Soil Mechanics Principles for Highway Engineering in Arid Regions

D. G. FREDLUND AND H. RAHARDJO

Highway construction is commonly required in arid regions. Soils in these regions are generally unsaturated and are characterized by highly negative pore-water pressures. An extension of saturated soil mechanics principles is required to fully understand their behavior and to perform the necessary analyses for engineering purposes. In recent years there has been a rapid increase in understanding of the behavior of unsaturated soils. Conventional equations for shear strength, volume change, and seepage have been extended to embrace unsaturated soils. Presented in this paper is a summary of unsaturated soil principles and theories particularly relevant to highway design in arid regions. The application of these theories to highway engineering is outlined. In addition, several techniques commonly used to measure soil suction or negative pore-water pressure are discussed. The measurement of soil suction is central to applying unsaturated soil theories.

Significant areas of the earth's surface are classified as arid zones. The annual evaporation from the ground surface in these regions exceeds the annual precipitation. Figure 1 shows the climatic classification of the extremely arid, arid, and semiarid areas of the world. Meigs *(1)* used the Thornthwaite moisture index to map these zones. He excluded the cold deserts. Regions with a Thornthwaite index between –20 and –40 are classified as semiarid areas. A Thornthwaite index less than –40 indicate arid areas. About 33 percent of the earth's surface is considered arid and semiarid *(2)*. The distribution of extremely arid, arid, and semiarid areas in North America is given in Figure 2 *(1)*. These cover much of the area bounded by the Gulf of Mexico in the south to Canada in the north, and over to the west coast.

Arid and semiarid areas usually have a deep groundwater table. Soils located above the water table have negative pore-water pressures. The soils are generally unsaturated because of excessive evaporation and evapotranspiration. Climate changes highly influence the water content of the soil in the proximity of the ground surface. When the soil is wetted, the pore-water pressures increase, tending towards positive values. As a result, changes occur in the volume and shear strength of the soil. Many soils exhibit extreme swelling or expansion when wetted. Other soils show a significant loss of shear strength upon wetting. Changes in the negative pore-water pressures associated with heavy rainfalls are the cause of numerous slope failures. Reductions in the bearing capacity and resilient modulus of soils are also associated with increases in the negative pore-water pressure. These phenomena indicate the important role of negative pore-water pressures in controlling the mechanical behavior of unsaturated soils.

When the degree of saturation of a soil is greater than approximately 85 percent, saturated soil mechanics principles can be applied with reasonable success provided the negative pore-water pressures can be measured. However, when the degree of saturation is less than about 85 percent, it becomes necessary to extend saturated soil mechanics principles to embrace unsaturated soils. Soils used in the construction of highways fall into this latter category, particularly in arid areas. Therefore, it is important that unsaturated soil mechanics be incorporated into engineering associated with highway design.

STRESS STATE VARIABLES

The shear strength and volume change behavior of an unsaturated soil can best be described in terms of two independent stress state variables, namely $(\sigma - u_a)$ and $(u_a - u_w)$ *(3)*. The terms $(\sigma - u_a)$ and $(u_a - u_w)$ are referred to as net normal stress and matric suction, respectively,

where

σ = total normal stress,
u_a = pore-air pressure, and
u_w = pore-water pressure.

A complete description of the stress state can be represented by two independent stress tensors.

$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & (\sigma_y - u_a) & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & (\sigma_z - u_a) \end{bmatrix} \quad (1)$$

and

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \quad (2)$$

where σ_x, σ_y, σ_z equal total normal stress in the *x*-, *y*-, and *z*-directions, respectively; and τ_{xy}, τ_{yx}, τ_{xz}, τ_{zx}, τ_{zy}, τ_{yz} equal shear stresses.

Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0, Canada.

