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LOCKHEED ELECTRONICS COMPANY, INC.
AEROSPACE SYSTEMS DIVISION

14911 EL CAMINO REAL

HOUSTON, TEXAS 77038

TELEPHONE (AREA CODE 713) 488-0000

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TECHNICAL MEMORANDUM

SOIL MOISTURE

- SOME FUNDAMENTALS -

by

B. W. Milstead

Approved:

J. O. Carney
J. O. Carney, Supervisor
Exploratory Investigation
Section

Distribution:

JSC/T. Buras

L. F. Childs

K. J. Demel

N. Hatcher

A. W. Patteson

LEC/O. N. Brandt

K. P. Eckel

K. Krishen ✓

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R. E. Tokerud

J. O. File

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1. INTRODUCTION

Soil science has developed to a high degree, and a wealth of information is available concerning the many aspects of soil types, such as their chemical makeup, origin and change, and of course, the significant soil characteristics that relate to agriculture. The handling, moving, and controlling of soil moisture are well understood by the agricultural community and several methods for measuring this are currently in use.

The Joint Soil Moisture Experiment has been in progress for several months, and a significant number of measurements have been accomplished for a variety of field conditions. Although the general idea of what the experiment is about is straightforward, a brief tutorial on soil moisture, as it applies to agriculture, is in order. Information in this report was taken from books and papers considered freshman college level material. It is an attempt to briefly present the basic concept of soil moisture and to acquaint the reader with a minimal understanding of how water interacts with soil.

2. SOIL COMPOSITION

Soil is a mixture of minerals, organic matter, water, and air. This mixture is highly variable and constantly subject to change. Chemical change due to weathering, plant growth and decay, leaching, etc. is a continuous process of nature. Freezing and thawing of water, root penetration, and chemical breakdown cause soils to loosen, minerals to decompose, and other minerals to be formed. Organic matter from plant decay and animal life (earthworms, microorganisms, etc.) is constantly being added to the soil. In addition, many changes are brought about by cultivation. Plowing breaks up the surface, soils are compacted by traffic, minerals and organic matter are added as fertilizer, and water absorption and drainage properties are changed.

From all of this it is obvious that the soil of a particular area does not remain "fixed." However, the amount of variation to be found over a given time span is definable, and somewhat predictable.

Many types of soils (about 8000 in the U.S.) have been categorized by soil scientists. However, in very general terms, cultivated land is composed of 45 percent minerals, 5 percent organic matter, 25 percent water, and 25 percent air. Within this mixture, air and water are interchangeable, that is, as water is added, air is displaced, and as water leaves the soil, air returns to fill the pore space.

2.1 SOIL MINERALS

Approximately 92 chemical elements are found in the earth's surface. Over 2000 recognized mineral compounds are formed from these elements. Of this large number, relatively few are of any real significance in agriculture. Of the 92 chemical elements, eight comprise 98 percent of the earth's crust. These are

listed in table 1. Several additional elements are required for plant growth.¹ Not only must these be available in sufficient quantities, but they must be in a chemical form that is absorbable by plants.

TABLE I. - CHEMICAL MAKEUP OF EARTH'S CRUST, PERCENT (BY WEIGHT)

Chemical element	Percent (by weight)
Oxygen	46.6
Silicon	27.7
Aluminum	8.1
Iron	5.0
Calcium	3.6
Sodium	2.8
Potassium	2.6
Magnesium	2.1

The mineral makeup of soil is constantly changing due to physical events such as weathering, leaching, and plant growth. Various minerals break down into other mineral compounds. Absorption of water causes many minerals to break down into compounds of oxygen and hydrogen. These compounds may, in turn, be readily leached from the soil, be subject to further chemical change, or may be available to plants as nutrients.

2.2 ORGANIC MATTER

Organic matter in soils is the accumulation of plant and animal residue left by the natural process of growth and death of both plant and animal life. It exists in an active state of decay

¹Plants require some 16 elements in the soil. Nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are required in relatively large quantities. Manganese, iron, boron, zinc, copper, molybdenum, and chlorine are required as trace elements.

and, compared to the mineral content, is a relatively transitory part of the soil. In general, organic matter depends on constant replenishment by plant decay and animal life and death in the soil.

