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THE SEDIMENTATION OF NATURAL CHANNELS

A Thesis

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YUNG-CHI CHUNG

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YUNG-CHI CHUNG

The author was born in Taiwan, China, on October 23, 1936. He attended Na Pu Public Elementary School for six years and Kao Hsiung Junior Middle School for three years. In September, 1952, he entered Kao Hsiung Vocational High School majoring in Civil Engineering for three years. He continued his education in Taiwan Cheng Kung University for four years and graduated in June, 1959 with a Bachelor of Science degree in Civil Engineering. After one and one-half years military service in the army; he was employed by Taiwan Sugar Corporation and served as a Civil Engineer in the Engineering Department of the Head Office. In September, 1968, he came to the United States and entered the University of Idaho for his advanced study. He completed the requirement for a Master of Science degree in Civil Engineering in July, 1970.

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ABSTRACT

A procedure for estimating the deposit ratio for sedimentation in soil under laminar flow conditions is developed from the Hagen-Poiseuille and Kozeny-Carman theories.

This procedure was substantiated by use of gamma ray scanning techniques. A chart is presented by means of which the final deposit ratio may be computed from the initial porosity and the final hydraulic conductivity. A series of experiments on laboratory soil columns was conducted to evaluate the procedure and the relationships between the characteristics of the sediment and the soil media.

NOTATIONS AND DEFINITIONS

(1) - A subscript denoting data obtained during sedimentation.

c - A subscript meaning "container".

d - Diameter of granular soil, dimension = L

D - Internal diameter of pipe, dimension = L

f - Friction factor, dimension, none

g - Gravity acceleration dimension = LT^{-2}

h - Loss of head in pipe flow, dimension = L

I - Intensity of transmitted beam, dimensionless (counting number)

I_o - Intensity of incident beam, dimensionless (counting number)

k - Shape factor, a dimensionless parameter which depends on the geometry of pore space but not on size, dimensionless.

K - Permeability, dimension = L^2

L - Length, the distance between two points in a porous medium, dimension = L

N - An assumed number of capillary tubes in the soil, dimensionless.

N_R - Reynolds number, dimensionless parameter.

P* - Piezometric pressure, the quantity $p + \gamma h$, dimension = $F\ L^{-2}$

R - Hydraulic radius - for tubes of uniform cross section, the cross-sectional area divided by the wetted perimeter. For tubes of non-uniform cross-section, the average hydraulic radius is assumed to be the volume of the tube divided by its internal surface area, dimension = L

s - A subscript meaning "soil".

S_a - Saturation - the ratio of the volume of wetting fluid to the volume of interconnected pore space in a bulk element of the medium, dimensionless.

S - Specific surface - the surface area of the solid pore boundaries per bulk volume of medium, dimension = L^{-1}

S_r - The residual saturation - a saturation at which the theory assumes the effective permeability of the wetting phase is zero and the effective permeability of the non-wetting phase is a maximum.

T - Tortuosity - the ratio $(Le/L)^2$, in which Le is effective length traversed by differential fluid elements in moving between two points in a porous medium, dimensionless.

U - Mean velocity of pipe flow, dimension = LT^{-1}

V - Macroscopic velocity, dimension = LT^{-1}

$\underline{V}$ - The total velocity vector - the vector sum of u, v and w the components of fluid velocity in the x, y and z coordinate direction respectively, dimension = LT^{-1}

w - A subscript meaning "water".

X - Thickness of absorbing material, dimension = L

Z - Atomic number of absorber.

ϕ - Volume porosity - the ratio of the voids volume of bulk volume, dimensionless.

ϕ_L - Linear porosity - porosity considered one direction only, dimensionless.

μ - Dynamic viscosity, dimension = FTL^{-2}

ρ - Mass density, dimension = $\frac{FT^2}{L^4}$

ν - Kinematic viscosity μ/ρ, dimension = $\frac{L^2}{T}$

μ_ℓ - Linear absorption coefficient, dimension = L^{-1}

$\mu_m(\alpha)$ - Mass absorption coefficient - μ_ℓ/ρ, dimension = FL^{-2}

λ - Wavelength, dimension = L

σ - Deposit ratio, $(\phi - \phi_1)$, volume of deposit per unit volume of porous media, dimensionless.

∇ - Denotes the gradient operator.

Δ - Denotes a difference.

SUMMARY

The Hagen-Poiseuille law for loss of head with laminar flow and the Kozeny-Carman equation for permeability are outlined and two equations were derived from these theories for measuring the deposit ratio for sedimentation during flow in saturated porous media. A method of using gamma ray attenuation to measure bulk density of saturated soil columns was developed and an equation for measuring the deposit ratio of sediment in soil was derived.

A series of experiments were conducted to analyze the relationship between the sediment size and the particle size of the media and the other characteristic of the sediment and the soil media. Sediment of 2 - 5μ size was found to be most effective in reducing the hydraulic conductivity of 50 - 150μ soil media in comparison with <2μ and 5 - 10μ sediments for these conditions; initial flow rate 9.50 ml/min. (volume flux 0.1775 cm/min.) and 500 ppm sediment concentration. The results of the calculation for the deposit ratio in experimental columns showed a satisfactory agreement between values calculated using an equation based on the hydraulic conductivity and values measured by gamma ray techniques. Other media size were not tested because bacteria growth on the soil-water interface in the soil column could not be controlled. Soil column sterilization with propylene oxide was attempted and toluene, phenol, xylene with emulsifier, and commercial instrument germicide were used to inhibit the microbial growth in the soil during the experiments. The number of bacteria per unit gram of the soil causing a reduction in hydraulic conductivity of 1 cm/day was determined.

CHAPTER I

INTRODUCTION

Since water was first transported from one place to another by means of canals, loss of water due to seepage through the canal bed has been a problem of considerable magnitude. This is particularly true in regions where much of the soil through which the canals are constructed consists primarily of sandy materials which are highly pervious to water. Many types of canal linings have been developed for the purpose of reducing seepage losses in canals to a realistic value. These include asphalt surface or buried linings, plastic and synthetic resin linings, Portland cement mortar or concrete linings, earth linings and chemical treatments. Experimental studies of earth canals sealed with bentonite and silt suspensions have been made in many installations both public and private. Most of these have been successful in reducing seepage. It is known that a clay or silt cake formed on the surface of the canal bed will reduce seepage considerably, however, the lining is susceptible to erosion, to cracking after an initial period of drying, or to damage by cattle and other animals. Further study and improvement have been encouraged. In some canals effective reduction of seepage can be obtained by applying sediments to the canal subgrade where they precipitate in the voids and render the subgrade less permeable to water. It is important to select the sediments small enough to penetrate into the soil in depth.

At least three theoretical equations have been derived from different theories for calculating the amount of the sediment remaining at different layers in the soil column at any time during the sediment run.

In this study, experiments designed to simulate a range of field conditions using a local canal sand and a milled fire clay for the soil column and sediments respectively were conducted to evaluate:

1. The relationship between the size of the sediment and the bed material on the reduction of seepage loss due to the penetration of the sediment.
2. The amount of the sediment retained in the soil column at different depths at any time during the sediment run and the reduction of hydraulic conductivity and permeability.
3. The validity of theoretically derived equations, particularly the deposit ratio volume of sediment deposit per unit volume of soil medium by comparing experimental results with theoretical predictions.

CHAPTER II

REVIEW OF LITERATURE

The materials in this chapter are included under three headings: (1) Flow in Capillary Tubes, (2) Kozeny-Carman Equation for Permeability, and (3) Radiation. A brief summary is made of the known information and the theory essential to an understanding of the basic concepts involved in the study.

A. Flow in a Capillary Tube

The loss of head due to pipe friction follows certain general laws based upon observation and experiment. These laws briefly stated are:

1. Frictional loss in turbulent flow generally increases with the roughness of the pipe. But when the flow is laminar the frictional loss is independent of the roughness.
2. Frictional loss is directly proportional to the area of the wetted surface.
3. Frictional loss varies inversely as some power of the pipe diameter.
4. Frictional loss varies as some power of the velocity.
5. Frictional loss varies as some power of the ratio of viscosity to density of the fluid.

Hagan-Poiseuille considered that a circular cylinder of fluid moving in a pipe with steady laminar motion is in equilibirum between the pressure difference at both sides and the shear resistance exerted by the surrounding fluid on the curved surface of the cylinder, and derived a mathematical statement of what is known as the Hagan-Poiseuille (12) law for loss of head with laminar flow which is:

$$h = \frac{32L\nu U}{gD^2}$$

This equation can be rearranged by multiplying numerator and denominator by 2U and replacing DU/ν, the Reynolds number, by N_R thus:

$$h = \frac{64}{N_R} \cdot \frac{L}{D} \cdot \frac{U^2}{2g} \qquad (1)$$

from which it is evident that for laminar flow

$$f = \frac{64}{N_R}$$

The loss of head with laminar flow is seen to be independent of the degree of roughness of the conduit surface.

B. Kozeny-Carman Equation for Permeability

For the case of fully saturated porous media containing pores which are uniform in size and not too eccentric in shape, a shape factor of 2.5 and a tortuosity of 2.0 is assumed. The average value of the hydraulic radius R is given by the ratio of the porosity ϕ to the specific surface S which is defined as the surface area of the solid pore boundaries per bulk volume of medium. The permeability equation is approximated by

$$K = \frac{\phi^3}{5S^2} \qquad (2)$$

which is known as the Kozeny-Carman equation (5).

Camp (3) presents the results of studies by Stein on the nature of the clogging process. From the observation of the experiments, Stein found that removal of the floc with a bed was accomplished primarily by "contact" of the iron floc particles with the surface of the grains, or with floc already deposited, and adherence thereto. Contact was brought about principally by the convergence of streamlines at contractions in the pore channels and in the vicinity of curved surfaces of the grains. Sedimentation and coagulation within the pores were of minor significance. Assuming clogging was by means of a sheath on each grain, an equation was derived for computing the deposit ratio which is defined as the volume of deposit per unit volume of soil media at any time during the sediment run.

$$\frac{id^2}{K} = \frac{(1 - \Phi + \sigma)^2}{(\Phi - \sigma)^3} \cdot \frac{1}{\sqrt{\frac{\sigma}{3(1 - \Phi)} + \frac{1}{4}} + \frac{\sigma}{3(1 - \Phi)} + \frac{1}{2}}$$

in which $K = \frac{jk^2\nu}{g} V$

Φ and d denote the porosity and grain size at the start of the run, σ and i represent the deposit ratio and the hydraulic gradient at any time during the run. The dimensionless constant j is the reciprocal of the constant in Kozeny's equation. k is the shape factor, V represents the approach velocity or rate of infiltration. ν represents the kinematic viscosity of the fluid or the absolute viscosity, and g symbolizes the gravity constant.

Stein also assumed that K did not change during a run, and that iron content of the deposited floc remained the same throughout a run. The above equation was expressed as the ratio of i to i_o, the initial hydraulic gradient, thus eliminating the effect of d and K, as follows:

$$\frac{i}{i_o} = \frac{(1 - \Phi + \sigma)^2 \, \Phi^3}{(1 - \Phi)^2 (\Phi - \sigma)^3} \cdot \frac{1}{\sqrt{\frac{\sigma}{3(1 - \Phi)} + \frac{1}{4}} + \frac{\sigma}{3(1 - \Phi)} + \frac{1}{2}}$$

C. Radiation

An ionization chamber can be used to study the penetrating ability of X-rays (13). The X-rays are collimated by slits and passed through an absorbing material, then their intensity can be measured by the ionization chamber. If we vary the thickness of the absorbing material and measure the intensity at the different thicknesses, the result of the plot of transmitted intensity against thickness looks like an exponential decay curve. The equation expressing this curve is:

$$I = I_o e^{-\mu_\ell x} \qquad (3)$$

where I is the intensity of the transmitted beam, I_o is the intensity of the incident beam, x is the thickness of absorbing material and μ_ℓ is usually called the linear absorption coefficient.

The value of μ_ℓ depends on the X-ray wave length (λ) and the absorbing material. The basic variation of μ_ℓ with λ is that μ_ℓ is very nearly proportional to λ^3, but this basic variation is profoundly influenced by the nature of the absorbing material.

The expression $\mu_\ell x$ can be written

$$\mu_\ell x = \frac{\mu_\ell}{\rho} x\rho$$

where ρ is the mass density of the absorbing material, the quantity μ_ℓ/ρ is called the mass absorption coefficient, μ_m or α. In these terms, the exponent of equation (3) becomes $-\mu_m x\rho$

$$I = I_o e^{-\mu_m x\rho} \tag{4}$$

Although variation of the mass absorption coefficient is far less than the linear coefficient, it is still far from constant. Material with large atomic numbers absorb X-rays more readily than the lighter element. In general, μ_m varies approximately as the atomic number cubed. Combining this empirical fact with the dependence on λ, we can say approximately that

$$\mu_m = c\lambda^3 . Z^3$$

where c is nearly constant and Z is the atomic number of the absorber.

Gamma rays (λ) emitted from radioactive substances are photons whose energy range overlaps that of X-rays and extends to several million electron volts (mev). When gamma rays pass through matter, they are absorbed exponentially. Both the linear and mass absorption equation for X-radiation are valid for gamma rays although the absorption coefficients for gamma rays are ususally much less than they are for X-rays.

Gardner and Calissendorff (8) studying gamma-ray neutron attenuation in the measurement of soil bulk density and water content determined that the attenuation of gamma radiation in matter involves both the chemical composition and concentration of matter and varies with gamma ray energy. For soil of unchanging chemical composition it is possible to infer overall density from attenuation measurement where the mass attenuation coefficient is known for the gamma energy used. If the soil is dry then the density inferred is the bulk density of the soil. If, on the other hand, the bulk density remains constant and attenuation is known for dry soil at this bulk density, then water content may be inferred from attenuation measurement. If the chemical properties, apart from changes in water content and soil bulk density, remain constant, and when the relationship between the attenuation coefficient for soil and water differs appreciably at two gamma energies, it is possible to infer both bulk density and water content by concurrent measurement of two different gamma energies.

CHAPTER III

Theory of Removal of Suspended Material

Several possible removal mechanisms have been studied by various investigators in considering the flow of clays, silts, or bacteria, in suspension through a porous matrix. Iwasaki (10) explained that the time rate of change of the deposit ratio at a particular depth and time in a filter is proportional to the rate of infiltration and the corresponding rate of decrease in volumetric concentration of floc in the water. In other words, if the volume of the floc particles does not change significantly as the particles pass from above the filter into the bed and are deposited on the grains to remain throughout the run, the volume removed from the water is equal to the volume deposited in the bed. Behnke (2) suggested that clogging is a surface sealing process and clogging is caused by two processes, gravitational settling and interstitial straining. If turbid suspensions have a range of grain size, gravitational grading initiates clogging. As the deposited layer becomes progressively more graded, the uppermost pores become small enough to strain out most of the remaining particles. At this point straining is the predominate clogging process. Corey and Filmer (7) studied albumin molecules used to simulate viruses being transported by water during steady downward flow through soils. They concluded that albumin retention by soil was probably due to an absorption mechanism.

Regardless of the mechanism postulated for removal, we know that porosity is the most important parameter affecting head loss or hydraulic conductivity or permeability during a sediment run. The deposit ratio is related to the change of porosity and should be some function of initial porosity, head loss, flow rate and hydraulic conductivity or permeability. The following theory is presented for the measurement of the deposit ratio, volume of deposit per unit volume of porous media, at any depth during the sediment run.

A. Hydraulic Theory

Flow through porous medium is a complex phenomena and affected by various properties of the fluid and the porous matrix. Many attempts have been made to derive the experimental law of flow, the Darcy formula, from basic hydrodynamic or hydraulic considerations using various physical or mathematical models. In this study, a model has been developed to investigate the amount of sediment retained in the soil during a sediment run.

In the model, it is assumed that the flow through porous media between two planes consists of many capillary tubes, straight or tortuous, round or irregular in shape. A fictitious capillary tube is considered to have an average diameter, D, and an average length, L, and to represent all of the tubes in the porous medium. The fluid flowing through the porous medium between two planes is then considered to be the sum of the flow through a large number (N) of the fictitious tubes.

Assumptions:

1. The porous medium is homogenous and isotropic.
2. Darcy's law is valid for the flow.
3. The porous medium is fully saturated.

4. The temperature variation during the test is negligible.

5. The soil structure in the porous medium is stable and no other factor affects the hydraulic conductivity other than the sediment remaining in the porous medium.

Applying equation (1) to a fictitious tube in porous medium, the head loss between the two planes is:

$$\Delta h = \frac{64}{N_R} \cdot \frac{L}{D} \cdot \frac{U^2}{2g} \qquad (5)$$

where N_R is Reynolds number

U is average pore velocity.

Substituting V/Φ for U, equation (5) can be rewritten for any time period 1

$$\Delta h_1 = \frac{64}{N_{R_1}} \cdot \frac{L_1}{D_1} \cdot \frac{\left(\frac{V_1}{\Phi_1}\right)^2}{2g} \qquad (6)$$

The relation between volume porosity and linear and areal porosity is difficult to determine. Zaslavsky (14) states that if the linear and areal porosities of every line and plane in every direction are equal to volume porosity, the porous medium is said to be randomly arranged in terms of pore geometry. Therefore, if the soil column is packed so that the pores can be assumed randomly arranged, then the relation between D (the initial pore diameter) and D_1 (the effective pore diameter after sediment accumulation) can be expressed by

$$D_1 = \frac{\Phi_1}{\Phi} D$$

Substituting D_1 and $\Phi_1 = \Phi - \sigma$ into equation (6) and assuming that the change of length of the average flow path during the run is very small, i.e. $L = L_1$, the following proportional relation is obtained.

$$\frac{\Delta h}{\Delta h_1} = \frac{N_{R_1} \, V^2 (\Phi - \sigma)^3}{N_R \, V_1{}^2 \, \Phi^3}$$

Simplifying the above equation, the deposit ratio will be

$$\sigma = \Phi \left(1 - \sqrt[3]{\frac{\Delta h N_R V_1^{\,2}}{\Delta h_1 N_{R_1} V^2}}\right) \qquad (7)$$

The viscosity of a water-sediment mixture can be changed by variation in water temperature or in concentrations of fine sediment. The relationship between the viscosity of distilled water and water temperature is accurately known. The relationship between the viscosity of distilled water and sediment concentration is difficult to determine, however. According to Colby (6) in natural channel investigations, if the sediment concentration is high, above 10,000 ppm, the viscosity will be affected. Below 10,000 ppm the affect is negligible. In this study, the sediment concentration is very low (500 ppm) and the room temperature is nearly constant; therefore, both the affect of sediment concenation and of temperature variation on viscosity are disregarded. If viscosity is assumed constant during the run and

$$D_1 = \frac{\Phi_1}{\Phi} D$$

then

$$\frac{N_R}{N_{R_1}} = \frac{V}{V_1} \qquad (8)$$

Substituting equation (8) into equation (7), then

$$\sigma = \Phi\left(1 - \sqrt[3]{\frac{\Delta h V_1}{\Delta h_1 V}}\right) \qquad (9)$$

If the initial porosity of the porous medium, ϕ, the head loss, Δh, and macroscopic velocity V are known at initial time and at any time during the sediment run, the deposit ratio, σ, may be computed by means of equation (9).

