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ACCUMULATION OF MOISTURE IN SOIL UNDER AN IMPERVIOUS SURFACE

by

Jack LeRoy Mickle

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Soil Engineering

Approved:

Signature was redacted for privacy.

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INTRODUCTION

The presence of moisture has a profound effect on the engineering properties of soils. For this reason good design procedures require that the moisture conditions in the soil structure be known. For the most part the soil-water system is in a continual state of fluctuation and only under certain circumstances is there any semblance of equilibrium. Because of this continual state of flux the evaluation of the design properties of the soil structure is at best difficult. It is common practice therefore to determine the properties of the soil under the worst possible conditions and subsequently use these as design criteria.

Highway engineers recognize that water will rise and remain in the soil above the free water table; the driving forces involved, the phase of the water during movement, and the equilibrium conditions, however, are not well understood. In addition, the engineer imposes certain conditions which affect the above phenomena and further complicate any quantitative determinations.

The quasi-virgin soil-water system, such as an open field, undergoes a complicated cyclic fluctuation of moisture content which is determined for the most part by the physical and chemical conditions of the soil, including cover, and the climatology of the area.

Greatly simplified, the cyclic fluctuation of the moisture content proceeds in the manner outlined below. Rainfall strikes the surface and is in part absorbed. Usually the soil surface is relatively dry, and the water flows into the soil under the influence of gravity, capillary attraction and moisture characteristics of the soil mass. The "wetting front" progresses downward toward the water table leaving behind only sufficient water to satisfy the moisture demand of the soil. As the wetting front continues downward the surface soil begins to dry under the influence of evaporation and transpiration, thus causing a deficiency in the upper portion of the soil column. As a result of the deficiency, water is brought up from the wetting front or water table to replenish the depleted supply. When water is being raised, however, the movement is in opposition to the influence of gravity and consequently moves slower than infiltrating water. Further depletion of the water in the upper soil layers causes additional water to be moved upward from the source. Conceivably the water can move either in the liquid or vapor phase, depending upon the conditions of the soil-water system.

Equilibrium is impossible as long as there is infiltrating water, plant transpiration or evaporation from the surface.

Temperature, although not as obvious as the above factors, also influences equilibrium. Primarily because of the temperature effect on the specific free energy of the water, a system which is otherwise in equilibrium will become thermodynamically unbalanced by the application of a thermogradient.

A highway pavement, or similar continuous mat or structure, imposes a quasi-equilibrium condition on the soil-water system. The pavement structure by its very nature is essentially impervious; this has the tendency to limit the infiltration of water into, and the evaporation of water from, the subgrade material. If the temperature conditions are relatively constant, an essential equilibrium is established under the pavement slab.

In the past there have been many misconceptions of what actually happens under the pavement slab. One such belief is that when evaporation is prevented, the subgrade becomes saturated. It has been shown that moisture contents do become relatively high under the slab, but only under certain conditions is saturation or supersaturation possible.

Conditions which can cause saturation of the subgrade are: first, the water table may be located just under the pavement slab; second, in the case of an extremely fine grained soil and a relatively high water table, the zone of capillary saturation may extend to the bottom of the pavement slab; and third, because of freezing temperatures in the subgrade, the water may "freeze out" thereby creating an apparently dry subgrade which will attract more moisture from below. Under the third condition it is possible to have sufficient water in the solid state in the upper reaches of the subgrade to effectively supersaturate the soil when thawing occurs. Frost action as described above, although a salient factor in determining subgrade moisture contents, will not be considered in this discussion.

When the water table is just beneath the pavement slab, the designer has no choice but to determine the strength of the soil at saturation and use the value ascertained for design purposes. If the water table is near the bottom of the pavement slab, the designer would still use the same procedure because the water table might rise, or the zone of capillary saturation might extend up to the pavement slab.

The application of the principles herein discussed lies in predicting the equilibrium moisture content of the subgrade soils which lie at a considerable distance above the water table. It is the usual practice to determine the strength of the subgrade soil by certain accepted methods which do not make allowance for different moisture contents of the same soil; in other words, the design strength of a given soil would be assessed at a certain value regardless of its position with respect to the water table.

The main objective of this dissertation is to investigate the possibility of developing a method whereby the moisture content of a soil under quasi-equilibrium conditions can be predicted by knowing its height above the free water datum, regardless of any soil layering or stratification that might be present. Actual design cases will require a knowledge of the moisture retention characteristics of the undisturbed soil, or the condition of the soil as it will be placed in the subgrade, and the height of the water table in question.

The experimental facilities discussed in this dissertation were designed and instrumented so that accurate observations could be made on the moisture conditions of the soil under an impervious surface. The experimental surface consisted of three layers of asphalt roofing paper laid with asphalt cement and covered with pea gravel. The surface was constructed over a plot of ground measuring 150 feet square. Data were taken on: soil moisture contents, water table elevations, soil temperatures, soil densities, and frequency and amounts of rainfall. The above data are available for a period of approximately four years, although the data taken at the later part of the period, because of certain instrumentation improvements and climatological conditions, are more complete and dependable.

In addition to the above investigation, laboratory analyses were run on undisturbed samples taken from the above field investigation to determine: soil textural classifications, Atterberg limits, desorption curves, densities and specific gravities.

Wherever possible the observed data will be correlated with known mathematical and physical concepts so as to develop an argument which explains and predicts the accumulation of moisture in soil under an impervious surface.

REVIEW OF LITERATURE

There is a great wealth of literature on the energy relationships of the soil-water system. The preponderance of the literature is found in the agricultural and soil physics fields, with a relatively minor part found in engineering publications. Buckingham (2) introduced the idea of using a potential function to describe the moisture conditions of the soil, for this reason his name is always linked to the "energy concept" of soil moisture. Russell and Spangler (25) are credited with being among the first to introduce the practical aspects of the energy concept of soil moisture in the engineering field. Spangler (27, 28) discusses in greater detail some of the problems involved in subgrade moisture control using energy relationships.

Buckingham (2) states that

> if a soil be saturated with water and then allowed to drain while protected from evaporation, it will, after losing a certain amount of drainage water by percolation under the action of gravity, reach a steady state in which no further loss takes place, the remaining water being held in the soil by capillary action, partly in drops at the points of contact of the soil grains and partly in thin films on the surfaces of the grains.

Buckingham refers to the water that remains in the partially drained soil column as "capillary water". He obviously recognized other contributing factors because he goes on to say that

> it (capillary water) depends to a certain degree on the nature and amount of the substances which dissolve from the soil into the water; it also depends on the temperature. But aside from these two influences, which are secondary in our present considerations, it depends primarily on the depth of the soil to the level of free drainage or of standing ground water, on the texture or ultimate fine-grainedness of the soil, and on its structure, i.e., its condition as regards granulation into compound particles and as regards arrangement or packing of these particles.

Buckingham explains that the soil exerts a certain attraction, measured by a "capillary potential", sufficient to hold the water against the action of gravity which tends to drain it perfectly dry. This attraction depends on the amount of water in the soil, for if there is more than a certain amount the excess drains away.

Buckingham defined the capillary potential as the mechanical work required to pull a definite mass of water away from a definite mass of soil. It is interesting to note that he was not completely satisfied with this simple mechanical means of defining the moisture potential of the soil because, by his own statement, he would have preferred to use the principles of thermodynamics.

Gardner (7) in 1920 proposed that the total energy equation for the soil moisture system should be

$$E = E_{\sigma} - E_g = S_1\sigma_1 + S_2\sigma_2 + S_3\sigma_3 - g\int_0^{v_1}\rho h\,dv \qquad (1)$$

where E = gross energy of the system

E_σ = gross surface energy of the system

E_g = gravitational energy of the system

S_1 = area of liquid-air interface

S_2 = area of liquid-solid interface

S_3 = area of solid-air interface

σ_1 = unit surface energy of liquid-air interface

σ_2 = unit surface energy of liquid-solid interface

σ_3 = unit surface energy of solid-air interface

g = gravitational constant

h = height above datum

v = aggregate volume

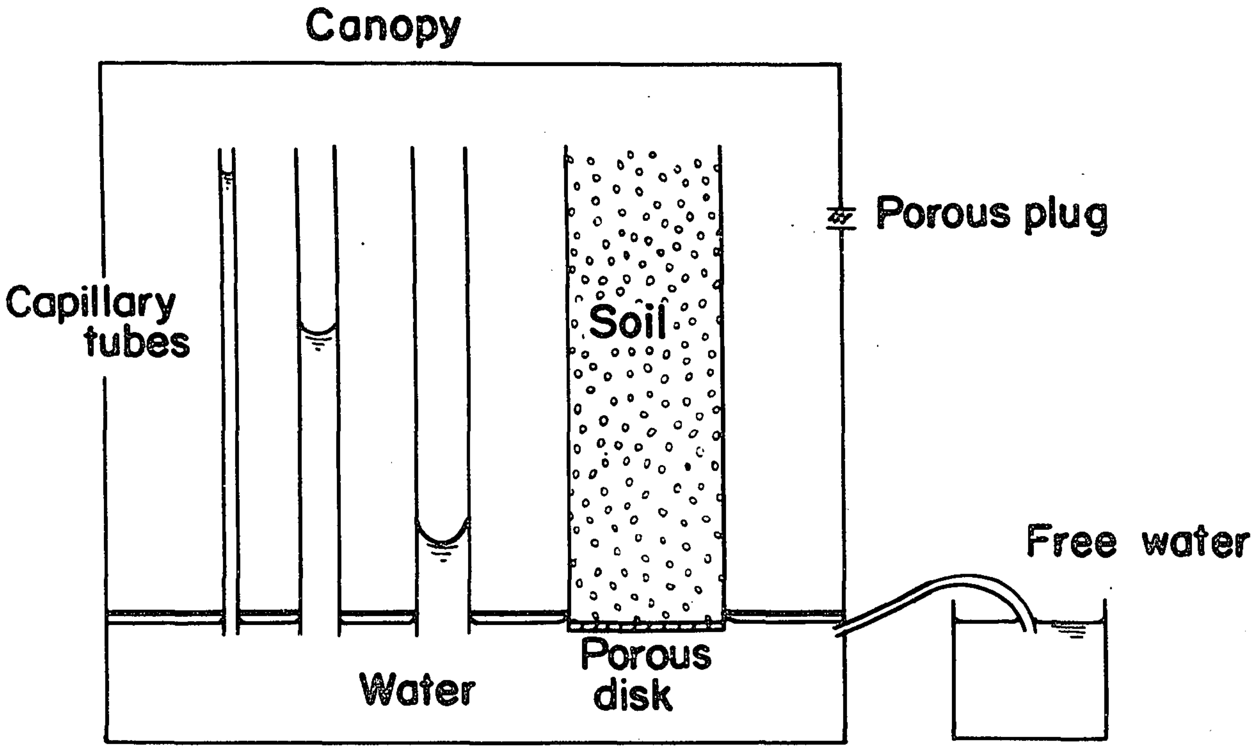
ρ = mass of water per unit aggregate volume

Gardner assumed that under a shallow mulch in a field soil the area of all solid-air interfaces are equal to zero and that the total area of the liquid-solid interfaces is equal to a constant. He further limited the variables by assuming the soil to be insoluble; it is assumed that here he wished to eliminate osmotic potentials. On the basis of the above assumptions he stated that there exists a capillary constant which, with the moisture content and moisture gradient, determines the magnitude and direction of the capillary current. In effect, Gardner theorized that under the above limiting assumptions, the moisture in the soil is controlled or distributes itself under the driving forces of the liquid-air interface energy and the gravitational potential.

Richards (16, 17, 18, 19, 20, 21) has been an outstanding leader in the development of the energy concept of soil moisture and apparatus for measuring the energy relationships. Richards (18) pictorially represented the capillary moisture tension phenomena by a simple capillary tube analogy. See Figure 1. A closed tank is fitted with capillary tubes having different diameters and a column of soil supported on a saturated porous plate in a larger tube. The entire apparatus is enclosed so that evaporation is prevented, but a porous plug in the enclosure is used to maintain atmospheric pressure. The tank is connected with a water source so that a steady free water level is maintained. It is assumed that the capillary tubes and the soil particles are perfectly wetted by the water.

When equilibrium is attained, all other variables being considered constant, the height of rise of the water level in any capillary tube is governed by the radius of the tube which in turn governs the curvature of the meniscus at the air-water interface. By analogy, the surface of the "capillaries" which are filled to the same level in the soil column will have the same curvature as the corresponding capillary tube meniscus. Thus it can be seen that the tension in the water at all points of equal elevation above a given

Figure 1. Capillary tube and soil moisture analogy


Canopy
Porous plug
Capillary tubes
Soil
Free water
Water
Porous disk

free water datum, whether in capillary tubes or in a soil column, is the same.

The curvature of the meniscus at an air-water interface in the soil column can be represented by two radii of curvature taken at right angles to each other. Haines (8), in a paper dealing with cohesion resulting from capillary attraction, showed that the pressure difference across such a meniscus can be expressed by

$$\Delta P = \sigma\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \qquad (2)$$

where σ = the surface tension of the water

r_1 = one radius of curvature

r_2 = the second radius of curvature.

In the above equation r_1 is measured in the opposite direction of r_2; the configuration developed describes the shape of a meniscus formed by a drop of water at the point of contact of two spherical bodies.

Kirkham (9) has shown that in addition to the above configuration a second type is described if both radii are measured in the same direction, i.e., the radii are added in Equation 2. The latter configuration can be visualized as the meniscus or water film covering a moist, rounded soil particle. The water film at any point on the surface of the particle can be described by the two radii, taken at right angles to each other, which define it. If the radii are equal, they define a portion of a sphere.

The first configuration is referred to as anticlastic; the second, synclastic.

In 1935 Schofield (26) proposed the pF scale for describing the condition of soil moisture. He presented the pF as the logarithm of Buckingham's (2) capillary potential. By analogy with Sorensen's acidity scale, pH, the symbol p indicates its logarithmic character, while the symbol F is supposed to suggest free energy. The basic reasons for this new scale were given as: first, the terms "capillary" and "suction" could be avoided because they frequently call to mind surface tension effects only; second, the scale can be transferred to any liquid, its pF being defined as the logarithm of the height of a column of the liquid; and third, the use of the logarithmic function permits the plotting of the moisture contents at all soil-moisture energies on a single graph. As pointed out by Baver (1) the serious weakness in the usage of pF is the fact that the usual tension measurements do not take into consideration osmotic-pressure effects, or pF is not always the equivalent of the logarithm of the tension.

In the light of Baver's comments, Edlefsen and Anderson (5) point out that when dealing with porous bulb apparatus the potential measured is not the capillary potential, the total potential or the free energy. They state that the capillary potential would be measured only when sufficient time was allowed for the diffusion of dissolved salts such that all parts of the system had equal concentration. They state that the total potential or free energy would be measured only if the equilibrium reading could be taken before any of the dissolved salts moved inside the apparatus.

According to Richards and Wadleigh (20) the osmotic pressure of the soil solution in non-saline soils is negligible, so that the total equivalent soil-moisture stress is substantially equal to the soil-moisture tension.

Spangler and Pien (20) conducted a laboratory investigation to determine the relationship under isothermal conditions between moisture content and capillary potential of stratified soils at various heights above a water table. They experimentally showed that the equilibrium moisture content can be predicted from sorption curves of various soil strata as determined by a tensiometer, and that the predicted moisture content is realized regardless of stratification in the soil column.

Spangler and Pien used the thermodynamic approach as outlined by Edlefsen and Anderson (5), but with certain modifications. The first modification was to assume that in the case of a highway subgrade the moisture content which significantly affects its stability is sufficiently great that any influence exerted on the soil water by electrical fields around the soil particles is negligible. The second assumption was that in the ordinary soils encountered, the concentration of dissolved salts is so low that the osmotic potential is also negligible. With the above assumptions the free energy equation reduced to the capillary potential equation.

Richards and Weaver (21) investigated the moisture retention of irrigated soils with pressure plate and pressure membrane apparatus. The investigation included 71 soils representing a wide variety of types and classifications.

They found it convenient to divide the forces contributing to the retention of moisture into two classes: first, those arising from the dissolved materials in the soil water; and second, all other forces. Richards and Weaver are convinced that only the second class of forces is measured by pressure plate and pressure membrane apparatus simply because the membranes are not impermeable to the dissolved salts. Once again Schofield was criticized for mentioning the use of suction plates and centrifugation as possible sources of free energy data.

Another phase of the above investigation included the determination of changes in the soil moisture retention characteristics as a function of temperature. A group of twelve soils, ranging from Tujunga sand to Yolo clay were used to determine the change in moisture retention at one-half and 15 atmospheres under different temperature conditions. The portion of their investigation devoted to one-half atmosphere tension is duplicated as Table 1. It is interesting to note that such a large range of temperatures caused so little change in moisture retention. Richards and Weaver noted that

Table 1. Effect of temperature on moisture retained at one-half atmosphere

Soil type	Per cent moisture retained at ½ atmosphere and indicated temperature (°C.)					$\frac{dPw}{dt}$[a]
	0[a]	12.2	21.2	29.7	37.2	
Tujunga sand	2.76	2.47	2.42	2.23	1.99	-.0193
Placentia sandy loam	6.10	5.94	5.80	5.63	5.60	-.0144
Hanford gravelly sandy loam	8.49	8.28	8.50	8.30	8.46	.0041
Placentia loam	12.62	12.48	12.41	12.16	12.24	-.0118
Sagemoor fine sandy loam	11.90	11.68	11.64	11.28	11.35	-.0163
Indio very fine sandy loam	18.99	18.31	17.86	17.98	16.87	-.0494
Chino loam	18.76	18.45	18.39	17.78	17.96	-.0252
Billings clay	22.92	22.15	20.66	20.82	19.81	-.0823
Altamont clay loam	15.36	15.32	15.28	14.86	15.28	-.0070
Meloland clay	28.25	28.00	27.60	27.51	27.32	-.0257
Antioch clay	28.29	27.67	26.67	26.31	26.00	-.0649
Yola clay	44.73	44.37	41.80	42.83	41.81	-.0808

[a] Values taken from least-square equation having the form $Pw = a - bt$, where Pw represents the moisture percentage, t represents temperature, a = Pw for t = 0 and b = dPw/dt.

the change of moisture retention per degree temperature difference seemed to increase with increasing fineness of texture.

Edlefsen and Anderson (5) published in 1943 probably the most complete and comprehensive theoretical study of the thermodynamics of soil moisture in existence. This treatise is considered a "classic" and is cited in nearly every publication dealing with soil moisture. No attempt will be made to review this treatise here because it will be cited and portions of it reproduced in other parts of this dissertation.

THEORETICAL CONCEPTS

The moisture retention characteristics of soils have been studied quantitatively in the past by using such tools as "capillary potential", "moisture potential", "soil-moisture stress", "free energy" and "total potential". It would seem that in each case only a fractional part of the total energy relationship was being evaluated, the balance being considered constant or negligible. There have been instances where there was some doubt as to what portion of the total energy was in fact being measured.

Probably one of the reasons for the confusion and use of the different notations is because of the investigators' special interests in particular ranges of moisture content. Also the various methods of measuring moisture retention are applicable only within certain moisture content ranges.

Thermodynamics appears to be the best approach because it evaluates the total free energy of the system in terms of component free energies. Thus the effects of adsorptive and gravitational force fields, temperature, pressure and dissolved materials are considered.

Thermodynamics

In applying thermodynamics to soil moisture the concept of free energy has been found to be most useful. The free energy, f, of the substance under consideration is defined in terms of other thermodynamic concepts by the equations

$$f = e + Pv - Ts \tag{3}$$

$$f = h - Ts \tag{4}$$

where e = internal energy per gram

P = pressure

v = specific volume

T = absolute temperature

s = entropy per gram

h = enthalpy or heat content per gram.

The above terms are derived and defined in any suitable treatise on thermodynamics (3, 5).

The total work done by a system may be divided into two parts: the work of expansion, Pdv, against a pressure P, and any other mechanical work, dw_m, including electrical work, that the system might perform. Therefore, the total work may be represented as

$$dw = Pdv + dw_m \tag{5}$$

where dw = the total work done by the system. Differentiating Equation 3, we have

$$df = de + Pdv + vdP - Tds - sdT. \tag{6}$$

According to the first law of thermodynamics

$$de = dq - dw \tag{7}$$

where dq = the heat absorbed by the system. Equation 7 states that the increase in the internal energy of a substance during any transformation is equal to the heat absorbed by the substance, minus the work done by the substance. Also from thermodynamics, for any reversible process

$$dq = Tds. \tag{8}$$

Combining Equations 5, 6, 7 and 8 we see that

$$df = vdP - sdT - dw_m. \tag{9}$$

Under isothermal conditions, dT = 0, and

$$df = vdP - dw_m. \tag{10}$$

If in addition isobaric conditions prevail, dP = 0, and

$$df = -dw_m. \tag{11}$$

It can be seen from Equation 11 that if a reversible process is taking place at isothermal and isobaric conditions the change in free energy, df, is equal to the negative of the net work being done by the system. The net mechanical work, dw_m, is that work being done by the system over and above the work of expansion against a constant pressure P.

Consider a finite change under isothermal and isobaric conditions. If the system goes from state A to state B

$$\Delta f = f_B - f_A = -\int_A^B dw_m = -w_m. \tag{12}$$

Note that the work, w_m, is the reversible work performed by the system on the surroundings during the transformation.

If a finite change occurs by increasing the pressure, all other factors being constant with no net work done, the free energy change is

$$\Delta f = f_B - f_A = \int_A^B vdP. \tag{13}$$

Thus the mere increase of the pressure P on the system will increase its free energy. By the same token, a decrease in pressure will cause a decrease in the free energy of the system.

If a reversible process occurs under isothermal and isobaric conditions such that no net work is done, then

$$\Delta f = f_B - f_A = 0. \tag{14}$$

Equation 14 describes the conditions at equilibrium or where two or more phases remain in equilibrium.

Free Energy Defined

In this dissertation the free energy, f, shall be defined as the free energy per unit mass of the substance in a single phase. This shall be referred to as the specific free energy, or simply the free energy of the substance in that phase. Changes in the free energy of the system will now consist of changes in the specific free energy of the unit mass within the same phase or changes in the specific free energy of the unit mass in going from one phase to another.

The free energy of a level body of free, pure water under a pressure of one atmosphere is taken as the zero point or datum for the free energy of soil moisture. No temperature is given in the above definition of the datum, but it is considered to be constant. The water table, or phreatic surface, will be considered as the datum in this dissertation.

If any unit mass of water exists within the system in such a manner that its physical or chemical conditions is unlike the water at the selected datum it will have a different value of free energy, or at least the component parts of its free energy will be different. If the entire system is in equilibrium, then all unit masses of water within the system will have the same free energy. The fact that the free energy is constant throughout the system at equilibrium does not mean, however, that the component free energies are equal, but only that the sum of the individual component free energies or partial free energies for each unit mass are equal.

Certain chemical and physical phenomena affect the free energy of water. Among these are changes in pressure, changes in height above the defined datum, the presence of dissolved materials and force fields. Temperature is also a factor but will be considered constant for the present. The effect of each of these contributing factors will be considered separately while holding all other effects constant. After all of the contributing factors have been considered individually, they will be added together to form an expression for the total free energy change per unit mass, or simply the change in free energy.

Effect of Dissolved Substances

Refer to Figure 2. The apparatus pictured consists of two compartments separated by a semi-permeable membrane. The membrane is semi-permeable insofar as it will pass only the solvent molecules but not the solute molecules. Pure solvent is placed into one of the compartments and a dilute solution (solvent activity essentially unity) is introduced into the other compartment. Because of the presence of the solute, a non-volatile salt, the vapor pressure of the solvent in the solution is reduced in conformity with Raoult's law

$$p = cx \tag{15}$$

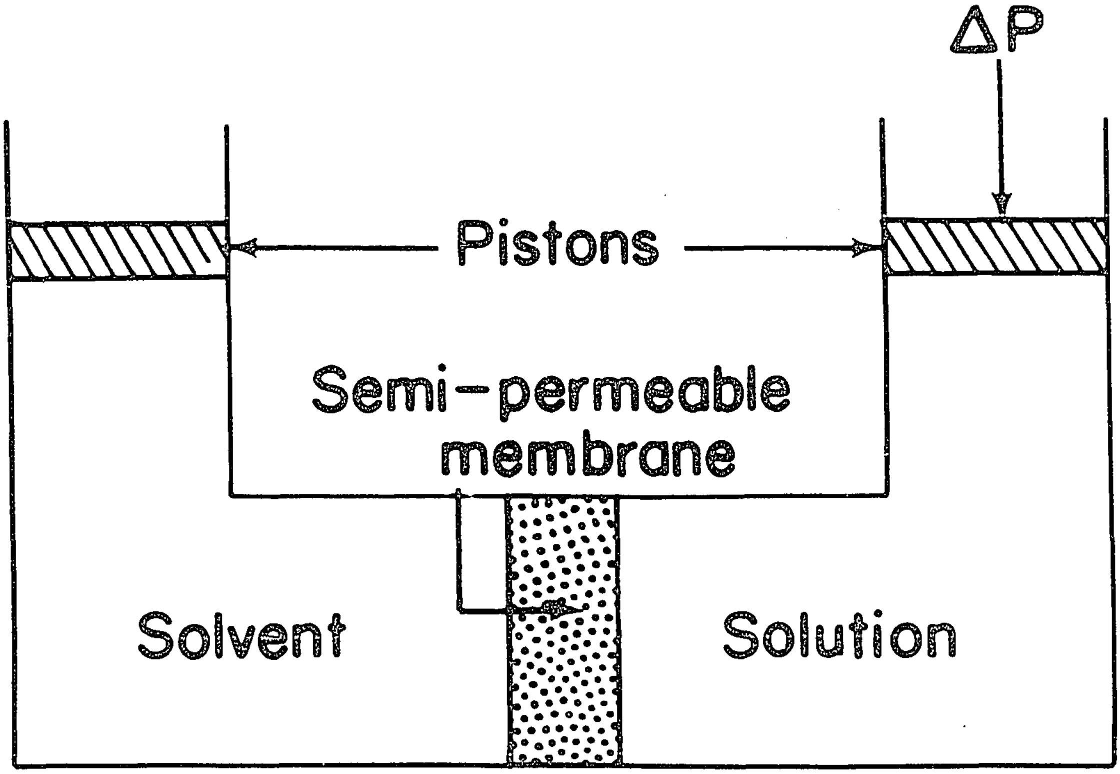
where c = proportionality constant

x = mole fraction of the solvent

p = vapor pressure of the solvent.

As a result of the lowering of the vapor pressure of the solvent in the solution there will be a free energy difference between the pure solvent on the one side of the membrane and the solution on the other. The free energy difference may be expressed in terms of the vapor pressures as

Figure 2. Equilibrium of solvent and solution through semi-permeable membrane


ΔP
Pistons
Semi-permeable membrane
Solvent
Solution

$$\Delta f = RT \ln \frac{p}{p_o} \qquad (16)$$

or in terms of concentrations

$$\Delta f = RT \ln \frac{x}{x_o} \qquad (17)$$

where R = gas constant per gram

T = absolute temperature

p_o = vapor pressure of the pure solvent

x_o = mole fraction of the pure solvent or unity.

Differentiating Equation 17, while holding pressure and temperature constant, we have

$$\left(\frac{\partial f}{\partial x}\right)_{Tp} = \frac{RT}{x} \,. \qquad (18)$$

In a solution the sum of the mole fractions of all of the components of the solution is unity, or

$$x + x_2 = 1 \qquad (19)$$

where x_2 is the mole fraction of the solute. Differentiating Equation 19, we have

$$dx = -dx_2 \,. \qquad (20)$$

Substituting Equations 19 and 20 into Equation 18, we have

$$\left(\frac{\partial f}{-\partial x_2}\right)_{Tp} = \frac{RT}{1 - x_2} \,. \qquad (21)$$

Since the mole fraction of the solute, x_2, is so small, we may assume that the term $1 - x_2$ is essentially unity. This approximation reduces Equation 21 to

$$\left(\frac{\partial f}{\partial x_2}\right)_{Tp} = -\bar{R}T \ . \tag{22}$$

For finite changes Equation 22 may be written as

$$\Delta f = -RTx_2 \ . \tag{23}$$

The extra pressure that must be exerted on the solution to equilibrate the free energies of the pure solvent and the solution in Figure 2 is

$$\Delta P = \frac{RTx_2}{v} \ . \tag{24}$$

Effect of Pressure on the Free Energy of Water

The change in free energy of a unit mass of material during a reversible reaction can be expressed by Equation 9 as

$$df = vdP - sdT - dw_m \ .$$

Given a unit mass of water at pressure P. If isothermal conditions prevail and no net mechanical work is done, then the change in free energy of the unit mass can be expressed as

$$df = vdP \tag{25}$$

integrating

$$\Delta f = \int_{P_o}^{P_1} vdP = v\int_{P_o}^{P_1} dP = v\Delta P \ . \tag{26}$$

Since v is essentially independent of the pressure, i.e., water is nearly incompressible, the v may be taken outside of the integral.

Also note that since $\underline{v}$ is essentially unity in the cgs system, the change in free energy of a unit mass of water due to a change in pressure under the stated conditions is numerically equal to the change in pressure. An increase in pressure will increase the free energy of the unit mass of water whereas a decrease in pressure will decrease the free energy, all other factors remaining constant.

The Change in Free Energy of a Unit Mass In a Force Field

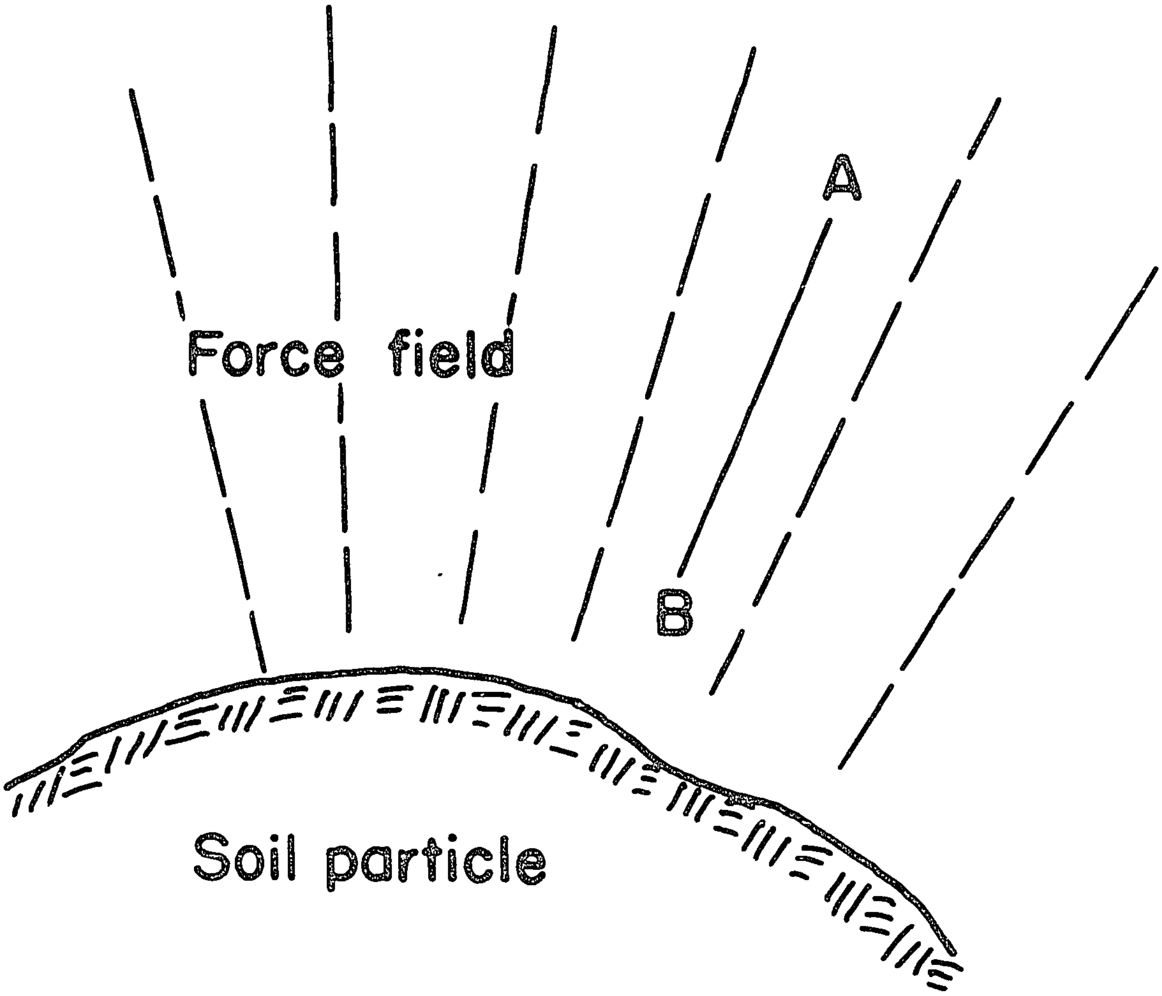
Under isothermal and isobaric conditions the change in free energy of a unit mass of material is equal to the net work done. As a sign convention, if work is done by the particle it is said to be positive; if done on the particle it is said to be negative. In further explanation, if a reaction occurs spontaneously such that work is done by the unit mass there is a decrease in the free energy of the unit mass. In equation form

$$df = -dw_m \quad . \tag{27}$$

Figure 3 shows an individual soil particle surrounded by a force field. The force field is probably made up of a series of individual components but for the purposes of this work the force field will be represented as a function K. The distance as measured from the soil surface along the lines of force will be noted as y.

Consider a unit mass of water at point A within the force

Figure 3. Soil particle and force field


A
Force field
B
Soil particle

field of the soil particle. If this unit mass moves to point B there will be work done on the surroundings by the unit mass and the resultant free energy decrease of the water mass will be

$$\Delta f = -\int_A^B K\,dy = -w_m \,. \tag{28}$$

If, however, the mass of water was taken from B to A against the force field, there would be work done on the water mass by the surroundings, and the resultant free energy change would be positive.

The effect of gravity is quite similar to the above phenomenon. If the earth is considered to be the soil particle in the above discussion, then the force field K will be represented by the gravitational constant g. Although g is frequently represented as a constant, it is actually a varying function just as is K. When considered over the range common to soil science, however, the change in g is so small that it may be considered negligible. If y is used to designate the distance measured along the lines of force in the force field, then the work done on a unit mass of water in raising it above an established datum is

$$w_m = \int_0^y g\,dy \,. \tag{29}$$

Since g is considered constant it can be brought outside the integral. If isothermal and isobaric conditions prevail, then the increase in free energy of the unit mass of water will be equal to the work done on it by the surroundings.

$$\Delta f = w_m = gy \qquad (30)$$

If, however, the unit mass moves closer to the mass exerting the force there will be a resulting loss of free energy because of its position in the force field.

The Effect of Surface Tension and Radius of Curvature on the Free Energy of a Liquid

The existence of surface tension and curved air-water interfaces are evidence of hydrostatic pressure differentials and corresponding free energy changes in the water of the soil-water system. At an air-water interface where the water is convex toward the gaseous phase there exists a greater-than-atmospheric pressure inside the interface. Conversely, if the water surface is concave toward the gaseous phase, the pressure inside the interface will be less than atmospheric.

Consider a spherical droplet of water of radius r completely surrounded by a gaseous phase at one atmosphere pressure. Using the principal of virtual work, allow the extra pressure inside the sphere to increase the size of the sphere to radius r + dr. The surface area of the droplet will increase by

$$dA = d(4\pi r^2) = 8\pi r dr \ . \qquad (31)$$

The increase in the energy stored in the surface of the sphere will be the product of the surface tension, σ, and the increase in area

$$de = \sigma 8 \pi r dr \ . \qquad (32)$$

The work to create this increase in stored energy is done by the extra pressure, p_{ex}, operating on the surface area of the droplet, $4\pi r^2$, through the distance dr.

$$de = p_{ex} 4 \pi r^2 dr \ . \qquad (33)$$

Equating Equations 32 and 33, we can solve for p_{ex}

$$p_{ex} = \frac{2\sigma}{r} \ . \qquad (34)$$

The change in free energy resulting from the hydrostatic pressure differential across the air-water interface is

$$\Delta f = \frac{2\sigma v}{r} \ . \qquad (35)$$

Equation 35 considers a single value for the radius of curvature. As was noted earlier, the pressure differential across a meniscus which is defined by two radii of curvature is

$$\Delta P = \sigma\left(\frac{1}{r_1} \pm \frac{1}{r_2}\right) \ . \qquad (36)$$

The change in free energy resulting from the pressure change given by Equation 36 is

$$\Delta f = \sigma v\left(\frac{1}{r_1} \pm \frac{1}{r_2}\right) \ . \qquad (37)$$

Component Free Energies Combined

The free energy of any unit mass of water in the system previously described is given by the following equation which sums the individual component or partial free energies due to the various factors.

$$\Delta f_{ST} = \Delta f_{\sigma S} + \Delta f_{PS} + \Delta f_{OS} + \Delta f_{FS} + \Delta f_{H} \qquad (38)$$

where Δf_{ST} = the total specific free energy of the soil water at temperature T

$\Delta f_{\sigma S}$ = partial free energy of the soil moisture due to the pressure resulting from surface tension and meniscus curvature effects

Δf_{PS} = partial free energy of the soil moisture due to the pressure resulting from the force fields surrounding the soil particles (effects of surface tension and meniscus curvature excluded)

Δf_{OS} = partial free energy of the soil moisture due to the presence of dissolved materials

Δf_{FS} = partial free energy of the soil moisture due to the presence of the soil moisture in the force fields surrounding the soil particles

Δf_{H} = partial free energy of the soil moisture due to its position above or below the selected datum.

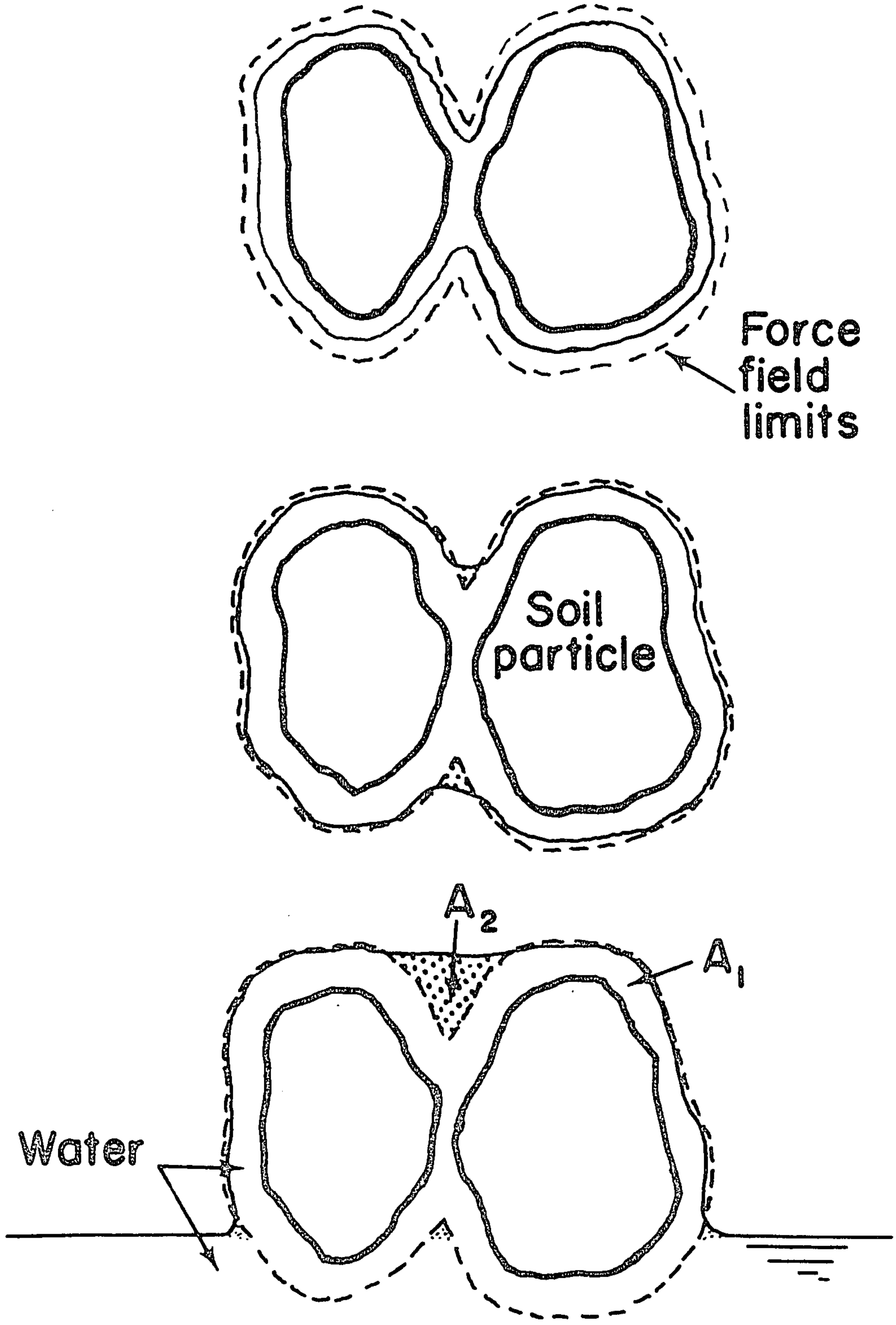
In applying Equation 38 care must be exercised in determining the individual effects to avoid duplication.

Soil-Water System

The phenomena discussed in the previous sections will be applied to the following soil-water system. Consider a column of soil and water reaching to great heights above a level surface of free, pure water at a constant temperature and pressure. The system is in complete equilibrium, therefore the specific free energies of all unit masses of water in the system are equal. Such a system is highly impractical and to even approach it would require extensive equipment and nearly immeasureable time; these nearly impossible requirements do not, however, in any way affect the conclusions based on this argument.

Consider Figure 4. The various parts of the figure represent small portions of the total soil column. Section A is taken near the datum or free water level and succeeding sections are taken at positions of higher elevation within the soil column. Although there will be a wide variation in the individual component free energies of each unit mass of water, the sum of the components, as expressed by Equation 38 will have the same value for every unit mass of water in the system. Further, since the free energy for a unit mass of water at the datum has been taken as zero, the sum of the component free energies for any mass of water in the system will also be zero.

Figure 4. Soil-water column at equilibrium


Force
field
limits
Soil
particle
A_2
A_1
Water

Consider a unit mass of water at A_2. The change in free energy of this unit mass as compared with the datum can be expressed by using Equation 38. The unit mass of water at A_2 was chosen specifically because the effects of the force fields associated with the soil particles are probably negligible at that position. If so, when Equation 38 is written for the unit mass of water at A_2, the component free energy attributed to the particle force fields can be dropped from consideration. In addition, the component free energy due to the pressure in the water produced by the attraction of the particle force fields can also be neglected. As a result, Equation 38, as written for the unit mass of water at A_2, reduces to

$$\Delta f_{ST} = \Delta f_{\sigma S} + \Delta f_{OS} + \Delta f_H = 0 \ . \qquad (39)$$

If the values that were calculated for these individual component free energies in the previous paragraphs are substituted into Equation 39, the result is

$$\Delta f_{ST} = -\frac{2\sigma v}{r} - RTx_2 + gh = 0 \ . \qquad (40)$$

If for the present the mole fraction of the dissolved materials is considered to be negligible, the component free energy due to the osmotic pressure can also be neglected. Equation 40 reduces to

$$\Delta f_{ST} = -\frac{2\sigma v}{r} + gh = 0 \ . \qquad (41)$$

rearranging,

$$h = \frac{2\sigma v}{gr} \qquad (42)$$

which is the expression for the height of rise of water in a perfectly wetted capillary. A more general form of Equation 42 which takes into consideration the two radii defining the curvature of the meniscus is

$$h = \frac{\sigma v}{g} \left(\frac{1}{r_1} \pm \frac{1}{r_2} \right) . \tag{43}$$

In order to obtain Equations 42 and 43 it was assumed that the mole fraction of the dissolved substances in the water at A_2 was negligible. Since the datum has been defined as a level body of free, pure water this assumption was necessary. Let us now assume that the water at the datum is not pure, but contains a definite amount of dissolved substances. The free energy of the datum is no longer zero as was assumed previously, but has a definite value which can be expressed as

$$\Delta f_{ST\ (datum)} = -RTx_d \tag{44}$$

where x_d gives the mole fraction of the dissolved substances in the water at the datum. Because of the equilibrium condition imposed on the system, we can then equate Equations 40 and 44.

$$\Delta f_{ST\ (datum)} = \Delta f_{ST\ (A_2)} \tag{45}$$

or

$$-RTx_d = -\frac{2\sigma v}{r} - RTx_2 + gh . \tag{46}$$

If the mole fraction of the dissolved substances in the datum is equal to the mole fraction of the dissolved substances at

A_2, i.e., the dissolved materials are evenly distributed, then the two expressions related to osmotic pressure components in Equation 46 will cancel and Equation 46 reduces to Equation 42 or the more general Equation 43.

In view of the previous arguments, it is not necessary to assume that the concentration of dissolved substances is low in order to simplify the relationships, but the same end can be achieved by assuming that the dissolved substances are evenly distributed in the entire system.