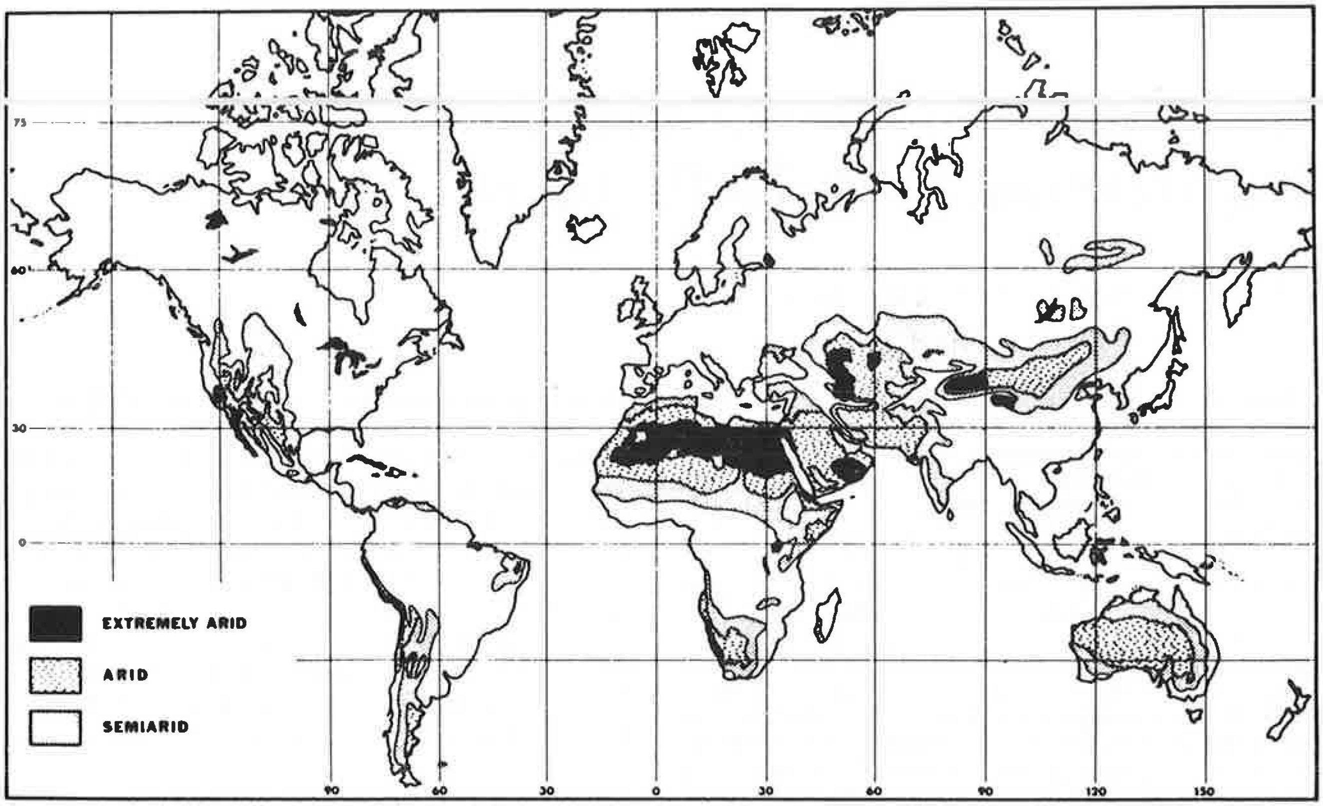

FIGURE 1 Extremely arid, arid, and semiarid areas of the world *(1, 2)*.

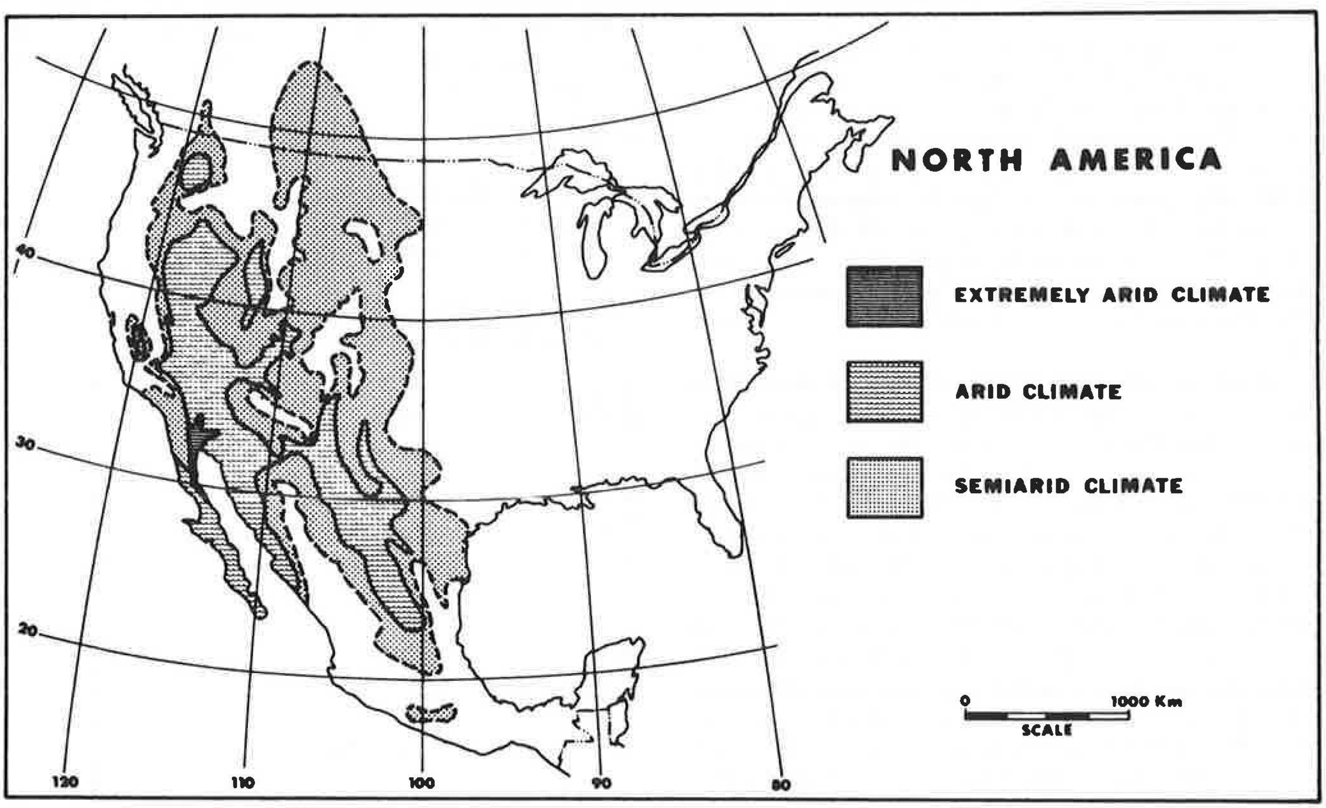

FIGURE 2 Extremely arid, arid, and semiarid areas of North America *(1)*.

The stress state variables can be shown to have smooth transition when going from an unsaturated soil condition to a saturated soil condition. As the degree of saturation approaches 100 percent, the pore-water pressure approaches the pore-air pressure. The matric suction term goes to zero. The net normal stress reverts to $(\sigma - u_w)$. The term, $(\sigma - u_w)$, is commonly referred to as effective stress in saturated soil mechanics.