Permeability - Porosity Theory in Measurement of Sediment

According to Kozeny and Carman, if the flow through porous medium is saturated flow and the porous medium is homogeneous and isotropic, the permeability is

$$K = \frac{\Phi^3}{5S^2}$$

where S is the surface area of the solid pore boundaries per bulk volume of medium. If it is assumed that the grains in the medium are spherical, then

$$S = \frac{6(1 - \Phi)}{d} \tag{10}$$

where d is the grain diameter. Substituting equation (10) into Kozeny-Carman's equation gives K for any time period 1, as,

$$K_1 = \frac{d_1{}^2 \ \Phi_1{}^3}{180 \ (1 - \Phi_1)^2} \tag{11}$$

and a ratio of the permeability at time 1 to the initial permeability, of

$$\frac{K}{K_1} = \frac{d^2 \ \Phi^{\ 3}(1 - \Phi_1)^2}{d_1{}^2\Phi_1{}^3 \ (1 - \Phi)^2} \tag{12}$$

where d and d_1 are the effective grain diameter before and during the sediment run. If it is assumed that the sediment is deposited or absorbed in a sheath around the grains, the d and d_1 relation can be computed.

Assume a unit spherical volume of diameter ℓ in which there is only one spherical grain of diameter d

$$\text{The unit volume} = Bl^3$$

$$\text{The volume of grain} = Bd^3$$

$$\text{The porosity} = 1 = \frac{d^3}{\ell^3}$$

Therefore the proportion of granular diameter will be

$$\frac{d^2}{{d_1}^2} = \left(\frac{1 - \Phi}{1 - \Phi_1}\right)^{2/3} \quad . \tag{13}$$

Substituting equation (13) into equation (12) and simplifying

$${\Phi_1}^3 = \Phi^3 \; \frac{K_1}{K} \; \left(\frac{1 - \Phi_1}{1 - \Phi}\right)^{4/3} \quad . \tag{14}$$

Further, substituting $\Phi_1 = \Phi - \sigma$ into equation (14) and simplifying the deposit ratio will be

$$\sigma = \Phi \left\{1 - \sqrt[3]{\frac{K_1}{K}} \; \left(\frac{1 - \Phi + \sigma}{1 - \Phi}\right)^{4/9} \right\} \quad . \tag{15}$$

If the initial permeability, K, the initial porosity, Φ, are known and the permeability at any time during the sediment run, K_1, is measured, the deposit ratio, σ, may be computed by means of equation (15) using a trial and error procedure. The deposit ratio, σ, is the volume of sediment deposit per unit volume of porous medium, and is numerically very small so that it is possible to consider the last term equal to 1 and equation (15) becomes

$$\sigma = \Phi \left(1 - \sqrt[3]{\frac{K_1}{K}}\right) \qquad (16)$$

The relationship expressed by equation (16) is shown graphically in Figure 1. Expressing the permeability in terms of velocity and head loss according to Darcy's law the ratio of K_1 to K is

$$\frac{K_1}{K} = \frac{\Delta h V_1}{\Delta h_1 V} \qquad (17)$$

substituting equation (17) into equation (16) gives

$$\sigma = \Phi \left(1 - \sqrt[3]{\frac{\Delta h V_1}{\Delta h_1 V}}\right) \qquad (18)$$

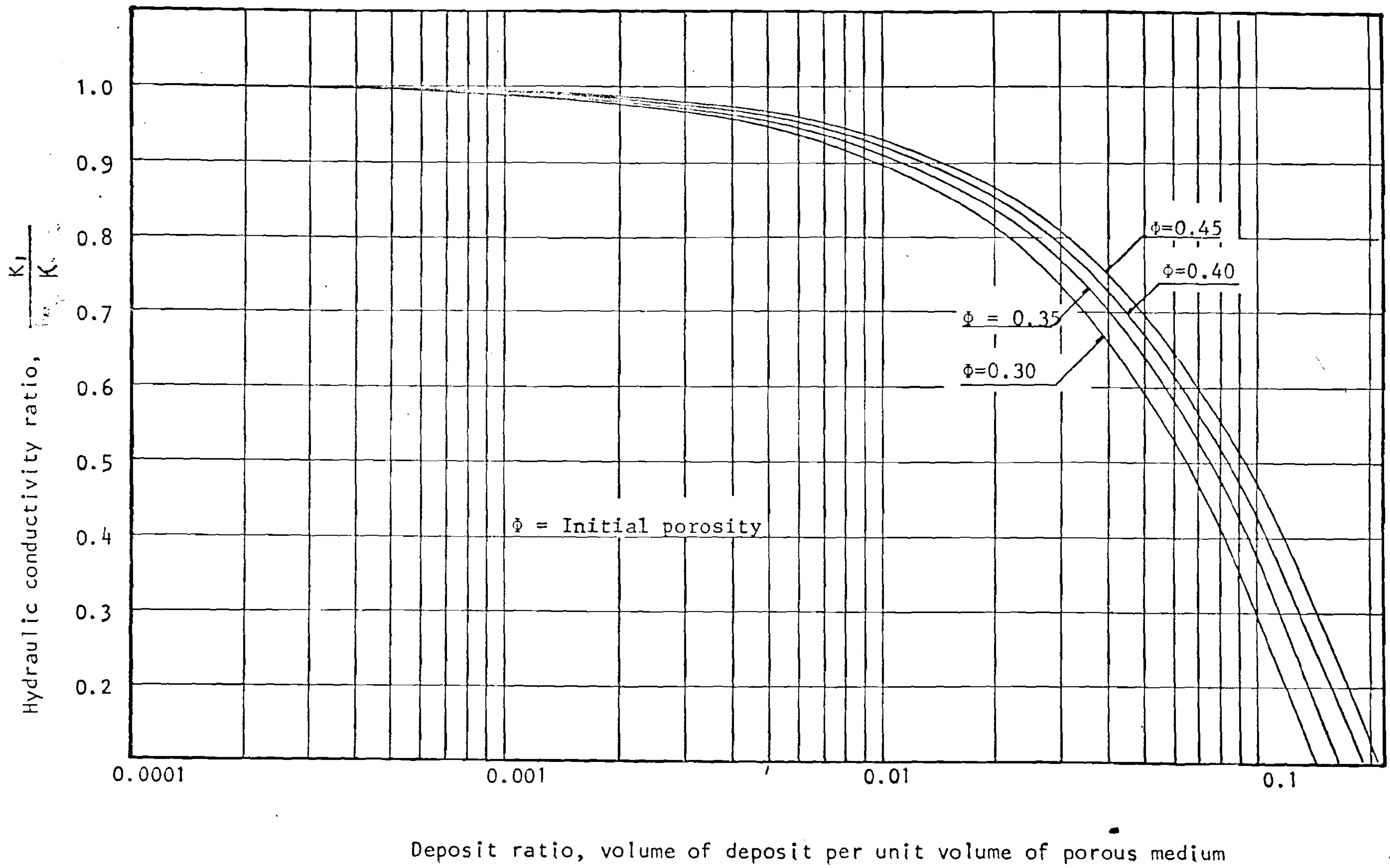


Figure 1. Graph of Equation (16) — Deposit ratio

Equations (18) and (9) are identical although derived using two different hypotheses. This relationship is greatly simplified from that of Stein as indicated by Camp (3) for computing the amount of sediment during the run, however, it may be as valid as any other.

C. Gamma Ray Theory in Measurement of Sediment

Gamma rays are quanta of electromagnetic wave energy similar to but of much higher energy than ordinary X-rays. When they pass through any substance, some amount of radiant energy will be absorbed or transformed into heat. The absorptive power of material varies with the character of the substance and the wave length of the incident energy.

If I_o is the original (incident) intensity of the gamma ray, I is the intensity of the gamma ray passing through a material of thickness, x, ρ is the density of the absorbing material, and α is the mass absorption coefficient, then the relation is, in general,

$$I = I_o e^{-\alpha x \rho} \quad \text{or} \quad \ln \frac{I_o}{I} = \alpha x \rho . \tag{19}$$

The term on the right may be expanded to include a combination of absorbers; for instance, soil, water and the walls of the container. Equation (19) then becomes

$$\ln \frac{I_o}{I} = \alpha_s x_s \rho_{bs} + \alpha_w x_w \rho_w + \alpha_c x_c \rho_c \tag{20}$$

where the subscripts, s, w, c, and bs denote soil, water, container material and bulk density of the soil column. The total thickness of water in the porous medium is x_w and is equal to linear porosity, Φ_L, multiplied by a soil thickness $(x_w = \Phi_L x_s)$. If the pores in the porous medium are randomly arranged, the linear porosity is equal to volume porosity, $(\Phi = \Phi_L)$. During sediment runs, the sediment will be retained in the soil column non-uniformly with the density and porosity being changed correspondingly. If the subscript "$_1$" is used to express the data during the run, equation (20) will be

$$\ln \frac{I_o}{I_1} = \alpha_s x_s \rho_{bs_1} + \alpha_w \Phi_1 x_s \rho_w + \alpha_c x_c \rho_c . \tag{21}$$

The relationship between the porosity and density is

$$\Phi_1 = 1 - \frac{\rho_{bs_1}}{\rho_s} \tag{22}$$

where ρ_s is soil particle density so that

$$\rho_{bs_1} = \frac{1}{x_s \left(\alpha_s - \alpha_s \frac{\rho_w}{\rho_s}\right)} \left(\ln \frac{I_o}{I_1} - \alpha_w x_s \rho_w - \alpha_c x_c \rho_c\right) . \tag{23}$$

The density during the sediment run, ρ_{bs_1}, can be calculated from equation (23) and Φ_1 calculated from equation (22). Then the deposit ratio is equal to $\Phi - \Phi_1$.

By scanning a soil column before a sedimentation run and after or during the run, the deposit ratio can be calculated as follows. Substituting $(1 - \Phi)\rho_s$ for ρ_{bs} in equation (21) the gamma ray intensity through the soil column prior to sedimentation is

$$I = I_o e^{-\alpha_s x_s (1 - \Phi)\rho_s - \alpha_w \Phi x_s \rho_w \quad \alpha_c x_c \rho_c},$$

and after sedimentation is

$$I_1 = I_o e^{-\alpha_s x_s (1 - \Phi + \sigma)\rho_s - \alpha_w (\Phi - \sigma) x_s \rho_w - \alpha_c x_c \rho_c}.$$

The ratio I/I_1 is given by

$$\frac{I}{I_1} = e^{(\alpha_s x_s \sigma \rho_s - \alpha_w \sigma x_s \rho_w)}$$

and

$$\sigma = \frac{1}{(\alpha_s \rho_s - \alpha_w \rho_w) x_s} \ln \frac{I}{I_1} . \qquad (24)$$

Equation (24) is more convenient to use than equation (23) since several constants have been eliminated. Nevertheless, before using these equations, the mass absorption coefficient for all materials used and the original intensity of gamma ray sources must be known. The absorption coefficient depends on the radioactive energy source and varies widely with different materials. This constant is completely independent of the environment, chemical combination, pressure, or temperature. Original intensity for a given material depends on the radiant source only. By scanning several pieces of the same material whose density and dimensions are known and plotting ln I, counting number, against x, thickness of material, straight lines with slopes, $-\alpha$, are produced. All lines for different materials intersect at one point on the ordinate which is zero thickness. This value of I is the original intensity, I_o, of the radiant source at a selected counting period. In this study, pieces of plexiglas, aluminum and steel were selected as materials to evaluate I_o (see Appendix A).

D. Calculation of Sediment Content by Gamma Ray Scanning

Before applying this technique for the measurement of the sediment accumulation during the run, studies were carried out, using small short plastic columns containing dry or saturated soil with or without sediment to determine whether the volume porosity could be substituted for linear porosity and whether the equations derived for calculation of the amount of the sediment in the soil column were valid. This procedure and results are outlined in Appendix B.

CHAPTER IV

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Equipment

The apparatus used consisted of nine permeameters equipped with Marriotte siphon constant-head water sources, magnetic stirring devices for the water and sediment sources, manometer board, gamma ray facility, and several items of auxiliary equipment. A general view is shown in Figure 2.

Permeameters

The permeameters were designed to measure hydraulic conductivity under both saturated and partially saturated flow. Water and sediments were introduced into the columns from the top. Tensiometers were used for measuring the pressure head and a porous plate was placed at the bottom to prevent air entry under tension. In this study, unsaturated hydraulic conductivity was not measured.

The columns were constructed almost entirely of plexiglas plastic material. Each column consisted of three sections, a top cap, a bottom cap, and a cylinder. The sections were connected with rubber gaskets and bolts. The cylinders were 8-1/2 in. long made of 3-1/4 in. internal diameter clear plastic with 1/4 in. walls. Three 2.5 in. long, 3/16 in. in diameter tensiometers were installed at approximately 2-5/8 in. intervals (Figure 3).

Constant-Head Water Supply

Twenty-liter glass carboys equipped with small glass air and outlet tubes were set on magnetic stirring devices and used as constant-head

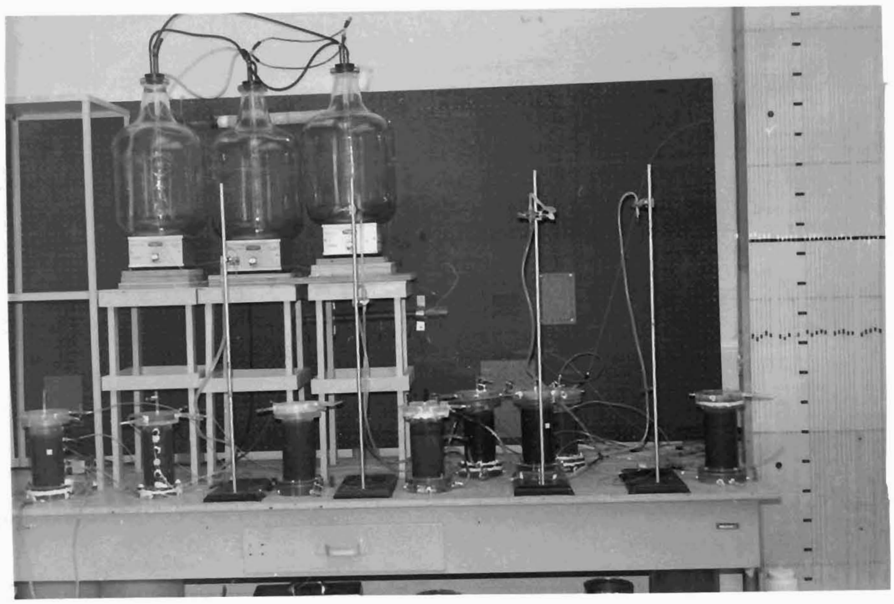
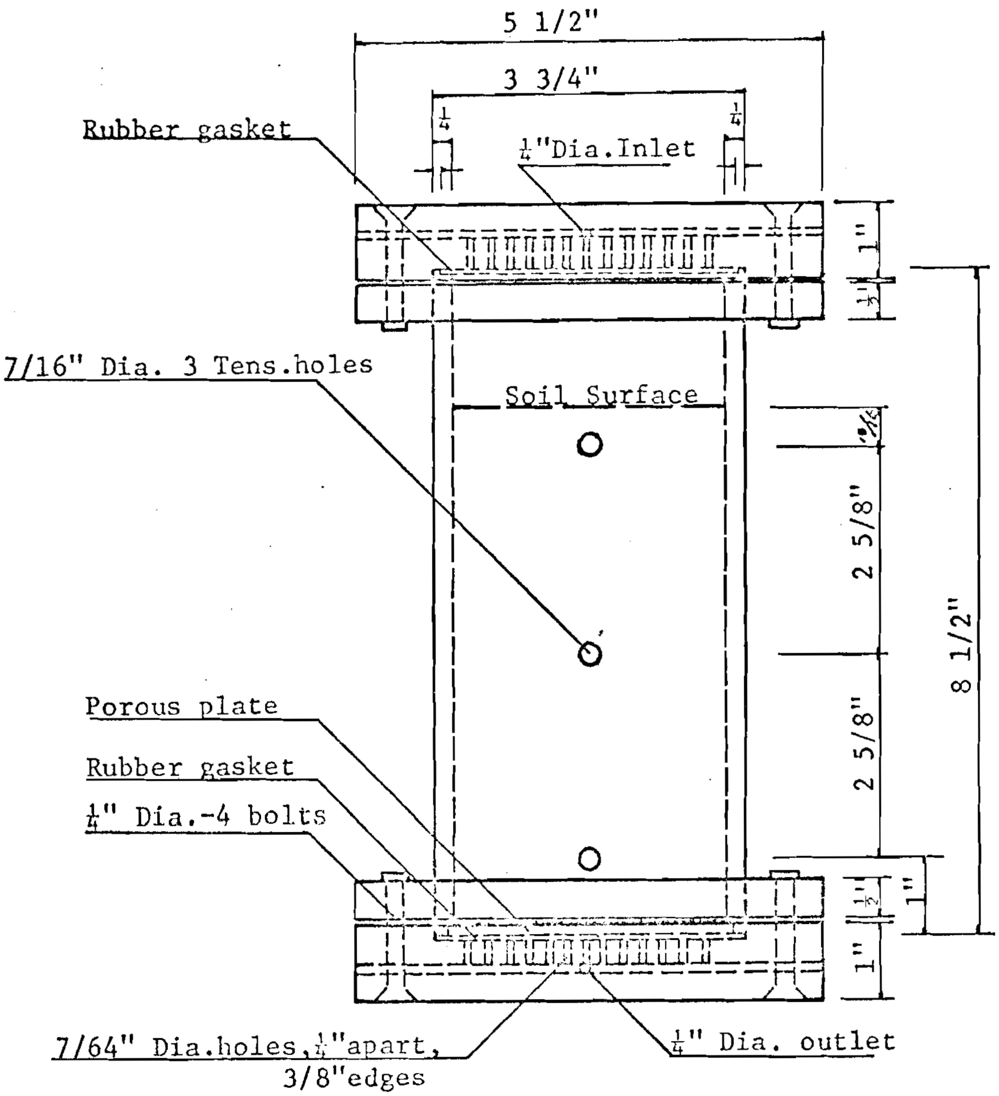


Figure 2 General view of apparatus



Scale = 1/5

Figure 3 Soil column construction

water supplies. The air tube was connected to an air filter which consisted of a 1-3/4 in. diameter plastic tube packed with sterilized cotton and Ascarite (sodium hydroxide coated with asbestos) as a CO_2 scrubber.