Let us now consider a unit mass of water at A_1 inside the film surrounding the soil particle. The change in absolute free energy of this unit mass as compared with the datum can also be expressed by using Equation 38. It is noted in this case, however, that none of the terms in Equation 38 can be neglected. Most of the individual component free energies of the unit mass of water at A_1 are difficult to determine. Let us consider each component part of Equation 38, as applied to the unit mass of water at A_1, in the order in which they appear. The partial free energy arising from the surface tension effects and the curvature of the meniscus is difficult to determine because the curvature of the meniscus depends upon the shape of the particle. The component free energy due to the pressure caused by the attractive forces within the field force system of the soil particle can be evaluated only if the true force system is determinable. The portion of the total free energy attributable to the osmotic pressure component can be determined only when information is available concerning the true situation with regard to the mole fraction of the dissolved materials at A_1. Because water undergoes a change in structure at the surface or interface of a solid phase (22) there is no real reason why we should assume that the mole fraction of the dissolved materials in the water within the soil-particle force fields is the same as the mole fraction of the dissolved materials in the water outside these force fields. The component free energy resulting from the force field effect is not determinable unless the manifestation of the force field system is known along with a knowledge of the true situation existing within the water substance. The component free energy of the unit mass of water with respect to its height above the datum is the only readily determinable component.

From the previous discussions it can be seen that many difficulties are encountered in the solution of Equation 38 as written for the unit mass of water which is within the effective limits of the soil-particle force fields. It is proposed that these difficulties can be circumvented for the purposes of this dissertation by assuming that collectively the quantity of water in the soil system which lies within the thin films surrounding the soil particles remains constant. This statement is obviously not true in general, but it conceivably approaches the truth as the soil moisture content approaches the saturation value. Under this condition the water lost when a saturated soil sample is raised above the datum comes only from the interstices or voids of the sample. This approaches the truth because the films of water lying within the effective limits of the soil-particle force fields would be reduced in thickness when the saturated sample was raised above the datum, but the decrease in thickness, since the strength of the force fields increase rapidly (5) as the particle surface is approached, would give rise to only a small quantity of water as compared with that portion lost from the soil structure interstices.

Sorption and Desorption Curves-Hysteresis

Curves showing the relationship between soil-moisture tension and moisture content may be obtained either by wetting a dry soil or by drying a wet soil. The curves thus obtained are called sorption and desorption curves, respectively. In either case the process is controlled so that incremental soil-moisture tensions and moisture contents can be measured. The sorption curve will usually give lower values of moisture content for a given moisture tension than will the desorption curve. The extent of this hysteresis effect is governed for the most part by the fineness of the soil; the finer soils exhibiting a greater hysteresis effect.

Kirkham (9) and Baver (1) summarize the concepts which have been proposed to explain the hysteresis phenomenon. One reason given states that if a saturated soil is being dried there are many large pores filled with water only because the tension in the water in the pores is controlled by small necks at the tops of the pores; if the same soil is being wetted, however, the large pores will not fill simply because of their large diameters. A second reason states that a saturated soil has few, if any, air voids; as it drains, air is admitted into the voids previously occupied by water. When the same soil is wetted, however, there is a certain amount of air entrapped in the voids, thereby giving a lower moisture content. It is possible, however, that the entrapped air may later dissolve thereby eliminating the air voids.

Whatever the reason for this hysteresis effect, it is possible that time will exert some influence. Perhaps over a long period of time some other curve lying between the observed sorption and desorption curves will control. Also since the history of a given soil with respect to saturation is generally not known it seems that the logical curve to use for design purposes is the desorption curve, *i.e.*, that curve which indicates higher moisture contents and therefore lower bearing strengths.

Temperature Effect

Thus far it has been assumed that the temperature was constant and single valued throughout the system. Although this may be true for some masses of soil at great depths, it is not true for soils near the surface. As will be shown later there is a uniform temperature gradient extending from the surface downward, which is continually changing. The actual surface, however, undergoes somewhat erratic variations in temperature.

As was pointed out earlier, Equation 42 will be used to relate changes in free energy for unit masses of water at various positions in the system. The discussion will therefore be confined to those masses of water which lie outside the effective limits of the soil-particle force fields, and are not affected by osmotic influences.

The free energy, as expressed by Equation 42, is directly related to the surface tension and specific volume of the water. A change in temperature will therefore result in a change in free energy.

Suppose for example that a given soil-water system such as has been discussed is considered at a series of temperatures. In each case the temperature will be considered to be constant and single valued and the system will be considered to be in equilibrium. Since the free energy is constant at all points in a system at equilibrium, the change in free energy of a unit mass of water at a given height above the datum, as compared with the datum, is zero. It can be seen, therefore, that the change in free energy caused by a gain in height above the datum is always just offset by the change in free energy caused by the surface tension and meniscus curvature. Now since the free energy change caused by an increase in height above the datum is always the same, regardless of temperature, the term expressing the change in free energy resulting from the surface tension and curvature effects is also always constant at a given height above the datum. As was noted earlier, a change in temperature will affect the surface tension and specific volume of water. Since the temperature effect on the surface tension is much more pronounced than the effect on the specific volume, then a third factor in the term must adjust so that the term is always single valued. The only other factor which can change is the meniscus curvature. In comparing the system at different temperatures it can be seen that the increase in surface tension caused by a lower temperature is just offset by an adjustment in the curvature of the meniscus, i.e., the radius of curvature will increase. An increase in the radius of curvature, with an otherwise constant soil structure, will result in an increased moisture content. Therefore, the moisture content of a given soil at a given height above the datum will increase with decreasing temperature. Rollins et al (23) review the literature concerned with this phenomena, and present experimental evidence regarding rates of movement of soil water under thermal gradients.

An Approximate Method Proposed for Determining Moisture Contents Under Quasi-Equilibrium Conditions

An approximate method is proposed herein which will predict moisture contents, under quasi-equilibrium conditions, in a soil column at any height above the datum and at any temperature. By being able to predict moisture contents in soil, full advantage may be taken of the strength of any particular soil in any position or environment. The phenomenon of frost heave is excluded from this discussion, however.

Equation 42 can be restated as follows:

$$\frac{r}{2} = \frac{\sigma v}{gh} \,. \qquad (47)$$

Note that the radius of curvature of the menisci at a given position above the datum is a function of the surface tension and specific volume of water, the gravitational force field and the height of the point in question above the datum, but that it is not a function of the soil itself. Obviously, the condition of the soil greatly affects the ultimate moisture content, however.

Equation 47 is idealized insofar as the radii of curvature of the menisci are stated in terms of a single radius, r. So as to generalize Equation 47 let us replace the term r/2 by some average or representative value, r_e, which will be referred to as the "equivalent radius of curvature".

$$r_e = \frac{\sigma v}{gh} \qquad (48)$$

It is now possible to make a plot of the equivalent radius of curvature versus height. There will be a series of such plots, each representing a different temperature.

Now using the desorption curve of a soil under study, it is possible, using a plot of equivalent radius of curvature versus height at the same temperature which was used to determine the desorption curve, to determine the equivalent radius of curvature for each moisture content of the soil. If the soil is uniform, a statement of the equivalent radius of curvature will then, under equilibrium conditions, indicate the moisture content of the soil.

A change in temperature will change the equivalent radius of curvature at a given height above the datum; the moisture content will then change so that the moisture content is in agreement with the new value of the equivalent radius of curvature. It is therefore possible to predict changes in moisture content which will occur as a result of a temperature change. Note that equilibrium moisture conditions must prevail in all instances when moisture contents are determined.

The method of predicting moisture contents as given above is referred to as an approximate method because: first, the equivalent radius of curvature is an average value used to represent the physical condition; and second, equilibrium, as such, probably never will be established simply because the temperature is continually changing.

The surface tension of water (5) is given by the following formula:

$$\sigma = 117 - 0.152\ T \qquad (49)$$

where σ is expressed in dynes per centimeter and T is expressed in degrees absolute.

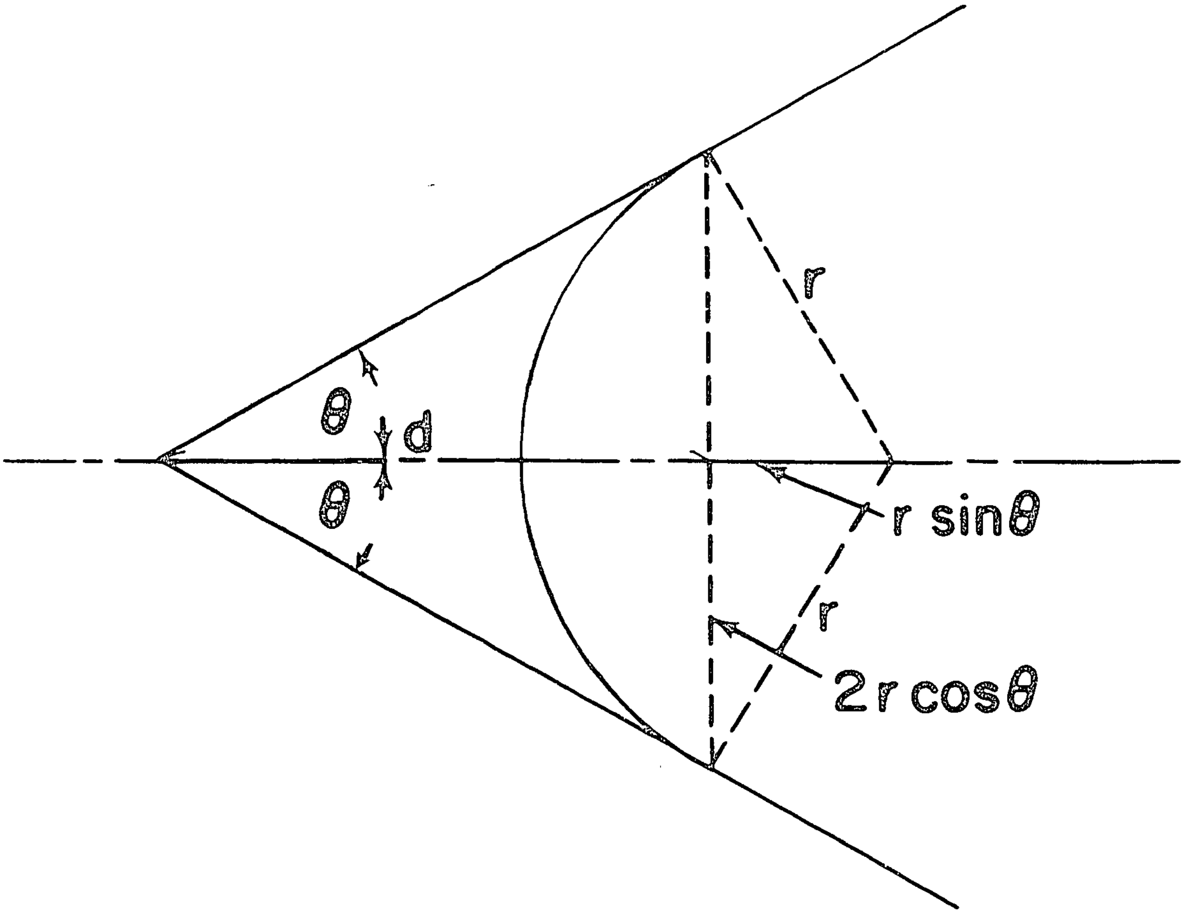
Using Equation 49 and a simple two dimensional model of a wedge of water shown in Figure 5 an expression can be developed to give the change in the water content in the wedge with a change in the radius of the meniscus. Note that since the model is two dimensional, a change in the volume of the water in the wedge can be represented by a change in the cross-sectional area of the water wedge.

The cross-sectional area of the water wedge shown in Figure 5 is

$$A = d\ r \cos \theta + r^2 \sin \theta \cos \theta - \frac{(180-2\theta)}{360} \pi r^2. \qquad (50)$$

So that a numerical comparison can be made, let us determine the equivalent radius of curvature for the water wedges in a soil at a height of 500 centimeters above the datum. Two determinations will be made; one for a temperature of zero

Figure 5. Two-dimensional water wedge


θ
θ
d
r
r sinθ
r
2r cosθ

degrees centigrade, and another for 40 degrees centigrade; v will be taken as unity.

At zero degrees

$$r_e = \frac{\sigma v}{gh} = \frac{(75.6)\ (1)}{980\ (500)} = 1.54\ \text{cm}^{-4} = 1.54\ \text{microns.}$$

At 40 degrees

$$r_e = \frac{(69.6)\ (1)}{(980)\ (500)} = 1.42\ \text{microns.}$$

Now if we further assume that the equivalent radius of curvature is the radius of the wedge of water as shown in Figure 5, and that the angle Θ is 30 degrees, we can determine the cross-sectional areas of the water wedges for each temperature condition.

The cross-sectional area of the water wedge when T = 0 is

$$A_0 = r^2 \left[(2 \cos\Theta) + \sin\Theta \cos\Theta - \frac{(180-2\Theta)}{360}\right]$$

$$= (1.54)^2 \left[(2)(0.866) + (0.866)(0.500) - \frac{\pi}{3}\right]$$

$$= (2.37) \left[1.732 + 0.433 - 1.047\right]$$

$$= (2.37)\ (1.118)$$

$$= 2.65\ \text{square microns.}$$

The cross-section area of the water wedge when T = 40 is

$$A_{40} = (1.42)^2\ (1.118)$$

$$= (2.02)(1.118)$$

$$= 2.26\ \text{square microns.}$$

The difference between A_0 and A_{40} is the change in area of the cross-section of the wedge in going from zero degrees to 40 degrees and represents the change in the volume of the water in the soil under like temperature conditions. The change is 0.39 square microns and represents a 15 per cent reduction when based on the area of the wedge at zero degrees. This means that if a soil was originally at zero degrees and contained, say 20 per cent moisture, it would contain only 17 per cent at 40 degrees.

As a generalization of the above, a review of Equation 50 will show that although θ was assigned a value of 30° in the sample computation, the per cent change in moisture content, as evidenced by the per cent change in area of the two-dimensional model, is independent of the angle θ. Further, when the same type of analysis is applied to a three-dimensional model, such as the shape taken by a drop of water at the point of contact of two spheres, the per cent change in moisture content resulting from changes in temperature is of the same order of magnitude as the example given. It is noted that reductions of this order of magnitude were recorded by Richards and Weaver (21). See Table 1.

EXPERIMENTAL INVESTIGATION

The objective of this investigation was to compare the long time accumulation of moisture in a soil subgrade beneath an impervious surface with the estimated equilibrium moisture content based upon measurements of the moisture retention characteristics of the soil and the elevation of the ground water. The basic purpose is to determine the feasibility of utilizing moisture retention measurements to predict the terminal or equilibrium moisture content of a subgrade under a proposed pavement.

The experimental investigation outlined in this dissertation was conducted in two phases. The first phase involved the routine tasks of periodically determining soil moisture contents, soil temperatures and water table elevations under an impervious surface. The second phase was conducted to determine the soil-moisture retention characteristics and other properties of a series of undisturbed soil samples taken from under, and adjacent to, the impervious surface near the close of the field investigation, or first phase.

Field Laboratory

The field laboratory site was located on the Iowa State University Experimental Farm at Ankeny, Iowa. The parcel of land selected for the investigation was on a gentle swell of an undulating, glaciated land form. Drainage in general was quite satisfactory with no standing water at any time. See Figure 6. In addition to the glacial till there were pockets of granular soil materials interspersed throughout the soil horizons. The presence of these inclusions of sandy and gravelly materials in such large quantities suggested the possibility of a glacial moraine. Since the terminal moraine of the Cary Lobe of the Wisconsin Glacier was only some 10 miles distant, this seemed to be a reasonable suggestion.

An area approximately 200 feet square was fenced and the existing vegetation was cleared. After only minor grading, an area 150 feet square was covered with an impervious surface. See Figure 7. The surface was constructed of alternate layers of heavy roofing paper and hot asphalt cement. Three layers of paper were used and the joints were broken where possible. The paper was then coated with a heavy application of hot asphalt cement and covered with pea gravel. The edges of the impervious surface were protected from mechanical wear by placing them in a shallow trench and covering with a shallow earth fill. This method of anchoring also prevented the direct infiltration of surface water. Construction on the

Figure 6. Field laboratory on Ankeny farm; September, 1960

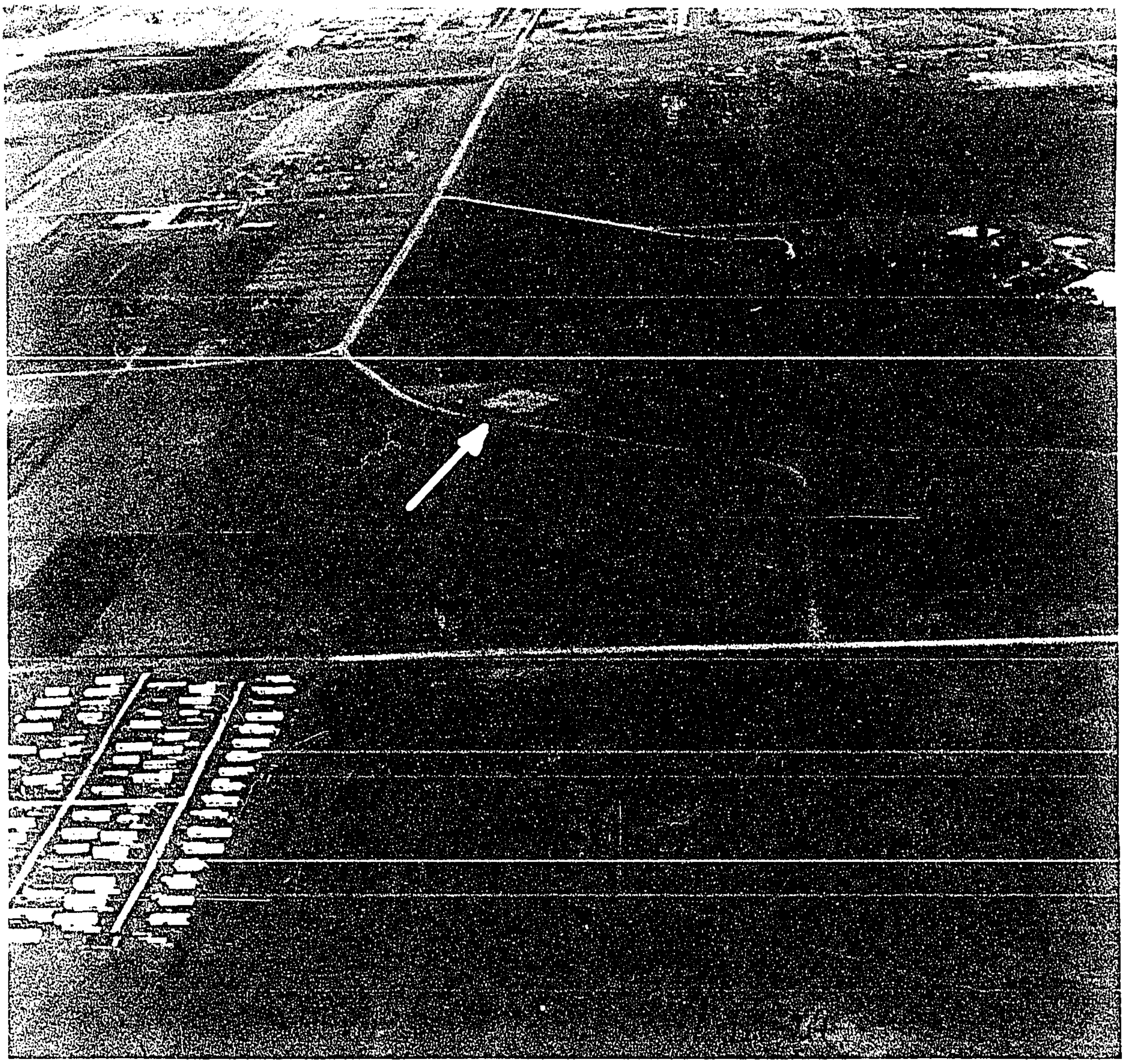
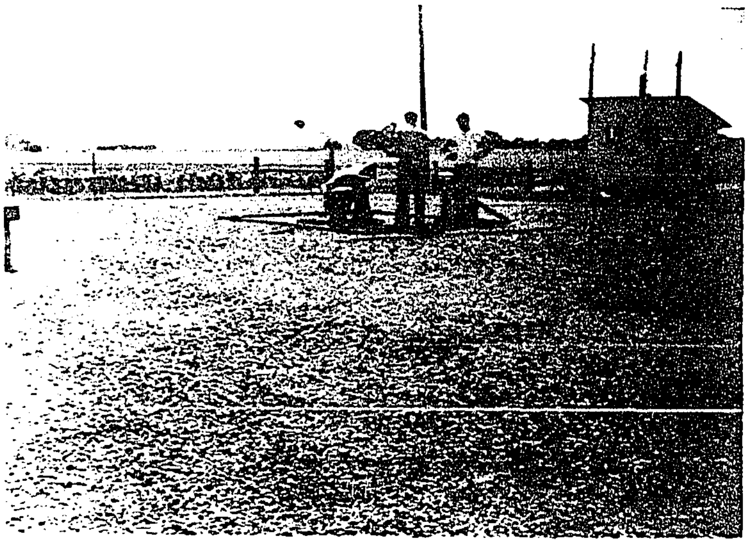
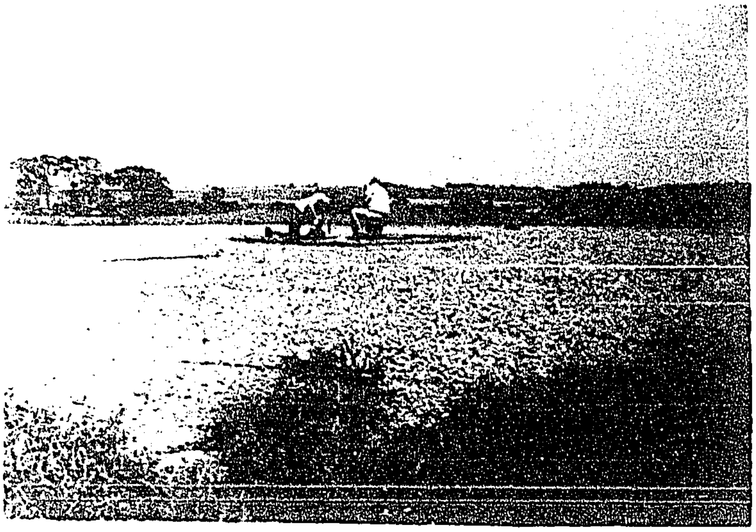


Figure 7. Field laboratory





surface was completed in August, 1954.

The impervious surface was inspected and maintained on a weekly basis throughout the investigation. Minor abrasions and punctures were patched with hot asphalt cement and gravel and, where necessary, additional roofing paper. After two years of service the impervious surface began to show several defects. A number of cracks were discovered along roofing paper splices and the asphalt and gravel cover was wearing thin. In order to lessen routine maintenance, the entire surface was coated with hot asphalt cement and pea gravel. This resurfacing was completed in September, 1956.

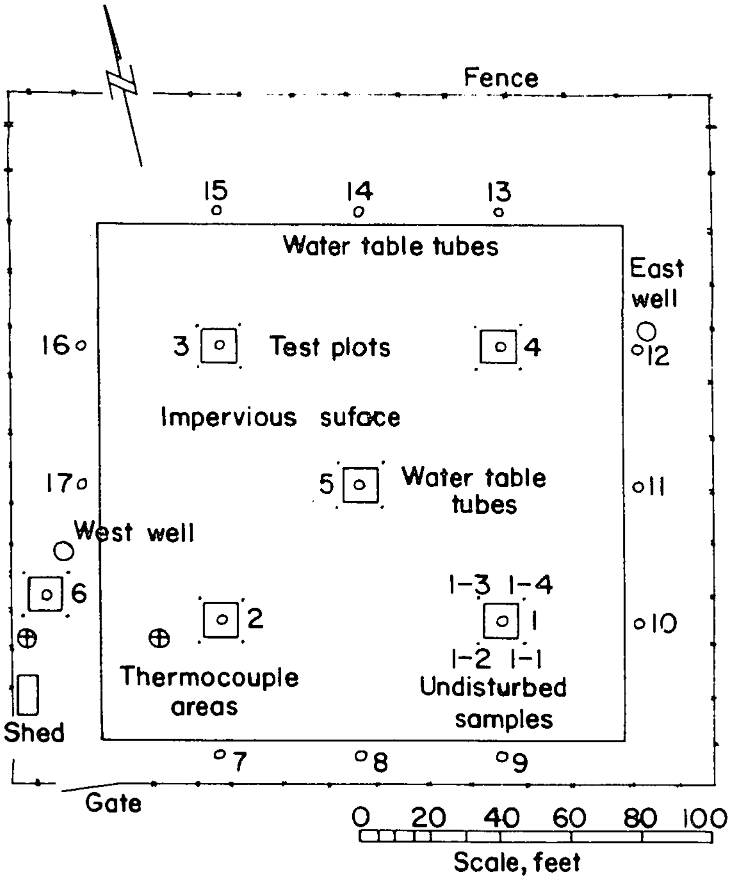
Five individual test plots were selected at various positions on the surface. See Figure 8. Each test plot was ten feet square and was marked off with a one foot grid system. The intersections of the grid lines were numbered and used as a means of control for routine soil-moisture sampling procedures. With some exceptions, samples were taken weekly from November, 1954 to October, 1958. Because an insufficient number of "holes" were provided within the original ten foot grid systems, the test plots were later enlarged.

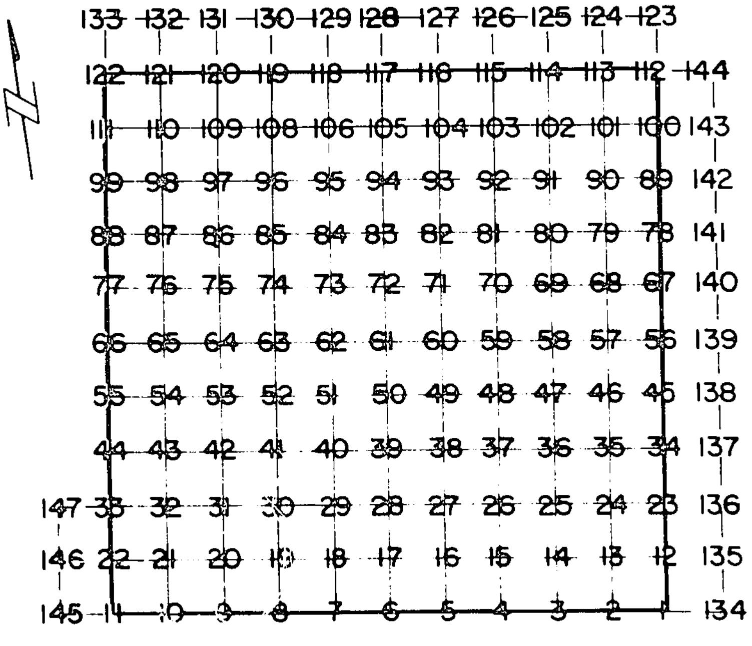
In addition to the five test plots situated on the impervious surface there was a control plot, supporting normal vegetation, located approximately 10 feet west of the west edge of the surface. The control area was marked off in the

Figure 8. Field laboratory

Above: planimetric layout

Below: test plot numbering system


Fence
15
14
13
Water table tubes
East well
16
3
Test plots
4
12
Impervious suface
17
5
Water table tubes
11
West well
6
1-3 1-4
2
1
10
1-2 1-1
Thermocouple areas
Undisturbed samples
Shed
7
8
9
Gate
0 20 40 60 80 100
Scale, feet


133 132 131 130 129 128 127 126 125 124 123
122 121 120 119 118 117 116 115 114 113 112 144
111 110 109 108 106 105 104 103 102 101 100 143
99 98 97 96 95 94 93 92 91 90 89 142
88 87 86 85 84 83 82 81 80 79 78 141
77 76 75 74 73 72 71 70 69 68 67 140
66 65 64 63 62 61 60 59 58 57 56 139
55 54 53 52 51 50 49 48 47 46 45 138
44 43 42 41 40 39 38 37 36 35 34 137
147 33 32 31 30 29 28 27 26 25 24 23 136
146 22 21 20 19 18 17 16 15 14 13 12 135
145 11 10 9 8 7 6 5 4 3 2 1 134

same manner as the other five areas and was sampled weekly also.

Sampling Procedure

As previously described, all six test plots were gridded at one foot intervals and each grid intersection was given a number. All six areas carried the identical grid numbering system so that a specific point on each area could be designated for a specific sampling period. The grids were established by using control pegs at two corners of each area and a portable template.

The soil samples were taken by first cutting through the surface with a circular hole saw and then using a two-inch sampling auger. Samples were taken for moisture content determination directly beneath the surface and at every foot of depth down to the water table. After the moisture sampling was completed, the remaining soil was returned to the hole in the proper sequence and as nearly as possible at the original density. The surface was then patched with the material cut from the surface along with additional asphalt paper and roofing cement. Particular care was exercised to tightly seal the broken surface.

The soil samples were then weighed and placed in a drying oven at 105° C. at the project site. The samples were allowed to dry at this temperature for a period of one week, after which the samples were reweighed and the moisture contents determined.

Water Table Determination

At the outset of the project the depth of the water table was determined in two 16-inch wells on either side of the covered area. These two wells were cased with concrete pipe and were each 20 feet deep. The water levels in the wells were measured by Gurley graphic recorders powered by Seth Thomas eight-day clocks. The charts for these clocks were replaced weekly.

The cased wells appeared to work reasonably well at first, but as time progressed it was noted that there were serious erratic fluctuations in the water level of the east well. Upon investigation it was found that the well was situated in a deep layer of sand. After each rainfall the water level in the well would rise quite rapidly and drop in much the same manner. The second well was much less sensitive to rainfall but showed a continual fall of the water table over the first two years of the project. It is noted, however, that these were very dry years and the falling water table was not surprising.

Because of the questionable data obtained from the wells it was decided that a more reliable method of measuring the depth of the water table should be employed. In 1957 a series of 17 water table tubes were installed. Each tube was made from a 21 foot section of 3/4-inch inside diameter black water pipe. The outside diameter was one inch. The lower 16 feet of each tube was perforated with 1/16 inch holes and points were welded on the tips to facilitate driving. The tubes were placed in one-inch holes augered to a depth of 18 feet. The tubes were then driven another two feet, thus penetrating the soil to a depth of 20 feet. The tubes were left protruding one foot above the ground and were loosely capped to prevent the entrance of extraneous materials. Six of the tubes were placed in the centers of the six test plots and the remainder were placed around the periphery of the impervious surface.

The depth of the water table was determined in each tube weekly, at the time that soil samples were taken. This was accomplished by lowering a weighted electrode suspended on a measuring tape into the pipe; when the electrode came in contact with the water surface an electrical circuit was created and was indicated by a galvanometer. Before the installation of the water table tubes the elevation of the water table was estimated by observing the water level in the wells and by the "feel" of the soil samples.

Soil Temperature Measurements

In order that the effect of temperature on soil-moisture equilibrium could be evaluated, a series of thermocouples were installed to measure soil temperatures both under the impervious surface and under normal vegetive cover.

Two areas approximately two feet in diameter were selected for the temperature measurements. The area under the impervious surface, referred to as the covered area, was located approximately 18 feet inside the surface near test plot two; the area under normal vegetive cover, or control area, was located approximately 20 feet outside the surface near test plot six. See Figure 8.

Thermocouples enclosed in small brass cylinders filled with moist, sterile sand were placed in the soil in a circular fashion at depth intervals of two feet. In both areas a thermocouple was placed at the soil surface with succeeding installations down to a total depth of 12 to 14 feet. The thermocouples were placed by augering a two-inch hole down to the proper depth and then gently forcing the brass cylinder into the undisturbed earth at the bottom of the hole. The holes were subsequently refilled with the excavated soil as near the original density as possible. In addition to the thermocouples in the soil another was placed approximately one foot above the ground near the control area to read the air temperature. All of the thermocouples were connected with long leads to a Minneapolis-Honeywell Brown 16-point recording potentiometer located in the field laboratory shed. A portable potentiometer was used to check periodically the accuracy of the recording potentiometer.

In general, the temperature-measuring apparatus performed satisfactorily but there were a few rather lengthy breakdowns. For the most part these interruptions were caused by lightning striking the power source or the building itself. Two such breakdowns were approximately four months in length; these particular interruptions were caused by stray currents which seriously damaged portions of the recorder and, in one case, destroyed all of the thermocouples which were subsequently replaced.

Undisturbed Sampling

As a part of the second phase of this project a very extensive series of undisturbed soil samples were taken at the field laboratory. The samples were taken in Shelby tubes by an Iowa State Highway Commission soil survey crew using a drilling rig outfitted with a standard drop hammer and sampling tube apparatus. The Shelby tubes had a 2-3/8 inch inside diameter with a 1/16 inch wall thickness and were two feet long. A total of 24 holes were sampled continuously down to a depth of approximately 10 feet. With few exceptions the Shelby tubes were forced into the soil by a screw mechanism rather than by using the drop hammer. An effort was made to take only 18 inches of soil sample in each 24 inch Shelby tube. In this manner no compaction of the soil was possible at the drill rod connection. It is felt that because of this procedure, the samples approached the undisturbed state as nearly as was physically possible. The nearly 240 feet of continuous samples were contained in approximately 170 Shelby sampling tubes.

The 24 test holes were driven so that all four corners of each of the six test plots were sampled. The southeast corner of each of the six test plots was given number one and the other corners were numbered consecutively through four in a clockwise direction. See Figure 8. The first tube filled in each test hole was given the letter A and each successive tube was given a letter in alphabetical sequence. In this fashion, the first sample tube taken at the southeast corner of test plot number one was identified as 1-1-A, the second as 1-1-B and so on. In the same manner, the first tube filled at the northwest corner of area two was identified as 2-3-A. The alphabetical sequence of numbering the soil samples in no way reflects soil horizons encountered.

Soil Physical Characteristics

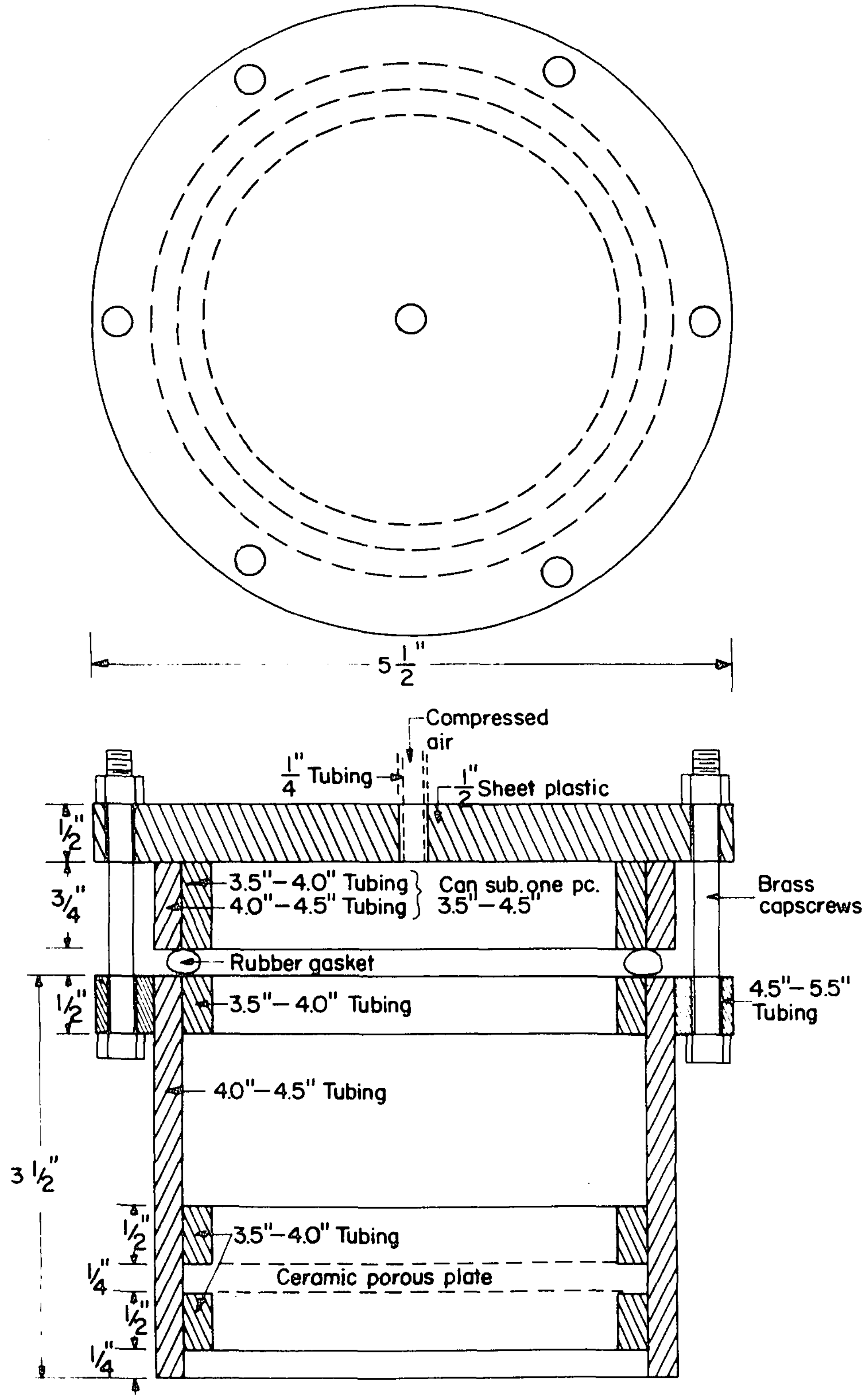
The Shelby tubes were transported to the laboratory from the field site after each day's sampling. Temporary aluminum foil and masking tape vapor seals were used to prevent loss of moisture during the trip. At the soil physics laboratory the contents of each tube was checked for moisture content by removing the first inch of soil from the bottom end of the tube, thereupon the tubes were sealed by pouring melted parafin into the ends. The parafin was carefully heated so the temperature was just high enough to permit an effective seal without causing a serious thermal unbalance in the remaining sample. The Shelby tubes were then stored in a horizontal position in a basement room of relatively constant temperature. Periodic inspections of the seals were made.

As time permitted, each tube was cut open and a large enough sample was taken for a particle size analysis using the sieve and hydrometer methods plus enough for the Atterberg limits determinations. At this time another sample was checked for moisture content. In addition, a section of tube approximately six centimeters in height was cut from the tube using a power hack saw. The ends of the cut specimen were then struck off gently to remove any filings and puddled soil. The section of the tube and the soil therein was then weighed and set in distilled water at a depth of approximately five centimeters for at least one week to permit nearly complete saturation. After saturation was essentially complete, the sample was subjected to moisture retention tests using pressure plate apparatus.

The pressure plate apparatus was designed by the staff of the Agronomy Department of Iowa State University and was constructed of large acrylic resin tubing and a porous ceramic plate made especially for such application. See Figure 9. The porous ceramic plate in the pressure plate apparatus may be thought of as a series of very tiny capillaries. When the plate is dry, it is readily permeable to air; when the plate is saturated, however, the capillaries become filled, thereby creating a membrane which is impermeable to air but permeable to water. If an excess of air pressure is introduced on one side of the plate, the water in the capillaries tends to flow in the direction of decreasing pressure until such time that the force caused by the excess pressure operating on the cross sectional area of each tiny capillary is just offset by the circumferential force in each capillary caused by the curvature of the meniscus and the surface tension of the water. The pressure required to push the water entirely out of the plate and thereby making it permeable to air is therefore a function of the size of the capillaries in the plate. The porous plates used in this investigation were capable of withstanding pressures in excess of one atmosphere but were used only in the range of zero to one-third atmosphere. The average curvature of the menisci in the plate can be calculated when the excess pressure is known by using Equation 34.

If a soil sample is placed on a porous plate in the saturated condition, the capillaries of the soil unite with

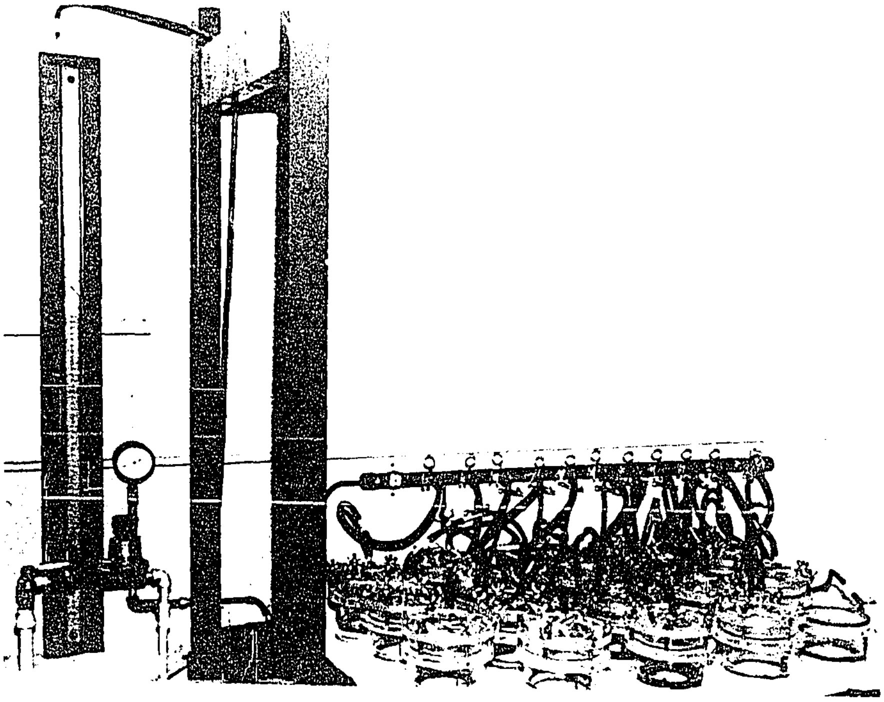
Figure 9. Construction of pressure plate unit

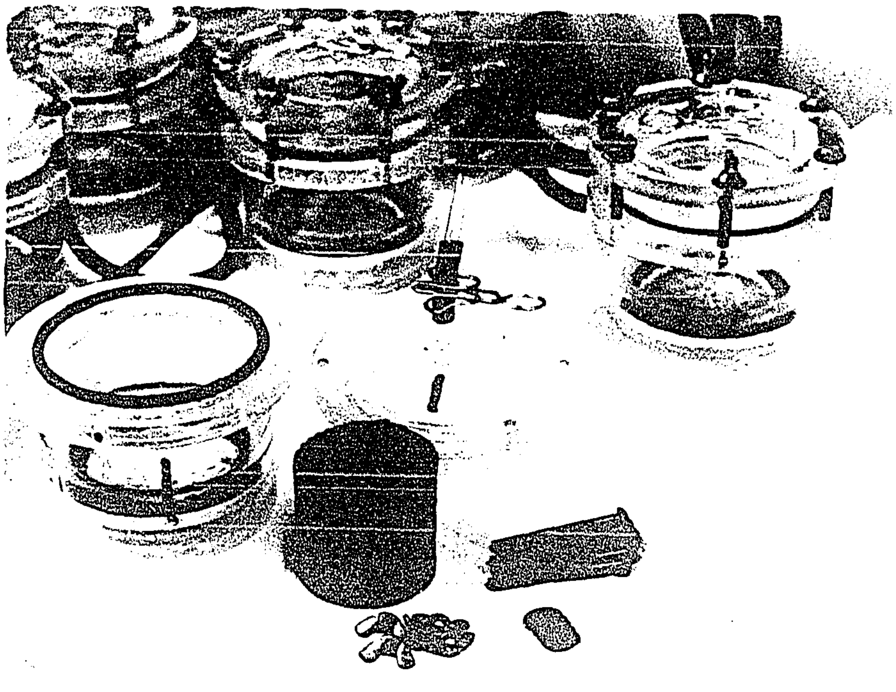

5 1/2"
Compressed air
1/4" Tubing
1/2" Sheet plastic
1/2"
3/4"
3.5"–4.0" Tubing
4.0"–4.5" Tubing
Can sub. one pc. 3.5"–4.5"
Brass capscrews
Rubber gasket
1/2"
3.5"– 4.0" Tubing
4.5"– 5.5" Tubing
4.0"–4.5" Tubing
3 1/2"
1/2"
3.5"–4.0" Tubing
1/4"
Ceramic porous plate
1/2"
1/4"

the capillaries of the porous plate thereby creating continuous capillaries for drainage. If air pressure is now introduced into the apparatus on the side of the porous plate holding the saturated soil sample the larger pores of the soil sample will be drained into and through the porous plate. When the pressure is held constant all the larger pores of the soil sample will drain until the pore or capillary size is reached where the meniscus is of sharp enough curvature so that the circumferential force just offsets the force due to the excess pressure across the porous plate. An equilibrium condition is then indicated and the menisci in the various soil and porous plate capillaries have the same, or equivalent curvature. If all of the pores in the plate and soil sample were circular then all of the menisci present at equilibrium would have the same curvature; this curvature would be equal to the curvature of a meniscus supporting a column of water equivalent to the air pressure difference across the porous plate.

A total of 20 such pressure plate units were utilized in this investigation. All of the units were hooked in parallel with a single regulated air pressure supply by three foot sections of rubber tubing. A direct reading gage was used for routine adjustments, but a mercury manometer was connected to the air supply at all times to check the calibration of the direct reading gage. See Figure 10.