The matric suction of a soil is a function of its water content. The relationship is referred to as the soil-water characteristic curve. The water content in the soil is predominantly influenced by the climatic environment. Therefore, the average matric suction in a region can be roughly correlated to the Thornthwaite moisture index. Both values become a reflection of the environment. In extremely arid, arid, and semiarid regions, the relative humidity in the soil pores can drop to as low as 30 to 40 percent (Blight, unpublished). This range of aridity corresponds to soil matric suctions as high as 165 MPa. In this environment, the role of the matric suction generally becomes more important than the role of the net normal stress for many practical problems.

MEASUREMENT OF SOIL SUCTION

From a thermodynamic standpoint, the total suction of a soil consists of two components, namely matric suction and osmotic suction.

$$\psi = (u_a - u_w) + \pi \tag{3}$$

where ψ equals total suction and π equals osmotic suction.

Several devices commonly used for measuring soil suction and their range of measurement are listed in Table 1. Tensiometers directly measure the negative pore-water pressures. They consist of a porous ceramic, high air entry cup connected to a pressure measuring device. The entire device is filled with deaired water. The water in the tensiometer comes to equilibrium with the pore water in the soil during a measurement. In the field, the pore-air pressure is usually atmospheric (i.e., u_a is equal to 0). In this case, the matric suction is numerically equal to the absolute negative pore-water pressure. Therefore, the tensiometer reading is equivalent to the matric suction.

Tensiometers are limited to measuring pore-water pressures greater than approximately –90 kPa and <0 kPa. Highly negative water pressures cause cavitation of the pore fluid in the measuring system. The Quickdraw tensiometer from Soilmoisture Corporation has proven to be a useful tensiometer to rapidly measure negative pore-water pressures. The water in the tensiometer is subjected to tension for only a short period of time. As a result, the tensiometer can repeatedly measure pore-water pressures approaching one atmosphere in tension when it is properly serviced. In the laboratory, an axis translation technique can be used to impose matric suctions higher than one atmosphere (i.e., 101 kPa). The pore-air pressure becomes greater than atmospheric conditions when using this technique. The tensiometer reading can be added to the pore-air pressure reading to give the matric suction value. The matric suction value must not exceed the air entry value of the ceramic cup.

The thermal conductivity sensor for measuring matric suction consists of a porous ceramic block containing temperature-sensing elements and a miniature heater. Heat is generated at one point in the porous block and the temperature rise at a second point is measured after a period of time. The temperature rise is inversely proportional to the water content in the porous block. The water content of the porous block can be correlated with matric suction using a pressure plate technique. An indirect measurement of the matric suction in a soil is obtained when the sensor is allowed to come to equilibrium with the pore water in a soil. The MCS 6000 sensor from Moisture Control Systems, Inc., is of the thermal conductivity type and has been used in the laboratory (Figure 3) and in the field (Figure 4). The sensors appear to be quite suitable for field

TABLE 1 DEVICES FOR MEASURING SUCTION

Name of device	Suction component measured	Range (kPa)	Comments
Tensiometers	Negative pore-water pressures or matric suction when pore-air pressure is atmospheric	0 to ~ 90	Difficulties with cavitation and air diffusion through ceramic cup
Thermal conductivity sensors	Matric	0 to ~ 400+	Indirect measurement on a porous ceramic sensor
Psychrometers	Total	100* to ~ 8,000	Constant temperature environment required
Filter paper	Total	(Entire range)	May measure matric suction when in contact with moist soil
Pore fluid squeezer	Osmotic	(No limit)	Used in conjunction with a psychrometer or electrical conductivity measurement

*Controlled temperature environment to $\pm$ 0.001°C

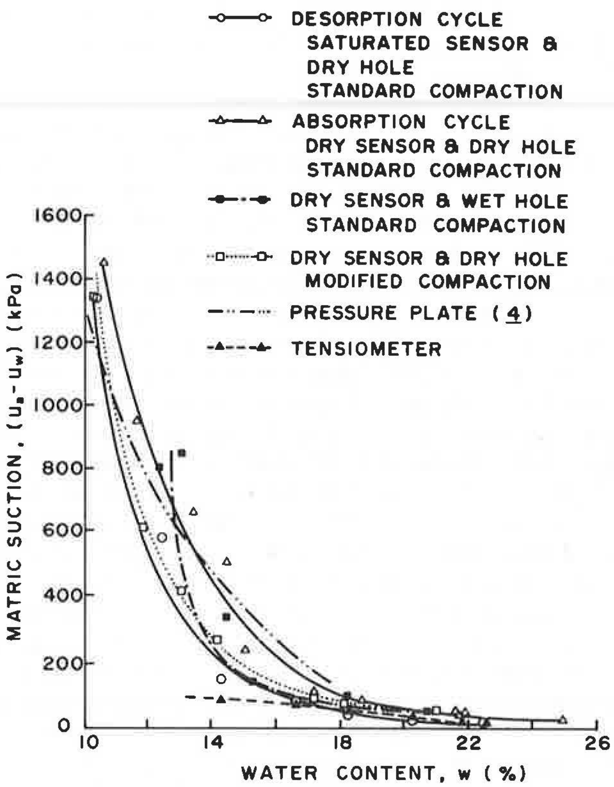

FIGURE 3 Laboratory measurements of matric suction on glacial till using thermal conductivity sensors (5).

use, being insensitive to temperature and salinity changes. Relatively accurate measurements of matric suctions below 300 kPa have been obtained *(4, 5)*. Poor contact between the porous block and the soil can cause the sensor to tend to measure total suction rather than matric suction *(6)*.