Gamma Ray Facility

The gamma ray facility included a gamma ray source (Isotope, Am-241, 100 millicuries), a detector (Model DS8-21, Nuclear-Chicago), a counter (main part: Model 33-10B, anti-walk, single channel analyzer, Radiation Instrument Development Laboratory) and an adjustable frame to focus the gamma ray source on any desired location. All equipment was housed in a constant temperature room (Figure 4).

Materials

Sand

Three size fractions of sand were prepared as porous media. A 50μ-150μ fraction was obtained from a blow sand area north of the Snake River near Kimberly, Idaho and 150μ-350μ and 350μ- 500μ fractions obtained from sand from the "C" Canal of the Minidoka Irrigation District near Rupert, Idaho. The size fractions were obtained by dry and wet sieving and the material was then oven dried at 110°C for three days. Grain-size distribution curves from the mechanical analysis are shown in Figure 5. The particle density of each fraction was determined by pycnometer methods.

Sediment

A milled fire clay obtained from the Denver Fire Clay Company was used as the sediment for this study. The material was fractionated into three size fractions, <2μ, 2μ-5μ, and 5μ-10μ, with an elutriator (1).

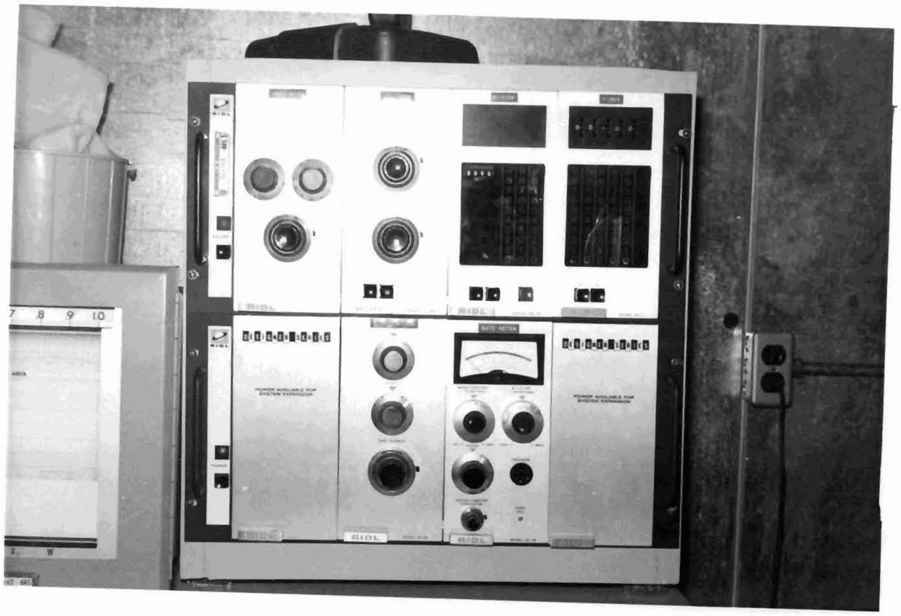


Figure 4   General view of gamma ray scanner.

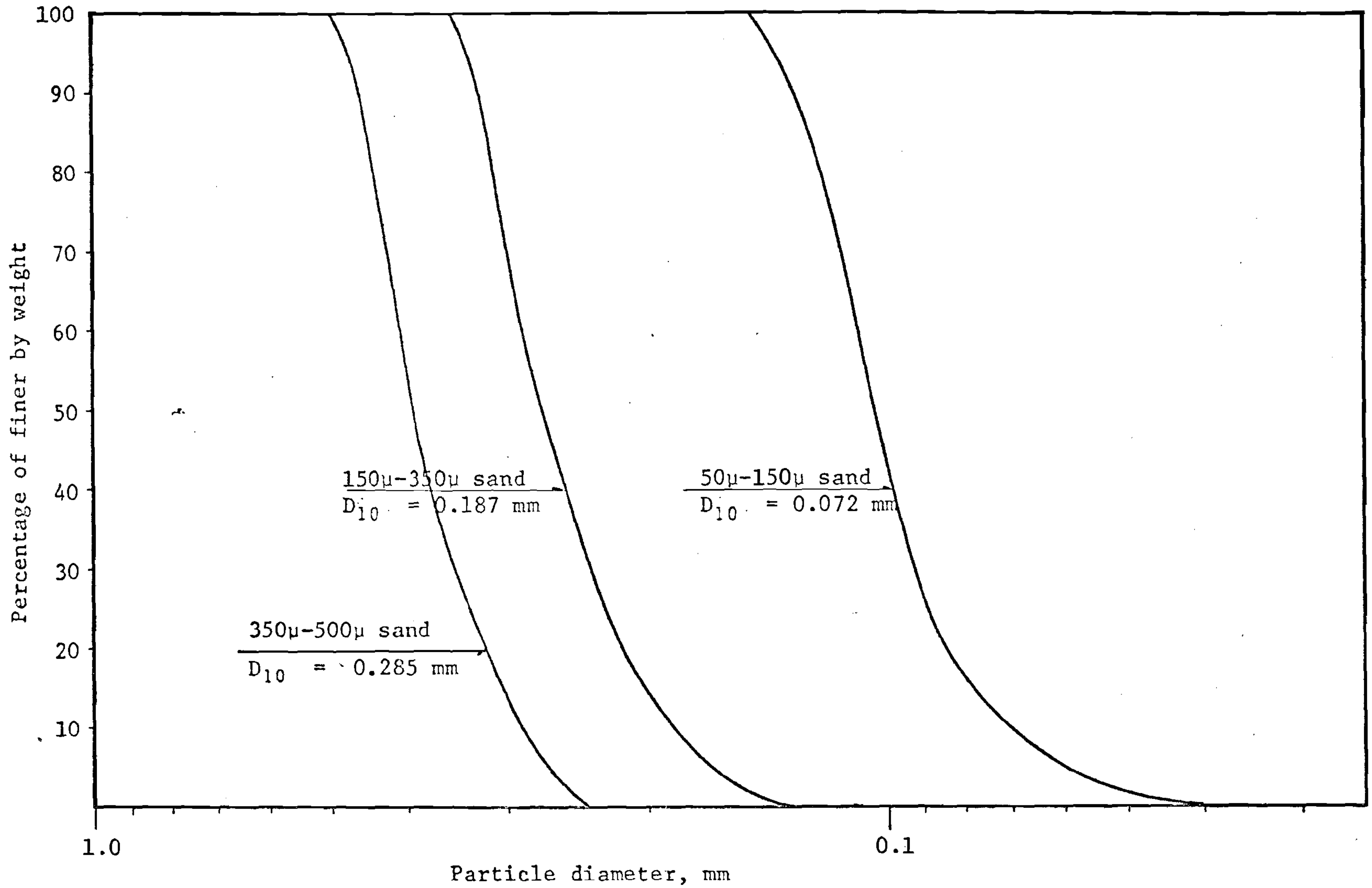


Figure 5 Grain-size distribution curves for soil

Procedure

Soil Column Packing

The plastic columns were packed with sand using a column packer which utilized a rotating foot and vibrating base. The column packer is similar to the equipment described by Jackson, Reginato and Reeves (11). The gamma ray intensity was measured at several layers throughout the column to check for uniform density. Sometimes a second packing was necessary. The tensiometers were installed after packing.

Soil Column Saturated using Carbon Dioxide (4)

Carbon dioxide (CO_2) was introduced into the soil columns from the bottom. After all the air in the columns was displaced by the carbon dioxide, the outlet tubes were clamped temporarily. Distilled water was allowed to enter the columns slowly from the bottom to minimize the possibility of trapped air pockets and channelings in the soil. After the carbon dioxide was completely dissolved, water was allowed to percolate downward through the saturated soil column thereby leaching out the dissolved carbon dioxide.

Measurement of Gamma Ray Intensity

The soil column was set in a frame and the gamma ray source was adjusted vertically and laterally to the desired location. The scanner settings, window, threshold, discriminator, range, and counting period were selected and fixed. Gamma ray intensity was measured at selected vertical intervals throughout the columns and the average count or intensity for the total column was calculated. In order to decrease Compton scattering and eliminate possible operational error, it was necessary to restrict the measurement to the highest energy peak of the gamma ray source and to select longer counting periods if possible.

Determination of Initial Hydraulic Conductivity

The experiments were conducted in an approximately constant temperature room, 72°F ±2. The temperature and the humidity were continuously recorded by a hygrothermograph. To determine hydraulic conductivity, the effluent was collected in a graduated cylinder and manometer readings and elapsed time were recorded for each determination. The electrical conductivity of the influent and effluent were measured. The discharge was increased by adjusting the level of the outlet until the differential between any two adjacent tensiometers was sufficiently large to allow an accurate determination of hydraulic conductivity.

It was observed that the sand surface started to seal periodically when the columns were run with distilled water. This also occurred with solutions of toluene, phenol, and other chemicals. A disproportionately high loss of head across the surface was indicated clearly by the manometers and the soil surface had a gummy appearance. Soil samples were taken from the top soil surface of columns E and F and a series of microbiological tests were performed (see the last two items in this chapter).

The hydraulic conductivity measurements were continued until the hydraulic conductivity remained constant and the electrical conductivity of the influent and effluent were the same. The last approximately constant hydraulic conductivity was used as the initial hydraulic conductivity, K.

Sediment Run

After the initial hydraulic conductivity had been established, the glass carboys were filled with a solution of 500 ppm of sediment in distilled water with growth inhibitor added. The magnetic stirring device maintained the sediment in suspension. Hydraulic conductivity measurements were made at frequent intervals and visible phenomena were noted. The initial effluent in runs A and B appeared turbid so the sediments in the effluent were collected and separated in a centrifuge so that total sediment remaining in the column could be determined. The experiments were continued until the flow rates were lower than 1 ml/min.

Determination of Final Hydraulic Conductivity

The procedure was similar to that for the initial determination using distilled water. The purpose of this procedure was to observe the effect on hydraulic conductivity of sediment migration in the soil at the low flow rate. The experiments were stopped after a few days observation.

Measurement of Final Gamma Ray Intensity

After the sediment runs, gamma ray attenuation was measured in the soil columns at the same locations as the initial measurements.

Calculation of the Amount of Sediment by Gamma Ray Analysis

The original intensity of the gamma ray source, I_o, and mass absorption coefficients, α, for all the materials used were calculated by using equation (19) or Figure 6 and the results were as follows:

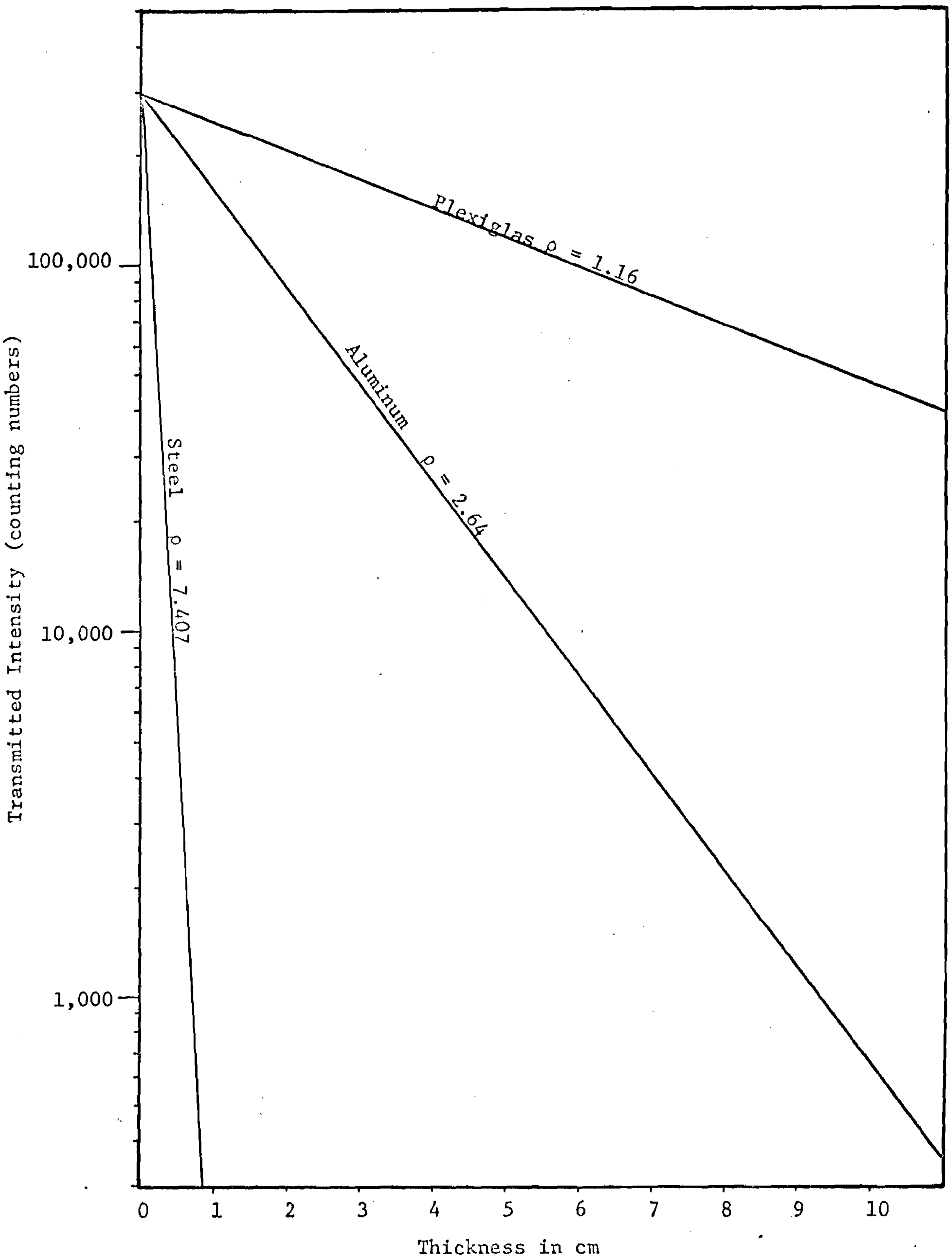


Figure 6 Graph of gamma ray transmission through materials

I_o = 298,000 counts (counting period 10 seconds)

α for plexiglas = 0.15993 cm^2/gm

α for steel = 1.09612 cm^2/gm

α for aluminum = 0.22007 cm^2/gm

α for distilled water = 0.16821 cm^2/gm

α for soil (sand) = 0.23743 cm^2/gm

α for distilled water with 235 ppm toluene = 0.18476 cm^2/gm

The deposit ratio, σ, is given by equation (24) as

$$\sigma = \frac{1}{(\alpha_s \rho_s - \alpha_w \rho_w) x_s} \ln \frac{I}{I_1}$$

in which the corresponding parameters for the experimental soil columns were:

α_s = 0.23743 cm^2/gm for sand

ρ_s = 2.7294 gm/cm^3 for 50μ-150μ sand

α_w = 0.18476 cm^2/gm for distilled water with 235 ppm toluene

ρ_w = 0.99763 gm/cm^3 for distilled water at temperature 22.7°C

x_s = 8.255 cm

Substituting these constants into the above equation and simplifying,

$$\sigma = \frac{1}{3.828} \ln \frac{I}{I_1}$$

In the experimental columns the intensity, I, prior to the sediment run was measured as well as the intensity, I_1, after the sediment run. Substituting these values in the above equation, the amount of the sediment remaining in the soil at any depth was calculated.

Pore-Size Distribution of Soils

Three representative soil columns 3-1/4 cm long and 8-1/4 cm in diameter were packed with media of the same size and density as the three experimental columns. Capillary pressure head as a function of saturation was determined and is shown in Figure 7. Details of the procedure for determining the capillary pressure-saturation characteristics are given in Appendix C. Figure 8 is effective saturation as a function of capillary pressure head.

Microbiological Activity at the Soil Surface

For the purpose of minimizing the microbiological activity in the soil during the sediment run, several growth inhibitors were used in the distilled water. Growth still occurred on the soil surface as indicated by high head loss across the soil-water interface. Samples were taken from the soil surface of column E and column F for microbiological tests. Tests were made for bacteria and algae. Soil samples of 0.2 gm from column E and 0.15 gm from column F were added to water blanks and three dilutions, 1/10,000, 1/100,000, and 1/1,000,000 were obtained. Three nutrient agar plates were made from each dilution. The media were incubated at a temperature of 34^{o}C for one week. Bacteria numbers and other data are shown in Table 1.

