2. Average results on delivered material showed that in general clods larger than 1" (2.5cm) constituted more than 25% of the total, while for sample #2 clods larger than 4" (10cm) constituted almost 10% of the total. These large clods were anticipated to present a problem during wetting and compaction of the clay.

TABLE 5.1. SELECTED PROPERTIES OF THE TILL USED AS LINER MATERIAL AS DETERMINED BY SUPPLIER, OUR (NWRC), AND EPA (HWERL) SOIL TESTING LABORATORIES

Property	Supplier	NWRC	HWERL
Silica	58.00%		
Alumina	16.06%		
Titania	0.58%		
Ferric Oxide	5.71%		
Sodium Oxide	0.13%		
Potassium Oxide	4.58%		
Loss on Ignition	9.56%		
Mineral Composition	---------- quartz, K-feldspar, kaolinite, illite, smectite ----------		
Attenberg Limits			
Liquid limit	36%	35%	36%
Plastic limit	20%	23%	19%
Plasticity index	16%	12%	17%
Type	CL	CL	CL
Water Content	13.61%		
Standard Proctor	110 pcf at 18% water content	109.5 pcf at 17.8% water content	112.1 pcf at 16.9% water content
Modified Proctor	118 pcf at 14% water content	--	120.3 pcf at 12.9% water content
Permeability Test	1.10 to 1.76 x 10^{-9} cm/sec	--	--

TABLE 5.2. CLOD SIZE ANALYSIS OF TWO LARGE SAMPLES

Sieve opening mm	Sieve opening inches	Sample #1 %	Sample #2 % by wt	Average % by wt
100	4	0	9.4	4.7
75	3	1.5	7.5	4.5
50	2	5.9	6.3	6.2
25	1	11.6	12.1	11.8
19	3/4	8.0	7.4	7.7
10	3/8	16.1	14.6	15.3
<10	<3/8	56.8	42.6	49.7

LINER CONSTRUCTION

Figure 5.3 shows the Standard Proctor compaction test results for the material used in this study. The maximum bulk density at 17.8% water content was found experimentally to be 1754 kg/m^3 (110 pcf), about the value furnished by supplier and somewhat less than subsequently determined by HWERL (Table 5.1).

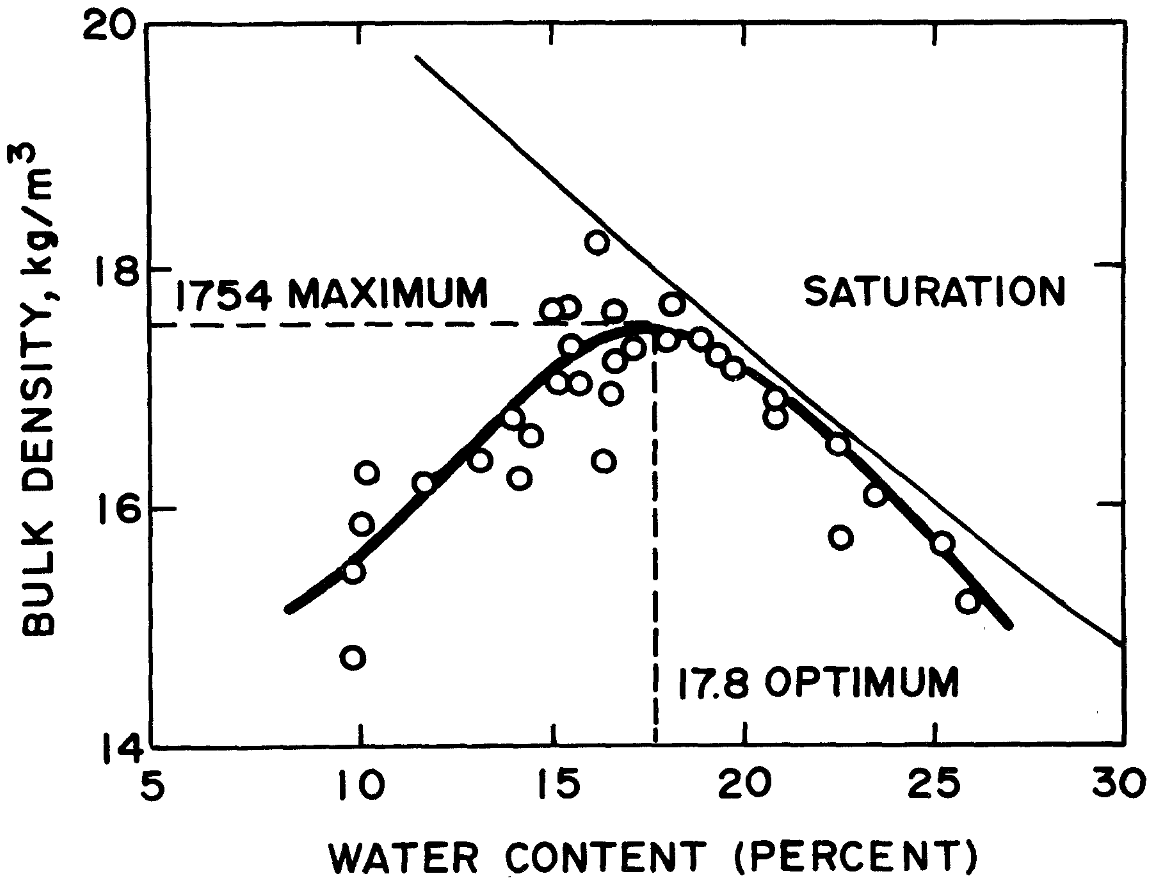


Figure 5.3. Standard Proctor compaction test on till material used in the liner.

Experimental Procedures

The contractor arrived on 10/30/84 with a Dratt backhoe, 5-1/2 ton ($5T_m$) caterpillar bulldozer tractor, 15 ton truck ($14T_m$), a 5-2 = 3 ($2.7T_m$) ton sheepsfoot roller (empty), Bolag "nervous turtle"--a small vibratory pull type compactor--and a jackhammer with a 6" x 6" (15 x 15cm) foot. The original plan was first to compact a test plot (Plate 5.4). For that purpose on a 10' x 10' area (3 x 3m) area about an 8" (20cm) layer of clay was deposited. It was underlain in one place by two access tubes horizontally imbedded in a concrete slab. Water contents were measured with a microwave (16.5%), and an adequate amount (see example) of water was added with a hose to bring the soil above the optimum water content. Application time turned out to be disproportionately long even for so small a test area although incorporating water into the soil with a garden rototiller appeared to work well.

Plate 5.4. Test plot is being compacted using a sheepsfoot roller.

Example.

A test plot ≈ 10' x 8' x 6" (3.05 x 2.44 x 0.15m) = 1.133 m^3 would contain, at Standard Proctor density of 1794 kg/m^3, 2032 kg of soil. It needs 386 kg of water to bring it to 19% water content from 335 kg of water at 16.5% water content. Therefore, we found we needed to apply 51 kg water (~ 14 gallons) to the test plot to bring it above the optimum.

The first lift was installed as follows. The backhoe operator loaded the truck with till, perched himself on the side of the platform (Plate 5.5) and spread the soil from truck on the pad which was covered with burlap and a thin layer of sand (Plate 5.2). In this manner several truck loads were spread on the platform ~ 6" deep and enough for a 4" finished layer. As the clay was spread with a backhoe it was wetted with 183 gallons of water to bring it to a water content greater than the optimum (19% by wt). As the operation progressed two rototillers (Plate 5.6) were used to incorporate the water into the soil and break layer clods. When the loose layer appeared ready for compaction, grab samples were taken at 36 grid locations for moisture, and

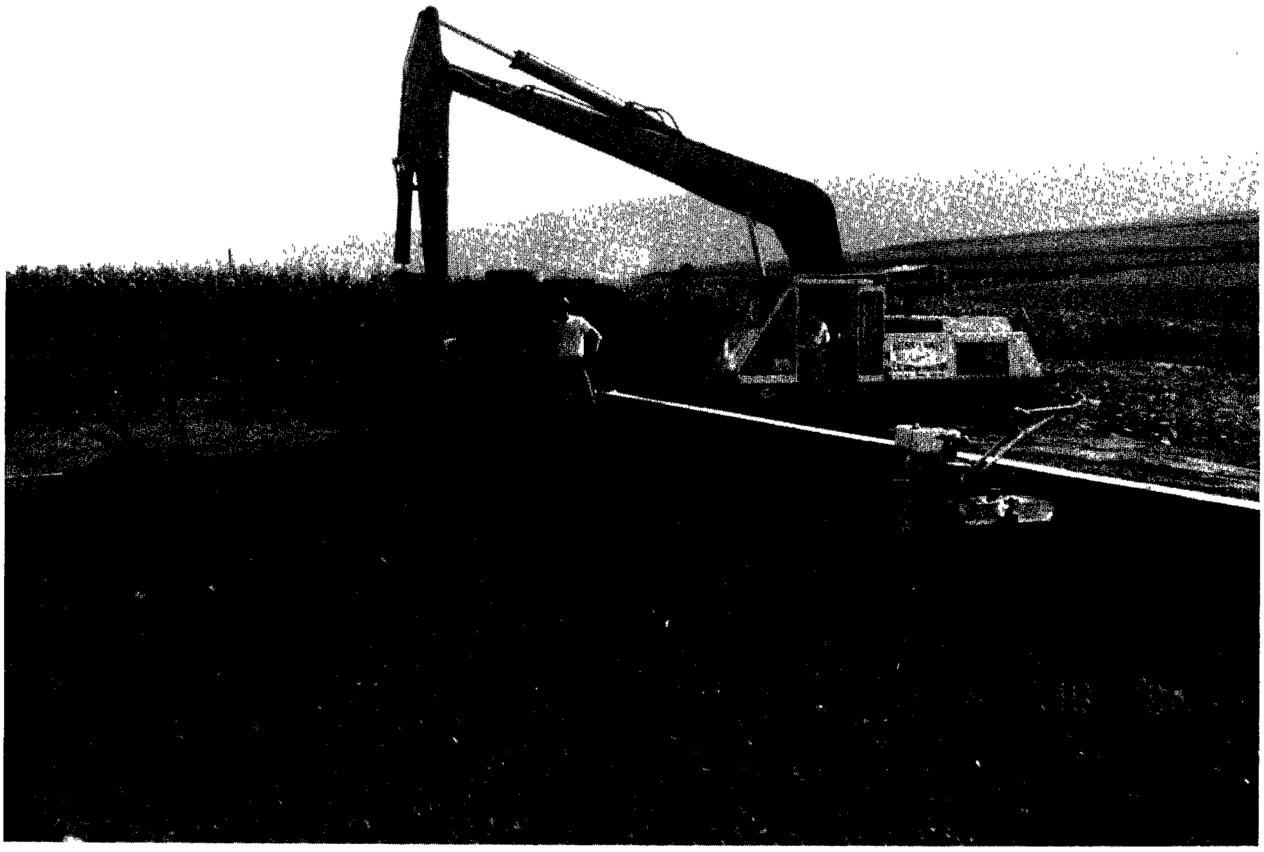


Plate 5.5. Clay material was brought in by trucks and spread on the platform with a large backhoe.

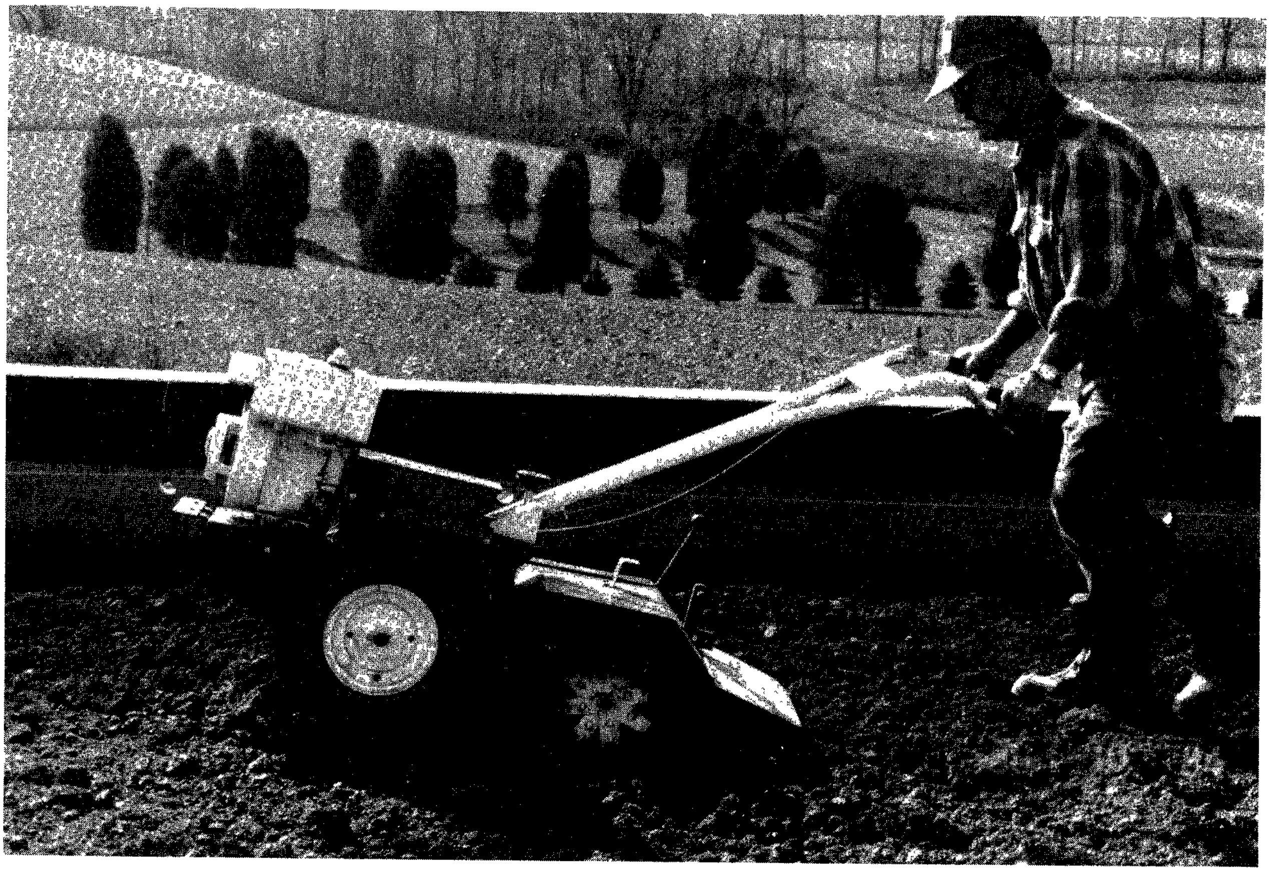


Plate 5.6. After the required amount of water was added, it was incorporated into the clay by rototilling.

clay was rolled first with a bulldozer then smooth with a 7-1/2 ($7T_m$) ton roller (rather than with sheepsfoot) to protect access tubes from being dented (Plate 5.7). Some access tubes were dented nevertheless, either by stones falling on them during the spreading of clay, mixing by rototiller process, or even by tamping with jackhammer along the edges. However, since cesium-137 source in the dual density probe was relatively small, only the guide geometry had to be changed (a pie slice was removed) to allow it to slide freely through the dented tubes. Following compaction we ended up with about a 4" (10cm) lift quite well compacted near the center, not so well compacted near the walls, particularly where jackhammer tamper influence ended and smooth roller compacting influence had not fully begun. Only 2 passes of the small--nervous turtle--roller (Plate 5.8) could be used on each side next to the wall so as not to collapse the access tubes. To make sure of a flat level surface elevations were taken at 48 locations, measured from the stretched string down, and surface probe moisture density (Plate 5.9) readings in the backscatter mode were made at 36 points. Prior to spreading the second lift the smooth surface was roughened (Plate 5.10) by running over it with a bulldozer.

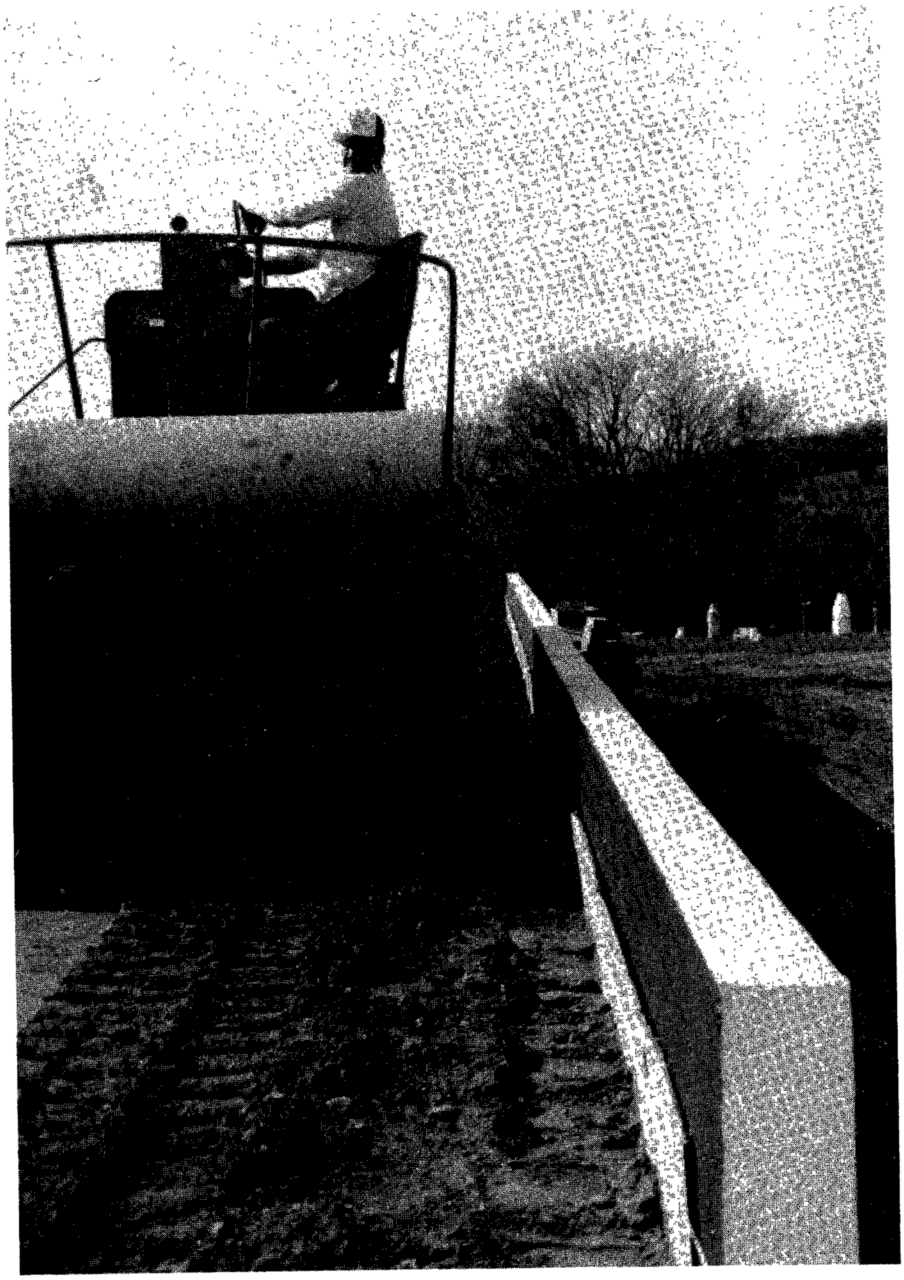


Plate 5.7. Following several passes with the bulldozer and sheepsfoot roller, each lift was smoothed out by large vibratory roller prior to measurement of density.

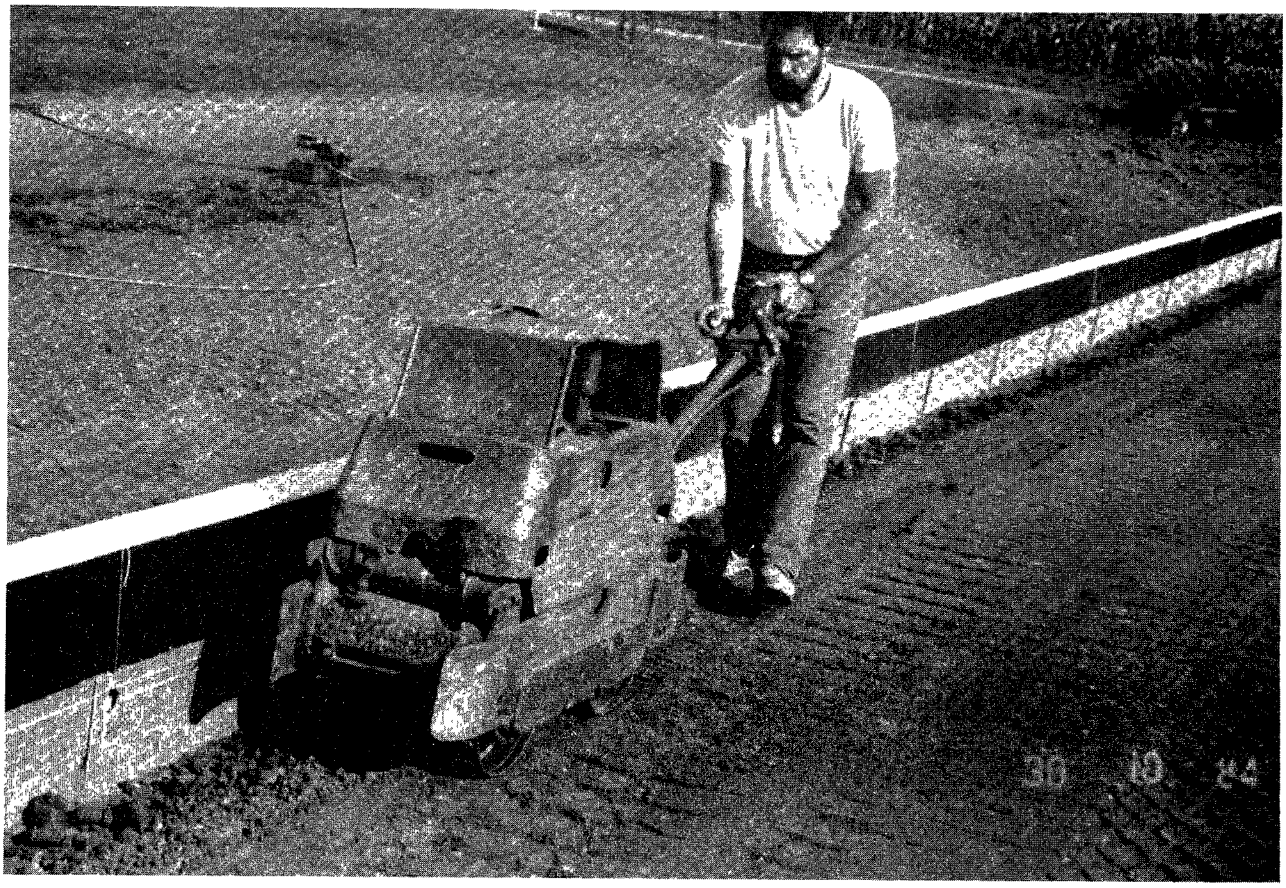


Plate 5.8. Near the walls clay was compacted using a "nervous turtle" roller (shown above) and jackhammer (not shown).

Plate 5.9. Water content and density were measured using a nuclear moisture-density probe.

Plate 5.10. Prior to installation of the next lift the clay surface was roughened by bulldozer treads.

Spreading the second layer (lift) was much easier. The material was wetted with 151 gallons of water as it was spread by the backhoe from the truck on the platform at about 3 p.m. It was rototilled and pushed around with the bulldozer. However, because of the weight of the bulldozer spreading the soil simultaneously compacted it, making it hard to rototill and mix the water with the entire 8" of loose second lift material. Subsequently a sheepsfoot roller pulled by the bulldozer made 30 passes over the area (this worked out to between 6 and 7 full coverages). Six "turtle" passes were made on the sides and finally the material was tapped against the walls with a jackhammer. Although it would have been preferable to see the sheepsfoot roller actually "walk out" as compaction proceeded, the bulldozer during spreading the clay already compacted the soil to a certain extent so that sheepsfoot roller appeared to "walk out" from the start. Pre-compaction, grab samples for water content determination were taken at 36 locations also from this layer.

After the bulldozer-sheepsfoot roller compaction, the surface was rough with many indentions. It had to be smoothed with the flat 7-1/2 ton roller used without vibration before 36 moisture-density readings could be made with a surface probe in the backscatter mode. Even then it was difficult to find a really good smooth surface necessary to make moisture-density measurements with a nuclear gauge. A number of Eley volumeter samples were also taken especially close to the walls where it was impractical to use the surface Troxler[1] gauge, and elevations of the clay surface was measured.

The third lift was spread on the surface of the second lift roughened with the caterpillar treads and wetted like lift 2. Soil water readings (microwave) indicated a somewhat higher initial water content (17.5%) although the soil did not look any wetter than before. Consequently, only 92 gallons of water were added to the clay. The material was spread as before with the bulldozer, but again it was difficult to rototill it, especially the eastern 1/3 of the platform which seemed wetter. The lift was again sampled for moisture at 36 locations, rolled with the bulldozer and sheepsfoot 28 times (6-7 passes), rolled on the sides 6 times with "nervous turtle" and tamped with the jackhammer immediately next to the wall. Water contents appeared satisfactory, but density values (taken with nuclear surface probe, in the backscatter mode) appeared lower, largely because of uneven surface conditions.

When the liner was trimmed across its entire width and on either side with a backhoe, all three lifts were well blended and could not be told apart. The installation was completed by noon of the second day. The surface again appeared rough, almost too rough for good surface moisture-density measurements, and the soil was too hard to attempt any physical smoothing.

Based on elevation survey, the center of the final lift was about 2" (5cm) higher than the sides. To make sure that the horizontal access tubes were absolutely level and parallel to the lower set they had to be installed by tapping a solid metal form into the clay on the straight chalkline. The clay was so hard that infiltration rings had to be hammered in with a sledge after a solid metal form was fitted into the ring top. Pedestals to measure swelling was tapped in place to provide good contact and a wooden walkway superstructure resting on the access tubes was constructed to provide access to installed instrumentation. After all instrumentation was installed a 1" (2.5cm) layer of sand was spread on the surface to minimize evaporation. The liner had to be periodically moistened to keep the surface from drying out until the sand layer could be applied.

Summary of Installation

To summarize, three six inch (15cm) thick layers of clay material were compacted to four inch (10cm) thick lifts following the procedure developed on a construction test plot, giving a finished twelve inch (30cm) thick clay liner. Although as delivered the clay was wet enough, by the time it was spread and compacted several weeks later, additional water was needed. The clay was, therefore, wetted with a known amount of water necessary to bring it to wet of optimum, tilled with rototillers to break clods sampled for water content, and compacted in place. Surface gauge readings of water content and density in 36 locations indicated the level of compaction achieved.

During the construction phase two problems surfaced: the bulldozer tended to compact the clay making it difficult to rototill, and the full scale compaction equipment could not approach safely any closer than a foot to foot and a half (30 to 45cm) from the sidewalls. These problems were addressed by a more intensive but slower rototilling and by the use of a small Bomag[1] vibrating roller 6" to 12" (15 to 30cm) from the sidewall and an electric jackhammer with a square 6" x 6" (15 x 15cm) foot right next to the wall. Degree of compaction achieved near the sidewalls was judged to be near to that obtained over the remainder of the area. However, detailed analysis of samples indicated considerably lower density values near to the sidewalls. Figure 5.4 shows the compaction achieved with a sheepsfoot roller and compares it with the degree of compaction achieved with a small vibrating roller and jackhammer next to the sidewalls where it was not possible to operate the full scale equipment. The results suggest considerably less compaction next to the sidewalls. Consequently, for analysis of flow only an inner 8 x 23 grid matrix of rings and drains was to be examined.

In Figure 5.5 density and water content values for each of the three lifts (sheepsfoot compaction) are compared against Proctor constants. The upper solid line represents the line of saturation (zero voids), while the lower one is the line of maximums for different compactive efforts and water contents. Dashed lines indicate optimum (vertical) water content (17.8%) and

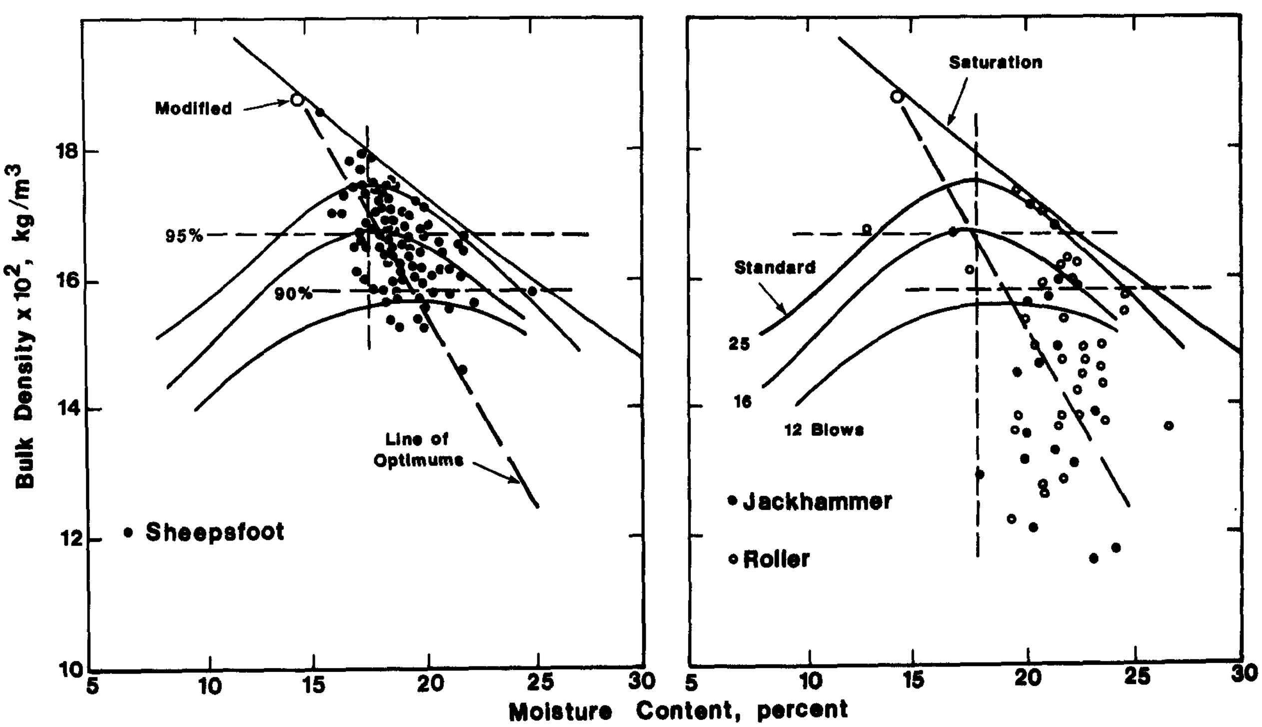


Figure 5.4. Values of water content and dry density measured with the nuclear surface probe for the sheepsfoot roller, and with Eley[1] volumeter, gravimetric samples for jackhammer and small vibratory roller; solid lines represent laboratory measured Standard Proctor compaction and saturation curves, dashed vertical lines give optimum moisture content (17.8%) and dashed horizontal lines represent 90% of the maximum density (1754 kg/m^3).

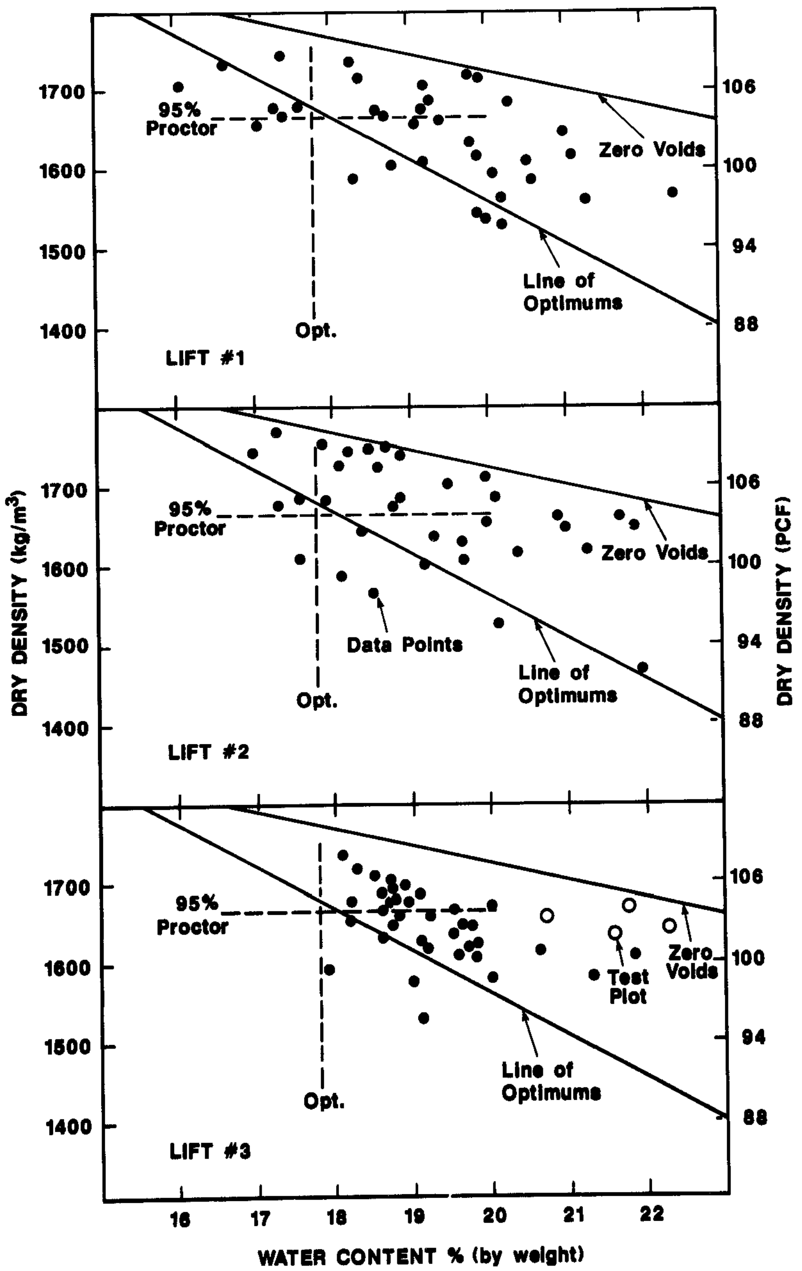


Figure 5.5. Distribution of water content (by wt) and dry densities (DD) on three compacted lifts measured with Troxler[1] surface probe in the backscatter mode, shown against the background of Proctor density at optimum water content (opt), lines of maximums and line of saturation (zero voids).

95% Standard Proctor (1754 kg/m^3) conditions (horizontal). The quality of individual lifts improved markedly from the first to the third. For lift #1 38% of locations had densities below the line of maximums and 15% had water contents less than optimum, whereas for lift #3 only 14% of locations had density below the line of maximums and none had the water content less than optimums.

Site, Scale, and Spatial Relationships

Water contents and density control data discussed above were collected during the construction of the liner along with gravimetric water samples, Eley[1] volumeter samples, and a Troxler[1] surface moisture density probe. Following construction bulk density readings were taken vertically with the dual gamma probe in horizontal position.

Table 5.3 lists the cross sectional areas and volumes associated with swelling, flux monitoring, bulk density, and water content measurements. Figure 5.6. shows the geometry and scale considerations for the different methods of density measurement.

TABLE 5.3. CROSS SECTIONAL AREAS AND VOLUMES ASSOCIATED WITH MONITORING OF WATER FLOW, WATER CONTENT, AND BULK DENSITY IN THE COMPACTED CLAY LINER

	Cross sectional area	Volume
	cm^2	cm^3
Swelling		
Pedestals (36)	232	
Flux monitoring		
Infiltration cylinders (250)	613	4,672
Leachate drains (250)	8,361	254.952
Sidewalls	551,844	16,820,207
Liner	2,090,318	63,712,905
Moisture and density monitoring		
Volumeter (24)	6	10
Dual gamma probe (240)	5	49
Nuclear surface probe (118)	465	10,619* 6,968

*For moisture at 17.8% water content by weight and backscatter density, respectively.

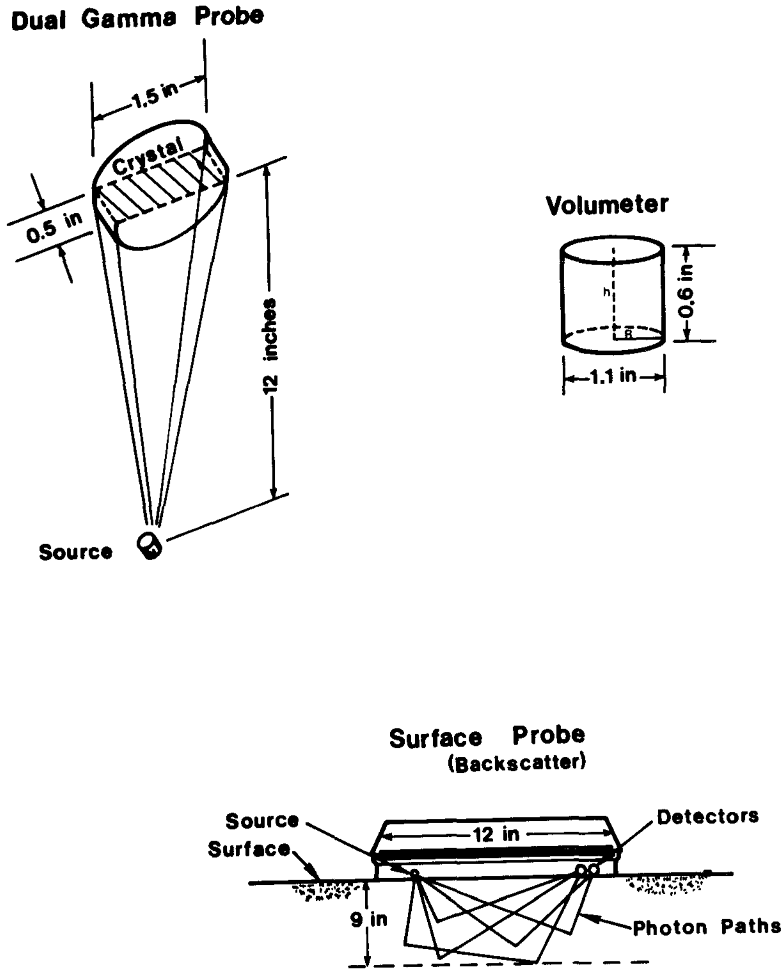


Figure 5.6. Geometry and scale considerations of Troxler[1] dual gamma probe, Eley[1] volumeter, and Troxler[1] surface moisture-density probe in backscatter mode.

On a relative basis, the dual gamma probe measures a volume about 5 times the volume of the volumeter, whereas the nuclear surface probe in the backscatter mode measures density and moisture over a volume 100 to 200 times larger than the volume measured by the dual gamma probe, and 700 to 1000 times larger than measured by the volumeter. The volume of the liner is ~ 6000 to 9000 times larger than the volume measured by the surface probe. Similarly, the volume of the liner as a whole is 55 times the volume of all the infiltration rings combined (250), whereas, the volume assumed associated with each leachate drain (3 x 3 x 1 ft) is ~ 55 times the volume of each infiltration ring. The sidewall and endwall drains together represent ~ 1/4 the volume of the whole liner, while swelling is recorded by a combined (36 locations) response of less than 0.5% of the area.