Although the normal organic content of soils is relatively small (approximately 5 percent by weight)² its effect on the soil is highly significant. In addition to its nutrient value, it serves to "granulate" the mineral particles. This tends to increase the water-holding ability of soil and to increase the "available water" content.

²Soils with an organic content of 20 to 30 percent or greater are called "Peat" soils. Chemical makeup, decay rates, etc. are subject to entirely different conditions.

3. PARTICLE SIZE AND SOIL CLASSIFICATION

One method of categorizing soil is by particle size. The inorganic material in soils is made up of rock fragments and minerals. This mineral content is composed of particles of various sizes and shapes.

Particle size is one of the most significant characteristics affecting the water-holding ability of a soil, in addition to affecting productivity, ease of tillage, etc. A system of categorizing soils by particle size is presently used in agriculture; other features such as chemical makeup and organic material, are not considered. Initially the various size particles are classified as sand, silt, or clay, as shown in table 2. Since most soils are a mixture of more than one group, a texture triangle, shown in figure 1, provides a ready means of categorizing a given soil for any mixture of sand, silt, and clay. This grouping has been developed to place soils with similar characteristics together. Highway engineers use a similar texture triangle when determining load-bearing features of a soil, with only the boundary lines between types being slightly shifted. Using figure 1, a mixture of 30 percent clay, 60 percent silt, and 10 percent sand would be a "silty clay loam" (point A).

Of the various size particles, clay content is the most significant, even though the volume occupied by solids is more or less independent of particle size. That is, a 10 percent change in clay content will have a greater effect on the features of a soil than will a 10 percent change in silt or sand content.

Sand particles expose relatively little surface area, compared to an equal weight of clay. In some cases, the total exposed surface area of clay may be over 100,000 times greater than the surface area of an equal weight of sand. Because of this small surface area, sand has an almost negligible effect on the

TABLE II. - CLASSIFICATION OF SOIL BY PARTICLE SIZE

United States Department of
Agriculture System

Soil separate	Diameter limits (mm)
Very coarse sand	2.00 - 1.00
Coarse sand	1.00 - 0.50
Medium sand	0.50 - 0.25
Fine sand	0.25 - 0.10
Very fine sand	0.10 - 0.05
Silt	0.05 - 0.002
Clay	below 0.002

