Percolation tests for septic tank suitability of typical southern Arizona soils

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PERCOLATION TESTS FOR SEPTIC TANK SUITABILITY OF TYPICAL SOUTHERN ARIZONA SOILS

by

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ABSTRACT

The percolation rates of nine typical southern Arizona soils varied from 1.75 to 21.5 cm/hr. By use of linear regression, it was determined that a significant linear relationship exists between test hole diameter and percolation rate on Pima cl, Gila vfsl, and Valencia sl soils. Comparison of rates in 10 and 30 cm diameter test holes indicated that rates in 10 cm holes were 2.3 times greater than those in 30 cm holes. Very significant correlations were found between percent sand and clay in subsoil and percolation rates, and a significant correlation was discovered between percent silt in subsoil and measured rates. By use of existing mathematical theories utilizing matric flux potential, infiltration from point or line sources were used to simulate flow from cylindrical holes or absorption trenches, respectively. A technique to relate percolation rate to actual flow rates in absorption trenches was established but believed to need improvement. An attempt to assign a value of α to three soils proved to be very difficult using the proposed technique. Mathematical modeling does, however, provide potential for comparing percolation rates to expected flow rates in operating disposal trenches.

INTRODUCTION

Rapid growth in urban areas and the construction of remote area subdivisions has prompted increased utilization of septic tank systems for sewage disposal in southern Arizona. Since a major segment of these disposal systems consists of tile lines that drain the sewage effluent into soil surrounding the tile line, percolation tests are required to determine the suitability of a site for sub-surface disposal. Consequently, the objectives of this research were to:

1. Measure the percolation rates of typical southern Arizona soils
2. Evaluate the relationship between test hole diameter and percolation rate
3. Determine correlation coefficients of percolation rate to soil parameters
4. Model the infiltration of water from a cylindrical test hole
5. Model infiltration from absorption trenches.

The percolation rates of nine typical soils found in eastern Pima county were measured from May to September, 1974. This thesis presents the procedures and data obtained. The theoretical analysis for water movement from cylindrical cavities and trenches is also prevented.

LITERATURE REVIEW

A field test to determine the suitability of a site for a septic tank system is required in most states. The test most commonly utilized was developed by Henry Ryon in 1928 (Salvato, 1972). Ryon investigated subsurface disposal systems that had functioned properly for approximately 20 years and compared these results with percolation tests conducted on different soils throughout New York state. This procedure still serves as the criterion for predicting effectiveness of a septic tank system in a particular soil type.

The Percolation Test

As discussed in the Manual of Septic Tank Practices (U. S. Public Health Service, 1957), percolation tests are required to determine the acceptability of a site for a septic tank system. Most of the recommended practices found in this publication are based on the results of Bendixen et al. (1950). These procedures allow a range of test hole diameters from 10 to 30 cm and a variable 4 to 24 hour period of pre-soaking the test site. Different individuals have investigated the effectiveness of the percolation test, the factors affecting the test, and alterations or refinements of the recommended procedures.

Because regulations for percolation tests can vary from state to state, a number of procedures have been employed to pre-soak test holes. The most common practice in coarse textured soils is to pond clear tap water in the test hole for approximately four hours before the percolation rates are recorded (Salvato, 1972; Luce, 1973; Winneberger, 1972). For finer textured soils, a range of 4 to 24 hours of pre-soaking has been recommended (Winneberger and Klock, 1972; Olson, 1964; Hill, 1966; Bouma et al., 1972; Luce, 1973). Kiker (1948) suggested soaking the test hole until steady flow rates are obtained. Hill (1966), Derr, Matelski, and Petersen (1969), and Bouma et al. (1972) used a constant head device for pre-soaking the test site for 6 to 8 hours, while others just add water to the test hole without provision for maintaining the water level (head) in the test hole (Winneberger, 1972; Bendixen et al., 1950; Luce, 1973; Salvato, 1972). Indigenous soil factors also affect the percolation rates measured.

Soil Factors Affecting Percolation Rates

A number of soil properties influence percolation rates. A general indicator of this relationship is accomplished by calculating correlation coefficients (Steel and Torrie, 1960) between the percolation rates and various quantitatively and qualitatively determined factors. Derr et al. (1969) found significant negative correlation coefficients (at the $\alpha=0.05$ level) for drainage class and percent clay in the subsoil and a significant positive correlation of percent coarse fragments and percent silt in the subsoil with percolation rates. However, of the variables correlated with percolation rate, multiple regression explained only 16 percent of the variations obtained in these measurements.

Luce (1973) found a very significant (at the $\alpha=0.01$ level) negative linear correlation between clay content and percolation rate, and the same relationship was found after log transformation (semi-log) of the clay content. A significant negative linear and semi-log correlation between bulk density and percolation rate was found, and a significant positive semi-log correlation was discovered between coarse silt and percolation rate. He also found significant correlations of the qualitative variables for subsoil consistence, subsoil chroma, natural drainage class, and type of vegetation with the percolation rate. By use of multiple regression on various combinations of these parameters, Luce (1973) could explain from 52 to 77 percent of the variability in the percolation rates.

Factors inherent in the percolation test procedure also influence measured rates. These factors include construction, diameter, and depth of the test hole as well as method of measuring the percolation rate (Bendixen et al., 1950; Winneberger, 1972).

For some parts of the United States, the season of the year or the antecedent soil moisture content can influence percolation rates (Morris, Newbury, and Bartelli, 1962; Healy and Laak, 1973; Mokma and Whiteside, 1973). In relation to this latter factor, the degree of presoaking of a test hole can produce significant differences in the measured percolation rates (Bendixen et al., 1950; Salvato, 1972). Allison (1947) found that clogging of soil pores occurs under prolonged submergence due to the products of anaerobic microbial growth. This factor can influence percolation rates as well as performance of actual leaching fields.

Alterations of Standard Tests

Some investigators have recommended modified tests to determine site suitability. Bouma et al. (1972) utilized the Bouwer double tube method (Boersma, 1965) to measure saturated hydraulic conductivity *in situ*. A procedure using infiltration through an artificial gypsum crust for field determinations of unsaturated hydraulic conductivity was also utilized. These results were then compared to the results of the standard percolation tests.

After investigating the effectiveness of the standard percolation tests required in Wisconsin, Bouma et al. (1972) states that the percolation rates found by standard procedures cannot accurately predict infiltration rates from seepage trenches. However, no workable alternative has been proposed to rank different soils as to their capacities to transmit liquids, and the percolation test is still commonly used.

Healy and Laak (1973) utilized laboratory determinations of saturated hydraulic conductivity for comparison to standard percolation rates. They used theoretical considerations of the percolation rate due to capillary and gravitational influences for comparison with actual percolation rates.

Ludwig and Ludwig (1949) determined the equilibrium percolation rate from graphical and mathematical analysis of actual data. A factor F was assumed for septic tank design so that the rate of sewage effluent infiltration in the soil was approximately one-twentieth of the percolation rate obtained for clean water. Ludwig et al. (1950) then applied this technique to design effluent leaching fields. These authors contend that their equilibrium method produces results which gives design criteria of the same order of magnitude as those obtained by standard percolation tests. Hill (1966) confirmed that percolation rates measured by standard procedures are approximately equal to the equilibrium rate as described by Ludwig and Ludwig (1949). However, soils containing discontinuities in texture and structure will cause variations between the two methods.

Use of Soil Surveys

Initial considerations of percolation rates and subsequent performance of septic tank systems can be obtained from soil surveys. Many soil scientists and engineers have recommended that soil survey information be utilized to help predict performance of subsurface leaching fields by interpreting recorded properties of soil map units.

Huddleston and Olson (1966) related percolation rate data to soil mapping units of a detailed soil survey in order to develop specific recommendations for septic tank usage. Bender (1971) reports soil surveys can reasonably predict the behavior of a subsurface absorption field. Olson (1974) discussed how soil survey information, when combined with other studies of the environment, can be useful in locating a leaching field when a number of alternatives exist. Bouma (1974) utilized an approach that emphasized soil potential rather than soil limitations in conjunction with soil maps. Federick (1952) explained how soil survey information can be utilized by sanitary engineers once the terminology used is understood. Morris et al. (1962) attempted to show that soils maps can replace percolation tests because of the unreliability of percolation tests and the differences in cost. Unquestionably, soil surveys are a helpful tool for determining sites for sewage disposal through septic tank systems. Even though soil surveys can be valuable in selecting areas that would be best suited for developments using septic tanks, on site investigations are still needed because of mapping inclusions.

Infiltration from Point and Line Sources

Mathematical modeling of infiltration is reviewed by Philip (1969). Steady state infiltration can be linearized for an isotropic soil when the unsaturated hydraulic conductivity is of the form:

$$K=K_o \exp(\alpha h) \tag{1}$$

where K_o is the saturated hydraulic conductivity (units L/T), α an empirical constant (units L^{-1}) and h the pressure head (units L). Use of Eq. 1 and defining a matric flux potential φ given by:

$$\varphi = \int_{-\infty}^{h} K(h)dh = K/\alpha \tag{2}$$

leads to a linear differential equation:

$$\nabla^2\varphi = \alpha \frac{\partial\varphi}{\partial z} \tag{3}$$

where z is taken positive in the downwards direction and "∇^2" is the Laplacian operator. Philip (1968) solved equation 3 for point and line sources in an "infinite medium". Raats (1972) generalized the relationship developed by Philip to depict infiltration from buried point and line sources at a specified depth. Warrick (1974) investigated time-dependent linearized infiltration from point sources. Included in the analysis was the advancement of a wetting front, variation in soil moisture content resulting from irrigation, and the matric flux potential (φ) field for two point sources. Lomen and Warrick (1974) investigated time-dependent linearized infiltration from single and parallel surface line sources. Lines of equal moisture content as a function of time and the response to cyclic inputs, which are analogous to irrigation periods, were calculated.

MATHEMATICAL ANALYSIS OF PERCOLATION FROM TEST HOLES AND TRENCHES

The generalized form of Philip's (1968, 1969) relationships as presented by Raats (1972) will be used to approximate flow from test holes and trenches. Combinations of point sources (for the cylindrical cavities) or line sources (for the trenches) will be used to simulate the free water-soil interface in a manner similar to the method of approximating tile surfaces by point sinks in drainage theory. Serious limitations are encountered due to necessary simplifications. An alternative approach considered was finite differencing, but this was discarded at least temporarily because it is more tedious. Other possibilities for analyzing flow from a trench are conformal transformations (e.g., Harr, 1962, Chapter 9) as well as the semi-analytical technique of Sawhney and Parlange (1974).

Raats (1972, Eq. 11) gives the solution to Eq. 3 for a combination of n points or lines:

$$\begin{aligned}\varphi[R,Z]=\varphi_\infty[R,Z-D]+\exp(-2D)\varphi_\infty[R,Z+D]\\ -2\exp(2Z)\int_{Z+D}^{\infty}\exp(-2t)\varphi_\infty[R,t]dt.\end{aligned} \qquad (4)$$

where φ_∞ is the corresponding solution for either a point or line source in an "infinite" medium. The dimensionless coordinates are X, Y, Z given by:

$$X=\alpha x/2 \qquad Y=\alpha y/2 \qquad Z=\alpha z/2 \qquad (5)$$

where α is the same as in Eq. 1 and $R^2=X^2+Y^2$. The dimensionless depth of the ith point or line source is $D_i=\alpha d_i/2$ where d_i is the true depth. Appropriate forms of φ_∞ for a point (φ^p_∞) and line (φ^l_∞) are:

$$\varphi^p_\infty=\frac{\alpha q^p}{8\pi}\,\frac{\exp[Z_\infty-(R^2+Z^2_\infty)^{\frac{1}{2}}]}{(R^2+Z^2)^{\frac{1}{2}}} \qquad (6)$$

and

$$\varphi^l_\infty=\frac{q^l}{2\pi}\exp(Z_\infty)K_0[(X^2+Z^2_\infty)^{\frac{1}{2}}] \qquad (7)$$

The ordinate Z is defined from the point (or line) source. In Eq. 6, q^p is the point source strength (units of L^3/T). In Eq. 7, q^l is the line source strength or flow per unit length of trench per unit time; K_0 is the modified Bessel function of the second kind of order zero (Abramowitz and Stegun, 1964).