Figure 10. Desorption apparatus





Differential pressures were applied to the pressure plate apparatus to simulate 20, 40, 60, 120 and 200 inches of water column. Although the maximum tension in the water was only about one-half atmosphere, this was considered adequate for the purposes of determining moisture contents in the range of interest to the highway engineer.

Naturally, because of the parallel hookup, all 20 units had to be kept at the same pressure at all times. This made it necessary to wait for the slowest sample to equilibrate before the next incremental pressure could be applied. As a general rule, approximately three to four days time was required for equilibration at each incremental pressure. At this rate, the units were in use for two weeks for each 20 samples.

Each sample was checked twice every day for weight loss. This was accomplished by disconnecting the pressure plate unit from the air supply by clamping off the rubber tube; the unit, still at the test pressure, was wiped to remove any excess moisture and then weighed. When the daily weights remained the same, indicating a steady state, the next incremental pressure was applied. The pressure plate units were kept on a thoroughly moistened cloth at all times to prevent evaporation from the porous plates themselves. No attempt was made to control the humidity of the atmosphere but the temperature of the laboratory was held at 25° C. through the use of a room air-conditioning unit.

After completion of the moisture retention investigation the individual samples were taken from the pressure plate apparatus and dried at 105° C. for one week. At the end of the drying period the weights were determined and the soils were removed from the Shelby tube sleeves. The sleeves were then accurately measured and weighed. Using the above data, along with the tare weights of the pressure plate units, the moisture contents of the soil samples were determined for each moisture tension. A plot of per cent moisture versus moisture tension was made for each soil sample; the resulting curve was a draining or desorption curve.

The average specific gravity of a series of six soil samples was found to be 2.68. This value was used in conjunction with the measured volumetric values to determine undisturbed dry soil densities.

PRESENTATION OF DATA

Routine data on soil moisture contents, water table levels, precipitation and soil temperatures were taken during the period 1955-1958. Because of serious instrumentation difficulties and severe climatic conditions the period October, 1957 to September, 1958 appears to be the only period of reasonable length wherein the data approach a state of quasi-equilibrium. For this reason, the field data presented herein are, for the most part, restricted to this period.

In addition to the field data, information determined in the soil physics laboratory are presented in the form of desorption curves, mechanical analyses, textural classifications, Atterberg limits and dry soil densities.

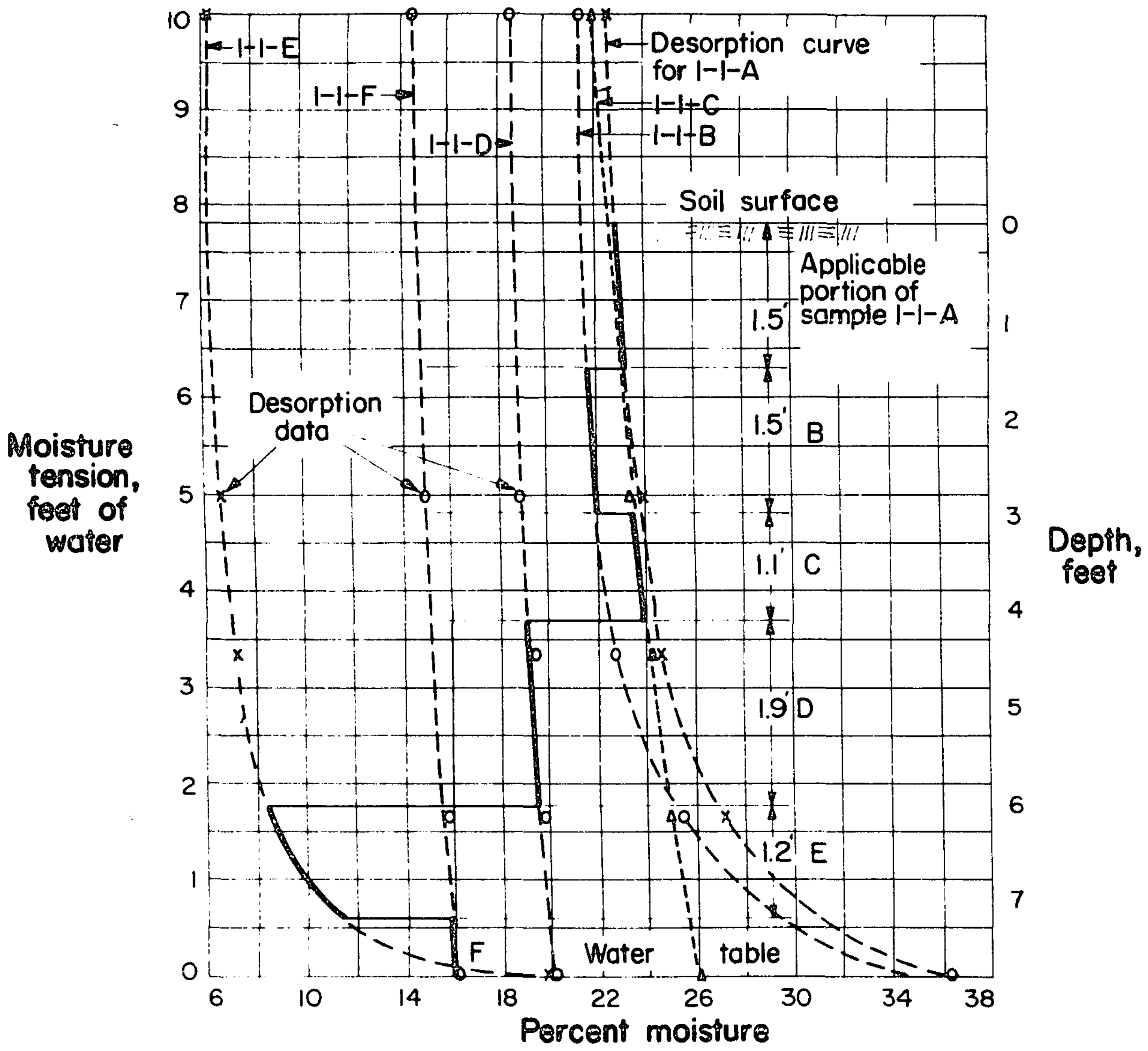
Desorption Curves

A desorption curve graphically portrays the moisture retention characteristics of a given soil under specific conditions. If for any reason a soil was altered in any way its retention characteristics were also altered. If a given soil existed in a profile in such a manner that its characteristics or environment did not change with depth, then a single desorption curve was adequate for depicting its moisture retention properties throughout the entire height of its profile. If, however, the density or any other physical or chemical property of the soil in a given profile changed with depth, then a series of desorption curves must be used to present the desorption properties of the composite profile, an additional desorption curve being necessary for each different soil or different manifestation of a given single soil. If two soils, each homogeneous within themselves, appeared in a given profile then the moisture retention characteristics of the entire profile can be presented by two individual desorption curves. The only applicable portions of the two individual curves, however, will be those portions at the exact levels corresponding to the actual appearance of the soils in the overall profile. If the applicable portions of a series of individual desorption curves, each describing a particular soil in a given profile are selected, then the result will be a composite desorption curve which graphically portrays the moisture retention characteristics of the composite profile. A sharp break in the soil type of a profile will therefore call for a sharp break in the corresponding composite desorption curve.

Desorption curves were determined for nearly all Shelby tube samples taken in the field. The only exceptions were those samples which, because of sampling difficulties or accidental damage, did not accurately represent the actual field conditions. As noted earlier, there were four test holes for each test plot and each test hole bore approximately seven Shelby tube samples, each containing approximately 18 inches of soil; therefore, a total of 28 to 30 desorption curves were determined for each test plot. It was necessary to determine all of the desorption curves because of the many soil types encountered and also because soil densities varied with depth.

Composite desorption curves were constructed for all 24 test holes. Figure 11 graphically shows the method used to develop the composite desorption curve for test hole 1-1; all others were similar. A complete desorption curve for each sample taken from test hole 1-1 was plotted on the graph. Next, the distance from the water table to the soil surface, 7.8 feet in this case, was laid off from the "water table", or saturation level as plotted on the desorption curve. A horizontal line was then drawn which corresponded to the soil surface. Then the length of each sample was laid off vertically on the appropriate curve starting with 1-1-A at the "surface" and working downward until the "water table" was reached. This system presupposes that the soil in any given tube is homogeneous throughout the length of the tube; whereas in reality, the only part of any desorption curve that is applicable is that part which represents the six centimeter sample that was actually tested in the desorption

Figure 11. Construction of a composite desorption curve


1-1-E
1-1-F
1-1-D
Desorption curve for 1-1-A
1-1-C
1-1-B
Soil surface
Applicable portion of sample 1-1-A
1.5'
1.5' B
1.1' C
1.9' D
1.2' E
F
Water table
Desorption data
Moisture tension, feet of water
Depth, feet
Percent moisture
0
1
2
3
4
5
6
7
8
9
10
6
10
14
18
22
26
30
34
38
0
1
2
3
4
5
6
7

apparatus. The six-centimeter sample was taken in each case from the lower one-third of the Shelby tube sample. A refinement of this nature was considered questionable, however. No attempt was made to run more than one desorption curve on the soil from any one given Shelby tube. Composite desorption curves are given for all 24 test holes in Figures 12 to 35. The plotted points on the above figures represent singular soil moisture contents taken during the undisturbed sampling period; these data will be discussed later.

Soil Identification Tests

A series of soil identification tests were made on all undisturbed samples. In each case the soil sample used for testing was taken from the approximate center of the Shelby tube. These tests included particle size analyses, Atterberg limits and dry, in-place soil densities. The results of these tests are also presented in Figures 12-35. Textural classifications given are based on the U. S. Bureau of Public Roads system.

Soil Temperature Data

Soil temperatures were obtained with continuous recording equipment both under the impervious surface and under normal vegetive cover. The temperatures were measured

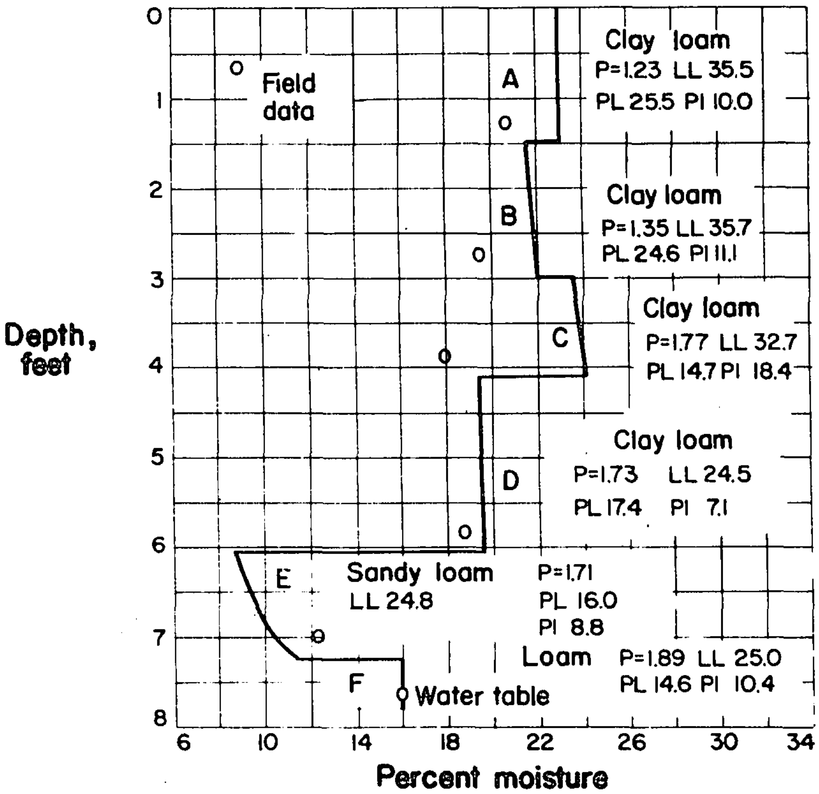
Figure 12. Test hole 1-1

Above: composite desorption curve

Below: particle size distribution curves

On Figures 12 - 35 the following symbols are used:

P = dry density
LL = liquid limit
PL = plastic limit
PI = plasticity index
NP = non-plastic


Depth, feet
0
1
2
3
4
5
6
7
8
Field data
A
Clay loam
P=1.23 LL 35.5
PL 25.5 PI 10.0
B
Clay loam
P=1.35 LL 35.7
PL 24.6 PI 11.1
C
Clay loam
P=1.77 LL 32.7
PL 14.7 PI 18.4
D
Clay loam
P=1.73 LL 24.5
PL 17.4 PI 7.1
E
Sandy loam
LL 24.8
P=1.71
PL 16.0
PI 8.8
F
Loam
P=1.89 LL 25.0
PL 14.6 PI 10.4
Water table
6
10
14
18
22
26
30
34
Percent moisture

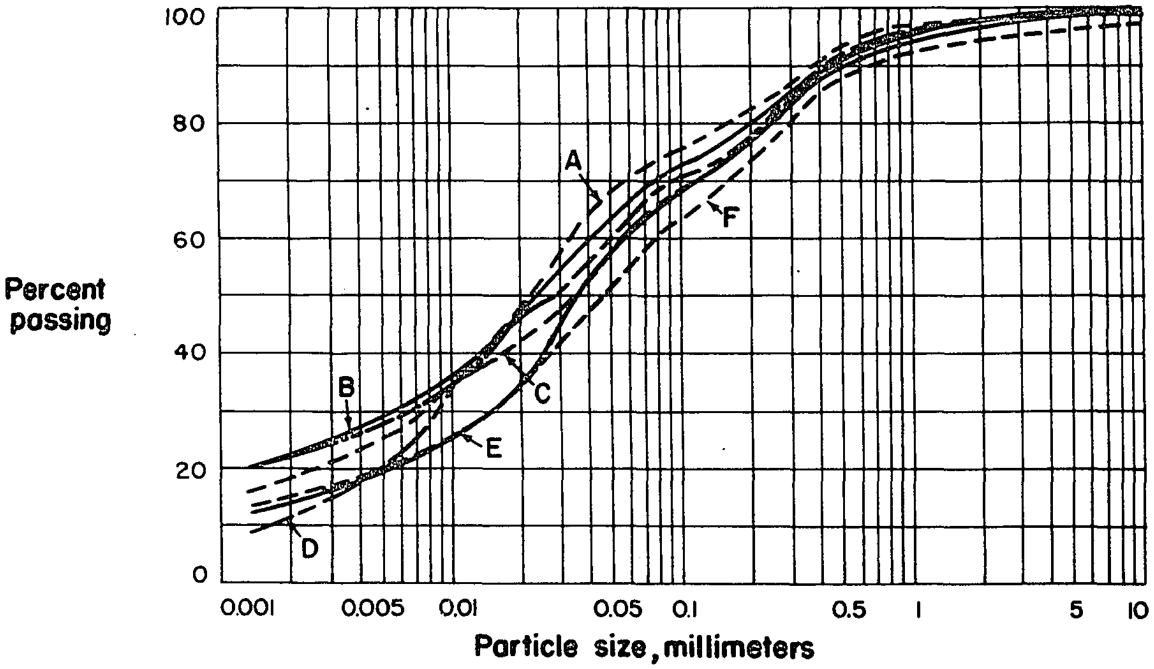
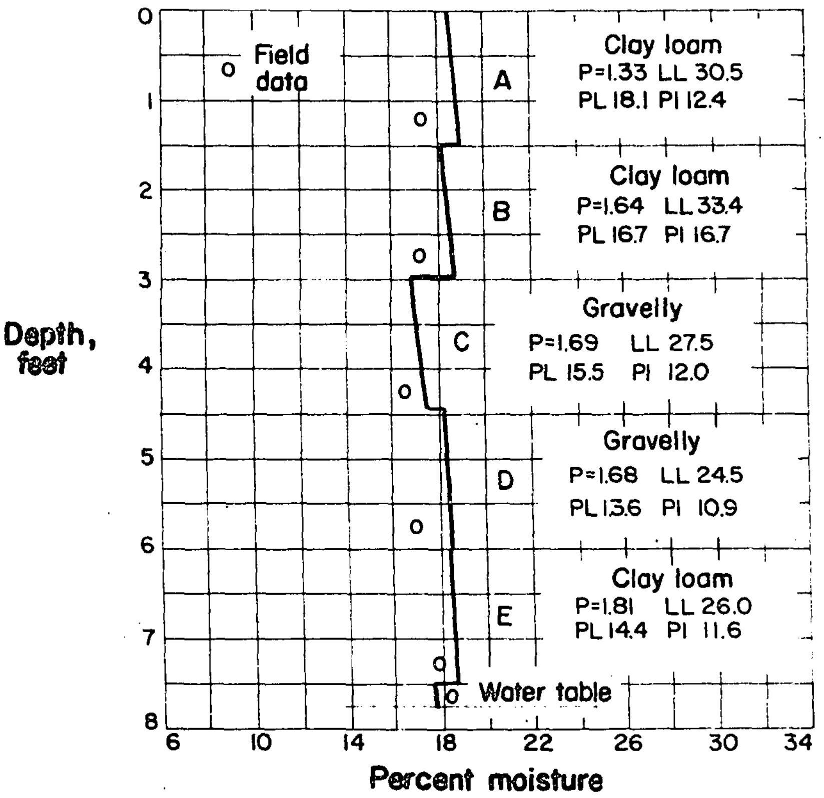

Percent passing
100
80
60
40
20
0
A
B
C
D
E
F
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 13. Test hole 1-2

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
A
Clay loam
P=1.33 LL 30.5
PL 18.1 PI 12.4
B
Clay loam
P=1.64 LL 33.4
PL 16.7 PI 16.7
C
Gravelly
P=1.69 LL 27.5
PL 15.5 PI 12.0
D
Gravelly
P=1.68 LL 24.5
PL 13.6 PI 10.9
E
Clay loam
P=1.81 LL 26.0
PL 14.4 PI 11.6
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

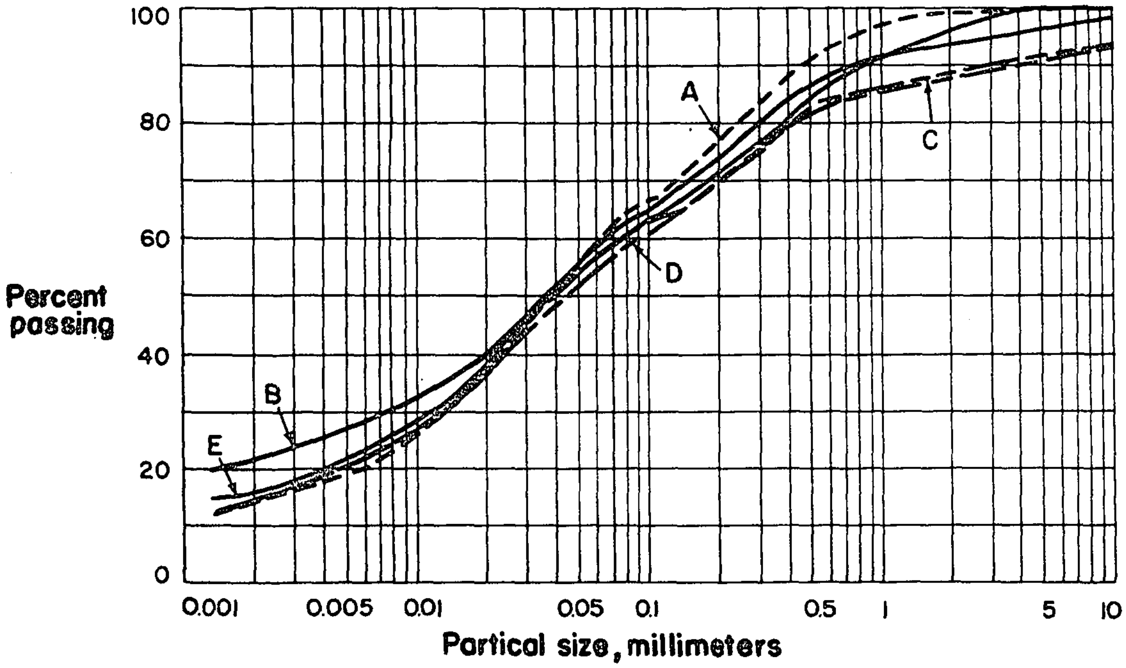
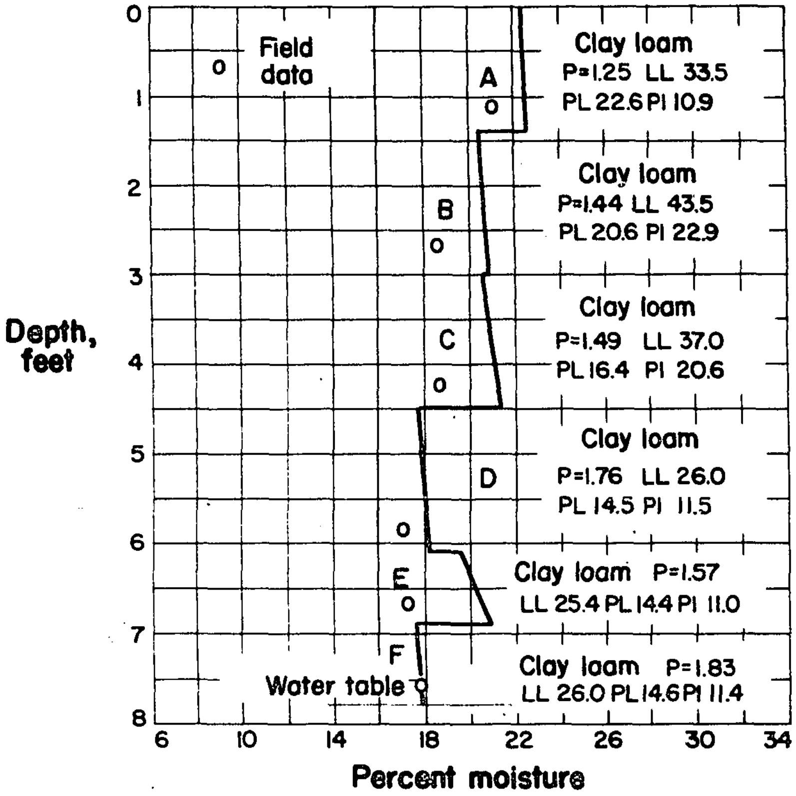

A
B
C
D
E
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Partical size, millimeters

Figure 14. Test hole 1-3

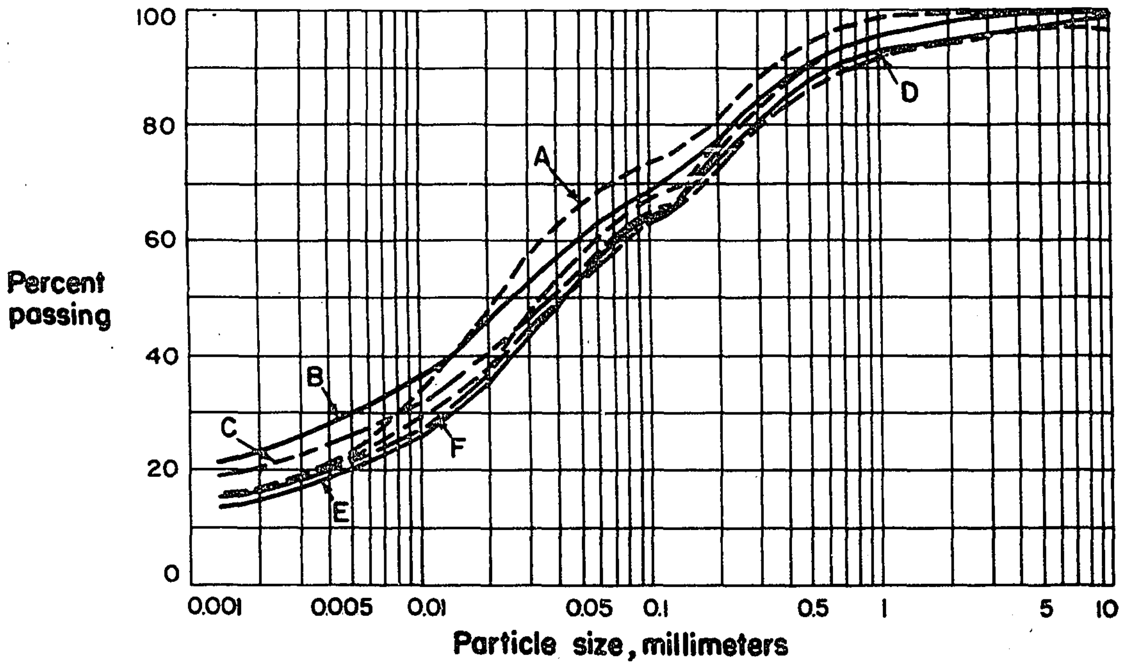
Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used



o Field data
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
A
B
C
D
E
F
Water table
Clay loam P=1.25 LL 33.5 PL 22.6 PI 10.9
Clay loam P=1.44 LL 43.5 PL 20.6 PI 22.9
Clay loam P=1.49 LL 37.0 PL 16.4 PI 20.6
Clay loam P=1.76 LL 26.0 PL 14.5 PI 11.5
Clay loam P=1.57 LL 25.4 PL 14.4 PI 11.0
Clay loam P=1.83 LL 26.0 PL 14.6 PI 11.4



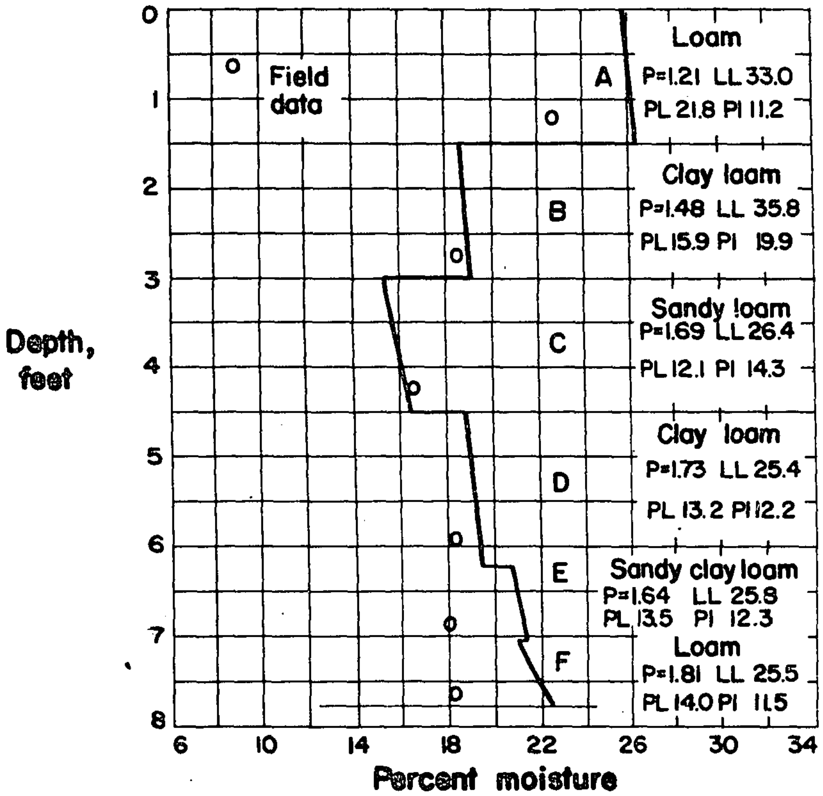
Percent passing
100
80
60
40
20
0
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters
A
B
C
D
E
F

Figure 15. Test hole 1-4

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
Loam
A
P=1.21 LL 33.0
PL 21.8 PI 11.2
Clay loam
B
P=1.48 LL 35.8
PL 15.9 PI 19.9
Sandy loam
C
P=1.69 LL 26.4
PL 12.1 PI 14.3
Clay loam
D
P=1.73 LL 25.4
PL 13.2 PI 12.2
Sandy clay loam
E
P=1.64 LL 25.8
PL 13.5 PI 12.3
Loam
F
P=1.81 LL 25.5
PL 14.0 PI 11.5
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

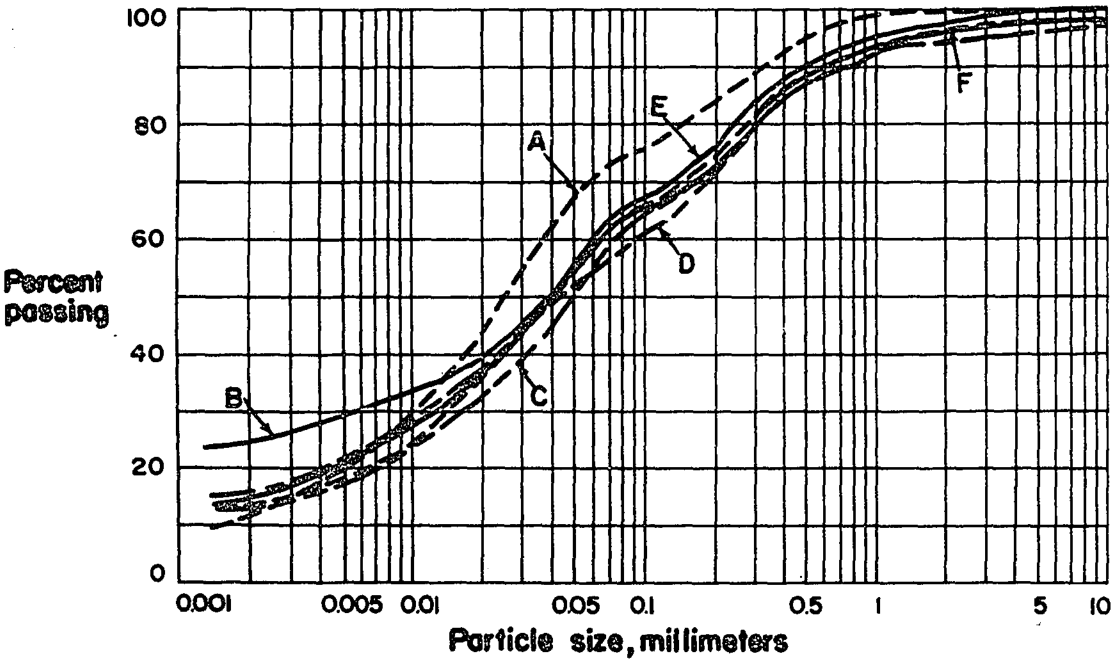
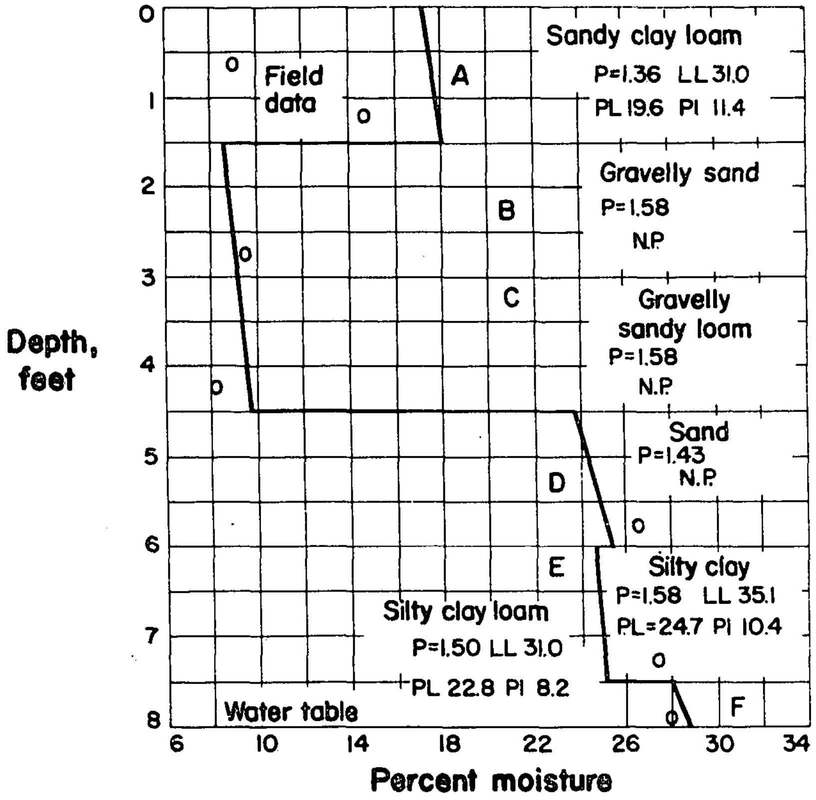

100
80
60
40
20
0
Percent passing
A
B
C
D
E
F
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 16. Test hole 2-1

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
Field data
A
B
C
D
E
F
Sandy clay loam
P=1.36 LL 31.0
PL 19.6 PI 11.4
Gravelly sand
P=1.58
N.P
Gravelly sandy loam
P=1.58
N.P
Sand
P=1.43
N.P
Silty clay
P=1.58 LL 35.1
PL=24.7 PI 10.4
Silty clay loam
P=1.50 LL 31.0
PL 22.8 PI 8.2
Water table
6
10
14
18
22
26
30
34
Percent moisture

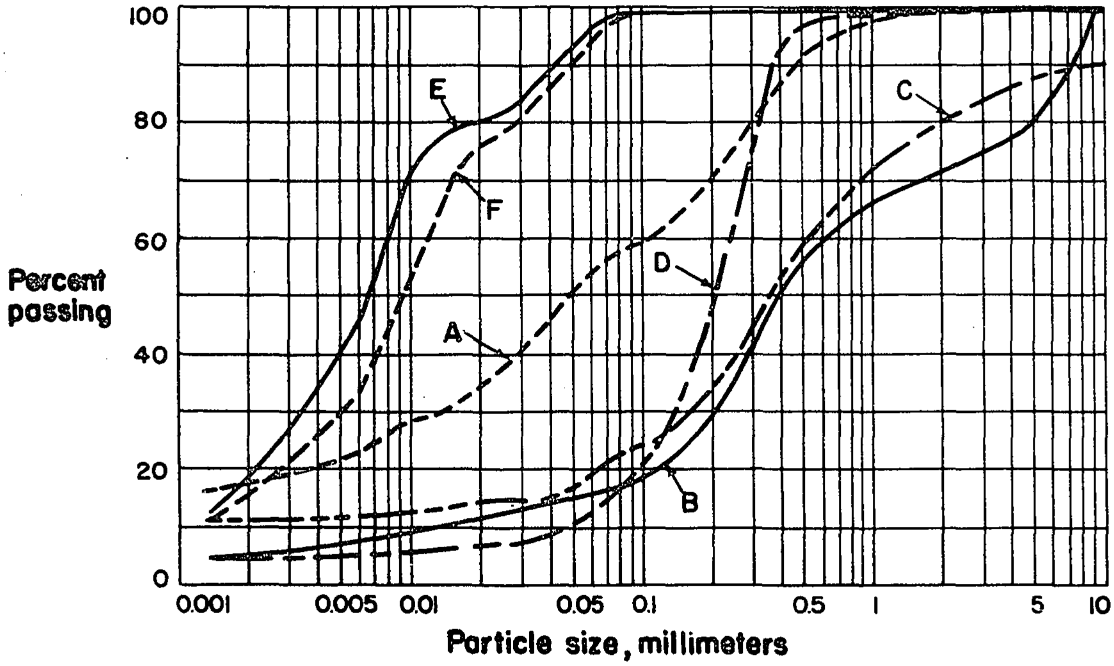
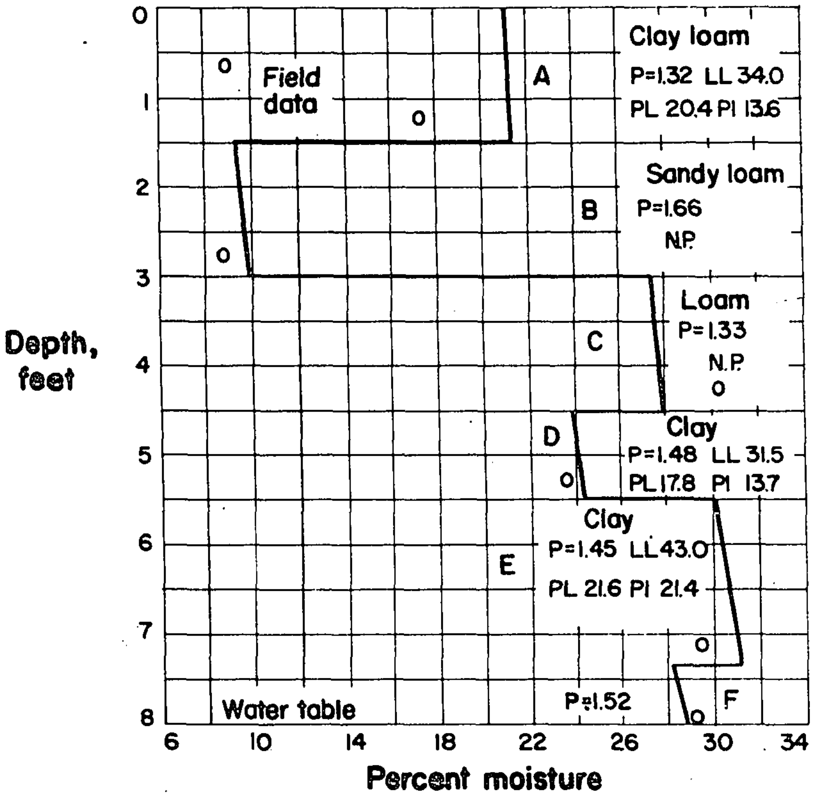

Percent passing
100
80
60
40
20
0
E
F
A
D
C
B
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 17. Test hole 2-2

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
A
Clay loam
P=1.32 LL 34.0
PL 20.4 PI 13.6
Sandy loam
B
P=1.66
N.P.
Loam
C
P=1.33
N.P.
Clay
D
P=1.48 LL 31.5
PL 17.8 PI 13.7
Clay
E
P=1.45 LL 43.0
PL 21.6 PI 21.4
P=1.52
F
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

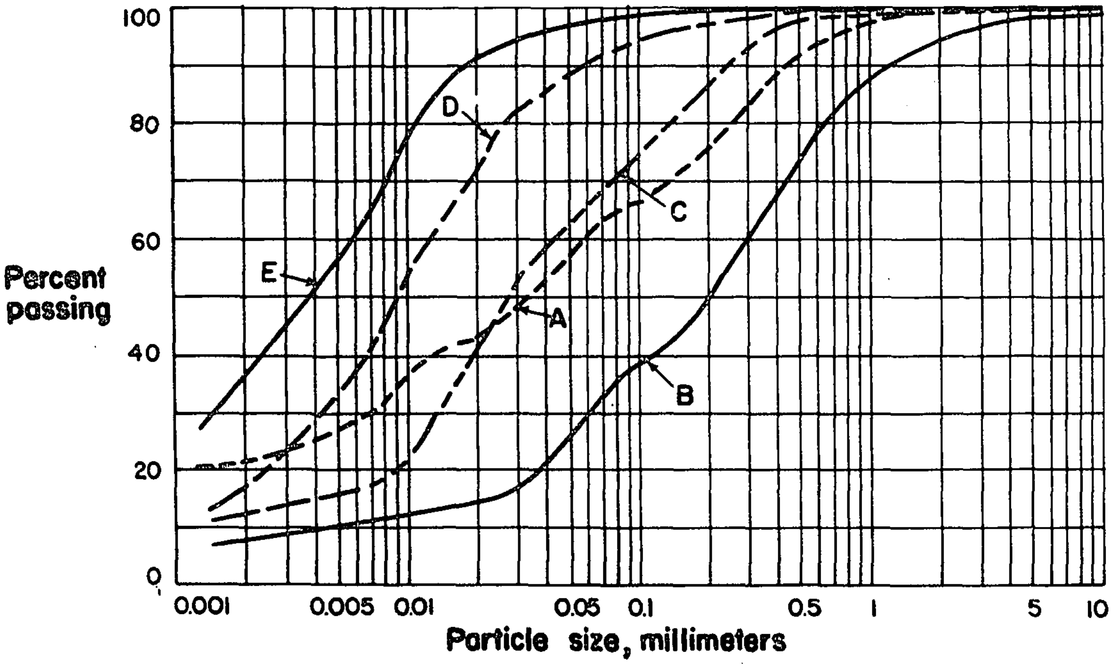
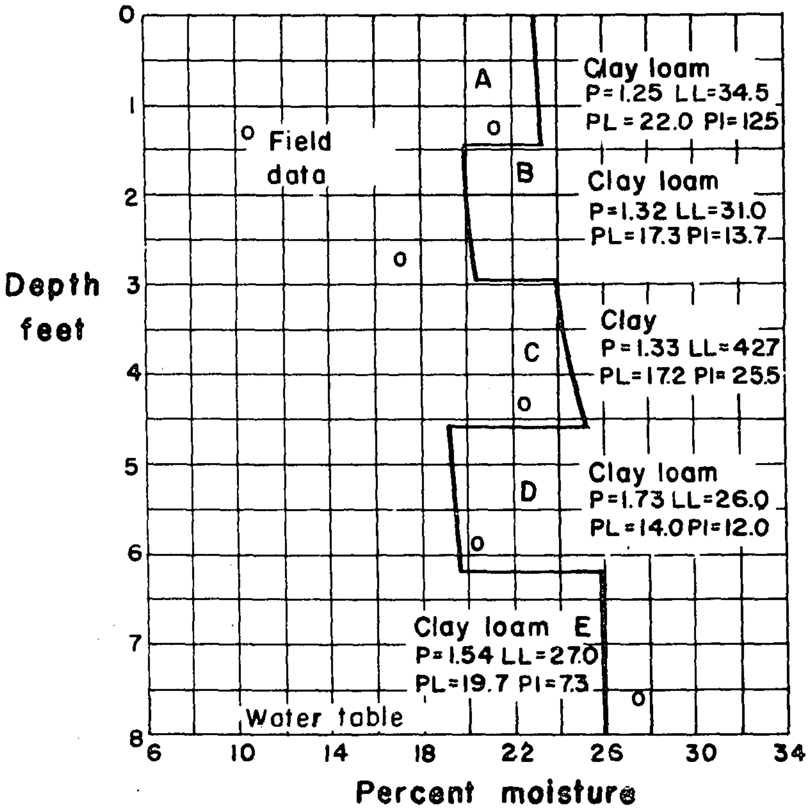

D
C
E
A
B
Percent passing
100
80
60
40
20
0
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 18. Test hole 2-3

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth feet
0
1
2
3
4
5
6
7
8
o Field data
A
Clay loam
P=1.25 LL=34.5
PL=22.0 PI=12.5
B
Clay loam
P=1.32 LL=31.0
PL=17.3 PI=13.7
C
Clay
P=1.33 LL=42.7
PL=17.2 PI=25.5
D
Clay loam
P=1.73 LL=26.0
PL=14.0 PI=12.0
Clay loam E
P=1.54 LL=27.0
PL=19.7 PI=7.3
Water table
6
10
14
18
22
26
30
34
Percent moisture

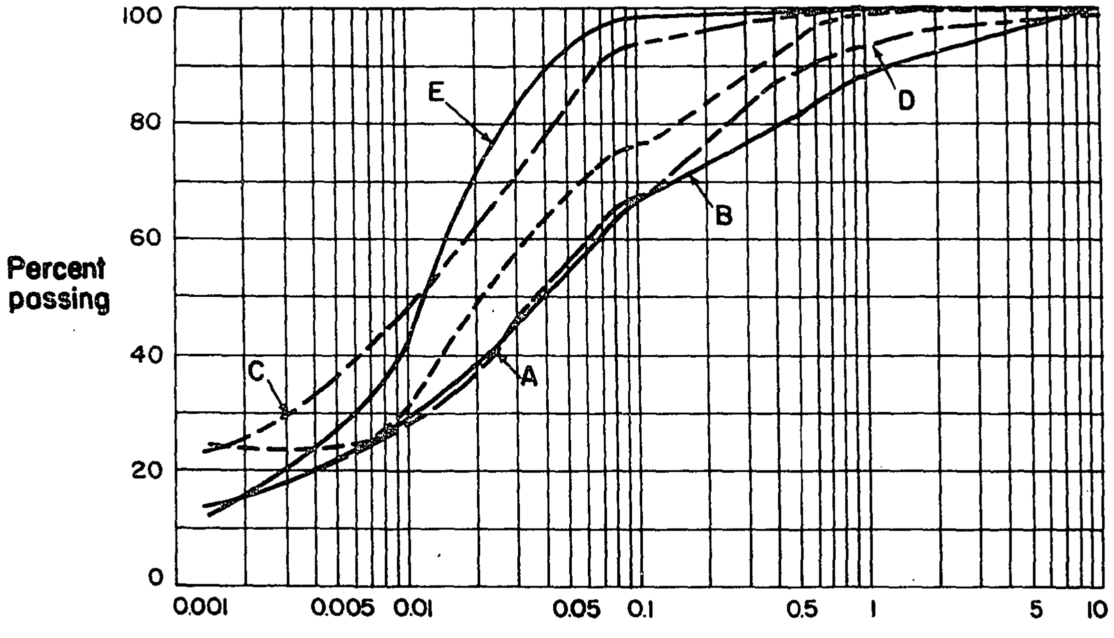
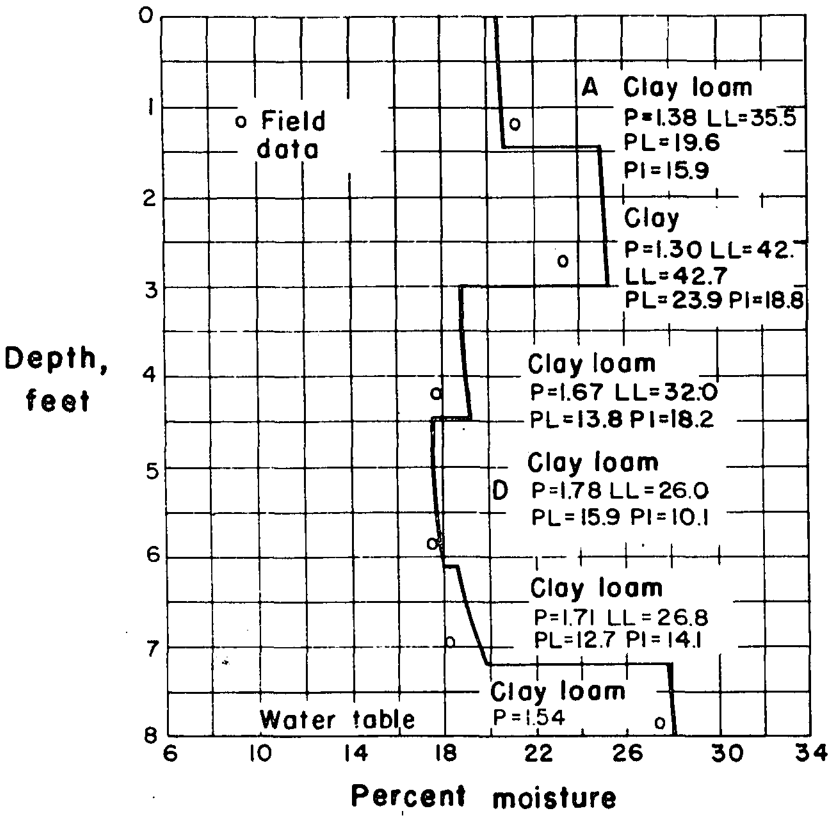

