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Publication of this paper sponsored by Committee on Environmental Factors Except Frost.

Characterization of Expansive Soils

R. GORDON McKEEN AND DEBORA J. HAMBERG

Most expansive soils encountered in engineering problems are at a degree of saturation below 100 percent. Knowledge of the moisture condition of such soils is best obtained by measuring soil suction. Soil suction can be determined routinely by using either the thermocouple psychrometer or filter-paper methods. The volume response can be characterized by obtaining a volume-change measurement along with a determination of suction change. This measure of soil response is called the suction compression index and is a fundamental property of unsaturated fine-grained soils. An empirical method of estimating the suction compression index from index tests is provided. The soil stiffness, or the reduction in swell behavior caused by loads, must also be accounted for in making heave predictions. A nondimensional equation is presented that was developed by regression techniques from a large number of data found in the technical literature. The equation provides a tool for reducing the volumetric response of expansive soils as applied loads are increased. The use of this information in predicting heave is illustrated.

Expansive soils undergo volume changes when their moisture condition varies. Designing transportation facilities for expansive-soil areas requires consideration of the volume changes that are likely to occur. Several decades of research on this problem have produced the tools of "expansive soil mechanics". Mitchell (1) recently presented three fundamental soil characteristics that must be considered in design: soil response to load, soil response to moisture changes, and the diffusivity of water moving in the soil. Techniques for obtaining these properties are available. This paper describes techniques for characterizing the moisture and load response of natural expansive soils.

SOIL SUCTION

Soil suction is a macroscopic property of soil that indicates the intensity with which a soil will attract water. Suction results from (a) the interplay of attraction and repulsion forces of charged clay particles and polar water molecules, (b) surface tension forces of water, (c) solution potentials caused by dissolved ions, and (d) density. A distinction must be drawn between pore-water tension and suction: Tension applies to the actual pressure state of the pore water; suction is total head, which includes pore-water pressure, osmotic pressure, and adsorptive pressure.

In engineering problems, suction is considered to be composed of matrix and osmotic suction components, and their sum is termed the total suction. Matrix suction is the negative gage pressure that, through a porous membrane, will hold soil water in equilibrium with the same soil water within a soil sample. Matrix suction is the result of surface adsorption and capillary forces. Osmotic or solute suction is a negative gage pressure that will hold pure water in equilibrium with soil water through a membrane that allows only water molecules to pass. Osmotic suction results from variation in ion concentration in the pore fluid.

Two independent stress variables have been used to describe the state of stress in unsaturated soils. The preferable stress-state variables are $(\sigma - u_a)$ and $(u_a - u_w)$, where σ = total stress, u_a = pore-air pressure, and u_w = pore-water pressure. The term $(\sigma - u_a)$ is called the total stress term and $(u_a - u_w)$ is called the matrix suction term. This combination of stress-state variables is most satisfactory because the effects of environmental variables can readily be separated in terms of stress changes. This approach assumes that u_a is approximately atmospheric and the osmotic component of suction remains constant. These assumptions are adequate for many engineering problems.

SUCTION MEASUREMENT

Thermocouple Psychrometers

A psychrometer is defined as essentially two similar thermometers, one of which has a bulb that is kept wet so that the resulting evaporative cooling makes it register a lower temperature than the dry one; the difference between the readings represents a measure of the dryness of the atmosphere. The difference between the two readings is called the wet-bulb depression. For a known wet-bulb depression and dry-bulb temperature, the ratio of the water vapor pressure in the air to that of pure free water at the same temperature and pressure can be computed. This ratio is the relative humidity.

In 1951, Spanner (2) demonstrated the use of a psychrometer based on two principles of thermoelectricity. The sensing junction was reduced in size to eliminate the requirement for ventilation. Cooling was accomplished by means of the Peltier effect, which cools the thermocouple with a small electric current. When the temperature drops below the dew point, water vapor condenses. As the water vapor evaporates, the Seebeck effect produces a measurable electric current.