If the relative strength of n point sources are given by $m_1, m_2, \ldots, m_n$, Eq. 6 becomes:

$$\begin{aligned}\Phi(R,Z)=\frac{8\pi\varphi}{\alpha q}=\sum_{i=1}^{n} m_i\Bigg\{&\frac{\exp(Z-D-\{R^2+(Z-D)^2\}^{\frac{1}{2}})}{\{R^2+(Z-D)^2\}^{\frac{1}{2}}}\\ &+\exp(-2D)\frac{\exp(Z+D-\{R^2+(Z+D)^2\}^{\frac{1}{2}})}{\{R^2+(Z+D)^2\}^{\frac{1}{2}}}\\ &-2\exp(2Z)\int_{Z+D}^{\infty}\exp(-2t)\frac{\exp(t-(R^2+t^2)^{\frac{1}{2}})}{(R^2+t^2)^{\frac{1}{2}}}\,dt\Bigg\} \qquad (8)\end{aligned}$$

and Eq. 7 becomes:

$$\Phi(X,Z)=\frac{2\pi\varphi}{q}=$$

$$\sum_{i=1}^{n} Mi\left\{\exp(Z-D_i)\chi_o\left[\left\{(X-X_i)^2\right.\right.\right.$$

$$\left.\left.+(Z-D_i)^2\right\}^{\frac{1}{2}}\right]+\exp(Z-D_i)\ {}_o\left[\left\{(X-X_i)^2\right.\right.$$

$$\left.\left.+(Z+D_i)^2\right\}^{\frac{1}{2}}\right]-2\exp(2Z)\int_{Z+D_i}^{\infty}\exp(-t)$$

$$\left.\chi_o\left[\left\{X-X_i)^2+t^2\right\}^{\frac{1}{2}}\right]dt\right\} \qquad (9)$$

where q is combined flow and Φ is the dimensionless matric flux potential as given by Philip (1968). As $\varphi\ (R_o,0)$ is K_o/α when h=0 by equations 1 and 2 we may use Eq. 8 to find:

$$\Phi(R_o,Z)=8\pi K_o/(\alpha^2 q) \qquad (10)$$

Thus, if the matric flux potential at $R=R_o$ and Z=0 is set equal to zero in order to simulate the top of the waterline adjacent to the soil interface and if the datum for gravitational head is set at the waterline using the hydraulic head H=h-z, then by Eqs. 6 and 8:

$$\alpha H=\ln\left[\frac{\Phi(R,Z)}{\Phi(R_o,Z)}\right]-2Z \qquad (11)$$

Eq. 11 was used to approximate the edge of a percolation test hole.

The following assumptions were assumed in applying Eq. 11:

1. No flow occurs across the free water surface of the simulated test hole.
2. $K = K_o \exp(\alpha h)$ as given in Eq. 1 applies.
3. Infiltration has reached a steady state.

To illustrate how Eq. 11 may be applied, consider Figure 1 which simulates a test hole of 5 cm radius. The shaded area on Figure 1 depicts the test hole area where free water is ponded. Figure 2 simulates a test hole of 15 cm radius. The dimensions of these test holes represent the extremes of the recommended test hole dimensions (U. S. Public Health Service, 1957).

The curve BC in each case is the approximation for the wall of the test hole ($\alpha H=0$). Line BD is the free surface line ($\alpha h=0$) and the region CBD is a region where h is actually positive or is saturated with water. The maximum error by use of Eq. 2 in the positive pressure range would occur at C and the resulting ratio of K to K_o would be $\exp(\alpha h)$ with h as the depth of water in the hole.

The location and strengths of the two point sources that best approximated the exact shape of the test hole were needed. The sensitivity using point sources at different locations and strengths was examined. Table 1

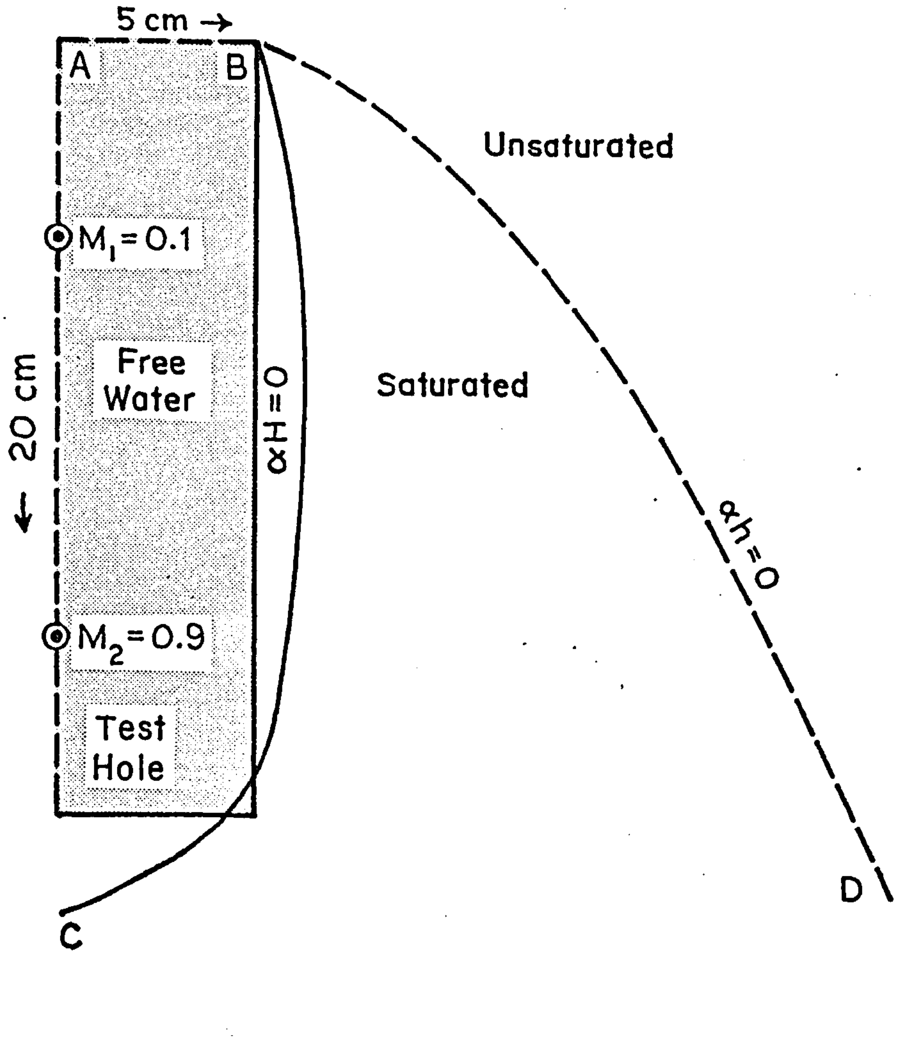

Figure 1. Approximation of 5 cm radius test hole by $\alpha H=0$ curve. -- Zones of saturated and unsaturated soil is indicated by $\alpha h=0$ curve ($\alpha=0.01$).

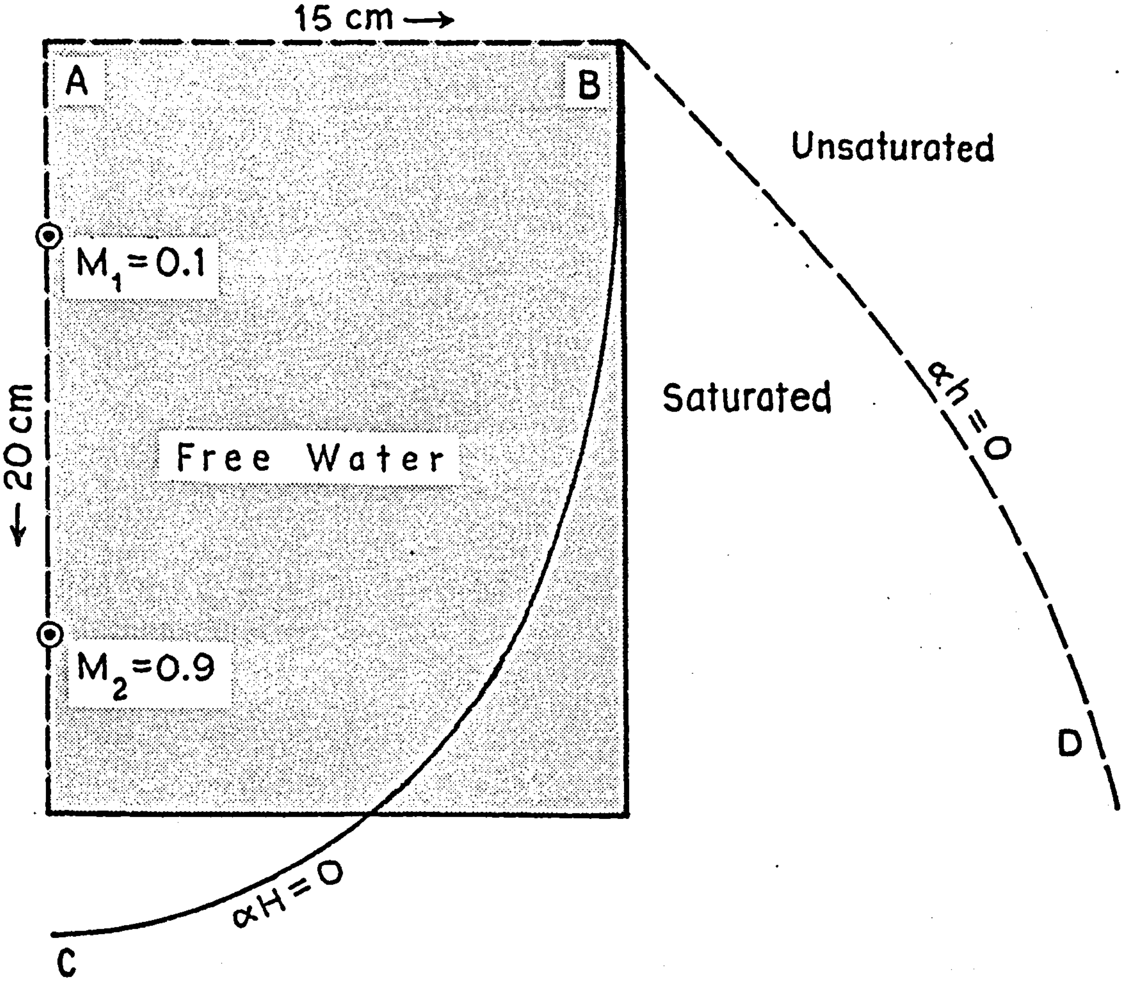

Figure 2. Approximation of 15 cm radius test hole by $\alpha H=0$ curve and zones of saturated and unsaturated soils ($\alpha=0.01$).

Table 1. Values of $\Phi(R_o,0)$ for two point sources of varying depth and strength in a 15 cm radius percolation test hole and assuming a value of α=0.10.

First Source		Second Source		
Depth (cm)	Strength	Depth (cm)	Strength	Φ(Ro,0)
8	0.10	18	0.90	0.15
10	0.10	15	0.90	0.19
10	0.25	15	0.75	0.21
5	0.10	15	0.90	0.21
10	0.50	15	0.50	0.25
5	0.33	15	0.67	0.28
10	0.75	15	0.25	0.28
5	0.10	10	0.90	0.33

indicates that for R_o equal to 15 cm, changes in depth and relative strength of the two point sources could produce significant changes in the resulting curves since the values of $\Phi(R_o,0)$, which is inversely related to q, vary considerably. The value of $\Phi(R_o,0)$ for point sources placed at 5 and 15 cm depth with 1 to 9 relative strengths represented the median value and was chosen for the later analysis.

The same basic relationships and assumptions can be employed to simulate infiltration from absorption trenches. By use of Eq. 9 and 11, line sources were taken at 5 and 15 cm with relative strengths of 1 to 9. Figure 3 illustrates the αH and αh equals zero curve for a 30 cm width absorption trench.