Percent passing
100
80
60
40
20
0
E
D
B
A
C
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 19. Test hole 2-4

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
o Field data
A Clay loam
P=1.38 LL=35.5
PL=19.6
PI=15.9
Clay
P=1.30 LL=42.
LL=42.7
PL=23.9 PI=18.8
Clay loam
P=1.67 LL=32.0
PL=13.8 PI=18.2
Clay loam
D P=1.78 LL=26.0
PL=15.9 PI=10.1
Clay loam
P=1.71 LL=26.8
PL=12.7 PI=14.1
Clay loam
P=1.54
Water table
6
10
14
18
22
26
30
34
Percent moisture

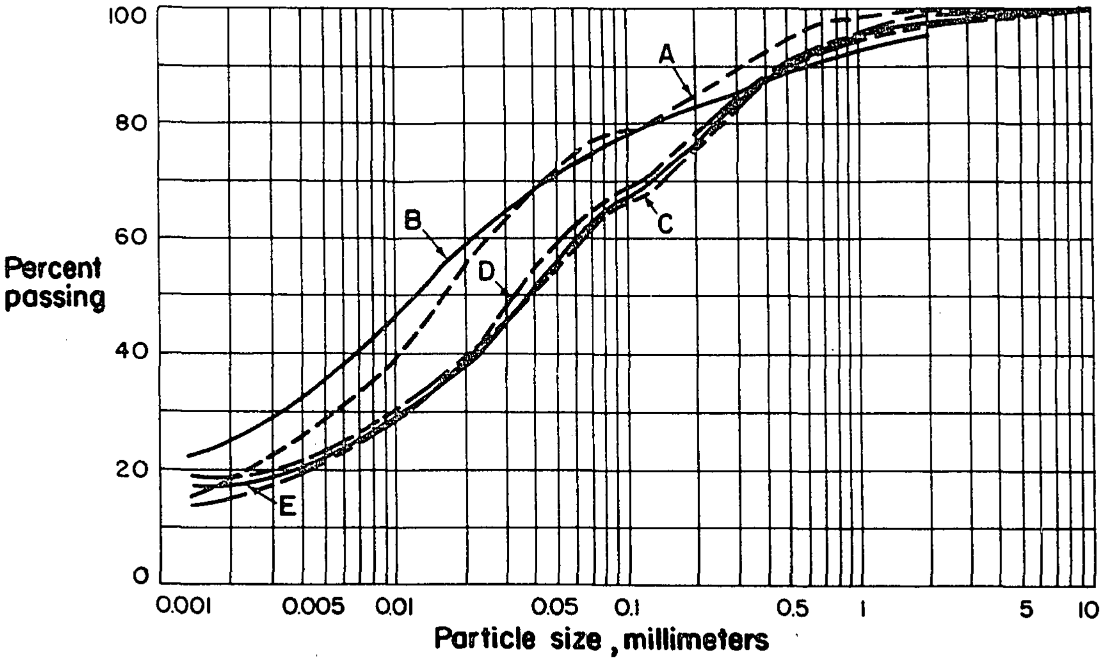
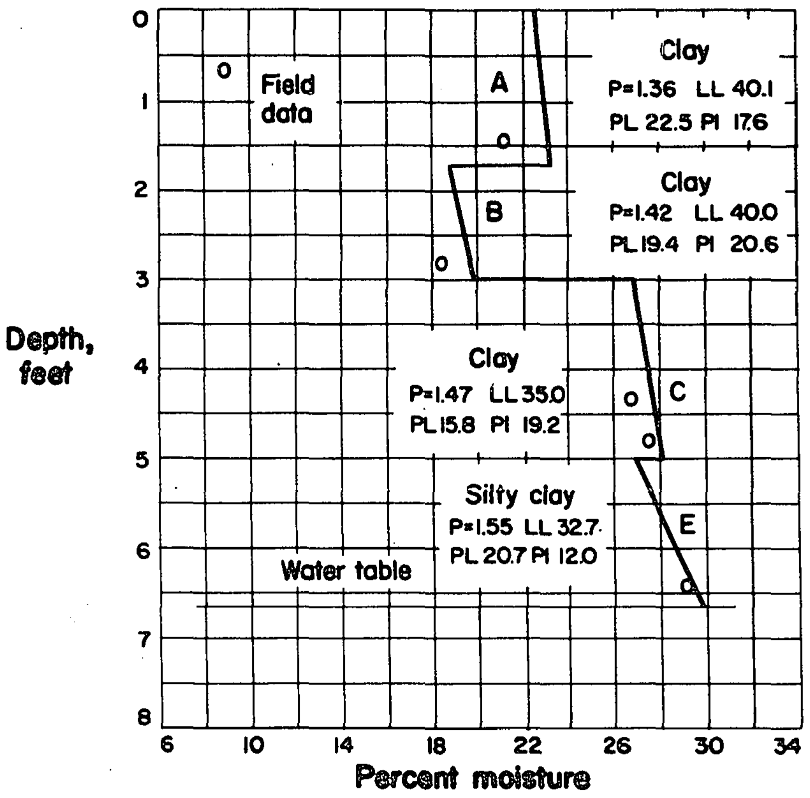

Percent passing
100
80
60
40
20
0
A
B
C
D
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 20. Test hole 3-1

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
Percent moisture
6
10
14
18
22
26
30
34
Field data
A
B
C
E
Clay
P=1.36 LL 40.1
PL 22.5 PI 17.6
Clay
P=1.42 LL 40.0
PL 19.4 PI 20.6
Clay
P=1.47 LL 35.0
PL 15.8 PI 19.2
Silty clay
P=1.55 LL 32.7
PL 20.7 PI 12.0
Water table

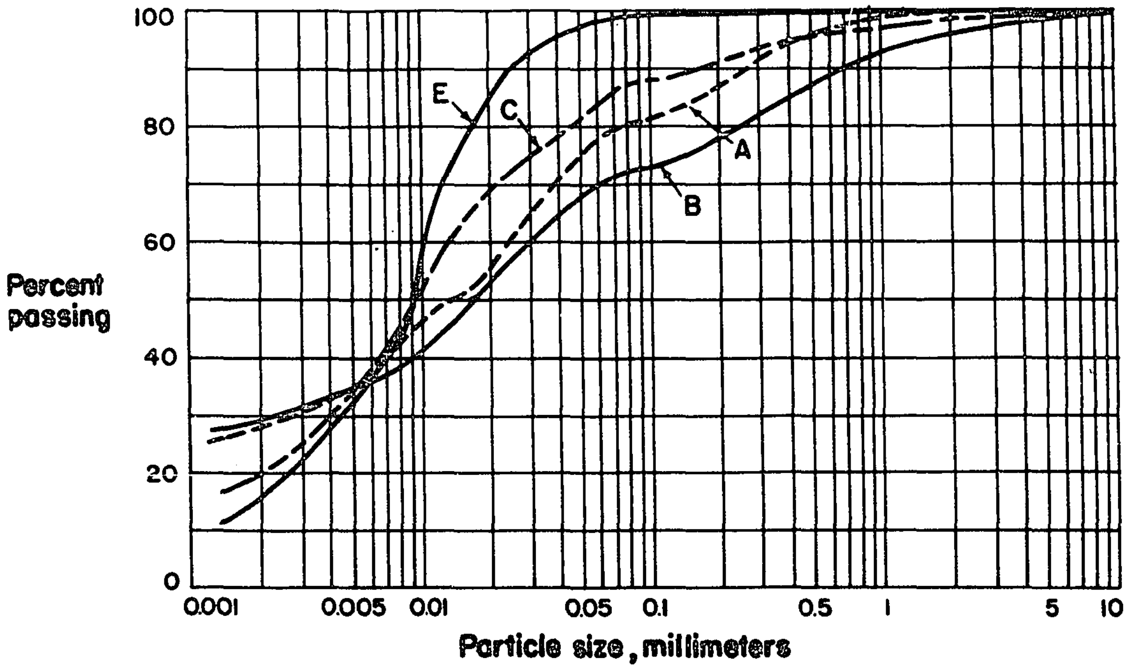
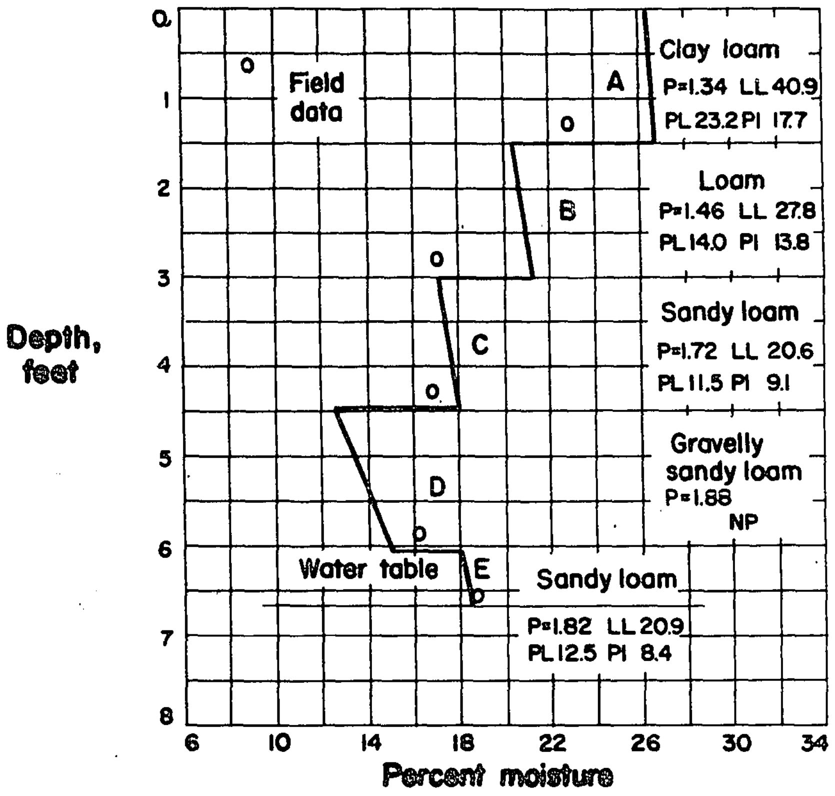

Percent passing
100
80
60
40
20
0
Particle size, millimeters
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
E
C
A
B

Figure 21. Test hole 3-2

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Field data
A
Clay loam
P=1.34 LL 40.9
PL 23.2 PI 17.7
B
Loam
P=1.46 LL 27.8
PL 14.0 PI 13.8
C
Sandy loam
P=1.72 LL 20.6
PL 11.5 PI 9.1
D
Gravelly sandy loam
P=1.88
NP
E
Water table
Sandy loam
P=1.82 LL 20.9
PL 12.5 PI 8.4

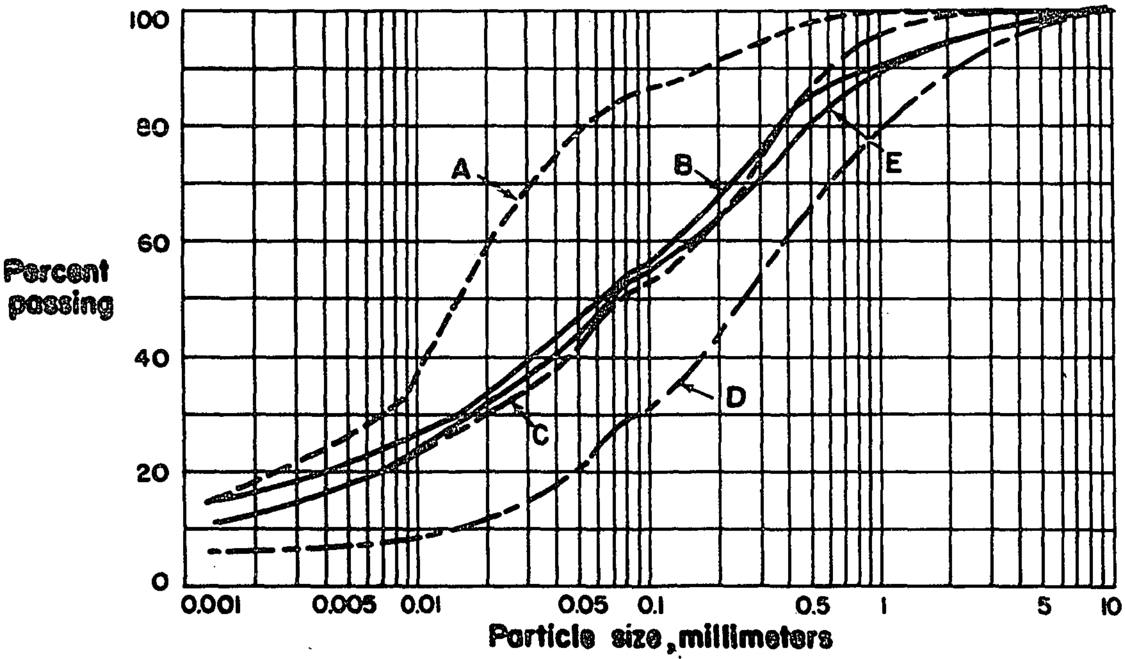
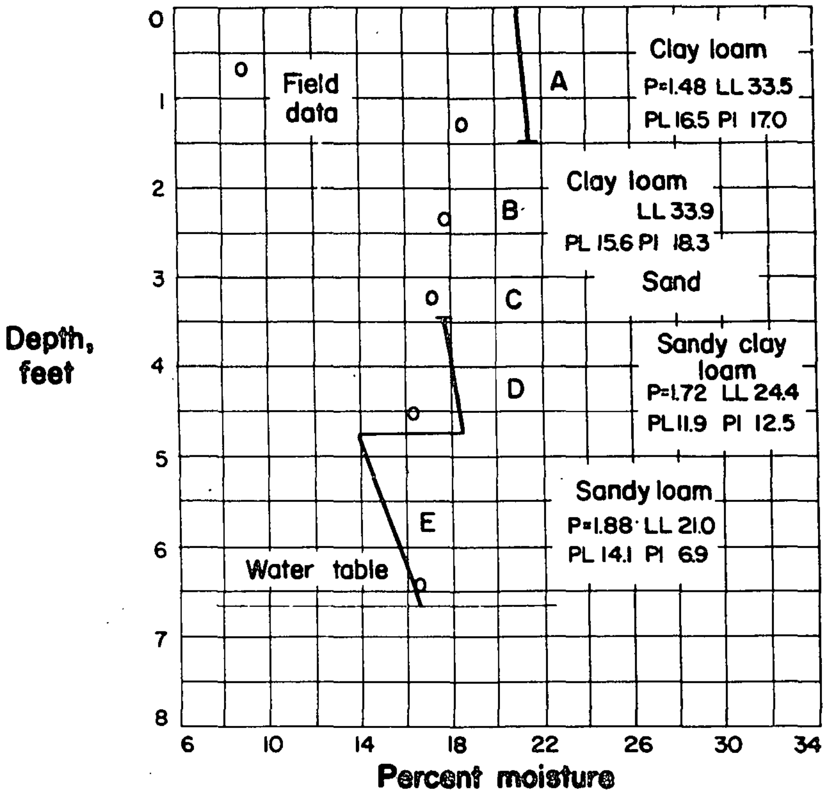

Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters
A
B
C
D
E

Figure 22. Test hole 3-3

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


0
1
2
3
4
5
6
7
8
Depth, feet
Field data
A
B
C
D
E
Water table
Clay loam
P=1.48 LL 33.5
PL 16.5 PI 17.0
Clay loam
LL 33.9
PL 15.6 PI 18.3
Sand
Sandy clay loam
P=1.72 LL 24.4
PL 11.9 PI 12.5
Sandy loam
P=1.88 LL 21.0
PL 14.1 PI 6.9
6
10
14
18
22
26
30
34
Percent moisture

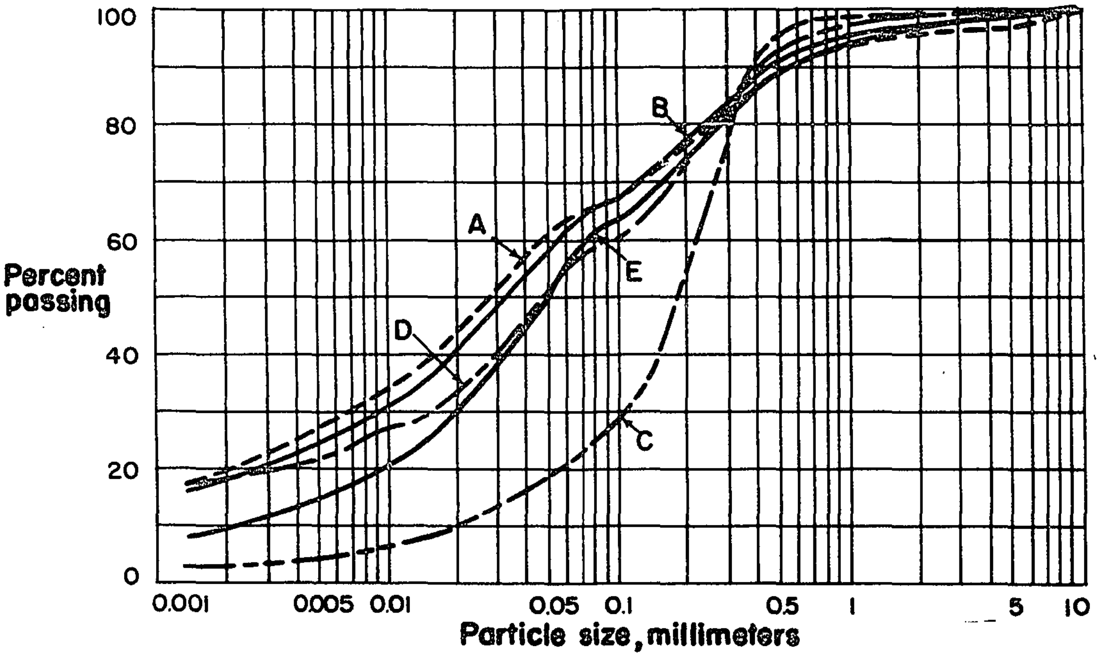
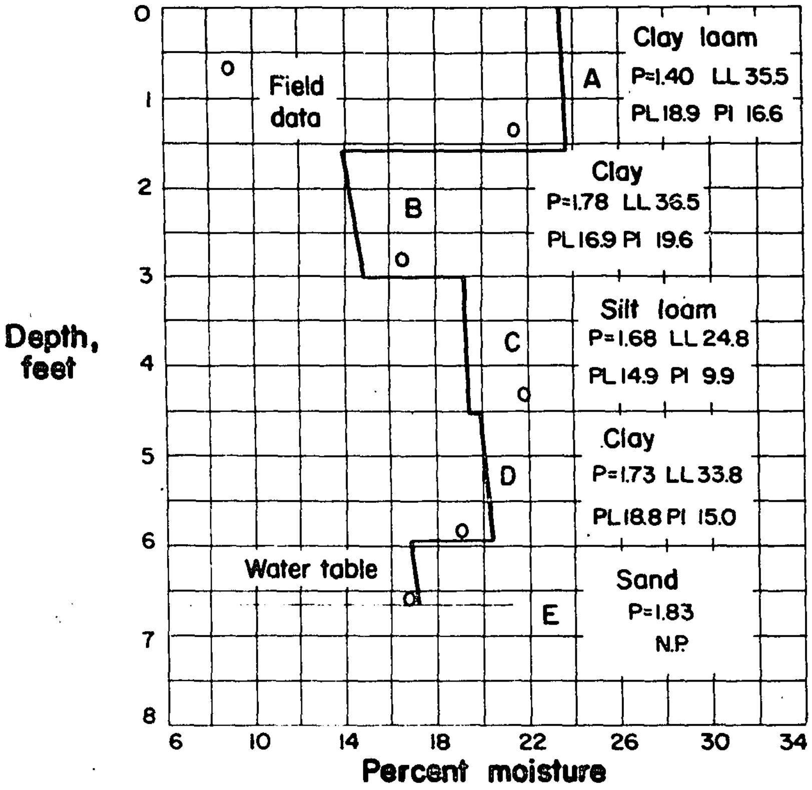

100
80
60
40
20
0
Percent passing
A
B
C
D
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 23. Test hole 3-4

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
Field data
Water table
A
Clay loam
P=1.40 LL 35.5
PL 18.9 PI 16.6
B
Clay
P=1.78 LL 36.5
PL 16.9 PI 19.6
C
Silt loam
P=1.68 LL 24.8
PL 14.9 PI 9.9
D
Clay
P=1.73 LL 33.8
PL 18.8 PI 15.0
E
Sand
P=1.83
N.P.
6
10
14
18
22
26
30
34
Percent moisture

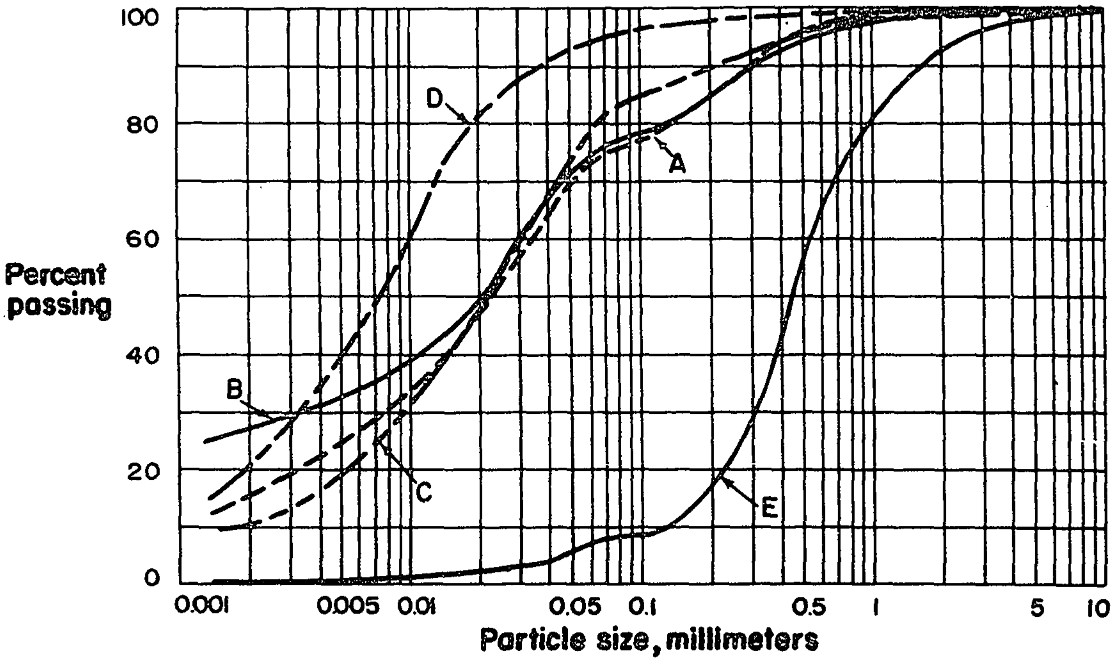
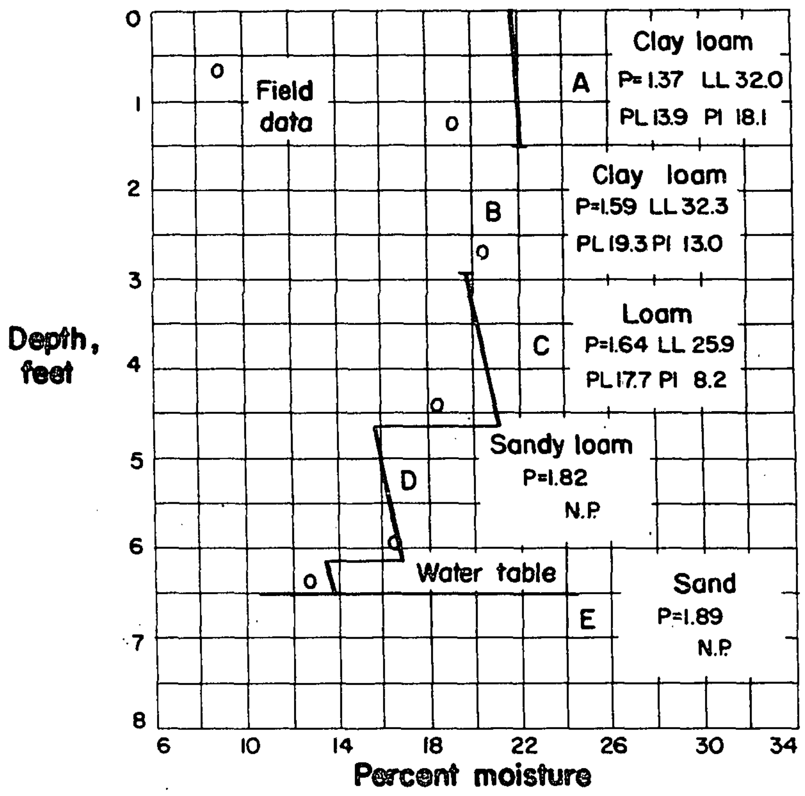

100
80
60
40
20
0
Percent passing
D
A
B
C
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 24. Test hole 4-1

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
A
Clay loam
P= 1.37 LL 32.0
PL 13.9 PI 18.1
B
Clay loam
P=1.59 LL 32.3
PL 19.3 PI 13.0
C
Loam
P=1.64 LL 25.9
PL 17.7 PI 8.2
D
Sandy loam
P=1.82
N.P.
Water table
E
Sand
P=1.89
N.P.
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

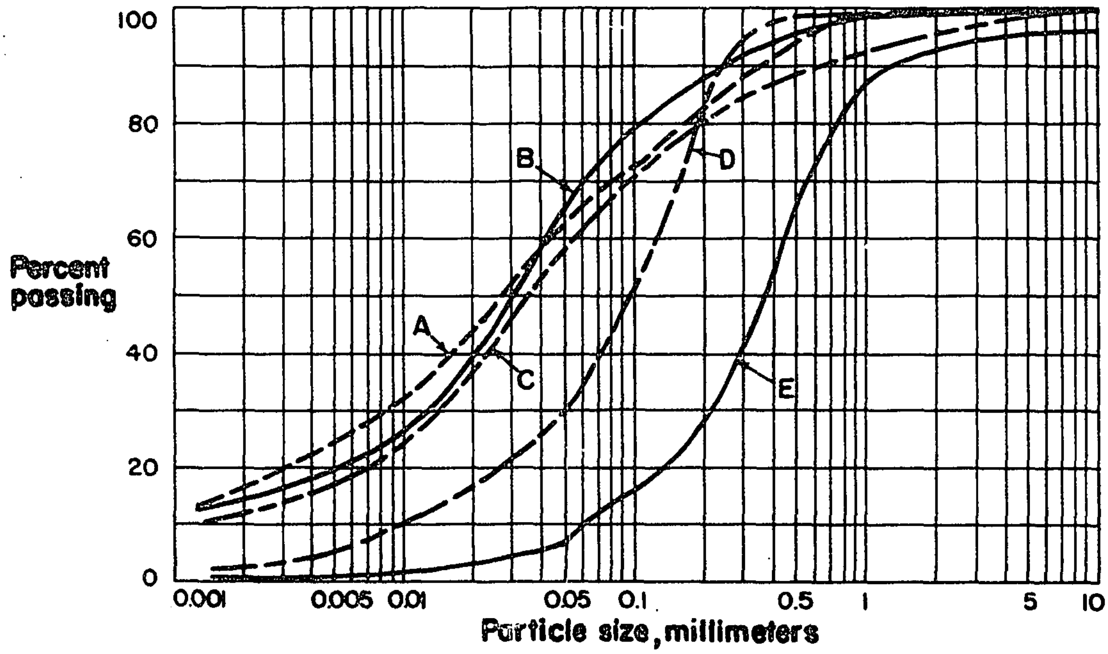
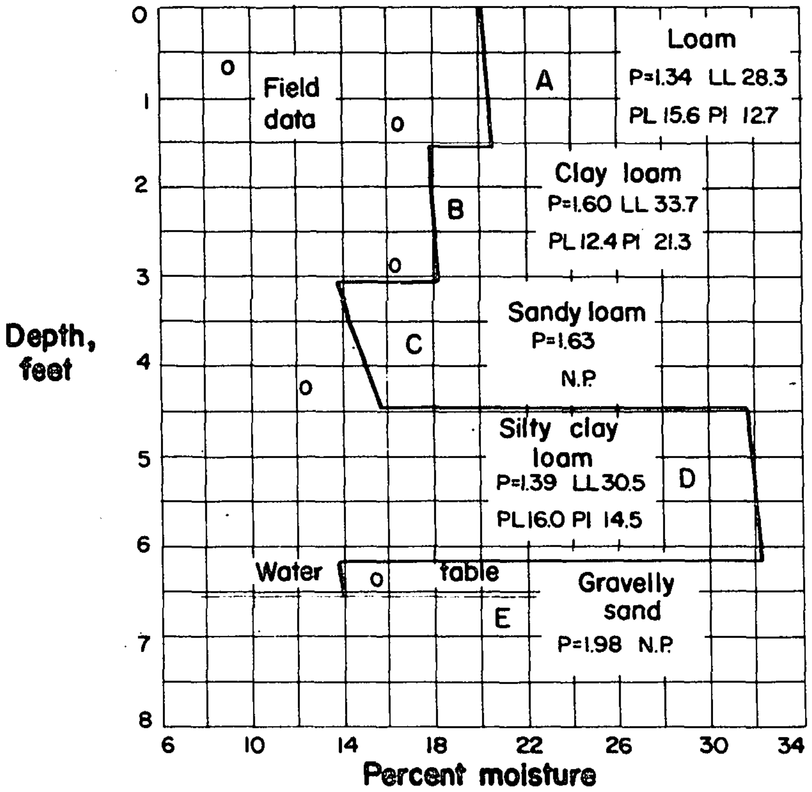

A
B
C
D
E
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 25. Test hole 4-2

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Loam
P=1.34 LL 28.3
PL 15.6 PI 12.7
A
o
Field
data
o
Clay loam
P=1.60 LL 33.7
PL 12.4 PI 21.3
B
o
Sandy loam
P=1.63
N.P.
C
o
Silty clay
loam
P=1.39 LL 30.5
PL 16.0 PI 14.5
D
Water
o
table
Gravelly
sand
P=1.98 N.P.
E
0
1
2
3
4
5
6
7
8
Depth,
feet
6
10
14
18
22
26
30
34
Percent moisture

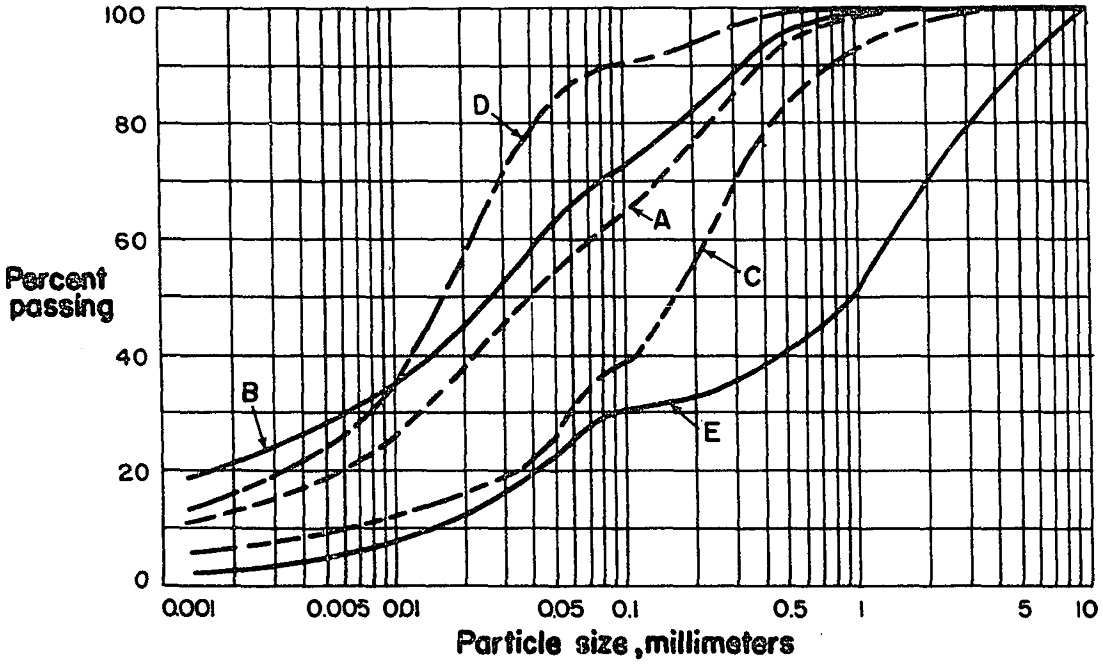
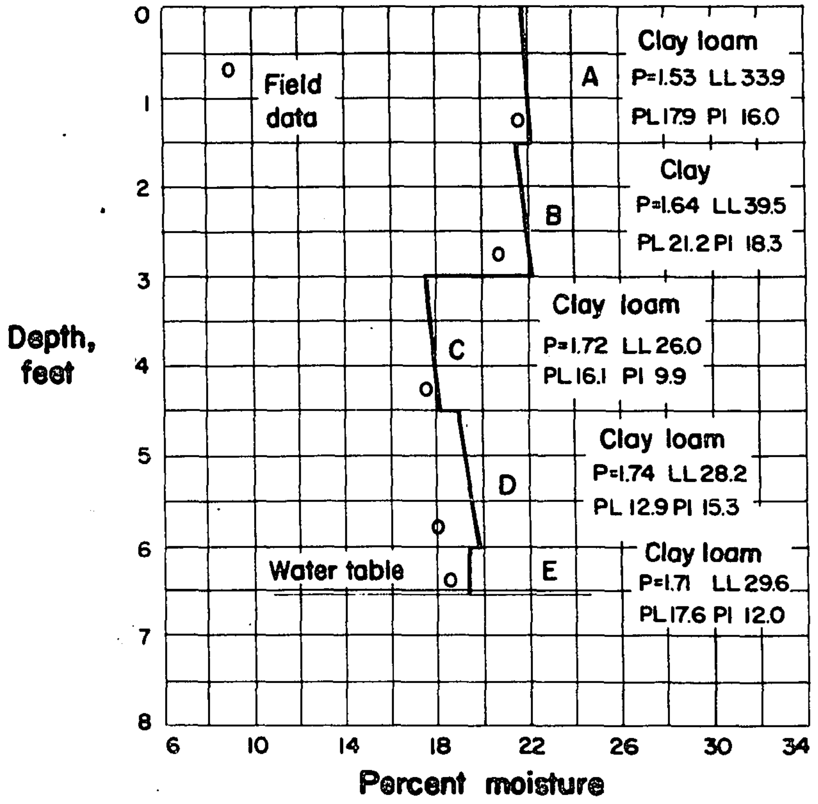

100
80
60
40
20
0
Percent
passing
D
A
C
B
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 26. Test hole 4-3

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
o Field data
A
Clay loam
P=1.53 LL 33.9
PL 17.9 PI 16.0
B
Clay
P=1.64 LL 39.5
PL 21.2 PI 18.3
C
Clay loam
P=1.72 LL 26.0
PL 16.1 PI 9.9
D
Clay loam
P=1.74 LL 28.2
PL 12.9 PI 15.3
Water table
E
Clay loam
P=1.71 LL 29.6
PL 17.6 PI 12.0

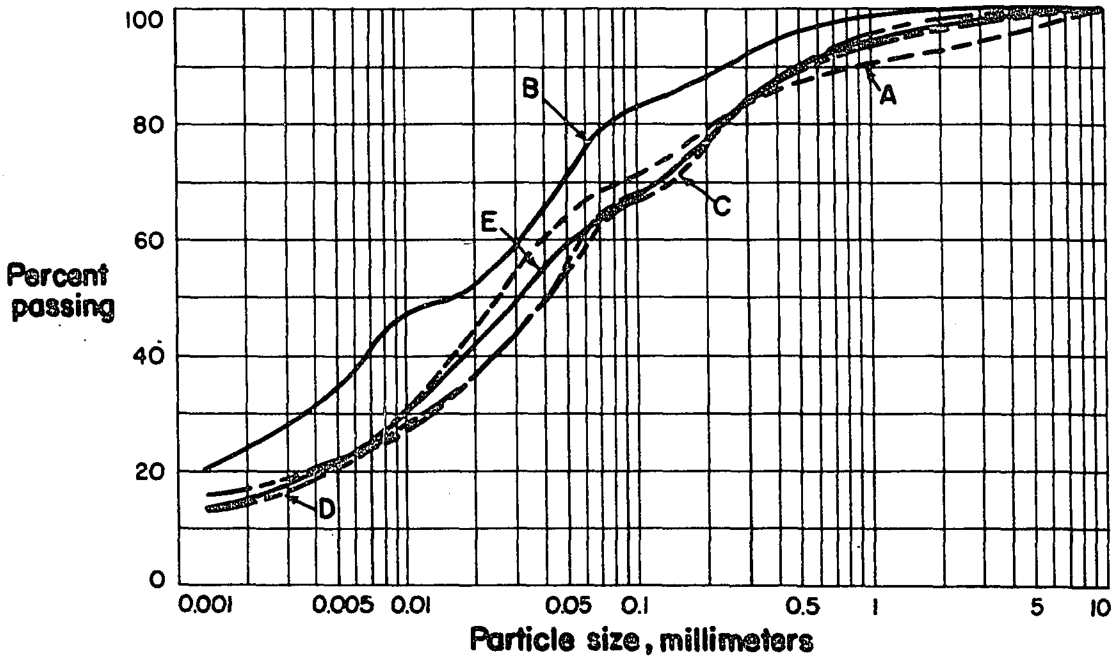
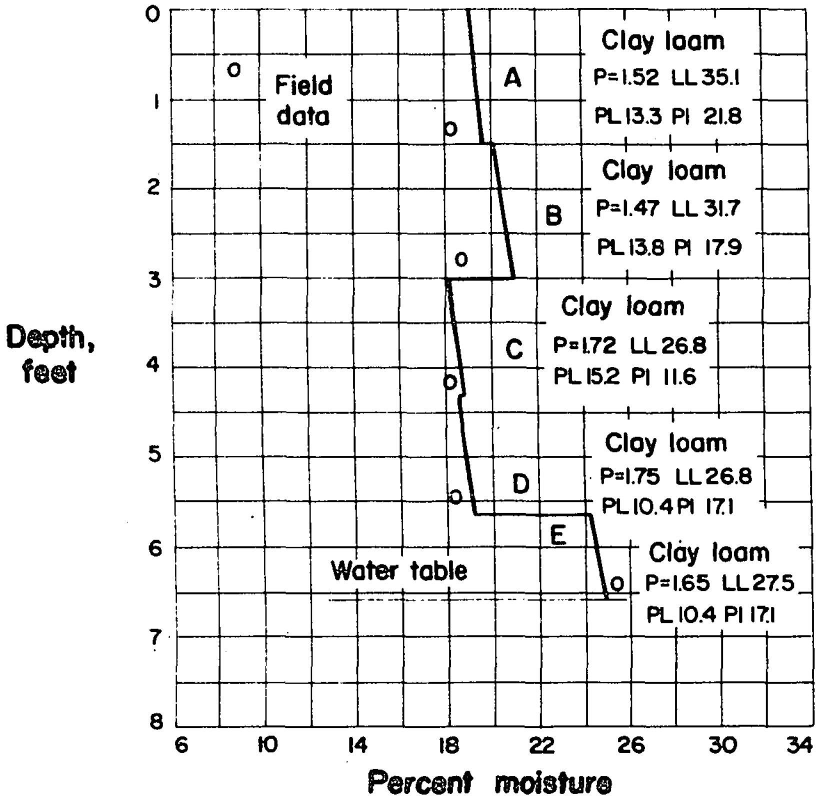

Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters
A
B
C
D
E

Figure 27. Test hole 4-4

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
Field data
A
Clay loam
P=1.52 LL 35.1
PL 13.3 PI 21.8
B
Clay loam
P=1.47 LL 31.7
PL 13.8 PI 17.9
C
Clay loam
P=1.72 LL 26.8
PL 15.2 PI 11.6
D
Clay loam
P=1.75 LL 26.8
PL 10.4 PI 17.1
E
Clay loam
P=1.65 LL 27.5
PL 10.4 PI 17.1
Water table
6
10
14
18
22
26
30
34
Percent moisture

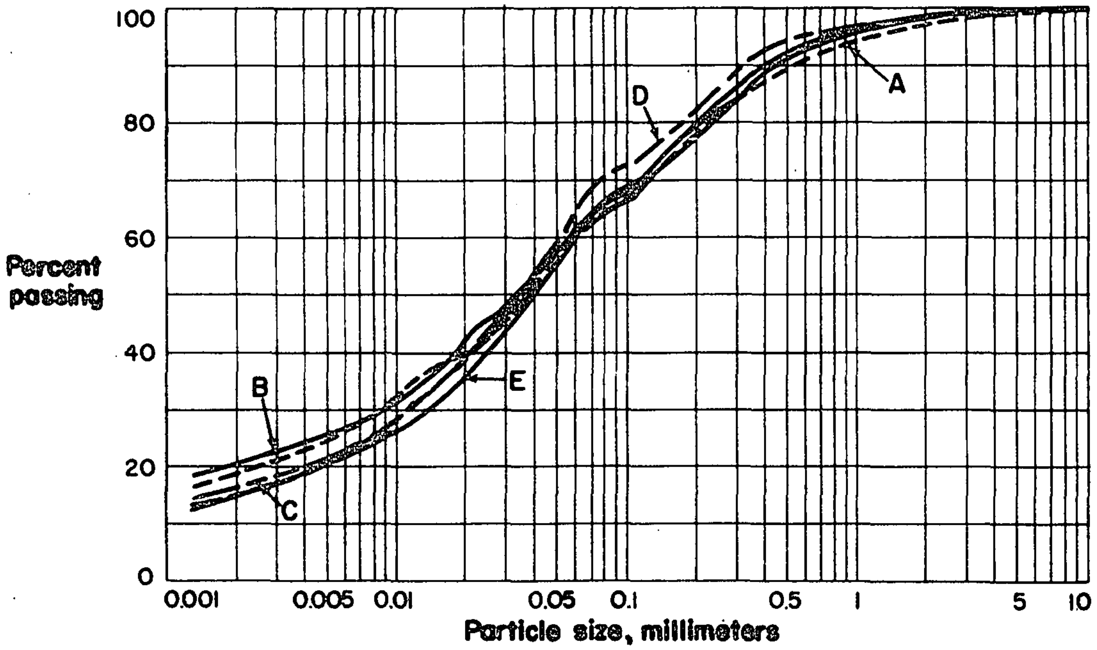
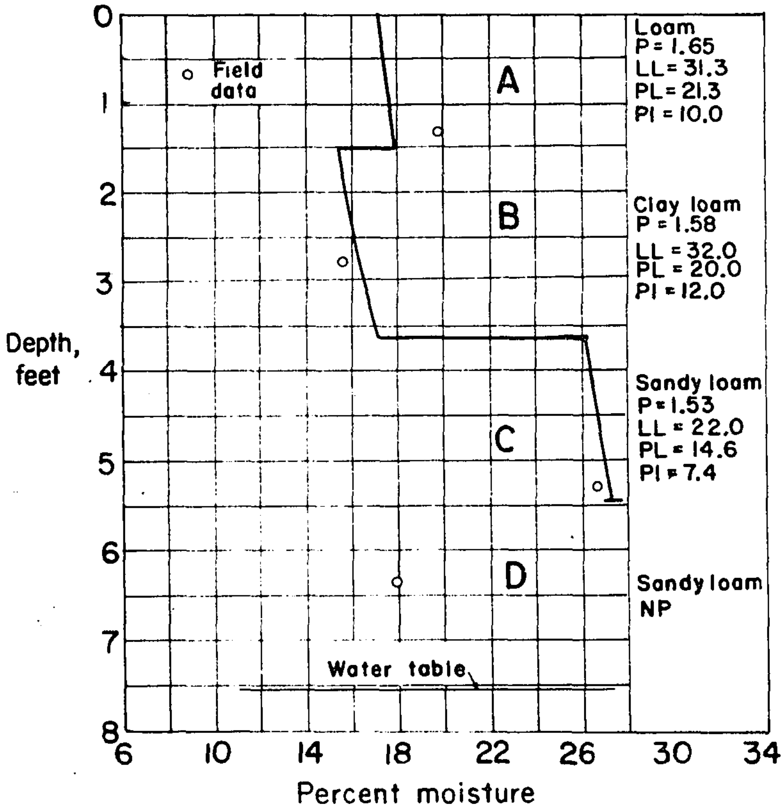