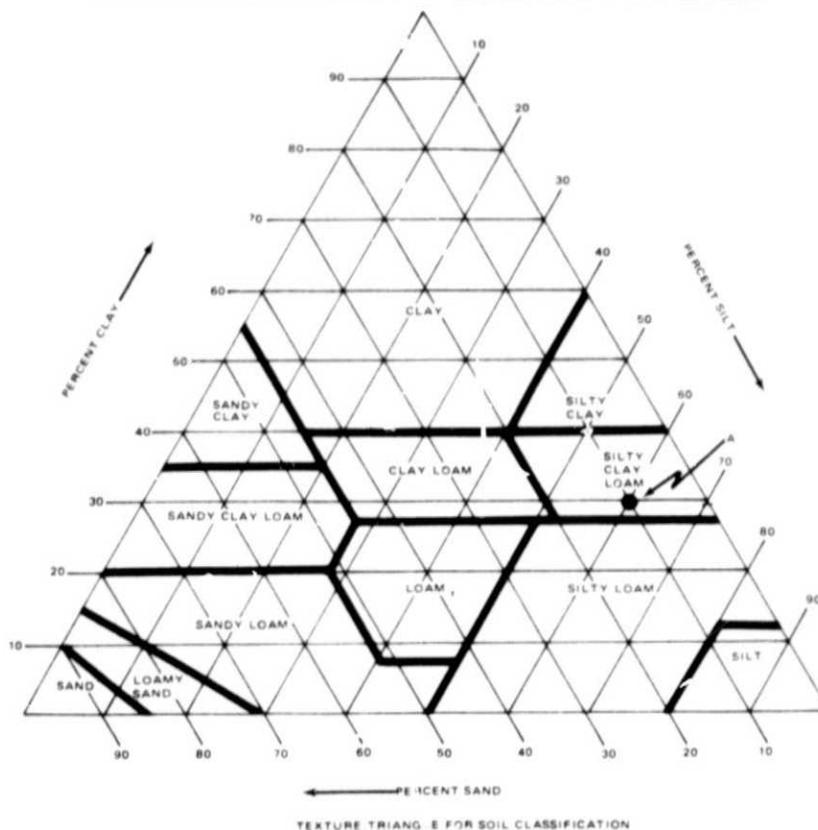


Figure 1. - Texture triangle for soil classification,
United States Department of Agriculture.

chemical activity of a soil. However, some sand is usually desirable, particularly in soils with a high clay content. The presence of some larger particles will keep the soil from compacting too tightly, which in turn provides more usable space for air, water, and water flow.

4. SOIL WATER

As stated previously, "soil" is approximately 50 percent solid particles and 50 percent air and water. This 50 percent air/water space is the volume that is available to be occupied by water. If the soil is completely saturated, then all available air space is filled with water; if the soil is completely dry, then no water is present and air totally fills this space. These are the two extremes and the major interest is obviously what happens between these extremes.

Soil is made up of various size particles and the spaces between these particles, called soil pores, are occupied by water and air. As the particle size varies, the pore size also varies, even though the total volume of pore space is somewhat independent of particle size.³

As water is added to the surface of a dry soil, water begins to fill pore space at the surface, and moves downward, filling

³ Consider a vastly simplified example: In figure 2a, the cube is 1 unit/side. The total volume occupied by the eight spheres is $v = 8 \times (4/3)\pi(1/4)^3 = \pi/6$. In figure 2b the total volume occupied by the 64 spheres is again $v = 64 \times (4/3)\pi(1/8)^3 = \pi/6$.

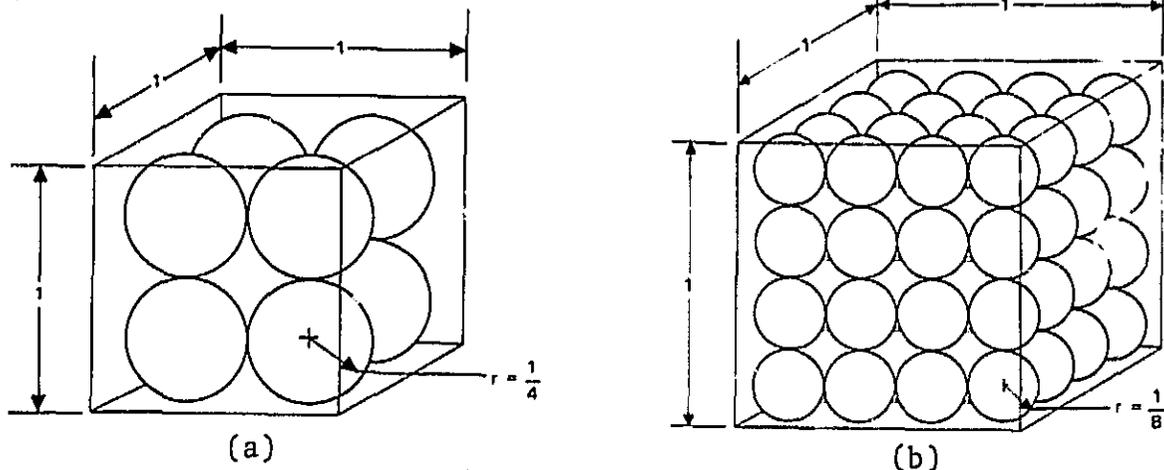


Figure 2. - Unit volume space.

pores deeper in the soil. When all pores are completely filled with water, the soil is "saturated" and any additional water must either move downward under the force of gravity or "runoff" the surface. If the water supply is now shut off, water will continue to move downward through the soil. The larger pores (called macropores) at the surface will begin to empty some of their water, leaving air space. At some point, water will cease moving downward, leaving the smaller pores (called micropores) completely filled, and some air space in the larger pores.