A psychrometer consists of a miniature chamber, covered with a fine screen or ceramic cup, containing a thermocouple. The psychrometer measures the relative humidity of the air. The relative humidity is inversely proportional to the total suction. Total suction can be computed when the air in the psychrometer is in equilibrium with the pore air of the soil. However, it is difficult to measure relative humidities approaching 100 percent. These humidities correspond to total suctions approaching zero. A controlled temperature environment of ±0.001°C is required to measure total suctions down to an accuracy of 10 kPa *(7)*. The lower limit of measurement for psychrometers is approximately 100 kPa under a controlled temperature environment. Psychrometers can be used for the in situ measurement of total suctions provided the magnitudes are greater than 300 kPa and the temperature fluctuations are small. Psychrometers are of most value for measuring high suctions in arid areas. Corrosion of the thermocouple wires may create a problem in measuring suction *(6)*.

The filter paper method can be used to estimate the total or matric suction of a soil *(8, 9)*. The filter paper is calibrated by establishing its water-characteristic curve. The water-characteristic curve relates the water content of the filter paper to its suction. When the water vapor in the filter paper is in equilibrium with the water vapor in a soil, the water content of the filter paper can be used to compute the total suction of the soil. On the other hand, the matric suction of the soil is measured when the filter paper is in contact and in equilibrium with the pore water in the soil *(9)*.

The osmotic suction of a soil can be determined from the electrical conductivity of the soil pore fluid. The pore fluid in the soil at a specific water content can be extracted using a pore-fluid squeezer or a pressure-plate apparatus.

CLASSIC PRINCIPLES AND EQUATIONS

Classic equations for describing the mechanical behavior of unsaturated soils can be presented as an extension of the equations commonly applied to saturated soils *(10)*. The extension

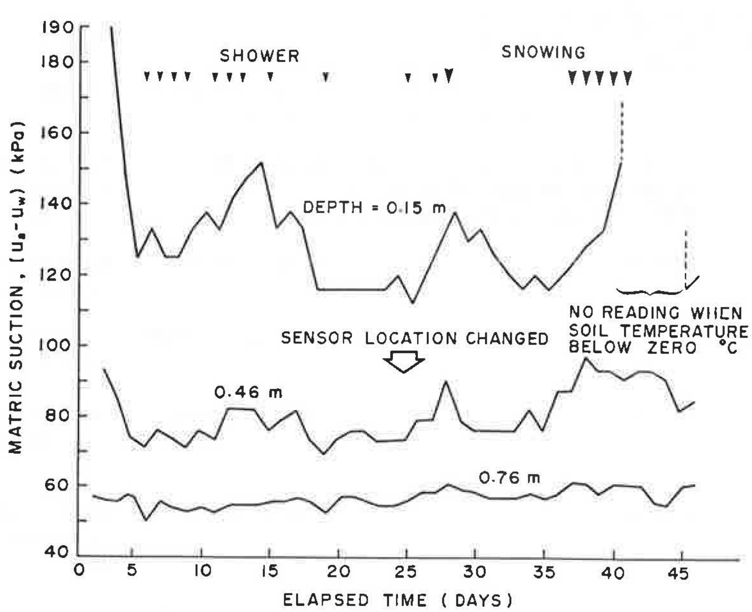

FIGURE 4 Field measurements of matric suction on glacial till using thermal conductivity sensors (from Lee, unpublished).

must be consistent with the number of stress state variables required for an unsaturated soil. Table 2 summarizes and compares some of the saturated and unsaturated soil mechanics equations. The variables used in these equations are described in the glossary. These equations are discussed in the next sections. When a soil approaches saturation, the unsaturated soil equations undergo a smooth transition to the saturated soil equations.

RESILIENT MODULUS

Fatigue prediction associated with pavement design requires the resilient modulus of the subgrade soil. The resilient modulus (i.e., analogous to an elastic modulus) can be obtained from a triaxial, repeated loading test on a soil specimen. Resilient modulus is computed as the ratio of the repeatedly applied deviator stress, $(\sigma_1 - \sigma_3)$, to the resilient (or elastic) strain in the major principal stress, σ_1, direction. The resilient modulus in a subgrade may vary in accordance with seasonal variations of matric suction in the subgrade soil. Pavement loading conditions also affect the subgrade resilient modulus. There have been numerous attempts to relate resilient modulus change to seasonal changes in the stress state *(11, 12)*. The stress state is related to the microclimatic environment.

The resilient modulus of an unsaturated soil can be a function of three stress variables, as shown in Equation 5 in Table 2. However, the net confining stress, $(\sigma_3 - u_a)$, is of relatively minor importance in comparison with the other two stress variables *(13)*. The influence of matric suction and deviator stress on the subgrade resilient modulus is illustrated in Figure 5. The resilient modulus increases as the matric suction increases or as the deviator stress decreases.