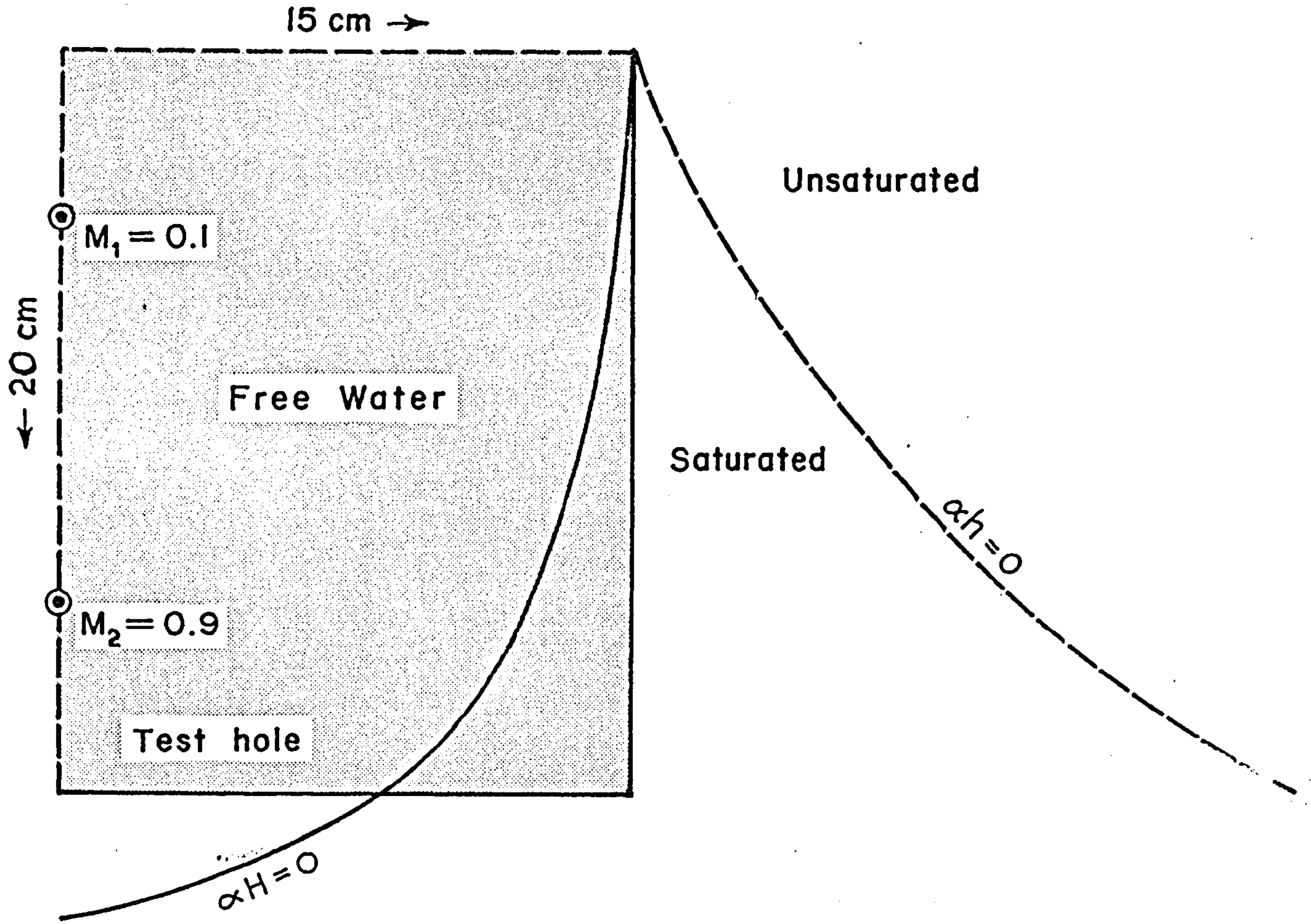

Figure 3. Approximation of 30 cm wide absorption trench by $\alpha H=0$ curve and zones of saturated and unsaturated soils for $\alpha=0.01$.

SOILS AND METHODS

Soils

Nine locations in eastern Pima county were selected for study. These soils were typical of the soil types on which on-going or planned development is occurring. Most of these soils are found near Tucson. The classification of the soils found at each site and a brief description of their characteristics are presented in Table 2. Detailed pedon descriptions and the locations for these soils are included in Appendix A.

Site Preparation

All test holes were dug using hand tools to minimize compaction and smearing of the sides of the hole. Four to six holes 10 to 30 cm in diameter and 60 cm deep were prepared. The 30 cm diameter holes were used for the standard percolation tests whereas the other variable diameter test holes were used to determine the relationship between test hole diameter and percolation rate. The pattern of test hole placement varied according to the number of test holes constructed. In general test holes were spaced 3 m apart. The entire study area for each site encompassed approximately 75 m^2. The sloughing

Table 2. Classification and description of the nine representative soils investigated in this research.*

Classification	Description of Characteristics
Pima fine-silty, mixed, thermic, Anthropic Torrifluent	Brown, moderately-fine textured alluvial soil which is under cultivation.
Guest fine, mixed, calcareous, thermic, Anthropic Torrifluent	Same as Pima except this soil is fine in texture. In some pedons, montmorillonite dominates.
Tubac fine-loamy, mixed, thermic, Typic Haplargid	Brown, fine-textured soil which contains a moderate amount of carbonates.
Palos Verdes (I) fine-loamy, mixed, thermic, Haplic Durargid	Brown soil which contains a duripan at approximately 50 cm which is hard when dry but friable when moist.
Mohave fine-loamy, mixed, thermic, Typic Haplargid	Same as Tubac except this soil is moderately fine in texture and contains buried B horizons at 38 cm.
Gila coarse-loamy, mixed, calcareous, thermic, Typic Torrifluent	Pale brown, medium textured alluvial soil which is under cultivation.
Palos Verdes (II) fine-loamy, mixed, thermic, Haplic Durargid	Same as Palos Verdes (I) except larger diameter coarse fragments can be found throughout the profile.
Grabe coarse-loamy, mixed, calcareous, thermic, Anthropic Torrifluent	Grayish brown soil that is moderate in texture and contains a moderate amount of carbonates.
Valencia coarse-loamy, mixed, calcareous, thermic, Typic Haplargid	Brown soil which consists of coarse alluvial material overlying Palos Verdes type soil to a depth of 55 cm.

*Taken from Soil Survey Staff, 1967.

of soil from the side walls was generally not as large a problem as reported by other investigators (Hill, 1966; Luce, 1973; Winneberger, 1972; Winneberger and Klock, 1972) possibly because most of the soils contained a relatively high clay content through the portion of the profile affected by the percolation test. To protect the bottom of the test hole from scouring and sedimentation, 5 cm of pea gravel (5 to 7.5 cm in diameter) was added to each test hole as recommended by the U. S. Public Health Service (1957).

Constant Head Device

Since the tests were conducted in late spring and summer when the antecedent soil moisture content was low, test holes were pre-wetted in order to obtain equilibrium percolation rates. After preparation of the test holes, constant head devices were utilized to maintain the water level at approximately 25 cm from the bottom of the test hole during the pre-soaking period. This device is illustrated in Figure 4.

This apparatus contains a 0.208 m^3 reservoir that serves as a source for the water in the test hole. The constant head regulator maintains the head in the test hole so that at equilibrium $h_1=h_2$ (see Figure 2). As the level of h_2 decreases, a pressure gradient is established, causing water to move from the reservoir through

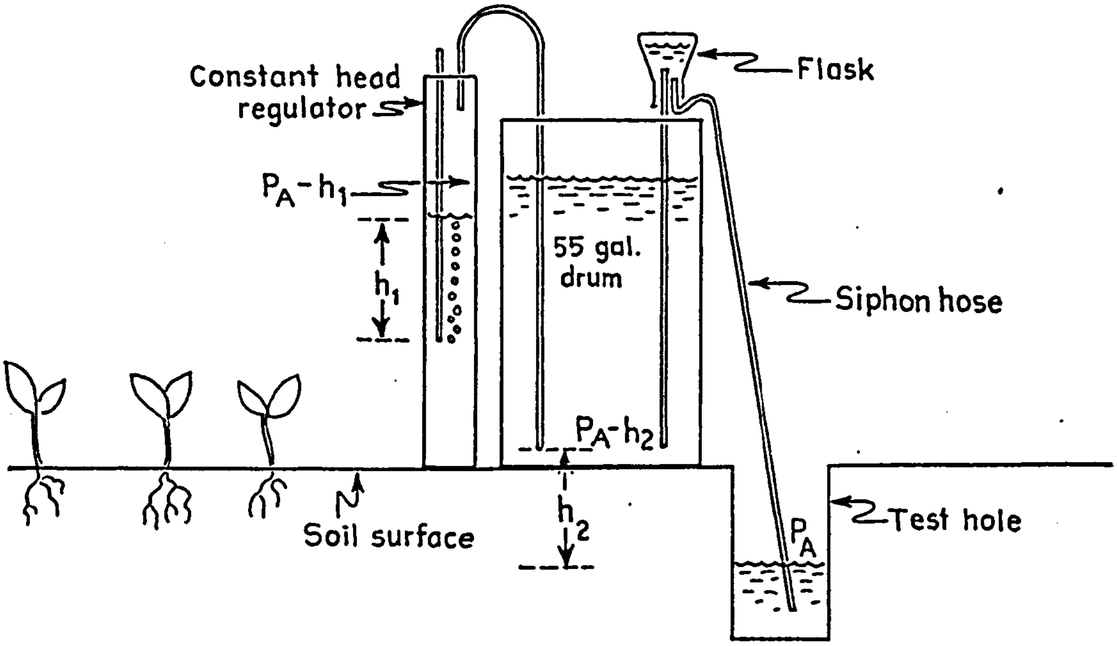

Figure 4. Constant head device

the siphon tube into the test hole. Concurrently, air enters the constant head regulator and displaces the water leaving the reservoir. Once equilibrium is attained ($h_1=h_2$), the siphoning device stops and bubbling ceases in the constant head regulator. The flask was filled with water so that air bubbles formed in the siphoning line could displace this water, therefore maintaining the siphon from the reservoir to the test hole. Coarse textured soils required 24 hours while fine textured soils needed 48 hours to reach a constant infiltration rate. The quantity of water used at each hole ranged from 0.42 to 0.83 m^3.

Measurement of Percolation Rate

After pre-soaking the test holes, the percolation rates were measured. A float gage (Figure 5d) was used to measure the standard percolation rate as recommended by Winneberger (1972). The water level in the hole was stabilized at 20 cm for the initial reading on the float gage. Next, the time required for the water level to fall from 20 to 17.5 cm above the bottom of the test hole was determined. The rate of this 2.5 cm fall in head was utilized as the standard percolation rate. These values were employed in the statistical analysis presented in the next section.

A pictorial sequence depicting the field procedures utilized is given in Figure 5.

Figure 5. Sequence of field procedures. -- A. Equipment to construct test hole. B. The siphon is forced into the reservoir. C. The test hole is allowed to soak. D. A falling head gauge measures the rates.

As reported by Derr et al. (1969) and Luce (1973), a number of soil parameters affect percolation rates in different soils. Consequently, soil samples from 40 to 60 cm in depth were collected at each test hole. The percent sand, silt, and clay were determined by use of the pipette method as described by Day (1965). The percent gravel was measured using a 2 mm sieve. The pH (Peech, 1965), electrical conductivity of the saturated extract (EC_e) (Bower and Wilcox, 1965), and the ml of EDTA (ethylenediamine-tetraacetic acid) required to chelate the calcium and magnesium in 1 ml of the saturated extract (Heald, 1965) were determined. Also, the percent carbonates in the subsoil was determined by the acid neutralization procedure described by Allison and Moodie (1965).

RESULTS AND DISCUSSIONS

Test Results and Variability

The percolation rates for each site indicate the suitability of that location for septic tank usage. Based on the standards recommended by the Manual of Septic Tank Practices (U. S. Public Health Service, 1957) and the regulations employed by the state of Arizona (Arizona State Department of Health, 1962), a standard percolation rate that is slower than 60 minutes per inch (2.5 cm per hour and/or 1 inch per hour) is unsuitable for a leaching system.

Table 3 presents the average results of the percolation determinations for the 30 cm diameter test holes.

The coefficient of variability (C. V.) was calculated as described by Steel and Torrie (1960):

$$C.V. = 100s/\bar{x} \qquad (12)$$

where "s" is the standard deviation of the percolation rate and "$\bar{x}$" is the mean value of the percolation rate for each site. The values for C. V. ranged from 7.4 to 47.6 percent with an average value of 23 percent. These values are lower than those obtained by Derr et al. (1969). By use of Duncan's Multiple Range test at

Table 3. Mean standard percolation rates, significant differences in mean rates, coefficient of variability and suitability of the nine sites for subsurface sewage disposal.

Soil.	cm/hr	in/hr	min/in	Stat. Sig.*		C.V.	Suitability
Pima	1.75	0.70	85.7	│		29.3	Unsuitable
Guest	1.85	0.74	81.1	│		25.9	Unsuitable
Tubac	2.02	0.81	74.1	│		7.4	Unsuitable
Palos Verdes (I)	5.18	2.07	29.0	│		10.2	Suitable
Mohave	7.22	2.89	20.8	│	│	14.6	Suitable
Gila	7.30	2.92	20.5	│	│	18.6	Suitable
Palos Verdes (II)	8.35	3.34	18.0		│	47.6	Suitable
Grabe	8.98	3.59	16.7		│	21.2	Suitable
Valencia	21.48	8.59	7.0			12.9	Suitable

*Duncan's Multiple Range Test at the 5% level.

the $\alpha=0.05$ significance level, Table 3 also illustrates between which soils a significant difference in mean percolation rate exists.