This is illustrated in figures 3a and 3b. Water is added to a container of soil until saturation occurs, as in figure 3a. (Standing water on top of the soil is not a necessary condition for saturation.) If the container is now allowed to drain, water will rapidly move downward, under the force of gravity, until a stable situation is reached, as in figure 3b. At this point the soil is no longer saturated and "field capacity" has been reached. Water will no longer move under the force of gravity and a thin film of water surrounds each soil particle. This water is held in the soil due to (1) adhesion (the attraction of a solid surface for water molecules) and (2) cohesion

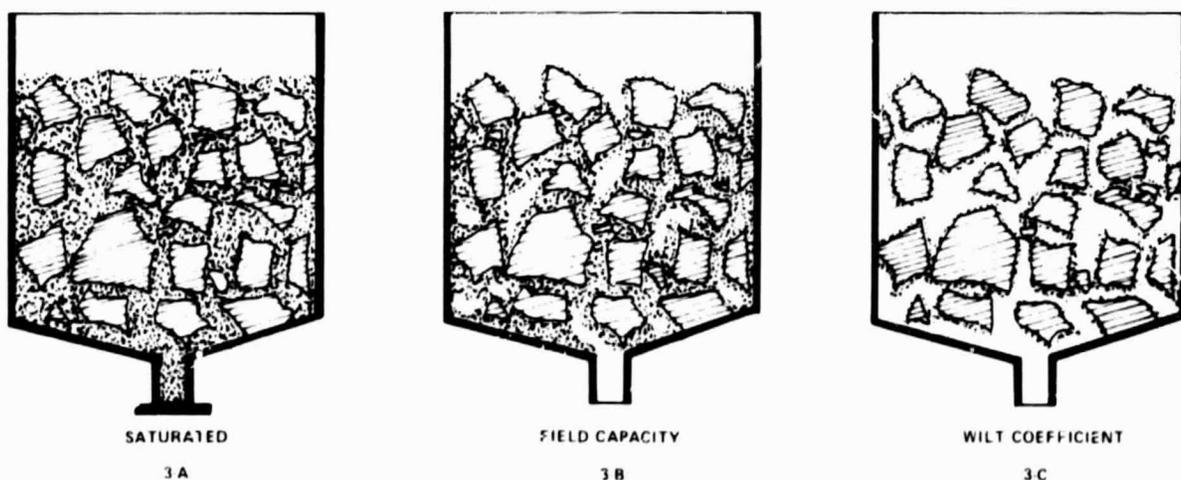


Figure 3. - Soil water flow.

(the attraction of water molecules for each other). For further movement of water to take place, some external force must be applied to overcome the tensile forces of adhesion and cohesion.

As might be expected, the volume of water at field capacity is directly related to the total surface areas available for adhesion, and, as indicated earlier, this is a direct function of the particle size. This field capacity, shown in figure 3b, is the 25 percent water and 25 percent air mentioned in the initial portion of this paper.⁴

Once field capacity is reached, several factors control further water removal and water movement through the soil. The binding force with which water is held to soil particles at field capacity varies, with soil types, between 0.1 and 0.5 atmospheres.⁵ An average value that is often used is 1/3 atmosphere. Stated another way, once field capacity is reached, a tension greater than 1/3 atmosphere must be applied to the water to cause any removal. If this force is applied, then water will flow toward the tension source, some water will be removed, water will flow through the soil to replace the lost water, and the moisture film around the soil particles will become thinner. As this film becomes thinner, the binding force between water molecules and soil particles becomes greater, that is, as additional water is removed adhesion increases.

At this point, it is easy to understand why clay is such an important consideration in soil classification. Consider footnote 3 again, with 1 cm³ of spherical particles with a diameter

⁴The percentage of water means percent by weight. That is
percent of water = $\frac{\text{weight of soil wet} - \text{weight of soil dry}}{\text{weight of soil wet}} \times 100$

⁵One standard atmosphere = 1033.3 cm of water.

of 1 mm (coarse sand). The total surface area is approximately $3 \times 10^3 \text{ mm}^2$. Now, if only 20 percent of the particles are replaced with particles of .001 mm diameter (clay), the total surface area is now $6 \times 10^5 \text{ mm}^2$, an increase of more than two orders of magnitude. The field capacity of this sandy loam would obviously be larger than sand alone.