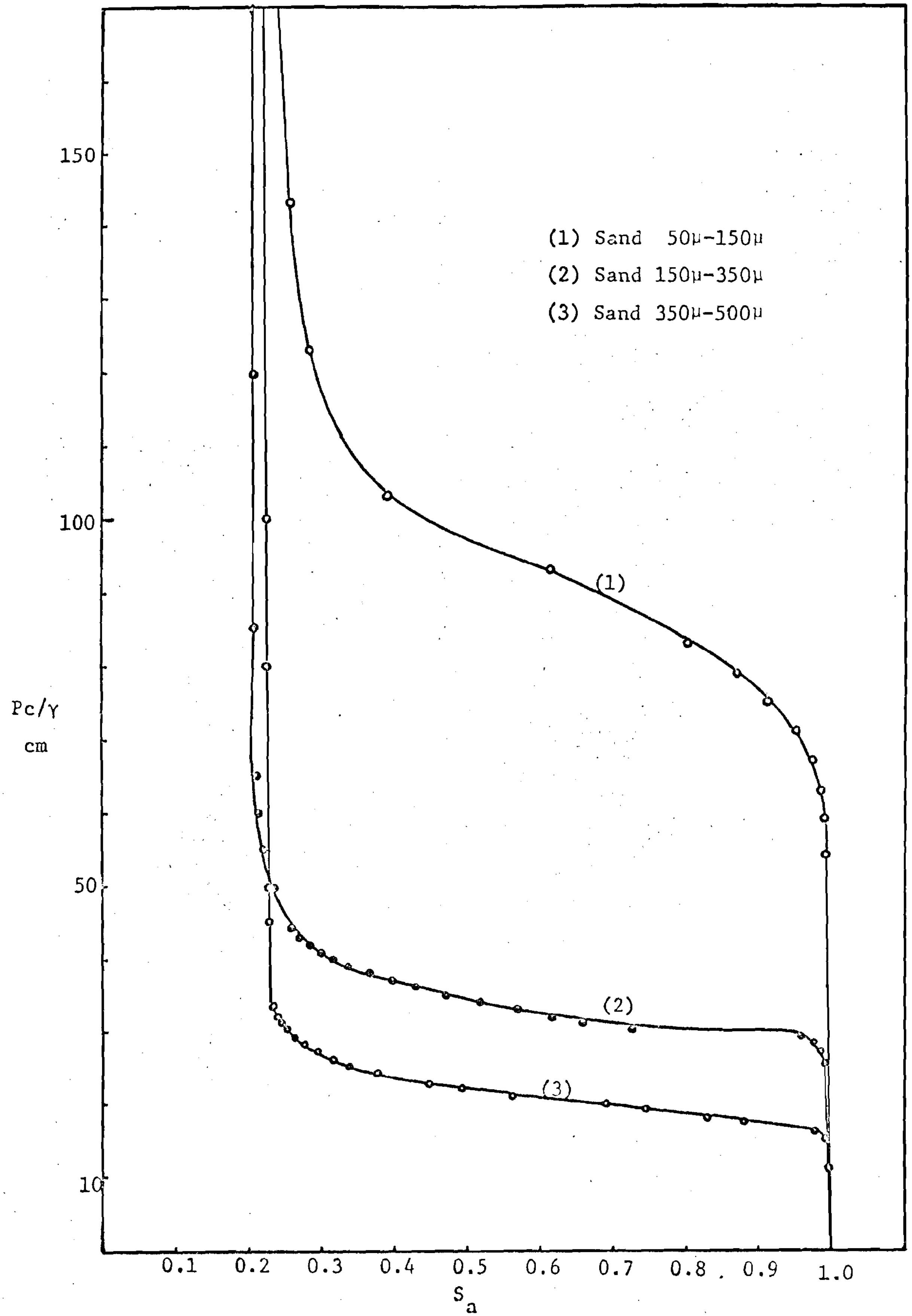


Figure 7 Capillary pressure head as a function of saturation for the sands used as porous media.

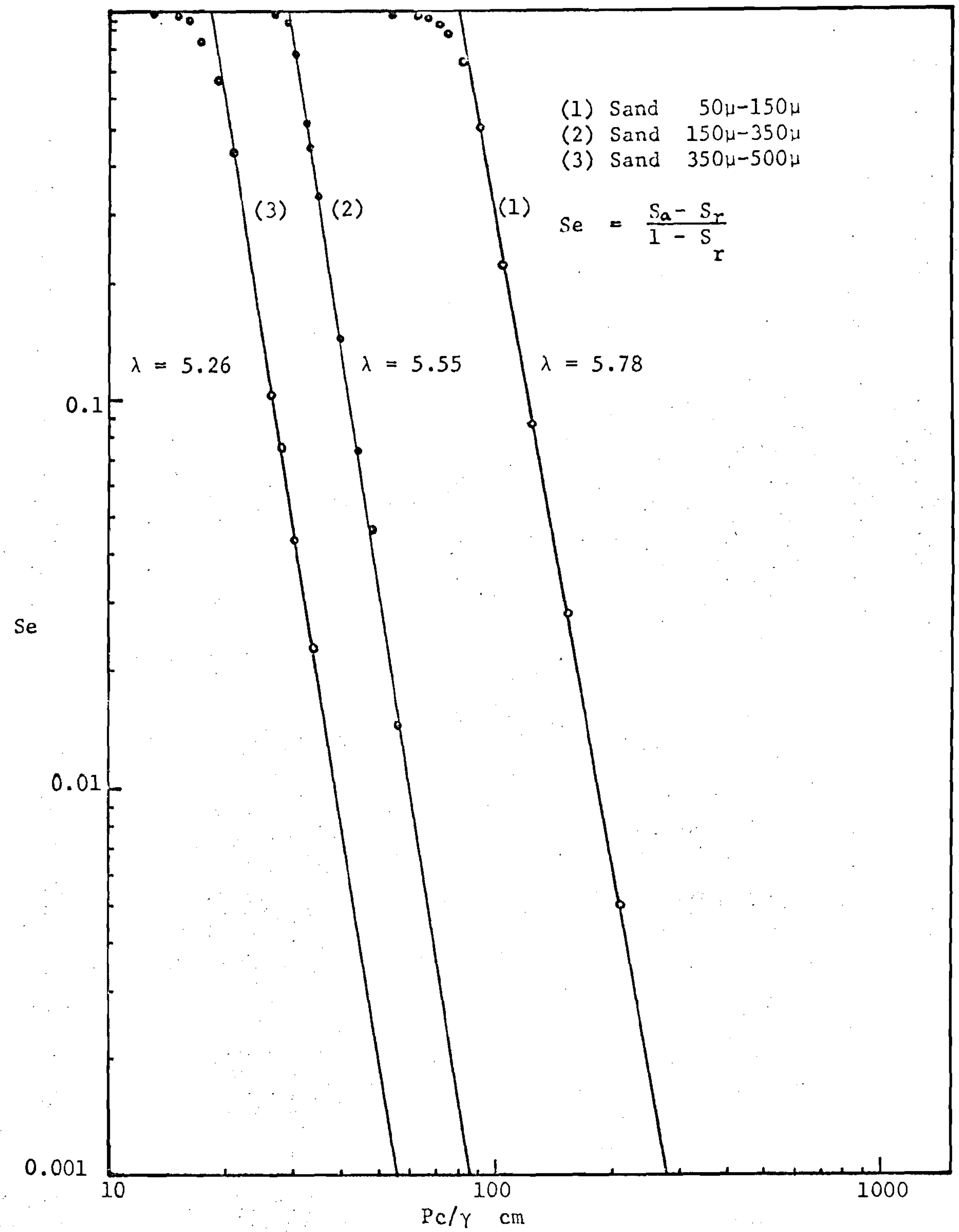


Figure 8 Effective saturation as a function of capillary pressure head for the sands used as porous media.

TABLE 1

BACTERIAL COUNTS AND HYDRAULIC CONDUCTIVITY

Column	Bacteria Number per gr of soil	Hydraulic Conductivity (cm/day)			Period of run (days)	Solution	Condition
		Initial	Final	Reduction			
E	39,330,000	2326	97	2229	8	4 days:0.1% phenol 0.086% $CaSO_4$ 4 days:0.15% phenol	Without light
F	877,000	518	16	502	14	4 days:0.086% $CaSO_4$ 10 days:0.1% phenol 0.086% $CaSO_4$	With light

The number of bacteria per unit gram of soil necessary to cause the reduction in hydraulic conductivity of 1 cm/day is:

Column E

$$N = \frac{39,330,000}{2,229} = 1,760$$

Column F

$$N = \frac{877,000}{502} = 1,750$$

Preliminary measurements indicate that all of the growth is bacterial. In these two columns the number of bacteria per unit gram of soil necessary to cause the reduction in hydraulic conductivity of 1 cm/day are nearly equal.

In the study of flow-associated reduction in the hydraulic conductivity of quartz sand by Gupta and Swartzendruber (9), major reductions in hydraulic conductivity did not occur for numbers of bacteria below 400,000 per gram of sand. Above this number, drastic reduction did occur and, within a range of 400,000 to 700,000 bacteria per unit gram of soil, the ratio of hydraulic conductivity (K final/K initial) dropped sharply from near unity to nearly zero. Usually this ratio was formed by using K, (first layer near inlet) and K_{23456} (the rest of the column); Ka (total column) was never used. Following their results using an initial K_1 value of 1.2 cm/min. the number of bacteria causing a reduction in hydraulic conductivity of 1 cm/day is calculated as:

$$N = \frac{700,000 - 400,000}{1.2 \times 1,440} = 1,736$$

The results show that 0.1% phenol solution is not effective for inhibiting microbial growth during the run for the conditions of room temperature 72°F and distilled water. High loss across the soil-water interface is caused by microbial growth and about 1,755 bacteria per unit gram of soil cause a reduction in hydraulic conductivity of 1 cm/day.

Media especially prepared for algae showed no growth in tubes which had been incubated for one month.

Study of Sterilization of Soil Columns

Several methods for sterilizing soil columns and inhibiting microbial growth in the soil were tested in the study, such as propylene oxide under vacuum and pressure treatment, 0.0235% toluene solution, 0.1% phenol solution, 0.2% xylene with emulsifier and 0.2% commercial instrument germicide. The propylene oxide treatment was used to sterilize the soil column before the run. This procedure of sterilization is outlined in Appendix D. The results of experiments with other chemicals to inhibit microbial growth are outlined in the next section.

RESULTS OF EXPERIMENTS

Size fractions of canal sand and milled fire clay were used as the porous media and the sediment in the experiments. Three size ranges of sand and three size ranges of sediment were used for a total of nine experiments as listed in Table 2.

TABLE 2. Test Arrangement

Series No.	Sand	Sediment <2μ	Sediment 3μ-5μ	Sediment 5μ-10μ	Other materials used in sterilization
I	50μ-150μ	A	B	C	Toluene
II	150μ-350μ	D	E	F	Phenol, xylene with emulsifier
III	350μ-500μ	G	H	I	Germicide

Hydraulic conductivity of the columns was measured over four layers from the top to the bottom: the first layer was the top 2 cm of the column, the second and third layers were about 6 cm thick, and the fourth layer consisted of 2 cm of soil and the porous plate (Figure 9).

Series 1: Results of these experiments are given in the summary Tables 3 through 5 and in Figures 10 through 17.

Run A: The flow rate prior to the introduction of sediment was 6.30 ml/min. Turbidity appeared in the effluent during the early hours and indicated that the sediment penetrated both the soil and the porous plate which was placed at the bottom of the column. After seven hours the flow rate decreased to 1.30 ml/min. and at this time the effluent appeared clear indicating no sediment passing through the porous plate. When the flow rate was low (about 1 ml/min. or lower), the calculation of hydraulic conductivity was not possible as almost the entire loss of head occurred at the soil surface and at the bottom across the pore plates, and the difference of pressure head across the second and third

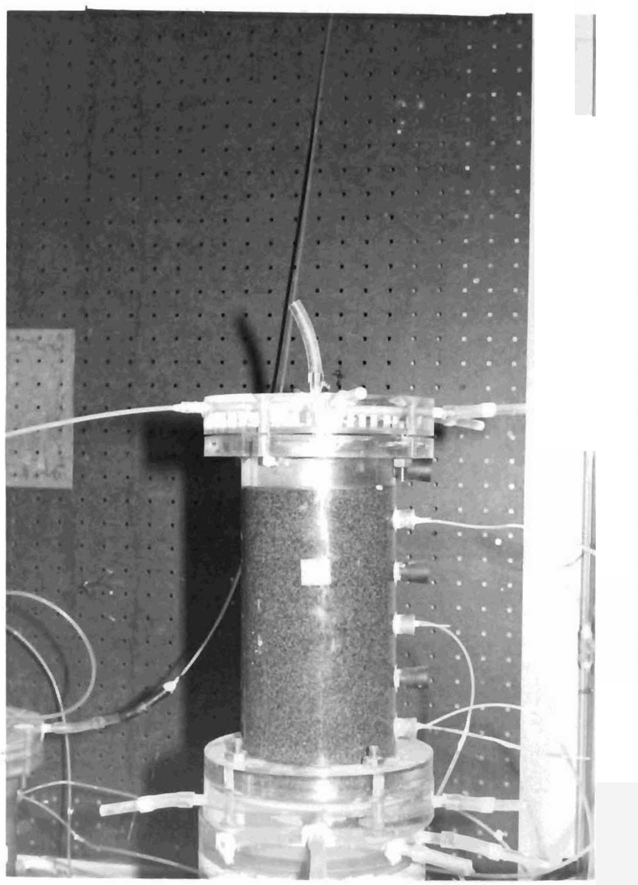


Figure 9 View of saturated soil column with tensiometers installed.

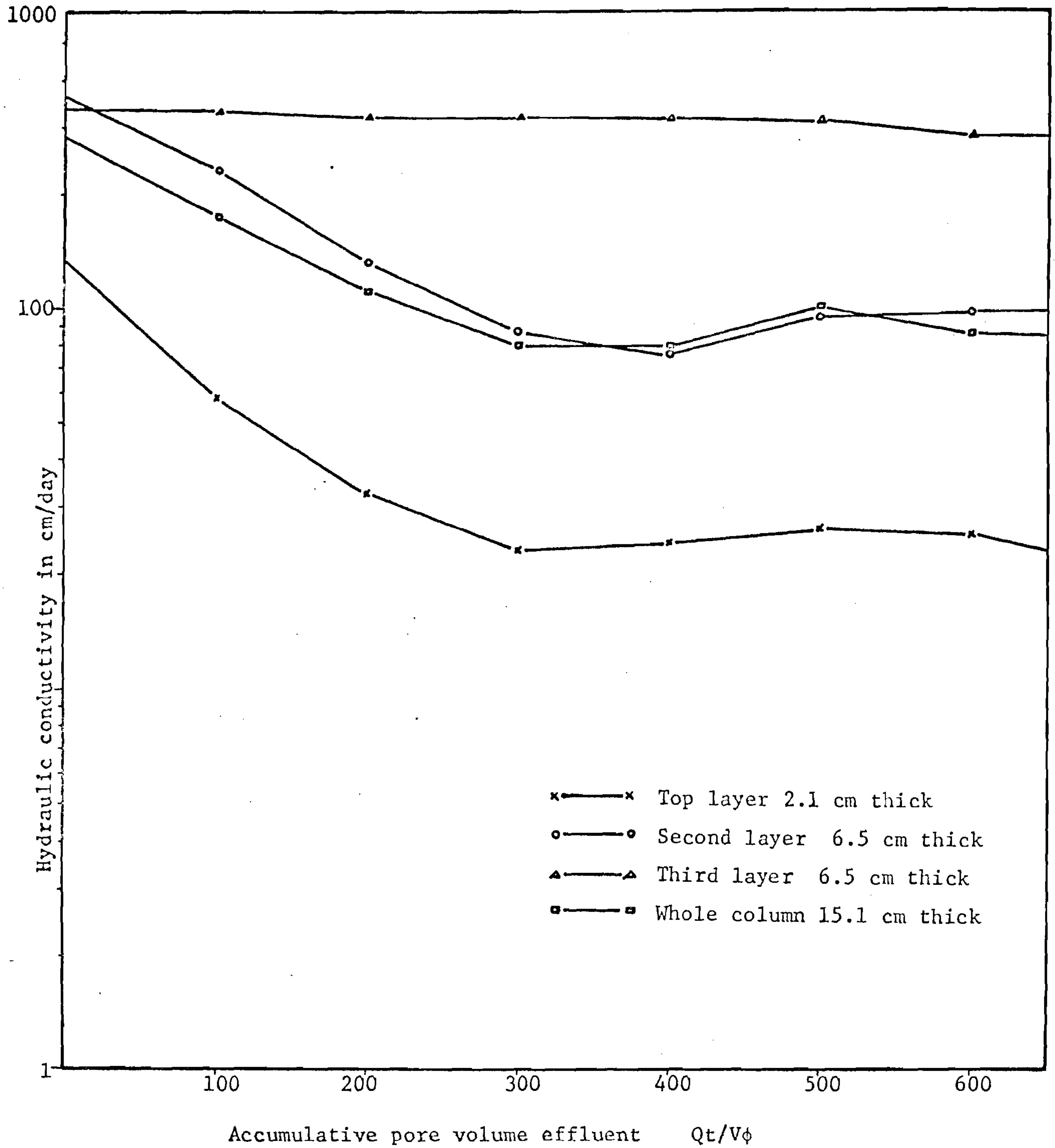


Figure 10. Variation of hydraulic conductivity with accumulated pore volume effluent - Series I Run A.