Surface Moisture and Density

Figure 5.7 shows distribution of water contents in the 9 x 23m (30' x 75') liner testing facility for lifts #1, #2 and #3 based on 36 small gravimetric grab samples taken from each lift before compaction, and Figure 5.8 gives the distribution of water contents in the same three lifts based on 36 nuclear surface gauge measurements following compaction. The differences between the two reflect primarily differences in methods and sample sizes used. Gauge data represent nuclear readings on a larger sample volume. Small (2 oz, 50g) grab samples dried in a microwave oven represent point measurements. Previous comparisons of surface gauge measurements with samples dried in a microwave during the prototype study indicated that, at least for our conditions,

$$\text{Moisture}_{\text{Nuclear}} = 1.16\ \text{Moisture}_{\text{Gravimetric}} \qquad (5.1)$$

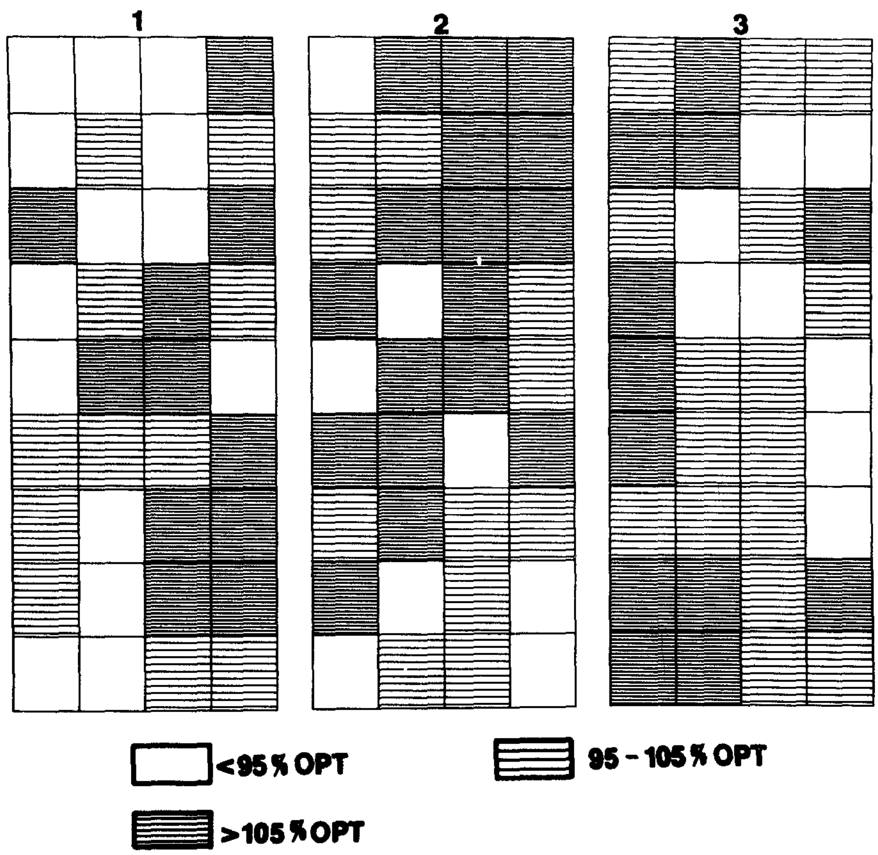


Figure 5.7. Distribution of water content in lifts #1, #2 and #3 of the experimental clay liner based on small gravimetric grab samples, optimum (OPT) moisture content is 17.8% by weight.

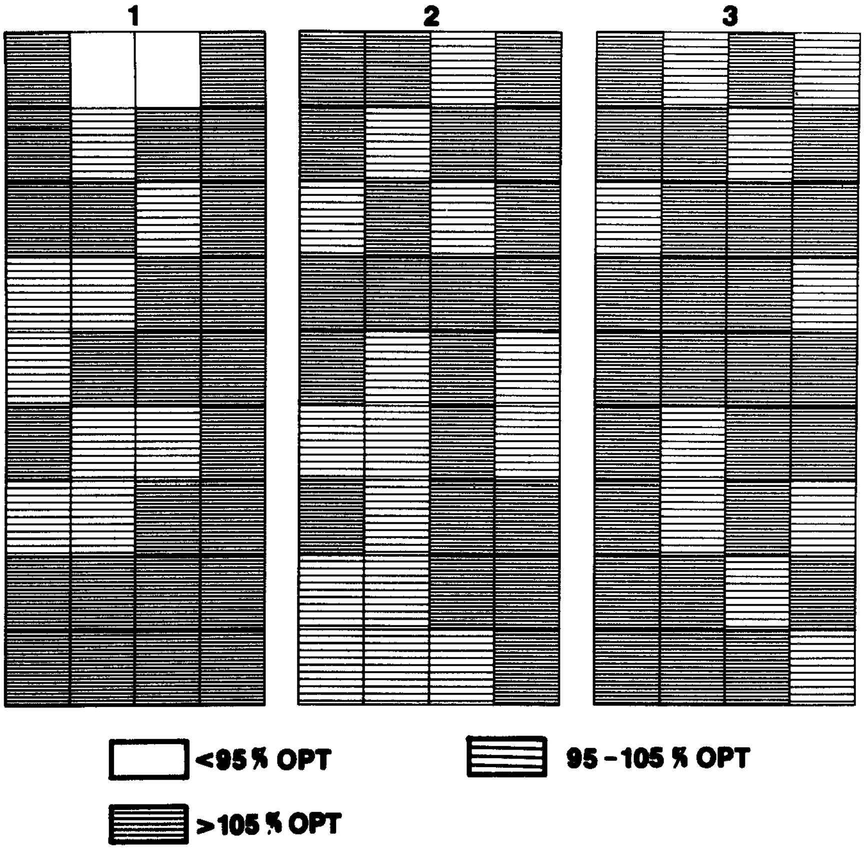


Figure 5.8. Distribution of water content in lifts #1, #2 and #3 of the experimental clay liner based on nuclear surface moisture gauge, optimum (OPT) moisture content was 17.8% by weight.

Nearly 90% of the water contents measured with a nuclear gauge were greater than optimum, more than 70% were greater than 1.05 optimum, and only 2% were less than 0.95 optimum. Nuclear gauge readings are affected most by the water content close to or at the soil surface. In that respect they correspond to gravimetric point samples. However, unlike the gravimetric point samples the overall depth of measurement for the surface gauge varies with the water content (M) of the soil[2],

$$\text{Depth (mm)} \approx 280 - 0.27\ M\ (\text{kg/m}^3) \qquad (5.2)$$

with M $\approx$ 178, the depth of measurement is approximately 9". Consequently, water content for a much larger and more representative volume of soil is

[2]Instruction Manual 3400-B Series surface moisture-density gauges, Troxler Laboratories, P.O. Box 12057, Research Triangle Park, NC 27709, USA.

averaged in nuclear gauge readings than in grab samples, with a tendency to smooth out individual lift values. Table 5.4 shows the actual mean and standard deviation values of water content for each lift for the two methods. Point grab samples show considerable variability, while a smoothing effect of nuclear gauge readings is quite apparent.

Figure 5.9 shows the spatial distribution of dry bulk density for three lifts of a compacted clay liner and Table 5.5 gives the proportional breakdown and partitioning of data as a function of Standard Proctor compaction test. The results show that more than 80% of values for lift #1 and more than 90% of values for lifts #2 and #3 were within 90 to 95% Standard Proctor or better. A poorer performance of lift #1 reflects a modified compaction procedure, whereby the lift was compacted using the dozer and smoothfaced roller only.

TABLE 5.4. DISTRIBUTION OF WATER CONTENT (GRAVIMETRIC) IN CLAY LINER COMPUTED FROM NUCLEAR GAUGE DATA AND POINT GRAB SAMPLES

Method	Lift 1	Lift 2	Lift 3	Average
	----------	kg/m^3	---------	
Nuclear				
Mean	193	192	192	192
Standard Deviation	1	1	1	1
Point				
Mean	178	185	180	181
Standard Deviation	23	17	15	18

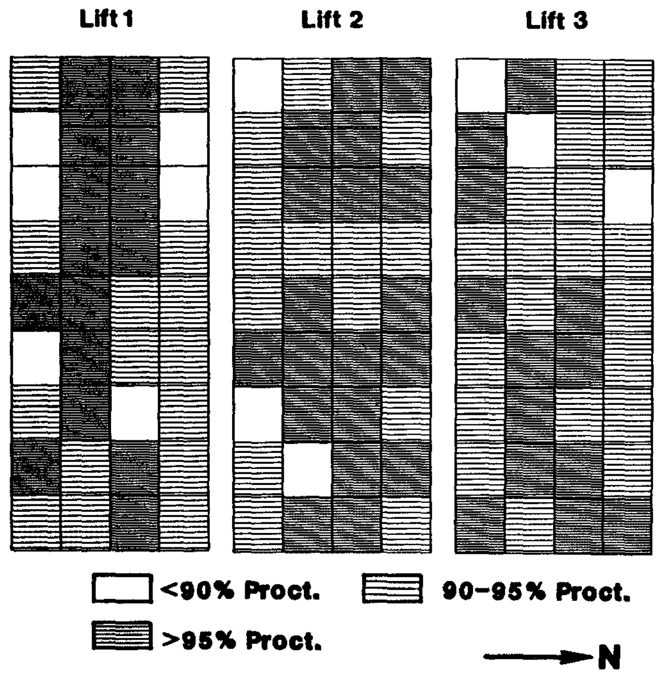


Figure 5.9. Distribution of dry bulk density in lifts #1, #2 and #3 of compacted clay liner in terms of Standard Proctor (PROCT) density (1754 kg/m^3, 110 PCF).

TABLE 5.5. DRY BULK DENSITY OF THE THREE LIFTS OF COMPACTED CLAY LINER AS A FUNCTION OF STANDARD PROCTOR COMPACTION TEST

Density	Lift 1	Lift 2	Lift 3	Average
	---------	percent	--------	
< 90% Proctor	17	6	8	10
90 to 95% Proctor	42	42	53	46
> 95% Proctor	42	52	39	44
> 94% Proctor	53	64	53	57

EXPERIMENTAL RESULTS

Preponded Stage

Density--

Collection of bulk density (wet) data using dual gamma probe (WD_d) in the horizontal access tubes begun immediately after the clay liner was constructed and the upper set of access tubes were installed. The initial thirteen sets of density readings were taken across the liner at one foot (30cm) intervals (rather than at 3' intervals which would have given 240 values) to give a total of 720 values for a liner. Table 5.6 gives the sample statistics for the thirteen data sets, taken prior to ponding, as well as their temporal mean and standard deviation. The temporal preponding mean in Table 5.7, based on all (9360) observations, differs only by 2 kg/m^3 from the mean based on observations taken at the locations 3' apart as specified in Figure 5.2a. The

TABLE 5.6. STATISTICS OF 13 BULK DENSITY (WET) DATA SETS TAKEN CONTINUOUSLY AND CONSECUTIVELY FOLLOWING INSTALLATION ON 11/1/84 AND PRIOR TO PONDING ON 3/26/85

	Data Set 1	2	3	4	5	6	7	8	9	10	11	12	13	Mean	Std. Deviation
	(kg/m^3)														
No. of Samples	720	720	720	720	720	720	720	720	720	720	720	720	720	9360	-
Mean	2185.5	2184.5	2181.6	2179.8	2202.2	2182.6	2191.5	2198.5	2198.4	2194.4	2183.7	2184.3	2181.5	2188	7
Median	2186.0	2188.0	2185.0	2186.0	2210.0	2185.5	2195.0	2206.0	2195.0	2201.0	2187.0	2188.5	2184.0	2192	9
T-Mean	2185.2	2183.7	2181.5	2180.4	2202.2	2181.6	2191.6	2198.7	2190.1	2194.2	2184.3	2184.8	2181.3	2188	7
Std. Deviation	86.9	90.6	87.2	88.7	90.9	83.5	89.1	90.1	87.4	90.3	86.5	87.1	87.0	88	2
Std. Error of the Mean	3.2	3.4	3.2	3.3	3.4	3.1	3.3	3.4	3.3	3.4	3.2	3.2	3.2	3	0.1
Max. Value	2452.0	2527.0	2461.0	2428.0	2478.0	2448.0	2447.0	2462.0	2435.0	2551.0	2455.0	2454.0	2466.0	2457	35
Min. Value	1889.0	1900.0	1934.0	1909.0	1952.0	1971.0	1933.0	1533.0	1934.0	1937.0	1939.0	1914.0	1940.0	1930	22
Third Quantile	2238.7	2234.0	2234.0	2235.0	2262.7	2233.7	2249.0	2256.7	2246.0	2250.0	2241.0	2238.0	2235.7	2243	9
First Quantile	2134.2	2129.0	2128.0	2126.0	2143.2	2128.2	2129.2	2143.0	2134.0	2140.0	2128.2	2131.2	2130.0	2133	6

TABLE 5.7. PARTICLE DENSITY[1] OF GROUND FRACTION OF CLAY LINER MATERIAL

Site	Specific gravity		Average
	(kg/m^3)		
A6	2626	2653	2640 ± 19
G6	2788	2793	2791 ± 4
K8	2795	2717	2756 ± 55
N7	2735	2663	2699 ± 51
T2	2680	2737	2709 ± 40
W1	2693	2691	2697 ± 1
Mean	2720 ± 66	2709 ± 52	2714 ± 52

[1]Determined using ASTM C-188-84 procedure at 26 °C.

difference between the two in standard deviation is somewhat larger but not alarmingly so (88 vs 83 kg/m^3). Figure 5.10 shows the spatial distribution of the average preponding bulk density over the liner as a whole. Highest density values appear to be in the west central portion of the site. The reason for this may be that as the clay was being compacted with rollers (sheepsfoot and smooth) they would travel back and forth with the central portion receiving relatively more passes than the side shown on a hypothetical example in Figure 5.11.

Total available pore space--

Dual probe density values (WD_d) measured prior to ponding did not correspond exactly to the surface probe density values (WD_s) measured during construction, possibly because of differences in respective volumes considered. The individual values of dual probe density (WD_d) may be adjusted to the surface probe readings (WD_s) by the ratio of their means (0.90) and expressed as corrected density isopleths (Figure 5.12a) together with water content by volume (Figure 5.12b). By subtracting the Figure 5.12b-matrix of values from

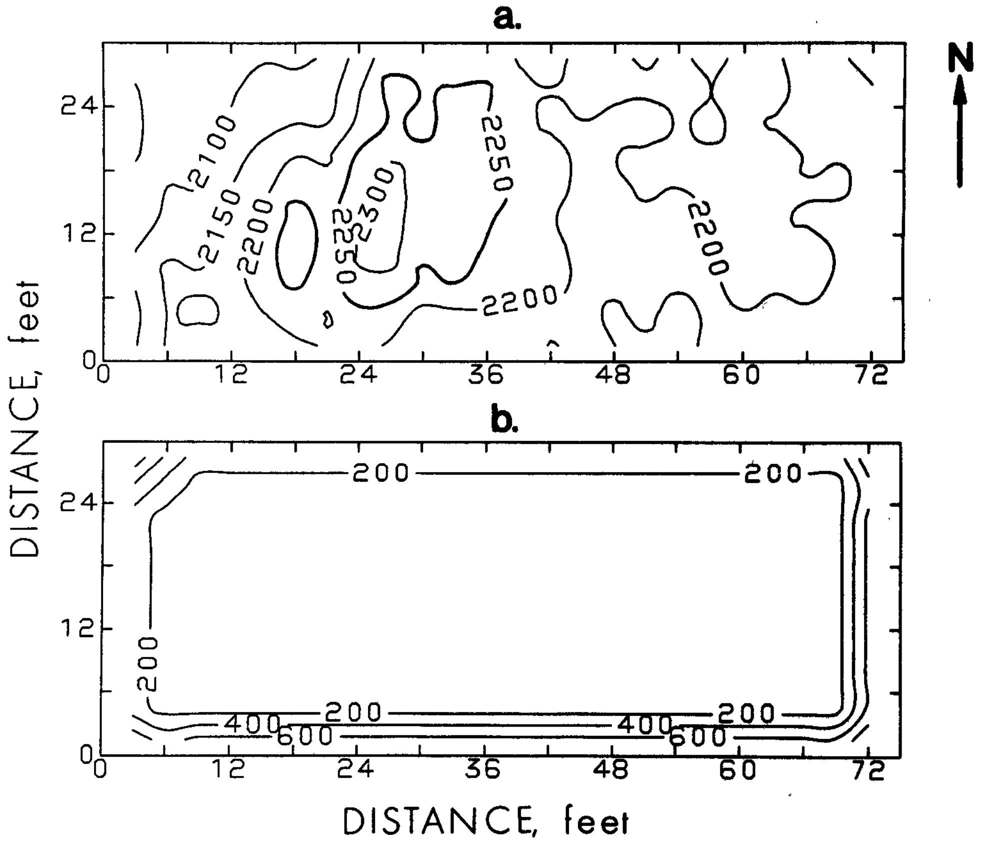


Figure 5.10. Average density distribution over the clay liner (a), and interpolation variance (b).

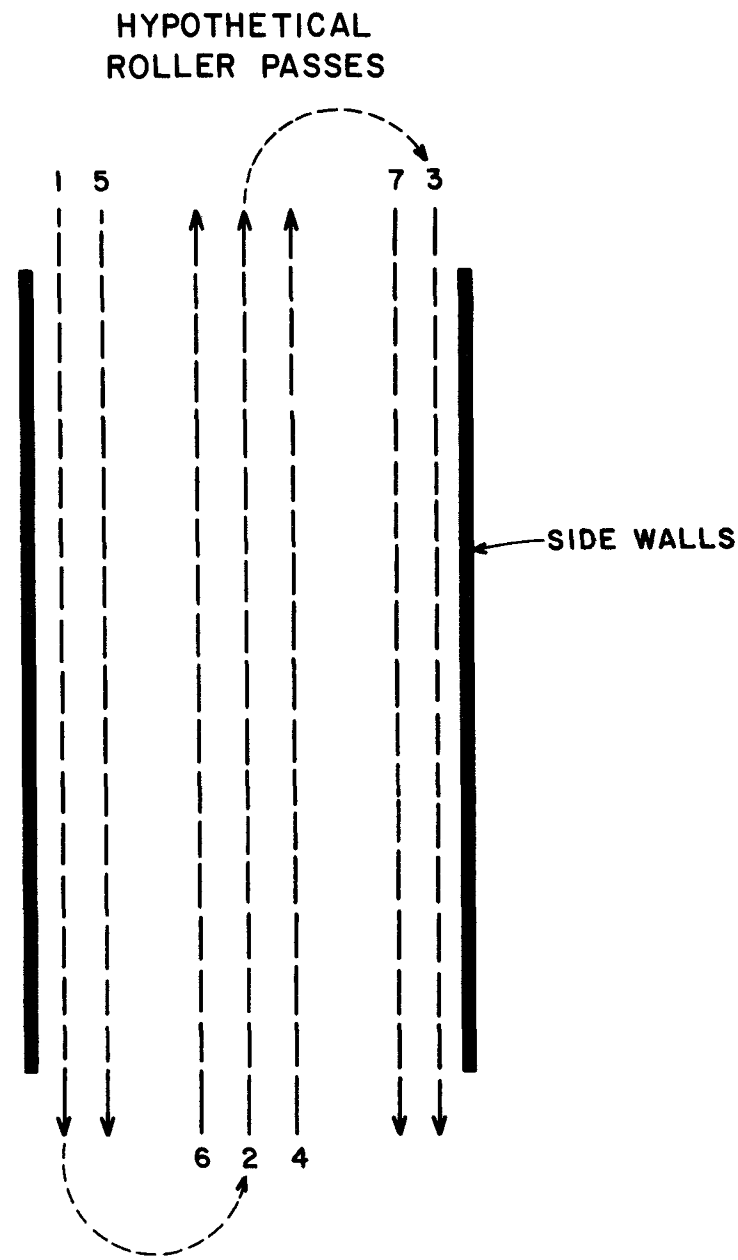


Figure 5.11. An illustration of why the center portion of the clay liner may have received more passes than the sides.

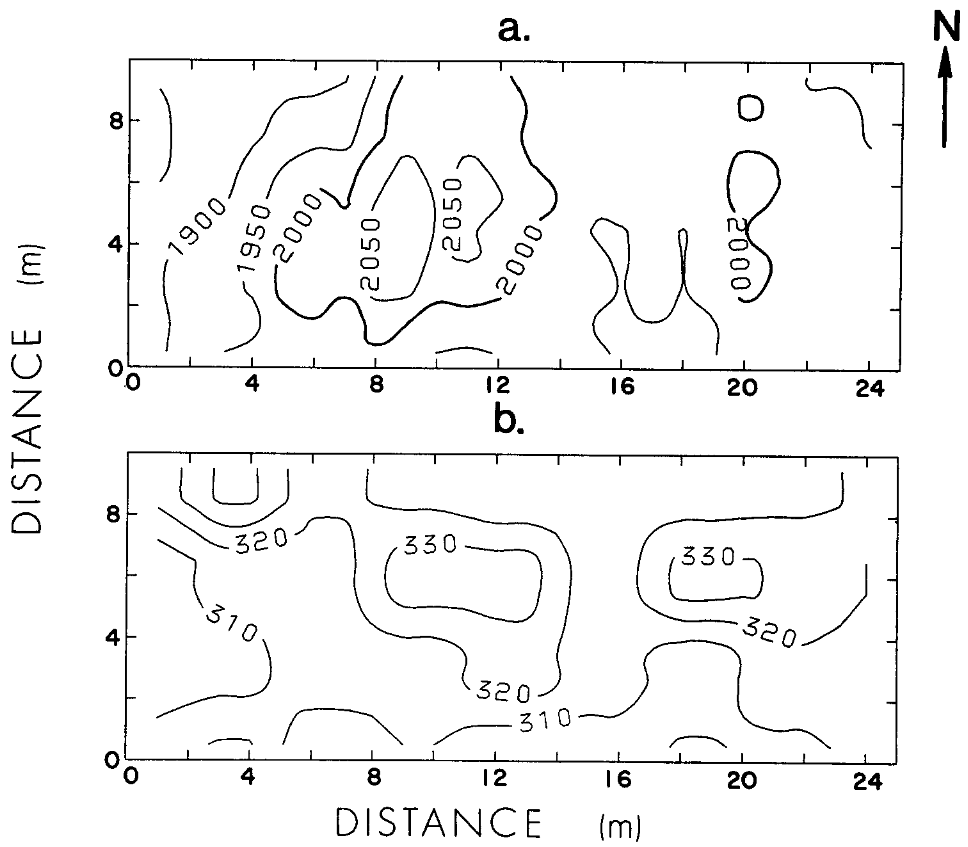


Figure 5.12. Contours of average density (in kg/m^3) adjusted to surface probe density values (a), and of surface probe moisture content (in kg/m^3) (b), before ponding.

the Figure 5.12a-matrix of values we are left with the dry spatial distribution of bulk density (DD) prior to ponding. The formulas used are as follows,

$$\frac{WS + WW}{VS} - \frac{WW}{VS} = \frac{WS}{VS} \qquad (5.3)$$

where WS is the weight of soil (kg), WW is the weight of water (kg), and VS is the volume of soil (m^3). The first term on the left is essentially an expression for the bulk density of wet material in (kg/m^3), the second term is water content by volume, and the last term on the right is the expression for dry bulk density. Similarly,

$$\frac{WW}{VS} \Big/ \frac{WS}{VS} = \frac{WW}{WS} \qquad (5.4)$$

where the term on the right is now the water content by weight (kg of water/kg of soil). The calculated matrix of dry spatially distributed bulk densities can now be used in conjunction with measured particle density values for the liner material (Table 5.7) to compute a 10 x 24 matrix of total available pore space (TAP) by volume (m^3/m^3). Measured water content by volume (kg/m^3) can also be,

$$TAP = (1 - DD/2714) \qquad (5.5)$$

expressed in the same units as TAP (i.e., 1 kg water/m^3 soil = 0.001 m^3 water/m^3 soil), subtracted from the TAP matrix, multiplied by 1000 (kg/m^3) and expressed as a matrix of the amount of water needed (in kg/m_3) to fully saturate the liner. Figure 5.13 shows such a spatial distribution of the amount of water needed (kg/m^3) to saturate the clay just prior to ponding. Such <u>a priori</u> computations may, however, be subject to considerable error for several reasons. First, the ratio of surface density to dual probe mean may not truly represent the extent of local variation. Second, the water content values used to correct WD_d to DD may not represent true water contents as perceived by the dual probe because of differences in geometry. Finally, particle density may be varying more than expected for a uniform material since the

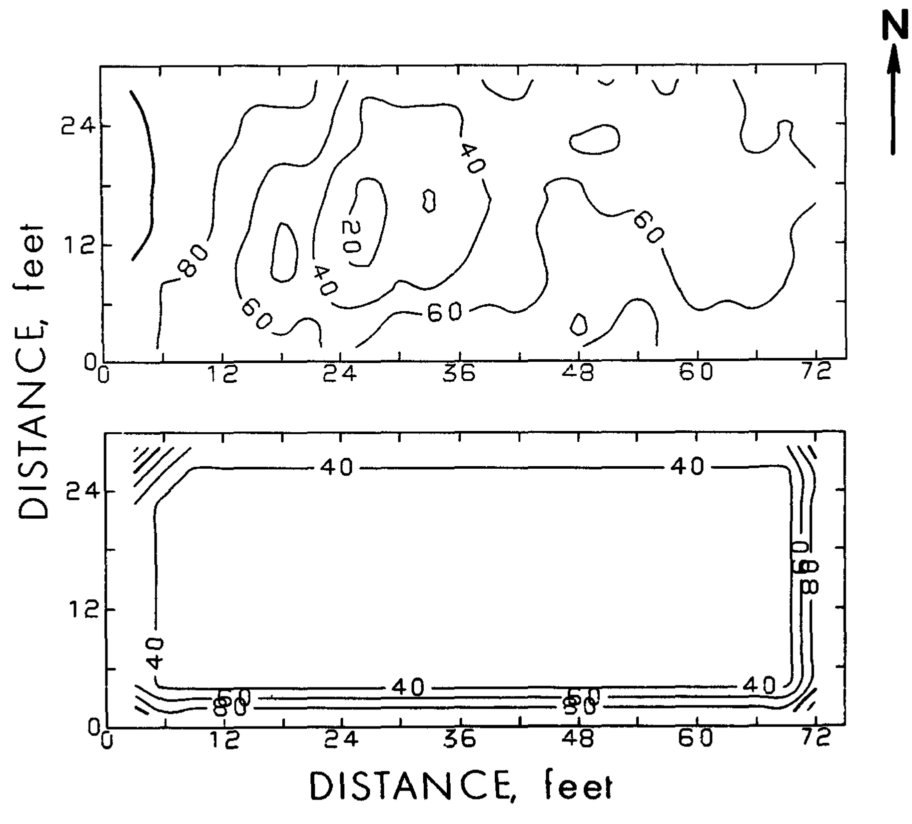


Figure 5.13. Interpolated isopleths of the amount of water needed to saturate the liner (in kg/m^3) at ponding and associated interpolation variance.

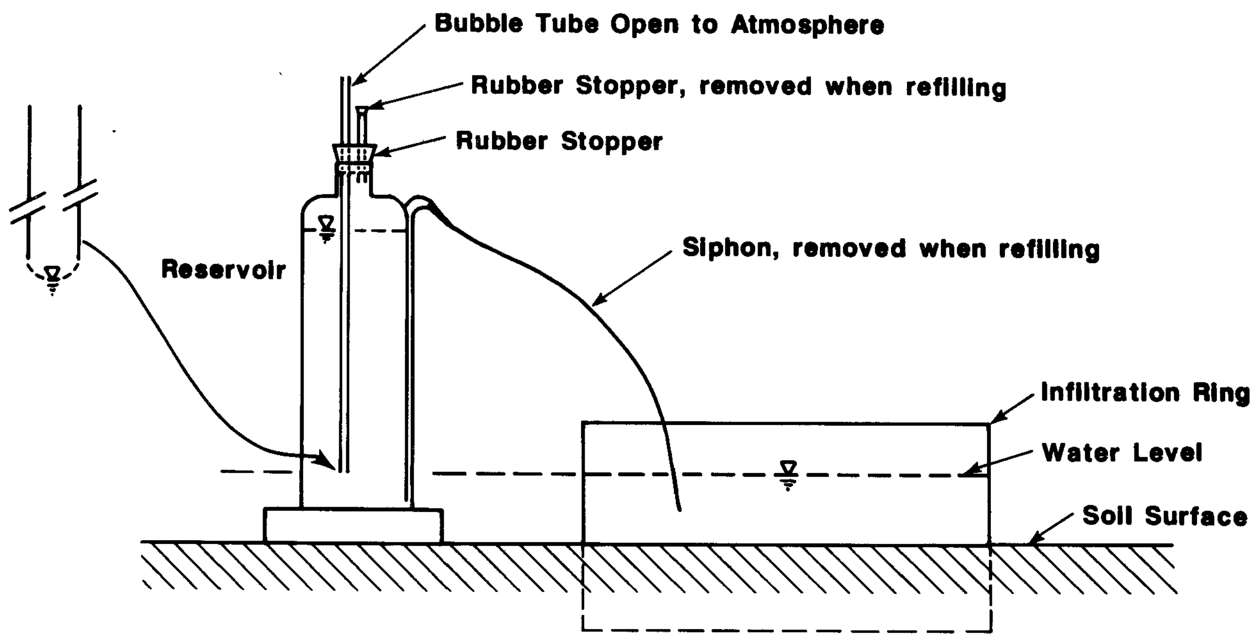
statistics given in Table 5.7 are somewhat larger than the ASTM C-188 precision guidelines call for in case of a uniform material (12 kg/m^3). Soil particle density is usually taken as 2650 kg/m^3. Larger values observed here for the clay liner material are probably indicative of high iron content in the soil (6%).

The amount of water needed to saturate the clay liner will be discussed in connection with ponding and compared with a similar matrix derived after the water is drained. In the meantime, changes in the amount of water needed over time may indicate that a part of infiltrating water is diffusing into the clay and part is passing rapidly through larger pores.

Ponded Stage

Sampling plan--

After the clay liner was compacted on October 30, 1984 and instrumented, a walkway resting on the topmost access tubes was constructed and a thin (~ 3cm) layer of sand was spread on the surface to minimize evaporation and subsequently to help distribute applied water. The area was ponded on March 26, 1985. Water was brought in two large tanker trucks on March 26, 1985 and 11,700ℓ (3080 gal) were applied to the liner through a slotted orifice onto a plastic sheet covering part of the surface to prevent washout damage to the clay surface. This initial water, which was ponded on the liner surface to the depth of 5.6 cm on the average, was obtained from a nearby farm pond (Klinger pond). Subsequent additions as needed were first taken from the water that remained in the tanker trucks (till 11-7-85), and then from a local well. The water level on the liner was maintained with an automatic constant head tank, and checked daily. Similarly, each of the infiltration cylinders and evaporation pans were equipped with a manometer type constant head 1 liter Mariotte bottle (Figure 5.14) set to the same water level as in the liner. Initially, leachate was to be collected in ~ 4ℓ milk bottles right under the drains. This proved impractical and individual drains were routed to the outside and leachate was collected in appropriately sized containers on the volume of outflow. Simultaneous readings of water level changes in class A evaporation pan and in a grid of evaporation pans, same size as the rings, gave the necessary evaporation corrections to be applied to the ring infiltration data. Corresponding to each set of ring inflow and drain outflow data (at 250 locations, Figure 5.2b) a set of wet density readings was taken (at 240 locations, Figure 5.2a) with the Troxler dual gamma probe, and a set of 35 Optocator[1] readings (Figure 5.2c) was used to check for any swelling. The ultimate purpose of this study was to develop a capability to describe areal distribution of hydraulic conductivity under field conditions and to relate it to tests performed in the laboratory on disturbed samples of clay liner materials, or on undisturbed cores taken from the liner during construction. The dilemma was that while the response of the liner as a whole was influenced by preferential flow pathways, zones of discontinuity and zones of higher effective porosity (Rogowski, 1988) point laboratory samples generally were not.



MARIOTTE BOTTLE AND INFILTRATION RING ASSEMBLY

Figure 5.14. Schematic representation of constant head Mariotte bottle assemblage.

Collection of infiltration, leachate and evaporation data (at locations indicated in Figure 5.2) began immediately after ponding. Initially, the data expressed as flux in m/sec x 10^{-9}, were collected on the daily basis with subsequent transition to weekly and longer intervals. Soon after the start it became apparent that the infiltration rings and leachate drains next to the sidewalls were responsible for much of the infiltration and drainage from the liner. Since these rings and drains were situated in a lower density zone, which was compacted with jackhammer and a small vibratory roller, the higher rates of flow were not totally unexpected. The leachate from all drains near the sidewalls was therefore isolated, combined into one, and measured separately from the central matrix of 184 individual drains and rings which represented the area compacted with sheepsfoot roller. The sampling density represented by the matrices in Figure 5.2 was on the order of 12,000 samples per hectare (5,000 samples per acre) with the overall experimental liner area of 209 m^2 (~ 0.05 acres). Particular attention was paid to the scale of measurement, the number of samples, and the representativeness of the values.

Average values--

Figure 5.15 shows the changes in average liner bulk density from one month after it was laid down and compacted (10/30/84) through ponding (3/26/85) and finally draining of the liner on 7/23/86. Figure 5.15 also depicts the chronology of events. A very rapid increase in density after ponding followed by a more gradual rise for the next 9 months was indicative of progressive matrix saturation. While at the time of ponding average water content was 18.1% by weight, water contents after the liner was drained and covered with plastic averaged 18.5%. Large fluctuations in density between 3/85 and 5/85 reflects probe malfunction which necessitated probe repair (6/85-8/85), subsequently a gradual increase in density continued through first half of 3/86 after which the readings stabilized. The drains were vented towards the end of 12/86. Neither the venting of drains nor the additional measurements affected measured density. Fluctuations from 3/86 until the end were only slightly larger than permissible experimental error which allowed standard count to vary within ± 200 cpm or ± 8.7 kg/m^3, or less than 0.4%. However, each such cycle was on the order of the average change in water content following ponding.

Infiltration rings, because of the their large number, had to be activated in stages. Figure 5.16 shows the average infiltration rate during the study period, and associated chronology of the events. Based on results obtained from the barrel and caisson prototypes infiltration into the compacted clay was expected to be reasonably slow ~ 1 x 10^{-9} m/sec or ~ 6 mℓ/day for a 30cm diameter infiltration ring. Anticipating a slow infiltration rate to begin with, measurement using a modified hook gage principle was tried to bring and maintain water level inside the cylinders at the same level as the water outside. This was done as follows. A sharply pointed metal pin was inserted into the clay, its point level with the water outside. The volume of water needed to just cover the pin was measured as the amount infiltrated between sequential readings. Since only a few millimeters change between the readings was expected, it was felt that differences in water level (Bower, 1963b) inside and outside the ring would not be significant. However, because of the rapid infiltration in some rings, it was not possible to maintain high

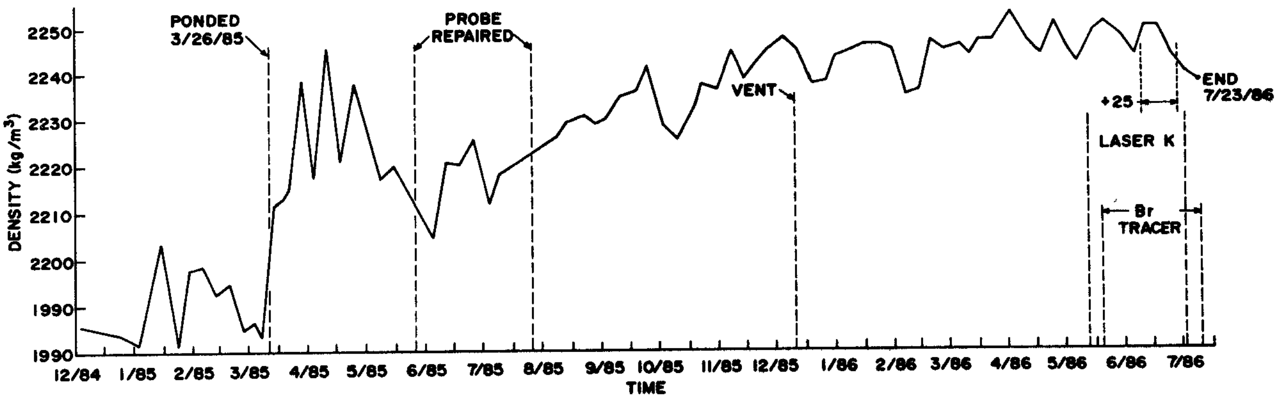


Figure 5.15. Average wet density measured with dual gamma probe before and after ponding.

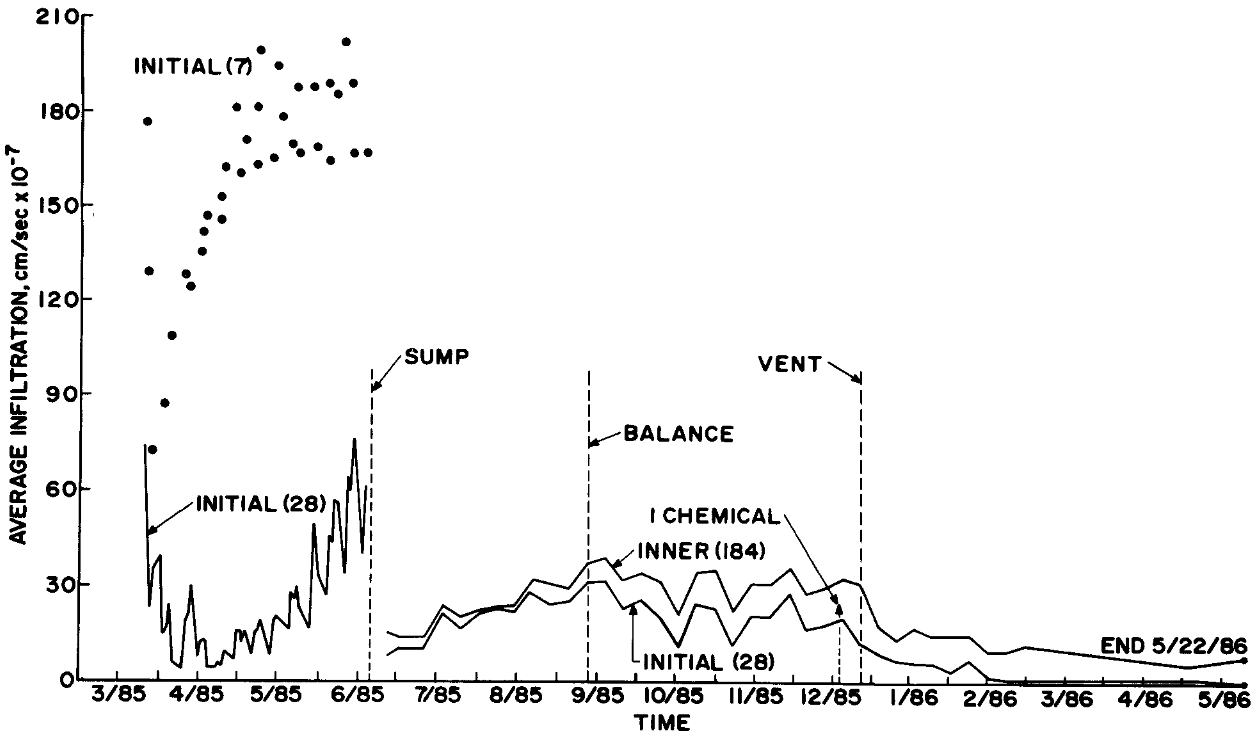


Figure 5.16. Average ring infiltration rate during a one year study period.

enough water level with this method and on 6/18/85 Mariotte bottles (Figure 5.14) were installed for all infiltrometers. The Mariotte bottles maintained a constant water level and were refilled to mark weekly. This procedure worked fine until very low infiltration rates needed to be recorded. It was difficult to measure accurately the small volumes of water required to bring the bottle level up to mark. At that time (9/11/85) weighing of all bottles was implemented.

Originally the intention was to start enough rings to see if hydraulic conductivity of a clay liner could be calculated using Philip's (1957) method. Initially, 35 rings were started at ponding, 7 of these were located near sidewalls (Initial 7 in Figure 5.16) and had a high average infiltration rate which increased with time. For the remaining 28 the average infiltration rate first appeared to decrease then to increase. Subsequently, a sump was installed (6/85) and all outer drains including "Initial 7" were allowed to empty into it together. By this time all rings had been activated, all were equipped with Mariotte bottles and all were being measured individually. The average infiltration rate for the Inner 184 rings was somewhat higher than the average of the Inner 28 rings started initially. The termination date for data collection was 4/30/86. Figure 5.16 shows when the sump and drain vents were installed, when chemical samples were taken, underdrains vented, and data collection ended. The word "Balance" signifies the time when infiltration begun to be recorded by weighing.

Figure 5.17 shows the average outflow rate observed during the study. The two curves represent data for the Outer 66 drains along the walls and Inner 184 drains in the center. The distinction between the two is the extent of compaction. The Inner zone was compacted with a crawler tractor and sheepsfoot roller, while a small vibratory roller and jackhammer were used in the Outer zone. Values after 4/30/86 indicate what other studies were conducted on the liner. We attempted for example, to monitor infiltration rate by bouncing a laser beam off a plate floating in the ring as a function of time. This procedure also involved raising the water level inside the rings about 10mm to measure ring area. Also during that time a chemical sampling of the 250 drains was carried out to compare results with those obtained in December, and Br^- tracer was used on selected drains to evaluate distribution of breakthrough time and to check for potential preferential pathways of flow. Before the liner was drained, fluorescein was introduced into all the rings to check for leaks and nontoxic fluorescent water color (Rich Glo[3]) was added to mark preferential flow pathways when the surrounding area was cored.

Figure 5.18 shows the inflow/outflow balance as a function of time for the liner as a whole corrected for evaporation. The difference between the two values is on the order of 10×10^{-9} m/sec (180ℓ/day), or a change in water level equal to 0.086 cm/day, well within experimental error of the instruments used for monitoring inflow and outflow.