Several limitations were noted. These included (a) a maximum cooling of about 1.8°C Verbrugge (3), (b) heating of the reference junction during Peltier cooling of the sensing junction, and (c) temperature gradients between the sensing and reference junctions. Thus, the relation between the measured wet-bulb depression and the water-vapor pressure is affected by a number of factors. In a theoretical study, Rawlins (4) listed these as (a) radii of wet junction, equilibrium chamber, and thermocouple wire; (b) thermal conductivities of wire and air; (c) diffusivity of water vapor in air; (d) latent heat of vaporization of water; (e) saturation specific humidity; (f) temperature; and (g) Peltier and Seebeck coefficients of the metals used.

Although the theoretical treatment has provided insights into the psychrometer response to various design factors, they are of minor interest in actual application. The complexities are overcome through calibration of the instruments, followed by cautious attention to measurement conditions.

Two types of instruments have been in common use. One uses the Peltier effect to condense water on the sensing junction (2). The other method requires manual placement of a water drop at the sensing junction (5).

The Peltier method is more appropriate for engineering problems. However, it can be used in two different modes of operation. The first is the previously described technique used by Spanner, the psychometric mode. Another technique uses an electric circuit to periodically cool the sensing junction and thus maintain the water condensed on it and produce a constant output. This is the hygrometric mode of operation. This technique offers no advantage in routine soil-suction measurements but can be used where continuous monitoring is required. The Peltier psychrometer operated in the psychrometric mode is thus the best instrument for use in routine engineering measurements.

The present state of the art of psychrometer use is based on calibration. Normally, the output is plotted versus water potential by making measurements in salt solutions of known concentrations. Typical calibration data for several conditions are shown in Figures 1 and 2.

Since both water potential and psychrometer output vary with temperature, it is necessary to calibrate at various temperatures for use in nonisothermal environments. Meyn and White (6) proposed a calibration model that accounts for temperature:

$$Y = b_0X_0 + b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_2^2 + b_5X_1X_2 \quad (1)$$

where

Y = water potential (bars),
X_0 = dummy variable = 1,
X_1 = electromotive-force output of psychrometer (µV),
X_2 = temperature (°C), and
b_0-b_5 = regression constants.

Similar models have been developed by Slack (7), Riggle (8), and McKeen (9). Some of the results given in Table 1.

It is important to note that the model is valid for measurements made in exactly the same manner as the calibrations.

Filter Paper

Another method developed for determining suction uses filter paper as a passive sensor. In work at the University of Copenhagen, Hansen (10) used

Figure 1. Calibration variation with cooling time.

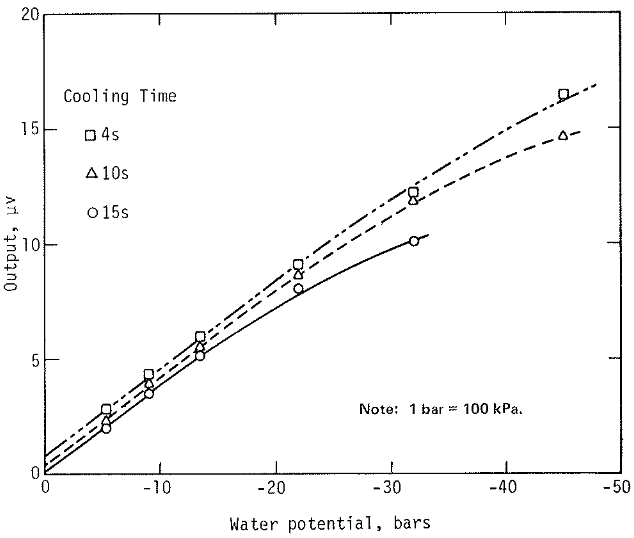
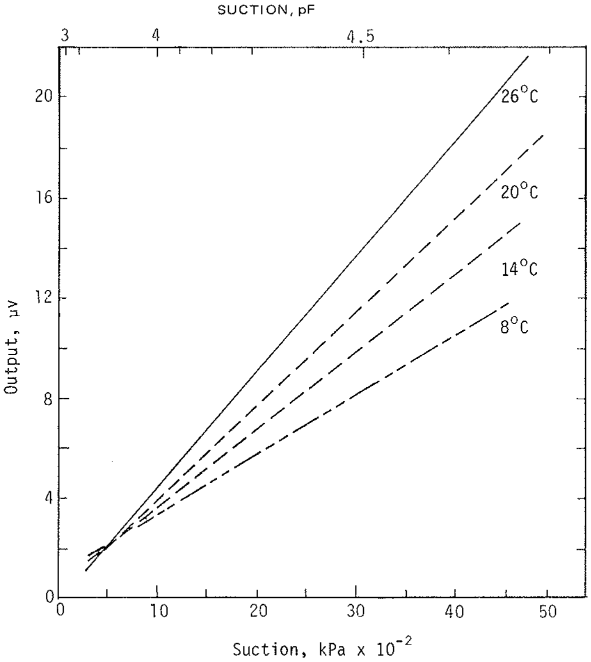