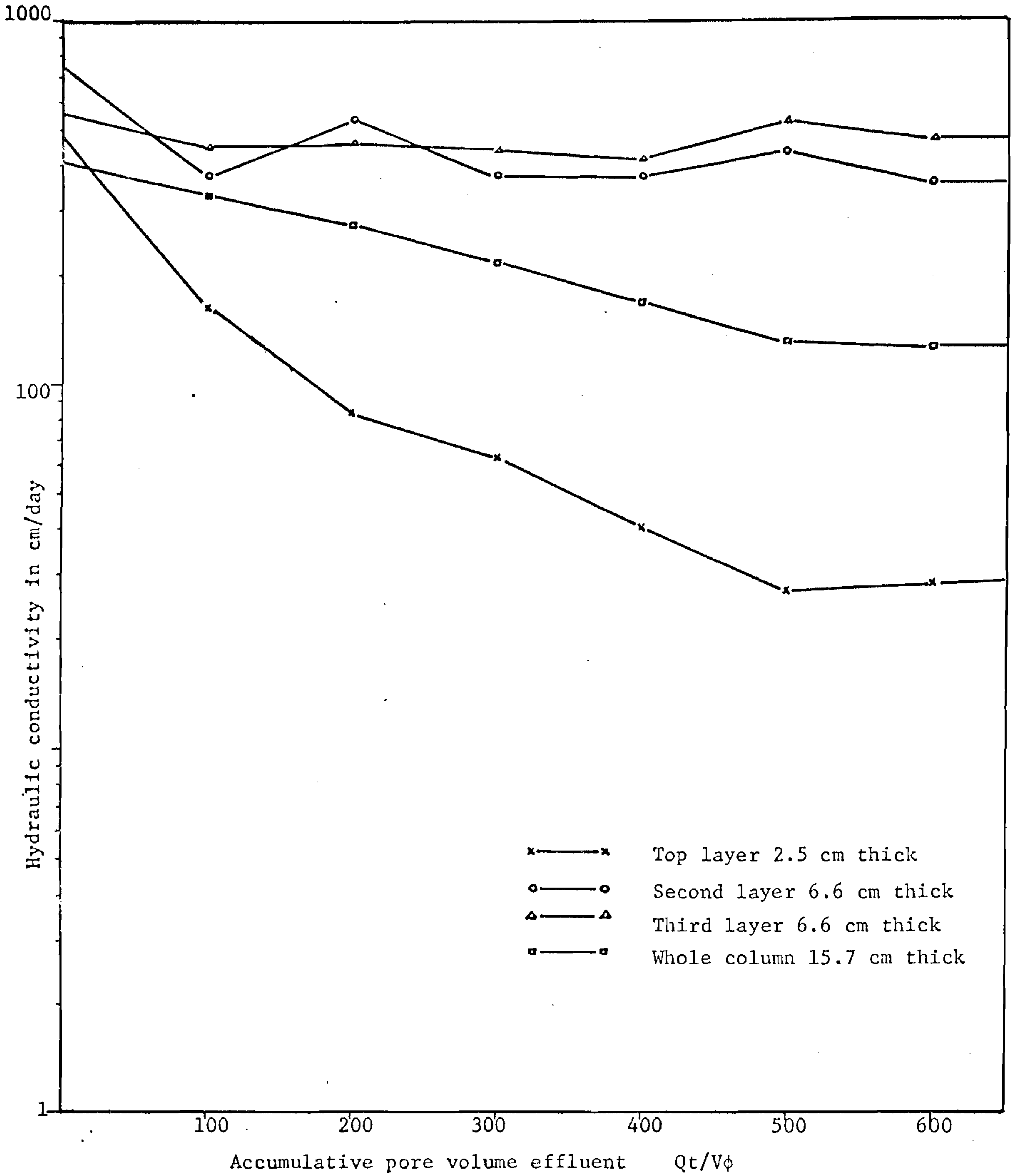


Figure 11. Variation of hydraulic conductivity with accumulated pore volume effluent - Series I Run B.

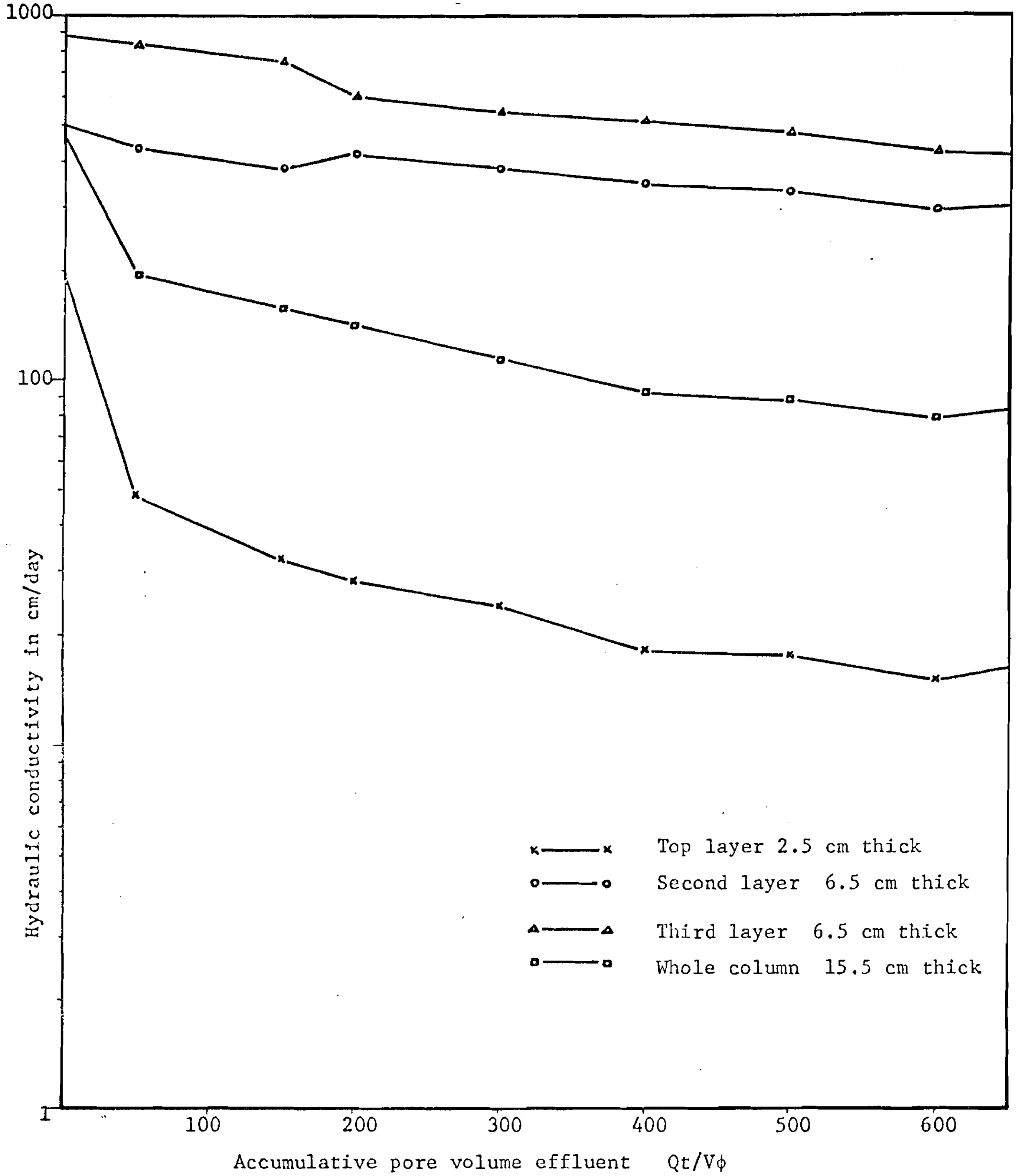


Figure 12. Variation of hydraulic conductivity with accumulated pore volume effluent - Series I Run C.

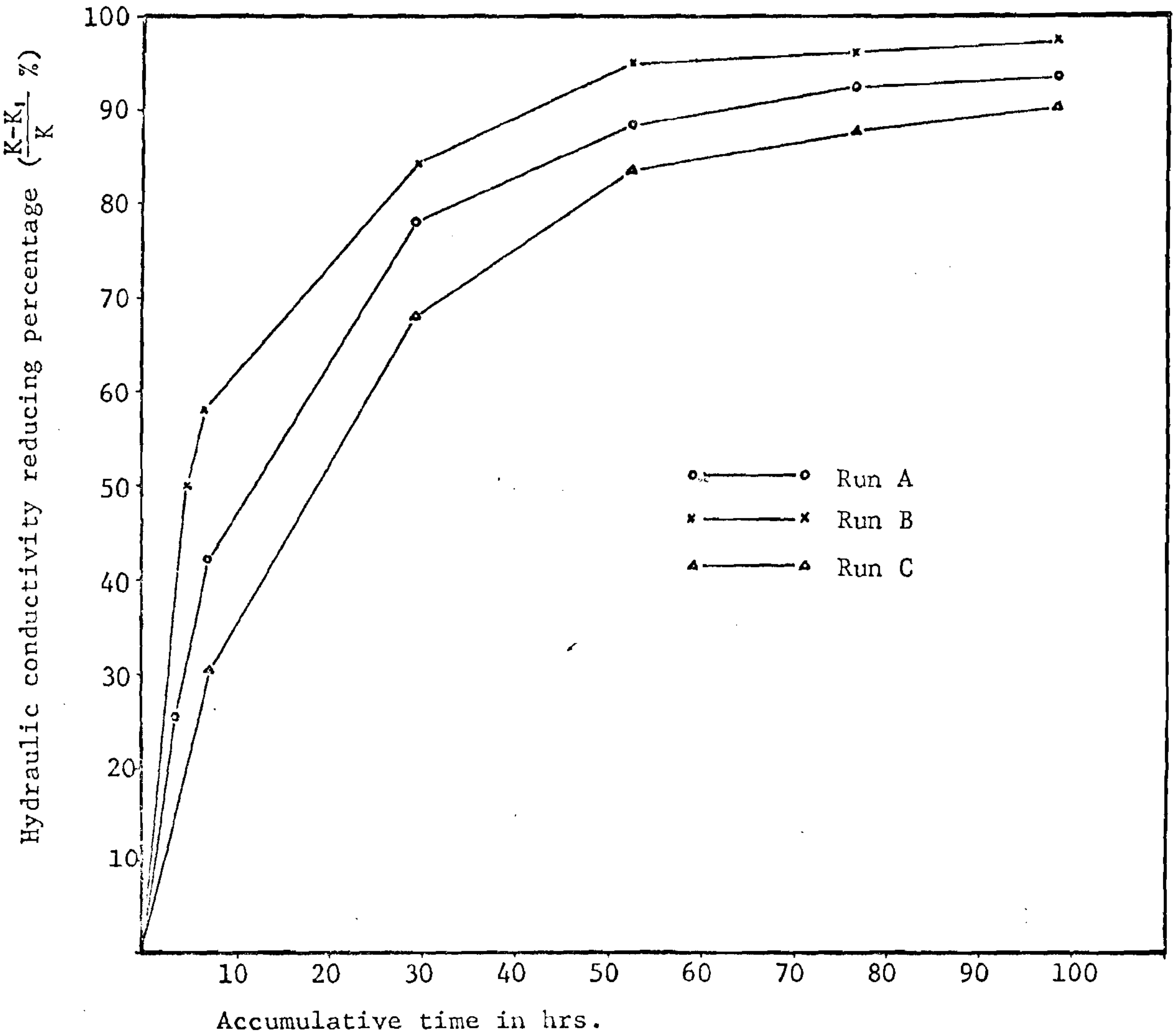


Figure 13. Comparison of hydraulic conductivity reduction between three experimental soil columns after sedimentation.

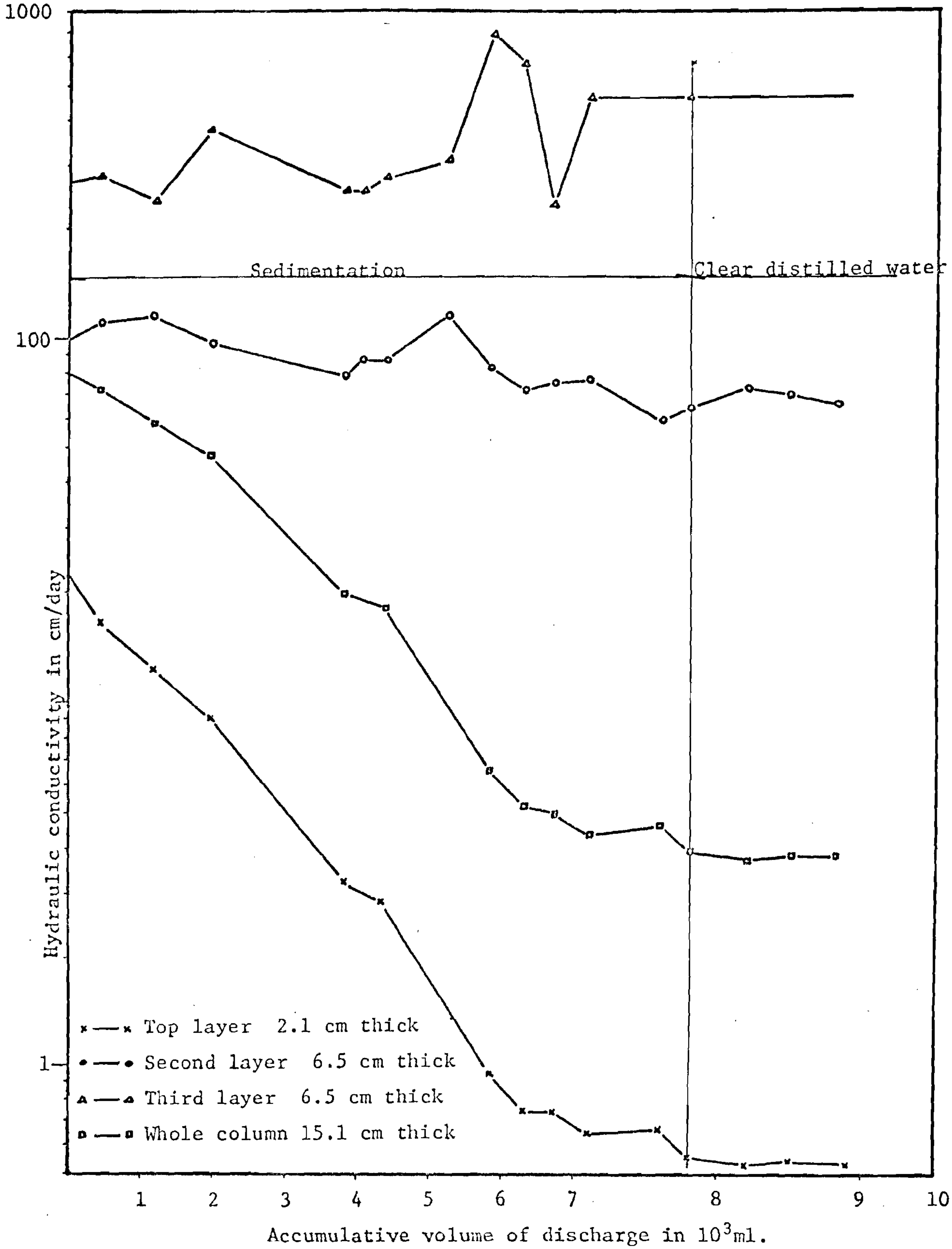


Figure 14. Variation of hydraulic conductivity with accumulated volume of discharge in sedimentation Series I Run A

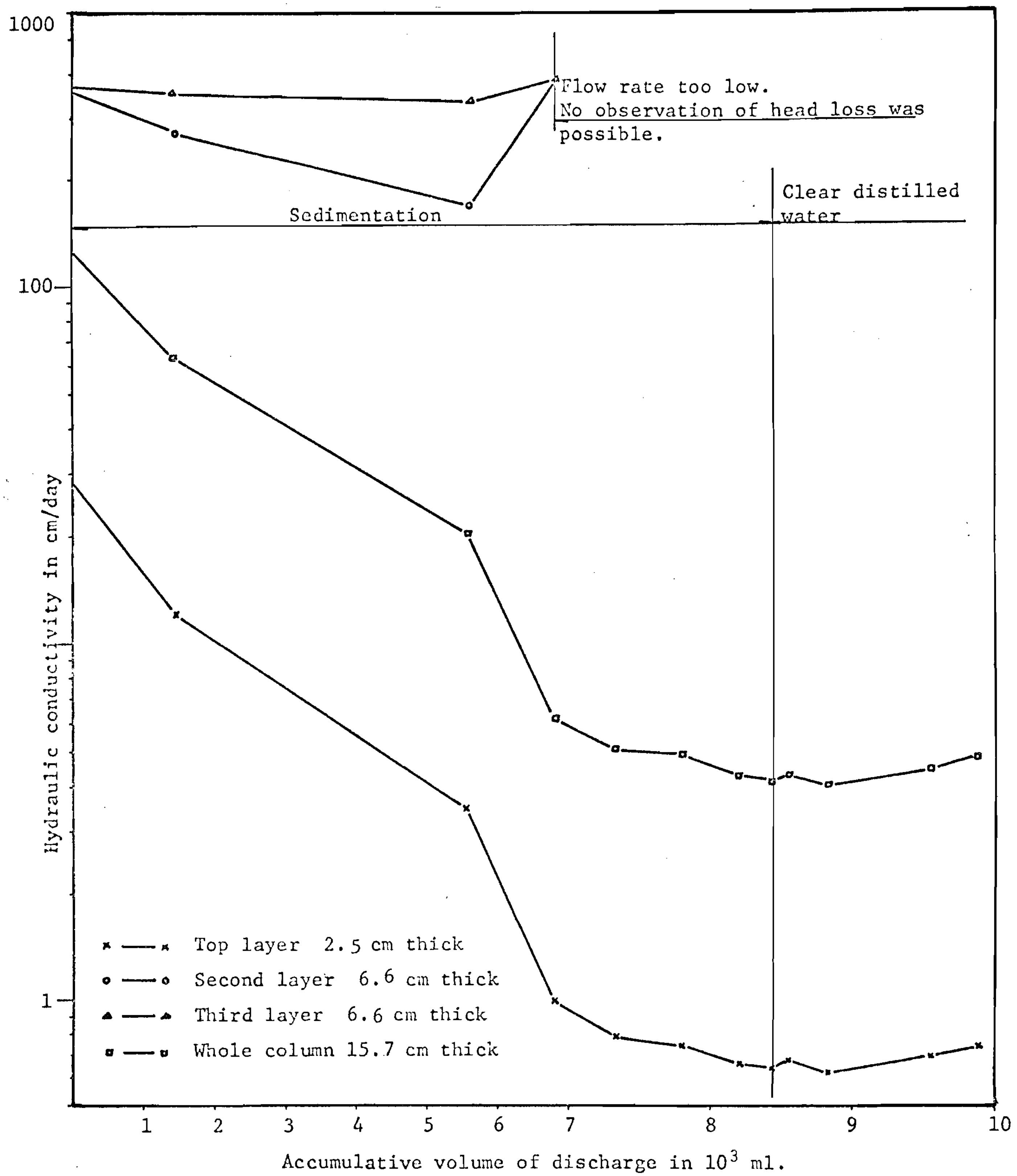


Figure 15. Variation of hydraulic conductivity with accumulated volume of discharge in sedimentation Series I Run B.