SHEAR STRENGTH

The Mohr-Coulomb failure criterion for a saturated soil is given by Equation 6. An extended form of the shear strength equation has been proposed for unsaturated soils [Equation 7 *(14)*]. The extended Mohr-Coulomb failure criterion can be represented as a three-dimensional surface, as shown in Figure 6. The failure surface is plotted using $(\sigma - u_a)$ and $(u_a - u_w)$ as abscissas. The intersection line between the failure surface and the front plane [i.e., τ versus $(\sigma - u_a)$ plane] represents the Mohr-Coulomb failure envelope for saturated conditions. On this plane the pore-air pressure is equal to the pore-water pressure or the matric suction is equal to 0. The failure envelope for a saturated soil has a slope and an intercept of ϕ' and c', respectively. The shear strength of the soil increases as the soil becomes unsaturated. The increase in the shear strength can be considered as an increase in the cohesion intercept because of an increase in matric suction (Equation 8). The increase in the cohesion intercept with respect to matric suction is defined by the intersection between the failure surface and the [τ versus $(u_a - u_w)$] plane. This line has a slope of ϕ^b, which can be

TABLE 2 SUMMARY OF CLASSIC SATURATED AND UNSATURATED SOIL MECHANICS PRINCIPLES AND EQUATIONS

Principle or equation	Saturated soil		Unsaturated soil	
Stress state variables	$(\sigma - u_w)$		$(\sigma - u_a)$ and $(u_a - u_w)$	
Resilient modulus	$E_r = f[(\sigma_3 - u_w), (\sigma_1 - \sigma_3)]$	(4)	$E_r = f[(\sigma_3 - u_a), (u_a - u_w), (\sigma_1 - \sigma_3)]$	(5)
Shear strength	$\tau = c' + (\sigma - u_w) \tan \phi'$	(6)	$\tau = c' + (u_a - u_w) \tan \phi^b + (\sigma - u_a) \tan \phi'$	(7)
			$c = c' + (u_a - u_w) \tan \phi^b$	(8)
Ultimate bearing capacity of clay	$q_{ult} = c\, N_c$	(9)	$q_{ult} = c\, N_c$	(10)
Constitutive equations for K_o loadings	Soil structure and water phase		Soil structure:	
	$de = G_s\, dw = a_v\, d(\sigma_y - u_w)$	(11)	$de = a_t\, d(\sigma_y - u_a) + a_m\, d(u_a - u_w)$	(12)
			Water phase:	
			$dw = b_t\, d(\sigma_y - u_a) + b_m\, d(u_a - u_w)$	(13)
Flow law for water (Darcy's law)	$v_w = - k_s\, \partial h_w / \partial y$	(14)	$v_w = - k_w(u_a - u_w)\, \partial h_w / \partial y$	(16)
	$h_w = y + u_w / \rho_w g$	(15)	$h_w = y + u_w / \rho_w g$	(17)
Steady state seepage	One-dimensional:		One-dimensional:	
	$d^2 h_w / dy^2 = 0$	(18)	$k_w\, d^2 h_w / dy^2 + (dk_w/dy)\, dh_w/dy = 0$	(20)
	Two-dimensional:		Two-dimensional:	
	$\partial^2 h_w / \partial x^2 + \partial^2 h_w / \partial y^2 = 0$	(19)	$k_w\, \partial^2 h_w / \partial x^2 + (\partial k_w / \partial x) \partial h_w / \partial x +$	
			$k_w\, \partial^2 h_w / \partial y^2 + (\partial k_w / \partial y)\, \partial h_w / \partial y = 0$	(21)

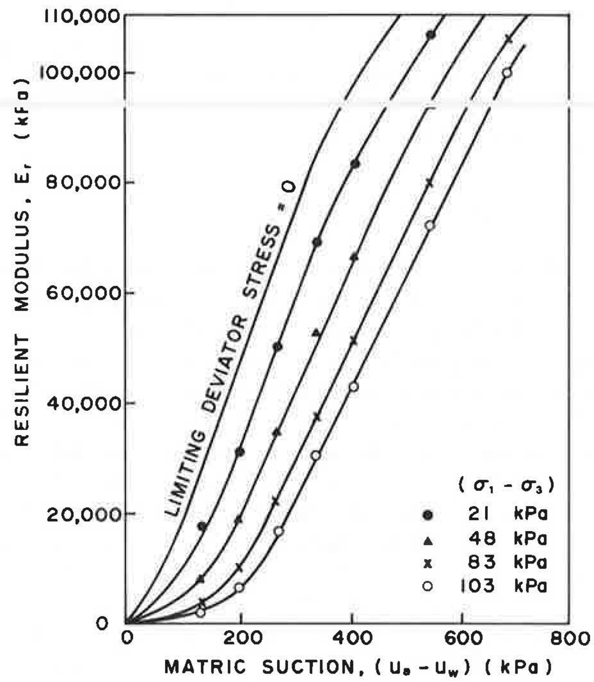

FIGURE 5 Influence of matric suction and deviator stress on the resilient modulus *(13)*.

measured experimentally (Figure 7). The value for ϕ^b is generally less than ϕ'.

Stability analyses for a saturated-unsaturated soil embankment can be performed using Equation 7 to define the shear strength of the soil. The factor of safety equations will be applicable to both the saturated and unsaturated zones. For the unsaturated zone, the cohesion is a function of matric suction (Equation 8). For the saturated zone, the matric suction goes to zero and the cohesion reduces to the effective cohesion intercept. Illustrated in Figure 8 is the effect of matric suction on increasing the stability of a simple slope. The increase in factor of safety due to soil suction has been demonstrated for unsaturated soil slopes in Hong Kong *(15)* and other regions *(16)*.

The ultimate bearing capacity of an unsaturated clay subgrade can be computed from Equation 10. The value of cohesion may be obtained from an unconfined compression test. The measured cohesion is a function of matric suction at failure (Equation 8). Excessive water infiltration into the subgrade soil can reduce the matric suction. This results in a reduction in shear strength that may, in turn, produce a subgrade failure. An understanding of unsaturated soil behavior is important in relation to the application of bearing capacity formulations in highway engineering.