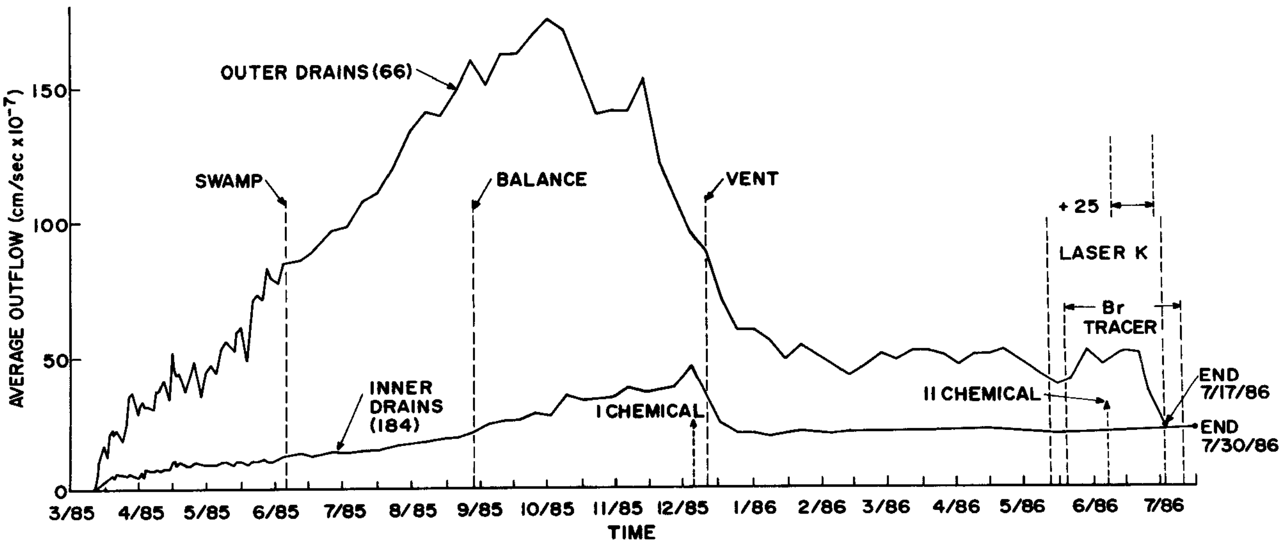


Figure 5.17. Average outflow rate during a one year study period.

[3]Rich Art Color Co., Inc.[1], Lodi, NJ 07644.

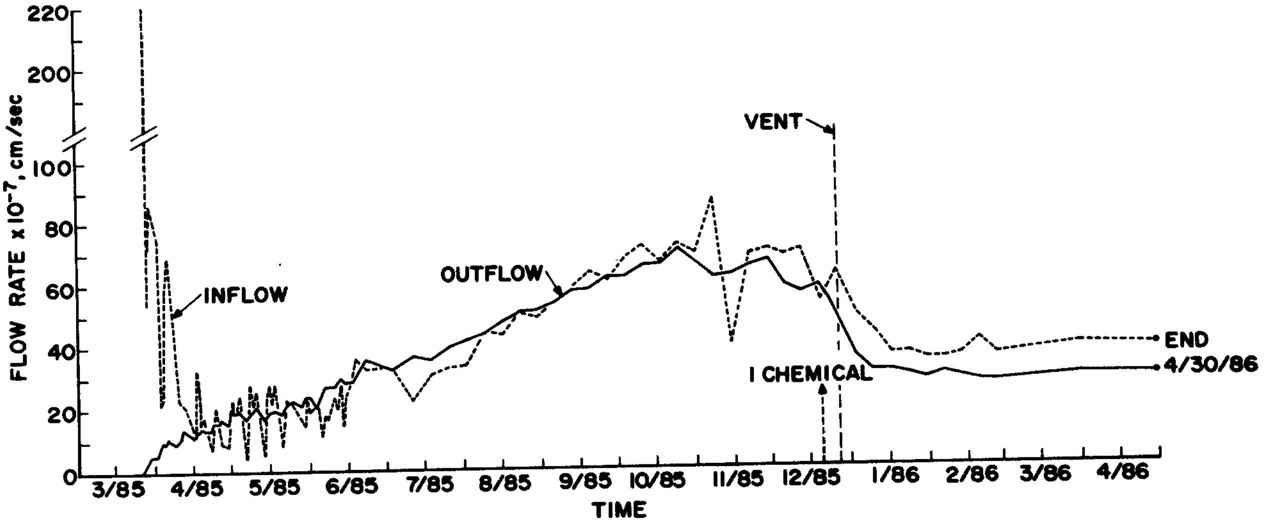


Figure 5.18. Average infiltration and outflow rates for a ponded liner as a whole during the one year study period.

Gradient--

In July 1985 (7/12-7/15) clay liner elevations in the center of each ring on top of the sand layer were measured (z), the level of ponded water was taken as h_2 and a permanent benchmark, established in one corner of the flat platform, became the outflow level h_1. The gradient i was computed for each location (250) as,

$$i = (h_2 - h_1)/L = (h_2 - h_1)/[z-(a+b)] \qquad (5.6)$$

where a and b were taken as 2.54cm (1") and 0.635 cm (1/4") respectively to correct for the thickness of the sand. Schematic representation of parameters is shown in Figure 5.19 and areal distribution of gradient is given in Figure 5.20.

Density--

Changes in bulk density as shown in Figure 5.15 suggest that following the initial rapid increase in density at ponding, the density increased only gradually for the next nine months, becoming essentially constant at about one year following ponding. Such changes may be due to water moving into and through the clay since the net gain in density appears to be small compared to data variability and the magnitude of experimental errors.

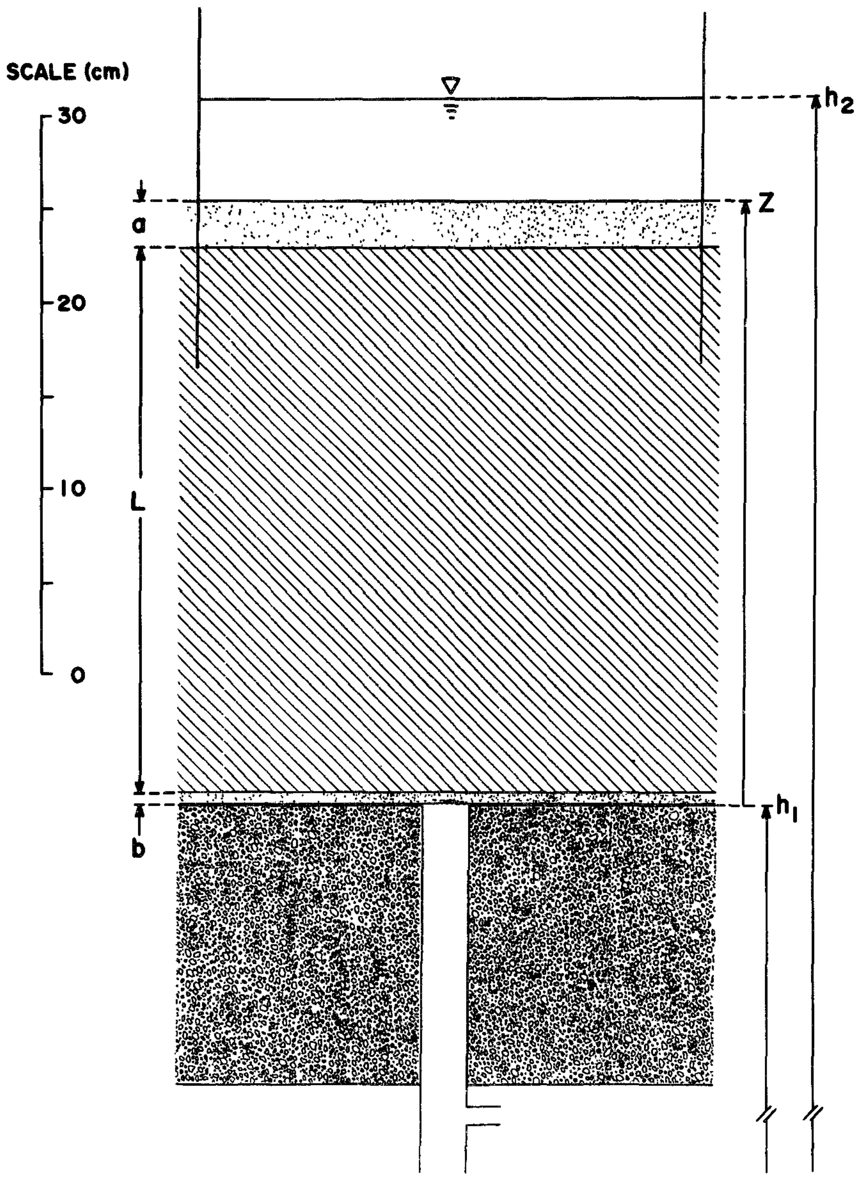


Figure 5.19. Schematic representation of gradient parameters for compacted clay liner at Klingerstown, Pa.

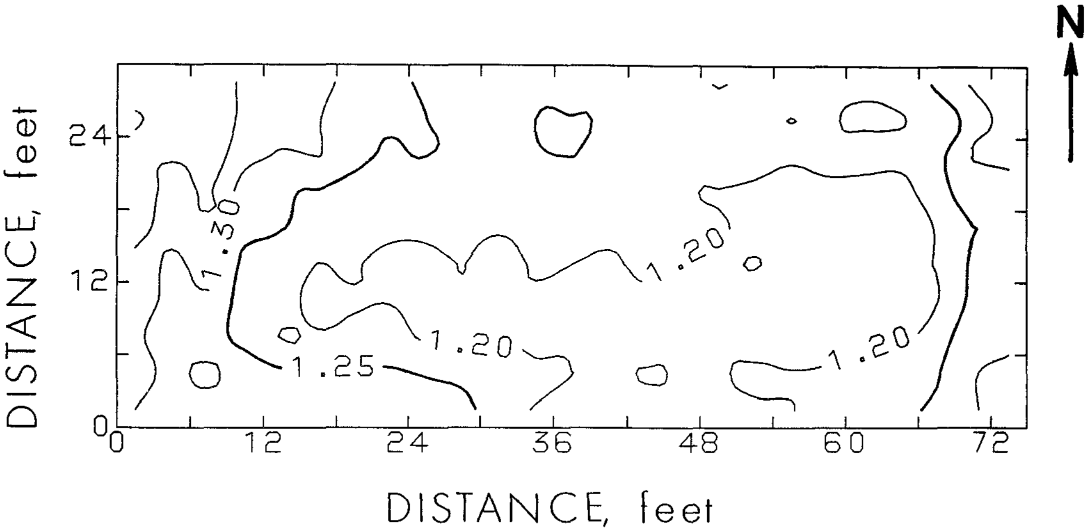


Figure 5.20. Interpolated distribution of hydraulic gradient over the study area.

Prior to construction gravimetric soil water content averaged 16.3% (Table 5.8). Following compaction and ponding the average water content was 18.6% by weight, was measured with an Eley volumeter (24 samples from 3 lifts), and an average adjusted (volume basis to weight basis) water content of 19.2% was measured radiometrically with a Troxler[1] surface probe (108 samples from 3 lifts). Coincident measurements of the dry density in the backscatter mode averaged 1655 kg/m^3. Just after the ponded water drained, gravimetric water content of the clay, based on 55 Veihmeier tube samples was 20.9%. Subsequently 3" and 2" cores were taken. Corresponding average water content and dry density of 3" cores (240 samples) and 2" cores (45 samples) was very similar to values observed before ponding. These figures suggest that values of 1660 kg/m^3 and 18.8% by weight could be taken as the average dry density and water content, respectively for the compacted clay liner. When the liner was sampled with the Veihmeier tube just after the ponded water was drained off the surface, some water still accumulated in the holes left by the Veihmeier tube, suggesting incomplete drainage from the body of the clay. This may account for somewhat higher values of water content (20.9% by weight). Assuming the figure of 20.9% is real results (including standard deviations) in Table 5.8 suggest a possible increase in bulk density due to ponding of at most [(0.209 + 0.022) - (0.186-0.018)] x 1660 = 105 kg/m^3. Table 5.9 shows that the differences between "prepond" and "one year" values are indeed less than that figure (60 kg/m^3).

TABLE 5.8. AVERAGE VALUES OF DRY BULK DENSITY AND WATER CONTENT BY WEIGHT

Time	Dry Density	Water Content
	kg/m^3	% by wt
Before construction		
• Veihmeier tube	Loose	16.3 ±0.9*
After construction		
• Volumeter		18.6 ±1.8
• Surface probe	1655±58	19.20±1.21
After drainage		
•Veihmeier tube		20.9 ±2.2*
•3" cores	1684±73	18.5 ±1.0
•2" cores	1643±63	18.7 ±0.6
Average[1]	1660±65	18.8 ±1.2

[1]Excluding starred *values.

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TABLE 5.9. SELECTED STATISTICS FOR THE DENSITY DISTRIBUTIONS BEFORE AND AFTER THE CLAY LINER WAS PONDED

Time	Mean	SD	Median	Mode	Range
			kg/m^3		
Prepond	2183	83	2181	2189	480
2 days	2211	87	2212	2212	496
10 days	2214	85	2220	2193	429
1 month	2217	85	2223	2248	499
3 months	2220	84	2219	2145	432
6 months	2234	85	2232	2232	442
9 months	2244	84	2244	2187	423
1 year	2243	83	2237	2260	387

The data in Table 5.9 represent average density statistics at specific times after ponding based on the dual gamma probe readings, while Figure 5.21 shows an example of associated spatial distributions. The results for gravimetric samples in Table 5.8 represent water content and density essentially at a point. Surface probe samples are based on backscatter and thermalizing of neutrons by water molecules in the vicinity ~ 0.4 cu ft (0.01 m^3) of emitter. Dual gamma probe data are based on the degree of attenuation of gamma radiation between the source placed in the bottom horizontal tube and the detector placed exactly 30cm (1') above in the second horizontal access tube at the clay surface. Density was computed by comparing observed counts with the standard counts for material of known density. Figure 5.6 shows the contrasting geometrics and Figure 5.22 gives an example of standard count distribution. The dual probe measurements of density were taken continuously at 240 locations following the clay liner construction, through ponding, until it was drained. Tables 5.10 and 5.11 and Figures 5.23 and 5.24 show the type of data which are given in detail by Appendix B (individual readings) and Appendix C (statistics).

Figure 5.23 gives the distribution in time of individual changes in bulk density for the sites #M4, I4, G4 and J4 between consecutive dates, while the dashed line shows a range of variability due to differences in the standard probe counts. Positive and negative changes in density suggest alternate filling and draining of pores where the density was being measured. Values within the dashed lines could be a result of variation associated with the standard counts, those which are lower or higher may be a measure of empty pores or pores filled with percolating water. Figure 5.24 contains information, similar to that in Figure 5.23, except that individual changes in density are accumulated over time. Again, the values are for only four (M4, I4, G4, and J4) of the 240 sites. The dark hatched areas describe net deficit and the light colored ones suggest surplus. The figure is similar to Figure 5.15 where average distribution of density over time is shown. For these four sites, initial deficit (because of liner drying) became a surplus after ponding. However, the net change in density (relative to 0-line) between construction and ponding amounted to -2 kg/m^3 for M4, and +85, +10 and +36

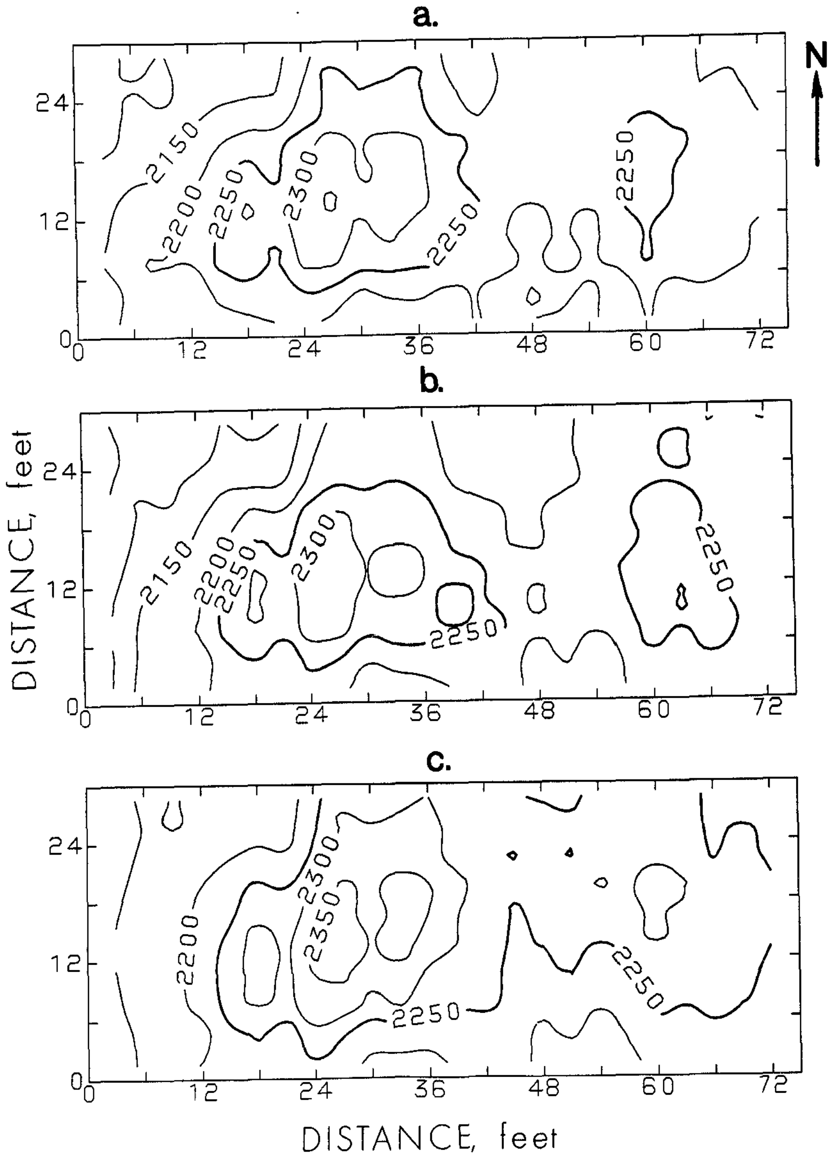
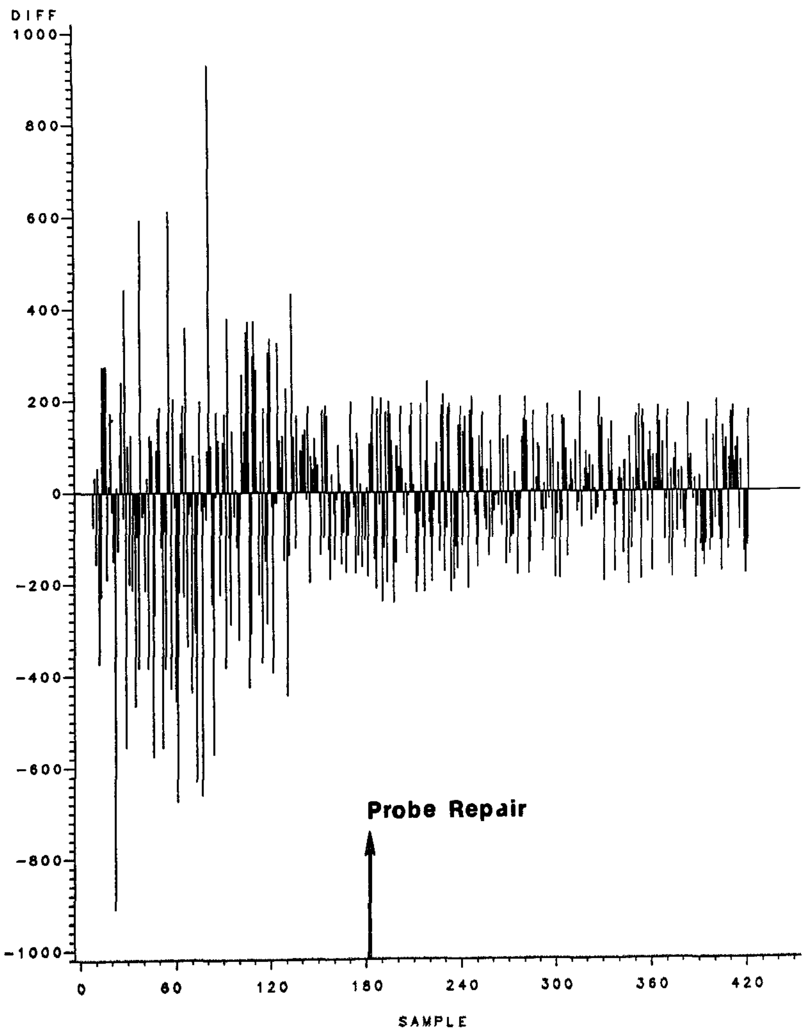


Figure 5.21. Interpolated contours of density two days (top), one week (middle), and one month (bottom) after ponding.

kg/m^3 for sites I4, G4 and J4. Despite the net gain, the pattern among other sites is quite similar suggesting that draining and filling of pores within the clay may well be the way water moves in compacted matrix. Figure 5.25 (a) through (h) shows spatial distribution of density for the same times as given in Table 5.8 (i.e., prepond, 2 days, 10 days, etc.). The density in the center of the platform appears to increase with little change elsewhere. In a gross sense the initial change between "preponded" and "2 days" plots may represent initial filling up of the larger cracks and conduits with ponded water. Subsequent increases would denote the movement of water into the compacted clay matrix. It should, however, be emphasized that observed changes were very small. Because the dual gamma probe "sees" a relatively small cross section of the clay matrix, the changes and fluctuations observed on a daily basis may actually represent alternate filling and draining of the

STANDARD COUNTS : DENSITY



READING DIFFERANCE

Figure 5.22. Distribution of standard counts for the dual density probe with time.

soil mass, especially since some results discussed previously suggest that little if any change in density and water content of the liner occurred during the time it was ponded.

A question may be raised regarding the adequacy of the standard count procedure used. Standard counts were taken at either end of each access tube pair. If the results did not agree to within ± 200 counts the entire set of readings (10) was repeated. Consequently we have a fair amount of confidence in these values and think that alternating fluctuations in observed density are real and represent a realistic picture of transport in the slowly permeable structured porous media.

TABLE 5.10. INDIVIDUAL VALUES OF BULK DENSITY OBTAINED USING DUAL GAMMA PROBE ON 9/25/85 (6 MONTHS AFTER PONDING)

	Bulk Density									
	0	1	2	3	4	5	6	7	8	9
A	2099	2158	2134	2066	2128	2130	2138	2123	2016	2126
B	2182	2218	2193	2222	2235	2192	2136	2104	2139	2120
C	2248	2322	2333	2222	2229	2181	2209	2177	2202	2156
D	2154	2228	2258	2289	2273	2243	2199	2154	2124	2095
E	2108	2148	2194	2243	2223	2239	2209	2082	2064	2026
F	2208	2349	2331	2299	2337	2303	2275	2183	2186	2094
G	2177	2390	2391	2416	2458	2373	2362	2267	2196	2080
H	2154	2223	2237	2301	2307	2270	2157	2156	2278	2178
I	2118	2334	2326	2441	2440	2381	2443	2318	2322	2205
J	2134	2243	2245	2398	2411	2382	2374	2386	2431	2266
K	2116	2232	2252	2295	2343	2363	2393	2349	2273	2162
L	2149	2232	2202	2278	2270	2359	2321	2188	2220	2153
M	2203	2296	2265	2283	2276	2244	2241	2217	2262	2198
N	2186	2291	2157	2183	2238	2305	2236	2185	2248	2174
O	2148	2258	2259	2301	2337	2280	2238	2207	2255	2143
P	2167	2259	2148	2076	2118	2098	2167	2214	2289	2229
Q	2053	2087	2099	2166	2232	2221	2193	2212	2256	2174
R	2202	2255	2226	2280	2316	2399	2316	2299	2277	2185
S	2116	2244	2204	2205	2257	2284	2319	2314	2334	2198
T	2243	2347	2328	2360	2265	2249	2264	2188	2220	2241
U	2133	2229	2240	2272	2316	2342	2288	2282	2262	2225
V	2146	2287	2250	2214	2221	2320	2291	2235	2232	2145
W	2161	2241	2160	2210	2276	2246	2214	2167	2303	2099
X	2275	2414	2332	2235	2201	2216	2195	2205	2195	2213

TABLE 5.11. SUMMARY OF STATISTICS FOR 9/25/85 BULK DENSITY DATA (6 MONTHS AFTER PONDING)

Moments				Quantiles (def=4)				Extremes	
N	240	Sum wgts	240	100% max	2458	99%	2442.18	Lowest	Highest
Mean	2234.5	Sum	536280	79% Q3	2288.5	95%	2390.95	2016	2431
Std dev	85.7879	Variance	7359.56	50% med	2232	90%	2348.8	2026	2440
Skewness	0.190179	Kurtosis	-0.140961	25% Q1	2177.25	10%	2124.2	2053	2441
USS	1200076594	CSS	1758934	0% min	2016	5%	2098.05	2064	2443
CV	3.83924	Std mean	5.53758			1%	2037.07	2066	2458
T=mean=0	403.515	Prob>|T|	0.0001	Range	442				
Sgn rank	14460	Prob>|S|	0.0001	Q3-Q1	111.25				
Num = 0	240			Mode	2232				

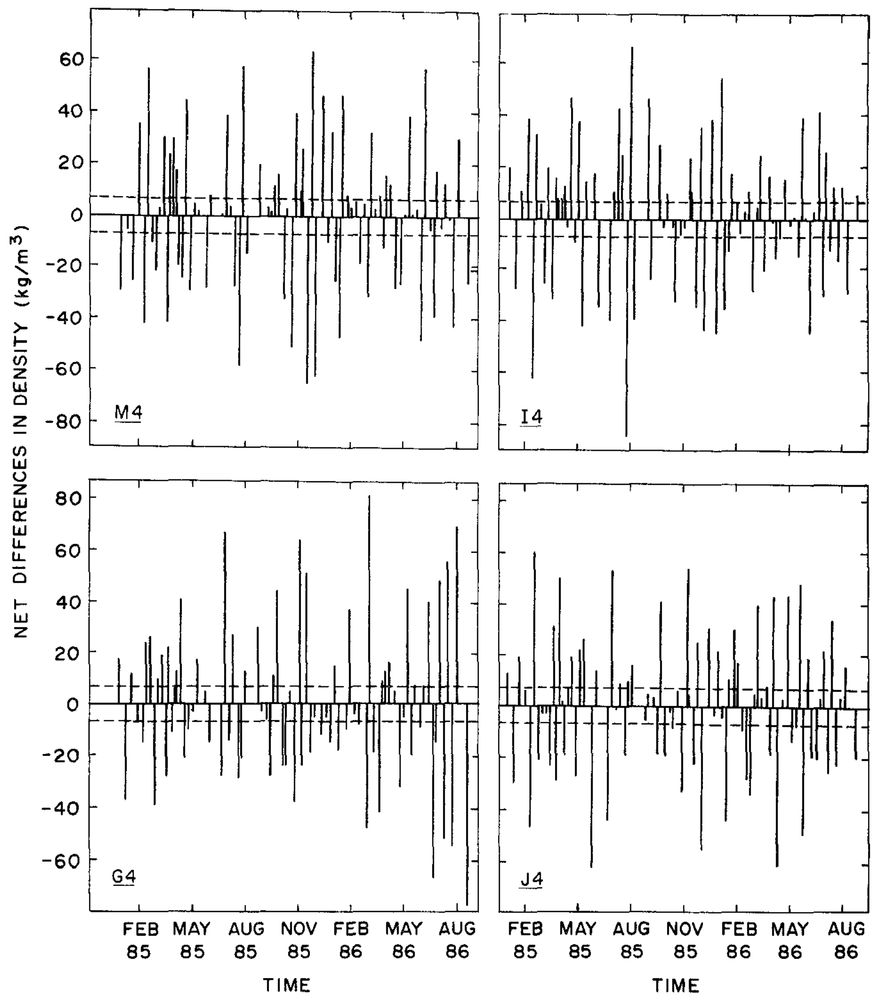


Figure 5.23. Net change in density for consecutive readings at the site M#4, G#4, I#4, and J#4, plotted as functions of time, dashed lines indicate possible extent of the error of measurement (± 8.7 kg/m^3).

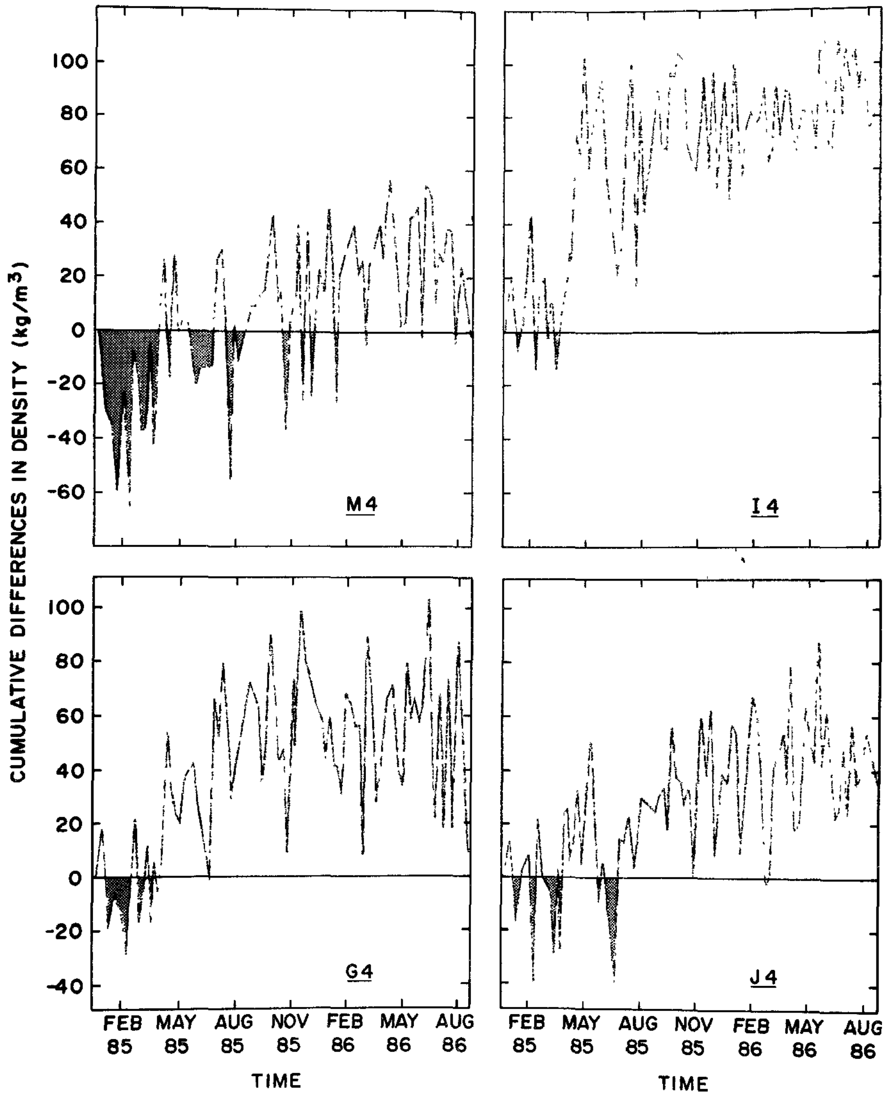


Figure 5.24. Cumulative change in density at the sites M#4, I#4, G#4, and J#4, plotted as functions of time, each value (•) has an associated uncertainty of ± 8.7 kg/m^3.

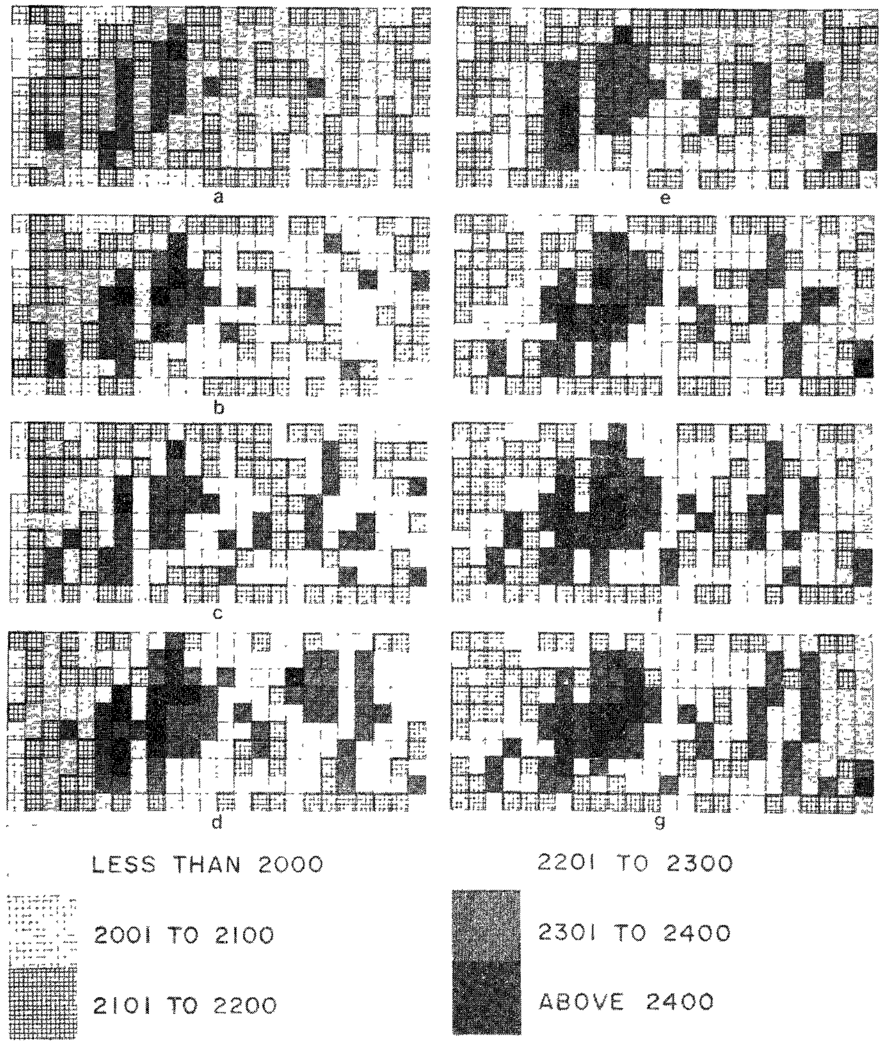


Figure 5.25. Spatial distribution of dual probe density values (kg/m^3) before ponding (a), and 2 days (b), 10 days (c), 1 month (d), 3 months (e), 6 months (f), 9 months (g), and 1 yr (h) after ponding.

Inflow and Outflow--

Inflow rate was measured with a battery of 250 cylinder infiltrometers within a ponded liner. Each galvanized metal ring infiltrometer was half covered with a concrete block to minimize evaporation, and a plastic 1ℓ Mariotte bottle was used to monitor infiltration. Design specifications called for 279.4mm diameter infiltration rings (11") to give a ring area of 613.116cm². To see how accurate ring areas were, water level in each ring was raised by adding a known weight of water and the height of the raise was measured with laser beam Optocator[1]. The ring area was then calculated for each ring and appropriate correction was applied to each cylinder infiltrometer.

The 66 perimeter rings and drains were routed separately to a sump and excluded from consideration because of the lower compaction and possible wall effects discussed earlier. To check the integrity of the inner 184 rings, fluorescein was introduced into the rings at the conclusion of the study and the surrounding ponded water was observed for leaks. Of the 184 rings that were checked individually 143 showed no leaks, 31 showed minor or very slight leaks, and only 10 appeared to have major leaks. Figure 5.26 shows relative distributions of rings with leaks. Under standard operating conditions in

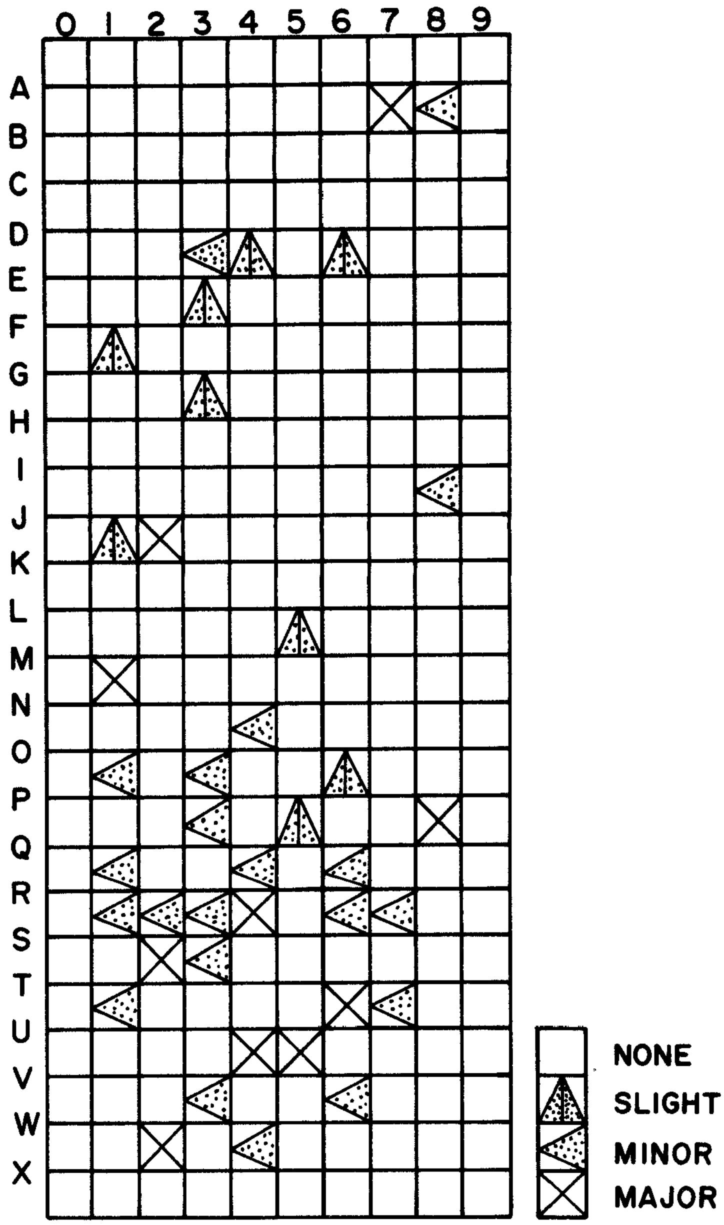


Figure 5.26. Distribution of infiltration rings which showed major, minor or slight leaks when fluorescein was added to each ring.

slow flowing rings, and when water in the liner and the ring was maintained at approximately the same level, effect of small leaks would have been relatively minor, however, in the fast flowing rings and where large differences in head between the cylinder and the water outside occur the error could be considerable (Bouwer, 1962). In general, we would expect such rings to overestimate flows. Table 5.12 compares average infiltration rates obtained for selected dates. There appears to be little difference whether or not a ring area and leaking ring corrections were included or not. If leaking rings are omitted from computations a somewhat higher (rather than lower as expected) average is obtained (27 vs 23 x 10^{-9}m/sec). The most significant effect seems to be the reduction of variance from 9.1 to 2.7 x 10^{-17} (m/sec^2). Computations of statistics given in Appendix C are for ring sets from which leaking rings have and have not been omitted. In this report only nonleaking rings are used in computations.

No such problems existed with outflow data. However, as a preventative measure drains next to the wall (66) were excluded from computations to eliminate possible wall effects. The outflows from these drains were also physically separated from the rest by having a bead of Vol-Clay[1]--a bentonite material placed between them and remaining drains on the floor of the structure (Plate 5.2). Each column (10) of drains, running south to north, was separated from the one next to it by a raised portion (~ 6mm) of the density access tube buried in the concrete base of structure. The drains were assumed to drain an overlying block of compacted clay 0.9m (3') on the side and 0.3m (1') thick. Since however, there were no partitions between such blocks, horizontal and diagonal flows within the clay could have occurred. Burlap and 3mm sand covered the level platform under the clay, and preferential flow to some drains within this layer, although unlikely, cannot be completely ruled out. The assumption under which the results are analyzed is that infiltration rates are represented by ring inflow rates and outflow flux for the 3' x 3' blocks is given by the drain outflow. Reported variability is assumed to be a function of soil properties as well as the spatial distribution of the preferential flow pathways within the experimental structure.

TABLE 5.12. AVERAGE INFILTRATION RATES FOR SELECTED TIMES UNCORRECTED (ALL) AND CORRECTED FOR RING AREA (AREA CORRECTION) AND LEAKING RINGS (LEAK RINGS OMIT)

Time	All	Area Correction	Leak Rings Omit
	x 10^{-9} m/sec		
3 months	15.37	15.51	16.39
6 months	31.86	31.96	37.05
9 months	31.29	31.47	37.24
1 year	5.29	5.31	6.41
AVG	23.56±9.55	24.03±4.17	27.15±5.22

Initial infiltration--Philip (1957) suggested that when water is ponded on a deep and homogeneous soil with a uniform initial water content infiltration (I) in millimeters is given by

$$I = St^{1/2} + At \quad (5.7)$$

where t is the time in seconds, S is the sorptivity, and A is a parameter related to the saturated hydraulic conductivity (K_{sat})

$$A \simeq 1/3\ K_{sat} \quad (5.8)$$

When equation (5.8) is written as,

$$I/t^{1/2} = S + At^{1/2} \quad (5.9)$$

a linear regression fit gives S as the intercept and A as the slope of the straight line segment. This approach has been routinely used, i.e., by Sharma et al., (1980) for field determination of sorptivity and conductivity values.