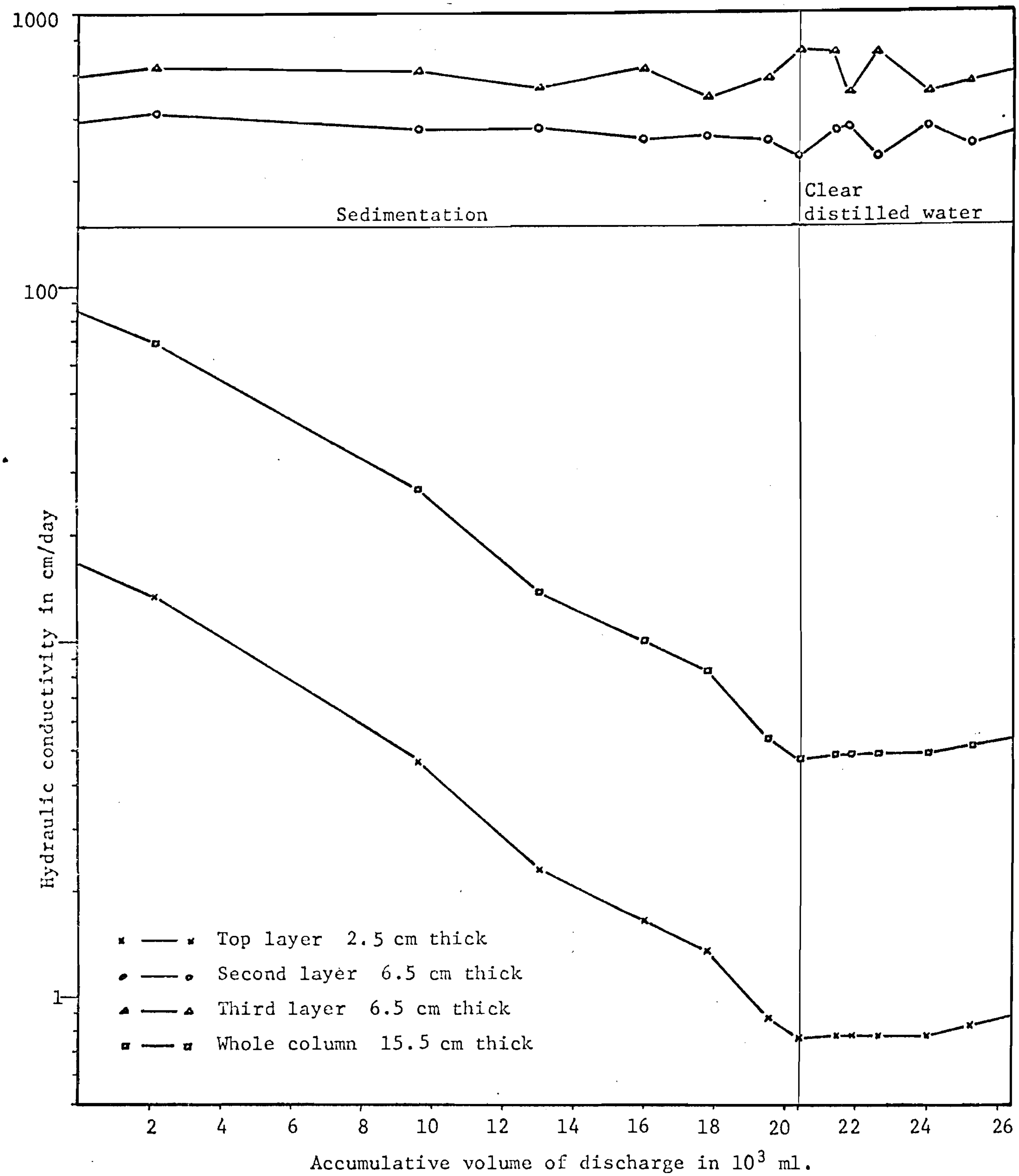


Figure 16. Variation of hydraulic conductivity with accumulated volume of discharge in sedimentation Series I Run C.

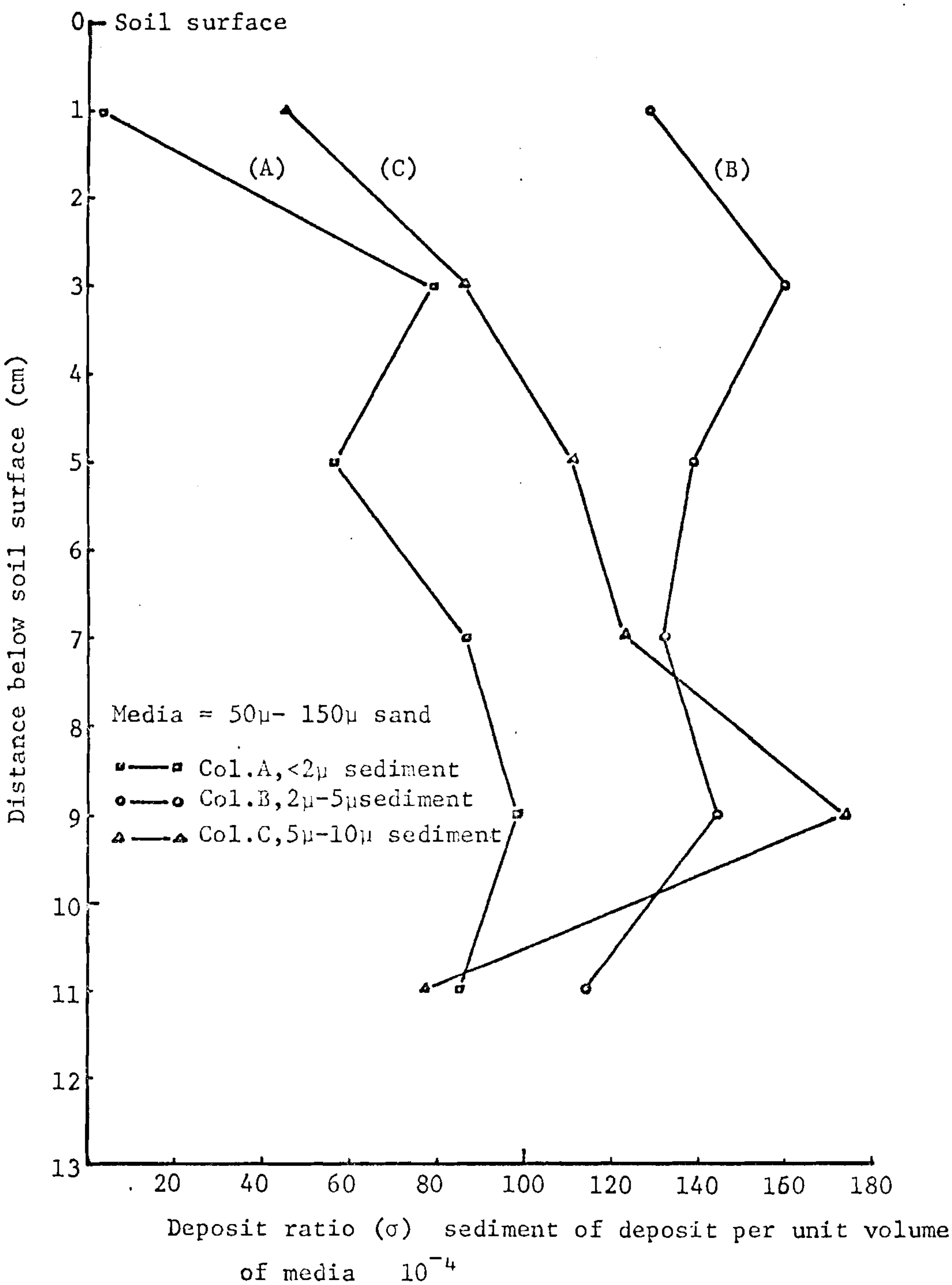


Figure 17. Distribution of the sediment retained in soil columns by gamma ray analysis.

layers became negligible. High loss of head occurred at the surface and the bottom indicating that most of the sediments were retained at the soil surface and porous plate. After the sediment run, clear distilled water was run through for several days. No indication of sediment migration in the soil was possible because the head loss across the second and the third layers was near zero, and no sediment migration showed at the top layer.

Run B: The initial flow rate was 9.42 ml/min. The effluent appeared turbid until the flow rate decreased down to 5.4 ml/min., approximately 3 hours from starting. It apparently indicated that during high flow rate some sediments still penetrated both the soil and the porous plate. During low flow rates no calculation of hydraulic conductivity was possible because of low head differentials. High loss of head still occurred at the surface and the bottom of the soil, but the loss of head across the porous plate and the bottom 2 cm of soil was not as high as in Run A, which indicated that sediments retained at the plate were much less than in Run A. During the distilled water run, the hydraulic conductivity at the top layer increased slightly indicating that some sediments originally retained in this layer were migrating down. At this time, the flow rate was apparently large enough to produce shear forces sufficient to dislodge some sediments and transport them along the column. No observation was possible in the second and third layers because the head loss across these layers was too small.

Run C: The initial flow was 9.53 ml/min. The effluent remained clear at all times during the run, indicating no sediment passing through the porous plate. As in runs B and C, high head loss occurred at the surface. Head loss across the porous plate remained constant, proportional to the flow rate indicating no sediment retained at the plate. During the distilled water run, the hydraulic conductivity in the whole column increased slightly indicating some sediment migration in the soil.

All columns in Series II except Run D and in Series III were difficult to sterilize so sediment was not introduced into these columns. The results of sterilization for all of these columns are briefly described as follows:

TABLE 3. Summary of Hydraulic Data.

Item	Run No. A			Run No. B			Run No. C		
Sand size (μ)	50 - 150			50 - 150			50 - 150		
Sediment size (μ)	<2			2 - 5			5 - 10		
Sand particle density	2.7221			2.7221			2.7221		
Dry bulk density	1.653			1.649			1.651		
Porosity of soil column	0.3927			0.3942			0.3935		
Initial hydraulic gradient	1.212 (2.16)**			0.735 (2.075)**			0.705 (3.10)**		
Sediment concentration (ppm)	500			500			500		
Sedimenting time (hrs)	192			144			145		
Initial flow rate (ml/min.)	6.30			9.42			9.53		
Final flow rate (ml/min.)	0.22			0.25			0.80		
Hydraulic conductivity (cm/day):	Initial	Final	Reduction%	Initial	Final	Reduction%	Initial	Final	Reduction%
top 2 cm layer	21.66	0.56	97	27.98	0.64	98	15.82	0.88	94
next 6 cm layer	97.56	87.58*	10	344.55	167.71*	51	295.75	260.29	12
next 6 cm layer	272.86	252.45*	7	866.61	335.42*	9	429.94	390.43	10
whole column	80.69	3.95	95	124.11	4.12	97	79.40	5.40	93
Visible phenomena in effluent.	Turbid effluent for 7 hours after start of sediment run.			Turbid effluent for 3 hours after start of sediment run.			No turbidity in effluent.		

*This was the value measured when the flow rate was slightly greater than 1 ml/min.

**Gradients in parentheses include the top soil surface.

TABLE 4. Summary of Gamma Ray Sediment Analysis.

Item	Run No. A	Run No. B	Run No. C
Sediment size (μ)	<2	2 - 5	5 - 10
Total weight of sediment introduced into soil column (gm)	4.59	4.04	4.67
Percentage of total sediment remaining above soil surface (%)	24.62	51.24	67.88
Percentage of total sediment passing soil surface (%)	75.38	48.76	32.12
Weight of sediment retained in the soil column at 1 cm to 11 cm below the soil surface (gm)	0.94	1.80	1.50
Percentage of voids filled with sediment (%)	1.13	2.16	1.76
Head loss caused by sediment at the bottom of the soil and porous plate (cm/unit flow rate)	380	94	14
Deposit ratio by Eq. (16)			
Average, 2 cm to 8.5 cm below soil surface	0.01407	0.08416*	0.01640
Average, 8.5 cm to 15 cm below soil surface	0.01005	0.01152	0.01244
Deposit ratio by gamma ray analysis (volume/unit of soil volume)			
Average value from 3 cm to 9 cm below the soil surface	0.00794	0.01433	0.01235
Average value from 9 cm to 11 cm below the soil surface	0.00912	0.01293	0.01258

*Reading of first tensiometer was not valid.

TABLE 5. Gamma Ray Data

Settings of gamma ray scanner: Window 0.00, Threshold 035, Range 5 x 10^5
Discriminator 5.00, Counting period 100 seconds.

Counts (gamma ray intensity) = Average of 10 counting periods.

Room temperature = 22.7°C

Run	A		B		C	
Sand (μ)	50 - 150		50 - 150		50 - 150	
Sediment (μ)	<2		2 - 5		5 - 10	
Distance*	Sediment run		Sediment run		Sediment run	
(cm)	Before	After	Before	After	Before	After
1	47052	47013	47264	44993	45684	44900
3	42106	40868	42910	40379	44286	42851
5	41236	40363	42562	40368	45489	43596
7	41818	40460	42545	40456	44924	42858
9	41222	49780	42576	40286	45624	42688
11	41725	40394	41968	40172	46702	45330
Average count of total column	42526	41468	43304	41108	45451	43704

*The distance is measured below the soil surface in the column.

1. Toluene solution: With 0.0235% toluene solution, the top approximate 1.5 mm layer of soil would become gummy in appearance and the hydraulic conductivity at this layer would gradually decrease. It seemed that toluene could not completely be dissolved in the water and remained a thick solution at the surface. The remaining layers of the column seemed all right and hydraulic conductivity remained constant (see Figure 18).

2. Phenol solution: With 0.1% phenol solution, the results were the same as with the toluene solution. The hydraulic conductivity of the surface layer decreased gradually, but the rate of decline was more rapid. It seemed that 0.1% phenol solution did not eliminate the microbiological activity at the surface for the conditions of room temperature $72^{\circ}F \pm 2^{\circ}$ and running with distilled water (see Figure 19). A total count of bacteria in the surface of this column was performed.

3. Xylene with emulsifier solution: Irrigation Districts in this region use the herbicide, xylene for moss control in canals and laterals. In this experiment, 0.002% xylene with emulsifier solution was tested. It caused both the surface and the bottom layer to gradually seal up. The reasons might be the same as the possibility mentioned for the phenol solution (see Figure 20).

4. Germicide solution: Hospitals usually use germicide to sterilize surgical and dental instruments, so 0.2% germicide solution was introduced in this experiment for sterilization. Hydraulic conductivity of the soil remained constant, but high head loss occurred across the porous plate. It is possible to use this chemical if the porous plate is not used in the bottom of the soil column. (see Figure 21)

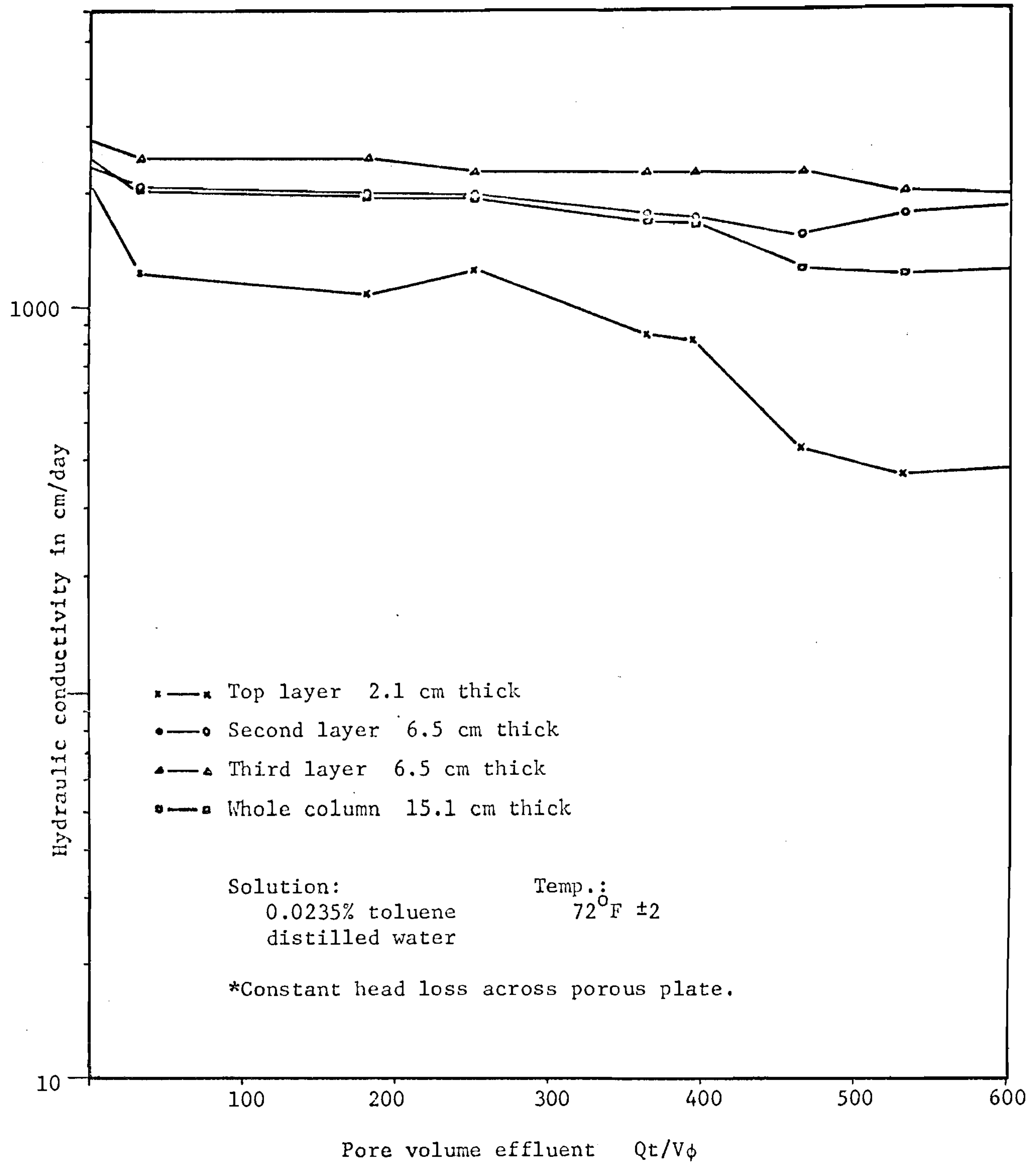


Figure 18. Hydraulic conductivity with toluene solution - Series II Run E.