VOLUME CHANGE

A change in the stress state of a soil produces a volume change. In a saturated soil, an effective stress increase results in settlement. In an unsaturated soil, a change in either the net normal stress or the matric suction can cause a volume change. However, heaves or settlements in unsaturated soils are most commonly caused by changes in matric suction. A net normal stress change of 10 to 1000 kPa commonly results from the construction of light-to-heavy structures. On the other hand, a desiccated soil in arid regions can undergo a change in matric suction ranging from 165 MPa to a practically zero suction. The matric suction changes are closely related to microclimatic changes.

Volume change in a saturated soil can be described using Equation 11. The equation relates void ratio and effective normal stress. In an unsaturated soil, two-volume change or constitutive relations are required. The constitutive equations for an unsaturated soil during K_0 loading can be represented by Equations 12 and 13, respectively. Volume changes associated with the soil structure and the water phase are represented by changes in the void ratio and water content, respectively. These constitutive equations can be plotted as three-dimensional surfaces (Figure 9). Similar to saturated soils, volume changes in an unsaturated soil can be predicted from the void ratio constitutive surface. Water content change may be of interest for some problems. The water content constitutive surface helps

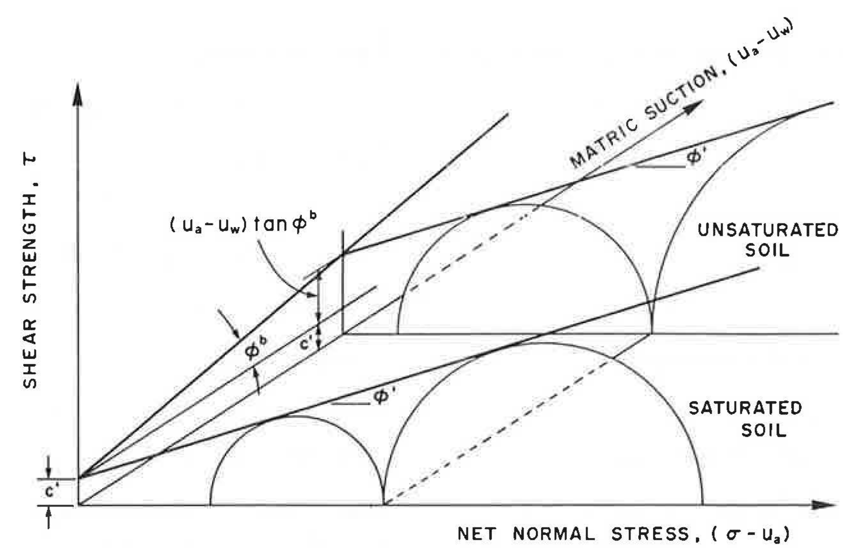

FIGURE 6 Three-dimensional failure surface for unsaturated soils.

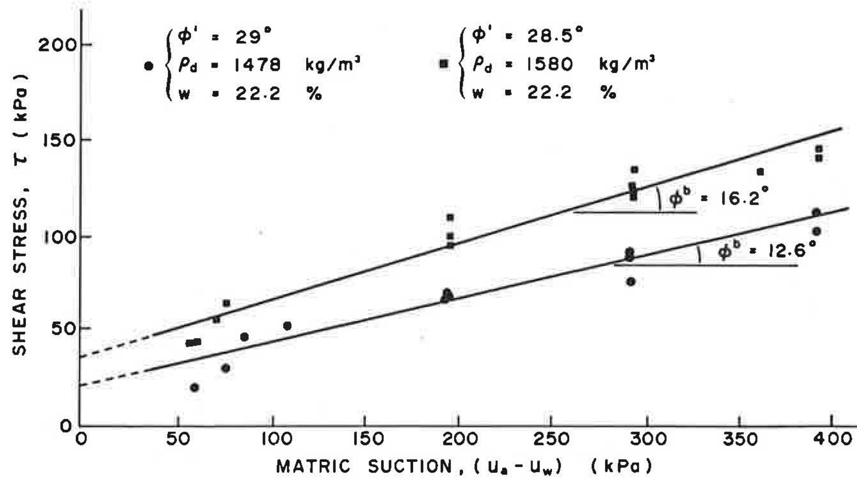

FIGURE 7 Experimental values of ϕ^b obtained from consolidated drained triaxial tests on Dhanauri clay (from Satija, unpublished).

understand the relationship among all the moduli for an unsaturated soil (i.e., a_t, a_m, b_t, and b_m).

Curve *A* in Figure 9 is essentially the one-dimensional consolidation curve for the soil in a saturated condition (Figure 10). The curve exhibits a linear relationship between void ratio and the logarithm of effective vertical stress, over a wide loading range. The coefficient of compressibility, a_t, is equal to a_v when the soil is saturated. The coefficient of water content change, b_t, can be computed as a_t multiplied by the specific gravity of the soil, G_s.

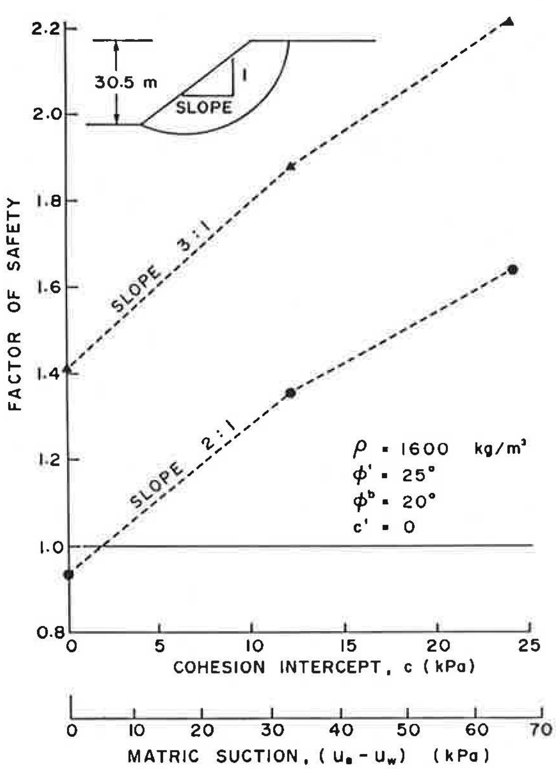

FIGURE 8 Increase in factor of safety due to an increase in matric suction *(18)*.