In our study water was ponded on reasonably homogeneous material derived from the same subsoil horizon which had been brought to a uniform water content and compacted to a uniform density. Although the clay layer was not deep in the strict sense of the word (0.3m), it was assumed to be sufficiently thick because of low expected values of hydraulic conductivity (1×10^{-9} m/sec). The initial portion of the infiltration curve following ponding (here 5 hours) was fitted with a linear regression and the values of S, A, and K_{sat} were estimated. The estimated values of K_{sat} were corrected for the appropriate infiltration ring area and for local gradient and expressed in terms of flux q for 23 out of the 35 infiltration rings that were started initially. Figure 5.27 shows the results for the site I1 and Table 5.13 gives the computed values of sorptivity (S), A-value, and saturated hydraulic conductivity (K_s) for the 23 rings. The last two columns give hydraulic conductivities for the same locations based on the full length of record for the inflow and outflow, respectively. Statistical analysis values of K_s estimated using Philip's method were significantly higher (at better than 1%) than hydraulic conductivities based strictly on ring or drain data which were not significantly different from one another ($t > 0.5$).

Flow at a point--Figures 5.28 and 5.29 a and b illustrates inflow and outflow behavior in time at four selected points on a platform along with associated values of bulk density on either side of a particular ring-drain location. Compared to the averages in Figures 5.16 and 5.17, individual observations in Figures 5.28 and 5.29 show much greater variation. The flux in rings and drains at location A3 (Figure 5.28a) was quite different from that at F1 (Figure 5.29b) varying greatly in time. At sites N8 and H5 fluxes were quite similar although both varied extensively in time, while at the site F1, a location that also showed a very slight ring leak, there was hardly any flux at all. Results illustrate the observed ranges in variability both spatially and in time.

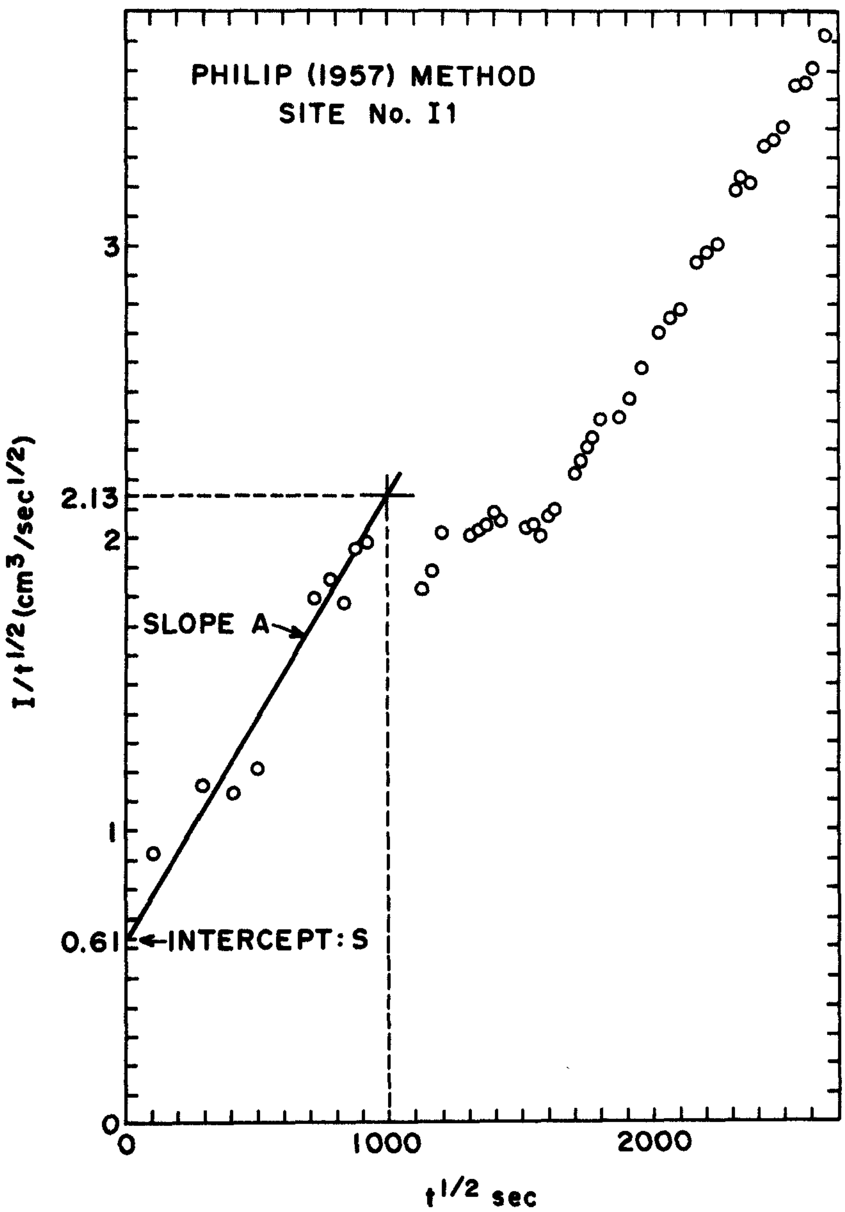


Figure 5.27. Illustration of Philip's (1957) method for calculation of sorptivity S, and A-values.

TABLE 5.13. SORPTIVITY, A-VALUES, AND SATURATED HYDRAULIC CONDUCTIVITY BASED ON INITIAL (1000 SECS) INFILTRATION RATES FOR SELECTED[1] DOUBLE RINGS (613 M^2 AREA INFILTROMETERS USING PHILIP'S (1957) METHOD)

Site	Slope	Intercept	S	A	K_s	K_{s-4301}	K_{s-4300}
	cm^3/sec	$cm^3/sec^{1/2}$	$cm/sec^{1/2}$	x 10^{-9} cm/sec		x 10^{-9} n/sec	
C1	.00135	1.90	.00310	22.02	66	6	11
C3	.00162	1.60	.00261	26.42	79	4	9
C5	.00116	1.48	.00241	18.92	56	6	1
C7	.00160	2.00	.00326	26.10	78	74	83
C9	.00600	1.00	.00163	97.86	293	-	-
F0	.00530	1.60	.00261	86.44	259	-	-
F2	.00121	1.41	.00230	19.74	59	1	6
F4	.00178	1.05	.00171	29.03	87	67	30
F6	.00185	1.20	.00196	30.17	90	6	23
F8	.00129	1.20	.00196	21.04	63	5	14
I1	.00152	0.61	.00099	24.79	74	8	3
I5	.00216	0.66	.00108	35.23	105	33	79
I9	.00327	1.33	.00217	53.33	160	-	-
L0	.00470	2.48	.00404	76.66	230	-	-
L6	.00145	0.55	.0009	23.65	70	10	31
L8	.00155	0.65	.00106	25.28	75	13	24
O1	.00128	0.58	.00095	20.88	62	4	8
O5	.00169	0.13	.00021	27.56	82	9	2
O9	.00575	0.40	.00065	93.78	281	-	-
R0	.00062	0.96	.00157	10.11	30	-	-
R4	.00042	0.37	.0006	6.85	20	1	1
R8	.00028	0.32	.00051	4.485	13	6	32
U9	.00065	0.05	.0008	10.60	31	-	-

[1] There were insufficient data on sites I3, I7, L2, L4, O3, O7, R2, R6, U1, U3, U5, U7, to warrant computation.

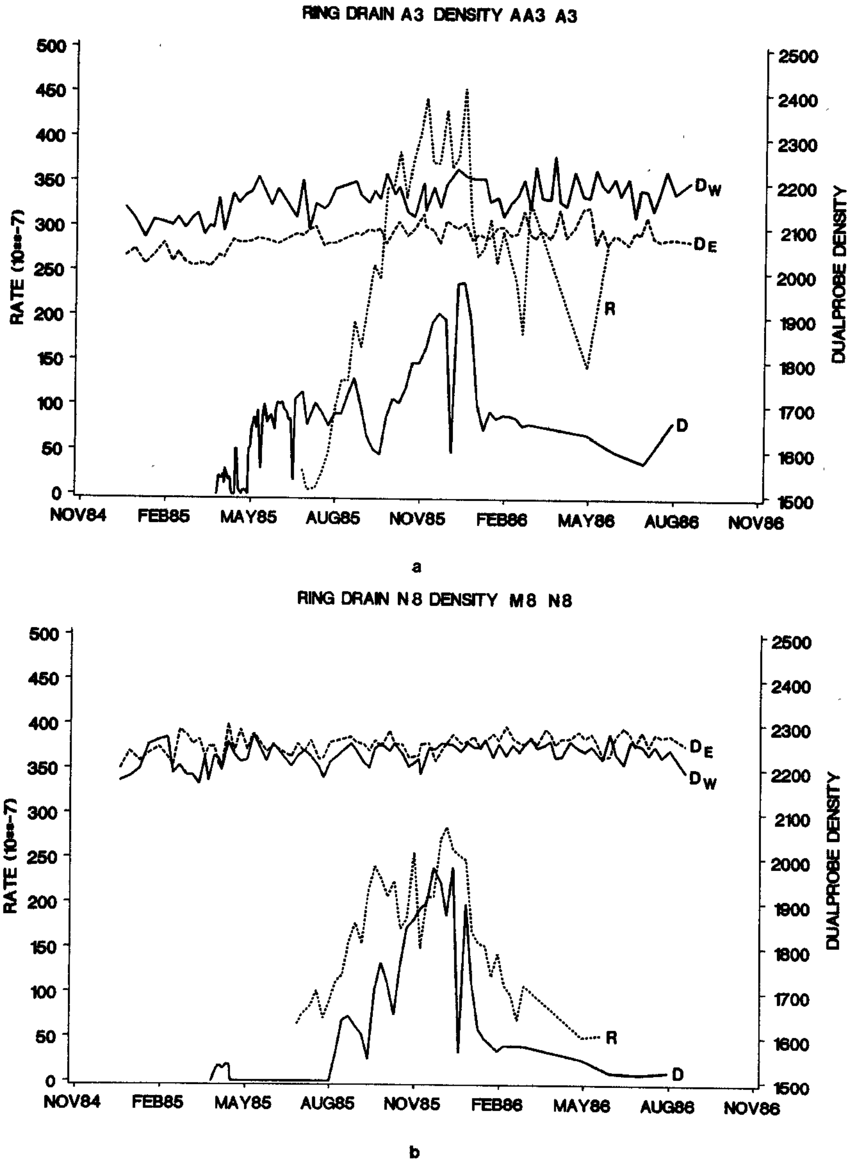


Figure 5.28. Ring inflow rate (R), drain outflow rate (D) and associated bulk density distribution to the east (D_E) and west (D_W) of the ring-drain, for the sites A3 (a), N8 (b).

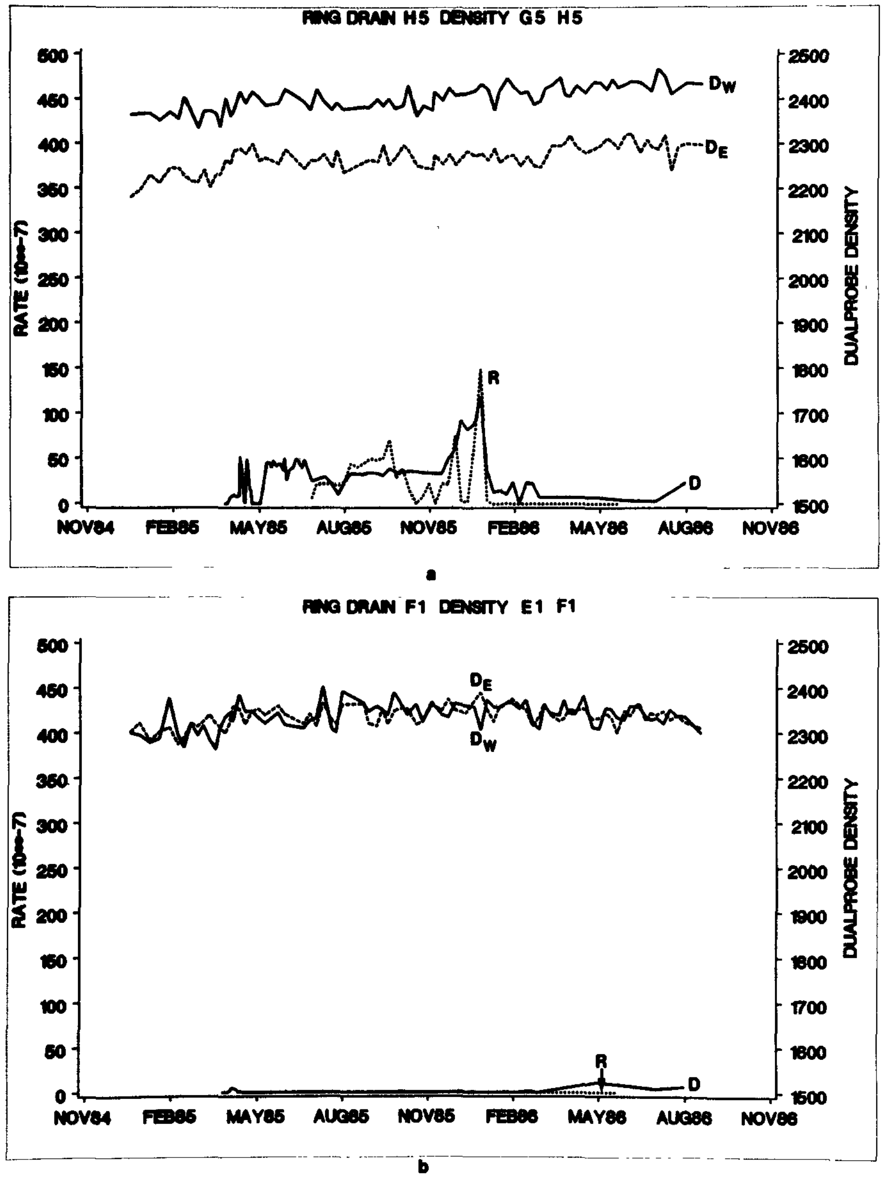


Figure 5.29. Ring inflow rate (R), drain outflow rate (D) and associated bulk density distribution to the east (D_E) and west (D_W) of the ring-drain, for the sites H5 (a), F1 (b).

In Tables 5.14 and 5.15 selected statistics for particular days after ponding are given for the raw and log-transformed ring and drain data.

Figures 5.30 and 5.31 show a comparison of hydraulic conductivity distribution computed from ring and drain flux at 3, 6, 9, and 13 months (1 yr) after ponding. Although quite similar at 3 and 6 months, infiltration and outflow appear different at 9 months and 1 year time, suggesting that reliance on a one time set of infiltration measurements as a criterion of liner quality may not be adequate. However, it is the outflow, the flux out of the lower bottom that appears to be the best descriptor of clay liner performance because it shows what actually gets through the liner. This, of course, causes a dilemma since under natural conditions 1m (or more) thick liners should take a long time to equilibrate.

Finally, Figure 5.32 shows a comparison of hydraulic conductivity distributions computed from time averaged ring infiltration and drain flux. The agreement between the two appears considerably better and the distribution of values are closer to what was observed in practice. Statistical comparisons showed that the ring inflow and drain outflow averages were not significantly different. However, ring inflows and drain outflows were significantly different at 3, 9, and 12 months following ponding.

TABLE 5.14. SELECTED STATISTICS FOR THE HYDRAULIC CONDUCTIVITY DISTRIBUTIONS IN TIME COMPUTED FROM NONTRANSFORMED (a) AND LOG-TRANSFORMED (b) RING INFILTRATION DATA FOR THE PONDED CLAY LINER

Time	Mean	SD	Median	Mode	Range
		(a) x 10^{-7} cm/sec			
2 days	30	25	28	0	93
10 days	19	32	2	0	98
1 month	37	62	12	0	144
3 months	13	19	3	0	76
6 months	30	53	7	0	334
9 months	29	64	<1	0	267
1 year	5	15	0	0	114
		(b) log-transformed			
2 days	3.33	0.73	3.36	1.62	2.91
10 days	2.95	1.40	3.17	0.65	3.93
1 month	3.14	1.43	3.08	0.36	4.91
3 months	2.57	1.48	2.89	-3.37	7.70
6 months	2.47	1.80	2.74	1.99	8.14
9 months	0.70	2.74	-0.27	-3.39	9.03
1 year	1.65	1.95	1.90	-2.42	7.17

TABLE 5.15. SELECTED STATISTICS FOR THE HYDRAULIC CONDUCTIVITY DISTRIBUTIONS IN TIME COMPUTED FROM NONTRANSFORMED (a) AND LOG-TRANSFORMED (b) DRAIN OUTFLOW DATA FOR THE PONDED CLAY LINER

Time	Mean	SD	Median	Mode	Range
		(a) x 10^{-9} cm/sec			
2 days	2	6	0	0	43
10 days	8	10	5	0	45
1 month	12	21	<1	<<1	127
3 months	11	21	<1	<<1	129
6 months	21	39	4	<<1	238
9 months	28	38	11	<<1	165
1 year	17	23	9	10	173
		(b) log-transformed			
2 days	0.69	2.27	1.73	-2.89	6.68
10 days	1.56	1.38	1.76	-2.69	7.61
1 month	-0.48	2.89	-2.80	-2.81	7.82
3 months	-1.85	3.79	-4.75	-4.76	9.79
6 months	-0.31	3.86	1.35	-4.75	10.34
9 months	-0.43	3.88	2.36	-4.75	9.93
1 year	1.86	1.66	2.05	2.29	8.83

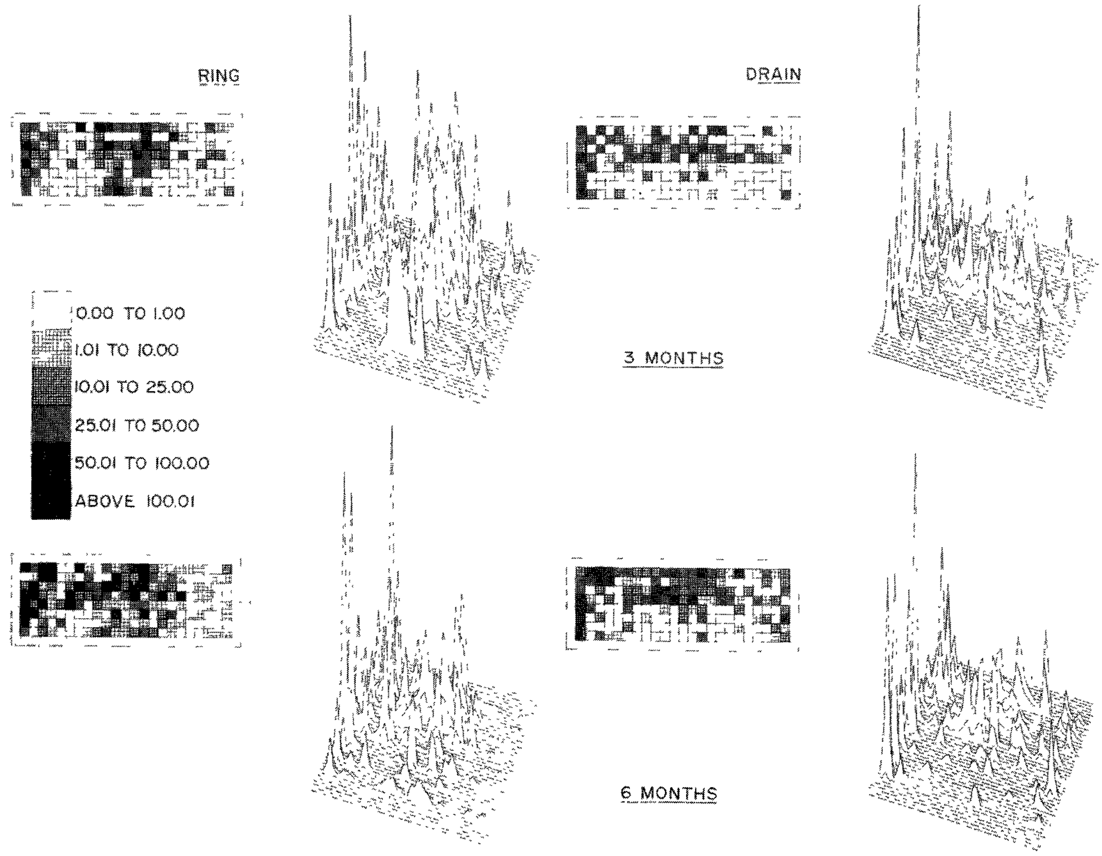


Figure 5.30. Comparison of hydraulic conductivity distributions computed from (ring) inflow and (drain) outflow at 3 months and 6 months.

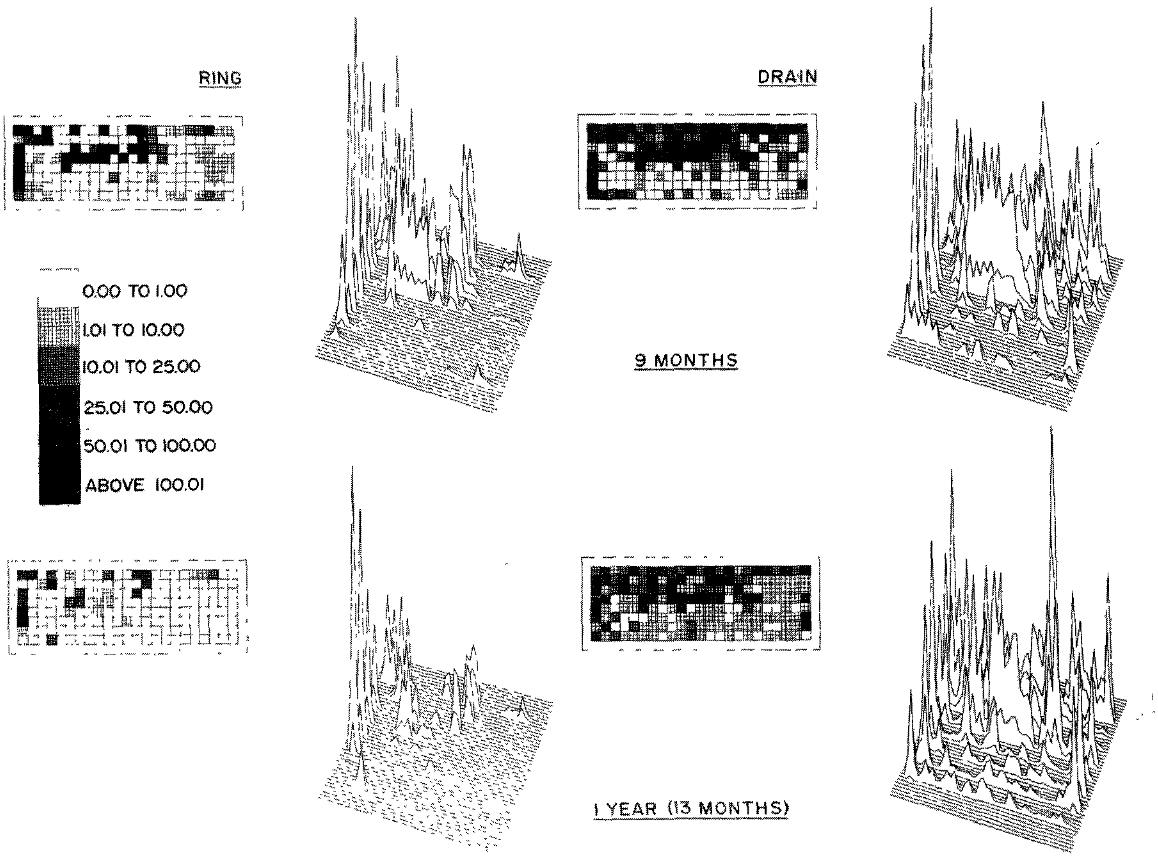


Figure 5.31. Comparison of hydraulic conductivity distributions computed from ring inflow and drain outflow at 9 months and 1 yr (13 months).

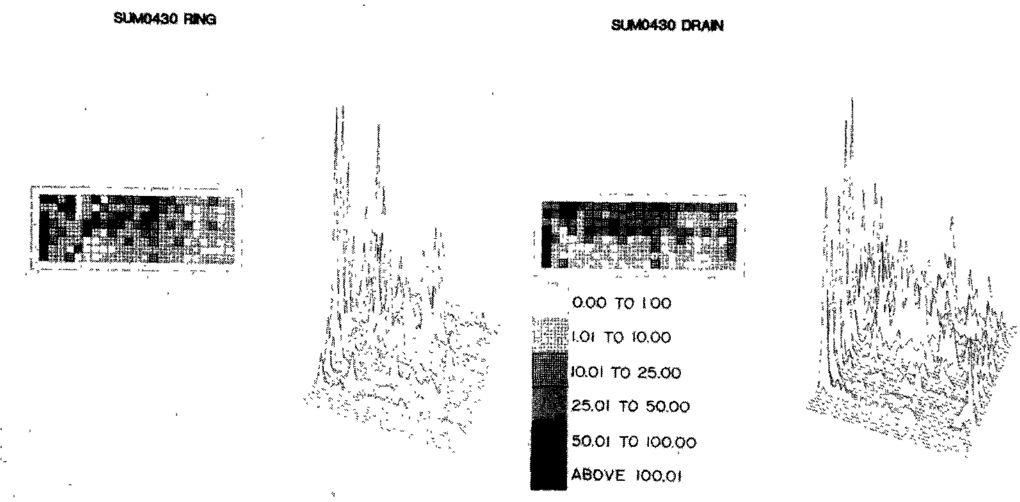


Figure 5.32. Comparison of hydraulic conductivity distributions computed from ring inflow and drain outflow averaged over time (6/27/85 to 4/30/86).

Tracer Studies--

Tracer studies were initiated at the conclusion of the main experiment. To prepare the tracer, 1 gram molecular weight of KBr (119.0 g) was dissolved in 1L of water to give 1M solution of Br^- (79.9 g/L). Either 50 or 100mℓ of this solution were diluted with ponded water to 2000mℓ and added to 15 rings (Figure 5.33) in one, two, or three 2000mℓ increments depending on the hydraulic flux rate and expected times (Table 5.16). At the time tracer solution was applied to rings initial (time = 0) samples of leachate from underlying drain and 8 (or 5) surrounding drains were taken. Sampling of leachate was continued at suitable intervals depending on the volume of accumulated outflow. Leachate samples were analyzed for Br^- concentration using Orion[1] Model 9435 bromide electrode, and Orion[1] Model 407A specific ion meter, and Orion[1] double junction reference electrode mode 90-02. Ion specific bromide electrode allows simple and rapid measurement of free Br^- ions in aqueous solutions. General experimental procedure and detailed results for each cluster of drains are given in Appendix D. Figure 5.34 illustrates the format of data in Appendix D data. Results are presented as $\log_{10}$ pulses of relative concentration (C/Co) at indicated times in hours after critical application. Relative concentration values less than 10^{-4} are not reliable and are included here to indicate primarily the first arrival times at a location, while the pulse (10^{-6}) at time = 0 denotes the starting time for each run.

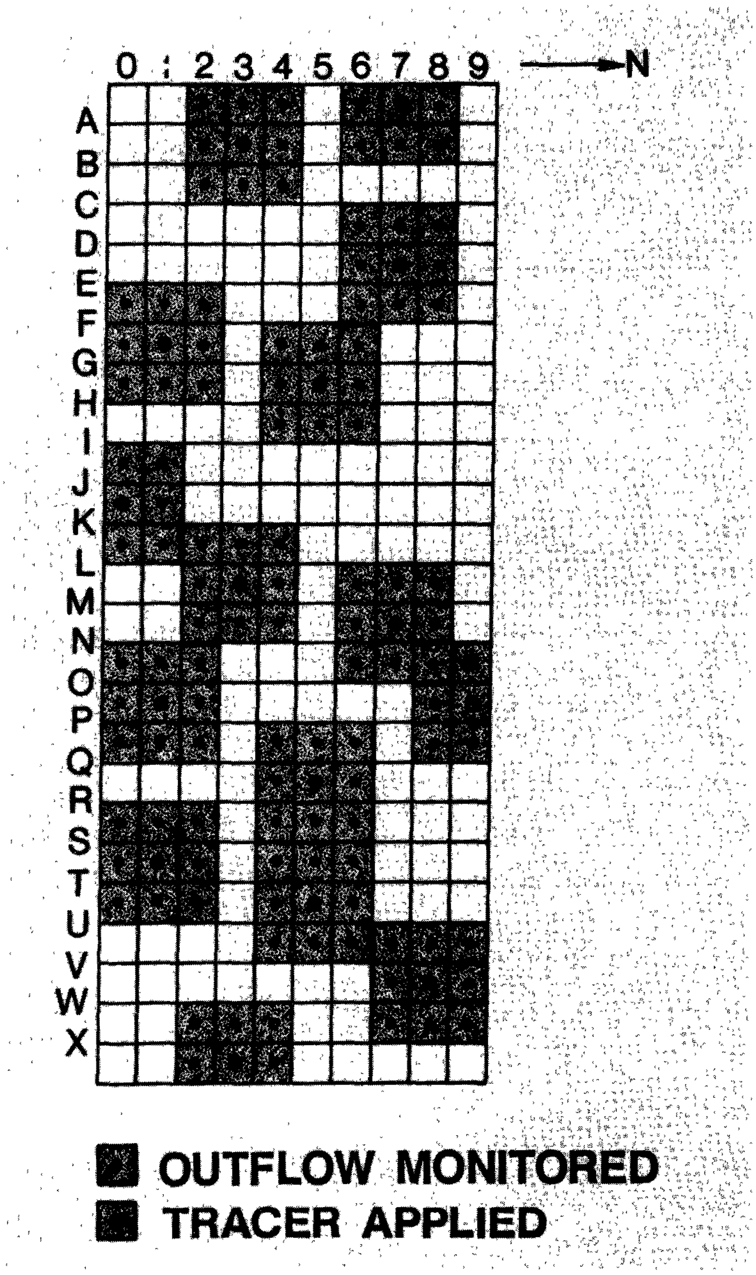


Figure 5.33. Location of 15 infiltration rings and respective sampling areas (shaded) to which 1M Br^- solution had been added.

TABLE 5.16. AMOUNTS OF 1M BR^{-1} DILUTED TO 2000Mℓ AND APPLIED TO RINGS IN 1, 2 OR 3 (USED) INCREMENTS OF 2000Mℓ; APPLIED CONCENTRATION (CO) IN PPM AND GRAMS (G)

Ring	1M Br^-	Used	Co	
	mℓ		ppm	g
AA7	100	1	4000	8.0
A3	50	1	2000	4.0
D7	100	2	4000	16.0
F1	50	1	2000	4.0
G5	100	1	4000	8.0
J0	100	1	4000	8.0
L3	100	1	4000	8.0
M7	50	1	2000	4.0
01	100	1	4000	8.0
09	100	1	4000	8.0
Q5	100	1	4000	8.0
S1	100	1	4000	8.0
T5	100	2	4000	16.0
V8	100	1	4000	8.0
X3	50	3	2000	12.0

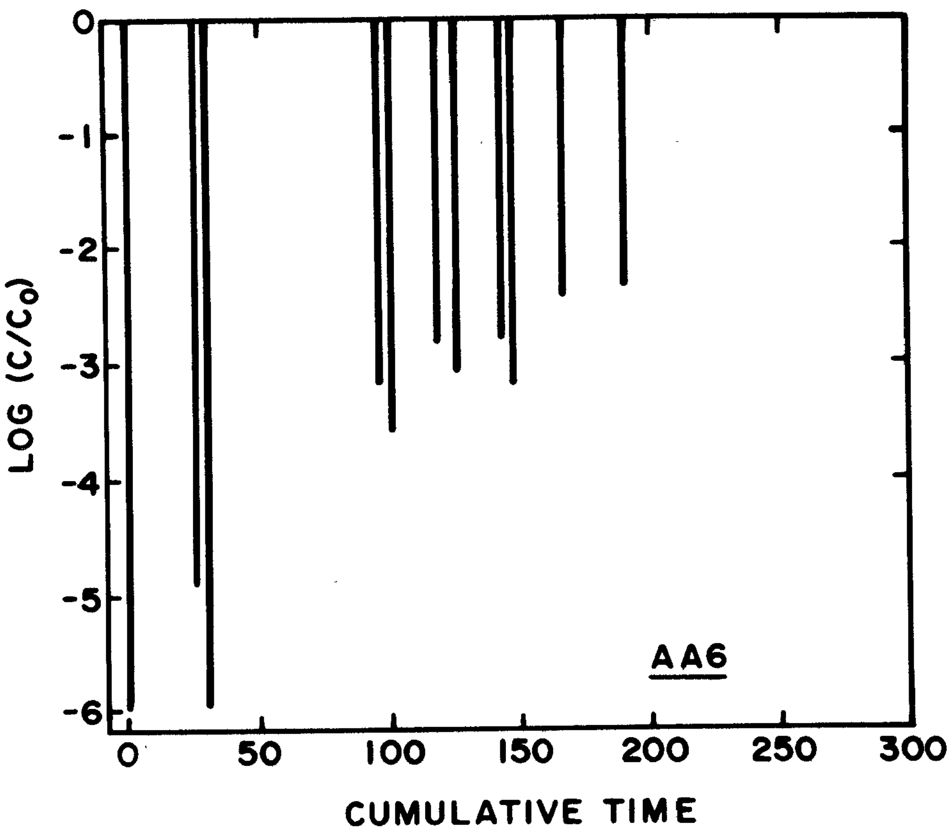


Figure 5.34. Logarithm (base 10) of relative (C/Co) breakthrough concentrations of Br^- pulses in hours at a particular drain (AA6) and arrival times after applying Br^- tracer to central ring (AA7).

Water and tracer breakthrough--Tracer tests with Br^- were carried out towards the end of the study, while 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. Although anion exclusion and Br^- reactions with positively charged portions of the clay matrix may affect tracer movement, short-circuiting flows through the macropores should be relatively free of these considerations, ether because the flow is more rapid, or because the size of transporting pores is larger then pores in the clay matrix.

Tracer breakthrough, given as the first arrival of tracer at the principal drain or one of the surrounding drains, originated from a centrally positioned, 600-cm^2 infiltration ring. Water breakthrough, however, was a result of ponding the entire facility, and outflow from a 8,000-cm^2 area surrounding each drain. In either case, the clay liner was not fully saturated. Initial water content distribution corresponded to a 100kPa tension, while water contents after the water was drained were 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.

Figure 5.35 shows histograms of water and tracer breakthrough data. The histogram in Figure 5.35a gives the distribution of breakthrough times for water, which is represented by substantial frequencies in all classes. However, breakthrough times for tracer (Figure 5.35b) are heavily skewed and primarily confined to one frequency class. Figure 5.35 a and b illustrates relative concentration (%) of Br^- in the leachate as a function of cumulative time (hrs) for drains underlying the rings to which tracer was applied.

In Figure 5.36 breakthrough times for water and interpolated breakthrough times for tracer are presented as mosaics of respective distributions. Numerical values for both fall within a similar range.

A constant water level was maintained over the clay following ponding. Preliminary calculations showed that, with assumed flux (q) through the clay matrix on the order of 1×10^{-9} m/sec, water should take as long as 10 years

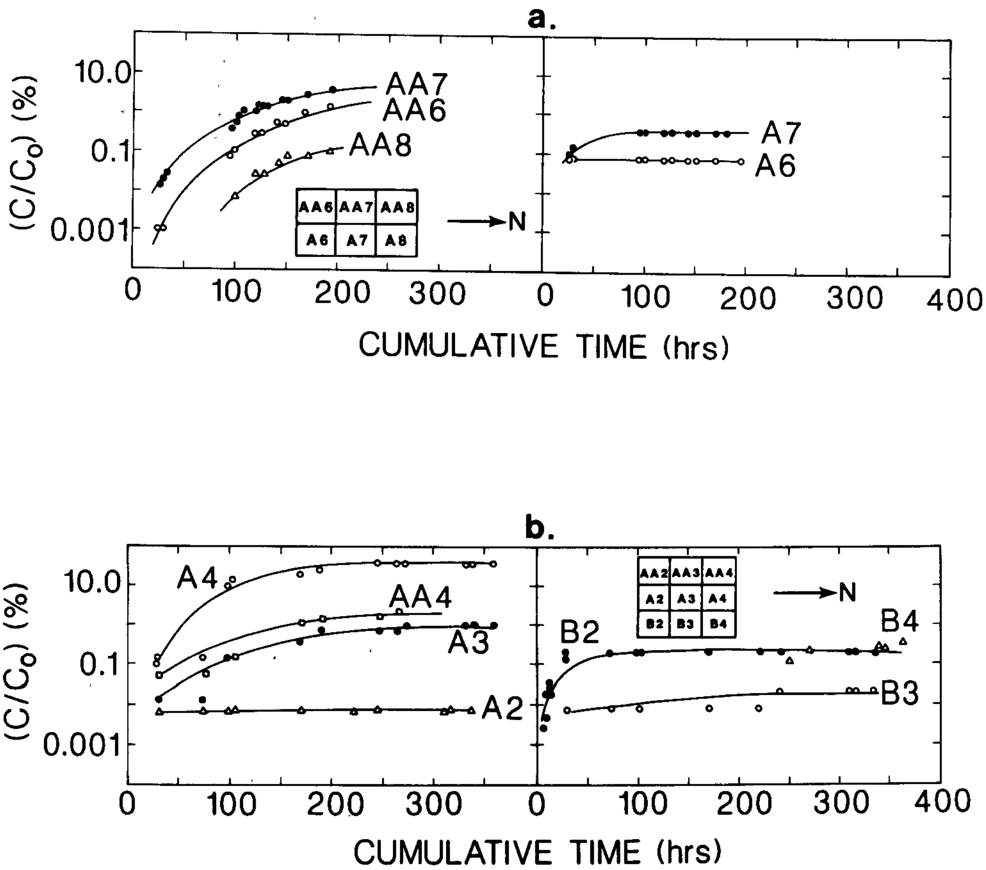


Figure 5.35. Relative concentration of Br^- in leachage AA7 and surrounding drains (a), and from A3 and surrounding drains (b).

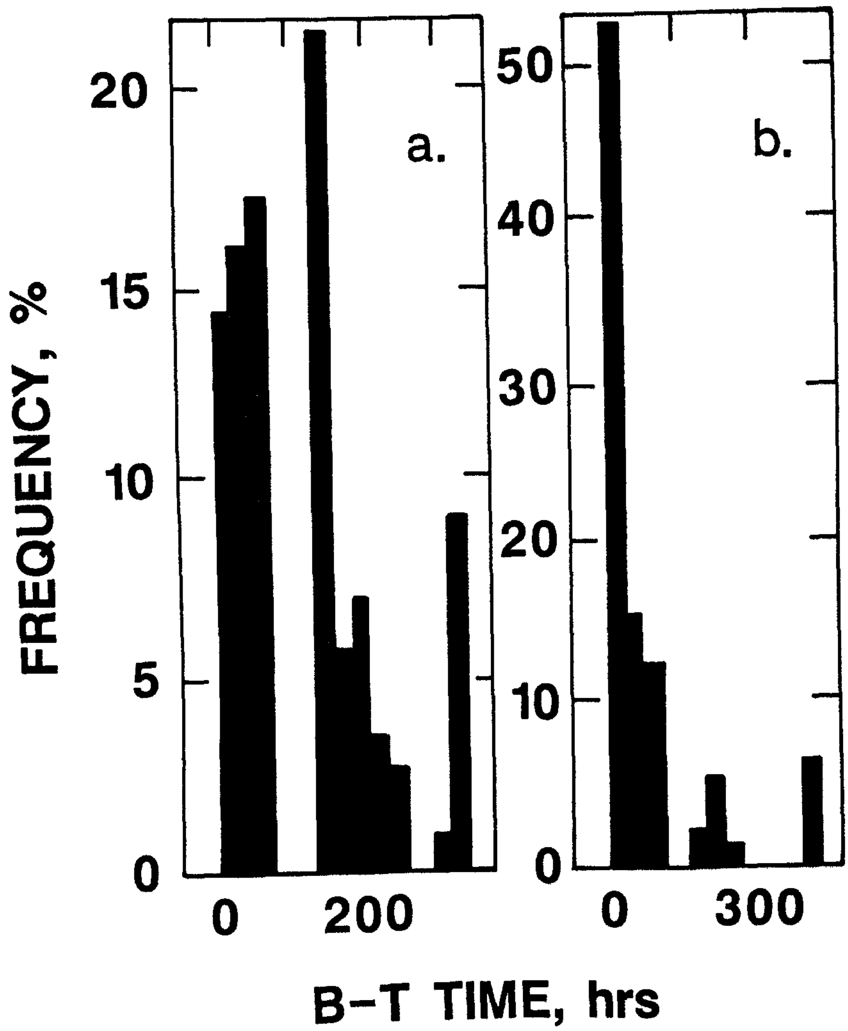


Figure 5.36. Frequency histograms of breakthrough times (B-T time) for water (a) and Br^- (b).

to pass through the experimental 30-cm-thick clay liner. Since considerably faster flow rates and breakthrough times were observed experimentally at several locations, it was concluded that short-circuiting flow was taking place through a few relatively larger continuous pores in the otherwise slowly permeable clay matrix. In contrast, Br^- tracer appeared to move only through that portion of the profile that was directly influenced by a spiked ring. The head in each ring was controlled separately. Tracer would have to diffuse into the clay matrix if the infiltration ring was not situated directly over, or close to a macropore. Consequently, tracer flow would be far less sensitive to overall hydraulic gradient in ponded water and more sensitive to local conditions associated with each ring.