Regression Analysis

Randomized complete 4 by 4 blocks (4 different test hole diameters and 4 replications for each of the 4 diameters) were utilized to determine the relationship of test hole diameter for Pima cl, Gila vfsl, and Valencia sl to measured percolation rates. Test hole diameters of 10, 20, 25, and 30 cm were constructed for each of the three sites studied. Pre-soaking and measurement of the standard percolation rate were conducted as previously mentioned. Regression analysis was completed on the resulting data, and the results of these tests are shown in Figures 6 to 8. The results indicate a significant linear relationship exists between test hole diameter and percolation rate. These findings are contrary to those found by Bendixen et al. (1950) who discovered that no significant relationship existed between test hole diameter and percolation rates. However, they failed to establish the initial level of water in the test hole at 20 cm before measuring the rate of fall of 2.5 cm of water which could significantly alter the results.

A simple mathematical investigation can illustrate the differences in percolation rate for test holes of

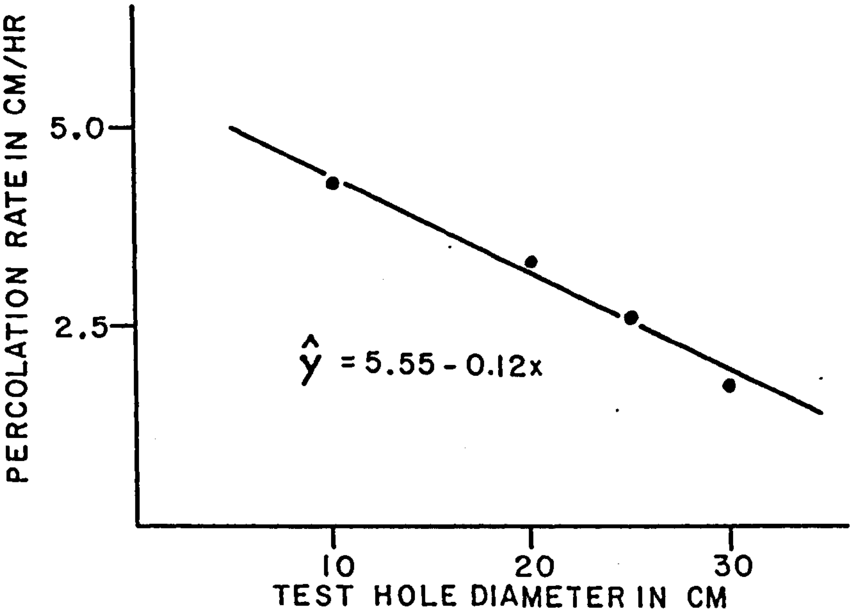

Figure 6. Percolation rate vs. test hole diameter for Pima cl

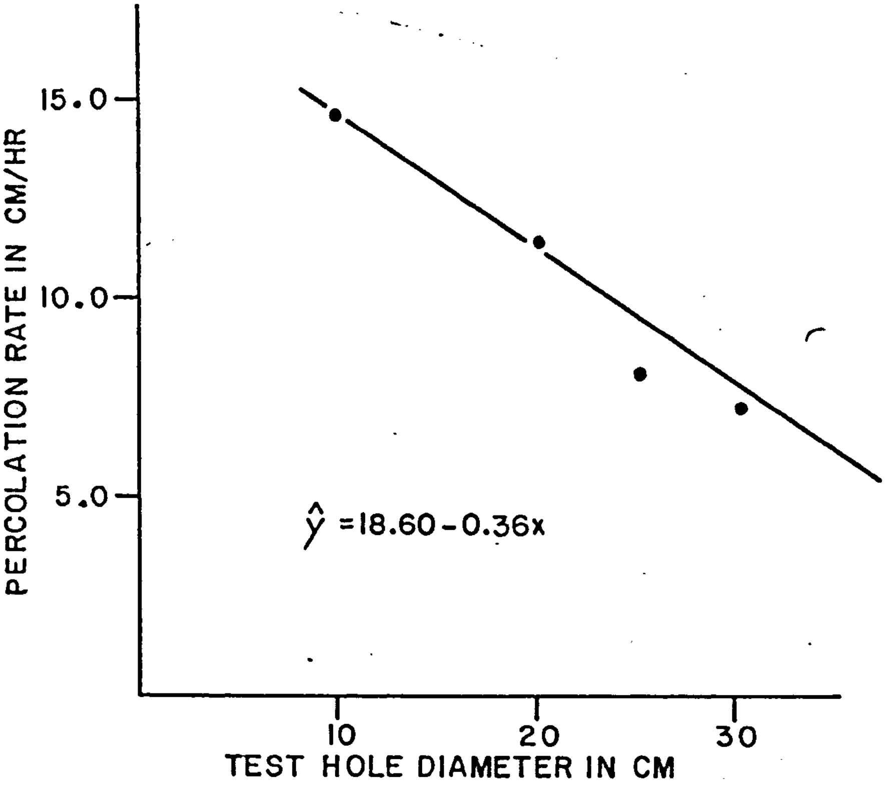

Figure 7. Percolation rate vs. test hole diameter for Gila fsl

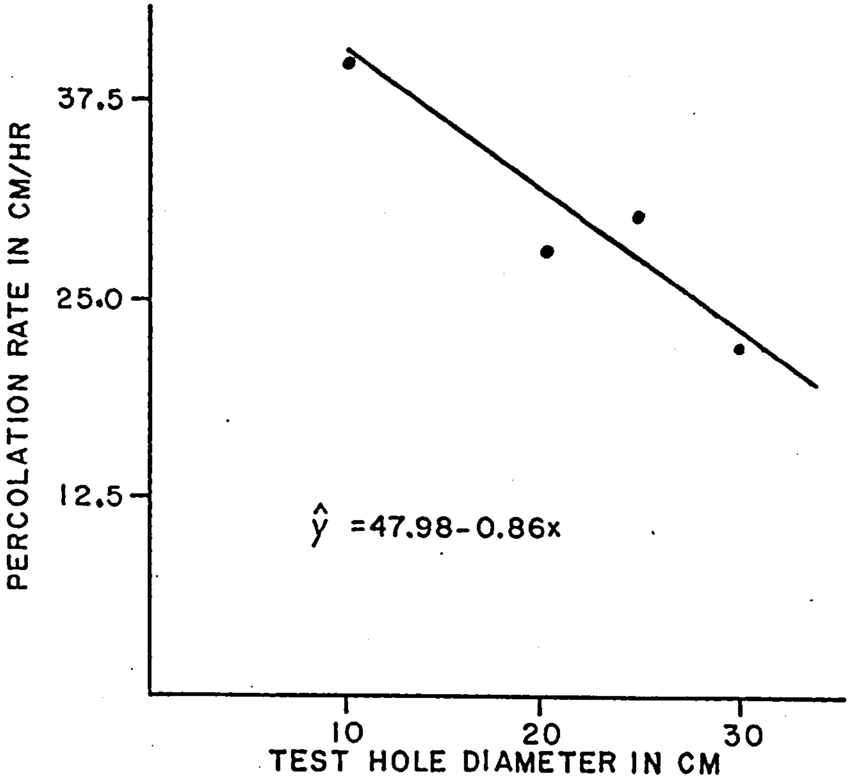

Figure 8. Percolation rate vs. test hole diameter for Valencia sl

different diameters. The average infiltration rate i over the water-soil interface (see Figure 1) during an increment of time is:

$$i = \frac{1}{A}\frac{\Delta V}{\Delta t} = \frac{\pi r^2 \Delta h}{(\pi r^2 + 2\pi r h)\Delta t} = \frac{r\Delta h}{(r+2h)\Delta t} \qquad (13)$$

where: i=average flux per unit area of soil-water interface

A=area of the side walls and bottom of the hole

Δ V=change in volume of water in the test hole

Δ t=an increment of time

r=radius of the test hole

Δh=initial depth of water (head) in the test hole

h=change in head in the test hole.

If i is assumed to be independent of test hole diameter, then the relationship between the average infiltration rates of two different diameter test holes in the same soil can be expressed by the following equations:

$$i_1 = i_2 \qquad (14)$$

therefore:

$$\frac{r_1\Delta h_1}{(r_1+2h_1)\Delta t_1} = \frac{r_2\Delta h_2}{(r_2+2h_1)\Delta t_2} \qquad (15)$$

If the percolation rates in the two test holes are expressed as:

$$PR_1 = \frac{\Delta h_1}{\Delta t_1} \quad \text{and} \quad PR_2 = \frac{\Delta h_2}{\Delta t_2} \qquad (16)$$

then Eq. 15 reduces to:

$$PR_1 = \frac{(1+2h_1/r_1)}{(1+2h_2/r_2)} PR_2 \qquad (17)$$

By use of this relationship, the percolation rates for holes of 10 cm diameter were calculated on the basis of the rates obtained in the 30 cm diameter test hole. These values were then compared to the actual values for the percolation rates for the 10 cm diameter test holes of the Pima cl, Gila vfsl, and Valencia sl test sites.

Table 4. Measured percolation rates for 10 and 30 cm diameter test holes. -- Values in parentheses are predicted values using 10 cm results and assuming "i" of Eq. 13 is independent of diameter.

	Percolation Rates in cm/hr	
Soil	30 cm dia.	10 cm dia.
Pima cl	1.75	4.28 (4.02)
Gila sl	7.30	14.92 (16.79)
Valencia sl	21.48	39.08 (49.04)

By Eq. 17, the percolation rate in a 10 cm diameter test hole would be 2.3 times faster than the rates in a 30 cm diameter test site.

Correlation of Various Soil Parameters to Percolation Rates

After analyzing each soil sample, the mean values for each of the soil parameters at each location were calculated. These data are presented in Table 5. The individual percolation rates for every test hole on the nine study sites are presented in Appendix B.

Table 5 indicates that no sodium (from the ml EDTA data) or salinity (from the EC_e data) problem exists in the subsoil of the nine sites. In some situations, however, these parameters could exert a great impact on the standard percolation rates and the absorption of sewage effluent. The pH for each subsoil sample is slightly alkaline and a slight to moderate quantity of carbonates can be found in the subsoil of each site. The presence of carbonates in indurated or unconsolidated form also affect the standard percolation rates and the absorption of sewage effluent.

Even though the two Palos Verdes sites indicate small differences in the measured subsoil parameters, the standard percolation rate for Palos Verdes (I) is slower than that for Palos Verdes (II). The Palos Verdes (I) contains considerably smaller diameter gravel particles than Palos Verdes (II) and is the possible cause of the observed differences in standard percolation rates.

Scatter diagrams can be used to depict general relationships. A scatter diagram of the percolation rate vs. percent sand in the subsoil is presented in Figure 9 for the results from the 30 cm diameter test hole. This diagram indicates a fairly linear relationship with a

Table 5. Average values for percolation rates and selected subsoil parameters.

Perc. Rate (cm/hr)	% clay	% silt	% sand	% gravel	pH	mmhos/cm EC.e	ml EDTA	% carbonates
				Pima Soil				
1.75	26.8	50.0	23.2	3.8	7.76	0.31	0.34	4.9
				Guest Soil				
1.85	38.4	27.2	34.4	21.4	7.75	0.11	0.22	3.2
				Tubac Soil				
2.02	47.5	17.8	34.5	10.3	8.06	0.19	0.22	5.2
				Palos Verdes (I) Soil				
5.18	21.4	15.9	62.7	51.8	7.75	0.23	0.44	7.4
				Mohave Soil				
7.22	30.3	22.8	46.7	19.6	7.66	0.23	0.42	4.0
				Gila Soil				
7.30	6.5	20.6	72.9	5.0	8.14	0.20	0.44	4.5
				Palos Verdes (II) Soil				
8.35	20.9	17.1	62.0	53.2	7.77	0.19	0.66	1.6
				Grabe Soil				
8.98	17.3	39.7	43.0	2.8	8.07	0.44	0.26	7.4
				Valencia Soil				
21.48	16.3	14.1	69.6	32.7	7.92	0.13	0.28	3.0