Figure 2. Calibration variation with ambient temperature.



blotting paper as a carrier for sugar solutions. Strips were saturated with different solutions and exposed to soils in closed containers. The one with the least moisture change at equilibrium was interpreted as being nearest the stress level of the soil. Stocker (11) improved accuracy by using more solutions. Gradmann (12) then calibrated the paper for water content versus moisture stress. When equilibrated with soil samples, the blotting-paper water content yielded a direct estimate of suction. Gardner (13) used an ash-free quantitative filter paper calibrated for water content versus suction as the passive sensor. From this technique came the present method in wide use by the U.S. Geological Survey (14,15). Evaluations by McKeen (16) and Johnson (17) have indicated that the method is suitable for studies of expansive soils.

Various papers and calibration techniques have been used in studies of soil moisture. Papers can be equilibrated with soil samples at known suction, suspended above salt or acid solutions, or equilibrated on a pressure plate or pressure membrane for calibration. The method used is normally dependent on the suction range of interest. McQueen and Miller (14) found that a two-part model best fit their calibration data. Figure 3 shows the filter-paper calibration data of McQueen and Miller. The upper portion represents water adsorbed to the paper fibers, and the lower portion shows the water held in capillary spaces within the paper. A similar relation was obtained by McKeen (16). Once a paper is calibrated, disks from the same lot are sealed inside moisture cans with the soil samples of interest for a period of seven days. Temperature fluctuations must be reduced during the equilibration period. After equilibration, the filter papers are removed and their water contents are determined. Soil suction is obtained by using the calibration relation. By also drying the soil sample, the moisture-suction relation can be determined. If volume change is measured as it dries, an estimate of the suction compression index can be obtained as well.

SUCTION COMPRESSION INDEX

A fundamental property of expansive soils is the volumetric response of the soil to suction changes. This property has been called the suction compression index (SCI) (18; 19, p. 119), the instability index (1,20), and soil modulus with respect to suction change (21,22). In this paper, the SCI is defined as follows:

$$\gamma_h = -[(\Delta V/V_i)/\log(h_f/h_i)] \qquad (2)$$

where

γ_h = suction compression index,
$\Delta V/V_i$ = volume change with respect to initial volume, and
h_f, h_i = final and initial values of suction (arithmetic units).