Since field capacity is normally reached within a few hours after water is shut off from a saturated soil, water that is moving through the soil due to gravity is available for plant nutrition for only a relatively short length of time. For this reason, soil moistures at or below field capacity are of primary interest. In this range of moistures, water movement through the soil is primarily a function of capillary action. Water loss from the soil occurs either from evaporation at the surface or plants remove water by sucking the water from both large and small pores. As this water is removed, water flows within the film around the particles. Thus water moves to replace lost water both in the immediate vicinity of plant roots, and at the soil surface.

When water in the soil is at field capacity, or slightly below, plants can easily obtain as much water as required. However, as the water content falls significantly below field capacity plants have more difficulty obtaining water, since the tenacity with which water is held increases as the water film becomes thinner around the individual soil particles. Plants can obtain water until the binding force between soil and water approaches 15 atmospheres. At this point plants wilt and die, and this is defined as the "wilt point" or "wilt coefficient." This is shown in figure 3c. The percentage of water remaining in the soil at the wilt coefficient varies widely with the type of soil.

The variation in field capacity and wilt coefficient for various soil types is shown in figure 4. As would be expected, the field capacity increases as the individual soil particles become smaller. The field capacity of sand \approx 6 percent, of sandy loam \approx 14 percent, of silt loam \approx 26 percent, etc. Of this field capacity, water that is held with a tension of less than 15 atmospheres is called "available water." The available water increases with decreasing particle size, up to a point, then begins to decrease, as shown in figure 5.

This decrease in available water is attributed to the high clay content and subsequent small pore space in which water is stored. With no larger particles, much of the pore space in clay soils is very small, and consequently a larger part of the field capacity water is held under higher tension.

For the example shown in figures 4 and 5, the typical field capacity of a silt loam is 26 percent, with an available water content of 12.6 percent.

When the wilt coefficient is reached additional water may be removed by oven drying.⁶ When binding forces reach 31 atmospheres the "hygroscopic coefficient" is reached. At this point the remaining water more closely resembles a solid in its characteristics, although the soil may still contain up to 8 percent water. Tension forces in the hygroscopic region vary from 31 atmospheres to as high as 10^4 atmospheres for the last water molecules immediately adjacent to soil particles. For soil moisture considerations, this water has been ignored since from an electrical or electromagnetic standpoint it does not resemble water. Its total effect on the dielectric properties of soil is not fully documented to date.

⁶Soil samples are oven dried at 110°C or less. At this temperature hygroscopic water is not driven off.