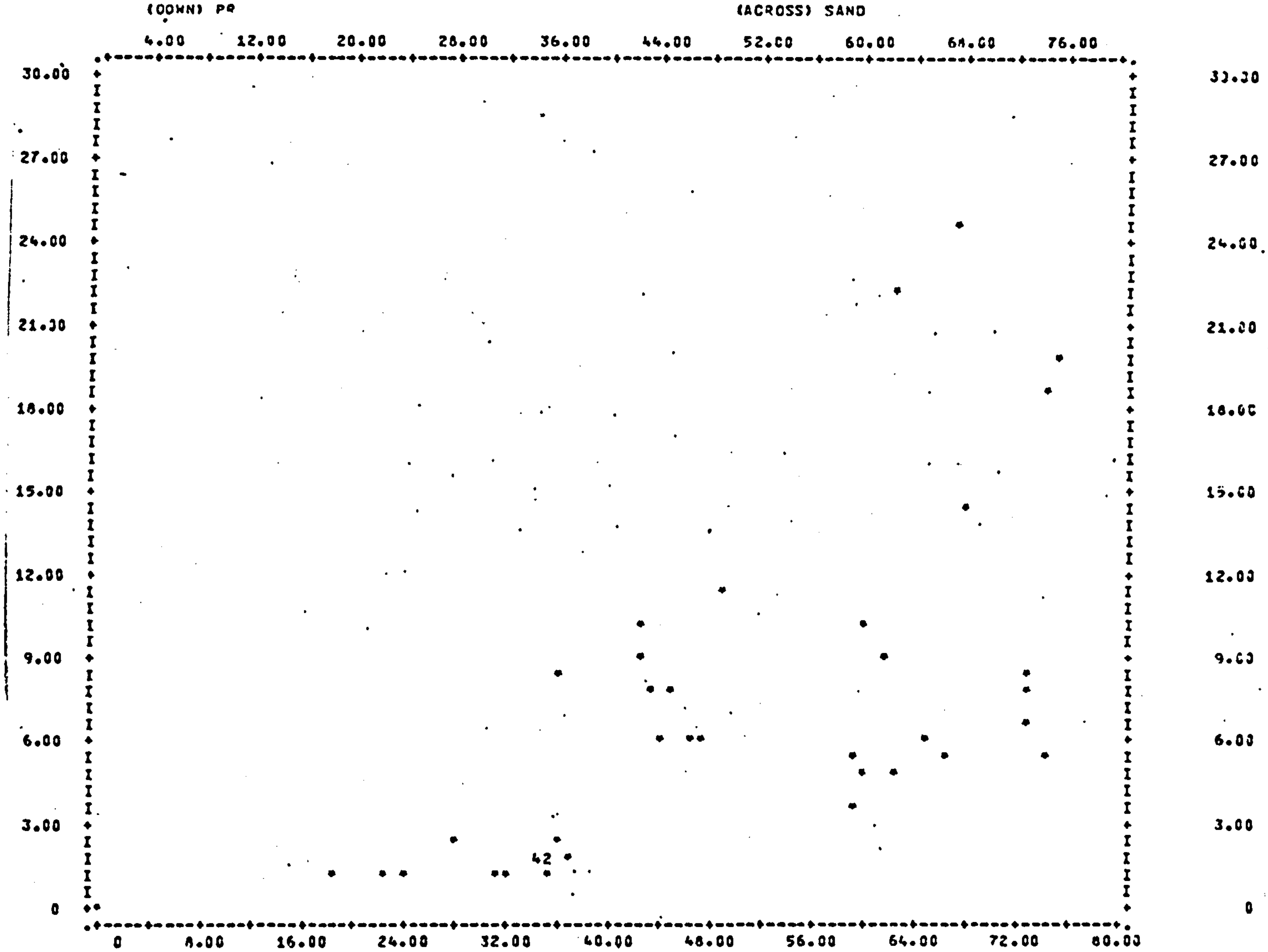

Figure 9. Scatter diagram of percolation rate vs. percent sand in the subsoil.

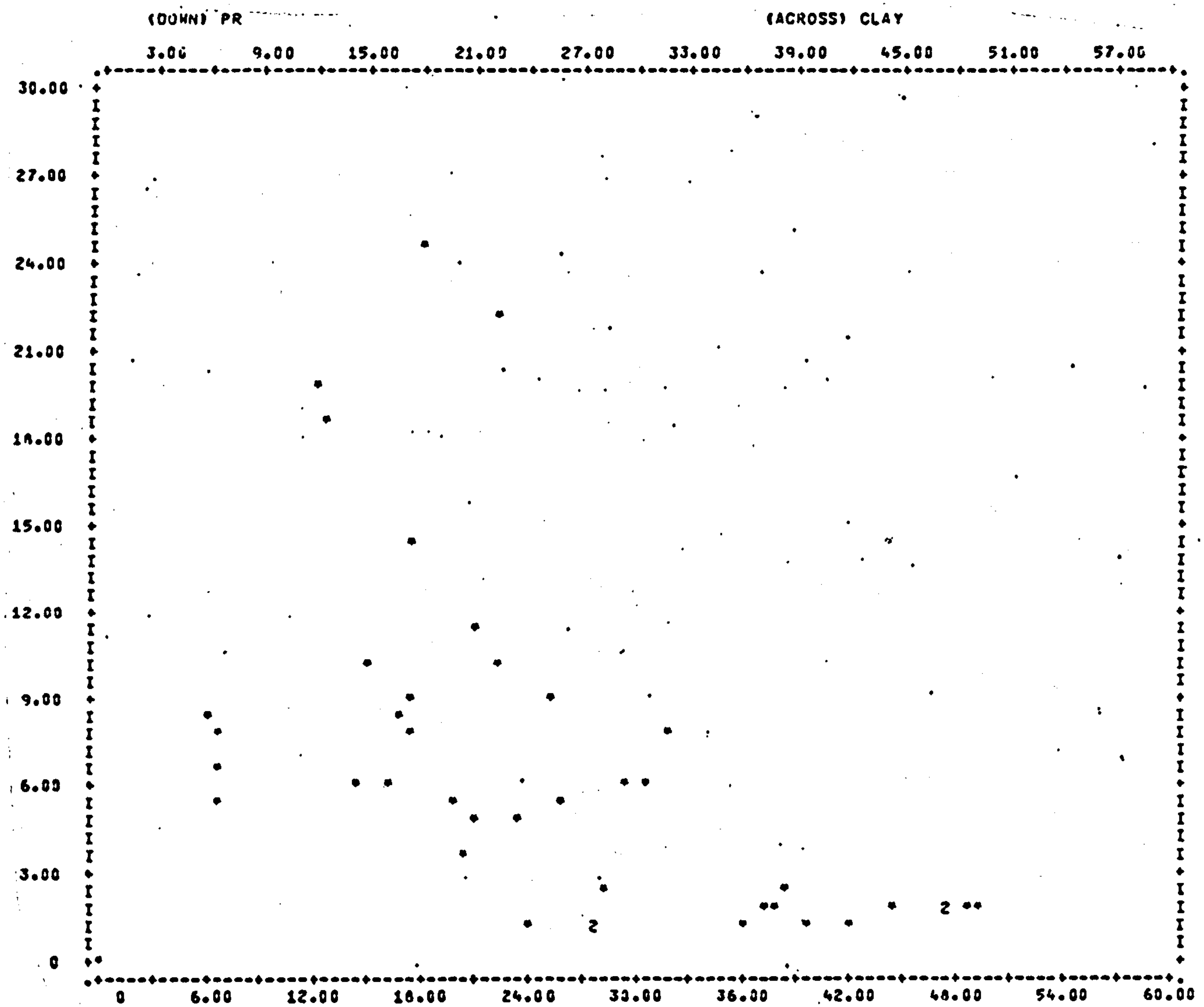

Figure 10. Scatter diagram of percolation rate vs. percent clay in the subsoil.

positive slope exists. Figure 10 provides the scatter diagram for the percolation rate vs. percent clay in the subsoil. A linear relationship with a negative slope exists.

The data for the subsoil parameters for the samples from each test hole were utilized for correlation with individual standard percolation rates. The resulting correlation coefficients (r) are presented in Table 6. These values were calculated as described by Steel and Torrie (1960).

Table 6. Correlation of standard percolation rates with selected soil parameters.

Soil Parameter	Correlation Coefficient (r)
Percent clay in subsoil	-0.549**
Percent silt in subsoil	-0.337*
Percent sand in subsoil	0.647**
percent gravel in subsoil	0.255
pH at the subsoil	0.086
EC_e of the subsoil	-0.016
ml EDTA for the subsoil	0.136
Percent carbonates in subsoil	-0.161

*,** Denotes significance at 5% and 1% levels respectively.

The following correlations to standard percolation rates were observed:

1. Very significant positive correlation with percent sand in the subsoil
2. Very significant negative correlation with percent clay in the subsoil
3. Significant negative correlation with percent silt in the subsoil.

The percolation rate measured in this study was correlated only with soil texture. Derr et al. (1969) found that drainage class, percent coarse fragments, percent silt, and percent clay in the subsoil were significantly correlated with standard percolation rates found on Pennsylvania soils. Luce (1973) discovered significant correlation of percent clay and bulk density of the subsoil on a number of soils found in Iowa.

Multiple regression, using the subsoil parameters listed in Table 6, produced a coefficient of determination (r^2) of 0.62. Consequently, the measured parameters explained 62 percent of the variation associated with standard percolation rates (Steel and Torrie, 1960). Derr et al. (1969) found a coefficient of determination of only 0.16 for their selected soil factors, while Luce (1973) found a range from 0.52 to 0.77 for his measured parameters.

An analysis of variance, as described by Steel and Torrie (1960), of the subsoil parameters indicated that all of the subsoil variables were significantly (at the $\alpha=0.05$ level) different between sites. The results in Table 7 are in agreement with the information reported by Derr et al. (1969).

Table 7. Analysis of variance for soil parameters related to percolation rates.

Soil Characteristic	F Ratio and Significance
% clay in subsoil	96.837**
% silt in subsoil	56.336**
% sand in subsoil	112.410**
% gravel in subsoil	32.241**
pH of subsoil	4.124*
EC_e of subsoil	11.237**
ml EDTA for subsoil	12.205**
% carbonates in subsoil	55.143**

*,** Denotes significance at 5% and 1% levels respectively.

Infiltration from Point and Line Sources

A relationship between the ratio of measured percolation rates in different sized test holes and the ratio for calculated values of $\Phi(R_o,0)$ for the same dimensions was established. As previously mentioned, two point sources at 5 and 15 cm depth and 1 to 9 relative strengths were utilized in the calculations. The standard values for the volumetric flow rate (q_s) found from the measured percolation rates and $\Phi(Rs,0)$ were taken for the largest test hole which was 15 cm in radius. The ratios of q for 10, 20, and 25 cm diameter test holes to the rates in the 30 cm diameter sites were compared for the Pima cl, Gila vfsl, and Valencia sl soils. These values were plotted against the radius of each test hole. On the same figure, the ratios of $\Phi(R_s,0)$ for a radius of 15 cm were compared to the value of $\Phi(R_o,0)$ at 5 and 10 cm for α values of 0.01, 0.05, and 0.10. These curves are shown in Figure 11.

Ideally, the slopes of the curves for q/q_s and $\Phi(R_s,0)/\Phi(R_o,0)$ could be compared so that a value of α could be assigned to each soil. Unfortunately, these curves did not match very well so that assignment of a value of α to the three soils was unfeasible.

A relationship between percolation rates in a cylindrical test hole and a disposal trench can be derived. Eq. 10 and the following equation were used to make this analogy:

$$\Phi(X_o,0) = 2\pi\varphi/q' \qquad (18)$$

where q' is the combined flow from the two line sources. Consequently, by combining Eqs. 10 and 18, the desired equation is:

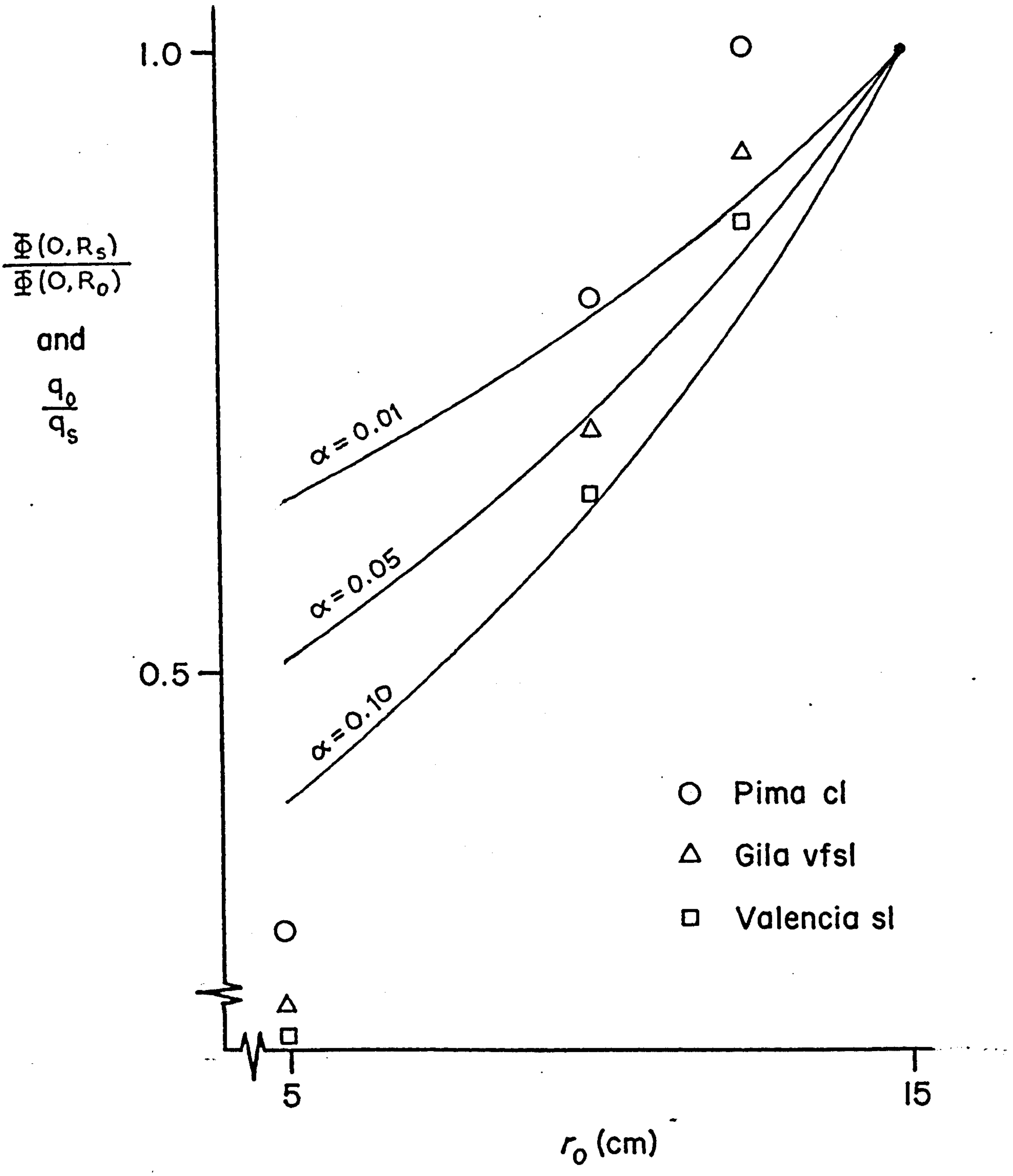

Figure 11. Relationship between α and volumetric flow rates (q) in different diameter test holes for the Pima cl, Gila vfsl, and Valencia sl soils.

$$q'/q = \alpha\Phi(R_o,0)/4\Phi(X_o,0) \qquad (19)$$

For values of the test hole radius (r_o) of 5 and 15 cm and the line source location (x_o) of 15, 20, and 45 cm from the center plane of the absorption trench and different values of α, Eq. 19 was used to produce the plots shown in Figure 12. Values for α of 0.01, 0.05, and 0.10 were used for low, medium, and high flow rates, respectively. These values are consistent with those reported by Braester (1973).

The curves may be used to convert the volumetric flow rate from a percolation test hole to the flow rate ($L^3/T/L$) from an absorption trench. The analysis is accomplished by multiplying the volumetric flow rate obtained from the standard percolation test times the right hand portion of Eq. 19. Therefore, once the standard percolation rates are measured and a value of α is estimated for a particular soil (Figure 11), the volumetric flow rate per length of trench can be predicted. This is shown by the following example. On substituting a value of q, Eq. 19 becomes:

$$q' = \alpha q\Phi(R_o,0)/4\Phi(X_o,0) \qquad (20)$$

As an example of how Figure 12 may be used, consider a percolation rate in a 30 cm diameter test hole of 1.00 cm/hr (a slow rate) and a trench of 90 cm in width. Therefore, the following values are given:

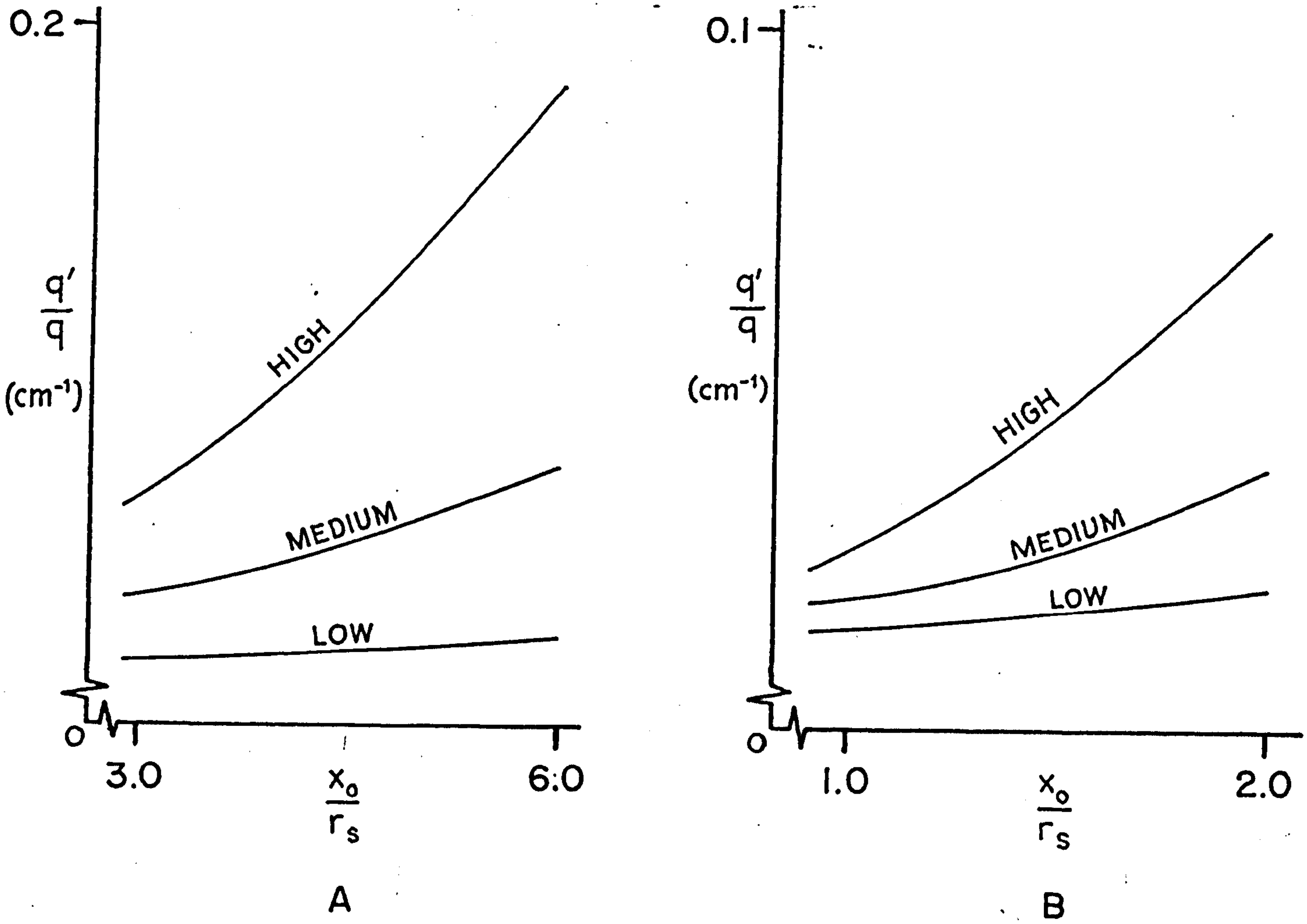

Figure 12. Relationship between volumetric flow rates in test holes to flow rates in simulated absorption trenches where r_s equals 5 cm (A) and 15 cm (B).

$q = 700 \text{ cm}^3/\text{hr}$

$\Phi(R_o,0) = 14$

$\Phi(X_o,0) = 1.8$

Substitution of these values into Eq. 20 yields a flow rate of 56 cm^3/hr/cm for an absorption trench placed in this type of soil. Consequently, this mathematical analysis effectively relates the standard percolation rates in a test hole to the flow rate anticipated in an absorption trench. With further refinement this technique could be used to establish standards for sewage loading rates through the septic tank system.

The use of finite differencing could improve the relationship between q/q_s and $\Phi(R_s,0)/\Phi(R_o,0)$ so that a value of α could be estimated. The advantage of this technique is that the boundaries of the test hole or absorption trench could be more realistically represented.

CONCLUSIONS AND RECOMMENDATIONS

Based on a study of the standard percolation rates on 80 test holes on nine typical soils found in eastern Pima county and measurement of various subsoil parameters, the following conclusions were formulated:

1. To obtain consistent results for percolation tests in Arizona, the test hole should be a standard diameter and pre-wetted before measuring the percolation rate.
2. A significant linear relationship exists between test hole diameter and percolation rate.
3. The following correlations to percolation rate were observed:
    a. Very significant positive correlation with percent sand in the subsoil
    b. Very significant negative correlation with percent clay in the subsoil
    c. Significant negative correlation with percent silt in the subsoil.
4. By assuming infiltration from two point sources and comparing calculated values of the dimensionless matric flux potential (Φ) to measured percolation rates, assignment of values of α to the Pima cl, Gila vfsl, and Valencia sl soils was very difficult.

5. Modeling of infiltration from line sources can be used to approximate the dimensions of an absorption trench. This technique can be used for prediction of infiltration rates from the disposal trenches. Finite differencing would be a better approach to use in order to relate percolation rates in a cylindrical test hole to actual flow rates in an absorption trench.

APPENDIX A

DETAILED SOIL PEDON DESCRIPTIONS

Soil type: Pima clay loam
Described by: O. J. Pereira (1971)
Location: 250 feet north and 150 feet east of the southwest corner of Field B-3 (Pereira, 1971) on the U of A Marana Experimental Farm.
Vegetation: Cultivated-fallow
Parent material: Mixed recent alluvium
Physiography: Nearly level floodplain
Slope: < 1%
Permeability: Moderately slow

A_p 0-11" (0-28 cm)--Brown (7.5YR 5/2) clay loam, dark brown (7.5YR 3/2) moist; massive breaking to weak medium and coarse subangular blocky structure; slightly hard to hard, friable, sticky, plastic; common very fine and fine roots; common very fine and micro tubular and interstitial pores; less than 1 percent gravel; common very fine mica flakes; strongly effervescent; abrupt smooth boundary.

A11 11-20" (28-50 cm) Brown (10YR 5/3) light clay loam, dark brown (10YR 3/3) moist; weak coarse subangular blocky structure; hard, friable, sticky, plastic; few very fine and fine roots; common micro and very fine tubular pores; common very fine mica flakes; strong effervescent; few very fine white (10YR 8/2) and light gray (10YR 7/2) lime filaments; abrupt smooth boundary.

A12 20-26" (50-65 cm). Light brownish gray (10YR 6/2) silty clay, dark brown (10YR 3/3) moist, with few medium faint dark brown (10YR 4/3) mottles; weak fine subangular and weak medium platy structure; hard, friable, sticky, plastic; common very fine roots; common micro and very fine tubular pores; less than 1 percent gravel; common very fine mica flakes; strongly effervescent; many very fine white (10YR 8/2) lime filaments, light gray (10YR 7/2) moist, abrupt wavy boundary.

C1	26-36" (65-90 cm). Brown (10YR 5/3) heavy silt loam, dark brown (10YR 4/3) moist; massive breaking to weak coarse subangular blocky structure; slightly hard, friable, slightly sticky, plastic; common very fine roots; common micro and very fine tubular pores; less than 1 percent gravel; common very fine mica flakes; strongly effervescent; common very fine white (10YR 8/2) lime filaments, light gray (10YR 7/2) moist; clear smooth boundary.
C2	36-54" (90-135 cm). Brown (10YR 5/3) light sandy clay loam, dark yellowish brown (10YR 4/4) moist; massive; slightly hard to hard, friable, sticky, plastic; few very fine roots; common micro and very fine tubular pores; 2 percent gravel; common very fine mica flakes; common very fine white (10YR 8/2) lime filaments, light gray (10YR 7/2) moist; clear smooth boundary.
C3	54-61" (135-152 cm). Pale brown (10YR 6/3) sandy loam, dark yellowish brown (10YR 4/4) moist; massive; slightly hard, very friable, slightly sticky, slightly plastic; few very fine roots; few very fine tubular pores; 5 percent gravel; common very fine mica flakes; strongly effervescent; abrupt smooth boundary.
C4	61-80" (152-200 cm). Pale brown (10YR 6/3) sand, dark yellowish brown (10YR 4/4) moist; single grain; very friable; nonsticky; nonplastic; 2 to 5 percent gravel; common very fine mica flakes; slightly effervescent.
C5	80-84" (200-210 cm). Pale brown (10YR 6/3) gravelly sand, dark yellowish brown (10YR 4/4) moist; single grain; loose, nonsticky, nonplastic; common very fine mica flakes; very slightly effervescent.