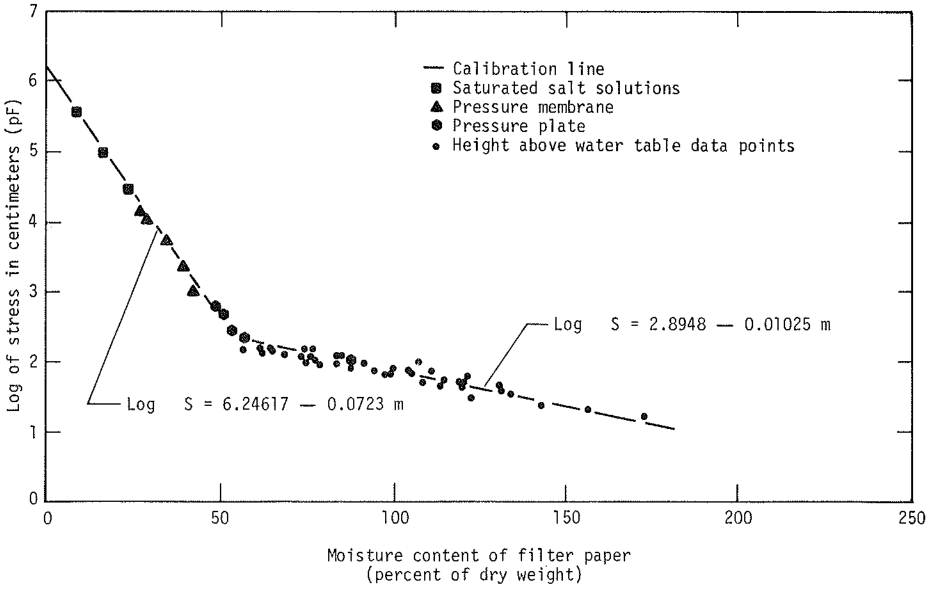
The determination of the SCI requires the measurement of a volume change and the suction change that occurred simultaneously, as shown by Equation 2. Since there are several methods of making such measurements, there are several methods of determining the SCI. The most reasonable methods involve a single suction determination on soil samples as they are removed from the study site. Methods were presented in the previous section for making these measurements. The next step is to cause the soil to change volume by wetting or drying it.

Wetting of the soil may be accomplished by inundating a sample in a conventional oedometer ring. Several properties of expansive soils must be recognized in order to determine the SCI. An extensive laboratory study (19) and other work in the literature by Compton (23) and Escario (24) indicate that changes in soil volume as a result of suction changes between levels of 0 and 33 kPa (2.5

Table 1. Regression models for determining temperature for psychrometer calibration.

Variable	Constant	Riggle (8)	Meyn and White (6)	McKeen (9)
X_0	b_0	2.292	0.1062	-16.4704
X_1	b_1	-4.138	-4.6283	-4.0883
X_1^2	b_2	-	0.0778	1.6769
X_2	b_3	-0.0557	-0.0076	0
X_2^2	b_4	-	-0.0075	-0.0413
X_1X_2	b_5	0.1110	0.1036	0.0728
R^2	-	0.976	0.962	0.963

Figure 3. Summary of calibration data.



pF) (pF = log to base 10 of pressure in centimeters of water) are not significant. Thus, for purposes of computing the SCI, h_f (the final suction of the soil) should be assumed to equal 33 kPa. Together with the measured swell, an SCI value can be determined. If these measurements are made with no load, the effect of actual loads must be considered in the evaluation. The oedometer has the advantage of including an easy method of applying various loads to the soil sample during swell. However, the restriction of lateral strain may differ markedly from that in the real soil.

Another method of wetting the soil is the procedure developed by the Soil Conservation Service (SCS) for the coefficient of linear extensibility (COLE) test. In this case, clods of natural soil are coated with a plastic resin and then permitted to wet up. Volume measurements are made by suspending the plastic-coated clod in water. This method does not permit the application of mechanical loads. The plastic coating has been shown to reduce volumetric activity (19).

Another approach is to dry a soil from its natural state. This cannot be done with a sample confined in an oedometer ring, but it is very easily done by using soil clods and the COLE technique of volume measurement. Changes in soil volume cease when the soil reaches the shrinkage limit. The convenience of this approach lies in the fact that the shrinkage limit for clay soils is at about 330 MPa (5.5 pF) (19). A single suction measurement on the natural soil sample, followed by a volume measurement at natural moisture and the oven-dry condition, is required. No loads can be simulated when this technique is used. A load-correction procedure is required.

The SCI can also be determined by using a chart method we have developed from data in the literature. Data published by SCS were used as a source for COLE, percentage clay, and cation exchange capacity (CEC) for a large number of samples (25, p. 383; 26, p. 637; 27, p. 337). By using a clay mineralogical classification system reported by Pearring (28) and Holt (29), a chart was produced that gives SCI values without requiring suction tests. The Pearring-Holt system classified soils into mineralogical groups according to empirical relations among mineralogy, plasticity index (PI), CEC, and clay content. A chart was developed that segregated mineralogical groups according to clay activity (Ac) and cation exchange activity (CEA_c), where Ac = PI ÷ percentage clay and CEA_c = CEC ÷ percentage clay.