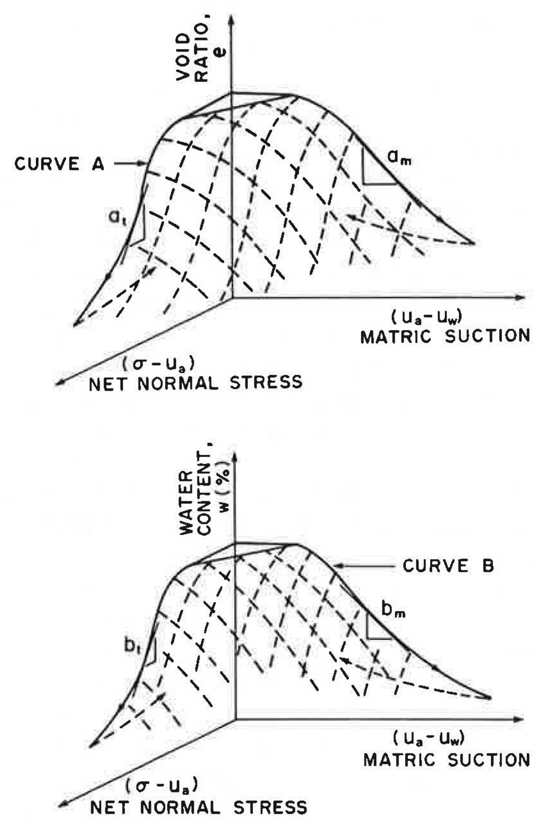

FIGURE 9 Three-dimensional void ratio and water content constitutive surfaces for an unsaturated soil.

Curve *B* in Figure 9 is a soil-water characteristic curve that can be obtained from a pressure plate test (Figure 11). The coefficient of water content change, b_m, can be computed from the soil-water characteristic curve. The shrinkage relationship for the soil relates the void ratio to the water content at various matric suctions (Figure 12). The slope of the shrinkage curve defines the ratio between the a_m and b_m coefficients of compressibility.

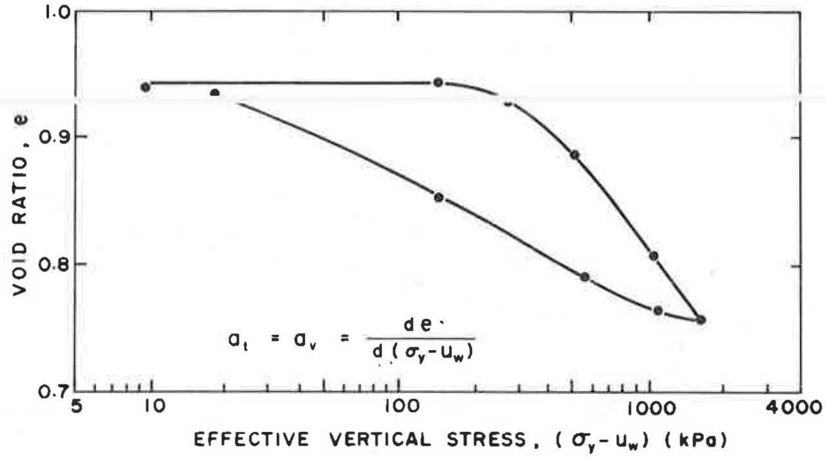

FIGURE 10 One-dimensional consolidation data for compacted Regina clay (from Gilchrist, unpublished).

The prediction of settlement or heave in a soil requires a knowledge of (a) the initial in situ state of stress, (b) the compression modulus or compressive index, C_c, or the swelling modulus or swelling index, C_s, and (c) the final state of stress. In a saturated soil, settlement is predicted using data from a one-dimensional consolidation test. The preconsolidation pressure and the compression index make up the essential data. The effective stress change between the initial and final conditions together with the compression index are used to predict the amount of settlement. The prediction of heave is an important application of the volume change theory in unsaturated soils. Heave is most commonly predicted based on a one-dimensional consolidation test. Either the constant volume or the free swell testing method can be used in order to obtain the swelling pressure and the swelling index of the soil. The stress state variable change between the initial and the final conditions together with the swelling index are used to predict the amount of heave.

Only the constant volume testing method will be discussed in this paper. In the constant volume consolidation test, the soil specimen is subjected to a token load and submerged in water. The specimen tends to swell because the negative pore-water pressure is released to atmospheric conditions. However, the specimen is maintained at a constant volume by increasing the applied load. The procedure is continued until the specimen exhibits no further tendency to swell. The applied load at this point is referred to as the uncorrected swelling pressure, P_s. Shown in Figure 13 is an average consolidation curve obtained from 34 constant volume consolidation tests performed on Regina clay. The deposit is proglacial lacustrine clay located in a semiarid region. The average uncorrected swelling pressure, P_s, for Regina clay was found to be 73.7 kPa.