Percent passing
100
80
60
40
20
0
A
B
C
D
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 28. Test hole 5-1

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
A
B
C
D
Water table
Loam
P = 1.65
LL = 31.3
PL = 21.3
PI = 10.0
Clay loam
P = 1.58
LL = 32.0
PL = 20.0
PI = 12.0
Sandy loam
P = 1.53
LL = 22.0
PL = 14.6
PI = 7.4
Sandy loam
NP
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

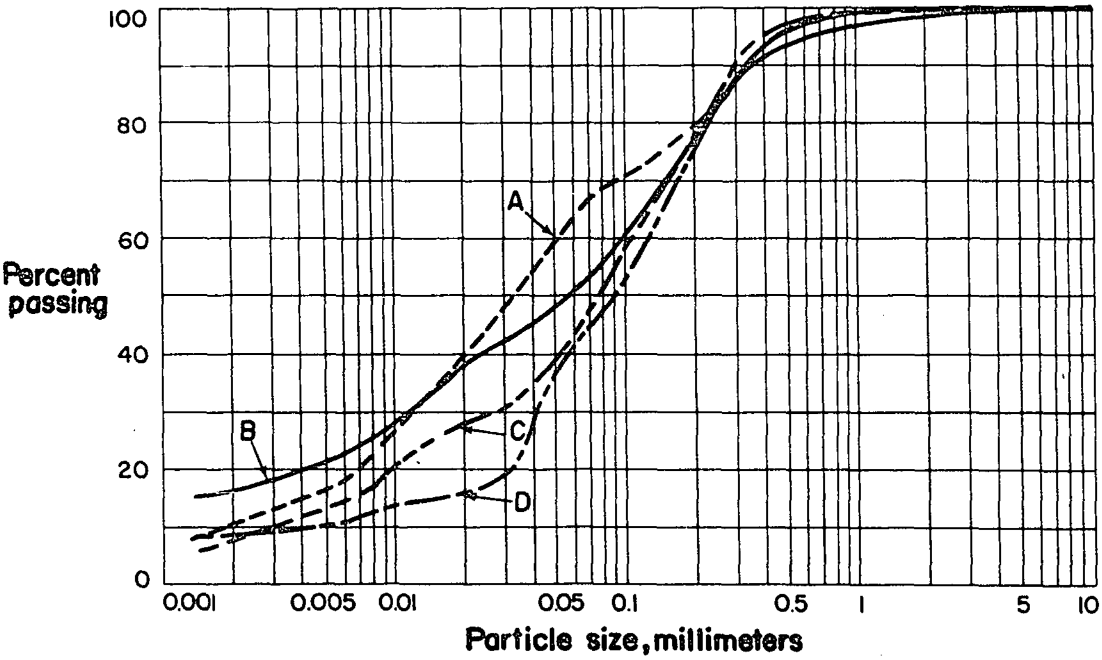
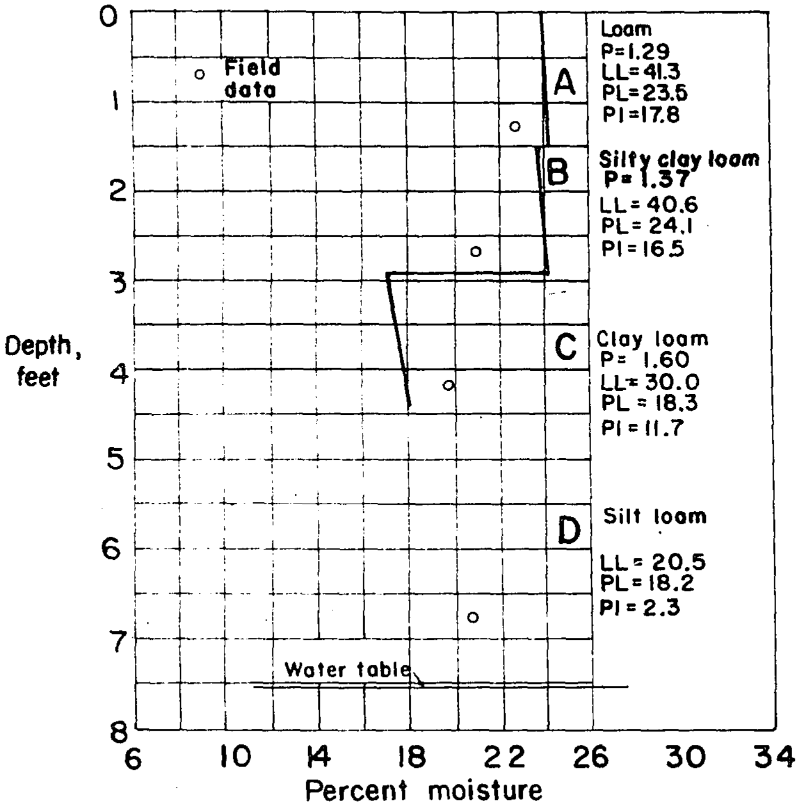

A
B
C
D
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 29. Test hole 5-2

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


○ Field data
A
Loam
P=1.29
LL=41.3
PL=23.5
PI=17.8
B
Silty clay loam
P= 1.37
LL= 40.6
PL= 24.1
PI= 16.5
C
Clay loam
P= 1.60
LL= 30.0
PL = 18.3
PI = 11.7
D
Silt loam
LL= 20.5
PL= 18.2
PI = 2.3
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture

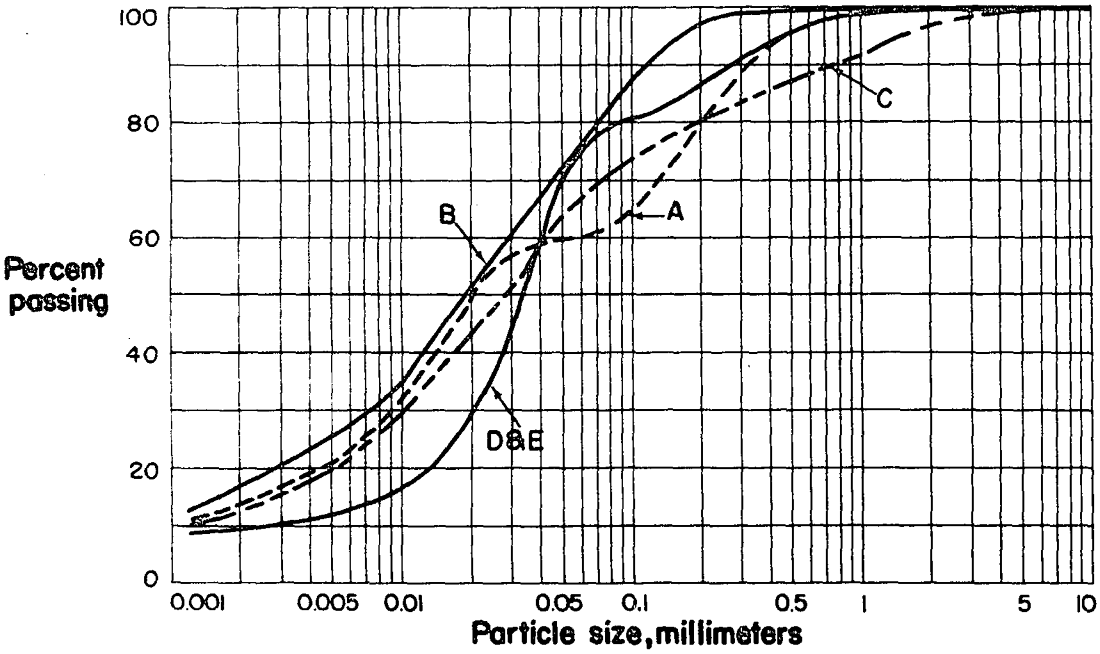
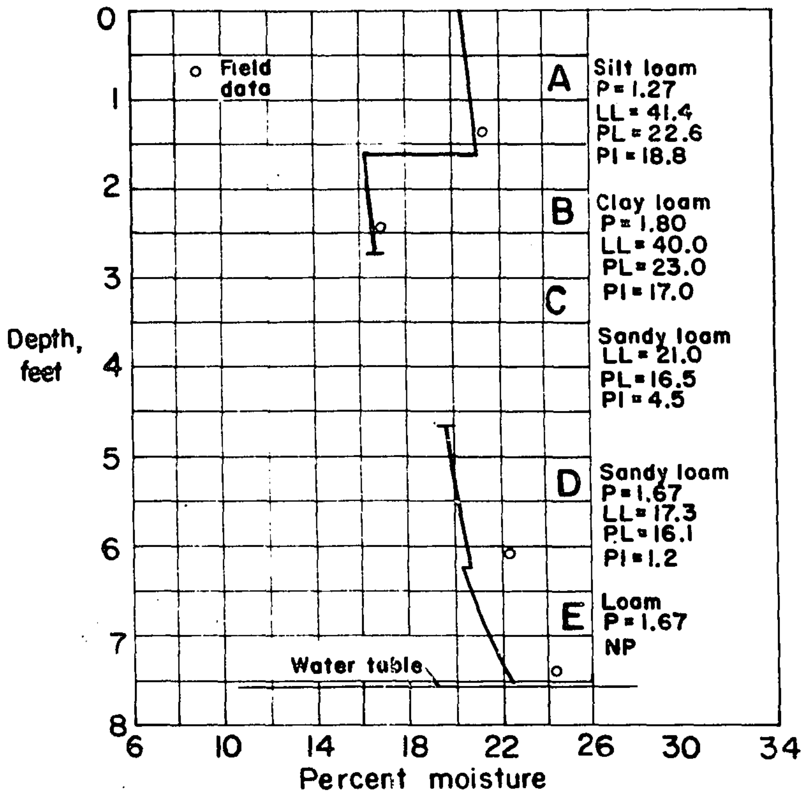

B
A
C
D&E
Percent passing
100
80
60
40
20
0
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 30. Test hole 5-3

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Depth, feet
0
1
2
3
4
5
6
7
8
○ Field data
A
Silt loam
P = 1.27
LL = 41.4
PL = 22.6
PI = 18.8
B
Clay loam
P = 1.80
LL = 40.0
PL = 23.0
PI = 17.0
C
Sandy loam
LL = 21.0
PL = 16.5
PI = 4.5
D
Sandy loam
P = 1.67
LL = 17.3
PL = 16.1
PI = 1.2
E
Loam
P = 1.67
NP
Water table
6
10
14
18
22
26
30
34
Percent moisture

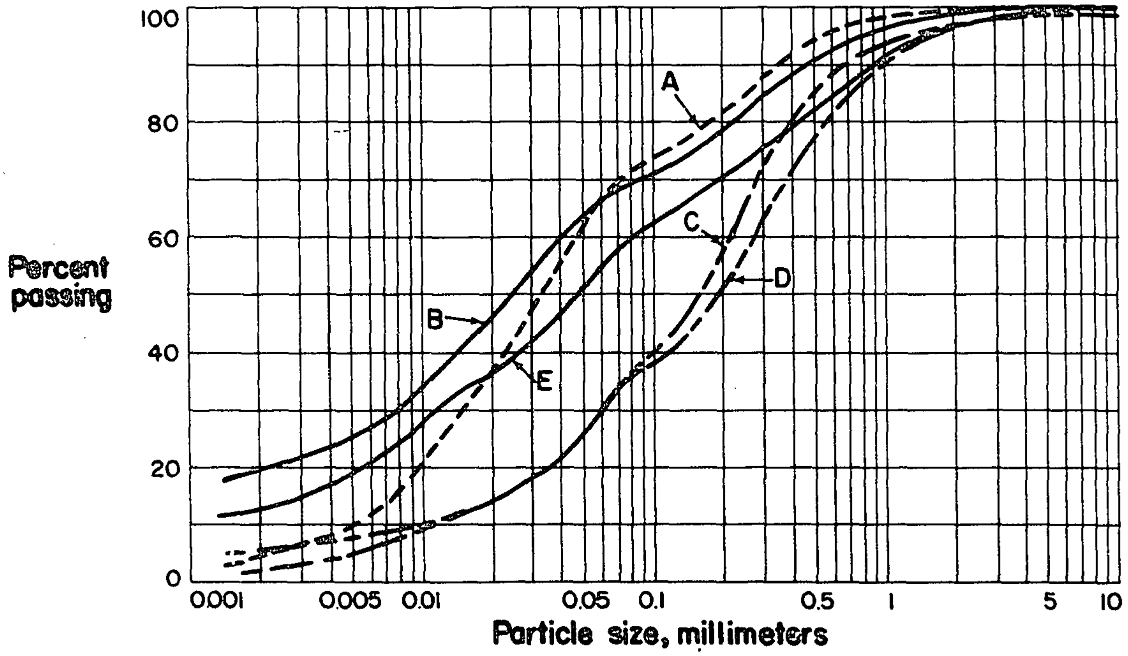
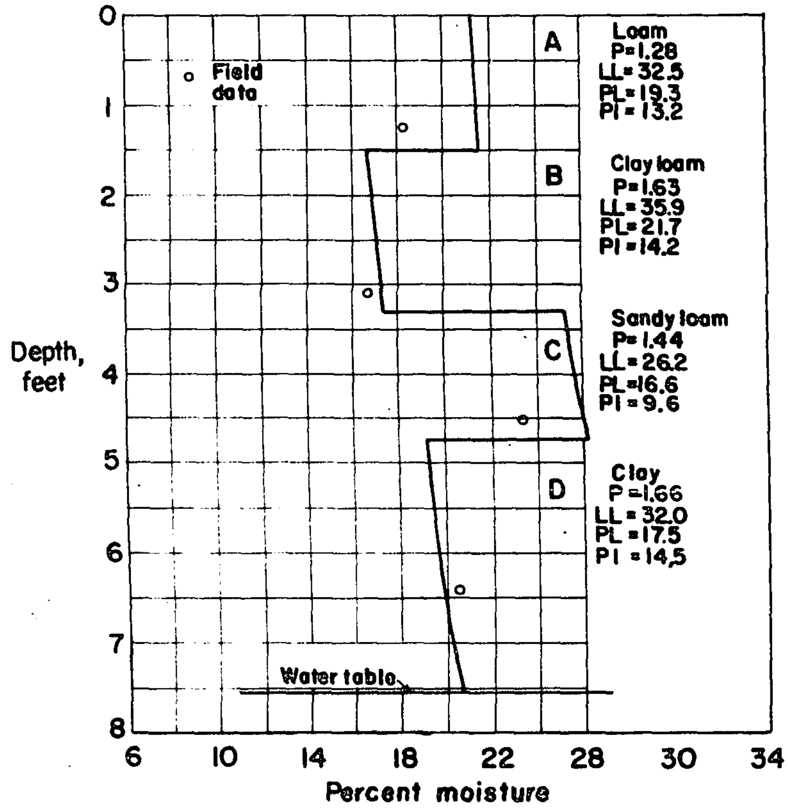

Percent passing
100
80
60
40
20
0
A
B
C
D
E
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 31. Test hole 5-4

Above: Composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


Field data
A
Loam
P=1.28
LL=32.5
PL=19.3
PI=13.2
B
Clay loam
P=1.63
LL=35.9
PL=21.7
PI=14.2
C
Sandy loam
P=1.44
LL=26.2
PL=16.6
PI=9.6
D
Clay
P=1.66
LL=32.0
PL=17.5
PI=14.5
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
28
30
34
Percent moisture

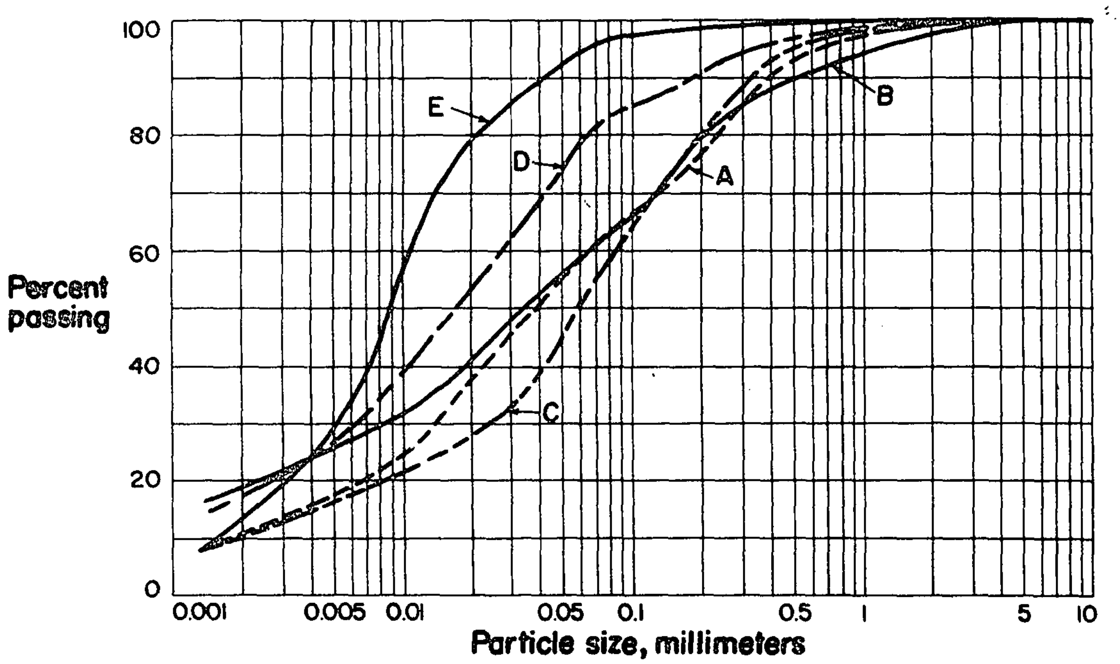
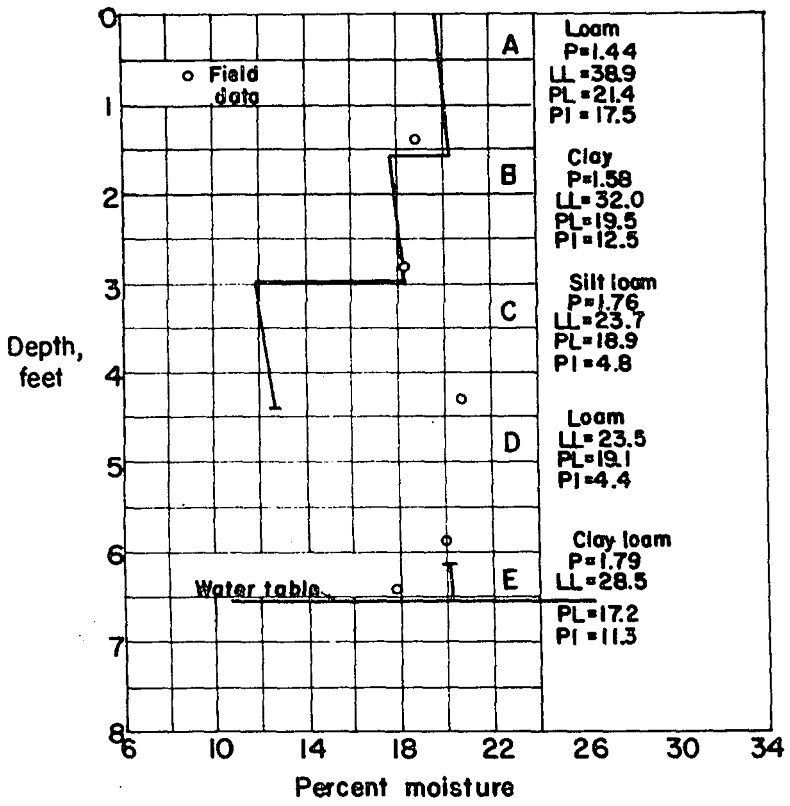

E
D
A
B
C
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 32. Test hole 6-1

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


0
1
2
3
4
5
6
7
8
Depth, feet
○ Field data
Water table
A
B
C
D
E
Loam
P=1.44
LL=38.9
PL=21.4
PI=17.5
Clay
P=1.58
LL=32.0
PL=19.5
PI=12.5
Silt loam
P=1.76
LL=23.7
PL=18.9
PI=4.8
Loam
LL=23.5
PL=19.1
PI=4.4
Clay loam
P=1.79
LL=28.5
PL=17.2
PI=11.3
6
10
14
18
22
26
30
34
Percent moisture

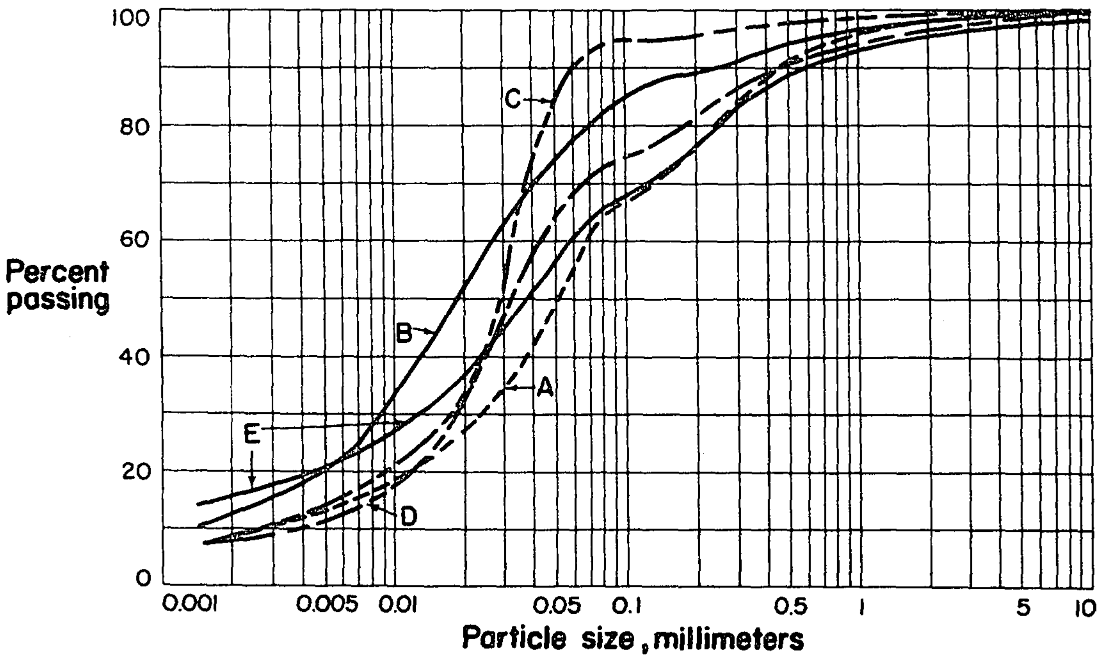
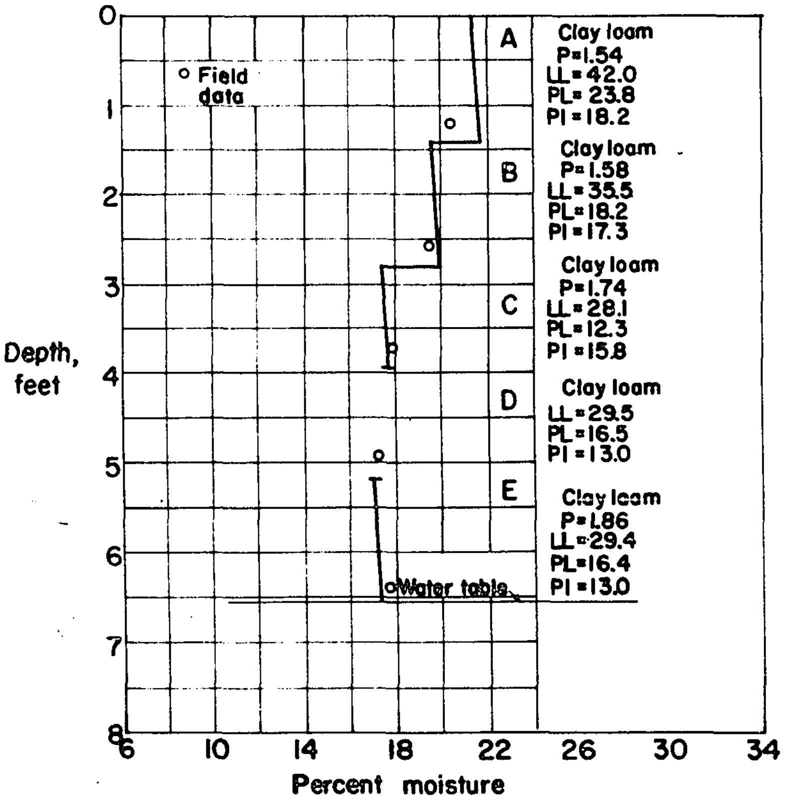

100
80
60
40
20
0
Percent passing
C
B
A
E
D
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 33. Test hole 6-2

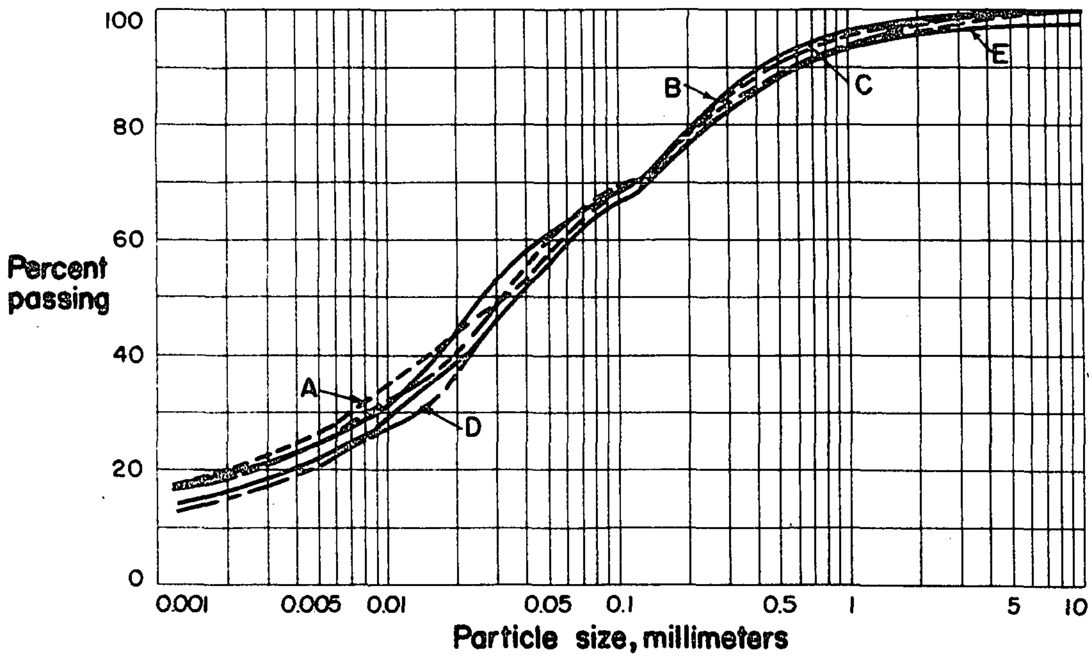
Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used



○ Field data
A
Clay loam
P=1.54
LL=42.0
PL=23.8
PI=18.2
B
Clay loam
P=1.58
LL=35.5
PL=18.2
PI=17.3
C
Clay loam
P=1.74
LL=28.1
PL=12.3
PI=15.8
D
Clay loam
LL=29.5
PL=16.5
PI=13.0
E
Clay loam
P=1.86
LL=29.4
PL=16.4
PI=13.0
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture



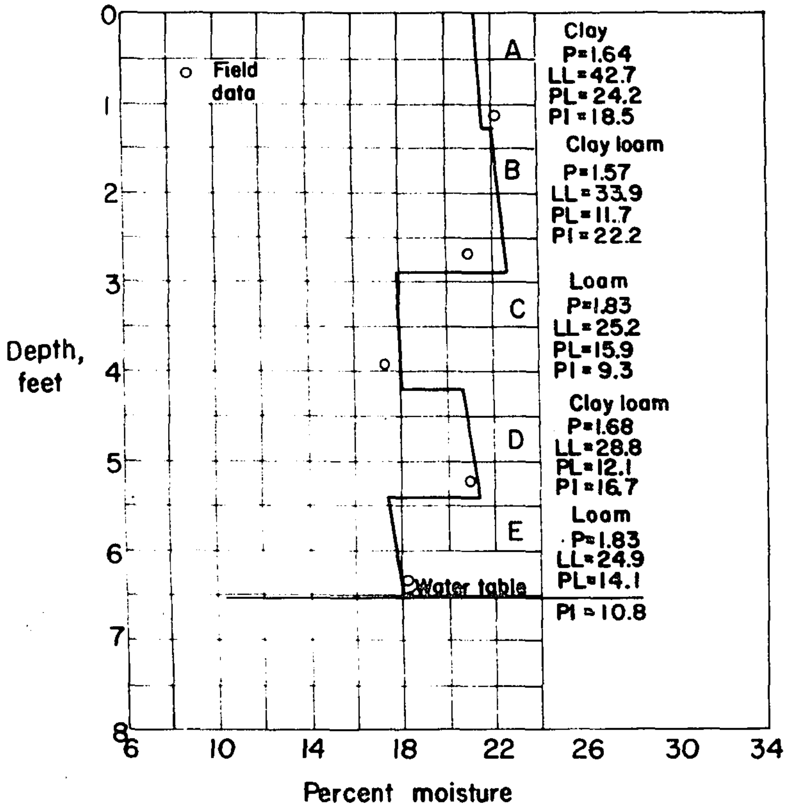
A
B
C
D
E
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

Figure 34. Test hole 6-3

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


0
1
2
3
4
5
6
7
8
Depth, feet
6
10
14
18
22
26
30
34
Percent moisture
○ Field data
A
B
C
D
E
Clay
P=1.64
LL=42.7
PL=24.2
PI=18.5
Clay loam
P=1.57
LL=33.9
PL=11.7
PI=22.2
Loam
P=1.83
LL=25.2
PL=15.9
PI=9.3
Clay loam
P=1.68
LL=28.8
PL=12.1
PI=16.7
Loam
P=1.83
LL=24.9
PL=14.1
PI=10.8
Water table

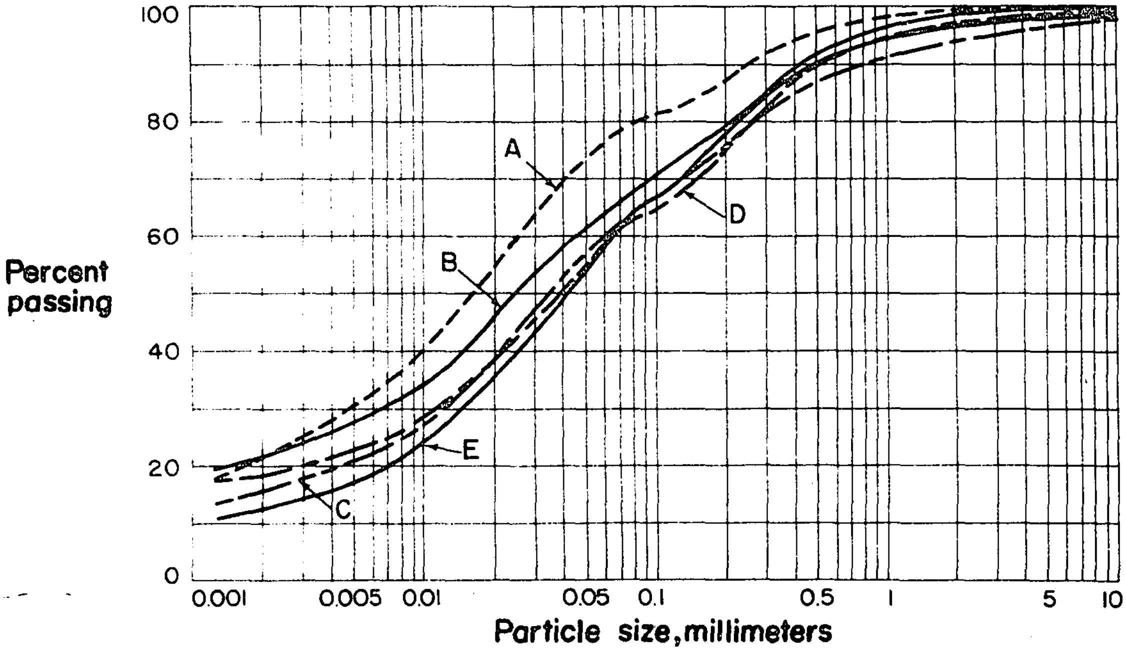
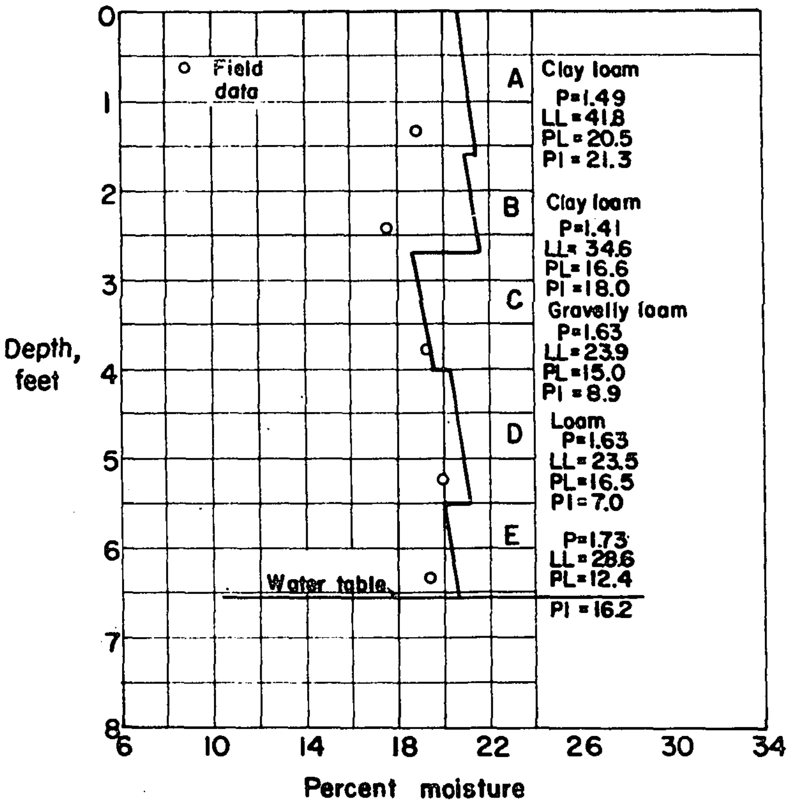

100
80
60
40
20
0
Percent passing
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters
A
B
C
D
E

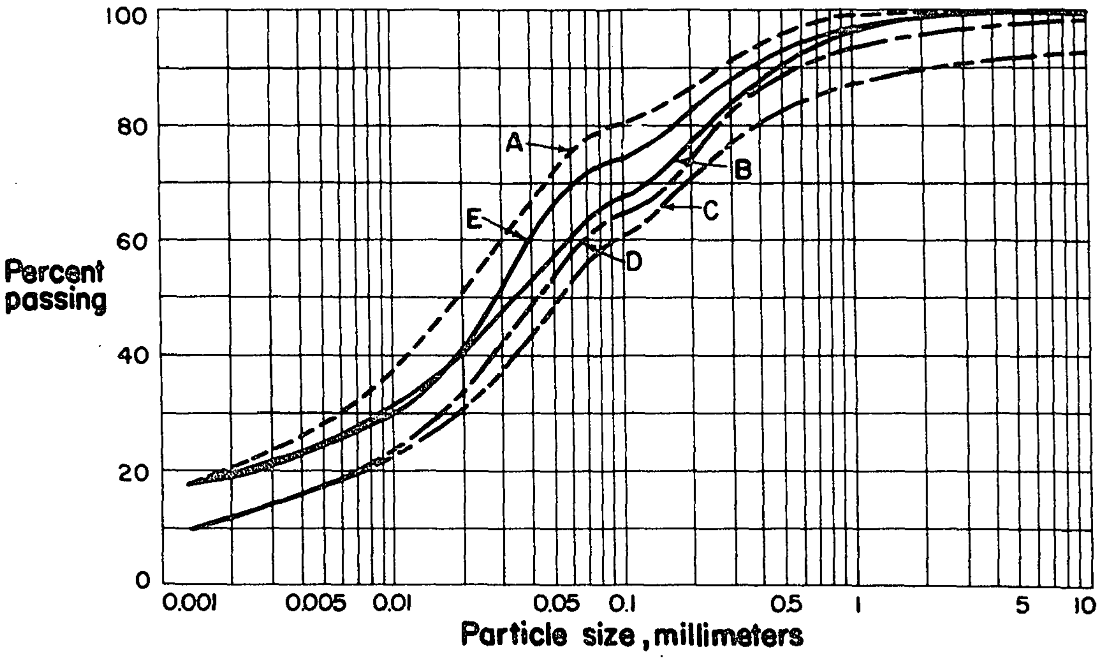
Figure 35. Test hole 6-4

Above: composite desorption curve

Below: particle size distribution curves

See Figure 12 for symbols used


○ Field data
A Clay loam
P=1.49
LL=41.8
PL=20.5
PI=21.3
B Clay loam
P=1.41
LL=34.6
PL=16.6
PI=18.0
C Gravelly loam
P=1.63
LL=23.9
PL=15.0
PI=8.9
D Loam
P=1.63
LL=23.5
PL=16.5
PI=7.0
E
P=1.73
LL=28.6
PL=12.4
PI=16.2
Water table
Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture


A
B
C
D
E
Percent passing
0
20
40
60
80
100
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
Particle size, millimeters

throughout the soil profiles at intervals of two feet of depth starting at the surface and extending to depths of 12 to 14 feet. In addition, the air temperature was determined at a height of approximately one foot above the ground. Because of lengthy breakdowns the temperature measuring equipment was operative only for the following periods: January through August, 1955; January through August, 1956; and February, 1957 through March, 1958.

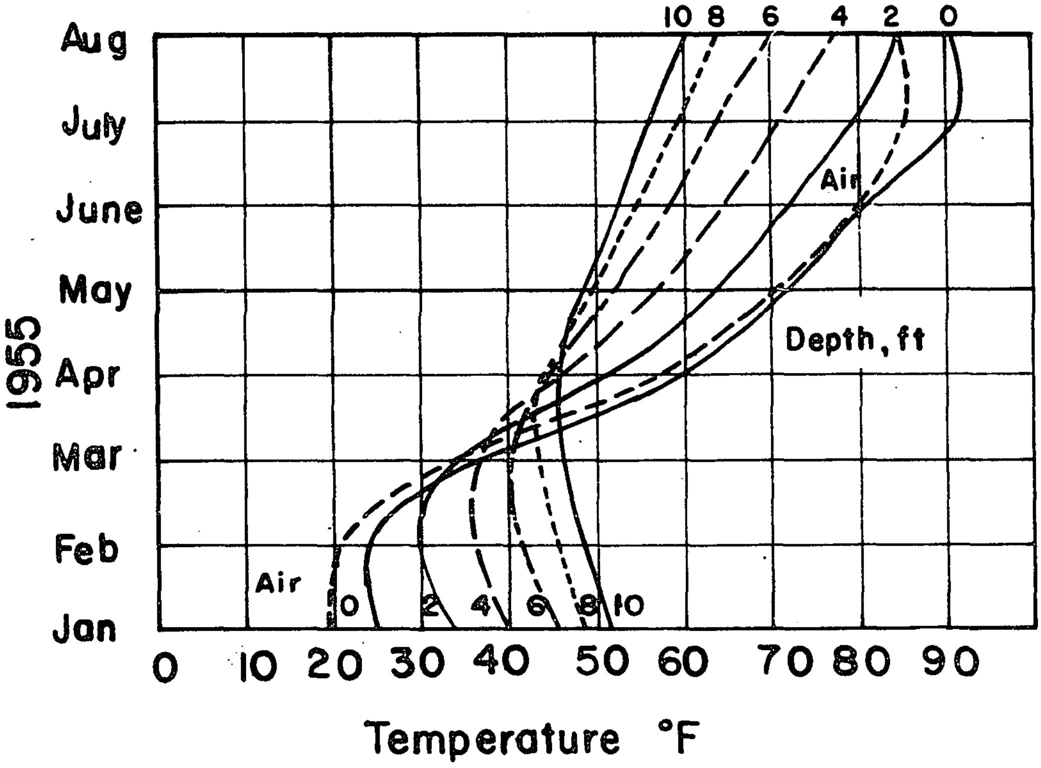
In order that the temperature data might be utilized it was necessary to reduce the multitude of readings per day per thermocouple to a few representative values. This was accomplished by using only the temperatures recorded at midnight, 6:00 A.M., noon and 6:00 P.M. The average daily temperatures were then obtained by averaging the four temperatures at the times given above. Subsequently, the average monthly temperatures were determined by averaging the daily values. The average monthly temperatures for the various positions in the profiles thus obtained are given in Figures 36-39. In each case temperatures are given for the soil under the impervious surface, or covered area, and under normal vegetive cover, or control area.