Soil type: Guest clay
Described By: M. L. Richardson, K. Barbarick (1-13-75)
Location: 1200' south and 660' east of the N¼ corner of Sec 14, T16S, R16E.
Vegetation: Tobosa, sideoats grama, whitethorn, vine mesquite
Parent material: Recent mixed alluvium over old alluvium
Physiography: Broad swale on valley plain
Slope: < 1%
Drainage: Well
%clay in control section: > 35%
Permeability: Slow

A1	0-1" (0-3cm)--Brown (7.5YR 5/2) light silty clay, dark brown (7.5YR 3/2) moist; weak fine and medium platy structure breaking to moderate fine granular; slightly hard, friable, sticky and plastic; few very fine and fine roots; many fine interstitial pores; slightly effervescent with disseminated lime; moderately alkaline (pH 8.0); abrupt smooth boundary.
C1	1-10" (3-48 cm). Dark brown (7.5YR 4/2) light clay, dark brown (7.5YR 3/2) moist weak medium subangular blocky structure; hard, friable, sticky and plastic; many very fine, common fine and a few medium roots; common very fine tubular pores; common medium slickensides 14-19"; strongly effervescent with disseminated lime; moderately alkaline (pH 8.0); clear wavy boundary.
C2	19-25" (48-63 cm). Brown (7.5YR 5/2) heavy clay loam, dark brown (5YR 3/2) moist; weak fine and medium subangular blocky structure; hard, firm, sticky and plastic; common very fine and a few fine roots; common very fine and a few fine tubular pores; common short slickensides; strongly effervescent with disseminated lime; moderately alkaline (pH 8.2); clear wavy boundary.
C3	25-39" (63-100 cm). Reddish brown (5YR 4/3) heavy clay loam, dark reddish brown (5YR 3/3) moist; massive; very hard, firm, sticky and plastic; common very fine and a few fine roots; few very fine and fine tubular pores; common fine faint pinkish white (5YR 8/2) lime veins; strongly effervescent; moderately alkaline (pH 8.2) gradual wavy boundary.

IIB2tcab 39-49" (100-125 cm). Reddish brown and yellowish red (5YR 5/4 & 5/6) light sandy clay, dark reddish brown (5YR 3/4) moist; weak medium angular blocky structure; hard, friable, sticky and plastic; common fine and very fine roots; common very fine and a few fine tubular and common fine interstitial pores; 10% fine gravel; common thin clay films on ped faces, bridging sand grains, and lining pores; many fine distinct pinkish white (5YR 8/2) lime veins and ped coatings; violently effervescent; moderately alkaline (pH 8.2); gradual wavy boundary.

IIB3tcab 49-60" (125-152 cm). Light reddish brown (5YR 6/4) gravelly sandy clay loam, reddish brown (5YR 5/4) moist; massive; hard, friable, slightly sticky and slightly plastic; few very fine roots; many fine and very fine tubular pores; 25% fine gravel; many fine distinct pinkish white (5YR 8/2) lime veins and gravel coatings; violently effervescent, moderately alkaline (pH 8.2).

Soil Type: Tubac gravelly loam
Location: Pima County, Arizona. 400' S, 2400' E NW corner Sec 5, T1rS, R15E, 75' west of road into USC & GS Magnetic Observatory.
Described by: J. Jay, M. L. Richardson, D. Nettleton, R. Barmore (12-17-74)
Vegetation: Creosotebush, cholla (jumping) cactus, mesquite burroweed, bush muhly, annual grasses, paper daisy, alfilaria.
Parent material: Old alluvium from igneous (mainly granitic) and sedimentary rocks.
Topography: Nearly level tops of old terrace.
Slope: < 1%
Drainage: Well drained.
Permeability: Slow, medium.

A1	0-1" (0-3 cm). Brown (7.5YR 5/4) fine gravelly loam, dark reddish brown (5YR 3/4) moist; weak coarse platy structure; slightly hard, very friable, slightly sticky and plastic; common very fine roots; common fine interstitial pores; 25% fine gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.
B1	1-4" (3-9 cm). Dark Brown (7.5 YR 4/4) fine gravelly loam, dark reddish brown (5YR 3/3) moist; weak fine and medium subangular blocky structure; many very fine tubular and a few fine tubular pores; 20% fine gravel; few clay bridges between sand grains; noneffervescent; mildly alkaline (pH 7.5); abrupt smooth boundary.
B21t	4-9" (9-22 cm). Reddish brown (5YR 4/3) fine gravelly clay, dark reddish brown (5YR 3/3) moist; moderate fine medium subangular blocky structure; hard, friable, very sticky and very plastic; many very fine roots; many very fine tubular pores; 20% fine gravel; many thin clay films bridging sand grains and lining pores; noneffervescent; mildly alkaline (pH 7.5); clear wavy boundary.
B22t	9-18" (22-45 cm). Reddish brown (5YR 4/4) clay, dark reddish brown (2.5YR 3/4) moist; moderate medium prismatic structure parting to strong medium angular blocky; hard, friable, sticky and very plastic; many very fine roots; a few fine and medium tubular and common fine interstitial pores; 10% fine gravel; many pressure faces; strongly effervescent with disseminated lime; moderate alkaline (pH 8.0); clear wavy boundary.

B23tca	18-25" (45-63 cm). Reddish brown (5YR 4/4) fine gravelly clay, reddish brown (5YR 4/4) moist; weak medium subangular blocky structure; hard; friable, sticky and very plastic; common very fine roots; common fine and very fine tubular and common fine and very fine interstitial pores; 15% fine gravel; many moderately thick clay films coating gravel and lining pores; common pressure faces; common fine and medium pink (5YR 7/3) soft lime masses; strongly and violently effervescent; moderately alkaline (pH 8.0) gradual wavy boundary.
B31ca	25-39" (63-100 cm). Reddish brown (5YR 5/3) fine gravelly clay loam, reddish brown (5YR 4/4) moist, massive; hard, friable, sticky and plastic; common very fine roots; a few fine and medium tubular pores; 20% fine gravel; common thin clay films bridging sand grains and lining pores; few fine and medium pinkish white (5YR 8/2) soft lime masses; many fine and medium ping (5YR 8/3) lime masses; violently effervescent; moderately alkaline (pH 8.0); gradual wavy boundary.
B2ca	39-52" (100 - 132 cm). Light reddish brown (5YR 6/4) fine gravelly clay loam, reddish brown (5YR 4/4) moist; massive; very hard, very friable, sticky and plastic; few very fine roots; many very fine and common fine tubular pores; 20% fine gravel; common thin clay films bridging sand grains and lining pores; few fine and medium pinkish white (5YR 8/2) soft lime masses; violently effervescent; moderately alkaline (pH 8.0); gradual wavy boundary.
C1	52-63" (132-165 cm). Pinkish gray (5YR 7/2) loam, reddish brown (5YR 5/3) moist; massive; hard, firm, sticky and slightly plastic; many very fine and common fine tubular pores; strongly effervescent; moderately alkaline (pH 8.0).

Soil Type: Palos Verdes gravelly sandy loam
Location: Pima County, Arizona, 500' west and 400' south of the NE corner Sec 34, T13S, R13E, 350' west of St. Marks Church.
Description by: J. Jay, M. Richardson, R. Barmore (12-16-74)
Vegetation: Palo Verde, bursage, creosotebush, bush muhly, barrel and prickly pear cacti, annual needle grama.
Parent material: Old alluvium from gneiss and other mixed rocks.
Topography: Nearly level to undulating shallowly dissected old fans
Slope: 2 percent
Drainage: well drained
Permeability: moderately slow to pan which is very slow
Remarks: This pedon is fairly modal. The pan may be more or less cemented and thicker or thinner.

A1 0-1" (0-3 cm). Brown (7.5YR 5/4) gravelly sandy loam, dark brown (7.5YR 4/4) moist; weak medium platy structure; slightly hard, very friable, nonsticky and nonplastic; a few fine roots; many fine interstitial pores; 30% fine gravel; noneffervescent; neutral (pH 7.0); abrupt smooth boundary.

B1 1-3" (3-8 cm). Brown (7.5 YR 5/4) gravelly heavy sandy loam, dark brown (7.5YR 4/4) moist; weak coarse platy structure parting to weak medium and fine subangular blocky; slightly hard, very friable, slightly sticky and slightly plastic; common fine and very fine roots; common fine interstitial pores; 20% fine gravel; few thin clay films as bridges and lining pores; noneffervescent; abrupt wavy boundary; mildly alkaline (pH 7.5).

B21t 3-8" (8-20 cm). Reddish brown (5YR 4/4) gravelly heavy sandy clay loam, dark reddish brown (5YR 3/4) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; many very fine and fine and a few medium roots; common fine and medium tubular and many fine interstitial pores; 30% fine gravel; common thin clay films on ped faces and in pores; noneffervescent; mildly alkaline (pH 7.5); clear wavy boundary.

B22t	8-15" (20-38 cm). Reddish brown (5YR 4/4) gravelly light sandy clay, dark reddish brown (5YR 3/4) moist; moderate medium subangular blocky structure; hard, friable, sticky and plastic; many very fine and a few medium and fine roots; few fine and medium tubular and common fine interstitial pores; 30% fine gravel; many thin clay films on ped faces and few moderately thick clay films in pores; noneffervescent; mildly alkaline (pH 7.5); clear wavy boundary.
B3sica	15-19" (38-48 cm). Yellowish red and reddish brown (5YR 5/6 7 4/4) gravelly sandy loam, yellowish red and reddish brown (5YR 4/6 & 4/3) moist; moderate coarse platy structure; very hard, firm, slightly sticky and slightly plastic; many very fine roots between plates and a few very fine and fine roots in peds; many very fine tubular and common very fine interstitial pores; 30% gravel; common thin clay films coating and bridging gravel; many medium distinct lime mottles that are pinkish white (5YR 8/2) dry and light reddish brown (5YR 6/4) moist; violently effervescent; mildly alkaline (pH 8.2); abrupt wavy boundary.
C1sicam	19-38" (48-97 cm). Pinkish white and pink (7.5YR 8/2 & 8/4) strongly cemented duripan, light brown (7.5YR 6/4) moist; weak coarse platy structure; very hard and strongly cemented, very firm, nonsticky and nonplastic; many very fine roots between plates and a few fine and very fine roots in matrix; common very fine and a few medium and coarse tubular pores and exped (interplate) pores; violently effervescent; moderately alkaline (pH 8.2); clear wavy boundary.
C2sica	38-64" (97-163 cm). Pinkish white and pink (7.5YR 8/2 & 8/4) gravelly loamy coarse sand, light brown (7.5YR 6/4) moist; massive; very hard and weakly to strongly cemented by silica; very firm, nonsticky and nonplastic; few very fine and fine roots; common fine and very fine interstitial and tubular pores and a few coarse tubular pores; violently effervescent, moderately alkaline (pH 8.2).

Soil type: Mohave sandy loam
Described by: M. L. Richardson, Ken Barbarick (1-13-75)
Location: 500' east and 1000' south of the NW corner sec 14., T16S., R16E.
Vegetation: Cholla, mesquite, whitethorn, 3 awn
Parent material: Old mixed alluvium
Physiography: Valley plain--upland
Slope: 1%
Drainage: well
% Clay in control section: ± 30%
Permeability: Moderately slow
Remarks: This pedon differs from modal Mohave in that the upper 15 inches appears to be a shallow soil that has formed over an older mohave-like pedon.

A11	0-1" (0-3 cm). Brown (7.5YR 5/2) sandy loam, dark reddish brown (5YR 3/3) moist; weak platy structure parting to weak fine granular; slightly hard, very friable, slightly sticky and slightly plastic; many very fine and a few fine roots; many fine interstitial pores; 10% fine gravel; noneffervescent, mildly alkaline (pH 7.5); abrupt smooth boundary.
B2t	1-10" (3.25 cm). Reddish brown (5YR 4/3) clay loam, dark reddish brown (5YR 3/3) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; many very fine and a few fine roots; common very fine and fine and a few medium tubular pores; 5% gravel; few thin clay films bridging and lining pores; noneffervescent, mildly alkaline (pH 7.5); abrupt smooth boundary.
B3t	10-15" (25-38 cm). Reddish brown (5YR 4/3) gravelly light sandy clay loam, dark reddish brown (5YR 3/3) moist; massive; slightly hard, friable, sticky and slightly plastic; many very fine and a few fine roots; many fine interstitial pores; 40% fine and medium gravel; few thin clay films bridging sand grains and lining pores; strongly effervescent with disseminated lime; moderately alkaline (pH 8.0); clear wavy boundary.