Water breakthrough times on the average appear to be longer than those for tracer, possibly because of initial radial diffusion of water from macropores into the adjacent, unsaturated clay matrix. Actual tracer breakthrough may well be faster still, since Br^- breakthrough distribution was determined in wet soil. Under these conditions tracer flow could lag behind due to displacement of tracerless water ahead of the infiltrating solution.

<u>Effective porosity</u>--In Table 5.17 laboratory values of hydraulic conductivity measured on selected 9cm diameter cores are given along with average flux density values based on inflow and outflow. These cores were taken within each infiltration ring. Laboratory hydraulic conductivity was determined using a flexible wall permeameter, and with a gradient of about 20. Results illustrate the extent of discrepancies possible between field and laboratory determinations.

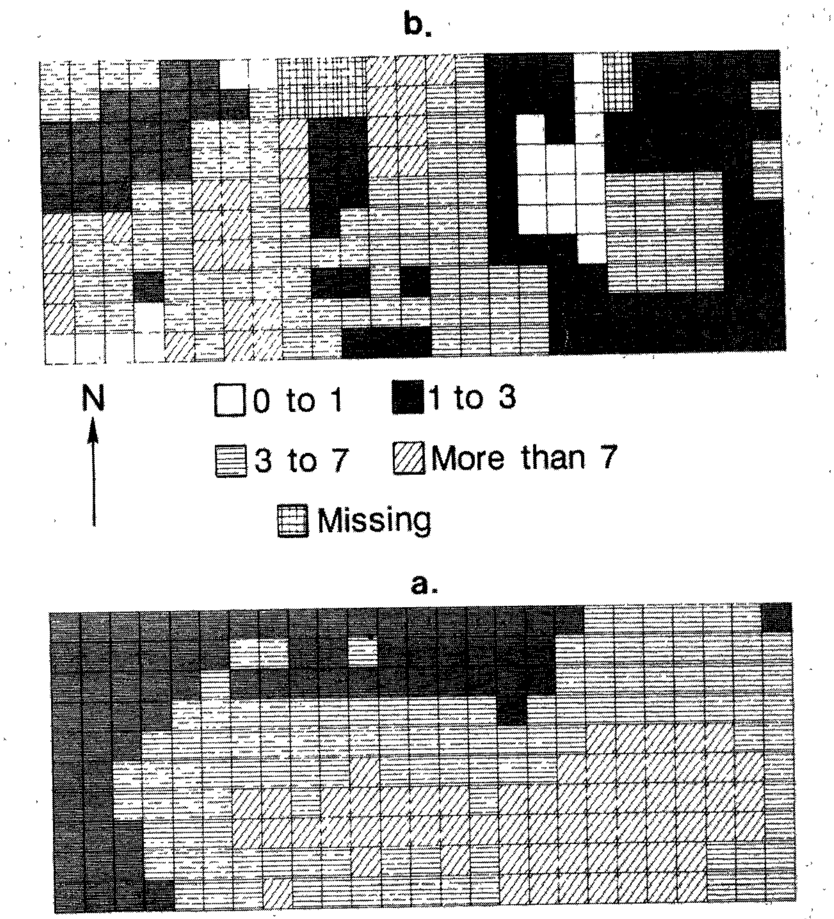


Figure 5.37. Distributions of breakthrough (first arrival) time (days) for water (a) and Br^- tracer (b) in compacted, spatially variable clay liner.

TABLE 5.17. LABORATORY VALUES OF HYDRAULIC CONDUCTIVITY[1] COMPARED WITH AVERAGE[2] FIELD VALUES OF RING INFLOW AND DRAIN OUTFLOW

Site	Lab	Field: Ring inflow	Field: Drain ouflow
		x 10^{-9} m/sec	
A1	1.1	40.1	164.4
A2	2.2	59.5	99.1
A3	5.9	235.2	105.7
A4	1.7	215.5	140.9
A5	2.6	155.0	149.2
A6	2.0	85.7	41.8
A7	0.4	4.0	98.4
C2	1.7	4.7	0.1
C5	1.8	6.8	0.6
C7	2.7	97.8	109.4
E3	1.5	7.0	0.0
F1*	1.0	0.1	2.2
F3	0.8	0.4	0.6
G2	2.6	0.7	0.6
G5*	4.2	43.4	40.8
G6	2.2	95.9	33.7
H5*	1.2	20.0	30.0
I2	0.5	0.3	0.3
J1	1.1	10.8	0.8
K6	1.2	43.4	39.9
N1	0.9	19.5	11.8
N7	1.2	155.4	62.0
S7	0.8	0.3	4.5
T2	1.5	1.1	0.4
V5	2.4	1.7	18.3
W1	0.8	9.3	12.0
Average	1.8±1.2	50.5±69.2	44.9±53.2

[1]Laboratory values obtained using flexible membrane hydraulic conductivity apparatus.

[2]Field values are for the "430" data set in which total inflow or outflow per unit area for the period of 6/11/85 to 4/30/86 was divided by total elapsed time.

Based on laboratory values of hydraulic conductivity breakthrough times (Table 5.18), for a 30-cm-thick clay layer should be several years. Even if larger inflow or outflow rates such as those in column 3 and 4 of Table 5.18 were used in calculations, breakthrough times of 336 and 552 hours, respectively, would be expected. Consequently, the considerably shorter breakthrough times observed for water and tracer suggest relatively low effective porosity. Table 5.18 gives computed values of effective flux density (q_e), observed breakthrough times, and relative amounts of tracer recovered in leachate from selected drains. Figure 5.38 shows calculated distribution of effective porosity (P_e). Results suggest 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. Two such locations, F1 (where flow occurred through less than 1% of the area) and G5 (where flow occurred through 5 to 10% of the area), will now be discussed in detail.

Macropore flow--To illustrate graphically the flow through soils that may contain macropores, we have chosen two sites that exhibit contrasting behavior, F1 and G5. Figure 5.39 shows respective distributions of ring

TABLE 5.18. BREAKTHROUGH TIMES (T_B) FOR BR^- TRACER AND WATER, AND CUMULATIVE TRACER CONCENTRATION (C/C_o), RECOVERED AND COMPUTED EFFECTIVE FLUX DENSITY (q_e) VALUES FOR SELECTED SITES BASED ON TRACER BREAKTHROUGH TIMES AND AVERAGE 30 CM THICKNESS OF CLAY

Site	T_b Tracer	T_b Water	C/Co	q_e
	hrs	hrs	%	10^{-9} m/sec
AA7	26	45	5	3,205
A3	30	22	43	2,778
D7	29	142	24	2,874
F1*	25	191	2	3,333
G5*	47	142	84	1,773
J0	170	46	2	490
L3	>265	170	2	>314
M7	53	71	29	1,572
01	48	311	<1	1,736
09	48	46	10	1,736
Q5	7	144	4	11,904
S1	54	316	2	1,543
T5	161	195	1	517
V8	167	144	3	499
X3	25	144	6	3,333

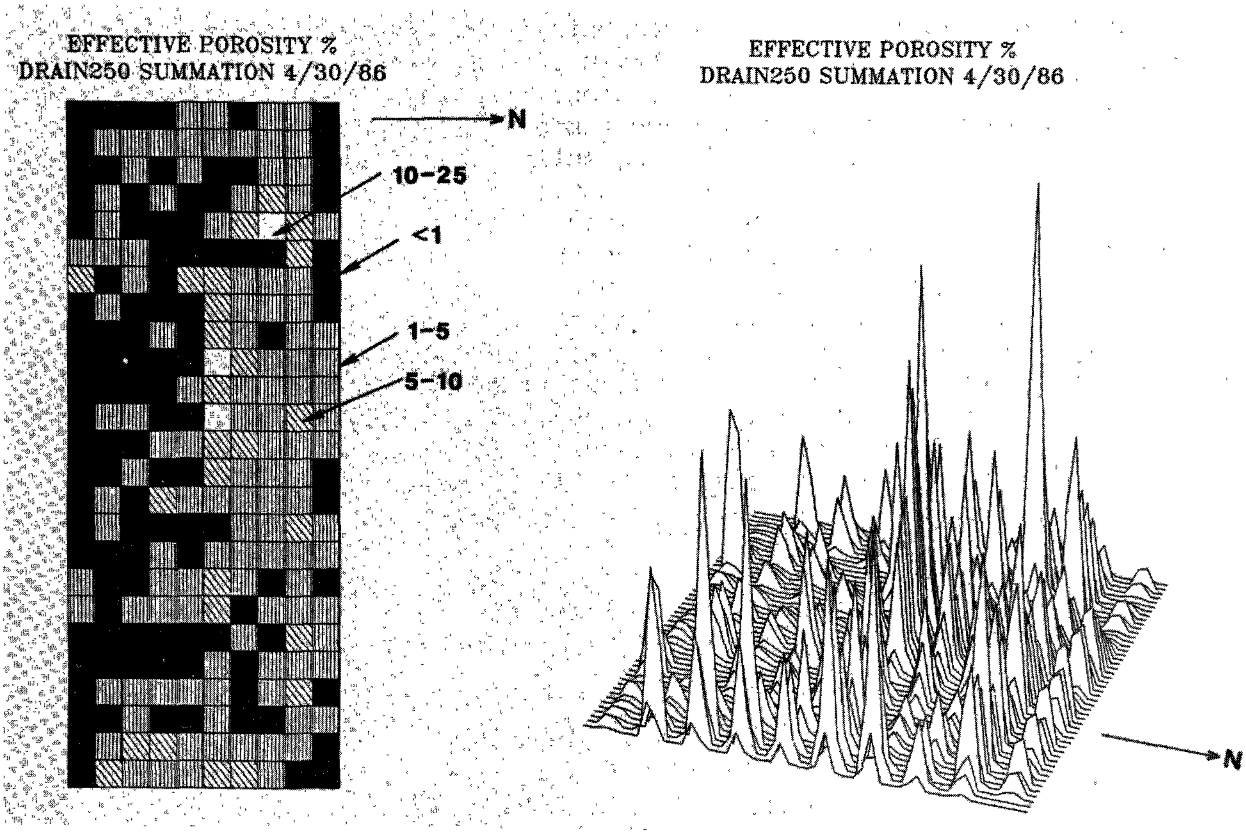
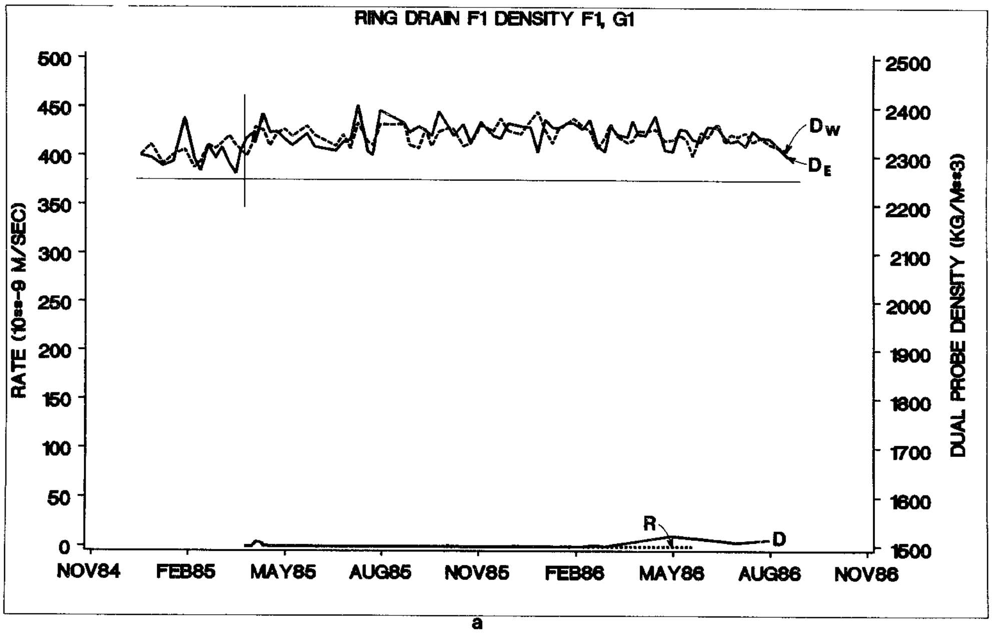


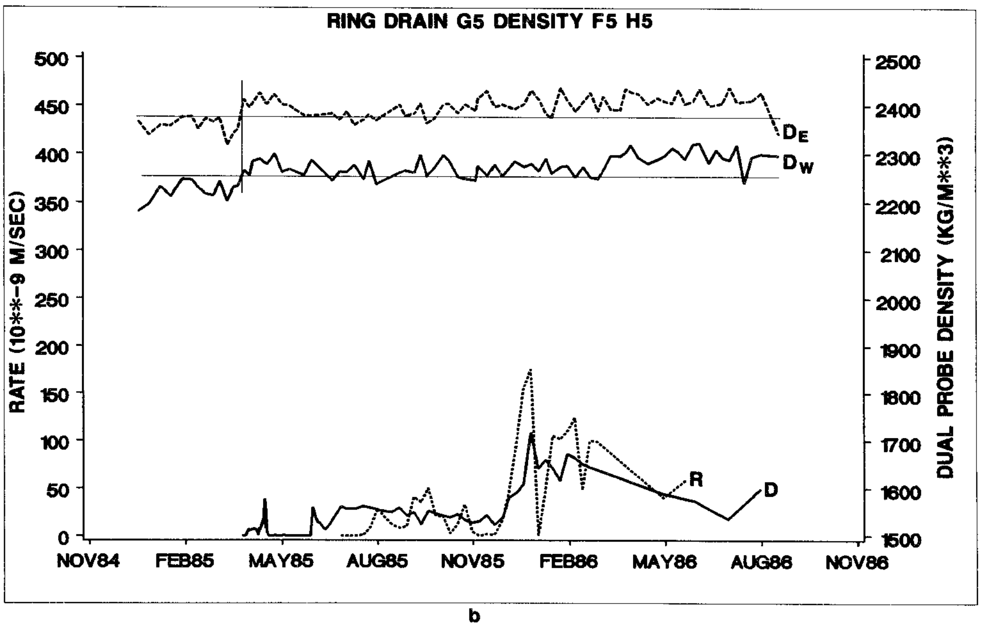
Figure 5.38. Distribution of effective porosity (P_e) in a compacted and ponded, spatially variable clay liner given as the percent of cross sectional area (A), based on first arrival times of ponded water.

inflow (R), drain outflow (D), and bulk density east (D_E) and west (D_W) of the flow-monitoring site. For the site F1 there appears to be some agreement between lab and field values (Table 5.18), largely because both inflow and outflow distributions are very low. This agreement between lab and field values could be related to rather stable bulk density surrounding the site F1 and to a relatively small effective cross sectional area involved in flow. The upper curves in Figure 5.39a, which give changes in bulk density with time adjacent to the ring and drain location, show that except immediately following ponding, bulk density both east and west of the site remained essentially the same for a whole year. Despite the high uniformity of clay material, a breakthrough time of 25 hours for Br^- at the F1 drain was recorded, although only 2% of the tracer was subsequently recovered (Table 5.18). These values translate to 0.1% effective porosity with most Br^- expected to be retained in surrounding soil.

In contrast, at the site G5 (Figure 5.39b) considerable inflow and outflow existed and density increased quickly at ponding and then more slowly during the remainder of the study. Such increases, also observed at other



a



b

Figure 5.39. Distribution in time of ring inflow (R), drain outflow (D), and bulk density in the east (D_E) and west (D_W) of the primary ring and drain locations for the slow-flowing site F1 (a) and fast-flowing site G5 (b).

sites, are probably indicative of surface wetting and inflow into macropores at ponding, with subsequent movement of water, either as a wetting front or by diffusion from macropores into compacted clay matrix.

Tracer distributions--Figure 5.40 shows relative cumulative concentration of tracer in drains under and around the infiltration rings F1 and G5, to which tracer was originally applied. Although the first breakthrough occurred after 25 hours from the drain F1 (directly under the ring to which tracer was applied), the largest amount of tracer (approximately 1% of that applied) came from drain F0.

Effective porosity calculations generally assume vertical flow. Results in Figures 5.40a and 5.40b suggest that this may not always be the case. For example, although 84% of applied tracer was recovered from the drain G5 (directly under the ring G5 to which tracer has been applied), the first arrival of Br^- tracer occurred at drain H5. Small amounts of applied tracer (approximately 0.5%) came also from drains G4, G6, and H6.

At the site H5 (Figure 5.40b), a relatively rapid (22 hours) breakthrough of Br^-, which had been applied to a G5 ring, was observed with a computed effective flux density (q_e) greater than 10,000 x 10^{-9} m/sec (assuming a diagonal tracer flux from ring G5 to drain H5, over a distance of about 1 m in 22 hours). Since observed water outflow flux (q) at H5 at that time was no

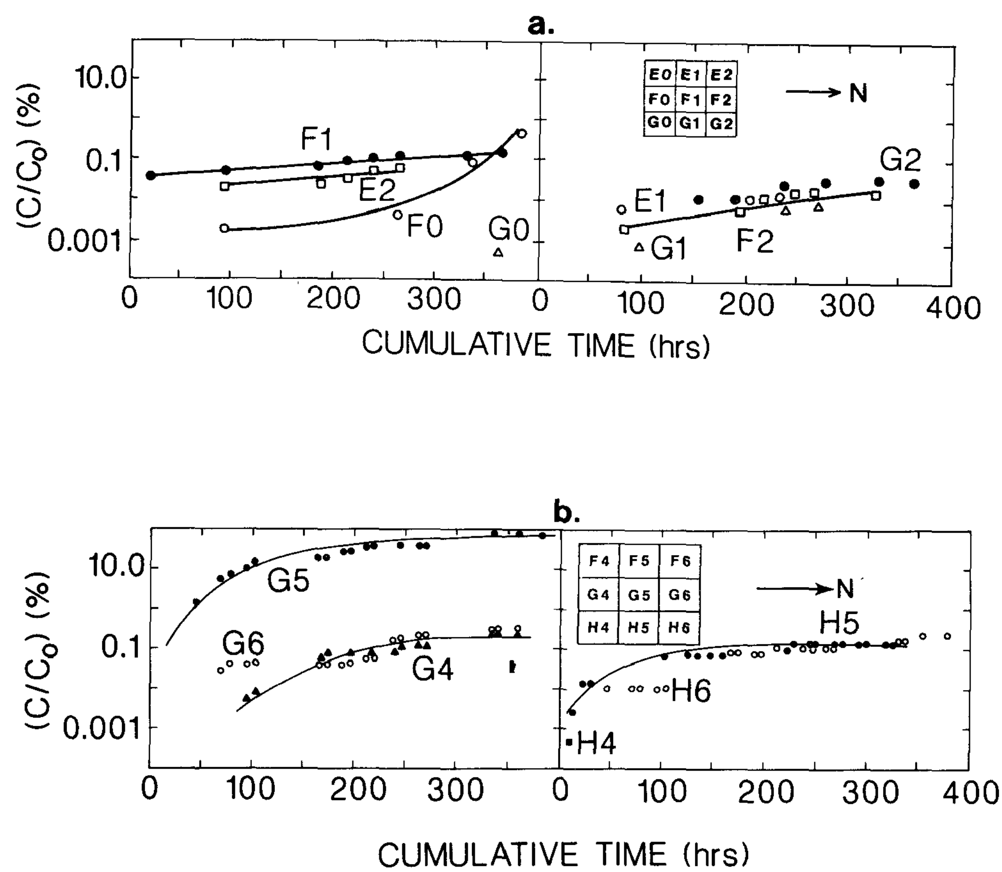


Figure 5.40. Relative concentration of Br^- as leachate from site F1 and surrounding drains (a) and site G5 and surrounding drains (b).

more than 10 x 10^{-9} m/sec, effective porosity (P_e) of the area through which the tracer must have passed could be as little as 0.1% of the local cross sectional area. Even at peak water outflow rate of about 125 x 10^{-9} m/sec the effective porosity (P_e) values would have been no more than about 1%.

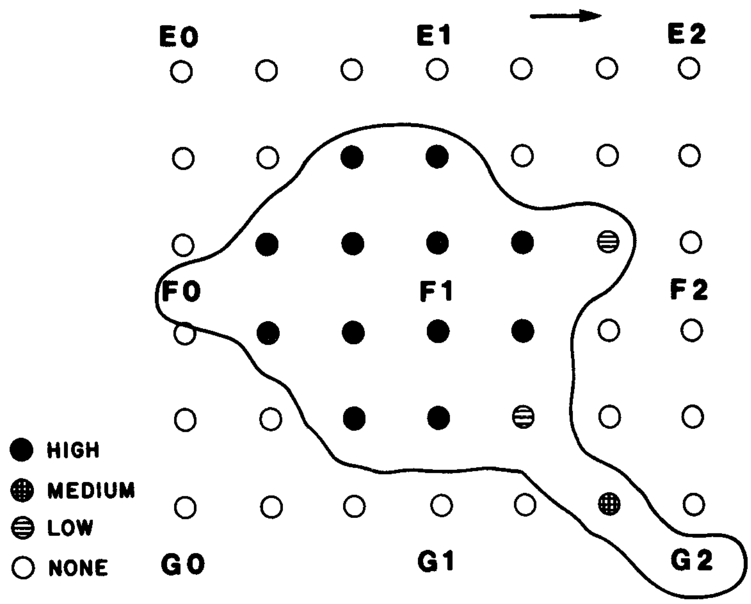
Such calculations may explain in part the absence of any major changes in bulk density adjacent to the sites F1 and G5 (Figure 5.39). In terms of environmental safety, the flow rate of concern would be the 10,000 x 10^{-9} m/sec breakthrough time for tracer rather than the very slow (approximately 1 x 10^{-9} m/sec) matrix flow component. However, in real-life situations, when we may wish to evaluate potential impact of pollutant on groundwater, such high flow rates may need to be considered in terms of cross sectional areas (effective porosity) that contribute to flow (≤ 1%) and the observed concentration of contaminant in recharge.

Breakthrough history at sites F1 and G5 and surrounding drains, as well as order of magnitude differences between lab and field values in Table 5.18, suggest that even a seemingly uniform clay liner is a highly variable one with an effective porosity that ranges from as low as 0.1% to more than 5%. Results suggest that, if potential impacts on groundwater from these sites are considered, breakthrough times, delivered concentrations, and contaminant toxicity should all be carefully evaluated.

Subsequent coring with a Veihmeier tube of the tracer application area and surrounding sites on the 0.3m grid and qualitative tests (Goldman and Byles, 1959) for Br^- corroborated preliminary observations. On sites such as F1, where little tracer was lost as leachate, strong evidence of tracer shows in corings as a tight, well-defined "plume" surrounding the infiltration ring to which tracer has been added (Figure 5.41a). However, for sites such as G5, where much tracer was lost as leachate, the Br^- distribution plume was quite extensive but rather diffuse throughout the area of nine drains (Figure 5.41b). This shows that the highly mobile tracers (or highly mobile contaminants) may be more difficult to detect close to the source of application, even though their impact could be greater and felt sooner further away. Additional corroboration of these findings may be found in Br^- plumes for other sites shown in Figure 5.42, 5.43, and 5.44.

Swelling--

A possible source of fluctuations in inflow, outflow, tracer concentrations, and density could be random swelling of smectite 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 is primarily illite and kaolinite with some smectite. Thus, although swelling based on prototype studies could not be ruled out, little was expected. It is also conceivable that in pockets of inadequately compacted clay local consolidation may have occurred. Figure 5.45 shows the interpolated surface elevation (mm) change as measured with a Selcom[1] Optocator unit. In general, the changes at nine months amounted to between 0.5 and 1.50mm. There were, however, two zones of contrasting behavior. On the north side of the liner, about the middle, there appeared a small zone of consolidation (-1.50 to -2.50mm), while on the south side to the



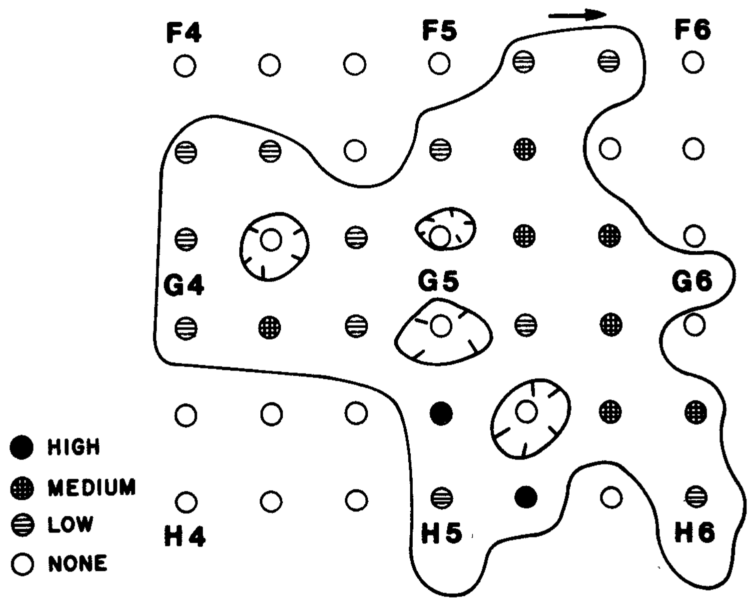


Figure 5.41. Relative distribution of Br^- tracer in soil around the sites F1 (a) and G5 (b) to which tracer has been applied.

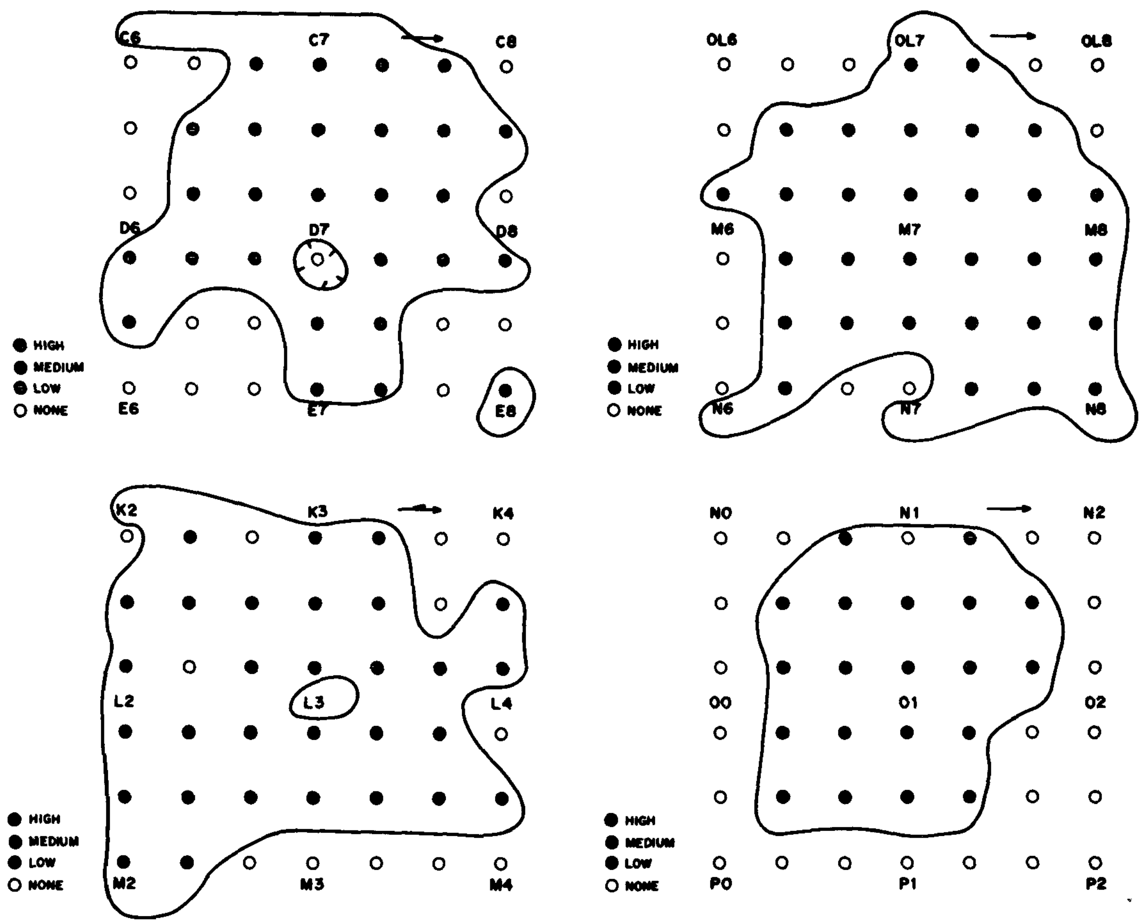


Figure 5.42. Relative distribution of Br^- tracer in soil around the sites D7, L3, M7, and 01 to which the tracer has been applied.

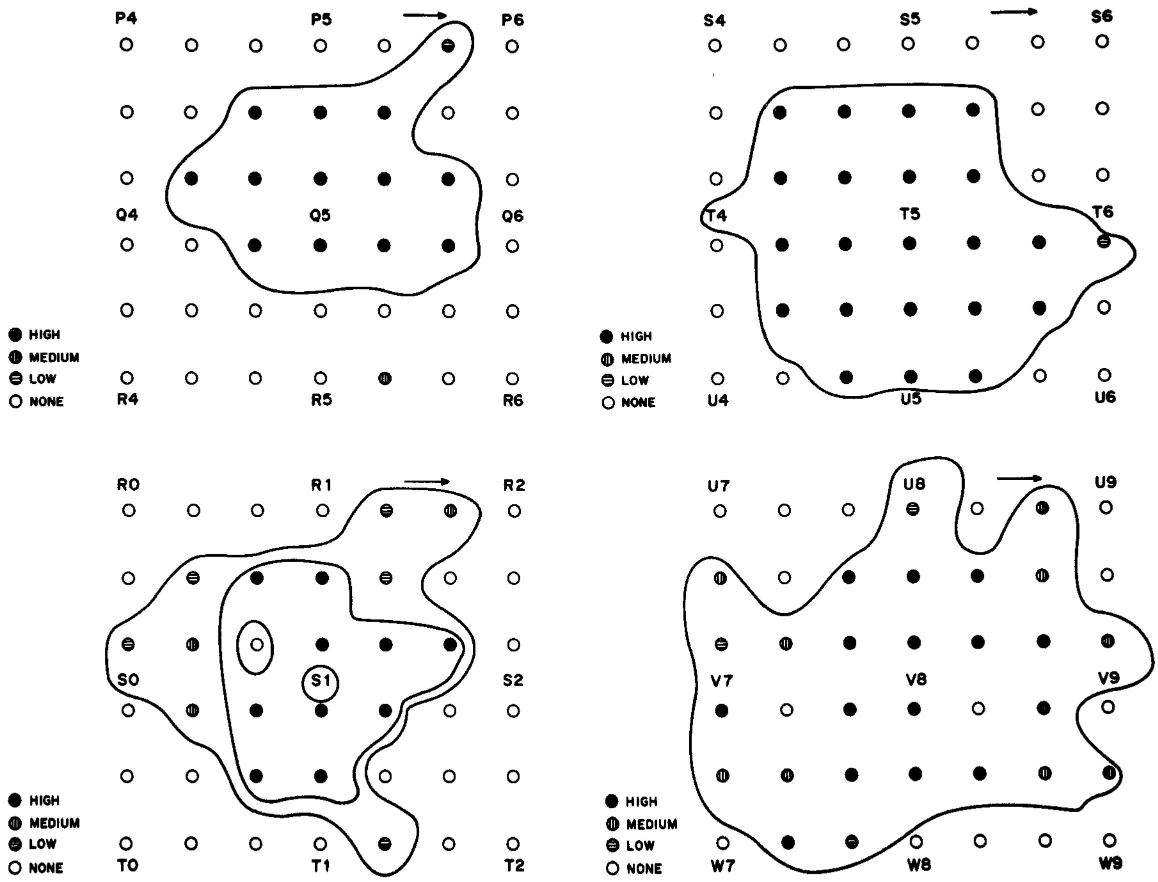


Figure 5.43. Relative distribution of Br^- tracer in soil around the sites Q5, S1, V8, and T5 to which the tracer has been applied.

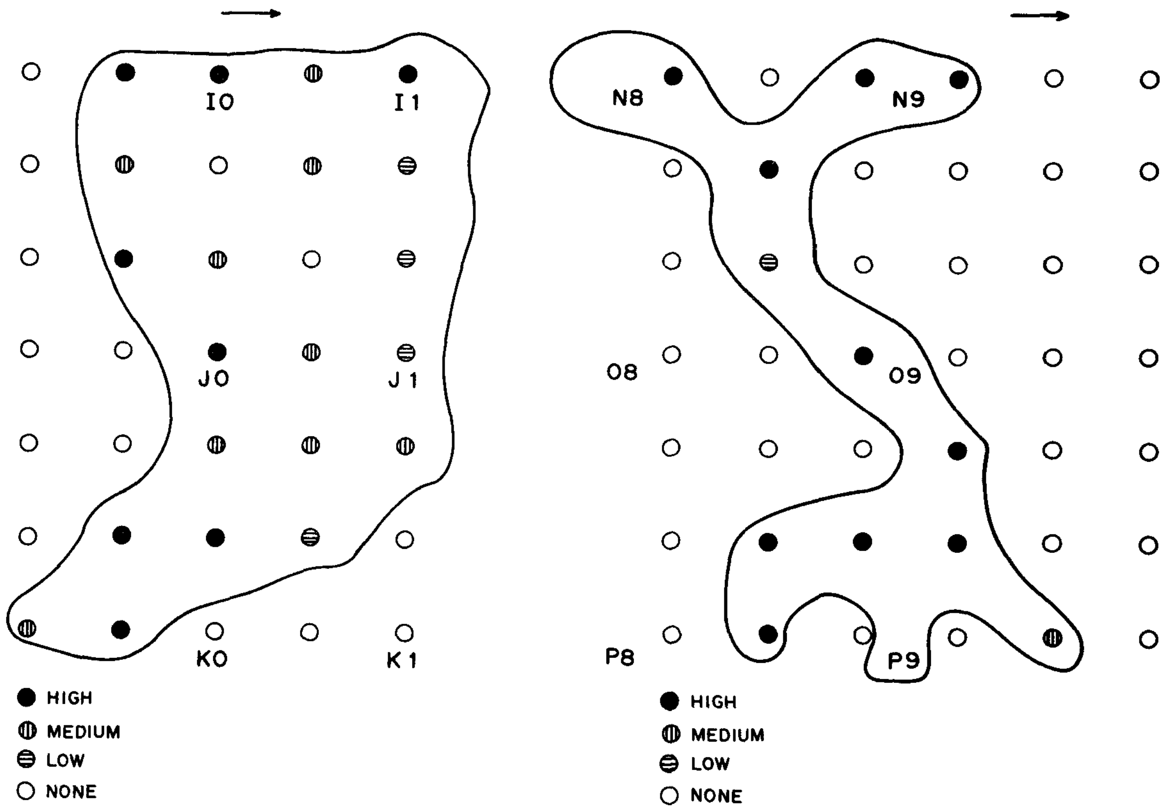


Figure 5.44. Relative distribution of Br^- tracer in soil around the sites J0, and 09 to which the tracer has been applied.

left of center, there was a corresponding small zone of expansion (2.00 to 3.50mm). Although expansion appeared to be associated with a less permeable zone and consolidation with a more permeable one, no correlation was found between the degree of expansion and observed conductivity.

Percolate Quality--

Percolate quality appeared somewhat related to hydraulic conductivity, degree of saturation, and number of pore volumes of percolate. Figure 5.46 shows the spatial distribution of pore volumes leached through the liner at nine months and the starred points indicate location of monthly leachate collection.

Initial changes in water quality as it passed through the clay liner are given in Table 5.19 for selected locations. Reported measurements were made once a month using standard testing procedures on the water supply from the tanker, ponded water on top of the liner, and percolate collected from the respective drains. Following 6/25/85 sampled water was recirculated through

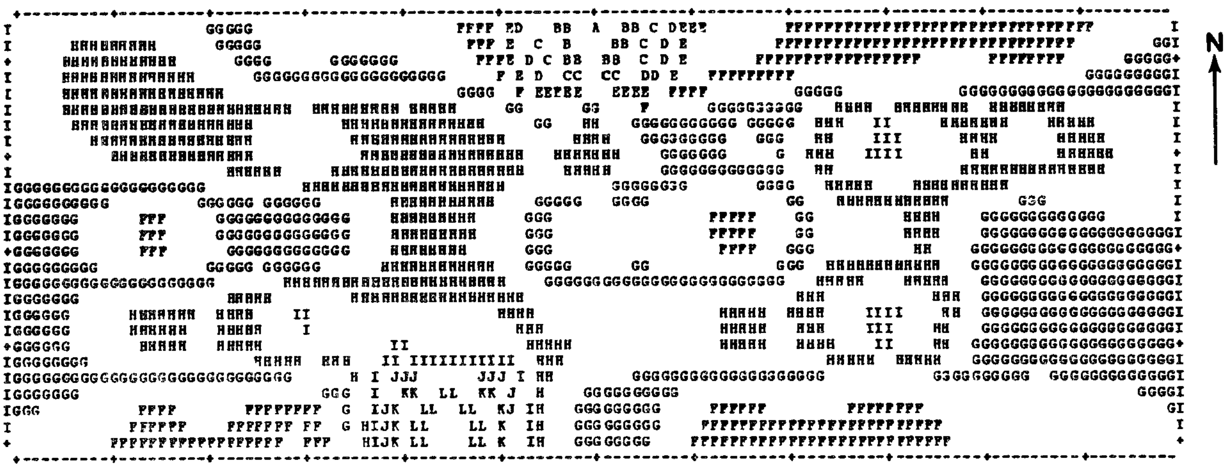


Figure 5.45. Elevation changes in millimeters (mm) for the compacted clay liner 9 months after ponding; positive symbols indicate swelling, negative symbols are indicative of shrinkage.

AAAA	-2.50 to -2.00 mm	GGGG	0.50 to 1.00 mm
BBBB	-2.00 to -1.50 mm	HHHH	1.00 to 1.50 mm
CCCC	-1.50 to -1.00 mm	IIII	1.50 to 2.00 mm
DDDD	-1.00 to -0.50 mm	JJJJ	2.00 to 2.50 mm
EEEE	-0.50 to 0.00 mm	KKKK	2.50 to 3.00 mm
FFFF	0.00 to 0.50 mm	LLLL	3.00 to 3.50 mm

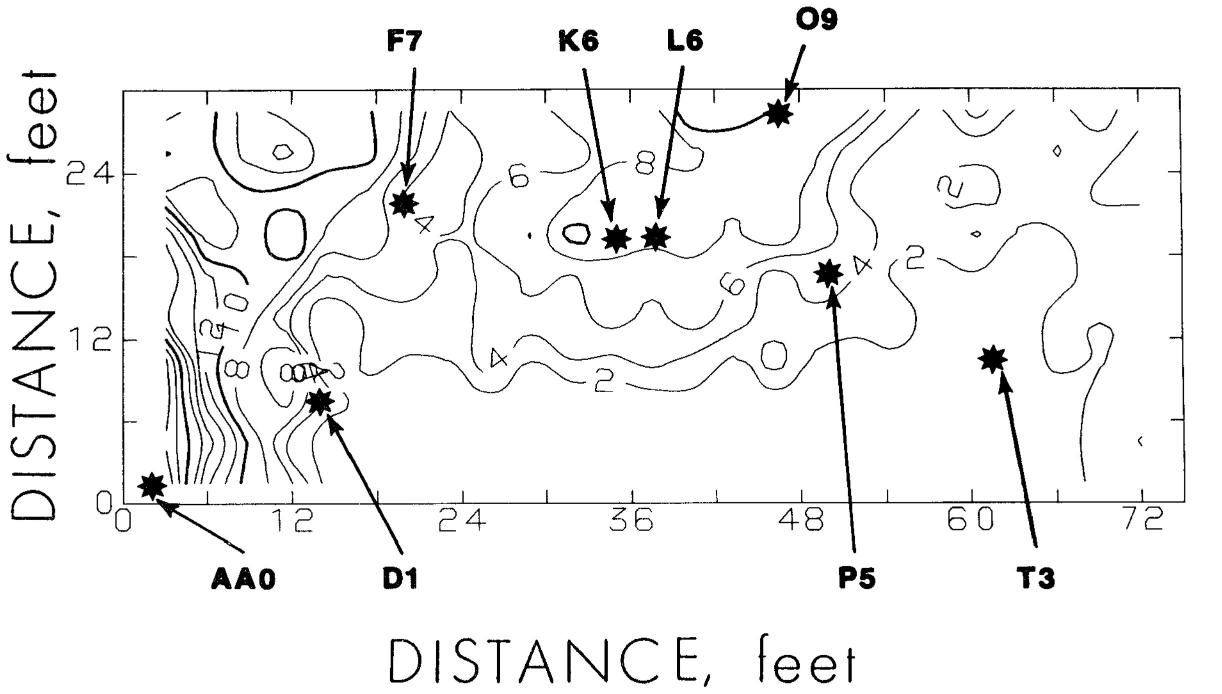


Figure 5.46. Number of pore volumes leached through the clay liner at nine months, starred points indicate locations where leachate has been sampled monthly.