It is unfortunate that temperature data were not available for the entire period of October, 1957 through September, 1958 during which the other data were considered useable, but it is apparent from Figures 36-39 that the annual soil

Figure 36. Soil temperatures

Above: covered area

Below: control area


10 8 6 4 2 0
Aug
July
June
May
Apr
Mar
Feb
Jan
1955
Air
Depth, ft
Air
0
2
4
6
8
10
0 10 20 30 40 50 60 70 80 90
Temperature °F

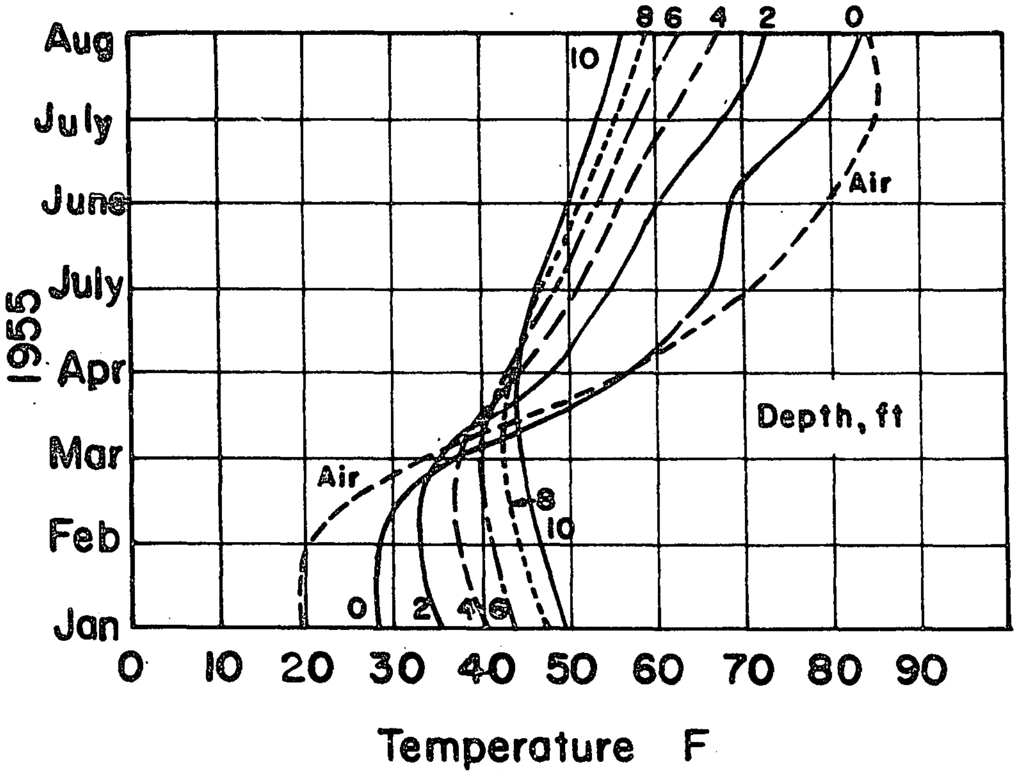
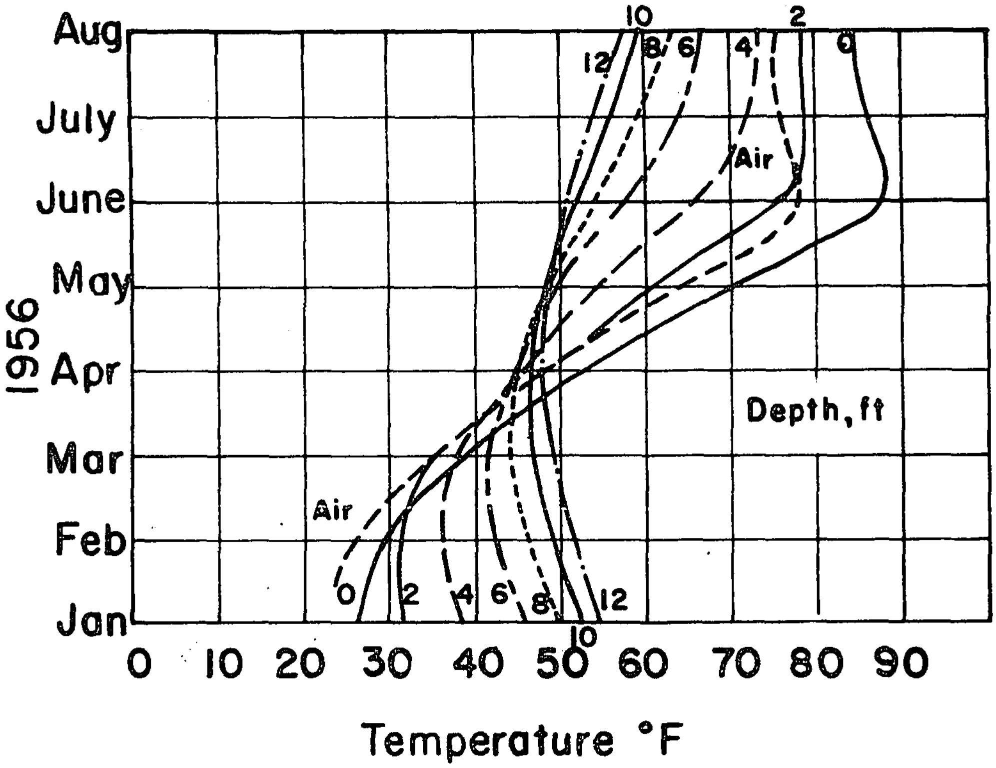

8 6 4 2 0
10
Aug
July
June
July
Apr
Mar
Feb
Jan
1955
Air
Depth, ft
Air
8
10
0
2
4
6
0 10 20 30 40 50 60 70 80 90
Temperature F

Figure 37. Soil temperatures

Above: covered area

Below: control area


Aug
July
June
May
Apr
Mar
Feb
Jan
1956
0
10
20
30
40
50
60
70
80
90
Temperature °F
Depth, ft
Air
Air
0
2
4
6
8
10
12

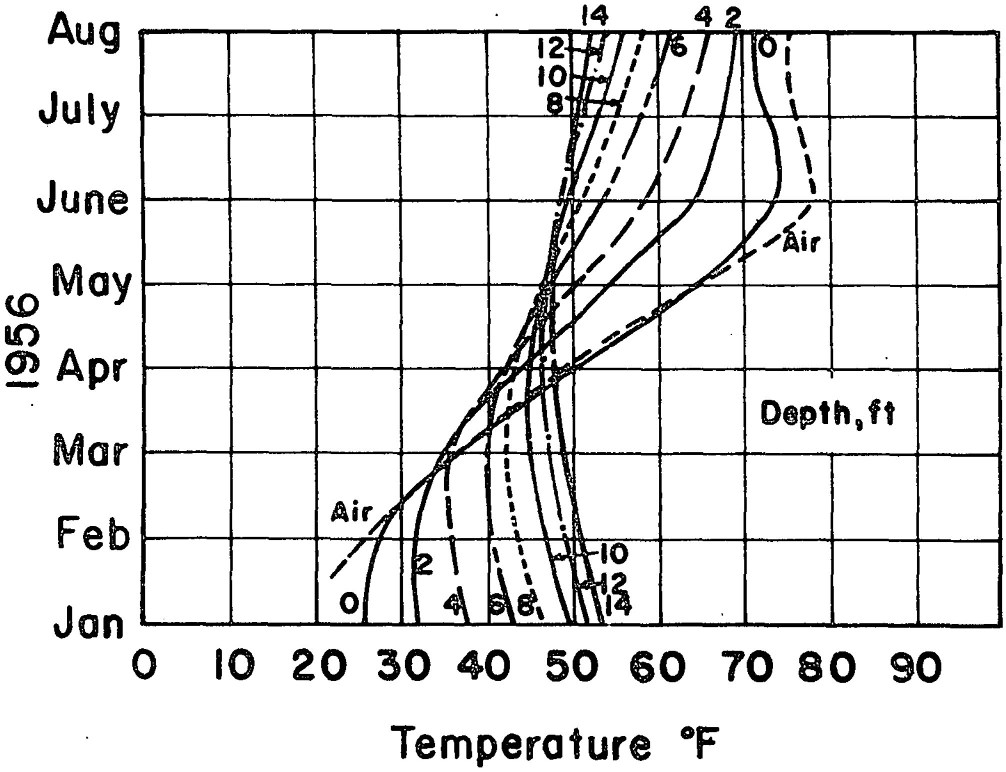

Aug
July
June
May
Apr
Mar
Feb
Jan
1956
0
10
20
30
40
50
60
70
80
90
Temperature °F
Depth, ft
Air
Air
0
2
4
6
8
10
12
14

Figure 38. Soil temperatures, covered area

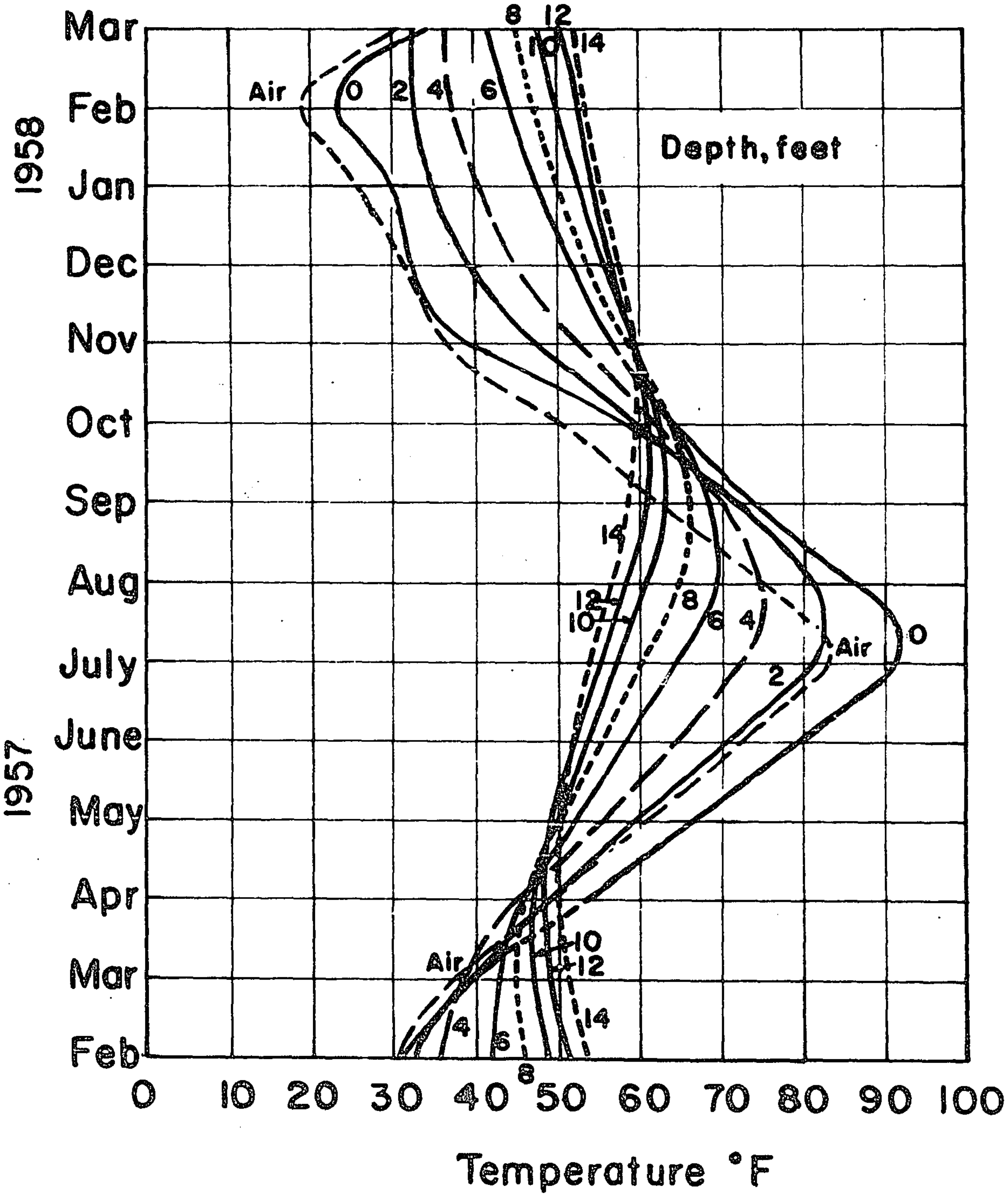
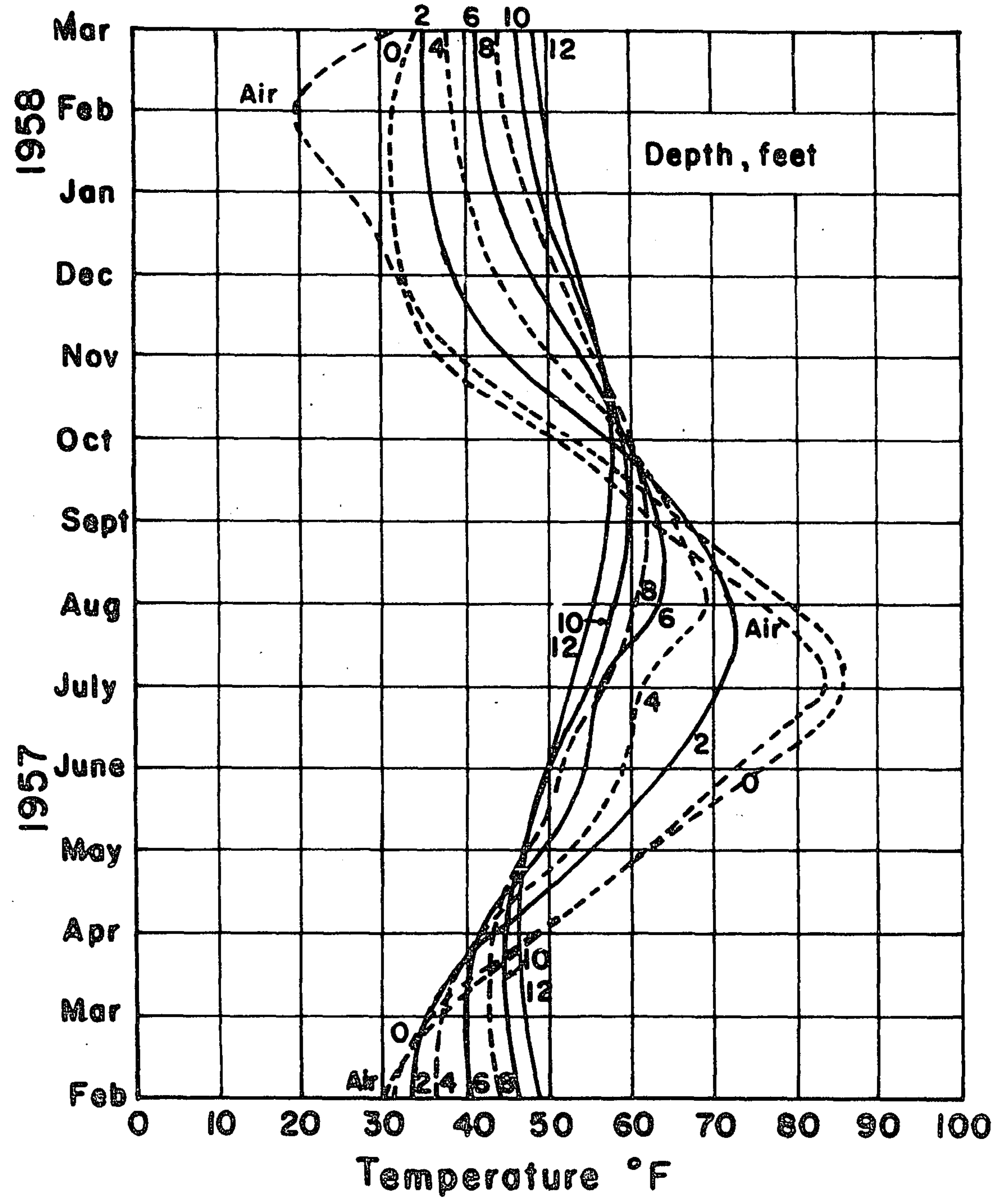

Depth, feet
Mar
Feb
Jan
Dec
Nov
Oct
Sep
Aug
July
June
May
Apr
Mar
Feb
1958
1957
Air
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80
90
100
Temperature °F

Figure 39. Soil temperatures, control area


Depth, feet
1958
1957
Mar
Feb
Jan
Dec
Nov
Oct
Sept
Aug
July
June
May
Apr
Mar
Feb
Air
0
2
4
6
8
10
12
0 10 20 30 40 50 60 70 80 90 100
Temperature °F

temperature cycle does not vary enough to invalidate the comparison of like months or seasons from one year to the next.

Because the average monthly temperature data minimize extreme measured values it was considered necessary to present examples of day-to-day temperature data with recorded extremes. For these examples July, 1957 and February, 1958 were chosen.

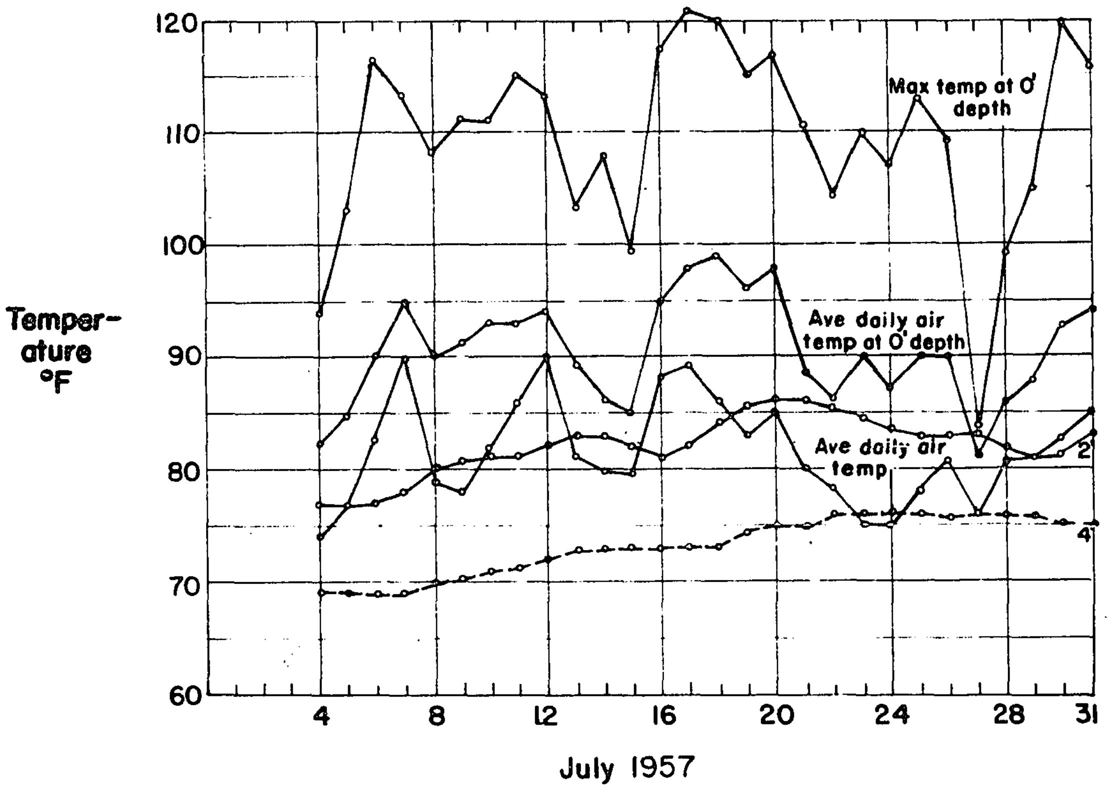
Figure 40 presents the average daily soil temperatures at various depths determined both for the covered and control areas during July, 1957. Also reported are the average daily temperatures and the maximum daily temperatures recorded at the surface of the soil. It will be noted that the maximum daily temperatures immediately under the bituminous surface far exceed the surface temperatures of the control area.

Figure 41 presents the average daily temperatures during February, 1958. In this case the minimum values at the soil surface were reported. The surface temperatures of the control area were much higher than the surface temperatures of the covered area; this is believed to be due primarily to ground cover in the form of snow and plant mulch. The covered area was nearly always free of snow probably because of its high elevation, color and surface texture.

Figure 40. Soil temperatures

Above: covered area

Below: control area


120
110
100
90
80
70
60
Temperature °F
Max temp at 0' depth
Ave daily air temp at 0' depth
Ave daily air temp
2'
4'
4
8
12
16
20
24
28
31
July 1957

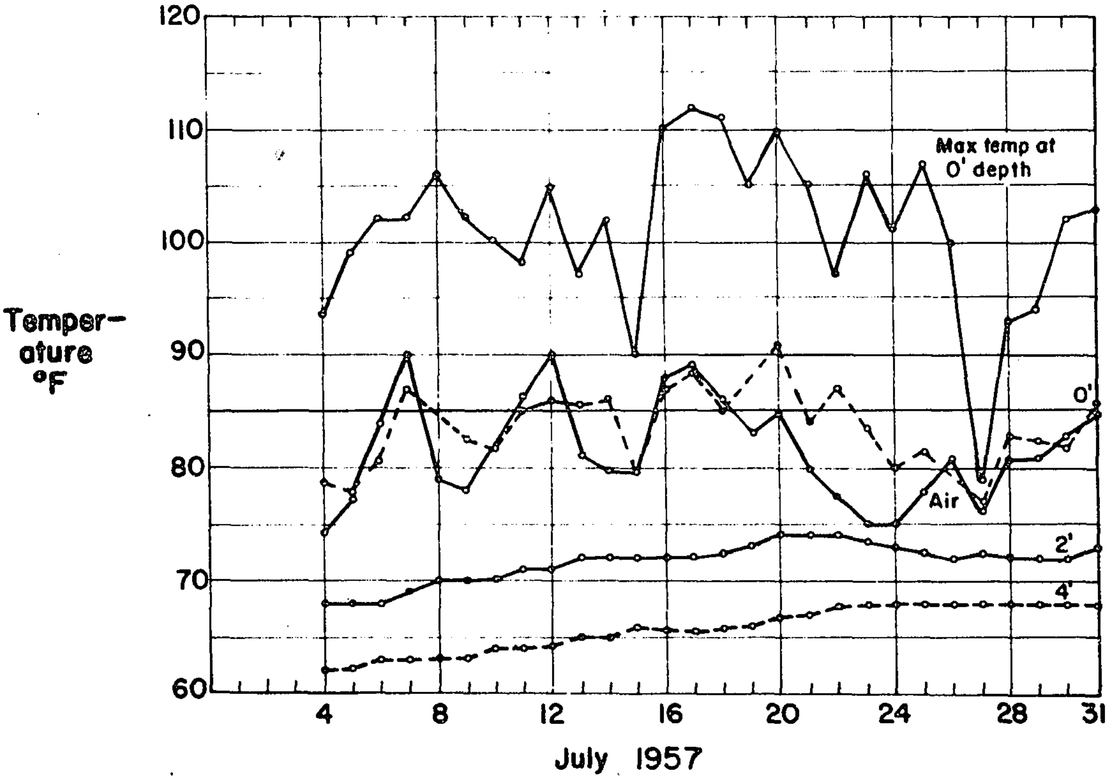
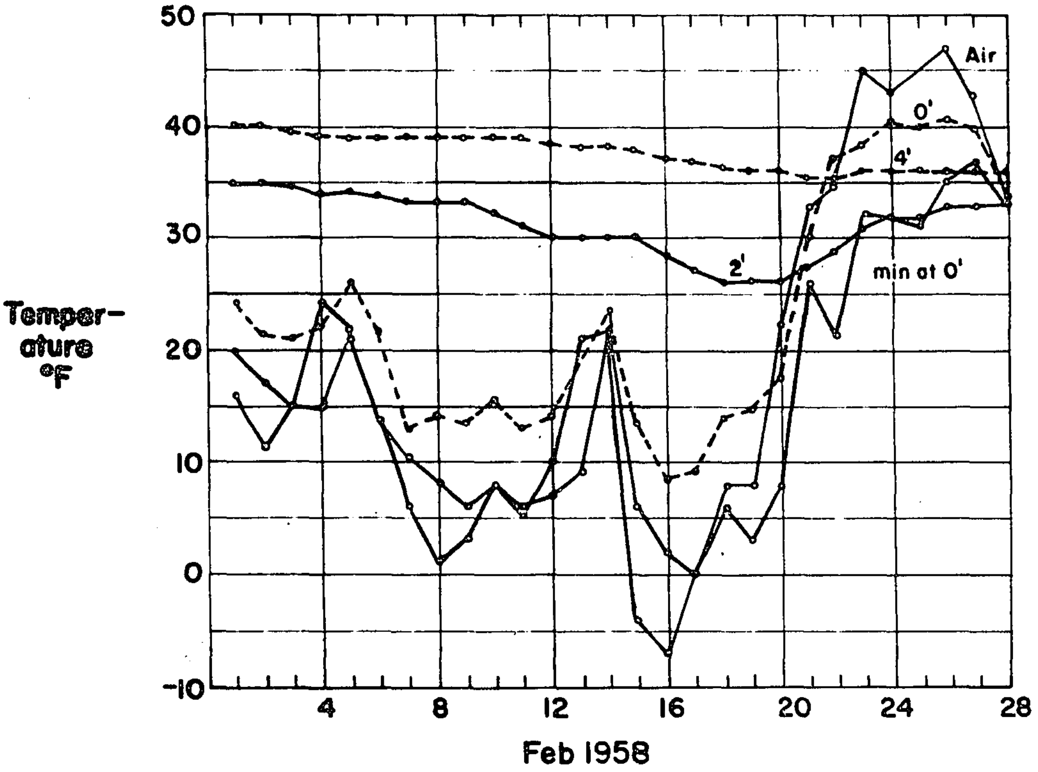
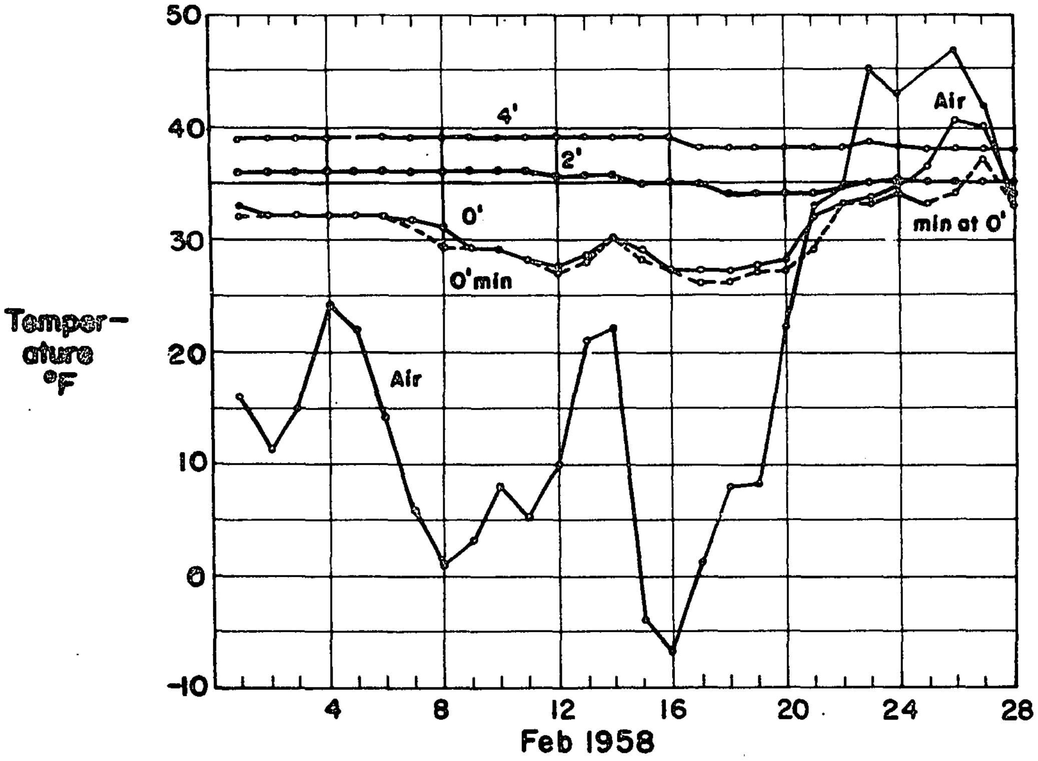

120
110
100
90
80
70
60
Temperature °F
Max temp at 0' depth
0'
Air
2'
4'
4
8
12
16
20
24
28
31
July 1957

Figure 41. Soil temperatures

Above: covered area

Below: control area


Temperature °F
50
40
30
20
10
0
-10
4
8
12
16
20
24
28
Feb 1958
Air
0'
4'
2'
min at 0'


Temperature °F
50
40
30
20
10
0
-10
4
8
12
16
20
24
28
Feb 1958
4'
2'
0'
0'min
Air
Air
min at 0'

Water Table Data

The average monthly water table depths are given in Figure 42 for each of the test plots for the period October, 1957 to September, 1958. Each plotted point is an average of at least four individual weekly measurements. The measurements were taken in the center of each test plot using the appropriate water table tube.

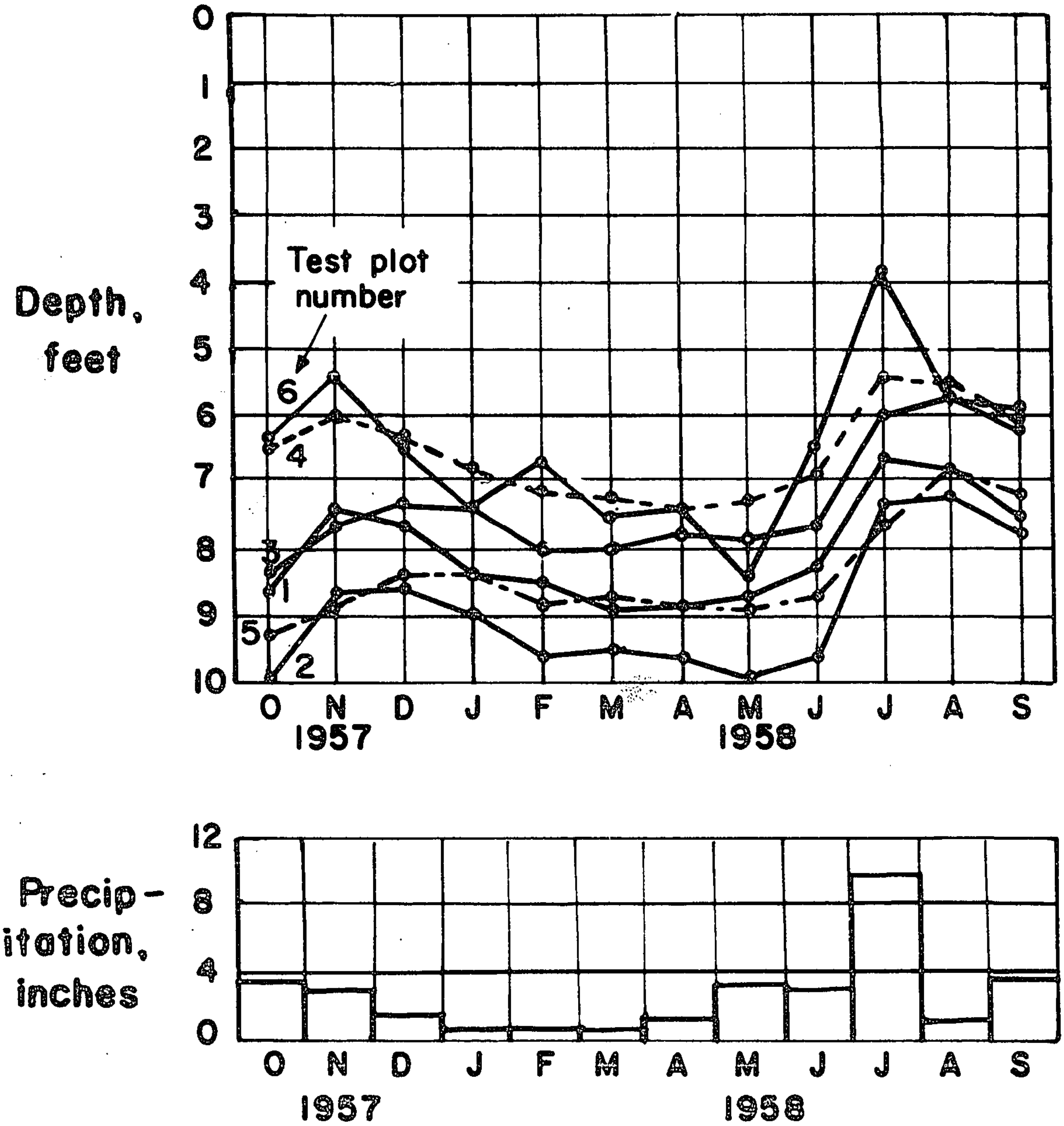
In addition to the graph of the water table depths a bar graph of the monthly precipitation data is included for direct comparison. The precipitation data were obtained from the official weather station at the agricultural experimental farm located at Ankeny, Iowa. The weather station is within a mile of the field laboratory.

Soil Moisture Measurements

The objective of this investigation was to study the accumulation of moisture in soil under an impervious surface, and to determine the responsible mechanisms. To accomplish this purpose it was considered necessary not only to present evidence of moisture accumulation but to correlate measured values in the field with values predicted from information determined in the laboratory using undisturbed soil samples.

All soil moisture contents determined during the period October, 1957 to September, 1958 are tabulated in Appendix A.

Figure 42. Water table depths and precipitation data


Depth, feet
0
1
2
3
4
5
6
7
8
9
10
Test plot number
6
4
3
1
5
2
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958
Precip-itation, inches
12
8
4
0
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

The tabular values are in chronological order and each test plot is listed in numerical order. Information included in the tables for each determination are the date of sampling, depth of sampling and the grid number indicating the position within the test plot from which the sample was taken. The grid numbers follow the system shown in Figure 8. In each case the moisture contents were determined at the surface and at every foot of depth down to the water table as indicated by the water table tube in the center of each test plot.

It was planned originally to make direct comparisons of the field data with the appropriate desorption curves determined in the laboratory. This plan presupposed a somewhat uniform status of the soil types and environment at the field site. It was later found that because certain other factors were present such a correlation involved the simultaneous treatment of several salient variables: soil moisture contents, soil characteristics, variations of the soil characteristics within a given test plot, soil sample depth, water table fluctuation, time and soil temperatures. Since such a comparison was virtually impossible with the limited amount of control and data available it was necessary to make some assumptions and adjustments in plan.

In order to eliminate water table fluctuation as a variable the period October, 1957 to September, 1958 was selected. During this period water table fluctuations were at a minimum and the individual water table tubes were in full operation. For these reasons the data obtained were considered to be the most dependable of all the data taken over the duration of the field investigation.

Time was eliminated as a variable by always assuming an equilibrium condition. Obviously an equilibrium condition was never reached but the assumption was necessary for simplification.

By holding the water table constant and assuming an equilibrium condition the problem was reduced to treating the five variables: soil moisture contents, soil characteristics, variations of the soil characteristics within the test plots, soil sample depths and soil temperatures.

As a first trial it was decided to compare the moisture contents of the undisturbed samples determined at sampling with the desorption curves determined from these same samples. In so doing a direct comparison was possible because the effect of changing soil characteristics within the test plots was eliminated and because during the sampling period, October, 1958, the soil temperatures at the various depths were approximately the same. The essentially constant temperatures throughout the soil profile were of the order of 50° F. to 60° F. This phenomenon of constant temperatures occurs semi-annually as a cyclic temperature "turnover". See Figures 38 and 39. Since the desorption curves were determined at a temperature of 77° F. the change in moisture content caused by the different temperatures in the field and in the laboratory is probably small. The data are compared with the individual desorption curves in Figures 12-35. It is noted that a good correlation exists in nearly every case.

The ideal situation would have permitted a direct correlation of all of the data determined during the period October, 1957 to September, 1958 with the desorption curves. Unfortunately such was not possible because of the nonuniformity of the soils within the test plots. It can be seen from the grid numbers given in Appendix A that the weekly soil samples were taken from all parts of the test areas. This prevented the singling out of any test hole as being representative of the entire test plot. Also there were not enough data in any one quadrant of the test plots to permit adequate correlation with a single composite desorption curve.

The individual soil moisture contents found in Appendix A were too voluminous to use effectively, so it was necessary to determine average monthly moisture contents for each foot of depth for each test plot. Appendix B presents this data. In most cases the monthly averages represent four to five weekly moisture contents although there were fewer determinations in some of the colder months.

The average monthly values tabulated in Appendix B are also shown in Figures 43 to 48. In these figures there are noticeable trends in the upper few feet of the soil profiles while the moisture contents at greater depths seemingly fluctuate without reason. A possible explanation for this behavior lies in the observed soil types. It will be noted in Figures 12 to 35 that the upper few feet of nearly every soil profile consisted of clay loam at a somewhat uniform density whereas the lower portions of the profiles were made up of widely divergent soil types and densities. Since the weekly moisture contents were frequently determined in numerical order, for example 83, 85, 87, 89 and etc., each time skipping a "hole", it is entirely possible that the average monthly moisture content determined for one month in a given test plot may be representative of one soil profile in the test plot while the next month's average may be determined from a markedly different soil profile in the same test plot.

The moisture content of the upper two feet of soil in every test plot fluctuated to a considerable extent throughout the year but all six test plots exhibited the same trend. This trend consisted of an increasing moisture content from October, 1957 through the colder months of the period and then decreasing moisture contents as the warmer months approached. Referring to Figure 42 which pictures the water table depths during these periods it is noticed that the

Figure 43. Soil moisture contents, test plot 1

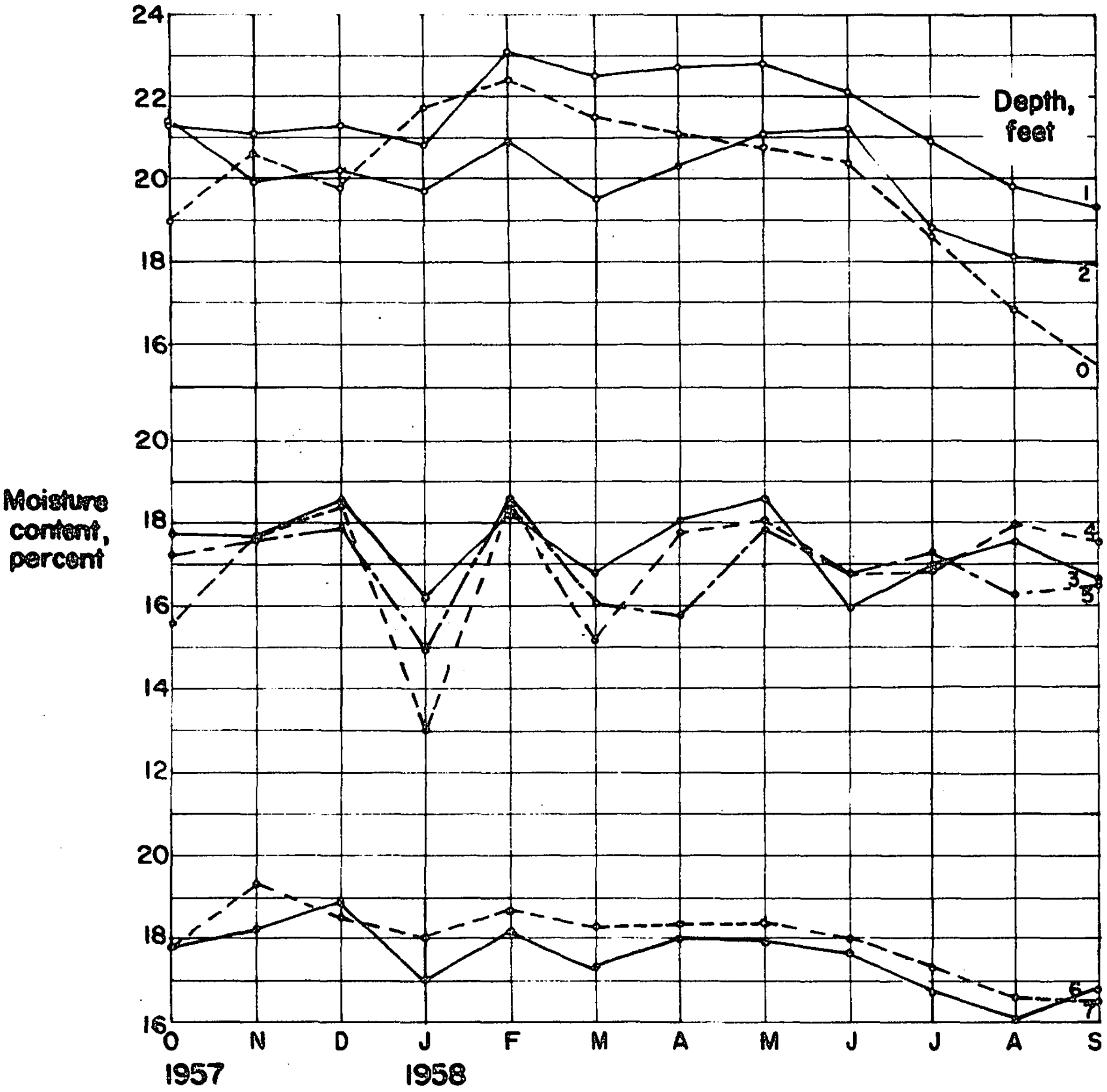

Depth, feet
0
1
2
3
4
5
6
7
Moisture content, percent
24
22
20
18
16
20
18
16
14
12
20
18
16
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

Figure 44. Soil moisture contents, test plot 2

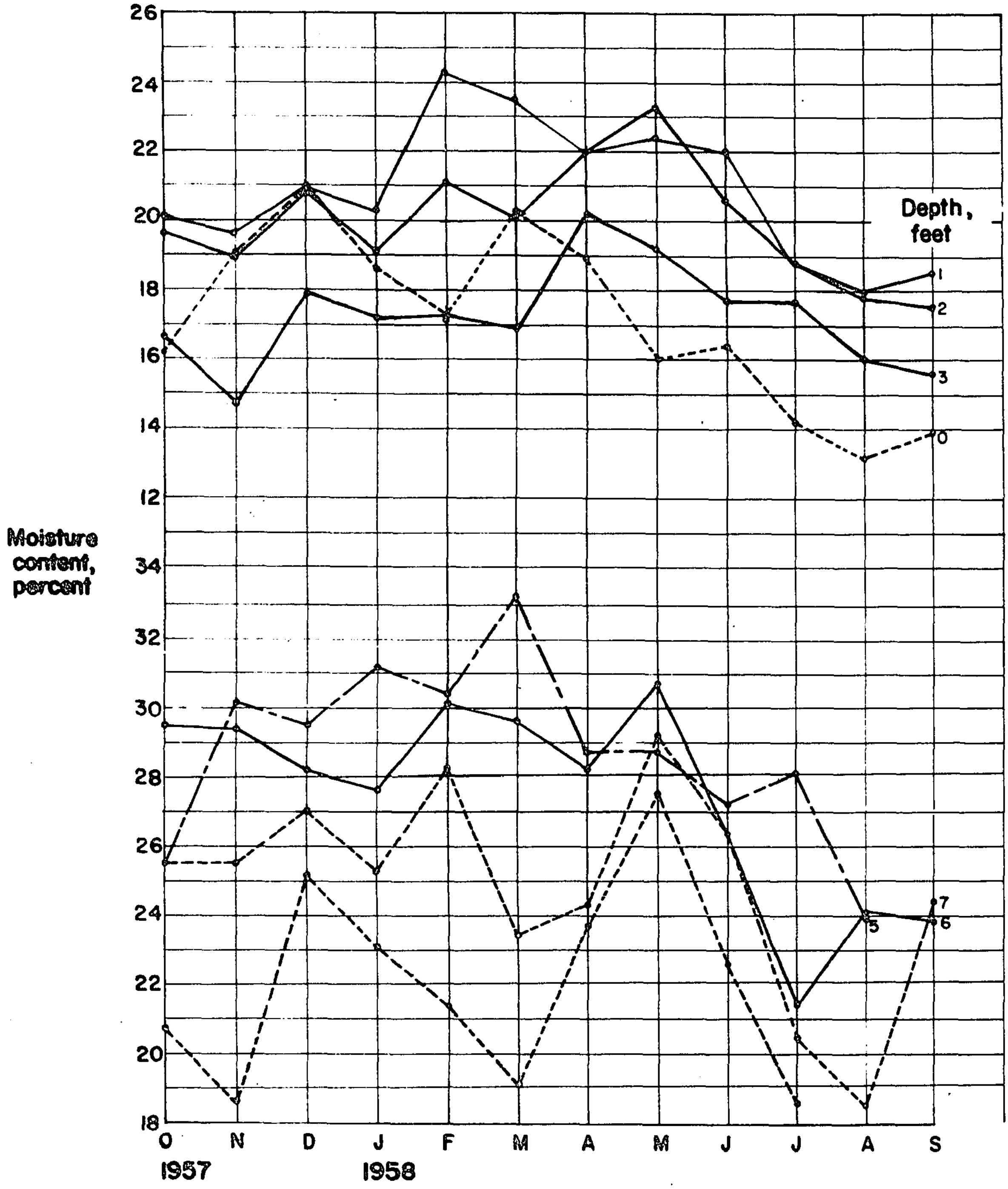

Moisture content, percent
26
24
22
20
18
16
14
12
34
32
30
28
26
24
22
20
18
Depth, feet
1
2
3
0
7
6
5
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

Figure 45. Soil moisture contents, test plot 3

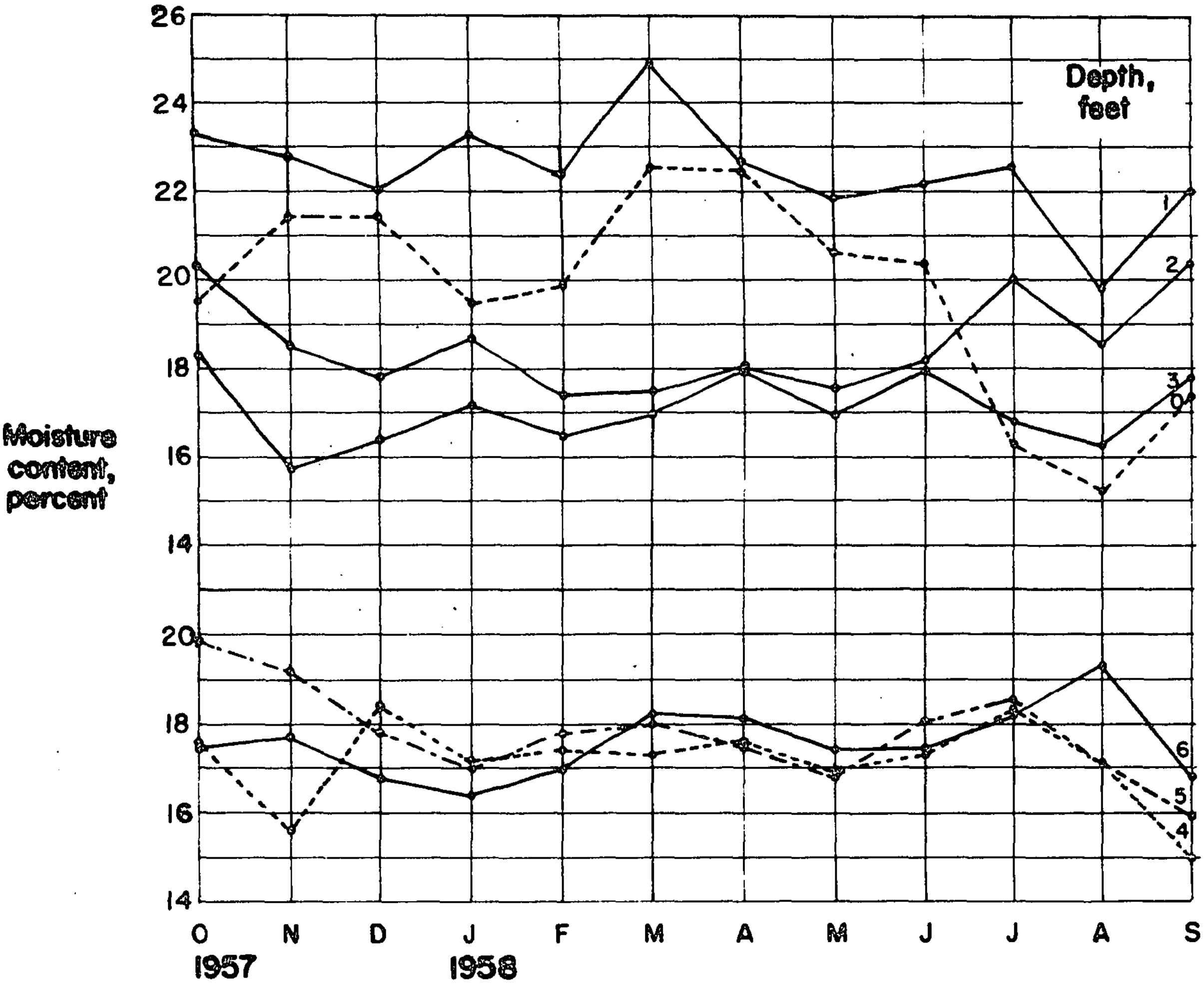

Moisture content, percent
26
24
22
20
18
16
14
20
18
16
14
Depth, feet
1
2
3
0
6
5
4
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