IIB'1tcab 15-26" (38-66cm). Reddish brown (5YR 4/3) clay loam, dark reddish brown (5YR 3/3) moist; weak medium subangular blocky structure; slightly hard, friable, sticky and plastic; common very fine and a few fine roots; many very fine and a few fine tubular pores; 5% fine gravel; few thin clay films bridging sand grains and lining pores; many fine distinct pinkish white (5YR 8/2) lime mycelia; strongly effervescent, moderately alkaline (pH 8.2), gradual wavy boundary.

IIB'21tcab.26-34"(38-86 cm). Reddish brown (5YR 5/4) clay loam, dark reddish brown (5YR 3/4) moist; weak medium fine and medium subangular blocky structure; slightly hard, friable, sticky and plastic; few fine and very fine roots; many very fine and a few fine tubular pores; 10% fine gravel; common thin clay films bridging sand grains and lining pores; many fine distinct pinkish white (5YR 8/2) lime veins; strongly effervescent; moderately alkaline (pH 8.2) clear wavy boundary.

IIB'22tcab 34-46" (86-117 cm). Reddish brown (5YR 5/4) heavy clay loam, reddish brown (5YR 4/4) moist; weak medium subangular blocky structure; slightly hard, friable, sticky and plastic; few fine and very fine roots; many very fine and a few fine tubular pores; 10% fine gravel; common thin clay films bridging sand grains and lining pores; many fine distinct pinkish white (5YR 8/2) lime veins; strongly effervescent, moderately alkaline (pH 8.2); clear wavy boundary.

IIB'3tcab 46-60" (117-152 cm). Light reddish brown (5YR 6/4) light clay loam, reddish brown (5YR 4/4) moist; massive; slightly hard, friable, slightly sticky and plastic; few very fine roots; many very fine and common fine tubular pores; 10% fine gravel; many medium distinct soft and a few hard lime masses that are pinkish white (5YR 8/2) dry and pink (5YR 7/3) moist; violently effervescent; moderately alkaline (pH 8.2); clear wavy boundary.

IIC1cab 60-66" (152-168 cm). Light reddish brown and pink (5YR 6/4 & 7/4) gravelly sandy loam, reddish brown and light reddish brown (5YR 5/4 & 6/4) moist; massive; slightly hard, very friable, slightly sticky and slightly plastic; many fine interstitial pores; 25% fine gravel; strongly effervescent with disseminated lime; moderately alkaline (pH 8.2).

Soil type: Gila very fine sandy loam
Described By: M. L. Richardson & Ken Barbarick (1-14-75)
Location: SE¼ Sec 19, T13S, R14E, 500 ' west and 700' north of SE corner, on the U of A Campbell Ave. Experimental Farm.
Vegetation: Cultivated--fallow
Parent material: Mixed recent alluvium
Physiography: Nearly level floodplain
Slope: < 1%
Drainage: Well
% Clay in control section: < 18%
Permeability: Moderate
Remarks: The control section of this pedon contains more fine sand than is modal for the Gila series. The control section for Gila is medium textured. The control section of Anthony is moderately coarse textured.

Ap 0-10" (0-25 cm). Pale brown (10YR 6/3) very fine sandy loam, dark brown (10YR 3/3) moist; massive; slightly hard, very friable, slightly sticky and slightly plastic; common very fine and a few medium roots; many very fine interstitial , common very fine and a few fine tubular pores; strongly effervescent with disseminated lime; moderately alkaline (pH 8.0); clear wavy boundary.

C1 10-33" (25-84 cm). Pale brown (10YR 6/3) very fine sandy loam, dark brown (10YR 4/3) moist; massive, slightly hard, very friable, slightly sticky and slightly plastic; many very fine, common fine and a few medium roots; many very fine, common fine and a few medium tubular pores; strongly effervescent with disseminated lime; gradual wavy boundary.

C2 33-51" (48-130 cm). Light yellowish brown (10YR 6/4) fine sandy loam with thin very fine sandy loam strata, dark yellowish brown (10YR 4/4) moist; massive; slightly hard, very friable, nonsticky and nonplastic; common very fine and fine roots; many very fine and common fine tubular pores; strongly effervescent with disseminated lime; clear wavy boundary.

C3 51-60" (130-150 cm). Light yellowish brown (10YR 6/4) loamy sand; dark yellowish brown 10YR 4/4) moist; massive; slightly hard, very friable, nonsticky and nonplastic; few very fine and fine roots; many very fine interstitial and common very fine and fine tubular pores; strongly effervescent with disseminated lime.

Soil type: Palos Verdes gravelly sandy loam
Described by: M. L. Richardson and Ken Barbarick (8-5-74)
Location: 500' south of Anklam Rd., 50' west of dirt road or about 1800' E and 1800' N of SW corner of Sec. 10 T14S, R13E.
Vegetation: Bursage, creosotebush, whitethorn, bush muhly, spike dropseed, palo verde, catclaw, saguaro, cholla and prickly pear, Christmas cacti.
Parent material: Old alluvium from ignimbrite, basalt, granodiorite, and volcanic ash and tuff.
Physiography: Undulating old alluvial fan
Slope: 3%
Drainage: Well
Surface coarse fragments: 50% gravel, 5% cobble
Permeability: Moderate
Remarks: Depth within the perc. test area to the Cicasi horizon ranges from 18 to 24 inches. Palos Verdes soils normally have this horizon at 20 inches. Gravel content in the control section is on the high end of the range for the series (15-35%).

A1 0-1" (0-3 cm). Brown (7.5 YR 5/4) gravelly sandy loam, dark brown (7.5YR 4/4) moist; weak medium and fine platy structure breaking to fine granular; slightly hard, very friable, nonsticky and nonplastic; common very fine roots; common fine and very fine and a few medium tubular pores; 35% gravel by volume; moderately alkaline; abrupt smooth boundary.

B21t 1-17" (3-43 cm). Reddish brown (5YR 5/4) gravelly heavy sandy clay loam, reddish brown (5YR 4/4) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; many very fine and common fine roots; common fine exped pores; few fine and very fine tubular pores; common moderately thick clay film bridging and coating gravel; 35% gravel by volume; moderately alkaline; clear wavy boundary.

B22tca 17-21" (43-53 cm). Reddish brown (5YR 5/4) gravelly sandy clay loam, reddish brown (5YR 4/4) moist; weak medium subangular blocky structure; hard, friable, sticky and plastic; many very fine and common fine roots; common fine exped and a few fine and very fine tubular pores; common moderately thick clay films bridging and coating gravel; 30% gravel by volume; slightly to strongly effervescent in spots*; abrupt wavy boundary.

*On bottom of gravel

C1casi 21-33"* (53-84 cm). Pink (7.5YR 8/4) cemented pan that breaks with difficulty to gravelly loam sand, pink (7.5YR 7/4) moist; weak coarse platy or massive; strongly cemented, very firm, nonsticky and nonplastic; few fine and very fine roots; many very fine and fine tubular pores; 25% gravel by volume; violently effervescent; few fine distinct coatings of reddish yellow (7.5YR 6/6) that are strong brown (7.5YR 5/6) moist on plate faces and common white (N8/) lime seams and coatings, violently effervescent, moderately alkaline.

*Pan continues below this depth

Soil type: Grabe loam
Described by: M. L. Richardson (1-21-69)
Location: Plant Materials Center, Field #10, plot #3. 25 feet east of west end and 10 feet from south edge of border, Tucson, Pima County, Az.
Vegetation: Cultivated grasses
Parent material: Mixed recent alluvium
Physiography: Flood plain of Santa Cruz River
Slope: .2 percent
Drainage: Well
Permeability: moderate

Ap1	0-2" (0-5 cm). Grayish-brown (10YR 5/2) loam, very dark grayish-brown (10YR 3/2) moist; massive; slightly hard, friable, slightly sticky and slightly plastic; common fine and very fine roots; common fine and medium discontinuous vesicular pores mainly in surface ½ inch, common very fine tubular pores; strongly effervescent; moderately alkaline (pH 8.0); clear wavy boundary.
Ap2	2-10" (5-25 cm). Grayish-brown (10YR 5/2) loam, dark brown (10YR 3/3) moist; few fine distinct white (10YR 8/) lime filaments, light gray (10YR 7/2) moist; massive breaking to moderate fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; many fine and very fine roots; many fine and very fine tubular pores; strongly effervescent; moderately alkaline (pH 8.0); clear wavy boundary.
C1	10-30" (25-75 cm). Brown (10YR 5/3) loam, dark brown (10YR 3/3) moist; few fine distinct white (10YR 8/) lime filaments, light gray (10YR 7/2) moist; massive; slightly hard, friable, slightly sticky and slightly plastic; common fine and very fine roots; many fine and very fine tubular pores; strongly effervescent; moderately alkaline (pH 8.0); abrupt wavy boundary.
C2	30-66" (75-165 cm). Brown (10YR 5/3) silt loam with thin strata of very fine sandy loam, dark brown (10YR 4/3) moist; few fine faint white (10YR 8/1) lime filaments; massive; slightly hard, very friable, slightly sticky and slightly plastic; strongly effervescent; moderately alkaline (pH 8.0).

Soil type: Valencia loam
Described by: M. L. Richardson and Ken Barbarick (8-5-74)
Location: 150' SSW of city well, 1200' N and 1150' E of SW corner Sec. 10, T14S, R13E along west edge of drainage.
Vegetation: Creosotebush, cholla, bush muhly, mesquite
Parent material: Recent alluvium over old alluvium from mixed rocks
Physiography: Swale
Slope: 1%
Drainage: Well
Permeability: Moderate
Remarks: The Valencia series is in a Hyperthermic temperature class. This soil is in a Thermic temperature class. Valencia soils normally contain 20% gravel in the profile. This pedon contains 25 to 35%, mostly fine, gravel by volume below 19 inches.

A1 0-9" (0-23 cm). Brown (7.5YR 5/4) light loam dark brown (7.5YR 4/2) moist; weak fine granular structure; slightly hard, very friable, slightly sticky and slightly plastic; common fine and very fine roots; common fine and very fine pores; <5% gravel by volume; strongly effervescent with lime disseminated; moderately alkaline; clear wavy boundary.

A12 9-19" (23-48 cm). Brown (7.5YR 5/4) heavy fine sandy loam, dark brown (7.5YR 4/2) moist; massive; slightly hard, very friable; nonsticky and nonplastic; many fine and very fine and few medium roots; common fine and very fine pores; <5% gravel by volume; strongly effervescent; moderately alkaline; clear wavy boundary.

A13 19-22" (48-56 cm). Light brown (7.5YR 6/4) gravelly loam, dark brown (7.5YR 4/4) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; many fine and very fine and few medium roots; common fine and very fine pores; 30% gravel by volume; strongly effervescent; moderately alkaline; abrupt wavy boundary.

B2tb 22-40" (56-102 cm). Reddish yellow (5YR 5/6) gravelly heavy clay loam, yellowish red (5YR 4/6) moist; weak medium subangular blocky structure; hard; friable, very sticky and very plastic; many very fine and a few fine roots; common fine and very fine tubular pores; common moderately thick clay films bridging sand grains and coating gravel; 35% fine gravel by volume; strongly effervescent; moderately alkaline.

APPENDIX B: PERCOLATION TEST DATA

Table B-1: Percolation rates on every 30 cm diameter test hole.

Soil	Replication #	Percolation Rate (cm/hr)
Pima	1	1.42
	2	2.51
	3	1.65
	4	1.44
Guest	1	1.69
	2	2.04
	3	1.22
	4	2.65
	5	1.82
	6	1.64
Tubac	1	1.85
	2	2.01
	3	2.12
	4	1.95
	5	2.24
Palos Verdes (I)	1	5.78
	2	4.88
	3	4.85
Mohave	1	6.12
	2	8.32
	3	6.54
	4	7.91
Gila	1	8.45
	2	6.75
	3	8.35
	4	5.62
Palos Verdes (II)	1	6.12
	2	10.78
	3	9.10
	4	14.64
	5	5.78
	6	3.70

B-1: Continued

Soil	Replication #	Percolation rate (cm/hr)
Grabe	1	9.10
	2	10.46
	3	11.55
	4	6.12
	5	8.11
	6	8.44
Valencia	1	18.75
	2	19.88
	3	25.00
	4	22.25

Table B2. Percolation rates on 10, 20, and 25 cm diameter test holes.

Soil	Replication #	Percolation rate (cm/hr) 10 cm	20 cm	25 cm
Pima	1	4.98	3.29	3.31
	2	4.00	3.42	1.66
	3	4.48	4.85	2.36
	4	3.61	1.56	3.38
Gila	1	13.34	16.24	13.62
	2	25.60	14.90	3.80
	3	10.19	4.92	10.50
	4	10.54	8.69	4.68
Valencia	1	23.08	21.54	40.18
	2	55.00	21.42	26.14
	3	60.00	37.50	24.04
	4	18.20	33.75	28.62

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