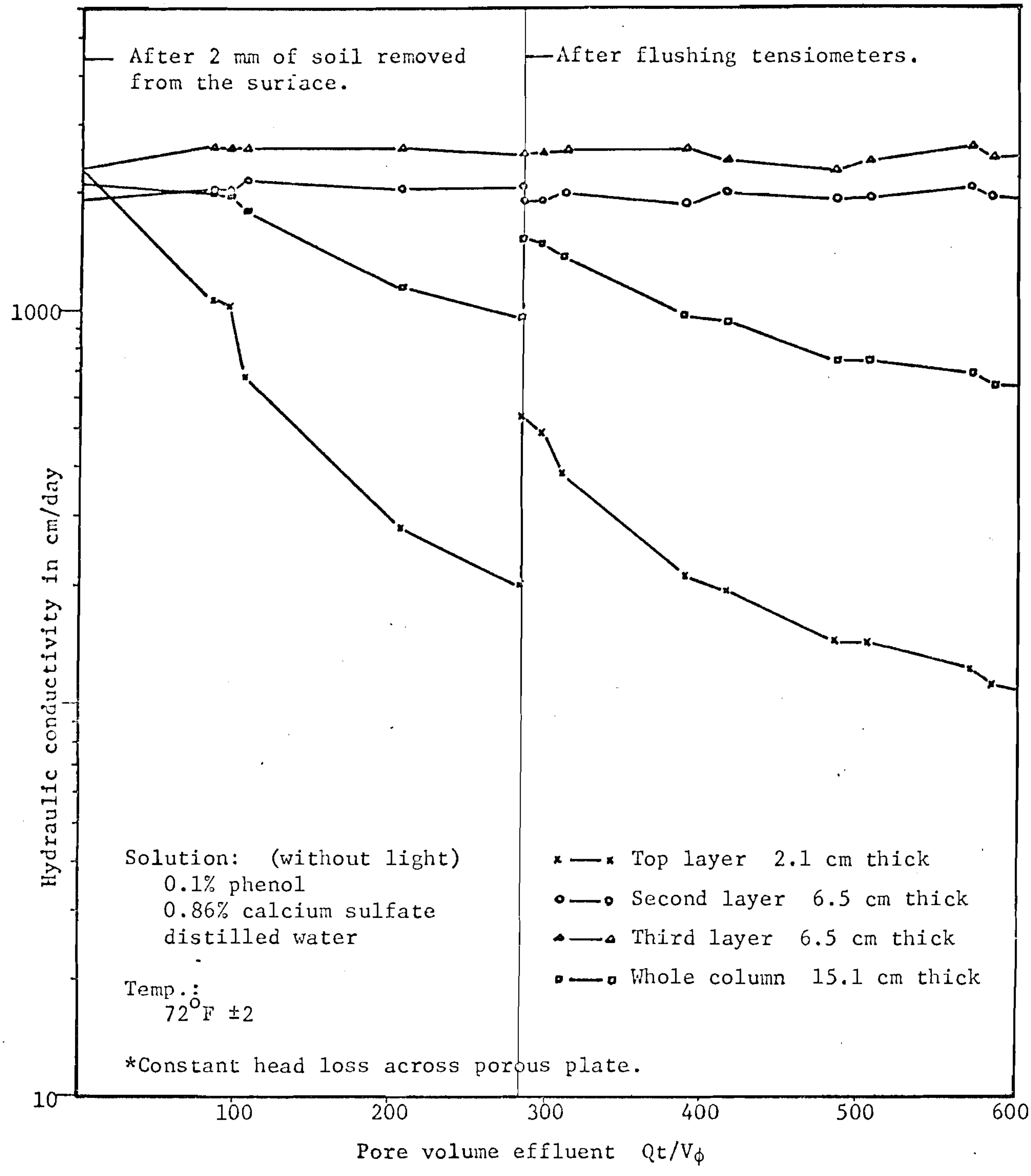


Figure 19. Hydraulic conductivity with phenol and calcium sulfate solution Series II Run E

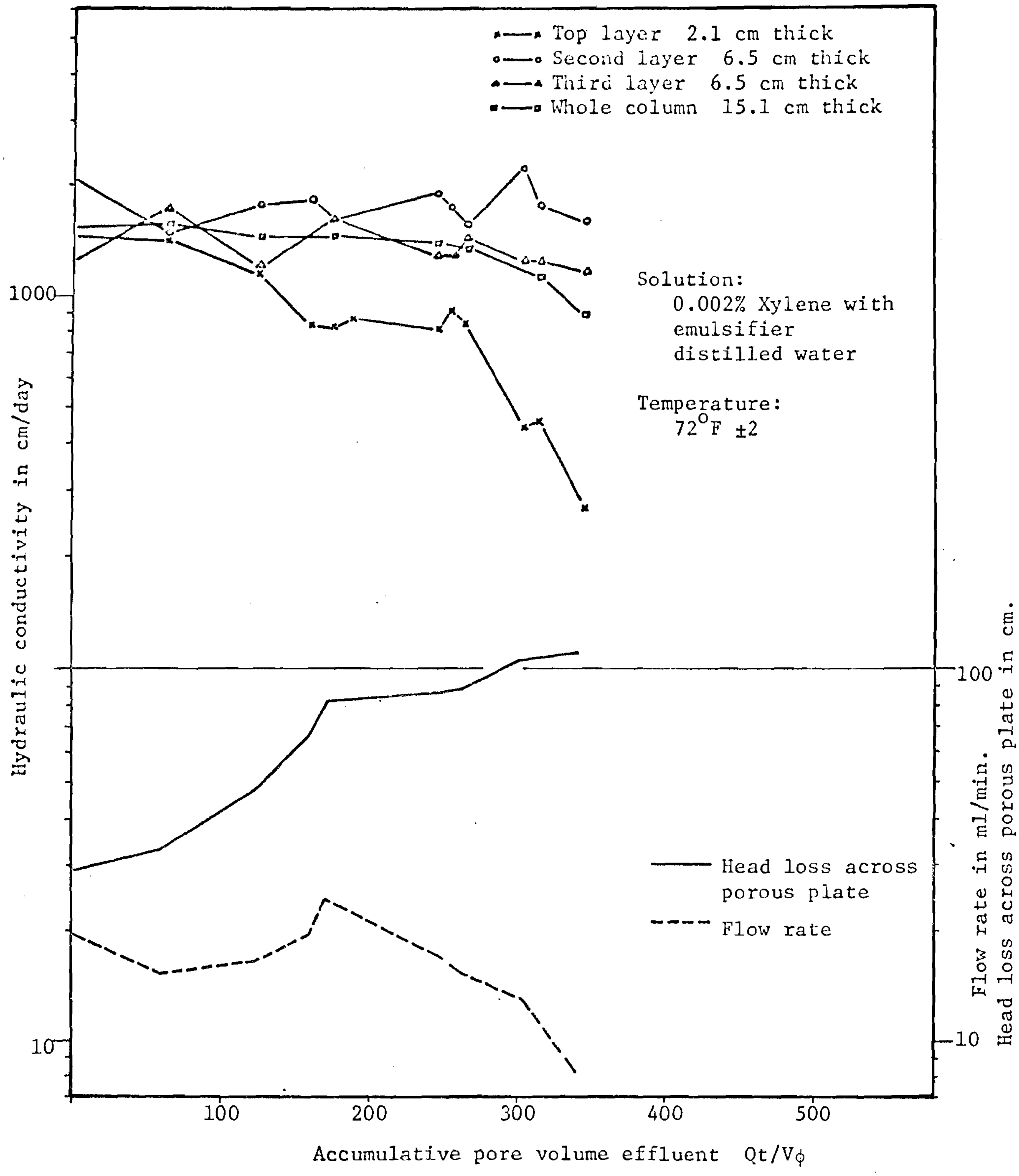


Figure 20. Hydraulic conductivity with Xylene - Series II Run F

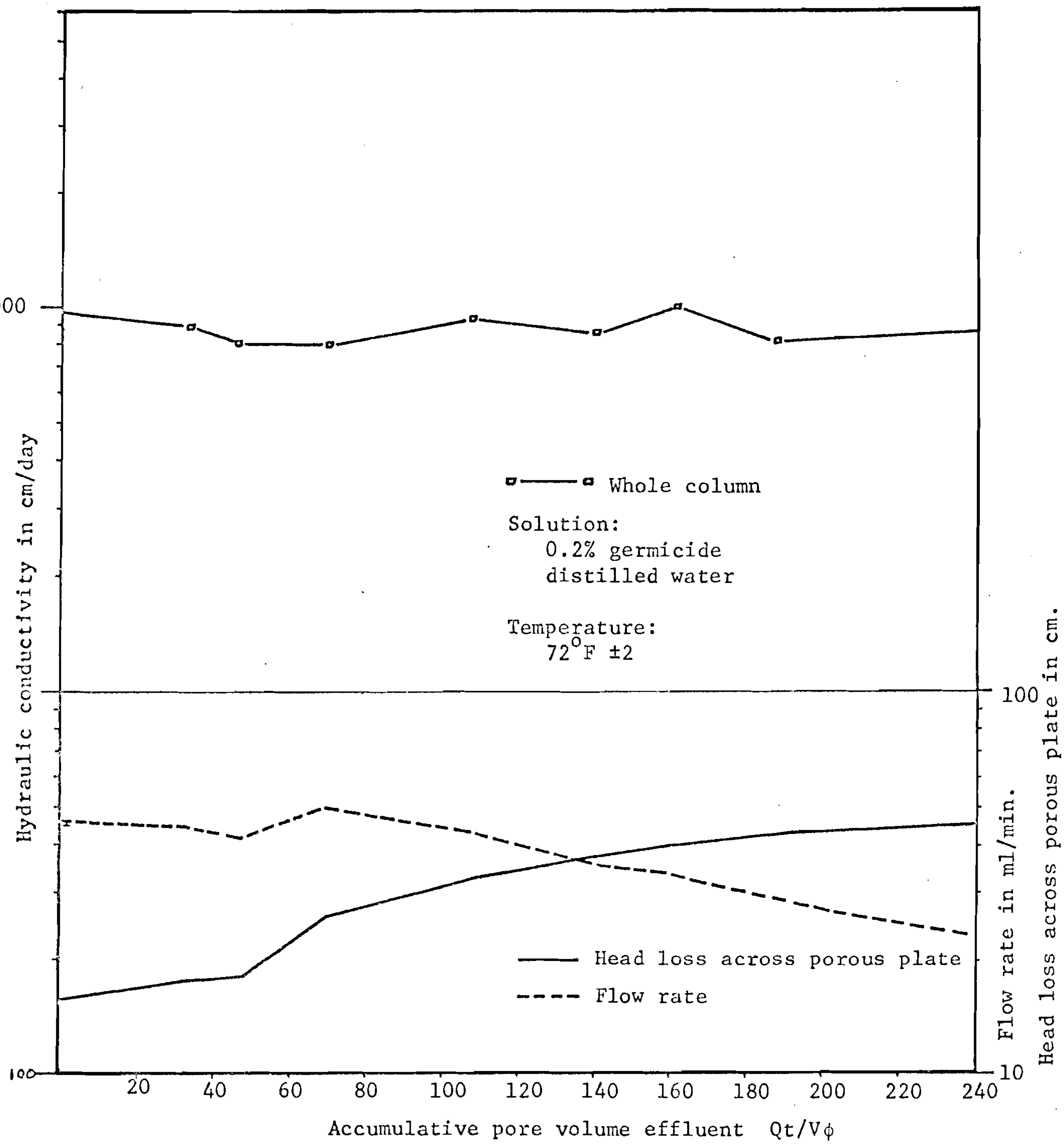


Figure 21. Hydraulic conductivity with germicide - Series III Run I

5. Dilute toluene solution: Based on the above experience, another attempt to improve the sterilization procedure with dilute toluene solutions was attempted by decreasing the toluene concentration from 0.0235% to 0.01%. This test was conducted on column #D. The results were satisfactory in that hydraulic conductivity at any layer in the soil column and head loss across the porous plate remained constant. Although the test was not carried on as long as previous tests, no decrease in hydraulic conductivity or increase in head loss across the plate appeared (see Figure 22).

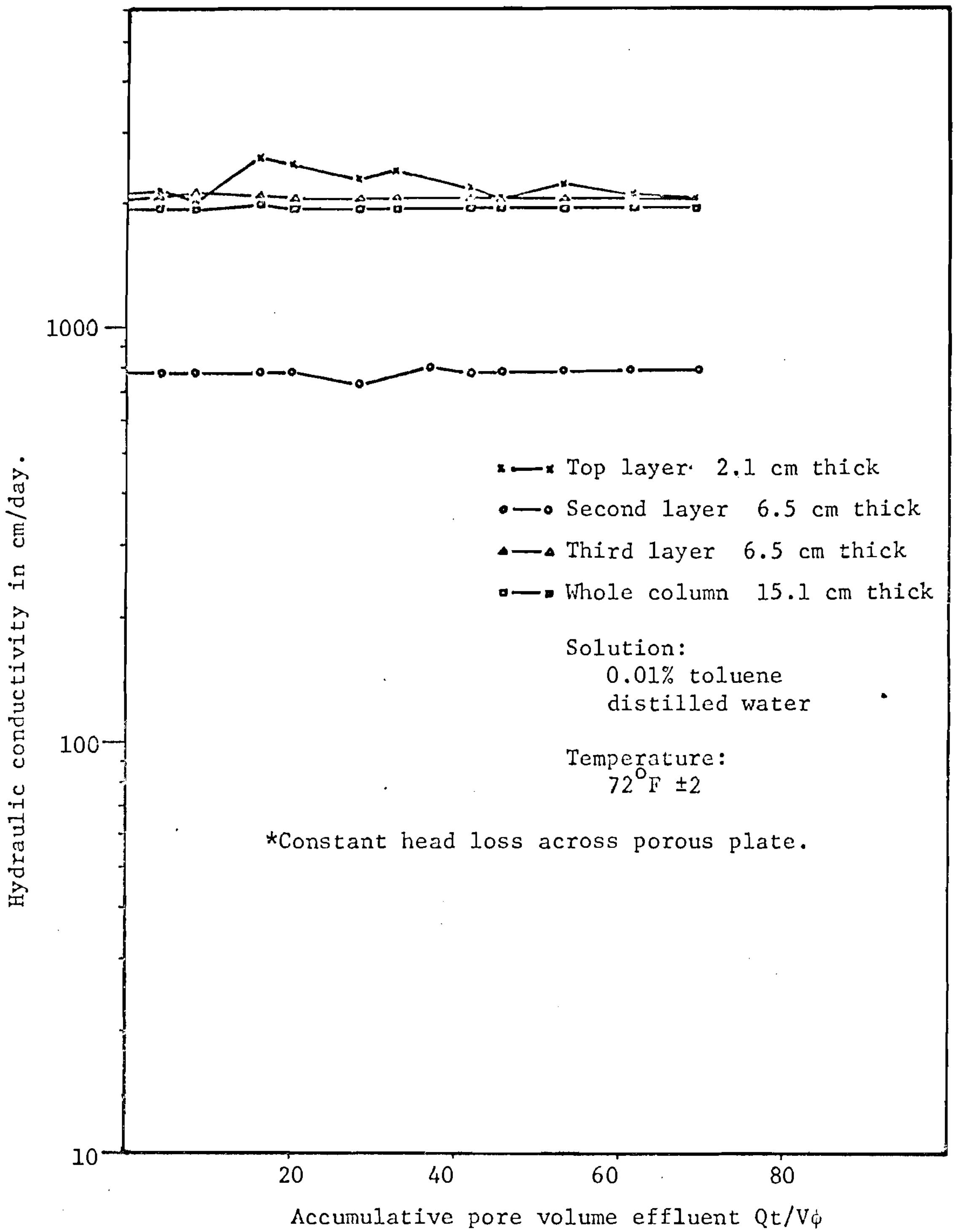


Figure 22. Hydraulic conductivity with dilute toluene solution - Series II Run D

CHAPTER VI

DISCUSSION

In this study, attempts were made in all experiments to simulate a range of field conditions by using nearby canal sands for soil columns and a milled fire clay for sediments. The objective was to find out the relationship between the size of the soil and the sediment in reducing seepage loss in the laboratory for subsequent application in the field.

Experimental columns were constructed and five tensiometers installed at different locations within the columns. Hydraulic conductivity was measured across the layers during the sediment run, then penetration and the movement of sediments in the soil were observed and measured with a final distilled water run. A profile of sediment deposited was obtained as shown in Figure 17. The accumulated volume of effluent was chosen as a basis for comparing the penetration of sediment in each column.

In run A, the sediment penetrated both soil and porous plate during high flow rates. When the flow rate decreased to below 3.00 ml/min., no sediment penetrated through the plate. Flow rate is clearly a predominant factor in sediment penetration with high flow rate resulting in deeper penetration. As shown in Table 4, although about 75% of the applied sediment passed into the soil column only 0.94 gm was retained from 1 cm to 11 cm below the soil surface. This amount of sediment was sufficient to fill only 1.13% of the voids in this length of the column. The high head loss measured at the bottom of the soil column and porous plate, indicates that most of the sediment entering into the soil penetrated to the bottom and was retained above the plate. If the porous plate was eliminated, the sediments would pass completely through the column. Determination of the sediment deposit ratio by gamma ray analysis shows that only about half as much sediment was retained in this soil column as compared with runs B and C using larger sediment. Although the hydraulic conductivity of the entire soil column was reduced 95% from the initial value, most of the reduction was in the surface layer. In Figure 14, hydraulic conductivity of the top layer decreased significantly and the rate of decrease is greater than for the other columns indicating that this size sediment accumulates more rapidly on the surface. In this run therefore the sediment introduced formed two main layers, one above the soil surface and one at the bottom above the plate. The <2μ sediment is too small for penetration and retention in the profile for the 50μ-150μ media. No migration of sediments was apparent at the top layer during the final distilled water run, probably because the flow rate was too low (0.200 ml/min.) to move the sediments down.