The new chart we developed carried this idea a step further by means of correlations found between COLE and mineralogical groups. About 200 samples were used to develop the necessary regressions. Data were plotted on the CEA_c-Ac chart. Boundaries were then established by using mineralogy percentages, particularly the amount of smectite. Five "regions" were established, ranging from pure smectite to none. Table 2 gives the mineralogical makeup of the regions.

Once the regions were identified, the SCI for soils in each region was studied. Linear regressions were calculated for SCI and the percentage clay in each region. All coefficients of determination were above 0.9. The SCI values for a pure clay are shown in the chart in Figure 4. To obtain a value for a real soil, the chart value is determined by plotting CEA_c versus Ac and multiplying the number obtained by the clay content as a decimal: For example, clay content = 52 percent; PI = 51 percent; CEC = 31.7 meq/100 g; Ac = 0.981; CEA_c = 0.610; and SCI = 0.52 (0.163) = -0.085.

Clay content, PI, and CEC must be obtained by testing. Then Ac and CEA_c are computed. In the example, the values of 0.901 and 0.610 are then plotted in Figure 4. This yields a value of -0.163 for a soil composed of 100 percent clay. The actual value for this soil is obtained by multiplying -0.163 by the clay content, 0.52, which yields -0.085 for γ_h.

SOIL STIFFNESS

When a mechanical load is applied to a soil element, the volumetric behavior of the soil is altered. As loads are increased, the amount of swell obtainable over a given suction change is reduced. This behavior can be represented in several ways. Here, the recommendation is the following nondimensional equation:

$$S_p/S_0 = -0.0812(P) + 2.4794(P)^2 - 6.3843(P)^3 + 4.9861(P)^4 \qquad (3)$$

where

S_p = swell under the applied load P_s,
S_0 = swell under no load,
P = percentage of swell pressure removed,
P = 1 - (P_s/P_0),
P_s = applied load, and
P_0 = load required for zero swell (swell pressure).

This fourth-degree polynomial regression equation was found to fit (R = 0.97) data from several sources where swell under varying loads was reported (23,30-33). It is a purely empirical equation, but

Table 2. Composition of mineralogical regions.

	Percentage of Clay Fraction			
Region	Smectite	Illite	Kaolinite	Vermiculite
1	>50	N	N	N
2	>50	Tr-25	Tr-25	N
3a	25-50	10-25	5-10	N
3b	5-50	5-25	Tr-25	N
4a	Tr-10	5-25	5-50	N
4b	<5	10-25	5-50	N
5a	N	Tr-25	5-50	Tr-25
5b	N	N	10-25	<5

Note: N = none; Tr = trace <5 percent.

Figure 4. Chart for prediction of γ_h.

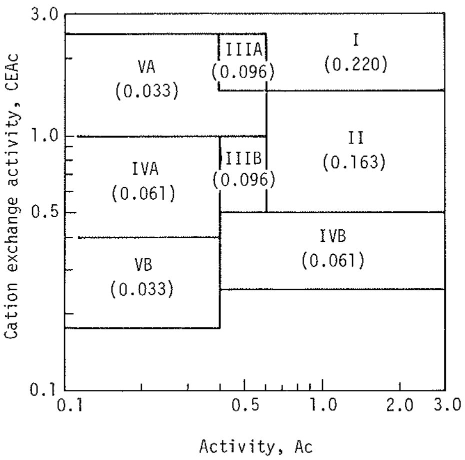


Figure 5. Suction data from field experiment.

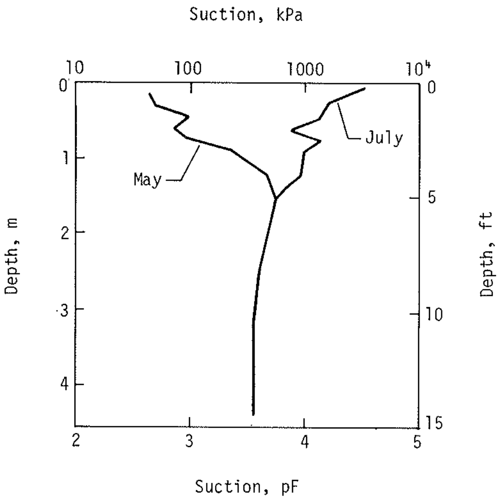


Table 3. Heave calculation.