TABLE 5.19. WATER QUALITY CHANGES AS A RESULT OF PASSING THROUGH EXPERIMENTAL LINER[1]

Source	pH	Bi-Carb	EC (°C)	NO_3-H	NH_4-N	SO_4	Cℓ	Na	K	Ca	Volume
		(mℓ)		(mg/ℓ)							(mℓ)
				4-2-85							
Tanker	7.2	-	155(27°)	3.9	0.02	13	-	3	-	-	
Drain (composite)	7.9	-	1550(27°)	8.6	1.50	255	-	72	-	-	
				4-25-85							
Tanker	5.9	1.6(.01NH_2SO_4)	120	5.2	0.22	17.1	7.9	3.4	5.7	10.2	-
Ponded water	6.9	3.2 "	150	5.2	0.02	22.7	9.4	7.6	5.4	15.2	-
K-6	6.9	42.2 "	985	3.9	0.12	146.0	27.5	22.5	70.4	114.8	5,050
O-9	6.8	32.9 "	795	7.6	0.05	139.0	18.1	95.3	32.8	83.2	14,200
L-6	6.8	39.1 "	900	-	0.08	182.0	29.0	19.2	58.0	116.0	4,260
AA-0	6.9	16.9 "	410	3.7	0.19	95.2	10.7	19.1	11.5	50.0	6,800
				6-25-85							
Tanker	6.0	2.3(0.01NH_2SO_4)	130(14°)	4.1	0.07	14.5	8.3	3.6		11.1	-
Ponded water	7.3	1.8(0.05NH_2SO_4)	220(14°)	2.1	0.08	28.1	9.2	10.0		23.6	-
AA-0	7.1	8.3(.01NH_2SO_4)	220(12°)	0.3		27.6	9.9	11.6		24.4	>50,000
F-7	7.3	7.8(0.05NH_2SO_4)	800(12°)	3.2	0.15	139.0	18.4	14.4		103.0	2,450
K-6	7.2	6.1 "	600(12°)	0	0.10	117.0	11.4	7.2		81.0	15,300
L-6	7.4	5.6 "	600(12°)	0.8	0.08	132.0	12.3	7.6		80.0	8,800
O-9	7.0	3.9 "	325(12°)	0	0.09	22.0	8.9	24.8		35.2	>10,000
P-5	6.8	6.3 "	700(12°)	0.2	0.16	135.0	12.3	6.8		102.0	15,000
T-3	8.1	10.4 "	900(12°)	0.3	0.07		35.5	64.0		44.0	400

[1]Ponded on 3/26/85.

the system. Subsequent to 6/25/82 sampling of all the 250 drains was carried out at 9 months (highest outflow rate) and again at 12 months when steady state conditions prevailed at the conclusion of the study.

Table 5.20 shows the means, standard deviations, and CV's of leachate quality parameters and Table 5.21 list correlation matrices for the 9 and 12 month data, respectively.

In general, average electrical conductivity (EC), SO_4, and Na in leachate declined substantially in the last three months. K and Mg remained about the same, while Ca concentration appeared to decrease.

Figures 5.47 and 5.48; 5.49 and 5.50; 5.51 and 5.52 show spatial distribution of leachate quality variables at 9 and 12 months respectively. The starred points represent locations of initial sampling sites. The spatial distributions suggest a modest decline in concentrations of Ca and Mg especially in the western half of the site, much change in K, Na and pH and substantial declines in EC and SO_4. Except for Ca, Mg and SO_4 results are quite similar to those given in Table 5.20 where averages were compared. Spatial distribution shows a sharper decline in Mg concentrations than the statistics in Table 5.20 would lead us to believe. Ca and SO_4 although declining spatially, show substantial increase in variability as evidenced by respective CV values. Inspection of contours alone especially for SO_4 in Figures 5.47c and 5.48c would lead us to believe the contrary.

Results in Tables 5.19 to 5.21 and Figures 5.47 to 5.52 illustrate several practical points. In a commercial facility under field conditions, effluent from below a clay liner is usually collected by a single drain system. Such a system tends to average out both the quality and quantity of water over an area. Results presented here illustrate how variable are the actual concentrations over time and in space. In general, magnitudes of EC, Ca and

TABLE 5.20. MEANS AND STANDARD DEVIATIONS, AND COEFFICIENT OF VARIATION (CV) OF LEACHATE QUALITY PARAMETERS SAMPLED AT 9 AND 12 MONTHS PONDING

Variable	Mean 9 mo	CV %	Mean 12 mo	CV %
EC (μmhos/cm)	630±273	43	279±109	34
pH	7.9± 0.3	4	7.8± 0.4	5
NO_3 (mg/ℓ)	0.047± 0.130	277	-	
Bi-carb (mℓ)	-		5.8± 1.9	33
SO_4 (mg/ℓ)	32.7±21.0	64	9.4±15.6	166
Ca	51.5±17.5	34	38.8±25.2	75
K	26.7±27.5	103	30.4±30.1	99
Mg	35.4±13.4	52	29.2±13.9	48
Na	20.2±11.1	55	8.1± 9.2	51

TABLE 5.21. CORRELATION MATRIX OF LEACHATE QUALITY PARAMETERS AT 9 AND 12 MONTHS FOLLOWING PONDING

Variables	EC	pH	NO_3	SO_4	Ca	K	Mg	Na
				9 months				
EC	1.00							
pH	-0.10	1.20						
NO_3	0.31	0.19	1.00					
SO_4	0.38	0.00	0.24	1.00				
Ca	0.82	-0.21	0.21	0.51	1.00			
K	0.93	-0.01	0.34	0.31	0.67	1.00		
Mg	0.97	-0.03	0.34	0.37	0.74	0.91	1.00	
Na	0.72	0.02	0.16	-0.01	0.33	0.74	0.69	1.00
				12 months				
EC	1.00							
pH	0.18	1.00						
Bi-carb	0.74	0.25	1.00					
SO_4	0.09	0.02	0.06	1.00				
Ca	0.29	-0.04	0.47	0.14	1.00			
K	0.65	0.35	0.85	0.06	0.48	1.00		
Mg	0.57	0.32	0.80	0.13	0.53	0.90	1.00	
Na	0.53	0.24	0.76	-0.02	0.39	0.84	0.82	1.00

Mg as well as K and Na in the Figures roughly correspond to their values in the Tables. There is little variation between pH values either in space or in time, and little apparent agreement between SO_4 values. This lack of agreement between the time and space averages of SO_4 appears to be due to extensive variation of SO_4 concentration. Since time averages provide a wide range of values it may be difficult to select any one value as representative of the chemistry of the liner. Closer inspection of hydraulic conductivity values derived from inflow and outflow suggests that the EC as well as Ca, Mg, K, and Na concentrations in effluent appear to be inversely correlated with hydraulic conductivity. Comparison of the "Storage" and "Ponded" water quality with that of the effluent indicates that under all circumstances higher concentrations of Ca, Mg, K and Na prevailed in the leachate than in ponded or applied (storage) water. Comparisons of values with distribution of pore volumes suggest that in general average concentrations in leachate were inversely related to the number of solute pore volumes passed through the liner.

Results to date suggest that considerable variability exists in spatially distributed properties and leachate chemistry of a compacted clay matrix which may affect the rate, quality, and pathway of leachate flow through a clay liner constructed to industry specifications. There also appears to be a discrepancy between the extent of saturation and observed outflow with higher flows originating in apparently unsaturated areas suggesting an existence of preferential flow pathways. Such preferential pathways may potentially pose a grave threat to underlying groundwater quality even in the presence of a clay liner.

Outflow and inflow rates from a liner spanning a range of two to three orders of magnitude were observed in this study and chemical concentration in the leachate appeared inversely related to hydraulic conductivity and number of pore volumes leached.

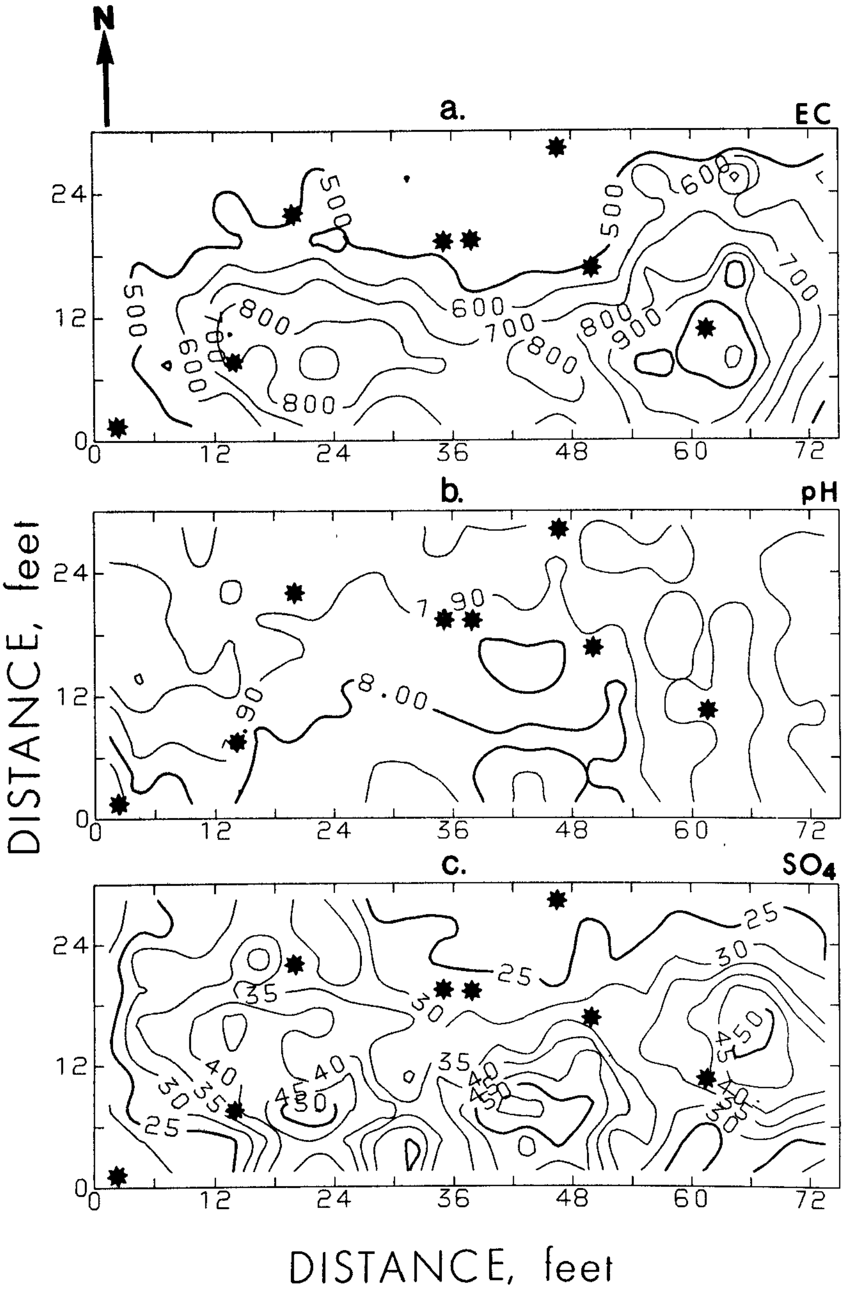


Figure 5.47. Spatial distribution of electrical conductivity (EC) in µmhos/cm (a), pH (b), and SO_4 mg/ℓ (c) in leachate from drains (250) at 9 months.

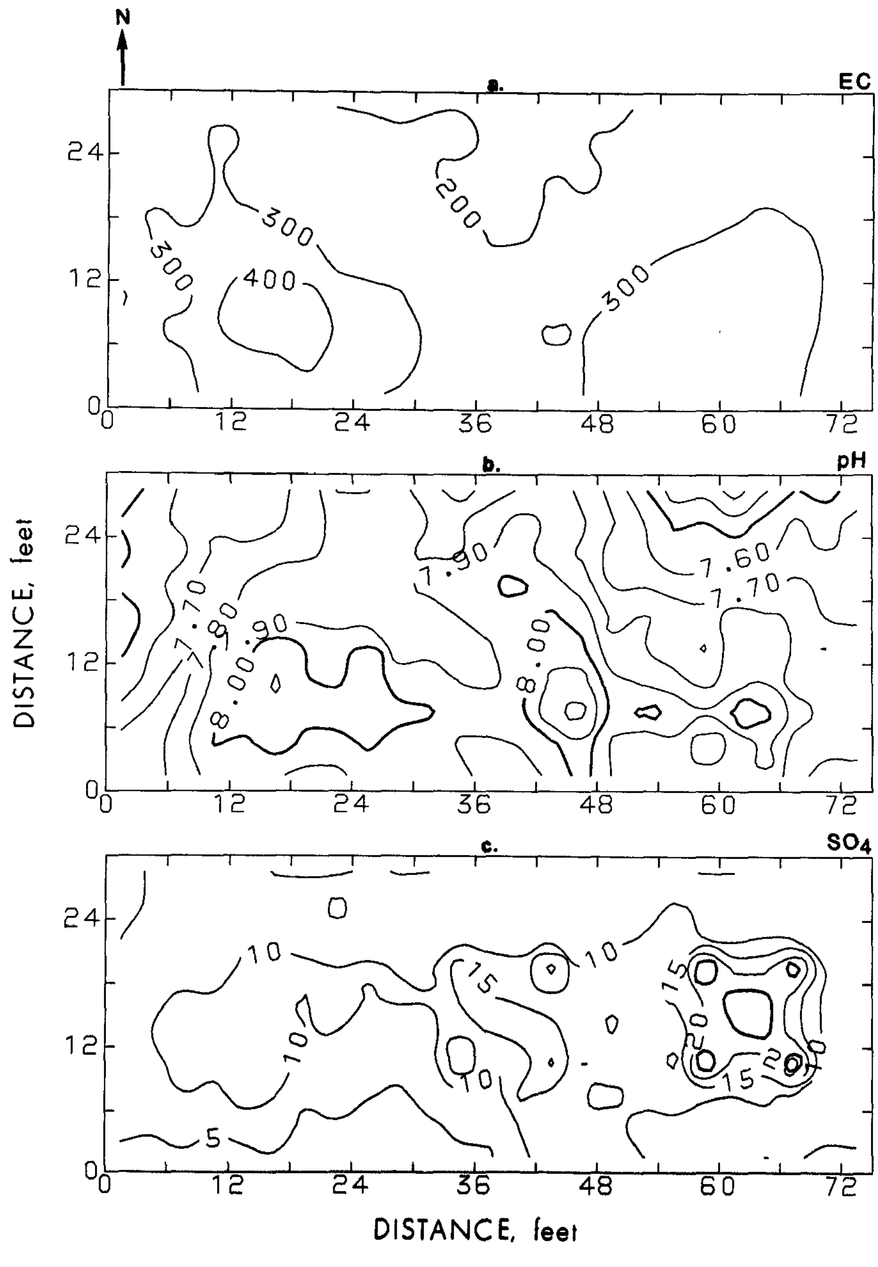


Figure 5.48. Spatial distribution of electrical conductivity (EC) in µmhos/cm (a), pH (b), and SO_4 mg/ℓ (c) in leachate from drains (250) at 12 months.

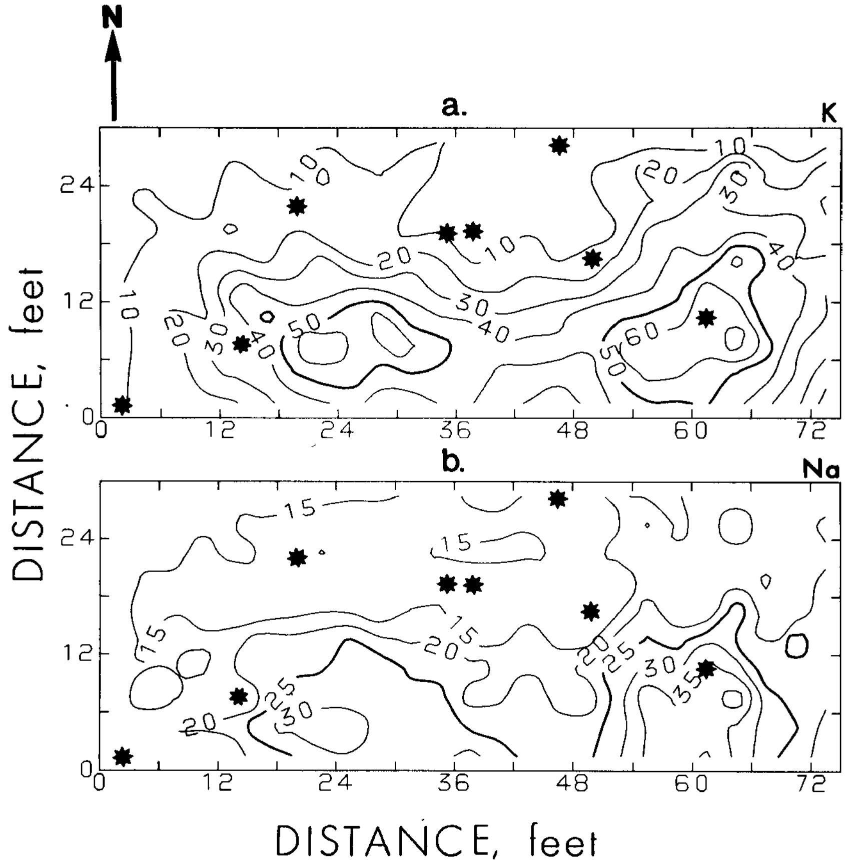


Figure 5.49. Spatial distribution of K (a) and Na in mg/ℓ (b) in leachate from drains at 9 months.

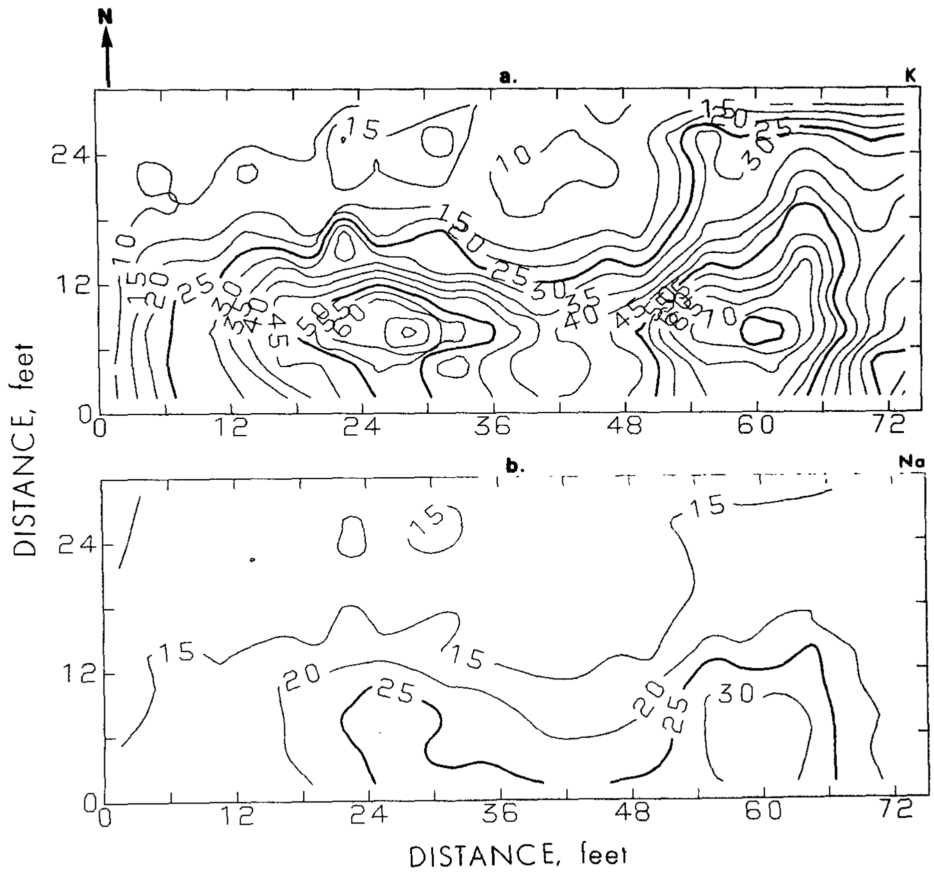


Figure 5.50. Spatial distribution of K (a) and Na in mg/ℓ (b) in leachate from drains at 12 months.

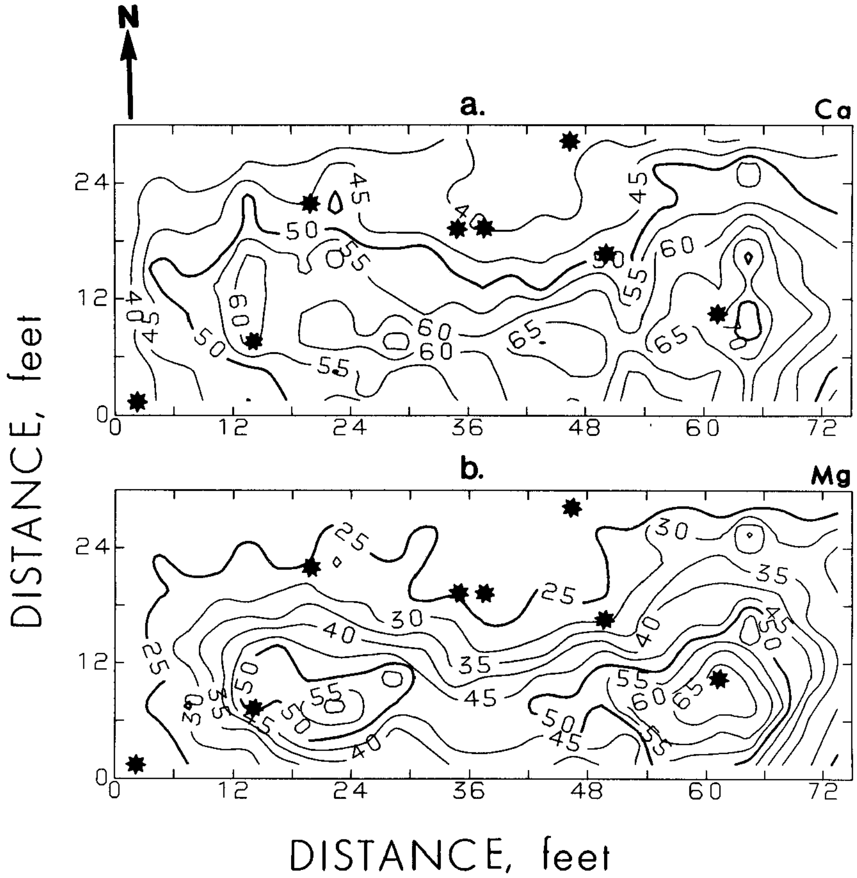


Figure 5.51. Spatial distribution of Ca (a) and Mg in mg/ℓ (b) in leachate from drains (250) at 9 months.

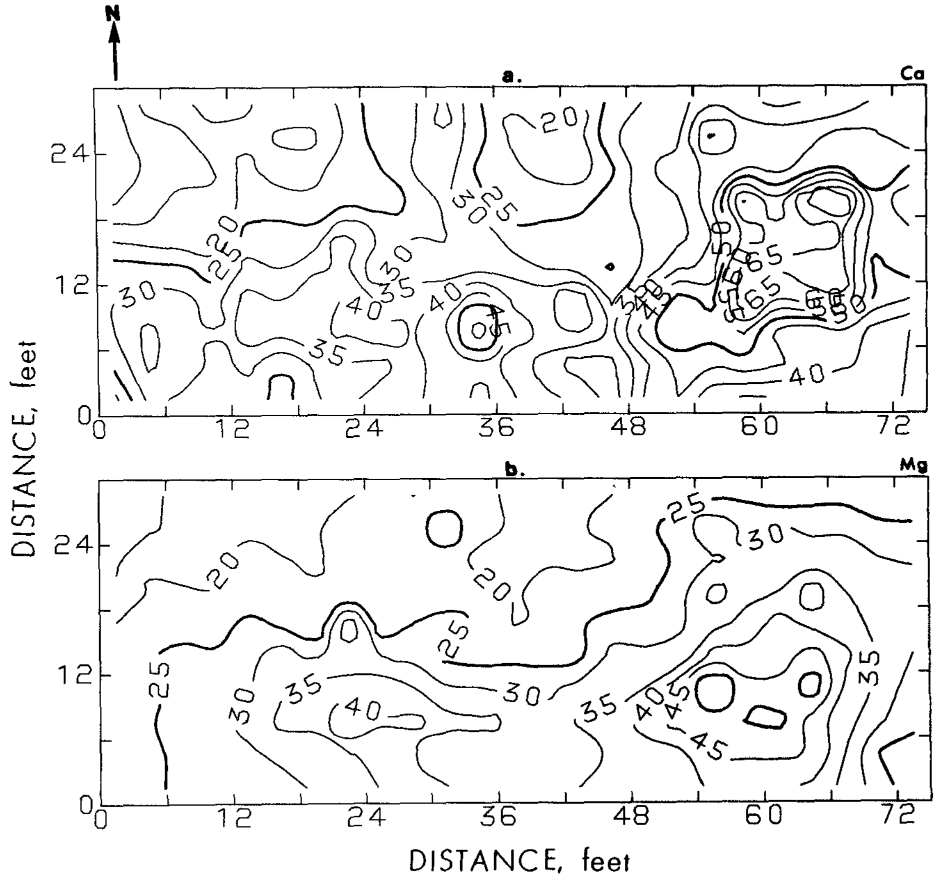


Figure 5.52. Spatial distribution of Ca (a) and Mg in mg/ℓ (b) in leachate from drains (250) at 12 months.

SECTION 6

CONCLUDING STUDIES

POSTPONDED STAGE

After the excess ponded water was siphoned off and the clay liner drained, several studies were initiated to check or corroborate observations made during the ponded stage. Complementing detailed inflow/outflow data for all ring/drain combinations, 3" (8cm) diameter 12" or 9" (30cm or 23cm) long cores were removed from the center of each ring infiltrometer (except the ones to which Br^- had been applied). The cores were taken using a standard Acker[1] split tube sampler. For each core the central portion, or the most homogeneous portion, was trimmed to size (~ 4", 10cm) suitable for storing in the refrigerator for use in subsequent laboratory analysis of saturated hydraulic conductivity. Some cores were split into two or even three segments to provide "replicates."

In addition, a large number of 2", 3", and 6" (5, 8, and 15cm) 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 assessment of the extent and distribution of coarse fragments within the clay liner. Using Troxler[1] surface probe, a set of surface moisture as well as surface and direct transmission density measurements at 2", 4", 6", and 8" was made to compare with initial surface probe readings and to evaluate the surface probe method as a field method for measurement of density. When the water had drained from the liner, a set of vertical access tubes was installed at each of 45 locations from which 2" cores were previously taken; simultaneously 45 gypsum moisture blocks were installed at 3" (8cm) depth. Monitoring of liner water content change began in the fall of 1986 and continued on a regular basis until May 19, 1988 when the liner was broken up, inspected, and removed from the site. Specific reference samples were saved for further analysis. Figure 6.1 shows a schematic distribution of scheduling, and duration of pertinent additional studies.

LABORATORY HYDRAULIC CONDUCTIVITY

Flexible Membrane Method

Standard test method for measurement of hydraulic conductivity of saturated fine grained materials with a flexible wall permeameter[4] was used to evaluate hydraulic conductivity of cores taken from the center of each infiltration ring. In Table 6.1 summary statistics of the results to date are compared with hydraulic conductivity values based on ring infiltration and drain outflow rates, while detailed data for individual samples are given in Appendix E.

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[4]Courtesy D. E. Daniel, University of Texas, Austin.

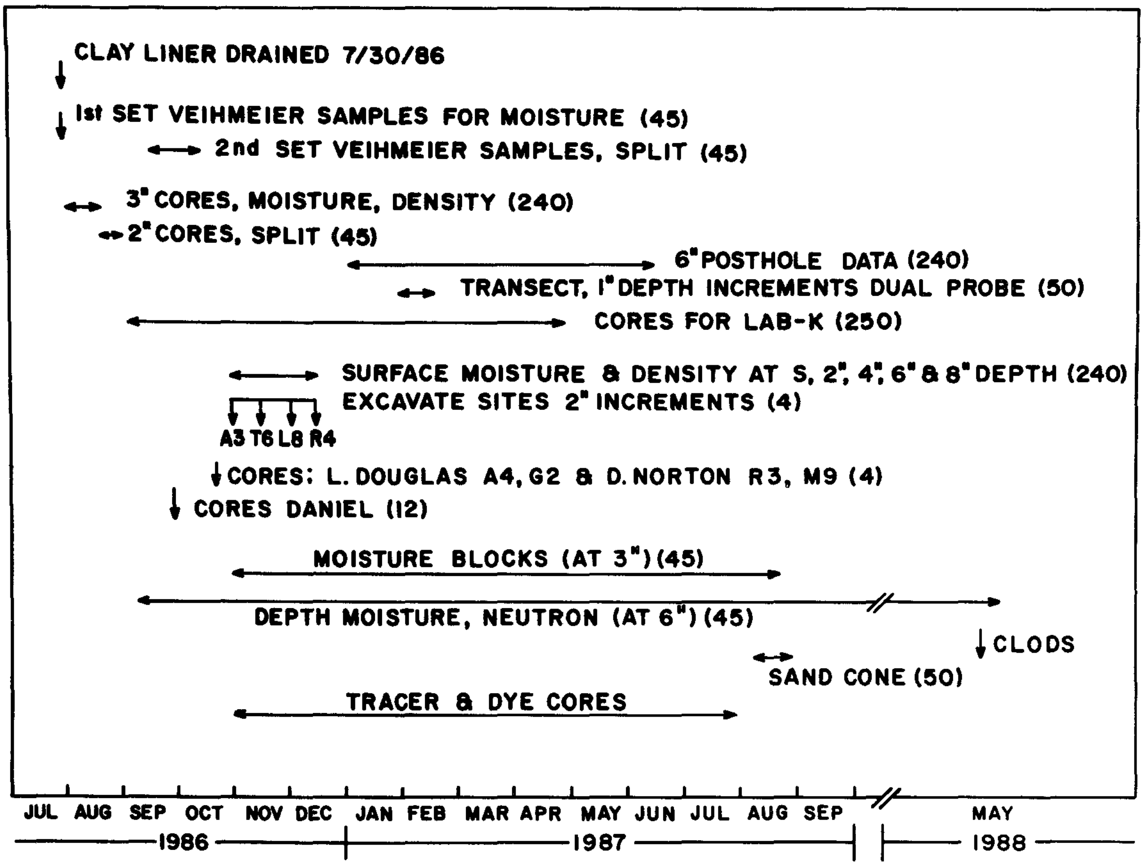


Figure 6.1. Chronological distribution of activities after the clay liner was drained.

The hydraulic conductivity analysis was carried out in 3" (8cm) diameter cores varying in length from 2-7/8" to 6" (7 to 15cm) 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 at times was very difficult.] Initially, only the most homogeneous portion of the original core was selected for analysis. The subsequent trimming constituted a further refinement. The cores were run using a cell pressure of 25 psi (170 kPa) inflow pressures of between 21.4 and 23.4 psi (145 to 165 kPa) and outflow pressures of 20 psi (140 kPa) giving a gradient of between ~ 15 and 30 (with most cores at ~ 25). Several cores (eight so far) either broke up during trimming or developed cracks during storage making them unusable for analysis of K. If analyzed, such cores would have abnormally high K-values to the point that some could not be run at all.

TABLE 6.1. SUMMARY STATISTICS FOR LABORATORY AND FIELD EVALUATED HYDRAULIC CONDUCTIVITY (x 10^{-9} M/SEC)

	Lab	Drains	Rings
		Moments	
N	95	193	150
Mean	7.5	19.0	19.9
Std Dev	11.9	24.8	35.6
Skewness	3.4	1.8	2.7
CV	159	130	178
T:Mean=0	6.1	10.6	6.8
Variance	142	6.6	1269
Kurtosis	15.3	3.7	8.0
Std Dev	1.22	1.78	2.90
Prob>| T |	0.0001	0.0001	0.0001
		Quantiles(Def=4)	
100% max	79.3	129.4	188.152
75% Q8	7.0	29.4	19.6977
50% med	2.6	8.0	5.27341
25% Q1	1.5	1.6	1.42623
0% min	0.45	0.03	0.08
Range	78.9	129.4	188.0
Q3-Q1	5.5	27.8	18.2
Mode	0.80	0.15	0.53
99%	79.3	116.4	181.7
95%	33.5	73.9	118.3
90%	20.48	50.6	67.4
10%	0.87	0.40	0.57
5%	0.73	0.19	0.27
1%	0.45	0.08	0.11
		Extremes	
Low	0.45	0.03	0.08
	0.46	0.08	0.13
	0.69	0.09	0.14
	0.72	0.09	0.16
	0.74	0.10	0.22
High	33.15	84	125
	35.2	96	125
	37.06	110	168
	51.98	115	175
	79.35	129	188

Comparative Analysis

In Table 6.1 comparative statistics for laboratory and field values of hydraulic conductivity (derived from ring and drain flux) are given. Although the moments of all three distributions are quite similar, comparison of the respective quantiles and extreme values suggests the laboratory distribution of K is essentially a nested distribution within a distribution of field values. Extreme variability is reflected by high CV values, and particularly the magnitude of outliers. It is perhaps worth recalling that more care goes into selection and preparation of lab cores compared to field data which are taken at a given site while not being aware how uniform or how variable and inhomogeneous is the underlying material. Such inhomogeneities tend to be avoided on a core scale but are included in analysis on a field scale giving rise to discrepancies between the lab and field values. Skewness, kurtosis, and a very low value of the Prob>| t | suggest (not unexpectedly) that hydraulic conductivity (whether lab or field) is not likely to be normally distributed. Surprisingly viewed as a whole laboratory and field distributions are not that different. While modes, medians, and lower quantiles are quite low and rather similar in both the lab and field distributions, the differences arise in the upper quantiles and outlier values. It would therefore be expected hydraulic conductivity to be always larger in the field unless perfectly homogeneous, and fine materials were used to construct the liner. Field values of hydraulic conductivity of the defective cores (eight to date) are listed in Table 6.2. Comparisons with the quantiles of distributions and outlier data in Table 6.1 suggest that in all but one case (Q8) the defective cores came from the upper quantile of the drain conductivities and upper half of the ring-K distribution, suggesting that the cores that broke up came primarily from the zones of high flow. Because of the high spatial variability of hydraulic conductivity, zones of low and high flow could very easily adjoin each other.

TABLE 6.2. FIELD VALUES OF HYDRAULIC CONDUCTIVITY NEAR THE SITES WHERE DEFECTIVE CORES WERE TAKEN

Site	Ring-K	Drain-K
	10^{-7} cm/sec	
AA4	-	-
B8	35	48
C8	9	62
F5	85	63
I5	33	79
L6	10	31
M5	36	68
Q8	4	19

Ring and drain K are based on the time averaged flux at each location.

Figures 6.2 and 6.3 represent scattergraph comparisons between laboratory and field derived values. In Figure 6.2 point to point comparisons are given. These comparisons suggest that there is little if any relationship between lab and field derived measurements of hydraulic conductivity. When, however, the same data are ranked in order and replotted as was done in Figure 6.3, the correspondence between the two distributions is apparent. The uppermost plots in Figure 6.3 (also Figure 6.2) represent comparisons between the lab values and ring or drain derived hydraulic conductivities, based on the final set of field readings made. The lower plots give the same comparison but for the time averaged values of ring and drain K. The results suggest a linear relationship between the lab and field distributions. In our case, laboratory values appear to underestimate field distributions of saturated K when compared on the distribution to distribution basis. It is expected that, in general, laboratory values on cores sampled from a clay liner will underestimate the field hydraulic conductivity values and that the point to point

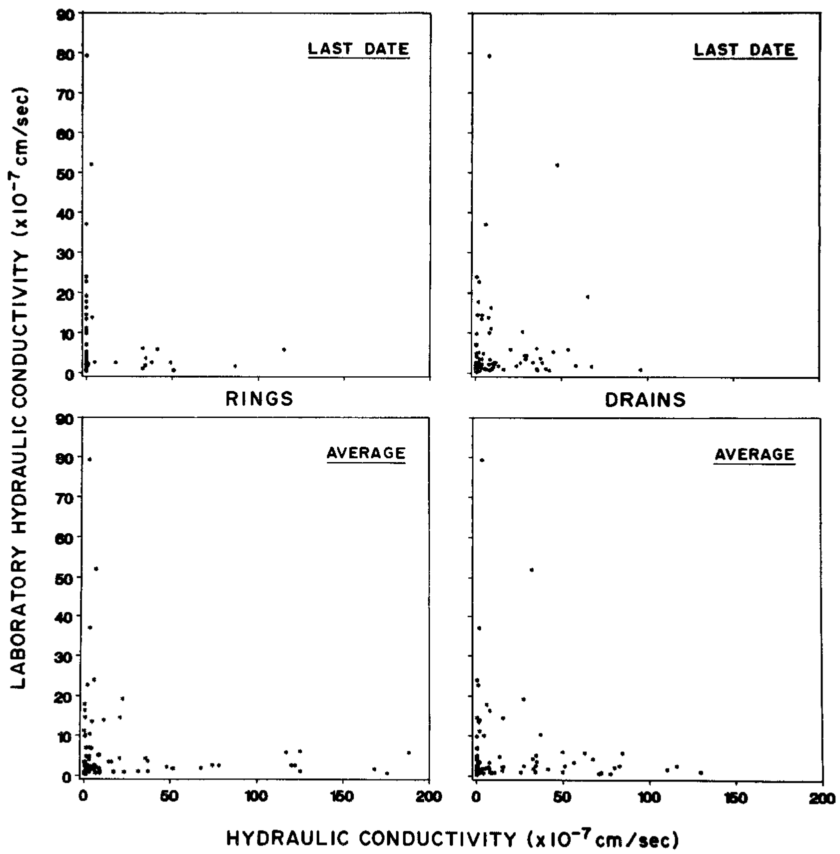


Figure 6.2. Point to point comparison of laboratory hydraulic conductivity (K) with field derived values based on last (upper plots) and average (lower plots) observed ring and drain flux.

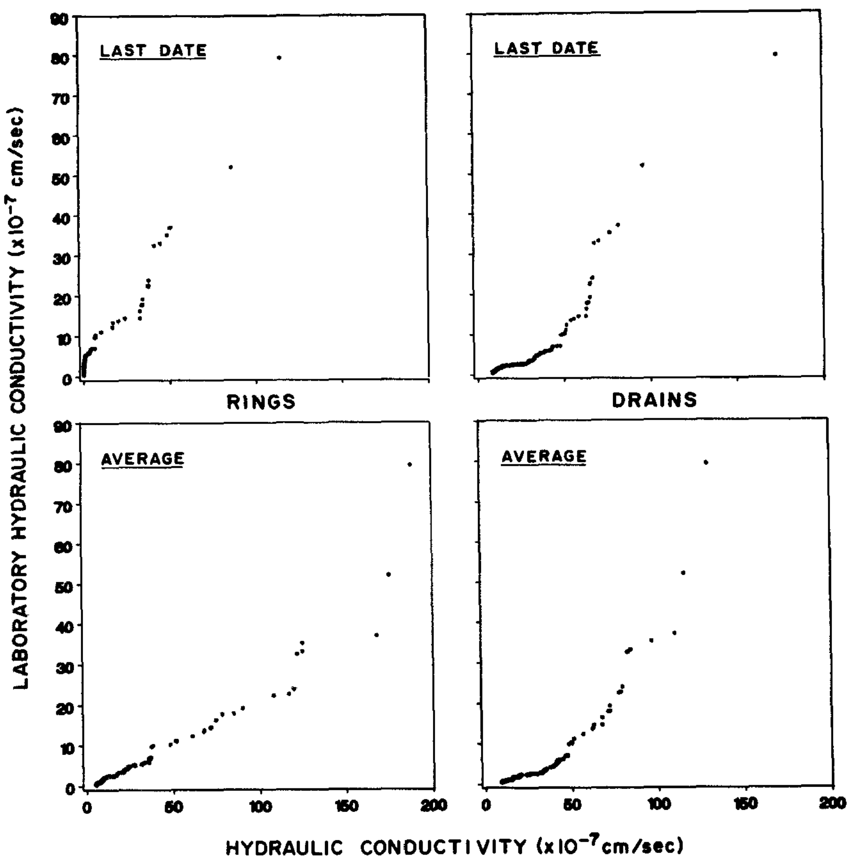


Figure 6.3. Rank to rank comparison of laboratory hydraulic conductivity (K) with field observed values based on last (upper plots) and average (lower plots) observed ring and drain flux.

correspondence is not likely to be observed. However, if sufficient numbers of samples are evaluated, field distributions may be found to be linearly related to laboratory distributions. For example, in our case, field values would have exceeded laboratory values by a factor of two to five. Compared to two or three orders of magnitude differences in the point to point comparisons, distribution to distribution comparisons look more realistic.