Figure 46. Soil moisture contents, test plot 4

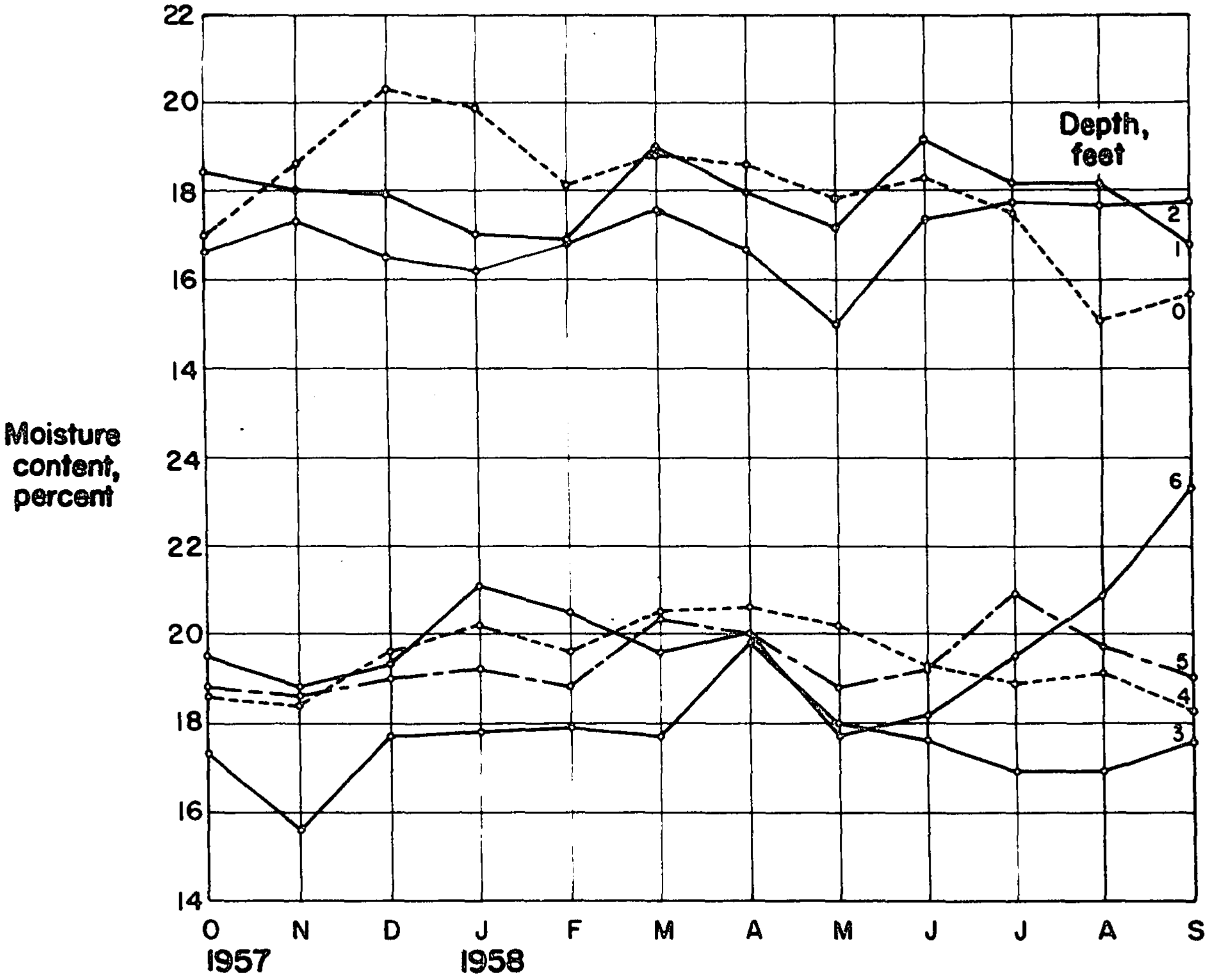

Moisture content, percent
22
20
18
16
14
24
22
20
18
16
14
Depth, feet
2
1
0
6
5
4
3
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

Figure 47. Soil moisture contents, test plot 5

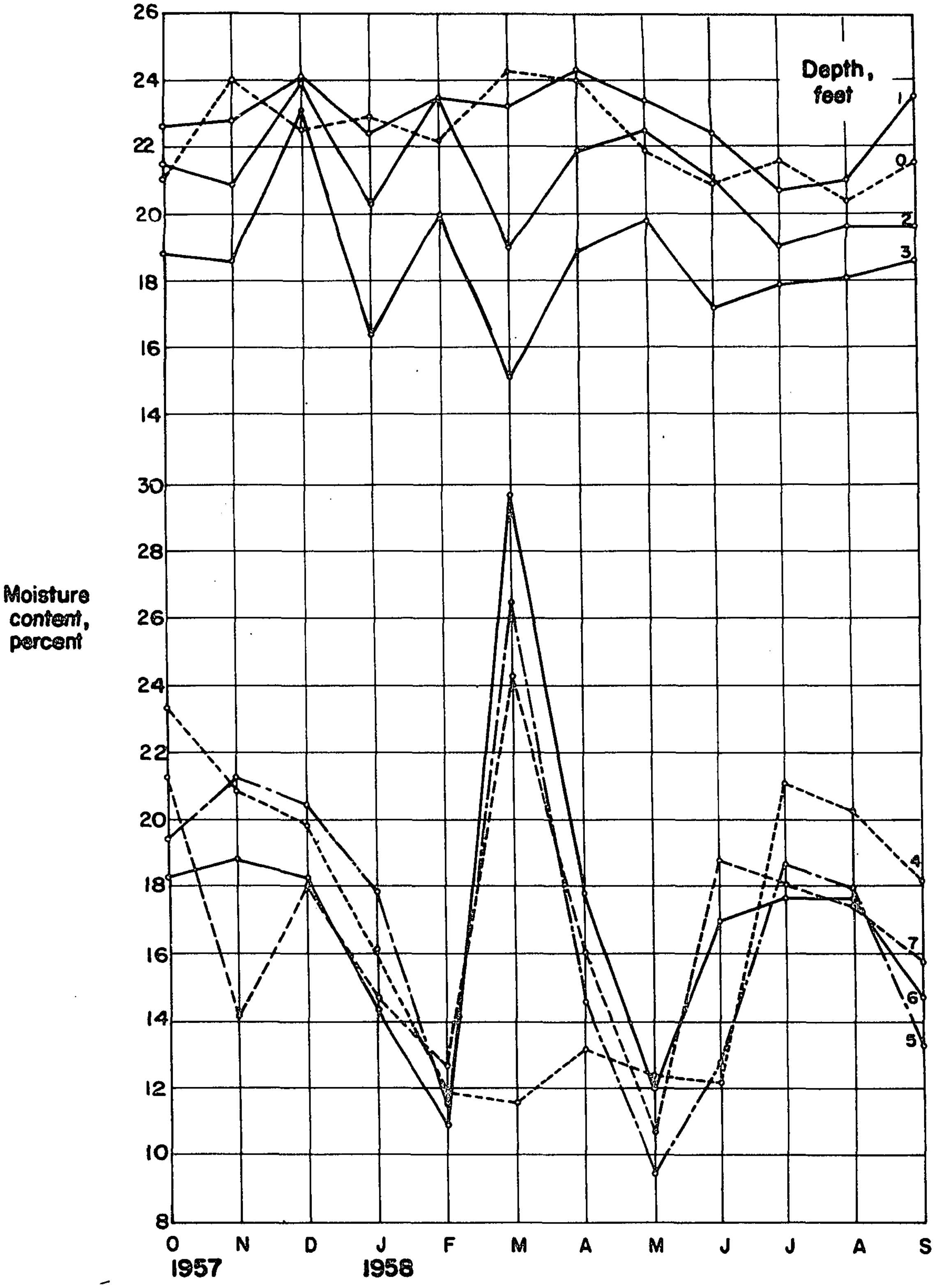
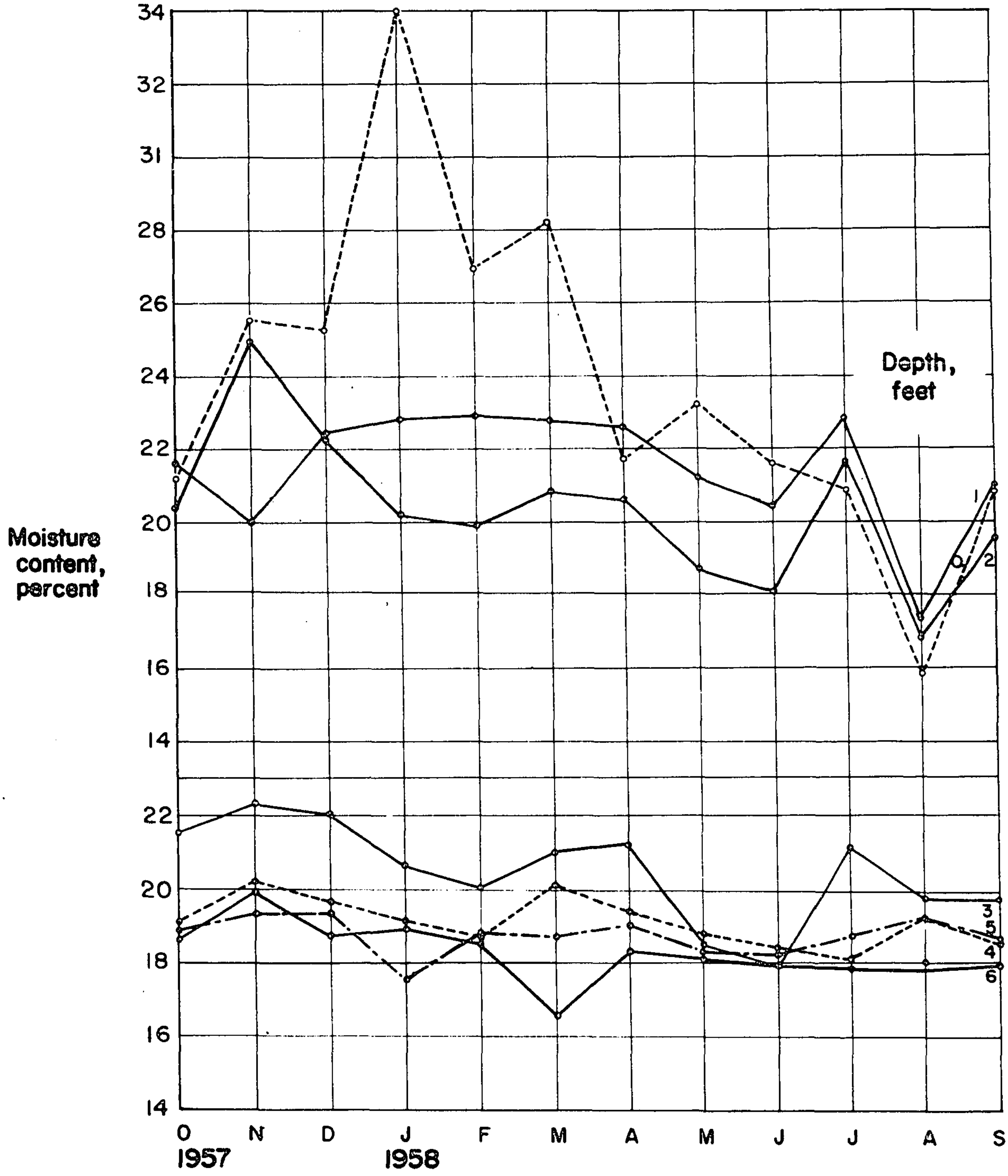

Moisture content, percent
26
24
22
20
18
16
14
30
28
26
24
22
20
18
16
14
12
10
8
Depth, feet
1
0
2
3
4
7
6
5
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

Figure 48. Soil moisture contents, test plot 6


Moisture content, percent
34
32
31
28
26
24
22
20
18
16
14
22
20
18
16
14
Depth, feet
1
0
2
3
5
4
6
O
N
D
J
F
M
A
M
J
J
A
S
1957
1958

increasing moisture contents in the upper reaches of the profiles observed during the colder months took place at a time when the water table was falling and the decreasing moisture contents during the warmer months actually took place at a time when the water table was rising. Apparently the changing moisture contents in the upper strata were not due to changes in water table level but due to some other cause. Actually with conservation of ground water it would be expected that the water table would fall during periods of increasing moisture contents in the upper horizons, and vice versa. In this case, however, it is believed that the water table adjustment is more the effect rather than the cause. Naturally there was no conservation of ground water because no impermeable boundary conditions, other than the surface, were imposed.

In order that a comparison between the field data and the desorption curves could be made and the above difficulties arising from variations of soils within the test plots could be circumvented, it was necessary to determine a master desorption curve for each test plot. In some cases this was done with relative ease, in others with an almost certain loss of accuracy. In each case the four desorption curves of each test plot were given equal weight and averaged. This was done by averaging the moisture contents indicated by the four curves at various depths and then passing a smooth curve through the values thus obtained. The depths were chosen so they coincided with the depths from which the actual desorption samples were taken.

The weekly moisture contents were averaged for each test plot in three month periods. These four periods are October-December, 1957; January-March, 1958; April-June, 1958 and July-September, 1958. The averages determined for these periods are compared with the six average or master desorption curves on Figures 49-54. By using this system of comparison the soil moisture contents are expressed in terms of the independent variables: soil sample depth as expressed as the ordinate, soil characteristics as represented by the sinuosities of the desorption curves, and temperature as indirectly represented by the four curves determined at different times of the year. The variable resulting from the changing soil characteristics within the individual test plots being accounted for by the averaging process.

Natural Variance of Soil Moisture Contents

It was noted throughout this investigation that specific moisture contents were hard to duplicate even when a comparison was made between samples taken at the same place and at the same time. In order to determine a quantitative concept of what variance between similar samples should be expected, a small scale investigation was made.

Figure 49. Master desorption curve, test plot 1

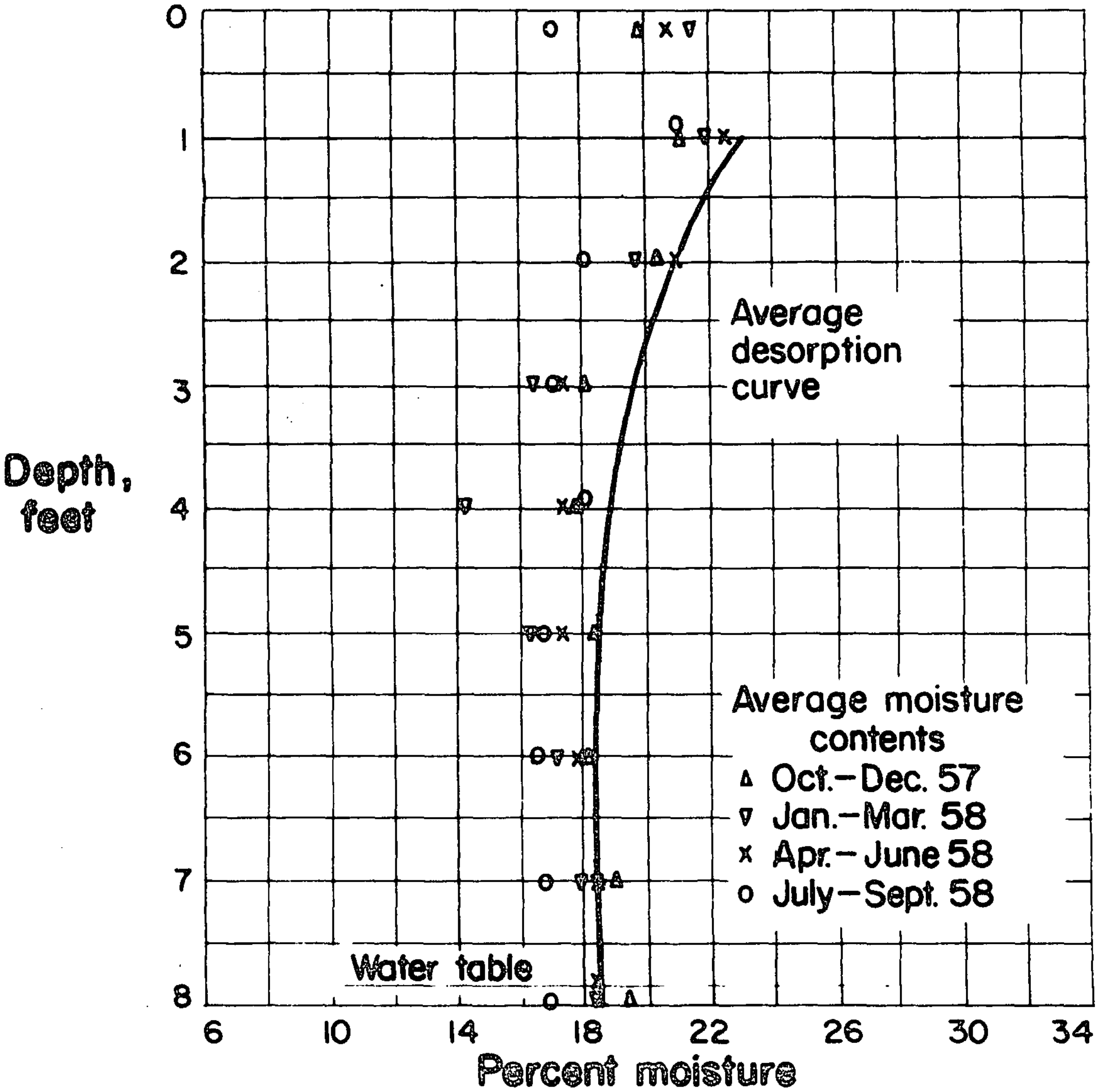

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Water table
Average moisture contents
△ Oct.–Dec. 57
▽ Jan.–Mar. 58
x Apr.–June 58
o July–Sept. 58

Figure 50. Master desorption curve, test plot 2

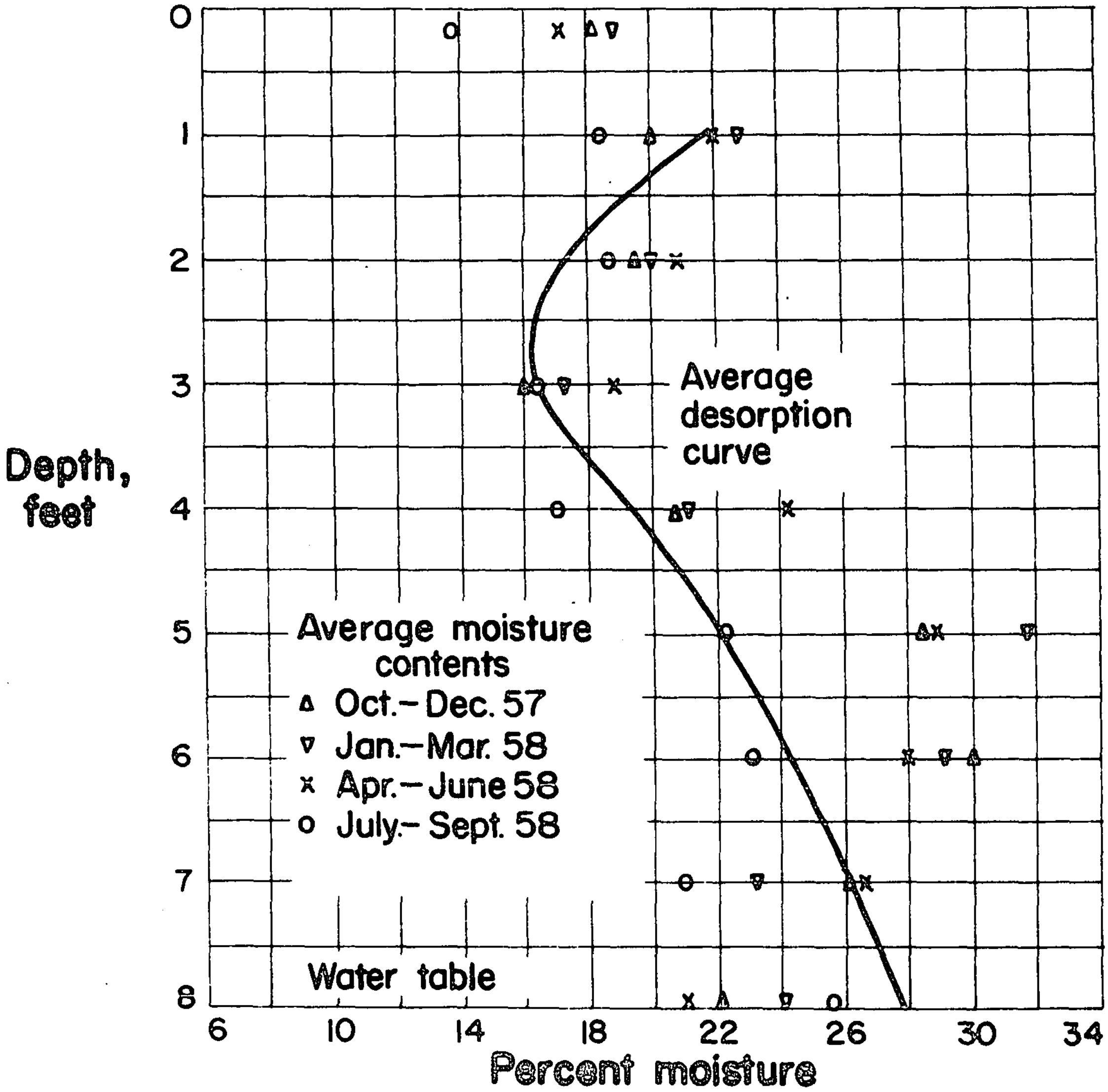

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Average moisture contents
▵ Oct.-Dec. 57
▿ Jan.-Mar. 58
x Apr.-June 58
o July-Sept. 58
Water table

Figure 51. Master desorption curve, test plot 3

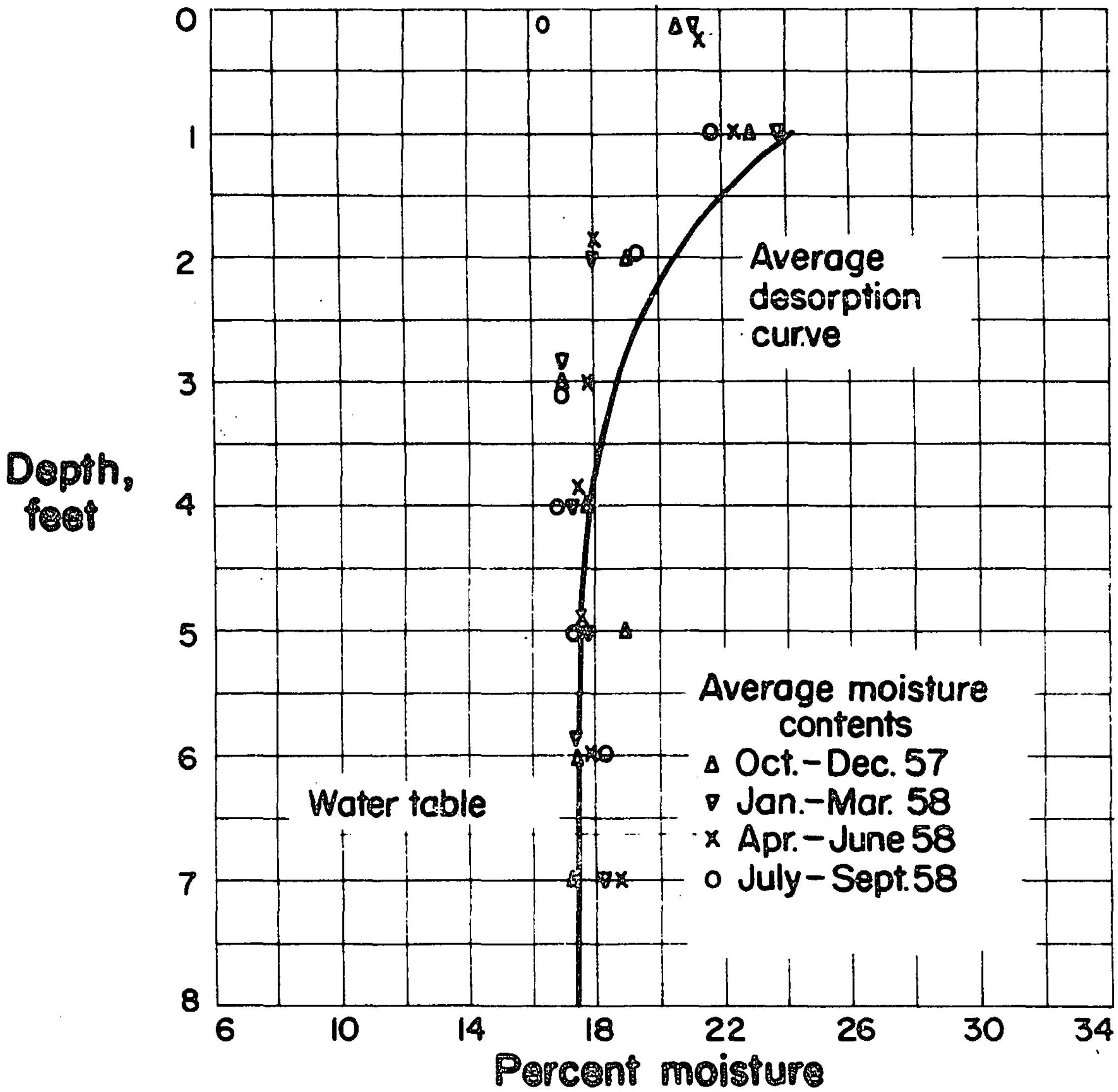

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Water table
Average moisture contents
▵ Oct.-Dec. 57
▿ Jan.-Mar. 58
x Apr.-June 58
o July-Sept. 58

Figure 52. Master desorption curve, test plot 4

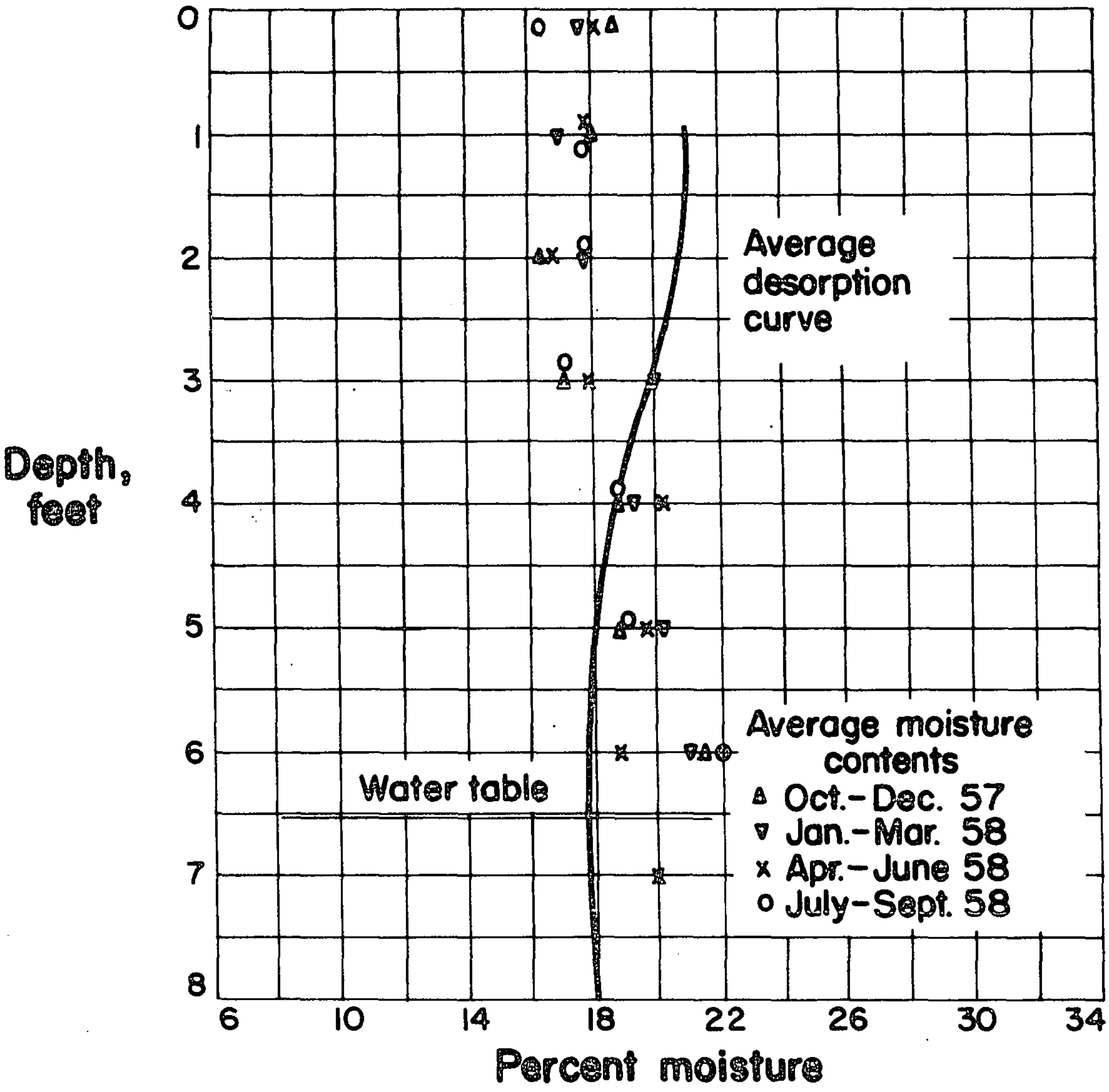

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Water table
Average moisture contents
▵ Oct.-Dec. 57
▿ Jan.-Mar. 58
× Apr.-June 58
○ July-Sept. 58

Figure 53. Master desorption curve, test plot 5

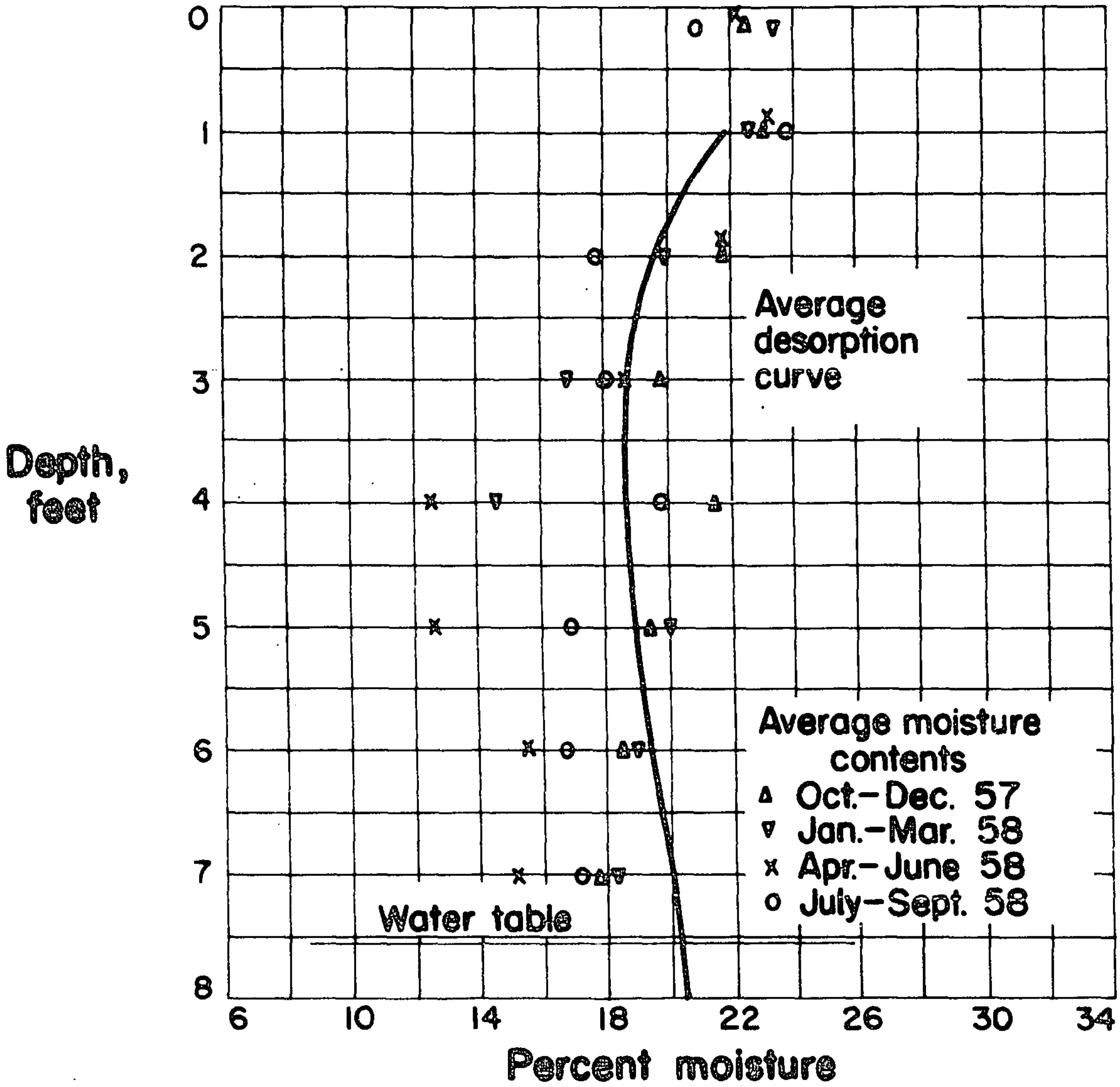

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Average moisture contents
△ Oct.-Dec. 57
▽ Jan.-Mar. 58
x Apr.-June 58
o July-Sept. 58
Water table

Figure 54. Master desorption curve, test plot 6

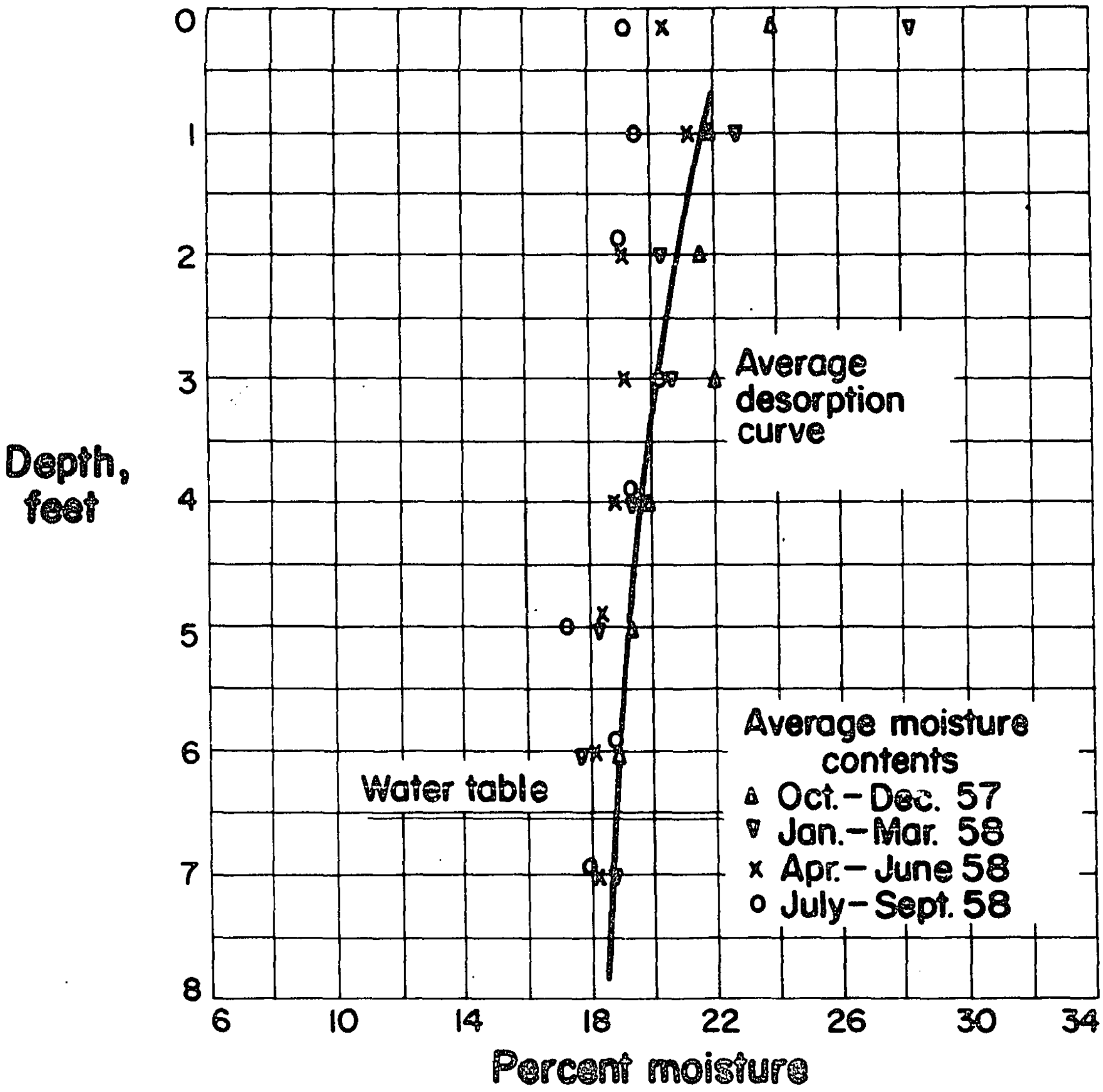

Depth, feet
0
1
2
3
4
5
6
7
8
6
10
14
18
22
26
30
34
Percent moisture
Average desorption curve
Water table
Average moisture contents
△ Oct.-Dec. 57
▽ Jan.-Mar. 58
x Apr.-June 58
o July-Sept. 58

Table 2. Natural soil moisture content variance

Test hole	Depth		
	Surface	1 foot deep	2 feet deep
	Moisture content per cent		
1	23.24	20.88	--
2	12.17	21.27	19.95
3	20.26	20.94	12.48
4	18.58	20.12	11.09
5	19.82	19.50	12.55

An area 12 inches square was chosen near the impervious surface and moisture content samples were taken at the center and at the four corners of the square down to a depth of 2 feet. A total of 15 samples were taken. The values obtained are listed in Table 2. It is interesting to note that although there were no obvious changes in soil type or condition, the soil moisture contents were quite variant; especially at the surface. Even when the surface moisture contents are discounted, a large variance is still noted at a depth of 2 feet. A mistake resulted in the rejection of one of the moisture contents determined at the 2 foot level.

Since the samples were all taken in such a small area with all conditions apparently the same, it is believed that a natural variance of approximately 2 per cent may be expected between individual determinations, at least in the upper reaches of the soil column, without indicating any trend.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to study the phenomenon of the accumulation of moisture in soil under an impervious surface such as a highway pavement. A list of findings appears in the latter part of this section.

The overall condition of a soil water system at equilibrium can be adequately studied by the application of thermodynamics. Use was made of this concept, particularly of the free energy function, in explaining the individual energy contributions, or component free energies, resulting from adsorptive and gravitational force fields, surface tension effects, pressures and dissolved materials. Equation 38, page 32, is a general equation which sums the individual component free energies resulting from the above.

It can be shown, by applying Equation 38, that the free energy of the water found in small wedges and interstices within a soil structure can be computed with relative ease providing the osmotic component is known, whereas the free energy of the water lying within the practical limits of the soil particle electrical force fields, because of the indeterminateness of the force fields, is difficult to ascertain. On the basis of the above, the thermodynamic treatment was greatly simplified by making the following assumptions: At relatively high moisture contents the quantity of water in a soil water system, which is held by the soil particle electrical force fields, remains essentially constant, and changes in moisture content result only from changes in the quantity of water held in the wedges and interstices of the soil structure. Also, for the soils in this study, the concentration of dissolved materials in the soil water was either so low or so evenly distributed that no appreciable osmotic component resulted. It is felt that the latter assumption is justified for Iowa soils where leaching is present, but some caution should be exercised in applying the same assumption in areas where saline soils are prevalent. With the above assumptions, the general thermodynamic treatment reduces to the well-known capillary potential concept.

An approximate method of determining moisture content changes resulting from temperature changes is proposed on page 43. This method is based on the temperature dependence of the surface tension of water. Given the desorption curve of a specific soil at a specific temperature this method permits prediction of the desorption curve of the same soil at a different temperature.

The experimental investigation was conducted in two phases: the first phase was conducted in the field where soil moisture contents, determined on an oven-dry weight basis, and soil temperatures were measured under an impervious surface; the second phase involved the determination of the physical properties of an extensive series of undisturbed soil samples taken at the field site.

The impervious surface was 150 feet square and was constructed of several thicknesses of heavy roofing paper and hot asphalt cement; a final coating of asphalt cement and pea gravel served to protect the roofing paper. Five individual test plots, each 10 feet square, were marked out on the surface for concentrated study. Four of the test plots were located near the corners of the surface and the fifth near the center. A sixth test plot under normal vegetive cover was selected near the impervious surface to serve as a comparison standard. A series of 17 water table tubes and two test wells were driven so that an accurate record of the water table could be kept. Soil temperatures were taken under the impervious surface and also under normal cover through the use of buried thermocouples and a recording potentiometer.

Soil moisture contents were determined weekly in all six test plots at every foot of depth down to the water table. The water table was ascertained for each test plot by using the water table tube located in the center of the test plot. When operative, the recording potentiometer gave a continuous record of the soil temperatures. These data were taken intermittently from 1955 to 1958. The soil moisture content and water table data were continuous throughout the entire test period except when severe weather either limited or did not permit field work. The earlier data are questionable because of the insufficiently accurate water table data obtained from the two test wells and because of unusual weather conditions. The wells were supplemented by the 17 water table tubes in July, 1957 and the data from then on are nearly complete.

The second phase of this investigation began in October, 1958 when the soils beneath the impervious surface and the control area were sampled extensively in $2\frac{1}{2}$ inch diameter Shelby tubes. A series of 24 test holes, one at each corner of the six test plots, were sunk and continuous samples were taken to a depth of approximately 10 feet. Each of the test holes required about seven Shelby tubes; therefore, a total of 170 tubes, each containing from one to one and one-half feet of sample, were taken. The tubes were forced into the soil by a screw mechanism in nearly every case, a drop hammer being used only in a few instances.

Laboratory analyses were run on each of the Shelby tube samples to determine the soil moisture tension characteristics, dry density, Atterberg limits, moisture content, and mechanical analysis. The Atterberg limits and mechanical analyses were determined primarily for identification purposes.

The soil moisture retention characteristics, shown by desorption curves in this case, were determined by first saturating a 2.4 inch portion of each Shelby tube sample with distilled water and then submitting the sample in an individual pressure plate apparatus to moisture tensions of 20, 40, 60, 120 and 200 inches of water. The desorption curves for all of the Shelby tube samples from a given test hole were then plotted on a single sheet. The point of saturation on the desorption curves was considered to be analogous to the water table at the field site and the average depth of the water table over the test period was laid off vertically on the desorption curves. A horizontal line was then drawn across the desorption curves at this height and labeled the soil surface. The portion of each desorption curve which was representative of the depth from which it was taken was used to construct a composite desorption curve for each test hole. Figure 11, page 77, illustrates the construction of a composite desorption curve. Moisture contents, taken at the time the undisturbed samples were taken, were compared with the composite desorption curves. See Figures 12 through 35, pages 79 through 126.

Since the weekly samples taken over the entire period of the investigation were taken from all parts of the test plots it was also necessary to make an average, or master desorption, curve for each test plot. This was accomplished by averaging the four desorption curves for each test plot. The weekly moisture contents in the form of tri-monthly averages were then compared with the average desorption curves. See Figures 49 through 54, pages 161 through 172.

Water table fluctuations are graphically presented for each of the test plots. In addition, the precipitation data obtained from the official weather station at Ankeny, Iowa are presented for correlation with the water table levels. See Figure 42, page 142.

Soil temperatures are given in the form of monthly averages at increments of two feet of depth for both the covered and uncovered areas. These data are presented for the periods January-August, 1955; January-August, 1956, and February 1957 to February 1958 in Figures 36 through 39, pages 128 through 135. In addition, day-to-day temperatures at the surface and at selected depths are graphed for July, 1957 and February, 1958 in Figures 40 and 41, pages 137 through 139.

At the outset of this investigation a preliminary survey was made to determine the logical site for constructing the impervious surface. Many possible sites were rejected because of gravel deposits, poor drainage or other objectionable aspects. The selected site, as it turned out, had some advantages and disadvantages not foreseen; specifically, there existed a wealth of soil types in a small area and a wide range of soil densities were encountered.