Layer	Overburden (kPa)	γ_{hp}	Δh (pF)	ΔV (m^3)
1	5.8	-0.0778	1.35	-0.053
2	17.2	-0.0702	0.93	-0.034
3	23.0	-0.0563	0.3	-0.017
Total				-0.104

it is in agreement with substantial amounts of data in the literature (19). In order to use this method, the swell under no load and the swell pressure of the soil must be known. An approximation to the swell pressure may be obtained from data reported from potential-volume-change tests by the Federal Housing Administration (34). The prediction is made as follows:

$$P_0 = -13.8 + 6.46(PI) \tag{4}$$

where P_0 = swell pressure (kPa).

HEAVE PREDICTIONS

The use of the techniques described above is illustrated here by using data from heave observations on an uncovered soil profile. Suction data are shown in Figure 5. Soil data are as follows: PI = 51 percent, CEC = 32 meq/100 g, clay content = 53 percent, γ = 1922 kg/m³ (120 lb/ft³), Ac = 0.962, and CEA_c = 0.604.

The SCI can be measured or determined directly from these data and the chart in Figure 4. From the chart we obtain γ_h = -0.163, and correcting for clay content we have -0.0864. For present purposes, the soil is divided into layers 0.5 m (1.65 ft) thick. The heave-calculation data are given in Table 3. Swell pressure can be measured or estimated as follows:

$$P_0 = -13.8 + 6.5(PI) = 315 \text{ kPa} \tag{5}$$

Now the γ_h = -0.0864 can be reduced for the appropriate loads. Rewriting Equation 3,

$$\gamma_{h_p}/\gamma_h = S_p/S_0 \tag{6}$$

where γ_{hp} is the value of SCI corrected for the overburden load present. Additional loads resulting from construction can also be accounted for in this manner. As Table 3 indicates, calculations are made for each layer and the result is expressed as a total volume change in the profile. Measured heave (-0.073 m) indicates that about 80 percent of the predicted volume change occurred in the vertical direction. The ratio of vertical elevation change in the profile to the total volume change is called the lateral restraint factor (f). In the present example, f = (0.073/0.104) = 0.70. At this time, there are no guidelines by which to evaluate the lateral restraint factor; it must be evaluated through experience. Its value varies between 1.0 and 0.33 theoretically. Therefore, this evaluation is an important part of expansive-soil mechanics.

SUMMARY AND CONCLUSIONS

The evolution of expansive-soil mechanics has reached the point of providing some analytic tools for assessing soil behavior. The description of these methods given in this paper is intended to explain them in the context of routine use. In doing so, simplification is required. Nevertheless, the methods presented are quite reliable when sufficient sampling is conducted.

Further development of our understanding of the equilibrium conditions beneath structures and lateral restraint in soil profiles is sorely needed. These aspects of in situ soil behavior are important and must be carefully evaluated in all analysis problems. At this time, only experienced engineers have the insights required to assess these characteristics. In this research, no further comparison of measured and predicted results was made because of lack of information concerning actual lateral restraint.

ACKNOWLEDGMENT

Much of this paper has resulted from work funded by the Federal Aviation Administration and conducted by the Engineering Research Institute, University of New Mexico.

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Publication of this paper sponsored by Committee on Environmental Factors Except Frost.

Pavement Roughness on Expansive Clays

M.O. VELASCO AND R.L. LYTTON

The roughness patterns of pavements on expansive-clay subgrades were measured by using the General Motors profilometer on 20 sections of pavement in Texas. The roughness patterns are analyzed by means of two methods: the Fast Fourier Transform and a technique that reproduces a rod-and-level survey. The analysis shows that the roughness of expansive clays can be viewed as a spectrum of sine wave amplitudes that vary directly with their corresponding