Distribution of Bulk Density and Water Content

We may recall that dual probe density values (D_W) measured prior to ponding did not correspond exactly to the surface probe values measured during the liner construction. To calculate the density for the evaluation of the spatial distribution of the available pore space, dual density readings were adjusted to the surface probe readings (multiplied by 0.9) and corrected for the volumetric water content as measured with the surface moisture probe during liner construction. The procedure was not completely satisfactory because water contents and densities were not measured on the same size grid (36 vs 240 sites). At the conclusion of the study and after draining the clay liner, representative 3" diameter cores (240) were therefore taken at the exact locations where dual probe densities were measured during the ponded stage. Bulk density and water content of cores were determined gravimetrically on these samples in order to provide a calibration for the dual probe readings at each of the 240 locations. Since bulk density measurements with dual probe had been taken continuously (consecutive readings at all locations) throughout the year of ponded study, changes in the water content of the clay with time as infiltration proceeded and water moved in and through the clay could be readily computed provided the correspondence between gravimetric and nuclear methods could be established for the dual probe and core data. A series of studies were therefore initiated to accomplish that purpose.

Veihmeier Tube Samples--

It was important to know the clay liner water content just after ponded water was removed from its surface. Thus, at the conclusion of the study when the ponded water was no longer visible on the clay the liner was sampled at 45 locations with a Veihmeier tube. The locations corresponded to the 35 sites where swelling was previously measured during the ponded stage, and to five additional sites in similar positions at each (E and W) end of the platform. At the time of sampling ten of the 45 holes still had water standing in them. Some of the cores had excess water on the outside (sites A and D) which was wiped off, and the cores were resampled. The average water content by weight was 20.8% with north and west side of the liner the wettest. Converted to water content by volume (34.5%), the results suggested, that on the average, the clay liner at best was only 90% saturated after one year of ponding. This would constitute an increase of 7.5% over preponded conditions. In the fall (10/86) after the liner was drained, water content began to be monitored on a regular basis at the 3" depth with gypsum blocks and at the 6" depth with the neutron probe. Calibration samples were taken at this time with the Veihmeier tube to provide a credible starting point for these measurements. The average water content at 1" depth was 19.1% (32.2% by volume) and 18.4% (30.9% by volume) in the remainder of the core somewhat lower than just after water disappeared from the liner surface but about the same as the water content of the liner drained by gravity (18.5% by weight, 31.1% by volume).

Core Data--

The final set of dual probe readings was taken on 8/18/86 just before the 3" diameter cores were removed from the same locations. The 8/18 dual probe readings essentially correspond to the reading taken immediately after (8/1/86) the clay liner was drained on 7/30/86 (Figure 6.4). Table 6.3 shows the appropriate statistics of the 3" core data compared to the dual probe (8/18) values. The parameters include wet and dry density (WD, DD), core volume (Vol), water content by weight (Θ_W) and water content by volume (θ_V). The volume of cores appears to have varied little. Core data showed moderate variability in density and water content while dual probe density readings appeared somewhat less variable. The water contents measured on cores, on the

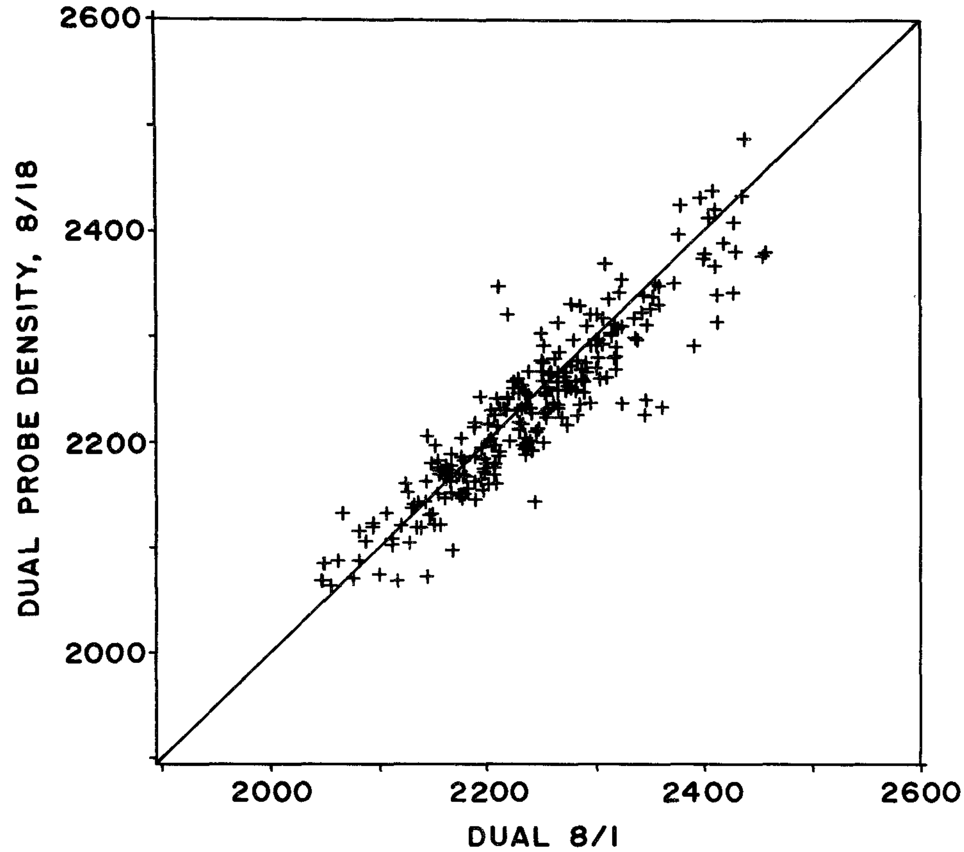


Figure 6.4. Comparison between dual probe readings on 8/1/86 just after the clay liner was drained and on 8/18/86 just prior to when 3" core samples were taken.

average, were less (18.4% by wt) than those obtained previously using a Veihmeier tube (20.8% by wt). Since at the time of Veihmeier sampling when water was observed standing in the holes, the liner was not completely drained. However, when the 3" cores were taken, all gravitational water would have left the liner and the values shown represent final moisture content held by the clay matrix.

Comparison with the initial and the final densities measured with the Troxler[1] surface probe (moisture-density) (Table 6.4) suggests that there is very little difference between the three sets of values. Similarly, the average ratio between initial, final and 3" core wet densities and dual density readings was found to be essentially constant (0.89), suggesting that the ratio may be used to correct the individual dual density values to standard density. It is necessary to assume that the 3" core data represents true density values. In Table 6.5 comparisons of wet density obtained using cores of different diameters and excavations (0.77 cu ft, 0.02 m^3) from different parts of the liner are given. Results basically agree and support the choice of 3" core data as a calibration standard for the dual probe values.

TABLE 6.3. STATISTICS OF THE 3" CORE DATA COMPARED WITH FINAL DUAL PROBE (8/18) VALUES

Variable	N	Mean	Std. Dev.	Min	Max	Std. Error	CV
							%
WD_{dual} (kg/m^3)	240	2233	81.6	2064	2488	5.2	3.6
DD (kg/cm^3)	240	1683	73	1401	1870	4.7	4.3
WD (kg/cm^3)	240	1995	87	1641	2223	5.6	4.3
Vol (cm^3)	240	1125	33	1043	1202	2.1	2.9
θ_W (%)	240	18.4	1.0	13.5	21.0	0.06	5.4
θ_V (%)	240	31.1	2.1	23.8	35.8	0.13	6.8

TABLE 6.4. STATISTICS OF THE WET DENSITY VALUES OBTAINED USING 3" CORES AND TROXLER[1] SURFACE MOISTURE DENSITY PROBE DURING CONSTRUCTION (INITIAL) AND AFTER THE LINER WAS DRAINED (FINAL)

Method	N	Mean	Std. Dev.	Min	Max	Ratio[1]	CV
3" cores	240	1995	87	1641	2223	0.89	4.3
Initial	240	1960	66	1784	2111	0.88	3.3
Final	240	2012	78	1697	2260	0.90	3.9

[1]Other/dual density, i.e., 3" core density/dual.

TABLE 6.5. COMPARATIVE STATISTICS FOR WET DENSITY VALUES (KG/M^3) OBTAINED USING 3" CORES, 2" CORES, 6" HOLES, EXCAVATIONS AND K-CORES

Method	N	Mean	Std. Dev.	Min	Max	Ratio[1]	CV
3" cores	240	1995	87	1641	2223	0.89	4.3
2" cores	45	1950	75	1760	2143	0.87	3.8
6" holes	240	2057	104	1782	2354	0.92	5.1
Excavations	4	2098	58	2025	2161	0.94	2.8
K-cores	104	2122	83	1869	2272	0.95	3.9
Sand cone	49	1831	123	1448	2097	0.82	6.7

[1]Other/dual density, i.e., 3" core/density/dual density.

Consequently, in Table 6.6 pertinent statistics of the 3" core wet density/dual probe 8/18 ratios are given and its distribution is illustrated in Figure 6.5. Figure 6.6 shows the distribution of dual probe density values prior to ponding, at two days after ponding and just prior to being drained. Using the correction in Figure 6.5 and relationship discussed in Section 5 (equations 5.4 to 5.6), amounts of water necessary to saturate the clay liner for the above times were computed and are shown in Figure 6.7. Density contours

TABLE 6.6. STATISTICS OF THE RATIO: (3" CORE DENSITY/DUAL PROBE DENSITY)

Variable	N	Mean	Std. Dev.	Min	Max	CV
Ratio: 3" core / Dual 8/18	240	0.89	0.05	0.74	1.03	5.8%

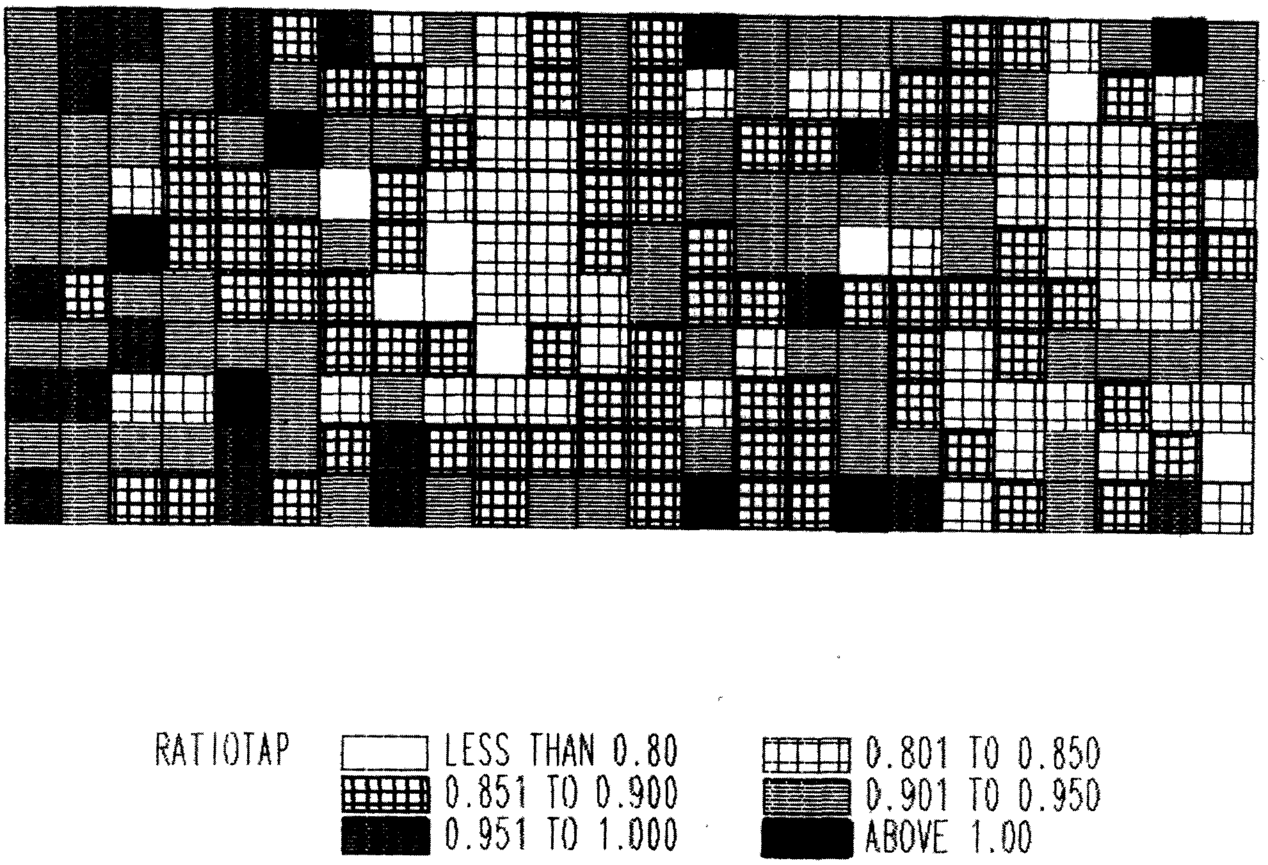


Figure 6.5. Spatial distribution of the 3" core/dual probe density ratio on 8/18/86 in the compacted clay liner.

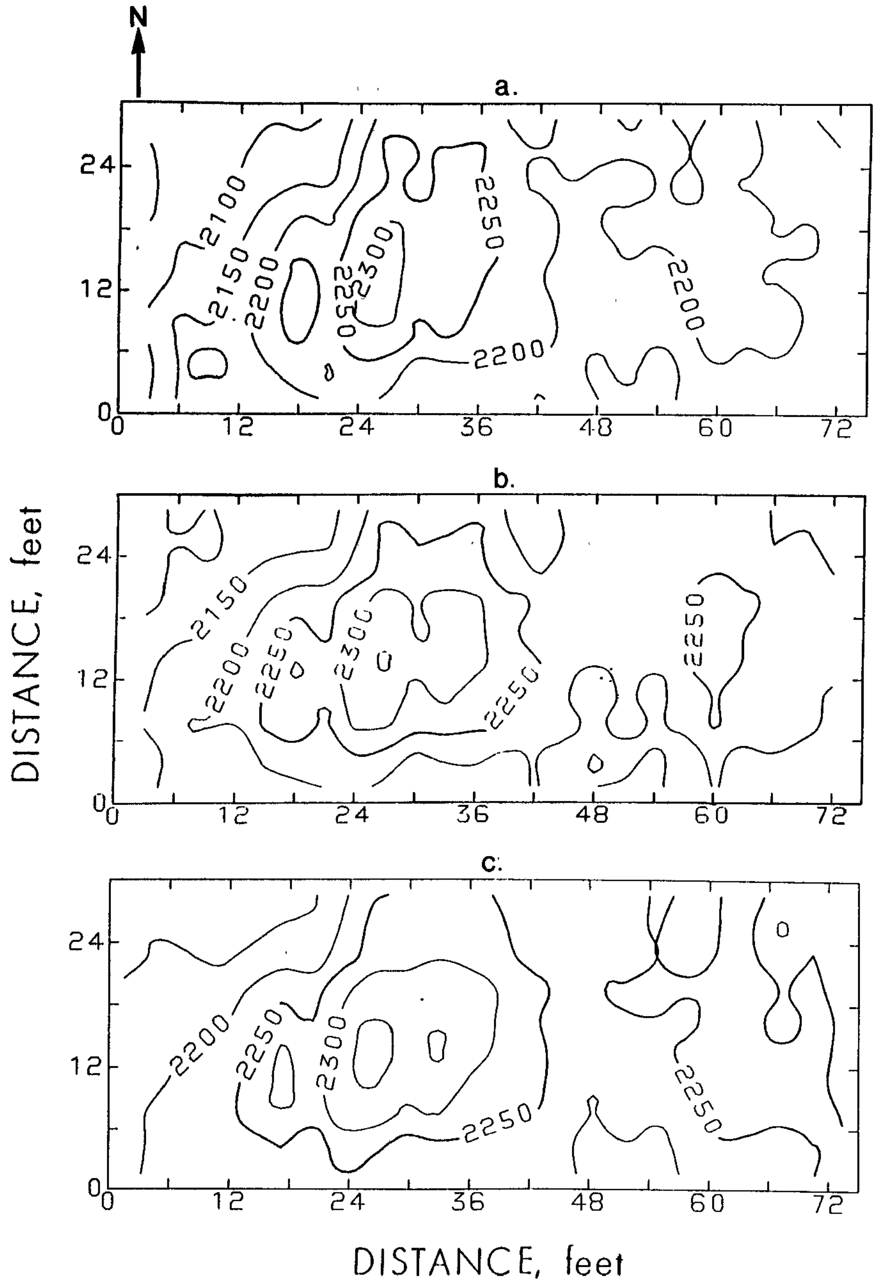


Figure 6.6. Contours of density (a) before ponding, (b) two days after ponding, and (c) just prior to being drained.

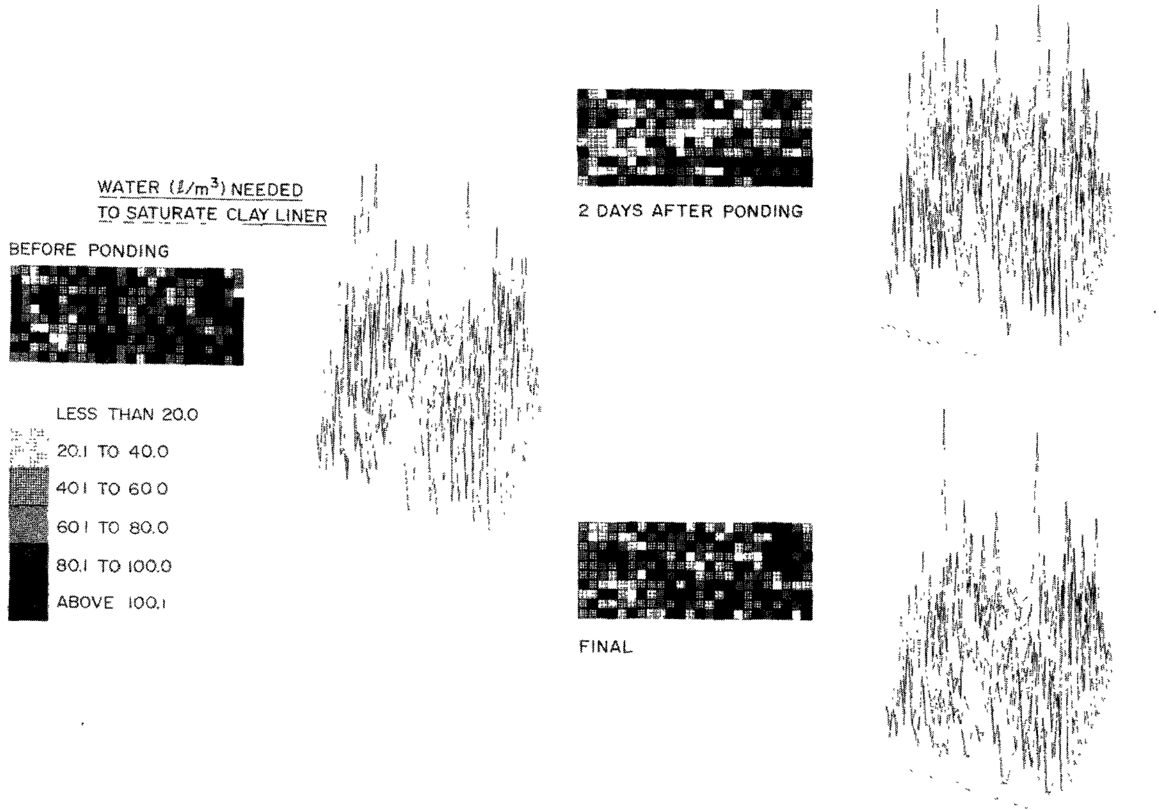


Figure 6.7. Spatial distribution of the amount of water needed (in kg/m^3) to saturate the clay liner before ponding, 2 days after ponding, and just before being drained.

plotted in Figure 6.6 show rearrangement but little change in density with time, particularly after the initial increase (two days) when the liner was first ponded; amount of water required for saturation (Figure 6.7) seem to corroborate these findings. The mosaics plotted in Figure 6.7 show water needed to saturate the clay in units of ℓ/m^3. The associated statistics in Table 6.7 for each time increment suggest that, on the average, the amount of water required to saturate the clay changed about 50 ℓ/m^3. This corresponds to average change in density of ~ 50 kg/m^3 (Figure 5.17). On the average (Table 6.8) the clay appears to have swelled 2.90mm. Translated into an increase in the available pore space, this amount would constitute a nontrivial ~ 20% increase in the available pore space that would account in part for an apparent lack of change in the observed density (Figure 6.6).

When the liner was first drained, questions arose as to whether there could be any differences in water content and density distribution with depth and how best should the water content of the clay liner be monitored with time. Table 6.9 shows the pertinent statistics for 2" diameter cores taken very near the locations (~ 30cm North of the sites) from which Veihmeier samples have

TABLE 6.7. COMPARATIVE STATISTICS FOR THE AMOUNT OF WATER NEEDED TO SATURATE THE CLAY LINER

Time	N	Mean	Std. Dev.
		------- kg/m^3 ------	
Prepond	240	79	36
At 2 days	240	57	48
At draining	240	29	45

TABLE 6.8. AVERAGE SWELLING OF CLAY

	N	Mean	Std. Dev.	Min	Max	CV
			mm			%
Swelling	36	2.90	1.67	-1.56	9.04	57.8

been previously removed. Possibility of water ponding on the surface of lift 1 and 2 could not be completely ruled out. Results in Table 6.9 suggest that water content throughout the clay was essentially constant, deviating very little from the average. To monitor incipient drying of the surface, the top layer was instrumented at 3" (8cm) depth with gypsum moisture blocks and moisture was measured periodically at 6" (15cm) depth with the neutron moisture probe. Both the blocks and the probe were corrected to observed 2" core readings and checked against subsequent Veihmeier sampling. To correct the values, moisture block readings at 3" were multiplied by 31.4/38.1 = 0.83, while neutron probe readings at 6" were multiplied by 31.4/39.2 = 0.80 assuming particle density of 2714 kg/m^3 (Table 5.8). Values in the numerator are the average water contents in 2" diameter cores at 0 to 3" and 3" to 6" depth, while the values in the denominator represent total porosity based on average bulk density at 0 to 3" and 0 to 6" depth. The respective changes in the degree of saturation at 3" and water content at 6" are shown in Figure 6.8. Because of the sand layer over the surface, drying of the clay liner after it was drained was very slow. One year after the liner was drained, drying, particularly in the surface 3" layer, increased dramatically after cores and other samples of the clay were taken exposing more clay to the air.

To evaluate the differences among layers of the clay, paired transects one foot apart of 2" diameter cores were taken (on 3' centers) East to West through the middle of the clay liner one foot apart. The cores were sliced into twelve, 1" increments to evaluate water content, access tubes were placed in the holes and density was measured using a dual probe in 1" increments of

TABLE 6.9. STATISTICS FOR THE 2" CORES, AVERAGE AND BY LAYER

Variable	N	Mean	Std. Dev.	Min	Max	Std. Error	CV
0-3"							
DD	45	1681	152	1273	1984	27	9.0
WD	45	1995	181	1519	2355	27	9.0
θ_W	45	18.6	1.3	15.4	23.7	0.19	7.0
θ_V	45	31.4	3.5	21.0	41.4	0.52	11.1
3-6"							
DD	45	1649	146	1166	1991	21	8.9
WD	45	1964	178	1360	2553	26	9.1
θ_W	45	19.0	1.1	16.5	22.7	0.17	6.1
θ_V	45	31.4	3.6	19.3	39.0	0.54	11.5
6-9"							
DD	45	1600	136	1213	1862	20	8.5
WD	45	1905	162	1490	2233	24	8.5
θ_W	45	19.0	1.3	14.8	22.8	0.20	7.0
θ_V	45	30.4	3.2	22.1	37.1	0.47	10.5
9-12"							
DD	45	1638	157	1306	2035	23	9.6
WD	45	1933	184	1533	2395	27	9.5
θ_W	45	18.0	1.5	11.8	20.2	0.22	8.5
θ_V	45	29.5	3.6	20.4	36.6	0.54	12.3
Avg							
DD	45	1642	63	1479	1806	9	3.8
WD	45	1949	75	1760	2143	11	3.8
θ_W	45	18.7	0.6	16.9	20.2	0.09	3.3
θ_V	45	30.7	1.5	27.7	33.7	0.23	5.0

depth. The primary purpose was to determine if any of the layers contained higher proportions of stones or else exhibited noticeable zones of lower density. For example, visitors suggested that a sheepsfoot roller might have pushed down stones within a clay matrix creating stony layers at the bottom of each lift. No evidence for such a layer was found during the excavations of various cores. Figure 6.9 shows the wet and dry density, respectively, for the transect and Figure 6.10 gives the details of the water content by weight for the north and south positioned access tubes. The results shown in these two figures do not suggest any particular layering within the clay; however, there appear to be several vertical zones of lower bulk density particularly noticeable in the wet density (upper) plot. Except for the wetter conditions at the clay surface, water contents within the liner showed no preferential orientation, confirming observations made previously when using 2" diameter cores.

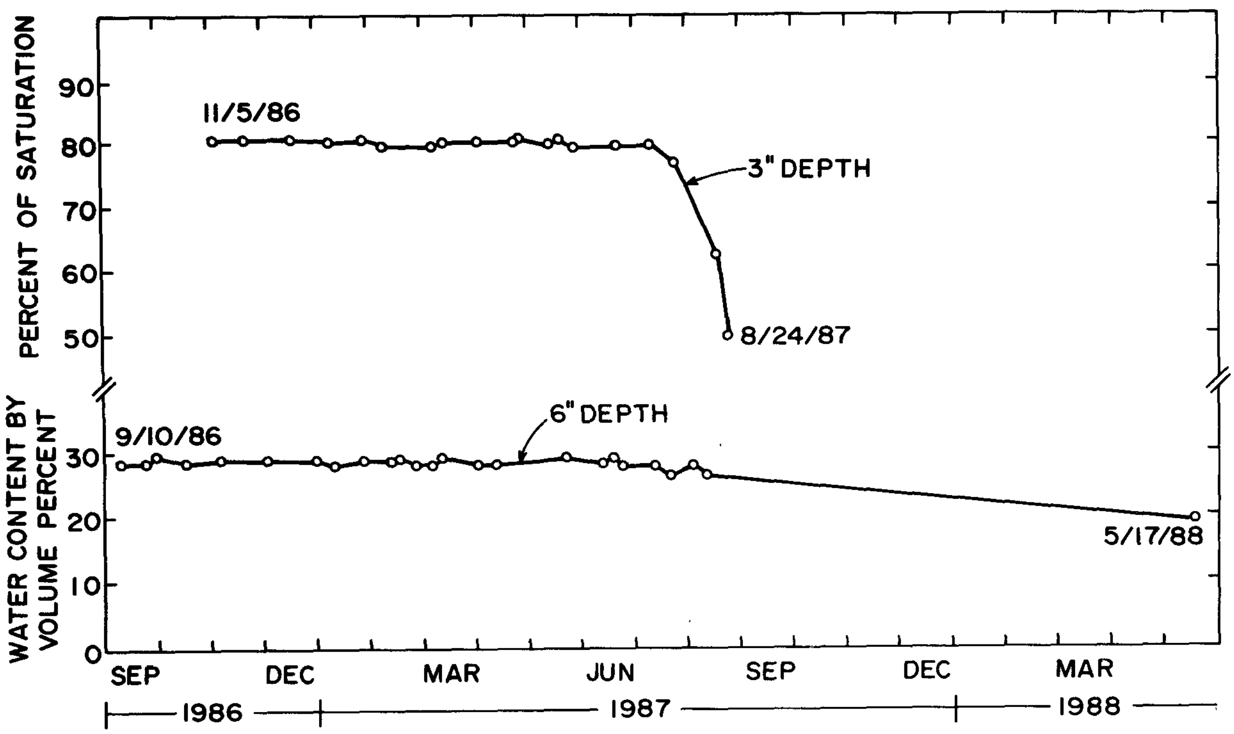
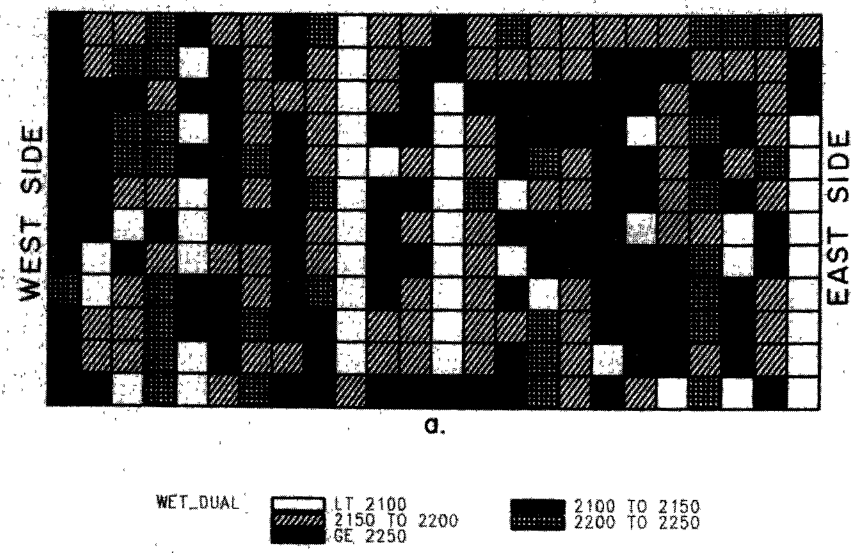


Figure 6.8. Changes in the degree of saturation at 3" (8cm) and water content by volume at 6" (25cm) in the drained clay liner with time.



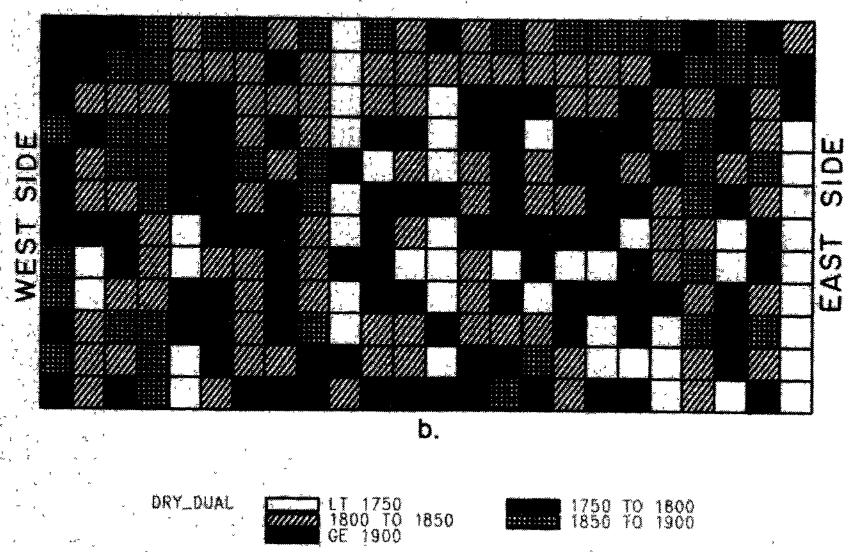


Figure 6.9. An east to west transect of wet (a) and dry (b) density in 1" (2.5cm) depth increments as measured with the dual gamma probe on 3' (91cm) centers.

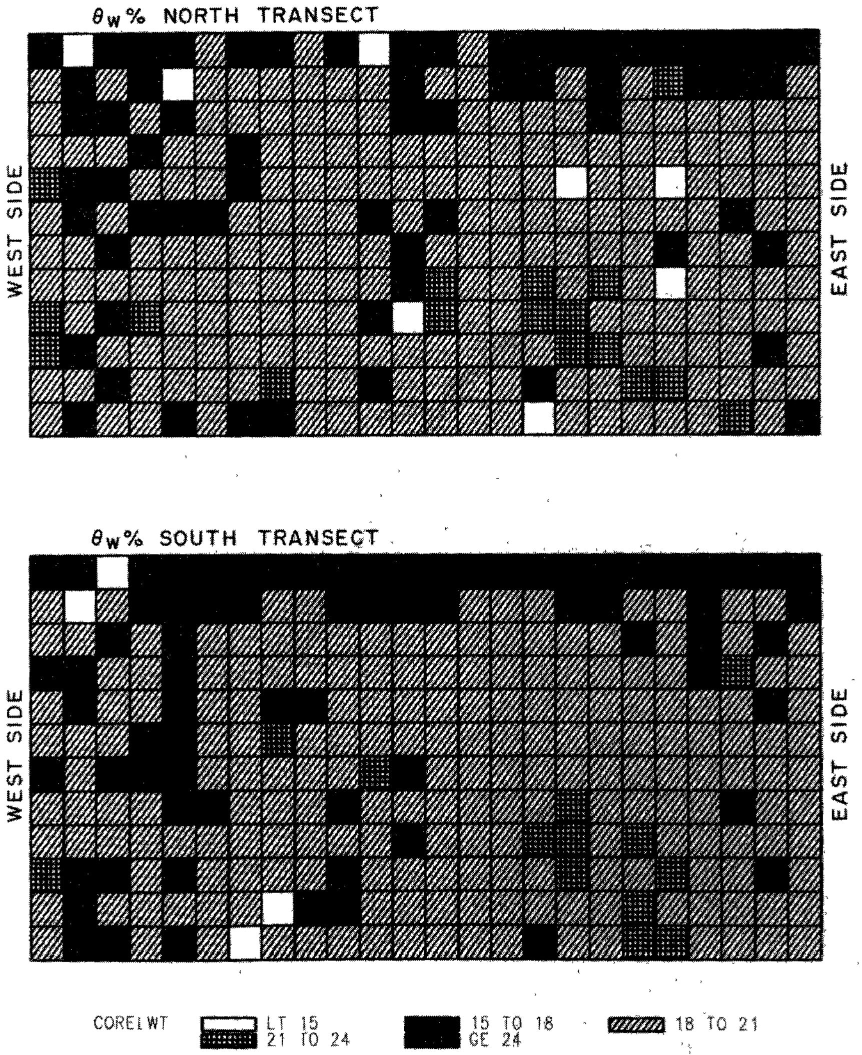


Figure 6.10. An east to west transect of water contents by weight in 1" (2.5cm) depth increments measured gravimetrically.

The clay liner appeared to contain many stones. In order to quantify the spatial distribution of stones relative to density and permeability posthole size holes (6" diameter, 12" deep) were excavated 7 to 12" (15 to 30cm) from where the 3" cores were previously taken. Hole volume (~ 100 cm^3) was measured by inserting a thin walled plastic bag and filling it with water. The solid material was weighed, dried, and weighed again to compute density and water content at each location. Subsequently, the soil was washed out through the #10 (2mm opening) and #6 (3.35mm opening) sieves. The material retained was classified as "Rocks" and their volume and weight were measured.

Table 6.10 gives the comparative statistics for posthole data. The data show that the wet and dry density of the posthole material, although somewhat larger, are about the same as those for 3" and 2" cores. However, proportion of rocks by volume was much greater than expected based in the preliminary specifications for this material. (The B-horizon of the Hubblersburg cherty silt loam on the average contains 9.5% by volume of coarse fragments.) Such a large proportion of rocks, even though it appears to be fairly uniformly distributed throughout the clay matrix, has a definite influence on the

TABLE 6.10. COMPARATIVE STATISTICS FOR POSTHOLE DATA

Variable	Mean	Std. Dev.	Min	Max	Std. Error	
Wet density (kg/m^3)	2057	104	1782	2354	6.7	5.1
Dry density (kg/m^3)	1729	89	1450	2020	5.8	5.2
Water (% by wt)	19.1	3.0	9.0	32.0	0.2	15.7
Water (% by vol)	33.0	5.0	15.0	52.0	0.3	15.0
Rocks (% by vol)	20.8	2.0	15.0	28.0	0.1	9.7
Dry density (soil)	1555	108	1248	1888	7.0	6.9
Dry density (rocks)	2389	48	2176	2703	3.1	2.0

compacted bulk density. Because of the high density of rock fragments (Table 6.10) soil fraction less than #10 mesh (2mm) when compacted together with rocks may be of lower density than called for by the specifications. Conversely, because little water is retained by rock fragments, the water content of the soil fraction may be correspondingly larger. These results suggest that materials used in the construction of clay liners should have a specified fraction of coarse fragments retained on the #10 sieve. For example, if the clay liner material contained only 5% by volume of the rock fragments the average density of the soil fraction would have been 1694 kg/m^3, a considerable improvement (97% Proctor) over the mean dry density of the clay liner soil (89% Proctor).

SECTION 7

DATA QUALITY

DATA ACQUISITION

Clay soil used as the experimental liner material was a subsoil horizon of a commercially available cherty silt loam from central Pennsylvania. On the average, the clay was compacted wet of optimum to better than 90% Standard Proctor. The soil is classified as a CL type having a permeability of 1.10 to 1.76×10^{-8} cm/sec as determined in the laboratory with a falling head permeameter at 90% maximum density (Modified Proctor) and a gradient of about 20. Mineralogically, the soil clay is predominantly a mixture of illite and kaolinite with some montmorillonite.

After the liner was constructed, instrumented, and ponded, water level was maintained with an automatic constant head tank. Similarly, each of the infiltration cylinders and evaporation pans were equipped with a Mariotte-type constant head, one liter bottle set to the same water level as in the liner outside. Individual leachate drains were routed to the outside and leachate was collected in appropriately sized containers. Simultaneous readings of water level changes in a grid of evaporation pans gave the necessary correction which was applied to ring infiltration data. Corresponding to each set of ring and drain data, a set of wet density readings was taken with the Troxler[1] dual gamma probe. Additional details of clay liner construction and instrumentation are given elsewhere in this report; here the emphasis will be on data analysis aspects of the study. The ultimate purpose is to develop a capability to describe areal distribution of hydraulic conductivity under field conditions and to relate it to tests performed in the laboratory on disturbed samples of clay liner materials, or on undisturbed cores taken from the liner during construction. The dilemma is that while the response of the liner as a whole may be influenced by preferential flow pathways, zones of discontinuity and zones of higher effective porosity, point laboratory samples generally are not.

Using surface probe, volumeter and gravimetric samples, moisture and density control data were collected during the construction of the liner. Following construction but prior to ponding, 13 sets of density readings with dual gamma probe were taken and averaged to provide a priori distribution of density and available porosity. Following ponding, changes in density with time were measured and changes in available porosity were evaluated. After the clay liner was drained, core samples were taken to calibrate dual probe density measurements and to evaluate spatial distributions of coarse fragments and water.

On a relative basis, dual probe readings are taken over a volume about five times the volume considered in the volumeter, while surface probe in the backscatter mode measures density and moisture over a volume 100 to 200 times larger than the volume considered in dual probe readings, and 700 to 1000 times larger than measured by volumeter. The volume of the liner is ~ 6000 to

9000 times the volume measured by the surface probe. Similarly, the volume of the experimental liner as a whole is 55 times the volume of all the infiltration rings combined (250), while the volume assumed associated with each leachate drain (3' x 3' x 1') is ~ 55 times the volume of each infiltration ring. The sidewall and endwall drains together represent ~ 1/4 the volume of the whole liner.

The variability of a property can be described by the probability density function (PDF) which not only contains information about the averages (mean, mode, median), but also their other moments, and these permit estimation of confidence limits for that property. Identifying the appropriate PDF for a parameter has important implications in computing the number of observations required to estimate the mean with a specified precision, and in determining the integrated response of an area.

In the traditional analysis of variability, properties measured at a number of sampling points within an area are assumed spatially independent and are represented by mean, standard deviation, and an assumed (or estimated) PDF. However, the assumption of spatial independence in soils, at least for sampling points close together, seldom holds. Nonparametric techniques can then be employed to evaluate the extent of spatial dependence.

Data quality is both the object and subject of this study. Quality indicators of the data collected in this research project are documented to meet the technical goals of this study. Table 7.1 describes the primary methods used and shows tentative data quality indicators for each parameter measured. Quality indicators for Density and change in surface elevation are taken from manufacturers specs for the instruments with which measurements are made (Figure 7.1). On the other hand, precision of infiltration, evaporation, and leaching rates measurements depends to a large degree on the volume of infiltrate, evaporate, or leachate. We have found gravimetric method superior to volumetric when measuring infiltrate and evaporate. Table 7.2 lists typical volumes of infiltrate and leachate collected by different means. For example, 400ℓ of water is typically added to a liner daily, while drain outflows range from 50mℓ to 20ℓ and infiltrate volumes vary between 50mℓ or less to 1000mℓ. Unfortunately, slow running rings and evaporation pans have evaporation losses on the order of 100cc or less with possibility of corresponding large errors. Current use of balance and gravimetric method obviates the need for volumetric measurement with graduated cylinders and improves the degree of attainable precision.