The stratified materials encountered were an advantage because their effect on the desorption curves could be studied. Unfortunately, the stratified materials were not uniform, so as a result many additional problems were encountered in correlating the data. Occasional marked offsets were observed in the composite desorption curves; many of these were caused by changes in soil types. It is noted that a soil with a very high moisture content may be in equilibrium with an adjacent soil type with a very low moisture content. This is of course, caused by the differences in the physical and chemical makeup of the soils. In the moisture tension range investigated, it is felt that the physical characteristics of the soil probably have more effect on the moisture contents than do the chemical characteristics. The data support the conclusion drawn by Spangler and Pien (29) that within a soil column the equilibrium moisture content of a given soil at a given moisture tension, as predicted from its sorption curve, is unaffected by stratification within the soil column.

At the outset of this investigation it was not realized that the equilibrium moisture content of a given soil at a given moisture tension was so greatly affected by its dry density. For this reason, the soil chosen to be covered by the impervious surface was not physically comparable to the soil that would normally be found under a highway pavement; the density of the soil under a pavement would be greater, no doubt, and more uniform. Actually the changes in density, although they introduced additional problems in correlation, were advantageous because their effect on the desorption curves was enlightening. Of particular interest is the apparently reversed trend of the composite desorption curves. As an example, where no changes in soil type were encountered, Figure 14, page 84, shows an increasing moisture content with increasing height above the water table. This trend is supported both by the composite desorption curves determined in the laboratory and by soil moisture contents measured in the field. Although other factors may contribute, it appears that the explanation for this behavior lies in the changing soil densities. The particle size distribution curves shown on Figure 14 do not indicate any appreciable differences in the mechanical analyses of the various components of the soil column. It seems, therefore, that the changing densities are caused merely by greater compaction. Apparently increased compaction changes the pore structure so that, over the range of moisture tensions investigated, the more dense form of a given soil is incapable of holding as much water at a given moisture tension as a less dense form of the same soil. Although the example cited is a special case, the above phenomenon occurs in most of the composite curves to a greater or lesser extent.

As pointed out above, for the particular soils and moisture tension ranges studied, the equilibrium moisture content at a given moisture tension increases with decreasing density. The increasing moisture content with increasing height above the water table merely points out that the equilibrium moisture content increase due to changes in density is greater than the decrease in moisture content because of increases in moisture tension. Individual desorption curves naturally displayed the universally accepted trend of decreasing moisture content with increasing moisture tension.

In contrast to popular opinion it was found that the temperature of the soil mass has only a relatively small effect on the equilibrium moisture content. This statement applies only to those ranges of soil moisture tension and temperatures investigated in this project but the information gathered does support the data presented by Richards and Weaver (21). See Table 1, page 16. This observation does not include the moisture concentrations due to frost action, but only the accumulation due to the temperature differential itself.

It was found (Figures 49 through 54, pages 161 through 172) that the average moisture content at zero depth in each of the test plots for the period January to March was consistently about 4.5 per cent higher than the corresponding average moisture content for the period July to September. Specifically, test plot number one had an average cold weather moisture content at 21.5 per cent and a warm weather moisture content of 17 per cent, both at zero depth. Using the proposed approximate method for estimating the change in moisture with temperature it is found that the method estimates a change of 15 per cent or a reduction of 3.3 per cent moisture content from the cold period to the warm period. The 4.5 per cent figure compares favorably with the 3.3 per cent figure when it is considered that frost accumulation during the winter is ignored and that the average temperatures at zero depth do not reflect the true picture of the extremes; temperatures directly beneath the impervious surface were measured in excess of 120° F. Such a high temperature probably would not be possible under a pavement slab because of the thickness of the pavement as opposed to the very thin impervious layer employed in this project.

It is noted that the moisture contents observed in the field were nearly always on the low side of the value predicted by the desorption curves determined in the laboratory. See Figures 49 through 54, pages 161 through 172. This may be because equilibrium was not in fact attained in the pressure plate apparatus or simply because the undisturbed samples, although taken with extreme care, were not in fact "undisturbed". The actual removal of the samples is of course a disturbing action because of pressure removal and also the samples were able to swell during the soaking process. As was noted earlier, decreasing density is accompanied by increasing moisture contents at specific moisture tension levels, so any swelling action caused either by pressure removal or soaking would tend to make the desorption curves indicate higher moisture contents. Another possibility is that, in the recent history of the soils under the impervious surface, saturation had not been complete. As a result, the observed moisture contents should have agreed more closely with the sorption, or wetting, rather than the desorption, or drying, characteristics of the soils. This would also account for the observed low moisture content values. The error involved is not considered to be of major consequence, however.

The findings of this investigation may be summarized as follows:

1. The equilibrium moisture contents in a soil column under an impervious surface can be predicted from desorption curves run on undisturbed samples of the soils providing that both the temperature and water table elevation are known.

2. Temperature has only a minor effect on the ultimate moisture contents predicted by the above except under extreme temperature conditions. The temperatures measured directly beneath the impervious surface during this investigation were considered to be abnormally high during the summer months and therefore rather large changes in moisture content resulted.

3. For soils such as were encountered in this

investigation the changes in moisture content attributable to changes in temperature can be predicted within close limits with the approximate method herein proposed.

4. Terminal moisture contents at various depths under an impervious surface as predicted by appropriate desorption curves are not affected by soil stratification.

5. At relatively low moisture tension values soil density has a decided effect on equilibrium moisture contents, higher moisture contents being observed at lower soil densities.

6. Under normal field conditions, where increasing soil density is noted with increasing depth, it is possible to note increasing moisture contents with increasing height above the water table, thereby giving the false impression that some mechanism is at work which causes saturation of the soil beneath the impervious surface.

By using the results of this study it would be possible for an engineer to predict the terminal soil moisture contents under an existing or planned impervious surface. To predict the terminal moisture contents the engineer would have to determine the desorption curves of the soils in the condition in which they occur, or would occur, in the embankment. In the case of a highway pavement structure the soil samples would be compacted to the design density. The engineer would also have to predict the highest level of the water table under the surface and estimate the probable soil temperatures. The highest moisture content of a given soil, all other conditions being the same, will occur when the temperature is the lowest. The proposed approximate method, page 43, estimates equilibrium moisture content changes resulting from temperature differentials. It must be emphasized, however, that this method will not account for moisture accumulation due to "ice lenses", nor would it necessarily be accurate if saline soils were encountered. With the above knowedge, the engineer could determine then the bearing capacity of the soil at the predicted moisture content rather than at saturation. This would permit the full use of some soils which are weak when saturated, but relatively strong at lower moisture contents, to be used in places above the water table where saturation is not apt to occur.

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APPENDIX

Weekly Soil Moisture Content Data

Table 3. Moisture Content versus depth, test plot 1

Depth, feet	Date							
	October, 1957				November, 1957			
	5	12	19	26	2	9	16	23
0	18.32	18.54	19.55	19.39	19.56	22.48	19.03	20.80
1	21.10	22.31	21.18	20.48	20.15	20.91	21.22	21.49
2	20.45	20.12	25.03	20.08	19.85	20.66	20.48	19.56
3	18.78	18.20	16.89	16.94	17.78	19.14	18.34	16.54
4	19.24	14.88	12.21	15.56	18.12	19.78	19.43	17.50
5	17.93	16.73	17.47	16.79	18.44	18.42	18.27	18.10
6	17.58	17.44	18.61	17.53	18.94	18.59	19.06	17.74
7	17.39	17.87	18.28	17.31	18.66	18.64	18.62	23.19
8	18.52	18.64	18.79	18.33				23.81
9	18.34	19.51						
Grid no.	122	67	69	71	73	75	77	79

Table 3. (Continued)

Depth, feet	Date							
	Nov.	December, 1957			January, 1958			Feb.
	30	7	14	21	4	11	25	1
0	21.24	19.14	20.19	19.12	21.34	22.59	21.04	22.38
1	21.60	21.83	21.25	20.74	20.62	20.25	21.44	23.12
2	19.02	19.97	20.05	20.64	19.18	19.24	20.59	20.94
3	16.73	18.58	31.70	18.60	14.73	15.58	18.26	18.30
4	14.19	18.40	18.92	18.05	11.18	9.87	17.88	18.54
5	14.84	18.01	17.40	18.24	15.44	11.54	17.84	18.65
6	16.75	18.00	20.03	18.59	16.38	16.73	17.83	18.24
7	17.58	18.10	18.65	18.84	18.12	17.56	18.18	18.66
8			5.82	18.37	18.18	18.03	18.06	18.82
Grid no.	81	83	85	87	91	93	57	97

Table 3. (Continued)

Depth, feet	Date							
	March, 1958				April, 1958			
	8	15	22	29	7	12	19	26
0	20.50	20.13	23.18	22.16	22.96	20.94	20.59	20.10
1	23.87	21.69	22.47	22.00	23.08	23.75	22.59	21.24
2	20.06	19.75	20.22	18.02	20.70	21.77	22.98	15.90
3	17.72	17.45	18.52	13.47	16.74	18.80	18.74	16.18
4	18.76	13.94	15.93	12.21	18.93	17.78	18.14	16.47
5	14.19	17.27	14.99	17.92	10.19	17.69	17.83	17.36
6	17.39	17.85	17.37	16.75	18.78	17.97	17.70	17.46
7	17.17	18.74	18.51	17.64	18.65	18.34	18.23	18.17
8	18.42	18.63	17.89	17.72	18.04	18.94	18.90	18.41
9	18.09	18.81	18.35	17.94	17.58	19.33	19.08	18.45
Grid no.	105	112	113	115	117	119	120	123

Table 3. (Continued)

Depth, feet	Date							
	May, 1958			June, 1958				
	3	10	24	1	7	13	21	28
0	23.38	19.62	19.22	20.28	20.85	20.86	19.06	20.75
1	24.00	22.93	21.54	21.94	22.64	21.62	21.63	22.82
2	23.61	21.89	17.83	19.76	21.68	18.52	19.31	26.68
3	20.98	19.80	15.15	13.33	18.66	14.32	16.98	16.79
4	20.41	19.00	14.76	17.14	18.81	14.78	17.13	16.01
5	18.24	17.96	17.49	17.56	17.92	16.68	14.36	17.45
6	18.05	17.84	17.78	18.70	17.30	17.55	17.19	17.65
7	18.56	17.80	18.96	17.62	18.12	18.07	18.12	18.17
8	19.02	17.83	17.73	18.17	18.60	13.13	18.34	18.31
9	18.80	18.99	18.46	18.36	17.15	18.45		
Grid no.	133	131	127	125	132	129	124	126

Table 3. (Continued)

Depth, feet	Date							
	July, 1958				August, 1958			
	5	12	20	26	2	9	16	26
0	16.78	19.70	22.31	15.44	17.00	16.65	17.27	14.84
1	20.40	22.09	21.64	19.39	19.99	18.95	20.70	19.29
2	19.97	19.10	20.04	16.19	17.44	17.21	17.76	18.90
3	19.47	16.96	15.98	15.38	16.37	16.79	15.97	17.20
4	18.14	18.23	18.64	12.67	17.14	19.45	17.53	19.14
5	17.69	17.72	17.52	16.21	16.57	16.31	15.86	16.27
6	15.18	18.14	17.48	15.84	16.38	16.61	16.63	16.07
7	17.23						17.68	16.17
Grid no.	134	144	141	136	143	138	142	138

	Aug.	September, 1958				Oct.
	30	6	13	20	27	4
0	18.26	--	16.39	14.60	15.40	17.55
1	20.30	--	20.09	19.09	18.73	19.20
2	18.97	18.21	18.68	17.55	17.34	16.62
3	21.67	16.38	17.81	16.63	15.90	16.75
4	16.63	17.90	17.60	17.42	17.50	18.66
5	16.48	16.34	16.68	16.60	16.46	17.28
6	14.50	16.63	16.80	16.76	17.10	17.52
7	15.91	14.92	16.59	17.09	17.28	17.35
8		17.04			16.71	17.37
Grid no.	135	137	140	145	146	147

Table 4. Moisture content versus depth, test plot 2

Depth, feet	Date							
	October, 1957				November, 1957			
	5	12	19	26	2	9	16	23
0	16.81	17.64	15.01	15.30	15.65	21.29	15.69	16.40
1	20.67	22.49	18.70	18.58	18.67	20.18	20.12	19.29
2	20.62	20.93	17.59	19.31	17.67	20.72	19.60	18.12
3	20.79	16.46	13.24	15.72	14.07	17.28	16.78	11.96
4	26.37	16.27	20.99	19.29	17.03	17.28	14.28	21.56
5	21.13	23.76	27.25	29.82	29.04	30.20	26.07	30.29
6	39.14	25.50	27.45	25.86	30.53	32.84	29.95	28.28
7	30.72	19.26	27.02	24.93	24.73	25.79	27.40	24.45
8	22.23	23.94	18.29	18.35	20.72	29.48	17.48	23.40
9	26.88	28.08	27.23	26.29	25.50		25.75	
10		27.06	30.73					
11		25.85						
Grid no.	122	67	69	71	73	75	77	79

Table 4. (Continued)

Depth, feet	Date							
	Nov.	December, 1957			January, 1958			Feb.
	30	7	14	21	3	11	18	1
0	25.91	22.93	21.46	18.71	18.10	15.90	21.92	17.02
1	19.89	20.71	20.41	21.78	19.62	19.73	21.66	25.29
2	18.42	19.62	20.10	22.60	18.88	17.70	20.78	20.72
3	13.58	15.86	17.29	20.69	16.15	16.00	19.58	19.14
4	22.80	25.56	25.54	24.49	23.12	20.92	25.28	19.30
5	34.75	32.04	28.80	27.72	31.03	30.58	32.05	29.06
6	25.43	25.46	31.04	28.19	27.32	26.10	29.34	31.14
7	25.14	26.17	24.63	30.15	25.91	24.70	25.36	30.31
8	20.37	19.53	19.80	27.16	29.49	24.14	20.35	24.60
9						26.58	26.17	27.00
Grid no.	81	83	85	87	91	93	95	97

Table 4. (Continued)

Depth, feet	Date							
	February, 1958		March, 1958				April, 1958	
	8	22	8	15	22	29	7	12
0	17.02	17.88	18.04	22.80	23.64	16.78	20.02	19.17
1	25.93	21.62	24.90	24.76	23.46	20.98	21.42	22.69
2	23.95	18.67	19.22	22.10	20.26	18.88	22.06	21.84
3	17.51	15.52	16.65	19.22	15.84	15.97	22.18	19.74
4	20.71	24.13	24.75	16.20	15.98	19.60	22.79	26.15
5	31.94	30.05	32.86	35.03	36.06	28.74	26.07	32.29
6	34.73	24.31	26.16	33.44	35.14	23.45	24.44	28.85
7	30.11	24.54	24.72	26.70	18.98	23.21	23.79	26.55
8	23.79	26.41	22.40	19.97	27.89	23.83	25.10	18.48
9	26.60	26.65	26.84		26.65	27.07	25.98	28.07
10		27.53	27.33				26.45	
Grid no.	99	103	105	109	113	115	117	119

Table 4. (Continued)

Depth, feet	Date							
	April, 1958		May, 1958			June, 1958		
	19	26	3	10	24	1	7	13
0	17.93	18.43	14.38	17.37	16.19	16.79	38.93	16.81
1	21.01	22.90	23.03	22.07	22.15	20.88	22.77	23.28
2	22.03	21.59	27.38	21.72	20.89	20.81	20.62	20.59
3	18.15	20.62	18.83	19.75	18.87	17.74	16.99	17.69
4	25.94	20.09	28.70	24.83	28.86	26.14	23.08	26.98
5	28.30	28.32	25.84	28.29	31.97	20.13	26.01	29.92
6	34.14	25.27	32.65	28.69	30.67	22.78	28.19	30.20
7	25.13	21.74	29.79	25.64	32.27	30.86	24.58	31.24
8	21.13	24.55	19.43	19.54	20.67	20.10	22.59	23.20
9	27.29	28.12	27.85	28.30	26.62	27.66	28.66	27.10
10	27.55	26.48	26.82	27.16		26.69	26.16	27.67
11						27.68	27.14	
Grid no.	120	123	133	131	127	125	132	129

Table 4. (Continued)

Depth, feet	Date							
	June, 1958		July, 1958				August, 1958	
	21	28	5	12	20	26	2	9
0	16.01	16.02	14.15	15.82	14.41	12.38	12.96	12.78
1	21.80	21.31	18.08	20.91	19.75	16.60	19.02	17.61
2	20.64	20.24	17.74	21.68	19.05	16.61	19.14	16.99
3	18.97	16.93	14.26	22.09	21.00	13.40	20.24	12.52
4	22.13	14.60	20.74	19.31	19.95	14.56	20.51	9.48
5	28.86	30.94	28.02	31.47	24.86	28.04	25.30	16.67
6	27.11	23.38	25.62	13.79	25.93	19.97	24.60	23.02
7	21.92	23.28	21.12	23.16	18.80	18.78	18.09	17.69
8	26.50	19.54	22.65					
9	27.05	25.89						
Grid no.	124	126	134	144	141	136	143	138

Table 4. (Continued)

Depth, feet	Date							
	August, 1958			September, 1958				Oct.
	16	26	30	6	13	20	27	4
0	13.55	13.73	13.30	--	13.33	14.78	13.72	16.33
1	19.45	17.17	16.57	--	19.01	17.86	18.76	18.61
2	19.90	17.33	15.68	28.76	18.73	17.09	16.78	17.80
3	19.32	14.76	12.90	17.42	17.09	14.05	13.93	14.94
4	17.51	15.26	15.26	--	20.92	11.90	11.05	11.70
5	26.97	19.81	30.50	16.92	21.72	12.93	11.44	22.39
6	25.23	22.92	24.69	17.00	25.42	28.71	23.97	25.12
7	18.54	17.73	20.18	18.46	19.04	30.31	29.64	31.26
8		25.56	25.35				28.63	29.82
Grid no.	142	139	135	137	140	145	146	147

Table 5. Moisture content versus depth, test plot 3

Depth, feet	Date							
	October, 1957				November, 1957			Dec.
	5	12	19	26	9	16	30	7
0	21.06	15.79	22.83	18.27	20.75	21.92	21.44	21.02
1	22.57	22.71	24.50	23.57	21.58	23.28	23.55	22.31
2	17.28	21.01	21.72	21.17	17.40	17.86	20.14	18.50
3	18.66	18.34	18.69	17.58	15.18	14.49	17.45	17.60
4	17.19	17.98	17.67	rock	18.68	11.19	16.95	18.27
5	19.58	17.80	22.46		18.77	21.22	17.07	17.56
6	17.15	17.45	18.04		17.69	17.34	18.15	16.43
7	15.49	17.93	17.79		16.96	17.44	17.64	17.35
8	18.31	14.59	25.39			21.55		
9	18.55	16.23						
Grid no.	122	67	69	71	75	77	81	83

Table 5. (Continued)

Depth, feet	Date							
	December, 1957		January, 1958			February, 1958		
	14	21	4	11	18	1	8	22
0	22.73	20.44	12.84	20.52	18.38	20.22	19.47	20.15
1	22.38	21.17	22.52	24.04	23.47	22.56	22.17	22.58
2	19.19	15.86	20.69	17.72	17.64	16.76	15.50	19.88
3	17.82	13.83	rock	17.85	16.56	14.78	17.99	16.80
4	18.11	18.67		17.19	17.23	17.42	18.49	16.28
5	18.38	17.58		18.01	15.98	19.50	17.41	16.59
6	17.57	16.29		16.92	15.95	17.32	16.96	16.64
7	18.09	16.32		17.55	17.42	18.67	17.77	16.85
8							20.03	19.52
Grid no.	85	87	91	93	95	97	99	103

Table 5. (Continued)

Depth, feet	Date							
	March, 1958				April, 1958			
	8	15	22	29	7	12	19	26
0	23.39	20.99	25.26	20.84	20.51	21.93	25.72	21.97
1	24.83	27.37	24.34	23.00	22.24	23.05	22.00	23.68
2	15.26	19.60	19.91	15.38	17.09	17.59	17.95	19.78
3	16.83	17.64	17.19	16.17	17.78	17.24	18.25	18.74
4	17.23	18.68	16.05	17.28	17.37	17.22	17.93	17.90
5	16.70	21.47	17.57	16.44	16.88	16.95	18.44	17.59
6	17.13	20.16	18.72	16.64	18.26	18.37	17.46	18.41
7	16.38	21.45	19.90	rock	18.67	17.51	17.11	18.88
8	16.71	17.71	17.73		16.56	19.00	18.50	17.41
Grid no.	105	112	113	115	117	119	120	123

Table 5. (Continued)

Depth, feet	Date							
	May, 1958			June, 1958				July
	3	10	24	1	7	21	28	5
0	22.88	20.78	18.43	21.54	20.82	19.39	19.83	17.84
1	21.80	21.81	22.17	23.08	21.53	22.06	22.29	23.66
2	17.70	17.02	18.19	16.31	17.29	19.39	19.99	21.02
3	17.88	15.38	17.66	17.14	17.52	17.13	19.77	16.68
4	17.72	17.50	15.49	16.86	17.40	16.52	18.50	18.76
5	17.06	16.56	16.65	18.75	16.96	18.28	18.13	15.46
6	18.06	17.00	17.21	16.81	18.16	17.28	17.51	18.19
7	18.41	18.09	17.09	20.58	16.87	22.56	21.29	18.52
8	18.89	17.72	20.88	17.73	17.77			
9					18.55			
Grid no.	133	131	127	125	132	124	126	134

Table 5. (Continued)

Depth, feet	Date July, 1958			August, 1958				
	12	20	26	2	9	16	26	30
0	16.74	18.06	12.68	17.16	14.22	17.78	11.45	15.42
1	22.22	23.29	21.05	18.52	21.34	21.12	21.66	21.93
2	18.63	21.21	19.11	17.55	18.76	12.98	19.19	18.91
3	16.62	18.54	15.46	16.54	16.34	16.17	16.47	15.87
4	18.30	19.08	17.09	19.19	15.89	17.29	17.39	15.95
5	21.57	18.62	18.33	19.32	17.38	17.57	16.85	14.25
6	18.74	17.80				20.98	18.79	18.12
Grid no.	144	141	136	143	138	142	139	135

	September, 1958				Oct.
	6	13	20	27	4
0	--	17.18	18.69	16.40	19.85
1	--	21.40	22.87	21.71	22.18
2	23.95	18.88	19.63	19.25	19.42
3	18.76	16.76	17.95	17.79	13.74
4	16.07	17.82	13.56	12.52	12.37
5	20.22	16.66	13.11	13.58	11.07
6	18.34	17.78	14.75	16.44	17.14
7					17.33
Grid no.	137	140	145	146	147

Table 6. Moisture content versus depth, test plot 4

Depth, feet	Date							
	October, 1957				November, 1957			
	5	12	19	26	9	16	23	30
0	17.10	17.00	16.83	17.12	18.40	17.86	21.63	16.56
1	17.30	18.60	19.14	18.60	17.30	18.68	17.51	18.33
2	16.44	18.47		14.79	15.72	18.18	18.35	16.86
3	18.39	17.41	17.16	16.27	13.25	14.05	17.39	17.51
4	18.29	19.27	17.82	19.09	18.06	18.36	18.31	18.67
5	17.77	19.42	18.87	19.11	17.74	18.90	19.79	18.07
6	17.68	20.61	21.26	18.63	--	18.56	19.83	17.88
7	18.91	30.66						
Grid no.	122	67	69	71	75	77	79	81
	December, 1957				January, 1958			Feb.
	7	14	21	28	4	11	18	1
0	21.25	19.70	16.59	23.57	20.15	19.69	19.95	18.41
1	18.43	16.98	17.22	19.06	16.03	17.66	17.00	16.05
2	16.09	15.18	15.70	18.82	18.56	14.68	15.26	13.69
3	17.46	15.90	18.72	18.69	17.03	19.86	16.46	19.61
4	20.66	19.35	18.46	20.06	20.29	21.24	19.20	18.82
5	18.87	18.68	18.47	20.12	18.44	19.68	19.37	19.02
6	18.74	18.00	18.68	21.83		19.23	22.90	19.33
7							19.21	19.02
Grid no.	83	85	87	89	91	93	95	97

Table 6. (Continued)

Depth, feet	Date							
	February, 1958		March, 1958				April, 1958	
	15	22	8	15	22	29	7	12
0	16.63	19.30	17.39	18.61	18.31	20.80	18.32	19.00
1	16.52	18.22	19.26	18.68	18.66	19.22	19.11	17.36
2	19.69	17.02	15.08	17.81	18.47	18.91	18.46	14.99
3	18.34	15.68	17.48	17.18	17.71	18.29	19.50	19.62
4	20.44	19.43	10.17	--	20.12	20.87	22.22	19.74
5	19.26	18.20	18.87	20.72	19.83	19.14	21.59	19.71
6	23.59	18.64	19.38	19.39	19.85	19.13	20.20	19.61
7	20.82	22.55	18.90	19.04	20.60	--	20.50	19.65
8						26.48		
Grid no.	101	103	105	112	113	115	117	119

Table 6. (Continued)

Depth, feet	April, 1958		May, 1958			June, 1958		
	19	26	3	10	24	1	7	21
0	17.97	19.30	18.07	17.96	17.40	18.34	16.81	18.29
1	15.89	19.45	16.71	17.79	17.09	17.85	17.04	19.61
2	15.35	18.15	rock	14.73	15.32	18.98	12.53	18.06
3	18.22	21.76		17.90	18.05	15.59	15.80	19.04
4	20.33	20.29		19.85	20.58	19.20	18.83	20.74
5	18.42	20.35		19.17	18.47	18.40	19.98	20.13
6	18.56	21.68		rock	17.65	18.56	17.43	19.18
7	19.95				19.47	19.76	15.82	20.62
8							18.07	
Grid no.	120	123	133	131	127	125	132	124

Table 6. (Continued)

Depth, feet	Date							
	June	July, 1958				August, 1958		
	28	5	12	20	26	2	9	16
0	19.83	16.61	18.18	20.44	14.74	11.19	16.49	16.41
1	22.29	15.80	20.21	20.22	16.70	20.88	17.27	17.69
2	19.99	16.85	19.14	19.53	15.71	18.45	17.01	18.33
3	19.77	17.75	17.62	18.42	13.72	15.58	16.91	16.92
4	18.50	18.60	21.75	20.26	15.11	16.80	19.06	19.35
5	18.13	22.51	20.78	23.12	17.11	16.34	19.29	20.25
6	17.51	19.00						20.21
7	21.29							
Grid no.	126	134	144	141	136	143	138	142

Depth, feet	August, 1958		September, 1958				October
	26	30	6	13	20	27	4
0	16.05	15.12	21.96	16.75	14.08	16.36	19.85
1	17.40	17.67	16.06	16.15	18.18	16.62	22.18
2	17.28	17.35	19.80	17.85	17.06	16.62	19.42
3	16.86	18.09	20.64	16.87	16.36	16.09	13.74
4	20.12	20.34	18.92	18.65	17.97	17.75	12.37
5	18.06	24.71	16.70	18.15	19.45	21.84	11.07
6	24.03	18.09	30.14	21.66	16.97	24.22	17.14
7							17.33
Grid no.	139	135	137	140	145	146	147

Table 7. Moisture content versus depth, test plot 5

Depth, feet	Date							
	October, 1957				November, 1957			
	5	12	19	26	9	16	23	30
0	21.27	21.15	20.46	21.56	23.94	21.74	26.80	23.66
1	24.65	20.20	21.72	23.78	23.58	23.39	20.91	23.53
2	24.42	19.32	19.64	22.64	23.54	22.68	18.06	19.18
3	23.61	17.12	15.63	18.77	23.76	22.84	14.63	13.68
4	14.71	25.02	27.05	26.79	15.96	25.40	13.72	28.63
5	12.39	17.67	19.73	28.08	20.92	14.09	23.00	27.08
6	8.77	17.72	19.46	27.43	17.34	15.69	19.57	23.11
7	11.49	25.49	24.96	23.19	10.80	12.94	11.92	21.03
8	9.16	17.96	14.54	18.56	9.83	22.25	15.61	17.69
9	16.08	20.73	16.57	19.27		14.33	22.55	
10	21.36	21.24						
Grid no.	122	67	69	71	75	77	79	81

Table 7. (Continued)

Depth, feet	Date							
	December, 1957			January, 1958			Feb.	March
	7	14	21	4	11	18	1	8
0	21.66	24.27	21.48	24.47	22.07	22.27	22.15	24.68
1	23.21	24.60	24.50	21.12	21.94	24.16	23.47	25.43
2	22.78	24.70	24.14	19.59	20.08	21.22	24.52	19.36
3	21.37	22.54	25.29	15.92	14.67	18.64	20.04	14.04
4	17.83	18.79	23.17	24.68	12.94	11.12	11.89	11.84
5	30.29	14.77	16.35	22.53	13.85	17.33	11.58	23.31
6	28.78	12.61	13.63	14.38	30.90	14.49	10.93	32.44
7	23.58	15.14	15.67	12.10	17.14	14.88	12.68	13.84
8	27.56	16.37	14.96	16.49	19.68	18.15		16.12
9		17.59						
Grid no.	83	85	87	91	93	95	97	105

Table 7. (Continued)

Depth, feet	Date							
	March, 1958			April, 1958				May
	15	22	29	7	12	19	26	3
0	23.13	26.39	23.15	22.97	24.07	26.53	22.55	22.04
1	22.74	21.99	22.57	23.94	24.76	25.38	23.29	23.28
2	18.52	19.24	18.90	22.55	23.06	23.98	17.87	23.15
3	15.05	15.79	15.31	19.70	19.19	21.63	15.05	20.85
4	12.39	11.88	10.22	13.03	9.76	12.59	17.27	14.45
5	24.84	31.37	rock	11.19	9.20	14.44	23.75	11.18
6	26.39	30.38		11.43	11.53	18.61	29.72	13.62
7	25.63	33.55		11.88	9.92	13.34	29.38	9.51
8	29.60	29.52		13.18	11.16	13.25	26.25	19.60
9		29.96		15.75	rock	19.61	30.64	19.96
Grid no.	112	113	115	117	119	120	123	133

Table 7. (Continued)

Depth, feet	Date							
	May, 1958			June, 1958				July
	10	17	24	1	7	21	28	5
0	22.21	21.48	21.74	21.11	21.67	20.36	20.51	21.75
1	24.25	22.98	23.22	21.37	23.38	21.22	23.46	21.58
2	23.71	21.36	21.64	19.57	23.19	17.85	23.95	19.10
3	24.30	16.43	17.63	13.79	16.85	14.55	23.78	16.64
4	10.72	13.88	10.41	11.85	13.36		11.29	22.28
5	7.74	--	9.70	13.08	12.49	14.42	11.10	17.71
6	10.17	14.13	9.94	23.35	10.47	25.44	8.77	19.59
7	7.16	14.94	11.25	28.26	11.21	26.03	9.62	19.04
8	13.22	15.48	15.67	26.67	13.96	27.55	11.70	17.63
9	19.34	13.30	22.94	27.34	18.44	28.25		
Grid no.	131	129	127	125	132	124	130	134

Table 7. (Continued)

Depth, feet	Date							
	July, 1958			August, 1958				
	12	20	26	2	9	16	26	30
0	21.72	22.13	20.78	18.20	21.72	20.59	20.50	21.06
1	21.11	23.09	21.05	20.14	21.45	21.23	21.31	21.13
2	18.58	19.08	19.32	18.54	21.18	18.27	20.73	19.15
3	18.20	18.44	18.17	16.58	20.51	17.65	18.37	17.23
4	22.95	20.14	19.19	20.03	18.89	24.86	17.75	20.15
5	21.06	18.45	17.39	16.68	16.21	21.13	16.79	18.98
6	14.83	17.75	18.64	16.32	17.08	17.48	18.43	18.97
7	16.02	18.48	19.03	14.75	17.26	19.87	16.79	18.84
8	14.85							
Grid no.	144	141	136	143	138	142	139	135

Table 7. (Continued)

Depth, feet	Date				
	September, 1958				October, 1958
	6	13	20	27	4
0	24.58	21.63	19.84	20.00	21.51
1	26.10	22.43	23.38	22.02	22.64
2	--	18.25	21.05	19.63	19.16
3	24.09	18.17	17.65	14.34	13.86
4	20.81	23.02	15.71	13.32	9.72
5		17.99	12.24	9.52	7.00
6	17.99	17.92	11.20	11.72	13.90
7	18.48	16.99	14.08	13.83	18.92
Grid no.	137	140	145	146	147

Table 8. Moisture content versus depth, test plot 6

Depth, feet	Date							
	October, 1957				November, 1957			
	5	12	19	26	2	9	16	23
0	13.65	24.65	23.58	22.53	23.43	22.65	25.84	25.65
1	21.49	22.76	21.04	21.12	21.38	20.98	23.19	22.36
2	19.05	21.95	21.65	19.02	21.41	21.19	36.08	23.57
3	18.93	23.17	21.65	22.26	22.13	20.48	22.03	24.60
4	16.85	20.24	19.40	19.87	20.00	20.06	18.60	22.01
5	16.62	19.73	19.30	19.74	19.52	19.05	18.01	20.36
6	16.75	19.80	19.35			18.08	20.49	20.98
7	17.08							
8	14.13							
9	21.41							
Grid no.	122	67	69	71	73	75	77	79

Table 8. (Continued)

Depth, feet	Date							
	Nov.	December, 1957				January, 1958		
	30	7	14	21	28	3	11	18
0	29.66	28.67	27.87	25.03	19.67	42.59	35.46	--
1	22.29	22.32	21.61	23.28	--	22.25	21.59	23.79
2	22.07	22.66	20.88	23.99	21.19	19.27	20.03	21.67
3	22.21	22.45	22.00	22.29	21.36	20.61	20.01	20.51
4	20.11	21.03	18.58	19.49	19.38	18.49	20.40	18.84
5	19.65	20.18	18.85	18.74	--	13.56	18.22	19.17
6		19.66	18.56	19.28	17.44	void space, water	18.74	18.50
7							18.69	18.23
Grid no.	81	83	85	87	89	91	93	95

Table 8. (Continued)

Depth, feet	Date							
	Jan.	February, 1958				March, 1958		
	25	1	8	15	22	8	15	22
0	24.42	21.95	27.91	31.08	26.82	41.35	25.73	22.92
1	23.38	23.19	22.36	21.23	24.64	24.43	23.06	21.84
2	19.89	20.13	19.99	19.74	19.64	19.31	21.19	21.15
3	21.31	20.79	20.62	19.66	18.93	21.73	20.66	20.58
4	18.80	18.72	19.50	water pocket	17.90	22.74	18.07	19.77
5	18.97	18.80	19.10		18.59	18.89	18.58	18.79
6	19.35	18.85			18.10	18.32	18.78	18.11
7	18.70	18.74			21.75	18.39	18.63	17.67
8					18.78	18.49		
Grid no.	57	97	99	101	103	105	109	113

Table 8. (Continued)

Depth, feet	Date							
	March	April, 1958				May, 1958		
	29	7	12	19	26	3	10	17
0	22.80	24.66	23.71	21.71	16.57	23.53	43.90	23.79
1	21.72	22.94	21.89	24.26	21.28	23.35	22.90	21.87
2	21.43	22.22	20.61	20.27	19.42	20.01	19.61	18.42
3	20.98	21.23	20.70	22.50	20.32	20.24	19.17	18.44
4	19.79	21.20	20.02	18.22	18.13	19.37	20.69	19.27
5	18.42	19.37	19.15	18.31	19.16	19.55	19.49	17.89
6	10.86	18.43	17.74	19.33	17.86	17.65	18.25	19.60
7	18.33	18.91	18.96	18.97	17.58	19.58	17.65	18.03
8	18.59			19.43	17.34	18.91	18.30	18.06
Grid no.	115	117	119	120	123	133	131	129

Table 8. (Continued)

Depth, feet	Date							
	May, 1958		June, 1958				July, 1958	
	24	31	7	13	21	28	5	12
0	14.12	10.67	18.08	24.38	19.31	24.66	24.41	23.50
1	19.70	18.30	20.95	20.24	21.08	19.26	24.08	22.92
2	18.27	17.28	18.07	17.52	20.96	15.84	22.99	21.18
3	17.89	16.55	19.06	15.76	20.20	16.45	23.00	22.03
4	17.64	17.13	19.43	16.01	18.46	18.28		19.07
5	17.38	17.13	18.43	18.10	18.45	18.26		
6	17.52	17.34	16.84		18.51	18.29		
7	17.88	17.20	17.91		17.10	18.37		
8	18.45	17.98	17.93					
9	18.52	18.60						
10		18.26						
Grid no.	127	125	132	129	124	126	134	144

Table 8. (Continued)

Depth, feet	Date							
	July, 1958		August, 1958					Sept.
	20	26	2	9	16	26	30	6
0	23.10	12.68	19.97	15.26	12.02	13.98	17.30	27.74
1	23.33	21.05	21.65	19.35	14.72	13.45	17.39	22.45
2	22.97	19.11	20.39	17.97	16.02	13.48	16.20	20.01
3	23.80	15.46	22.67	17.44	19.61	16.25	22.66	21.32
4		17.09	19.94	17.52	17.13	19.86	21.57	19.59
5		18.33		17.66	17.59	17.58	24.10	19.42
6					17.61	17.90	23.11	
7						17.72	18.10	
Grid no.	141	136	143	138	142	139	135	137

	September, 1958			October, 1958
	13	20	27	4
0	19.42	17.39	18.10	12.27
1	21.03	20.38	19.76	18.74
2	20.24	19.83	17.88	17.95
3	20.00	19.45	17.82	16.71
4	18.20	19.16	16.91	17.75
5	20.61	18.03	16.13	17.65
6	18.05	18.13	17.38	17.10
7				16.87
Grid no.	140	145	146	147

Average Monthly Soil Moisture Content Data

Table 9. Moisture content versus depth, test plot 1

Depth,	Date							
	1957			1958				
feet	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
0	18.95	20.62	19.48	21.66	22.38	21.49	21.15	20.74
1	21.27	21.07	21.27	20.77	23.12	22.51	22.66	22.82
2	21.42	19.91	20.22	19.67	20.94	19.51	20.34	21.11
3	17.70	17.71	18.59	16.19	18.30	16.79	18.12	18.64
4	15.47	17.80	18.46	12.98	18.54	15.21	17.83	18.05
5	17.23	17.61	17.88	14.94	18.65	16.09	15.77	17.89
6	17.79	18.22	18.87	16.98	18.24	17.34	17.98	17.89
7	17.71	19.34	18.53	17.95	18.66	18.26	18.35	18.44
8	18.57			18.09	18.82	18.16	18.57	18.49
9						18.30	18.61	18.75

	1958			
	June	July	Aug.	Sept.
0	20.36	18.56	16.80	15.46
1	22.13	20.88	19.85	19.30
2	21.19	18.82	18.06	17.94
3	16.02	16.95	17.60	16.68
4	16.77	16.92	17.98	17.60
5	16.79	17.28	16.30	16.52
6	17.68	16.66	16.04	16.82
7	18.02		16.58	16.47
8	17.31			16.88
9	17.98			

Table 10. Moisture content versus depth, test plot 2

Depth, feet	1957		Date		1958	
	Oct.	Nov.	Dec.	Jan.	Feb.	March
0	16.19	19.00	21.03	18.64	17.30	20.32
1	20.11	19.63	20.96	20.33	24.28	23.52
2	19.61	18.91	20.77	19.12	21.11	20.12
3	16.55	14.73	17.94	17.24	17.29	16.92
4	20.73	18.59	25.19	23.10	21.38	19.13
5	25.49	30.07	29.52	31.22	30.35	33.17
6	29.48	29.41	28.23	27.58	30.06	29.55
7	25.49	25.50	26.98	25.32	28.32	23.40
8	20.70	22.29	22.16	24.66	24.93	23.52
9	27.12	25.62		26.38	26.75	26.85

Table 10. (Continued)

Depth, feet	April	May	June	July	August	September
			Date		1958	
0	18.89	15.98	16.41	14.19	13.26	13.94
1	22.00	22.41	22.00	18.84	17.96	18.54
2	21.88	23.33	20.58	18.77	17.81	17.53
3	20.17	19.15	17.66	17.68	15.95	15.62
4	23.74	27.46	22.58	18.64	15.60	14.62
5	28.74	28.70	27.17	28.10	23.85	15.75
6	28.18	30.67	26.33	21.33	24.09	23.78
7	24.30	29.23	26.37	20.46	18.45	24.36
8	23.32	19.88	22.38		25.45	
9	27.36	27.58	27.27			
10	26.82	27.00	26.84			

Table 11. Moisture content versus depth, test plot 3

Depth,	1957	Date		1958		
feet	October	November	December	January	February	March
0	19.48	21.37	21.39	19.45	19.94	22.62
1	23.34	22.80	21.95	23.34	22.43	24.88
2	20.30	18.46	17.85	18.68	17.38	17.54
3	18.32	15.70	16.42	17.20	16.52	16.96
4	17.61	15.60	18.35	17.21	17.39	17.31
5	19.94	19.02	17.84	17.00	17.83	18.04
6	17.54	17.72	16.76	16.43	16.97	18.16
7	17.07	17.34	17.25	17.48	17.76	19.24
8	19.43				19.78	17.38
9	17.39					

Table 11. (Continued)

Depth, feet		Date			1958	
	April	May	June	July	August	September
0	22.53	20.69	20.40	16.33	15.21	17.42
1	22.74	21.92	22.24	22.56	20.91	22.00
2	18.10	17.63	18.24	20.00	18.60	20.42
3	18.00	16.97	17.89	16.82	16.28	17.82
4	17.61	16.90	17.32	18.31	17.14	15.00
5	17.46	16.75	18.03	18.50	17.07	15.89
6	18.12	17.42	17.44	18.24	19.29	16.83
7	18.04	17.86	20.32			
8	17.87	19.16	17.75			

Table 12. Moisture content versus depth, test plot 4

Depth, feet	1957		Date		1958	
	October	November	December	January	February	March
0	17.01	18.61	20.28	19.93	18.11	18.78
1	18.41	17.96	17.92	17.00	16.93	18.96
2	16.60	17.28	16.45	16.16	16.80	17.57
3	17.31	15.55	17.69	17.78	17.87	17.66
4	18.62	18.35	19.63	20.24	19.56	20.50
5	18.79	18.62	19.04	19.16	18.82	20.32
6	19.54	18.75	19.31	21.06	20.52	19.64
7					20.79	20.05

			1958			
	April	May	June	July	August	September
0	18.65	17.79	18.32	17.49	15.05	15.71
1	17.95	17.18	19.20	18.23	18.18	16.75
2	16.74	15.02	17.39	17.81	17.68	17.83
3	19.78	17.97	17.55	16.88	16.87	17.49
4	20.64	20.22	19.32	18.93	19.13	18.32
5	20.02	18.82	19.16	20.88	19.73	19.04
6	20.01	17.65	18.17		20.75	23.25
7	20.03	19.47	19.37			

Table 13. Moisture content versus depth, test plot 5

Depth,	1957		Date		1958	
feet	October	November	December	January	February	March
0	21.11	24.04	22.47	22.93	22.15	24.34
1	22.59	22.85	24.10	22.40	23.47	23.18
2	21.50	20.86	23.87	20.29	23.52	19.00
3	18.78	18.63	23.06	16.41	20.04	15.05
4	23.39	20.93	19.93	16.24	11.89	11.58
5	19.47	21.27	20.47	17.90	11.58	26.50
6	18.34	18.93	18.34	14.44	10.93	29.73
7	21.28	14.17	18.13	14.70	12.68	24.34
8	15.05	16.34	19.63	18.10		25.08
9	18.16	18.44				
10	21.30					

Table 13. (Continued)

Depth,		Date			1958	
feet	April	May	June	July	August	September
0	24.03	21.87	20.91	21.60	20.41	21.51
1	24.34	23.43	22.36	20.71	21.05	23.48
2	21.86	22.47	21.14	19.02	19.57	19.64
3	18.89	19.80	17.24	17.86	18.07	18.56
4	13.16	12.36	12.16	21.14	20.34	18.22
5	14.64	9.53	12.77	18.65	17.96	13.25
6	17.82	11.96	17.00	17.70	17.66	14.71
7	16.13	10.72	18.78	18.14	17.50	15.84
8	15.96	16.00	19.97	16.24		
9	22.00	18.88	24.67			

Table 14. Moisture content versus depth, test plot 6

Depth,	1957		Date	1958		
feet	October	November	December	January	February	March
0	21.10	25.45	25.31	34.12	26.94	28.20
1	21.60	20.04	22.40	22.75	22.86	22.76
2	20.42	24.86	22.18	20.22	19.87	20.77
3	21.50	22.29	22.02	20.61	20.00	21.00
4	19.09	20.16	19.62	19.13	18.70	20.09
5	18.85	19.32	19.25	17.48	18.83	18.67
6	18.63	19.85	18.74	18.86	18.47	16.52
7				18.54	20.25	18.25
8						18.54

			1958			
	April	May	June	July	August	September
0	21.66	23.20	21.61	20.92	15.71	20.66
1	22.59	21.22	20.38	22.84	17.31	20.90
2	20.63	18.72	18.10	21.56	16.81	19.49
3	21.18	18.46	17.87	21.07	19.73	19.65
4	19.39	18.82	18.04	18.08	19.20	18.46
5	19.00	18.29	18.31		19.23	18.55
6	18.34	18.07	17.88		17.75	17.85
7	18.60	18.07	17.79			
8	18.38	18.34				