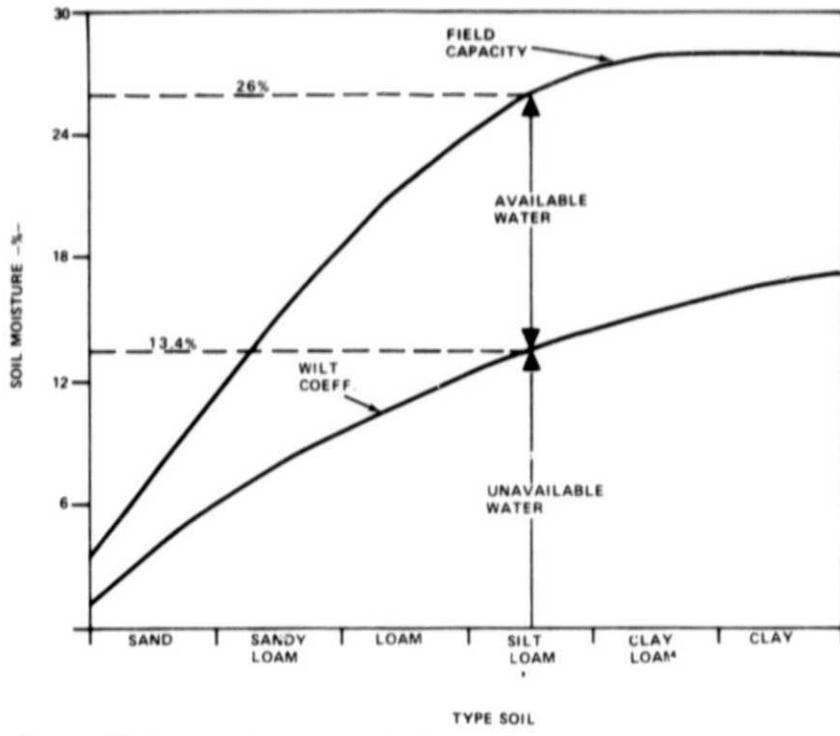


Figure 4. - Water storage capacity of various soil types.

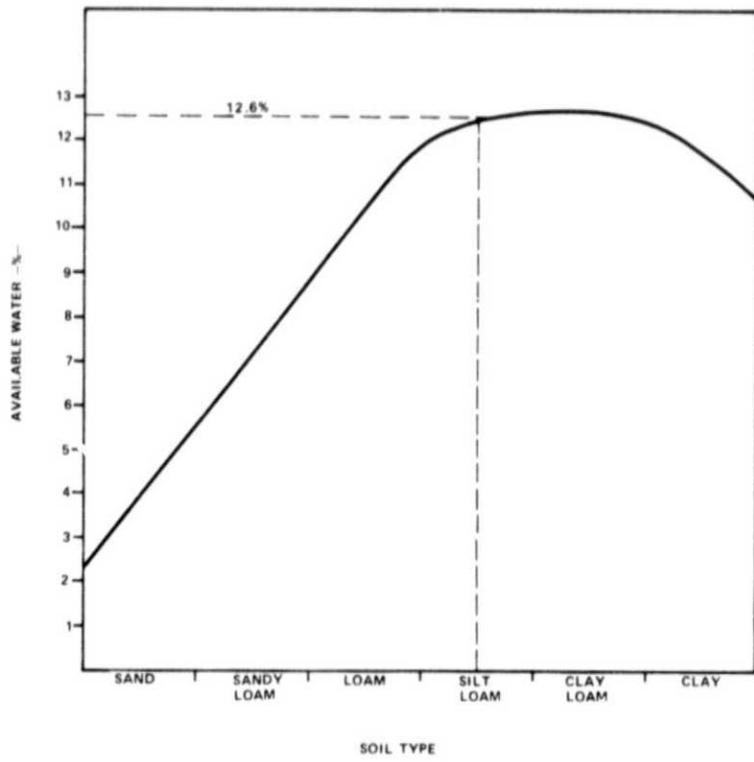


Figure 5. -- Available water at field capacity.

APPENDIX A

FIELD METHODS OF MEASURING SOIL MOISTURE

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APPENDIX A

FIELD METHODS OF MEASURING SOIL MOISTURE

Several methods are commonly used for measuring soil moisture. A brief summary is presented here that describes only basic principles of operation. Most, but not all, of these are an indirect measurement and depend on some type of calibration to a particular soil.

Soil moisture measurement instruments may be divided into the following classifications, based on principle of operation.

1. Gravimetric methods - weighing specific soil samples before and after a water exchange.
2. Water exchange measurements - indirect measurement of water removed or added to a known material buried in the soil.
3. Neutron scattering measurements.

GRAVIMETRIC MEASUREMENTS

Using this method, soil samples are weighed, and then oven dried at 105°C until a constant weight is obtained. The sample is then reweighed with the difference being the initial weight of water in the sample. Although very time-consuming, this is the most accurate method currently in use.

WATER EXCHANGE MEASUREMENTS

This method depends upon burying some known porous material in the soil, letting water flow by capillary action into or out of the material, and measuring specific characteristics of the material after this water exchange. Several different adaptations of this have been developed and each has its advantages and disadvantages and is subject to specific errors.

Although the several adaptations of this are given different names and are considered different instruments by field personnel using them, they all depend upon the same principle for operation. The "best" method depends on soil characteristics, the range of soil moisture to be measured, or even the personal preference of the operator. Porous materials commonly used are plaster of Paris, blocks of gypsum, nylon fibrous material, or fiberglass.