According to Lumb (1974) if a specimen of, for example, clay is tested and there exists a true value e and a corresponding test value x, replicate testing of the same specimen will give different values of x because of lack of "precision" of the test being used. The average of several replicates will likely differ from the true mean because of lack of "accuracy." For an ith replication, test value x_i is,

$$x_i = \alpha \cdot e + \beta + \delta_i \qquad (7.1)$$

TABLE 7.1. METHODS USED AND CLASSICAL DATA QUALITY INDICATORS FOR INFILTRATION, EVAPORATION AND LEACHATE RATES, BULK DENSITY, AND CHANGE OF SURFACE ELEVATION (CSE)

Variable	Units	Method	Precision	Accuracy	Completeness
			%	% bias	%
Infiltration	cm/sec	Gravimetric	± 1	± 2	99
Evaporation	cm/sec	Gravimetric	± 1	± 2	99
Leachate	cm/sec	Volumetric	± 5	± 2	99
Density	kg/m^3	Nuclear probe	± 0.32	± 1	99
CSE	mm	Laser beam	± 0.05	± 1	99

TABLE 7.2. PERCENT ERROR AS A FUNCTION OF VOLUME OF LEACHATE

Volume	Error	
	%	
20	3.6	Bucket, drains
15	2.4	
10	2.1	
5	1.4	
5	1.4	Beaker, drains
4	0.7	
3	0.7	
2	3.5	
1	7.1	
0.80	2.7	Graduated cylinder, drains
0.40	1.6	
0.20	10.0	
0.05	10.0	
1.00	1.0 to 2.6	Graduated cylinder, rings
0.80	3.3	
0.40	1.3	
0.20	11.0	
0.05	22.0	
100	9.5	Sum, sidewall drains
400	2.3	Liner, tank

PERFORMANCE DATA	
MODEL	3862MP8
WEIGHING RANGE	16.500g
READABILITY	0.1g
STANDARD DEVIATION (REPRODUCIBILITY)	$\leq \pm 0.05$ g
MAXIMUM LINEARITY DEVIATION	$\leq \pm 0.15$ g
TARRING RANGE (BY SUBTRACTION)	16,500g
MEASURING TIME	2s
INTEGRATION TIME	4 OPTIMIZED DIGITAL FILTERS
DISPLAY SEQUENCE	0.1...0.4s (SELECTABLE)
AMBIENT TEMPERATURE RANGE (0°C...+40°C)	273K...313K
SENSITIVITY DRIFT (AMBIENT TEMPERATURE RANGE (283K...303K)	$\leq \pm 2 \cdot 10^{-6}$/K
LINE VOLTAGE (SELECTABLE)	100/120/220/240V, -15%...+10%
FREQUENCY	50-60 Hz
CONSUMPTION	15 VA
DATA OUTPUT (OPTION)	RS 232/V24-V28/RS 423 V10; 7 BIT; PARITY EVEN, ODD, MARK, SPACE; TRANSFER RATES 150 TO 9600 BD.

Figure 7.1. Gravimetric balance performance data.

where δ is a random variable of zero mean and with variance $V(\delta)$. The average of a large number of such tests gives an expected value $E(x)$,

$$E(x) = \alpha \cdot e + \beta \qquad (7.2)$$

α and β express bias, or lack of accuracy, $V(\delta)$ represents the lack of precision. In a study such as this one, it is difficult to determine bias factors α and β unless an absolute way of measuring e is available. Occasionally e is inferred from calibration or model tests but bias effects are mixed since they may be due to a model or to a test. Changes from specified test conditions may introduce deviations in the results which can be interpreted as either bias or precision factors and which include such effects as machine, operator, or interaction effects. The above procedure is difficult to apply to a study such as ours which attempts to evaluate distributions of changes in density and surface elevation of water as well as infiltration, evaporation, and percolation rates both spatially and in time for a prototype clay liner.

Accordingly, novel data quality indicators need to be developed to be used in the field by field personnel on a large scale, this study's 10 x 24 sampling matrix simulating actual liner conditions. One objective of this study was to design acceptable field QA/QC plan. Thus, even though 250, 1000cc constant head bottles can probably be filled with less than 1% error (± 10mℓ), this error increases as the volume added decreases, i.e., if only 10mℓ were needed to be added we could easily have a 100% error. One way to cope with this problem is to have constant head bottles and leachate drains that are run slowly being left on for longer time periods so that the total volume added can be measured with precision 3% or better.

The second aspect to remember (and this also pertains to Density and CSE parameters) is that each set of measurements in this study is not an independent sample but a part of continuous time series distribution, each succeeding value highly correlated with the preceding ones. Consequently, QA/QC plan outlined here will rely heavily on developing appropriate criteria and methodology of data collection and analysis.

It should also be remembered that a single point sample in this study (infiltration, leachate, evaporation, density, or CSE) cannot be replicated and has no meaning per se. Replication consists of additional (250) comparative samples taken over an area at approximately the same time assuming spatial stationarity. To be comparable, such samples need to be easy to obtain and require a relatively short collection period. Quality of the data is dependent on proper equipment operation (density and CSE), or operator's repetitive ability (infiltration, evaporation, leachate). We have found, for example, that our technicians can fill 1000mℓ constant head bottles used in measuring infiltration with better than 1% precision and within 2% error between different operators. How well could other operators function or be expected to function under field conditions? To get answers to some of these questions, in this study, the sampling is carried out on regular grids. The liner, although large, is essentially a prototype of a field scale facility. Details of procedures used and data reduction are summarized in the following sections.

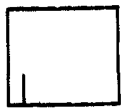
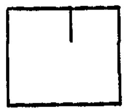
Analytical Procedures

Density--

Use Troxler[1] dual gamma probe. Measure at 240 locations once a week. Take standards at the beginning of each new tube, the reading is to agree within 200 counts with the previous standard reading.

CSE--

Use optocator equipment, take readings in 36 locations once a month. Make sure standards are carefully read. Map (on each pedestal) where the readings are actually being made.

 or  (This is a one time set of observations)

Leachate Drains--

Measure individual outlets at 250 locations when needed, report as once a week cumulative reading (Friday), for individual drain grid (8 x 23) and for combined sidewall drains. Once a month take samples for chemical analysis from drains: AA-0, D-2, F-7, K-6, L-6, O-9, P-5, T-3, Ponded water, Tanker, at 9 and at 12 months take samples from all the drains.

Analyze according to "Standard Methods of Analysis of Water and Wastewater" for Temp, EC, pH and bicarbonate at the site, send to University Park for analysis of NO_3, SO_4, Na, K, Ca, and Mg.

Infiltration Rings--

Read as needed by adding preweighed water carefully through a small opening in a stopper with a funnel. Report combined total weekly (every Friday). General procedure:

a) Remove siphon line, close it with a nail, and place between two glass tubes.

b) Remove "00" stopper, add measured amount of water through a funnel up to one liter mark.

c) Close carefully the small "00" stopper, replace line in the ring, make sure the system operates properly. Do not move bottle or large stopper unless absolutely necessary. Water level to be the same as on the outside in liner. To check, place tube outside the ring, tilt bottle slightly, the bubbler should now engage. Reweigh containers from which water was added.

Liner--

Measure as needed amounts of water used by liner. Report cumulative value weekly (every Friday).

Evaporation--

Measure large pan and small pans on the same schedule as rings.
P.S. Place brass pins inside rings level with water, use as a quick check to see if bubblers are working properly.

Data Reduction, Validation and Reporting

Field data was recorded on field data collection forms. Any subsequent needed transformation or summaries were performed on the micro- or mainframe computers. Data reduction and processing flow chart is shown in Figure 7.2.

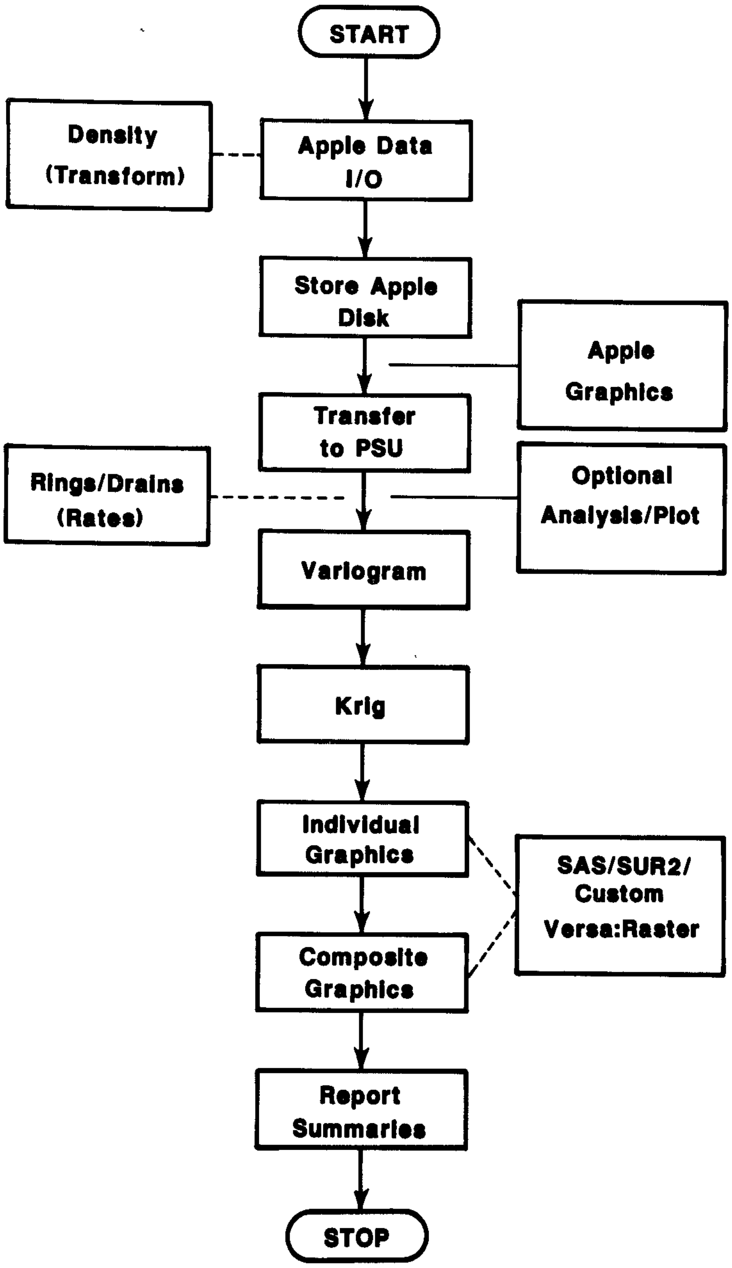


Figure 7.2. Data processing flow chart.

An Apple IIe microcomputer was used to enter the data and create data files in a format for transfer to The Pennsylvania State University mainframe computer. This was done as soon as possible after the data were taken.

Density data was transformed on the Apple computer from counts to kg/m^3 using the equation

$$\text{Density} = \left(1756.0956 + (-625.7235 \cdot \log_e(\text{count/std}))\right)$$

where

Std = average values of standard count.
Density is computed to an Integer value.

Inflow/Outflow were computed as rates on The PSU system using the formula

$$\text{Rate} = \text{volume}/(\text{area} \cdot \text{time})$$

where

Volume was the volume adjusted for evaporation, time, etc. as necessary.

Ring area = 613.1190 cm^2 - drain area = 8361.2736 cm^2

Time = seconds between successive measurement.

At the conclusion of the study exact areas of infiltration rings were evaluated using preweighed water and laser beam optocator for sensing level changes. These were the ring areas used in final analysis. Each ring was also checked for leaks using fluorescein. Only those rings which had no leaks were used in analysis.

The field facility is a two-dimensional matrix and the data are kept in formats that allow for printout to screen and hard copy in a two-dimensional format. All field forms must have a value in each cell. Data transfer from the field site to PSU presents the data in a 24 x 10 or 25 x 10 matrix and allows for easy edit of data format.

Due to the nature of this data, outliers were hard to define. Any value strongly suspected of being in error was treated as a missing value; however, this value is carried in computations until sufficient justification is accumulated to remove it from the data base, or correct it.

Statistical analysis was the major editing activity to validate correct data entry. Printouts provide maximum, minimum, and variance values. These values were expected to be within known limits and to follow similar patterns. Any deviation from these limits and patterns required checking of the data set. It is not feasible to check each value at each data step. Since 250 drain values were taken daily with a recording step, Apple data entry step, a PSU transfer step, and data setup step, i.e., there were 250 x 5 x 4 = 5000 possible data checks during initial data collection of one weekly set of values.

The software developed for data reduction incorporates known limits to edit the data during entry and processing. Programs developed for the Apple IIe check for such items as negative values, non-numeric data, and values outside upper and lower limits are postulated.

Internal QC Checks

Density measurements used Troxler[1] standards to calibrate and check instrument operation. After initial data analysis these standards were required more frequently. As a minimum the operator must take a standard at the beginning of each access tube.

Inflow measurements required a visual measurement and ten quality samples have been included on which the technician repeated the same process as on the data samples. These samples were routinely checked for accuracy to provide a percent error expected due to visual measurement volume cutoff. Evaporation data was treated similarly to infiltration rings.

Inflow/outflow flux rates were measured using either volumetric containers or a balance. Appropriate equipment checks such as standard weights for balances and cleanness of graduated cylinders, were used on a regular basis.

CSE measurements required an internal standard on a fixed rigid stand and five additional standards permanently mounted to the wall of facility, to check on the mobile platform performance.

Chemical analyses were not involved in any significant measurements within this study. However, in leachate and Br^- tracer analysis, standard methods and procedures were followed.

Volumetric devices used to measure flow rates were calibrated using laboratory volumetric glassware of a grade traceable to National Bureau of Standards for accuracy. In some cases weight measurements were used in lieu of volume to obtain liquid quantities; in these cases a balance of known accuracy was used. The balance was regularly calibrated in accordance with the manufacturer's directions.

In-house proficiency testing was accomplished by periodic checks of water volume measurements for uniformity and consistency among inflow and outflow measurements from the clay liner system. In addition, different individuals double checked raw data on a periodic basis.

The capability and performance of the total measurement systems was determined by intercomparison of data collected by the several parametric measurement systems installed within this study. For example, inflow/outflow measurements or density evaluation using nuclear probe and core data.

Technical systems audits were part of the research effort. In order to ensure that the best data possible were being collected, newer or better monitoring apparatus or systems were implemented if it was determined that better data could be obtained.

A performance evaluation audit was made as part of the ongoing data interpretations. Examination of data trends and differences obtained over time was used to determine whether any changes in data generating systems were occurring which adversely affected data quality.

Examination of data collected during the course of this investigation will provide an opportunity to develop precision and bias information with respect to variations of flow of water through compacted clay soil over a large area. Data completeness is simply defined as obtaining flow measurements from each installed inflow and outlet. It is possible that at other locations resource constraints mandate that fewer points be sampled.

Spatial variability can be systematic or random. Systematic variability is a change in clay liner properties as a function of compaction effort, initial water content, and management. While, in general, spatial variability will increase as the size of the area increases, maximum variability of individual properties may occur within a readily definable and at times small area. It thus appears that many soil variables may be considered continuous at least within a certain size area.

The data being generated within this research study will be used to describe the spatial variability of hydraulic conductivity of water over the experimental area. This study represents the first known attempt to conduct such an spatial study, and thus the data generated is specifically representative only of the soil and construction included within this research project. Caution must be exercised when applying the ultimate results of this research to other soils, systems, constructions, and measurement devices. The results of this work demonstrate soil hydraulic variability in a way which is useful to both the USDA and the EPA from the standpoint of better understanding spatial variation in soil properties.

Final Density Check

Clay liner dual probe densities were originally recorded by a technician on field sheets. This data was entered onto Apple IIe diskettes. The program used to compute and record the computation to disk contained computer code to check the input standard counts and dual probe counts for upper and lower limits. The standard counts check worked well, as acceptable limits had been defined. This also provided a structure that kept the data entry person in data sequence. The dual probe counts check had a limit that was larger than necessary for the upper limit, which allowed values to enter the data sets that were in error, but detected by data checks during data processing. During initial computations, outlier values were checked for accuracy, errors were corrected as found, and new statistical computer runs were processed.

This initial data checking has removed any gross data errors and provided good quality data for preliminary and quarterly phase reports. The final data base was edited for errors not previously identified. Prior to this editing all density values ranged between 1900 and 2500 kg/m^3. Three methods were used to check the data for entry accuracy, outliers and precision.

Method 1 was to select five of the 80 data sets (Table 7.3) which were reentered into the Apple IIe and new printout of wet density was created. The original printout and the new printout were compared and errors were identified. The five data sets selected were one from the pre-pond time period, three from the ponded time period (a random selection from each four month time interval between March 1985 and April 1986), and the last post-pond data set.

At the completion of this method three errors were found in five data sets. The error of greatest magnitude was a value of 2111 kg/m^3 instead of 2103 kg/m^3. This error was within the measurement error of the instrument. Another error of concern involved using the wrong standard counts from the field sheet. This actually was a field sheet problem and not totally the fault of the data entry person. This method indicated that less than 0.5% data contained errors and that each error was less than 0.5% of data value.

Method 2 was a statistical/graphical check. The graphical check allowed visual inspection of density and ring/drain flow rates. A plot was made of each site for the ring/drain inflow and outflow. The density on the east and west of each ring/drain site were also plotted on the range plot. (NOTE: The ring/drain on the east and west edge of the platform were matched to the A and X density rows.) This produced graphs of the data and identified some inconsistent data values which were checked and corrected if necessary. This procedure identified values that were within the expected range but deviated from the site trend. As an example, a site may have generally had a density value near 2100 kg/m^3 and then a value of 2350 kg/m^3 would appear.

This graphical check was then processed as a statistical check. Each observation for a site was subtracted from the preceding measurement. Differences greater than 99 kg/m^3 were flagged. The need to check the accuracy of the flagged values was evaluated. The data were printed in a table by date and by site (Table 7.4). A table of differences was also printed. After identifying the flagged differences, the associated density values were flagged in the density table. The eight values surrounding the value were then used to evaluate the need to check this value. If the difference between this value and the eight values was greater than 99 kg/m^3 then this value was

TABLE 7.3. DENSITY DATA SELECTED FOR QC/QA VALIDATION

Set	Data Collection Date Start	Data Collection Date Stop
1	2/ 7/1985	2/13/1985
2	5/17/1985	5/23/1985
3	10/30/1985	11/4/1985
4	3/10/1986	3/12/1986
5	8/ 4/1986	8/18/1986

TABLE 7.4. EXAMPLE OF DENSITY DATA RECORD

Date	Site 024	025	026
	------- kg/m^3 ------		
85/10/18	2185	2181	2177
85/10/25	2203	2441	2156
85/11/04	2244	2125	2130

checked. (NOTE: One of the eight values was what caused the flag, so the value was only compared to seven values.) This procedure checked the data for consistency to the adjacent measurements and to the preceding and following observed values.

Patterns of flagged values were then evaluated for the site. Any value that seemed to deviate from a pattern was validated. An example of a pattern is a site that has a few values near 2200 then a value near 2300 then a few values near 2200 then a value near 2300 again. Data with a pattern such as the above was accepted as valid.

During the flagging process, two types of flags were noted. One type was a single value where the difference would make a one time change exceeding the flag limits (99 and -99 kg/m^3) and the density would remain consistent thereafter. This appeared to be an artifact of the probe count. The second type was a pair of values with opposing differences. The first would be a change in one direction (99 kg/m^3) and the second would be in the opposite direction (-99 kg/m^3) such that the sum of the difference would be about zero. These values frequently were found as errors or were inconsistent with the remaining site data.

The flagged values (Table 7.5, Table 7.6) were classified after identification and as expected the calibration and background data collected prior to ponding are valid and consistent. The data collected after the second repair of the Troxler instrument are valid and consistent. The data collected prior to the first and second repairs contained most of the flagged data. Standard count measurements during these three time intervals reflect the same pattern and were the quality control measures which the factory used to determine the need for repair.

TABLE 7.5. GROUPING SUMMARY

	Count	Errors
Single Flag	51	3
Paired Flag	21	5

TABLE 7.6. SUMMARY DENSITY FLAGGED VALIDATION VALUES

Totals Summary

Total Measurements	19200	**80 data sets at 240 measurements**
Flagged Measurements	100	**0.52% of all dual probe measurements**
Errors	8	**0.04% total; 8.00% flagged**

Time Summary

	Flag Values	Months	Number Errors Identified
Calibration	10	3	0
Pond/1st repair	36 (11)*	2	1
1st/2nd repair	13	2	0
2nd/postpond	32	14	7
Postpond (2 sets)	9 (9)**	1	0

*First week after ponding
**After water removal

Flag Summary

Site	Count	Site	Count	Site	Count	Site	Count	Site	Count	Site	Count
002	1	033	1	122	1	156	1	198	2	232	1
003	2	045	1	216	1	158	1	200	1	236	1
005	2	061	4	128	3	167	3	202	1	237	2
007	1	080	1	133	2	168	2	203	3	240	1
017	1	082	1	134	1	176	3	217	2		
018	1	084	1	138	2	182	3	218	2		
024	5	087	2	139	1	183	1	222	1		
025	2	088	1	148	2	188	1	223	2		
026	2	100	4	150	1	189	1	224	4		
030	3	118	2	153	1	190	1	225	2		
031	1	120	1	154	1	197	1	228	1		

The method of data collection for this study allowed for only one measurement because of time and technique constraints. Improved data quality assurance would have been obtained by echo printing to hard copy the input data. Due to the intensity of data collection, it was not possible for the current man power to check all data entered at the time of data entry. However, after data collection terminated, all the data could have been checked and corrected in a few weeks.

Method 3 is related to dual probe precision. Although no two consecutive measurements at a point were taken at the same time, sets of 240 measurements were being continuously taken during the study. Consequently, comparison of differences observed for adjacent dates gives an estimate of precision. Such comparison was run with the following results:

PREPOND

	(kg/m^3)
Mean difference between consecutive dates	-0.21
Mean standard deviation between consecutive dates	2.30
Observed maximum between consecutive dates	8.67
Observed minimum between consecutive dates	-7.25

PONDED

Mean difference between consecutive dates	0.33
Standard deviation between consecutive dates	0.68
Observed maximum between consecutive dates	3.05
Observed minimum between consecutive dates	-1.44

Taking the observed average maximum of 7.96 kg/m^3 and an average reading of about 2189 kg/m^3 precision error would be on the order of 0.36% compared to 0.32% given in the probe calibration chart (enclosed).

Inflow/Outflow Balance

Table 7.7 gives the difference between total inflow and outflow on days when both were sampled together. On the average the difference was 4   7.9%.

Statistical Stability Tests

Table 7.8 shows an example of a statistical stability test on a surface probe during the final readings of moisture and density on a drained clay liner. Table 7.9 shows an example of a personnel check during inflow measurements. Finally in Figure 7.3 distribution of standard counts for the dual density probe is given for a whole study period. Following the initial repair the standard count stayed essentially constant.

TABLE 7.7. MASS BALANCE OF INFLOW AND OUTFLOW OF CLAY LINER WATER

Date	Inflow			Outflow			Difference
	Rings			Drains			
	Inner	Open Area	Liner	Inner	Outer	Liner	
	x 10^{-7} cm/sec						%[1]
850620	0.00	0.00	0.00	0.00	0.00	0.00	
850627	15.51	34.50	32.68	13.65	96.78	35.60	- 8.2
850702	15.03	34.65	32.79	13.16	93.31	34.32	- 4.5
850711	14.76	29.70	28.21	13.52	95.88	35.26	-20.0
850718	17.12	30.17	28.78	13.57	96.25	35.40	-18.7
850725	17.76	31.01	29.59	13.73	98.58	36.13	-18.1
850801	18.63	31.67	30.25	13.92	101.43	37.02	-18.3
850808	19.37	33.78	32.24	14.30	104.09	38.00	-15.2
850815	19.93	35.20	33.58	14.66	107.77	39.24	-14.4
850822	21.31	37.10	35.41	15.03	111.45	40.48	-12.5
850829	22.28	38.50	36.75	15.43	114.22	41.51	-11.5
850905	22.92	40.18	38.34	15.78	117.32	42.58	-10.0
850912	24.13	41.90	39.99	16.24	120.83	43.85	- 8.2
850919	25.28	43.77	41.78	16.91	123.09	44.94	- 7.0
850926	25.76	45.19	43.12	17.53	125.82	46.12	- 6.5
851003	26.31	46.93	44.76	18.09	128.19	47.16	- 5.1
851010	26.66	48.73	46.44	18.71	130.72	48.28	- 4.0
851017	26.38	50.02	47.60	19.19	133.28	49.31	- 3.5
851024	26.86	51.46	48.96	20.06	135.36	50.50	- 3.0
851031	27.32	52.59	50.03	20.76	136.43	51.29	- 2.5
851107	27.09	54.53	51.80	21.39	136.56	51.79	+ 0.02
851114	27.31	53.89	51.23	21.99	136.76	52.29	- 2.0
851121	27.49	54.72	52.00	22.69	136.95	52.86	- 1.6
851129	27.94	55.68	52.91	23.34	137.72	53.54	- 1.2
851205	27.95	56.28	53.46	23.81	137.12	53.73	- 0.5
851212	28.03	56.99	54.12	24.37	135.94	53.83	+ 0.5
851219	28.22	56.96	54.11	25.17	134.41	54.01	+ 0.2
851226	28.34	57.29	54.41	25.51	132.73	53.81	+ 1.1
860102	27.97	57.13	54.25	25.43	130.50	53.17	+ 2.0
860109	27.46	56.76	53.88	25.25	128.05	52.39	+ 2.8
860116	27.09	56.14	53.29	25.10	125.75	51.68	+ 3.1
860123	26.68	55.58	52.74	24.92	123.49	50.95	+ 3.5
860130	26.31	54.98	52.18	24.78	121.14	50.22	+ 3.9
860206	25.96	54.43	51.65	24.67	119.09	49.60	+ 4.1
860213	25.49	53.98	51.20	24.54	117.06	48.97	+ 4.6
860220	25.04	53.66	50.88	24.41	115.04	48.34	+ 5.3
860227	24.67	53.22	50.46	24.32	113.03	47.74	+ 5.7
860430	20.85	49.79	48.11	23.71	100.50	43.98	+ 9.4
860522	20.01	49.44	47.73	0.00	0.00	0.00	
860530	0.00	0.00	0.00	23.39	91.73	41.43	
860630	0.00	0.00	0.00	23.17	88.09	40.31	
860731	0.00	0.00	0.00	23.09	81.36	38.47	
Average							4.0±7.9

[1]Percent difference = $\frac{\text{Inflow-Outflow}}{\text{Outflow}} \times 100$

TABLE 7.8. STATISTICAL STABILITY AND DRIFT TEST - SURFACE MOISTURE GUAGE

N/T Number	Moisture Std Cts m	Error E=(n-n̄)	E^2	Density Std Cts n	Error E=(n-n̄)	E^2
1	431	4.3	18.49	3199	16.2	262.44
2	427	.3	.09	3186	3.2	10.24
3	415	-11.7	136.89	3176	- 6.8	46.24
4	420	- 6.7	44.89	3198	15.2	231.04
5	428	1.3	1.69	3183	.2	.04
6	431	4.3	18.49	3199	16.2	262.44
7	426	- .7	.49	3175	- 7.8	60.84
8	424	- 2.7	7.29	3182	- .8	.64
9	424	- 2.7	7.29	3170	-12.8	163.84
10	427	.3	.09	3175	- 7.8	60.84
11	434	7.3	53.29	3164	-18.8	353.44
12	427	.3	.09	3179	- 3.8	14.44
13	427	.3	.09	3199	16.2	262.44
14	419	- 7.7	59.29	3172	-10.8	116.64
15	426	- .7	.49	3173	- 9.8	96.04
16	432	5.3	28.09	3202	19.2	368.64
17	436	9.3	86.49	3171	-11.8	139.24
18	430	3.3	10.89	3182	- .8	.64
19	425	- 1.7	2.89	3186	3.2	10.24
20	425	- 1.7	2.89	3185	2.2	4.84

$\bar{n} = 427.7$ $\Sigma = 480.20$ $\bar{n} = 3182.8$ $\Sigma = 2465.2$

$\sqrt{\bar{n}} = 20.66$ $6 = \sqrt{\frac{\Sigma}{N-1}} = 5.03$ $\sqrt{\bar{n}} = 56.42$ $6 = \sqrt{\frac{\Sigma}{N-1}} = 11.39$

Ratio = .24 Ratio = .20

Test Number	Moisture Std Cts	Density Std Cts
1	428	3180
2	426	3179
3	430	3188
4	424	3180
5	430	3170
Avg.	427.6	3179.4

Moisture:

Difference = 426.7-427.6 = -.9

Total Avg. = 426.7+427.6/2 = 427.15

$\text{Drift} = \frac{-.9}{427.15} = -.21\%$

Density:

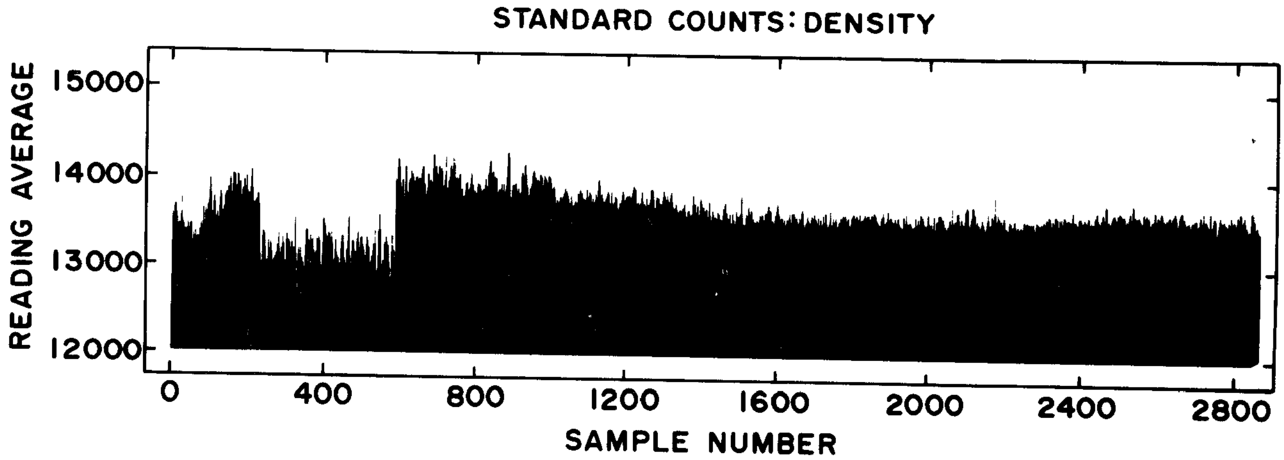
Difference = 3182.8-3179.4 = 1.7

Total Avg. = 3182.8+3179.4/2 = 3181.1

$\text{Drift} = \frac{1.7}{3181.1} = .05\%$

TABLE 7.9. PERSONNEL CHECK, INFLOW MEASUREMENTS

Site	Wt. Empty	Wt. Filled to Line
	Technician #1 filled and Technician #2 weighed (lbs)	
1	0.45	2.66
2	0.44	2.65
3	0.45	2.65
4	0.41	2.63
5	0.41	2.64
6	0.40	0.64
7	0.39	2.63
8	0.43	2.64
9	0.40	2.60
10	0.40	2.62
	0.418±0.023 (5.5%)	2.636±0.017 (0.6%)
	Technician #1 filled and Technician #2 weighed	
1	0.48	2.62
2	0.46	2.60
3	0.46	2.65
4	0.49	2.65
5	0.48	2.64
6	0.49	2.66
7	0.47	2.65
8	0.48	2.63
9	0.47	2.64
10	0.49	2.67
	0.477±0.012 (2.5%)	2.641±0.020 (0.8%)



Figuare 7.3. Distribution of dual density probe standard counts during the study period.

Number of Samples

Figure 7.4 shows the standard error of the estimate as a function of the number of observations for ring infiltrometers. For example, approximately 100 samples would need to be taken to keep the standard error below 25 x 10^{-7} cm/sec, but only 20 to keep it below 5 x 10^{-7} cm/sec. Table 7.10 and Figure 7.5 shows the comparisons of the relative number of samples required to attain a given degree of accuracy. The standard error is expressed here as a percentage of the mean for 5, 10, 25, and 50 random samples from a population of N observations. Comparisons include density and water content observations as well as flux and hydraulic conductivity measurements. Ring, drain, and laboratory values of hydraulic conductivity follow a pattern similar to that shown in Figure 7.4. Optimally, to reduce standard error to less then 25% of the mean 20 to 25, observations would be needed in our case. Even if all the observations are utilized (N), standard error did not appear to drop much below 10% of the mean at best. In contrast, both density and water content would require the same number of samples to keep the relative standard error in the 1% to 2% range for all except the surface probe water content values (2% to 4%). Thus, on a field scale clay liner far fewer (in our case 1/10 as many) samples of density and water content are needed than hydraulic conductivity to characterize the system with the same degree of precision.

For infiltration measurements, the cutoff point for our data appeared to be 10 to 20 samples. The question is: over what area? The study represents 2250 ft^2 plot of land (5/100 of an acre) suggesting that for best results we might need to have permeability measurements on the 15' x 15' grid. The soil material from which the clay liner was constructed, water content, and construction techniques were quite variable, both spatially and in time. It is possible that with more homogeneous material and water content distribution, fewer sampling locations may be necessary.

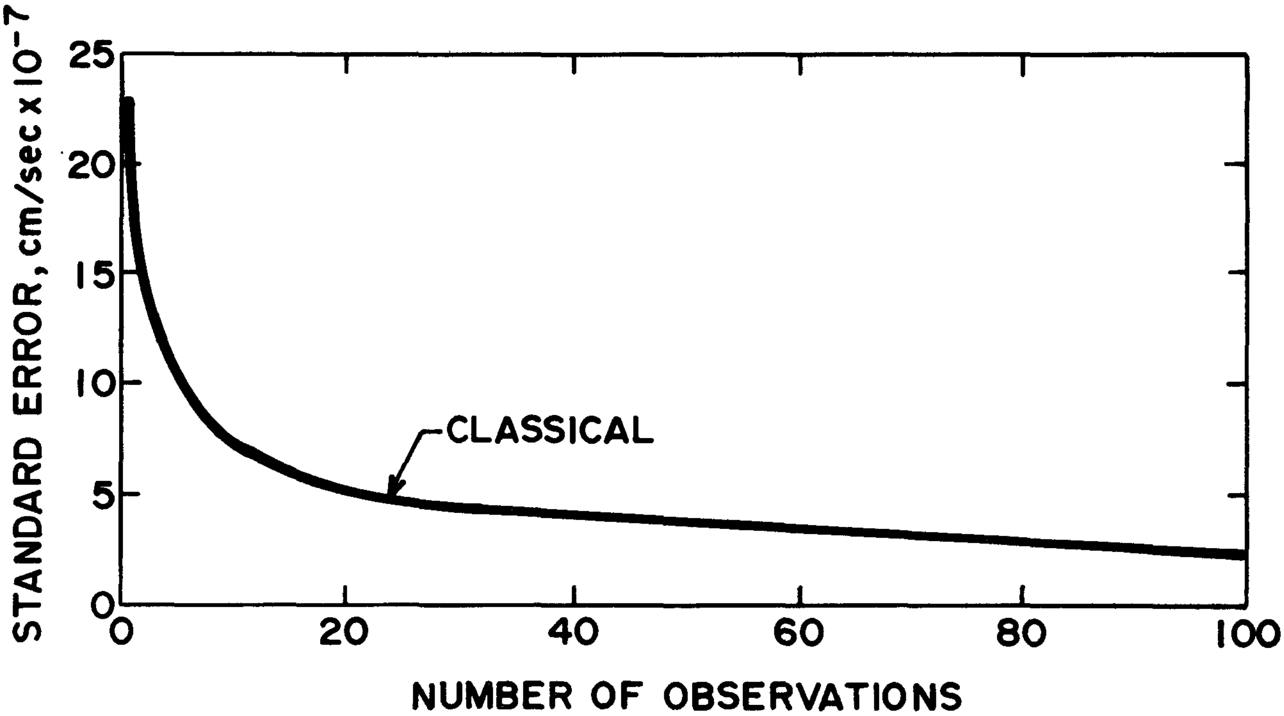


Figure 7.4. Standard error of estimate as a function of the number of observations for ring infiltrometers.

TABLE 7.10. COMPARISON OF THE RELATIVE VALUES OF STANDARD ERROR[1] FOR DENSITY, MOISTURE, AND HYDRAULIC CONDUCTIVITY MEASUREMENTS

No. of Samples	5	10	25	50	N
	--------- % of the mean ---------				
Dual Probe					
Wet density	1.58	0.92	0.57	0.42	0.24/240
3" Core					
Dry density	2.90	1.76	1.00	0.67	0.28/240
Wet density	2.71	1.69	1.04	0.68	0.28/240
Water by wt	1.09	0.93	1.10	0.95	0.35/240
Water by vol	1.80	1.53	1.56	1.14	0.44/240
Surface Probe					
Dry density	1.63	1.92	1.20	0.78	0.42/264
Wet density	1.45	1.36	0.80	0.51	0.32/264
Water by wt	3.04	4.90	3.16	2.01	0.81/264
Water by vol	2.66	3.60	2.20	1.37	0.52/264
Hydraulic Conductivity-K					
Drains[2]	34.0	25.0	25.0	22.0	9.8/193
Sum drains[3]	54.0	36.0	21.0	20.0	9.4/193
Sum rings	62.0	51.0	29.0	25.0	13.7/193
Laboratory	50.0	36.0	31.0	23.0	16.3/ 95

[1](Standard Error/Mean) x 100.

[2]Based on drain flux at 1 yr after ponding.

[3]Based on drain flux averaged over time (9 mos).

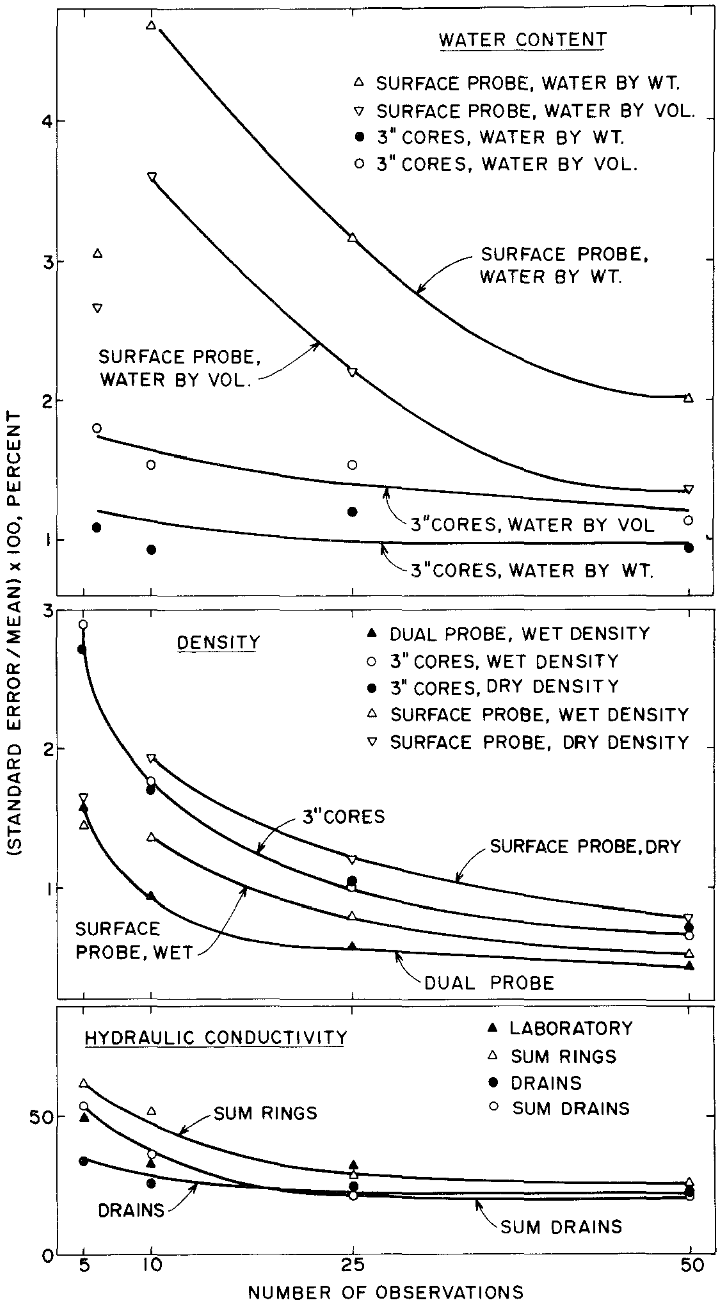


Figure 7.5. Relative values of the standard error as a function of the number of observations for density, water content, and hydraulic conductivity measurements.

LITERATURE

The literature reviewed (Phase I) was divided into six categories. Each book or article was first evaluated and classified on a literature review sheet and subsequently logged on the computer. The following table shows the appropriate review categories followed by the list of references.

Review Categories	
Class I	Background Material a) general chemistry b) general physics, soil physics c) soil chemistry d) clay
Class II	Hydraulic Conductivity Measurements a) saturated b) unsaturated c) laboratory d) field e) clay f) organic fluids g) factors influencing h) calculated
Class III	Solid and Hazardous Waste a) background b) case histories c) design d) regulations
Class IV	Clay Liners a) problems b) suggestions and recommendations
Class V	Geostatistics
Class VI	Scaling

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