In run B the sediment penetrated the porous plate during the early hours and was retained at the surface and the bottom to form two main layers as in run A. In this run, however, the sediment retained above the plate was much less than in run A (see Table 4). Since the initial flow rate in run B was considerably higher than in run A the finer sediment may have flushed out through the plate leaving the coarser sediment above the plate. Larger amounts of sediment were retained in the soil in run B than in the other two columns and the sediment distribution was very uniform throughout the column as indicated by the comparison of the deposit ratios calculated from the gamma ray measurements. Approximately one-half of the applied sediment entered the soil column and 2.16% of the voids were filled in the column between 1 cm and 11 cm below the surface. The hydraulic conductivity of the entire column was reduced 97% from the initial value and the second layer was reduced 51%. These indicate that reduction in hydraulic conductivity was caused by not only sediments deposited at the surface but sediments retained in the soil at the second and third layers. The migration of sediment from the top layer during the final distilled water run was evident from the increase of hydraulic conductivity in this layer. Hydraulic conductivity across the lower two layers of this column could not be measured when the flow rate was below 1.70 ml/min. because the difference in manometer readings was less than 1 mm.

In run C, the effluent remained clear at all times. The head loss across the bottom 2 cm of soil and the porous plate caused by sediment was negligible compared with the high loss in the other two columns (Table 4). This indicates that sediment neither penetrated the plate nor was retained in the bottom 2-1/2 cm of soil above the plate. Gamma ray intensity measurements showed that some sediment was retained at 11 cm below the soil surface. The depth of penetration of 5μ-10μ sediment into 50μ-150μ media was around 15 cm below the soil surface at this flow rate condition as indicated by hydraulic conductivity measurements. Most of the sediment entering the soil was retained around 9 cm below the surface. Only about one-third of the applied sediment entered the soil. The reduction of hydraulic conductivity by sediment in the entire column was 93%. Some migration of the sediment was evident during the final run with distilled water in the overall column. The total amount of the sediment retained in the soil was more than in run A but less than in run B.

CHAPTER VII

CONCLUSIONS

All of the results in the reduction in hydraulic conductivity, the percentage of the applied sediment entering the soil column and the distribution of sediment retained in the soil column, show that 2μ-5μ sediment gives the best results for the 50μ-150μ soil particle medium for these conditions; initial flow rate about 9.5 ml/min. (volume flux 0.1775 cm/min.) and 500 ppm sediment concentration.

Comparisons of the deposit ratio calculated by equation (16) on a hydraulic conductivity basis and measured by gamma ray intensity at corresponding layers show good agreement. Estimates of the amount of sediment retained in soil during the sedimentation by use of equation (16) on field data should be valid. Deposit ratios were measured in volume per unit volume of the media and used only for a comparison between columns in this study.

Deposit ratios were measured in volume per unit volume of the media and then transformed into the weight of sediment retained in the soil. In these three experimental columns, the results of the weight of sediment calculated by deposit ratios are larger than that of actual measured values, but the proportion of these two values are approximately the same for all of the columns. The reasons for the gamma ray intensity decrease which caused higher calculated deposit ratios are probably that the columns were idle for four months after the first measurement of gamma ray intensity and the counter and detector system could have drifted during this period.

The calculated weights of sediment in Table 4 were based on sediment distribution curves plotted by gamma ray analysis (see Figure 17) and the measured weight of sediment in column C which indicated that all sediments entering the soil were retained above 15 cm below the soil surface during the sediment run.

High head loss across the soil surface during the measurement of initial hydraulic conductivity with distilled water and chemicals was caused by the bacterial activity. Approximately 1755 bacteria per unit gram of soil caused a reduction in hydraulic conductivity of 1 cm/day as indicated in preliminary measurements. Distilled water with 0.01% toluene will eliminate this reduction in hydraulic conductivity throughout the column during the run.

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APPENDIX A

GAMMA RAY TRANSMISSION DATA

Data for Mass Absorption Coefficient of Materials

Materials:

1. Plexiglas

   density: 1.16 gm/cm^3

   dimension: 9.586 cm long, 6.556 cm wide

2. Steel

   density: 7.407 gm/cm^3

   dimension: 0.328 cm thick (1 piece)

3. Aluminum

   density: 2.64 gm/cm^3

   dimension: 0.625 cm thick (1 piece)

Gamma ray facility settings:

Window: 0.00

Threshold: 035

Discriminator: 5.00

Counting period: 10 sec.

Counts (gamma ray intensity): Average of 10 counting periods

1. Plexiglas

   x = 9.586 cm average count = 50499

   x = 6.556 cm average count = 88583

2. Steel

   x = 0.328 cm average count = 20784

   x = 0.565 cm average count = 1451

   x = 0.984 cm average count = 306

3. Aluminum

x = 1.25 cm average count = 135,597

x = 1.875 cm average count = 94,309

x = 2.50 cm average count = 63,308

Data for Mass Absorption Coefficient of Soil

Soil was packed in a small 7.7 cm long plexiglas column. Gamma ray intensity (counts) was measured at 0.5 cm vertical intervals throughout the column. The scanner settings were the same as for the steel, plexiglas and aluminum determinations. The following are the data for calculation:

Internal diameter of column = 5.08 cm

Volume of column = 157.66 cm^3

Weight of dry soil (50 μ-150 μ sand) = 268.15 gm

Bulk density = 1.7008

Porosity = 0.3752

Counts (gamma ray intensity): Average of 10 counting periods

Vertical Scale Reading	Average Count
62.5	33952
62.0	34507
61.5	35090
61.0	34795
60.5	34504
60.0	34346
59.5	34822
59.0	34910
58.5	34787
58.0	34296
57.5	33537
Average counts of total column =	34504

Data for Mass Absorption Coefficient of Distilled Water

The small 7.7 cm long plexiglas column contained distilled water only. The dimensions of the plexiglas column, the procedure of measurement of gamma ray intensity and the scanner settings were the same as for the determination of the mass absorption coefficient of soil. Room temperature was 22.7°C, so the density of distilled water was 0.99763 gm/cm^3.

Counts (gamma ray intensity): Average of 10 counting periods

Vertical Scale Reading	Average Count
62.0	112,270
61.5	112,459
60.5	113,655
59.5	113,767
58.5	113,786
57.5	113,048
Average count of total column =	113,164

APPENDIX B

EXPERIMENTS FOR VALIDATING THE USE OF LINEAR POROSITY AND THE DERIVED EQUATIONS

Equipment and Materials

1. Radiant facility

   gamma ray scanner

2. Plexiglas column

   internal diameter = 5.08 cm

   height = 7.79 cm

   thickness of walls = 0.635 cm

3. Soil

   washed sand (50μ-150μ)

4. Water

   clear distilled water

Experiments on Dry Soil Column

1. Procedures:

   a. Sand was manually packed in the plexiglas column and bulk density was measured.

   b. The gamma ray intensity was measured at 0.5 cm vertical intervals throughout the length of the column.

   c. The soil column was repacked with the same weight of sand and with 5 gm (2μ-5μ) of sediment distributed uniformly throughout the column. The intensity was measured the same as before.

   d. Bulk density was calculated using the absorption equation and was compared with that of the actual weight measurement.

2. Gamma ray data of dry soil column with and without sediment.

The scanner settings were the same as for the determination of the mass absorption coefficient of soil. The average count was obtained by taking the average of 10 counting intervals. The gamma ray intensity is as follows:

	Without Sediment	With Sediment
Volume of column (cm^3)	157.66	157.66
Weight of dry soil (gm)	258.90	263.90
Bulk density (gm/cm^3)	1.64212	1.67383
Porosity	0.3967	0.3851

Vertical Scale Reading	Average Count	Average Count
62.5	36,451	
62.0	36,308	35,951
61.5	36,855	35,362
61.0	36,583	35,542
60.5	36,577	35,853
60.0	36,628	36,069
59.5	36,938	35,957
59.0	37,056	35,753
58.5	36,532	36,184
58.0	36,667	36,089
57.5	36,252	35,283
Average count of total column	36,623	35,804

3. Calculation and comparison

Equation (23) for dry soil will be

$$\rho_{bs_1} = \frac{1}{x_s \alpha_s} \left(\ln \frac{I_o}{I_1} - \alpha_c x_c \rho_c\right)$$

Substituting the average count of the total column and other constants into the above equation, a bulk density of 1.67025 gm/cm^3 was calculated. Comparing this density with that of the actual weight measurement, 1.67383 gm/cm^3, the difference is only 0.00358 gm/cm^3 (0.22%).

Experiments on Saturated Soil Columns

1. Procedures:

   a. Sand with sediment was manually packed in the column and bulk density of the soil column was measured.

   b. The soil column was completely saturated using carbon dioxide.

   c. Average gamma ray intensity of the entire column was measured using the same procedure as that of the dry soil column.

   d. Using the derived equation, bulk density was calculated, and also the amount of sediment was obtained by comparison with the density determined without sediment in the dry condition.

   e. The bulk density and the calculated amount of sediment were compared with that of the actual weight measurement.

2. Gamma ray data:

Volume of column = 157.66 cm^3

Weight of soil = 267.03 gm

Bulk density = 1.6937 gm/cm^3

Porosity = 0.3778

Room temperature = 22.7°C

Scanner settings = same as before, counting period 10 seconds.

Vertical Scale	Average Count	Average Count*
62.5	26,060	26,182
62.0	25,431	25,624
61.5	25,065	25,046
61.0	25,045	25,102
60.5	25,273	25,382
60.0	25,939	25,619
59.5	25,682	25,870
59.0	25,382	25,463
58.5	24,836	24,797
58.0	24,652	24,605
57.5	24,262	23,925
Average count of column	25,189	25,238

*The data taken on the following day.

Substituting the gamma ray intensity of the entire column (two day's average counts) and the other constants into equation (23), a bulk density of 1.6942 gm/cm^3 was calculated. Comparing this value with that of the actual weight measurement, 1.6937 gm/cm^3, the difference was only 0.0005 gm/cm^3.

The amount of sediment in the soil column was calculated from the difference in bulk density of soil with sediment and without sediment as follows:

$$\Delta\rho = \rho_{bs}' - \rho_{bs}$$

$$= 1.6942 - 1.64212 = 0.05208 \text{ gm/cm}^3$$

$$\text{Weight of sediment} = \Delta\rho \cdot V = 0.05208 \times 157.6624$$

$$= 8.211 \text{ gm}$$

$$\text{Actual weight of sediment} = 267.03 - 258.90$$

$$= 8.03 \text{ gm}$$

The difference between the calculated and measured amounts of sediment $= 8.211 - 8.03 = 0.181$ gm

Results:

1. Comparing the calculated results from gamma ray data and weighed measurements, the difference in bulk density of the dry soil column is 0.00358 gm/cm^3 and of the saturated soil column is 0.0005 gm/cm^3, and the difference in the amount of sediment in the saturated soil column is only 0.181 gm in a total of 8.0 gm sediment. Use of gamma ray techniques to determine bulk density and amounts of added sediment gives satisfactory results.
2. The above approach uses volume porosity to replace linear porosity in the equation derived for calculating bulk density and sediment. The result is satisfactory; therefore, volume porosity may be substituted for linear porosity for the conditions of this study.

APPENDIX C

Desaturation Curves:

Three 8-1/4 cm diameter, 3-1/4 cm long soil columns were packed with media of the same particle size and density as the experimental columns and were instrumented to determine their saturation-capillary pressure curves. Figure 23 is a schematic diagram of the apparatus used in determining the desaturation curves.

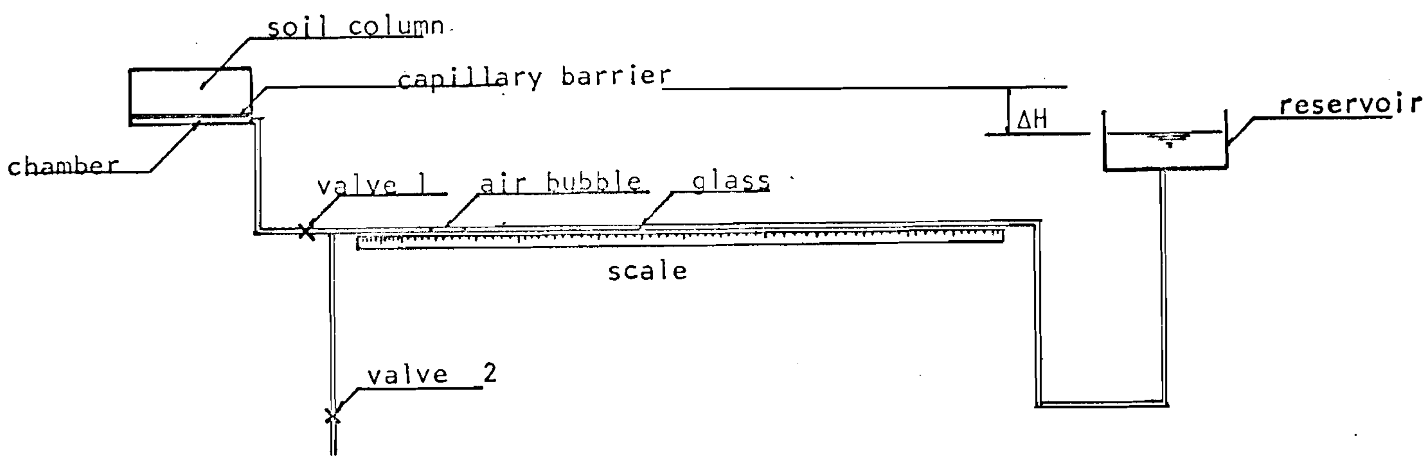

Figure 23. Schematic diagram of saturation-capillary pressure apparatus.

Procedures:

1. The soil column packed with oven dry soil was weighed, saturated, and weighed again to determine the total weight of water in the saturated soil column for subsequent calculation of saturation during increasing capillary pressure.

2. The water level of the reservoir was adjusted to the same elevation as the soil column and the bubble in the level tube was adjusted to the starting point.
3. By lowering the reservoir and raising the column the capillary pressure in the column increased and water moved out of the column into the tube. After some finite time, when the bubble had halted and had just begun to recede, the location of the bubble was recorded from the level scale. Then the reservoir and the column were lowered and raised again respectively.
4. From the movement of the bubble at each capillary pressure, the weight of water drained could be calculated and the saturation of the soil column at corresponding capillary pressure was obtained.
5. This procedure was followed until residual saturation was reached.

TABLE 1

Saturation-Capillary Pressure Curve

Sand 350μ - 500μ

ρ = 1.56 λ = 5.26 $\frac{P_b}{\gamma}$ = 18.5 cm

Φ = 0.3796 S_r = 0.22

P_c/γ (cm)	S	P_c/γ (cm)	S
2	1.00	25	0.3398
6	1.00	26	0.3140
11	0.9980	27	0.2947
12	0.9969	28	0.2786
13	0.9957	29	0.2624
14	0.9939	30	0.2533
15	0.9909	31	0.2456
16	0.9796	32	0.2379
17	0.8801	33	0.2341
18	0.8289	34	0.2337
19	0.7467	40	0.2327
20	0.6902	45	0.2304
21	0.5612	50	0.2286
22	0.4905	80	0.2246
23	0.4472	100	0.2214
24	0.3774		

TABLE 2

Saturation-Capillary Pressure Curve

Sand 150μ - 350μ

$\rho = 1.618$ $\lambda = 5.55$ $\frac{P_b}{\lambda} = 29.4$ cm

$\Phi = 0.3962$ $S_r = 0.20$

P_c/γ (cm)	S	P_c/γ (cm)	S
4	1.00	37	0.3936
10	1.00	38	0.3616
15	1.00	39	0.3356
20	1.00	40	0.3149
22	0.9981	41	0.2958
23	0.9968	42	0.2808
24	0.9945	43	0.2696
25	0.9928	44	0.2590
26	0.9884	46	0.2535
27	0.9833	47	0.2497
28	0.9733	49	0.2372
29	0.9579	50	0.2325
30	0.7255	55	0.2114
31	0.6550	60	0.2100
32	0.6125	65	0.2085
33	0.5674	75	0.2056
34	0.5111	85	0.2034
35	0.4683	120	0.2009
36	0.4281		

TABLE 3

Saturation-Capillary Pressure Curve

Sand 50μ-150μ

ρ = 0.670 λ = 5.78 $\frac{P_b}{\gamma}$ = 82 cm

Φ = 0.3865 S_r = 0.215

P_c/γ (cm)	S
54	0.9900
59	0.9877
63	0.9832
67	0.9730
71	0.9490
75	0.9073
79	0.8696
83	0.7990
93	0.6080
103	0.3899
123	0.2811
143	0.2550
163	0.2370
193	0.2271
210	0.2190

APPENDIX D

Sterilization of Soil Column with Proplyene Oxide

Equipment:

Pressure cooker, vacuum pump, vacuum-pressure gauge, funnel hypodermic needle, soil column and some proplyene oxide.

Sterilization procedure:

The pressure vessel was equipped with gauges and a valve with a rubber stopper in it. A hypodermic needle attached to a funnel was used to introduce the propylene oxide through the stopper into the vessel.

The column was placed in the pressure vessel and the vessel sealed. It was then evacuated to -25 inches mercury pressure. At this vacuum, the hypodermic needle was placed in the stopper and the funnel was filled with propylene oxide which was at a ratio of 100 ml per kilogram of soil. The valve was then opened and the liquid was introduced into the pressure cooker which had been preheated to 200^{o}F for 20 minutes. The vacuum decreased rapidly to -6 inches mercury pressure by the time injection was finished. This vacuum disappeared and a maximum pressure of 6.6 psi was attained. The gauge read -11 inches of mercury pressure after the system had stood for two days. The hot plate was turned on to 250^{o}F for one hour and then turned off, the gauge read -9.3 inches mercury pressure. The vacuum was then released and the column was tested for sterilization.

Nutrient Broth Tests:

Two columns, one treated with propylene oxide and the other with no treatment, were prepared and tested for sterilization by the following procedure:

Nutrient broth (0.4 gm) was dissolved in 50 ml of distilled water. This solution was divided equally among 10 test tubes which were placed in an autoclave for sterilization.

Samples from the columns were introduced into the tubes, one sample was taken from the top of the column and four more from approximately equal increments throughout the entire column.

The tubes were placed in a 37°C incubator for 48 hours. After 48 hours in the incubator, the tubes from the treated column were all negative, tubes from the check column were all positive. Microscope slides were taken from the tubes and stained with crystal violet. Slides from the check column showed large quantities of Bacilus Megatherium. No organisms were apparent in tubes from the treated column.

Although the results of the soil column sterilization with propylene oxide under vacuum and pressure were satisfactory, the plexiglas columns became soft and deformed during the steriliztion process. This problem along with the fact that some discoloration of the plastic occurred prevented the use of this sterilization technique.