After the porous blocks have been buried, and sufficient time has elapsed for water to flow into the material by capillary action, changes in electrical resistance,¹ dielectric constant, or rate of heat flow are all proportional to the amount of water absorbed. Once the particular parameter of interest is measured, the amount of water in the soil may be inferred.

One adaptation of this principle is the tensiometer, shown in figure A-1. A sealed tube, fitted with a porous cup and a vacuum chamber, is driven into the soil. Water flows from the tube into the soil, leaving a partial vacuum in the upper chamber. Water will flow out of the chamber, into the soil, until pressure in the vacuum chamber equals the external tension with which water is held in the soil. Water tension is read directly on the vacuum gauge.

Another method that uses this same principle is to weigh the porous material before and after exposure to the soil. The weight difference is the water absorbed by the porous material, and for a known material, the amount of water in the soil may be inferred.

¹Early attempts at direct measurement of soil electrical resistance were unsuccessful because of the variation in dissolved salts in the soil, which causes significant variation in resistance.

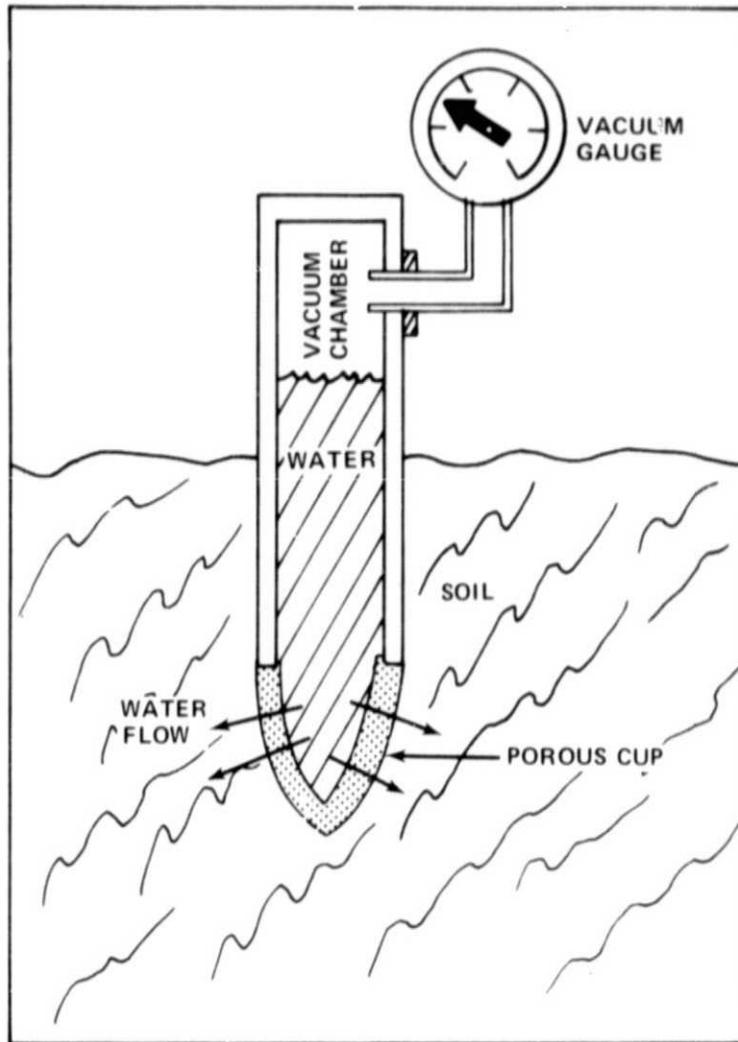


Figure A-1. - Tensiometer.

NEUTRON SCATTERING METHOD

This method of soil moisture measurement depends on scattering of neutrons by hydrogen atoms in water. In practice, a 1-inch access pipe is placed in the soil, with the bottom sealed. A neutron source and detector is lowered into the pipe. Neutrons will penetrate the metal pipe but will be scattered by a moist soil, with the number of scattered neutrons increasing as the amount of water increases. Scattered neutrons are detected by the sensor and for a known source, the soil moisture may be inferred from the neutron detector reading.

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