The swelling pressure, P_s, must be corrected for sampling disturbance *(17)*. Sampling disturbance results in a reduction in the swelling pressure, P_s. A technique for correcting the swelling pressure is illustrated in Figure 13. This technique is a modified form of Casagrande's construction to estimate the preconsolidation pressure of a soil. The corrected swelling

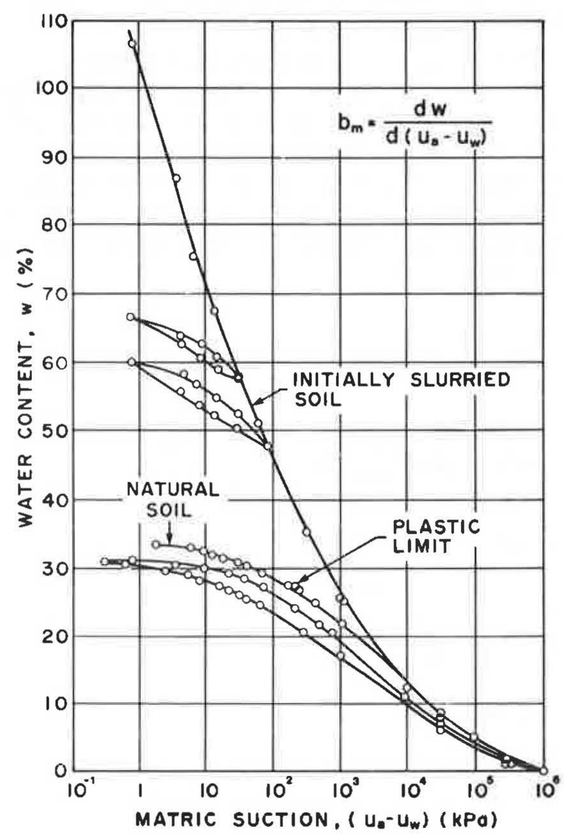

FIGURE 11 Soil-water characteristic curve for a heavy clay soil *(19)*.

pressure, P_s', for Regina clay is 134 kPa. The corrected swelling pressure represents the initial stress state of the soil. Swelling occurs from the corrected swelling pressure to the final stress state along the rebound curve (i.e., C_s). The final stress state can be estimated based on local experience. The swelling index for Regina clay is on the order of 0.065. Heave predictions using the corrected swelling pressure can be as much as

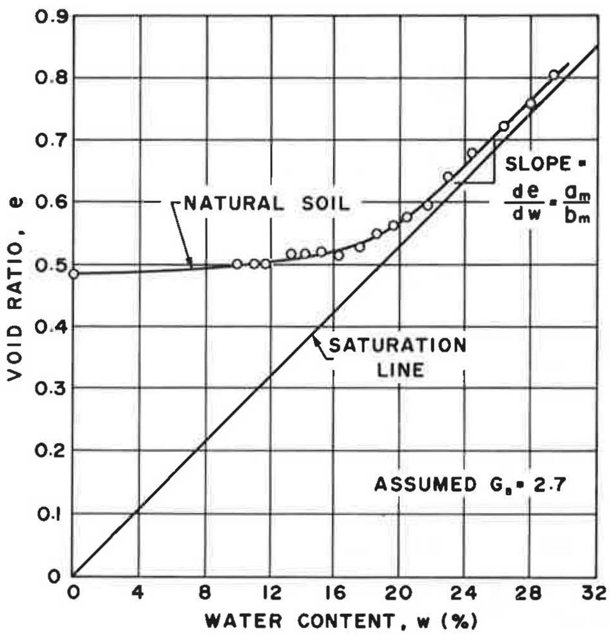

FIGURE 12 Shrinkage relationship for a heavy clay *(19)*.

two times the predictions using the uncorrected swelling pressure.

SEEPAGE AND MOISTURE MOVEMENT

Moisture movement in unsaturated soils results in numerous engineering problems. In an unsaturated soil, changes in microclimatic conditions cause the soil water to flow. Precipitation and evaporation generate moisture flows in and out of the soil. The rate of infiltration or evaporation can be used as a flux boundary condition in analyzing the flow of water in unsaturated soils. Temperature gradients also produce moisture and water vapor movements. However, thermally induced flows are not considered in this paper.

Water content and matric suction are directly affected by moisture movement. The pore-water pressure head (i.e., $u_w/\rho_w g$) distribution may vary from a static equilibrium condition to a steady state flow condition, as depicted in Figure 14. These variations also reflect variations of matric suction, as the pore-air pressure remains at atmospheric in the field. Changes in matric suction produce changes in the volume and shear strength of the soil.

Water flow in an unsaturated soil can be described using Darcy's law (Equation 16). The coefficient of permeability in an unsaturated soil is a function of the water content or matric suction of the soil. Hydraulic head gradients produce the driving potential for the flow of water in an unsaturated soil. The hydraulic head is the sum of the gravitational head (i.e., elevation) and the pore-water pressure head (Equation 17). In this case, the pore-water pressure head is negative. The use of the hydraulic head applies equally to both saturated and unsaturated soils. The water content should not be used as the driving potential for water flow.

The equations for the steady state seepage in one and two dimensions are presented as Equations 20 and 21, respectively. The equations describe the hydraulic head distribution in a soil during steady state water flow. The pore-water pressure head distribution (Figure 14) can be obtained by subtracting the elevation from the hydraulic head. The steady state equation for an unsaturated soil contains more terms than the equation for a saturated soil. The extra terms account for the variation in permeability with matric suctions at different locations in the soil.

PROSPECTS FOR THE FUTURE

A practical science for understanding the behavior of unsaturated soils is rapidly developing. The principles of unsaturated soil mechanics can be visualized as an extension of saturated soil mechanics. The understanding of unsaturated soil behavior

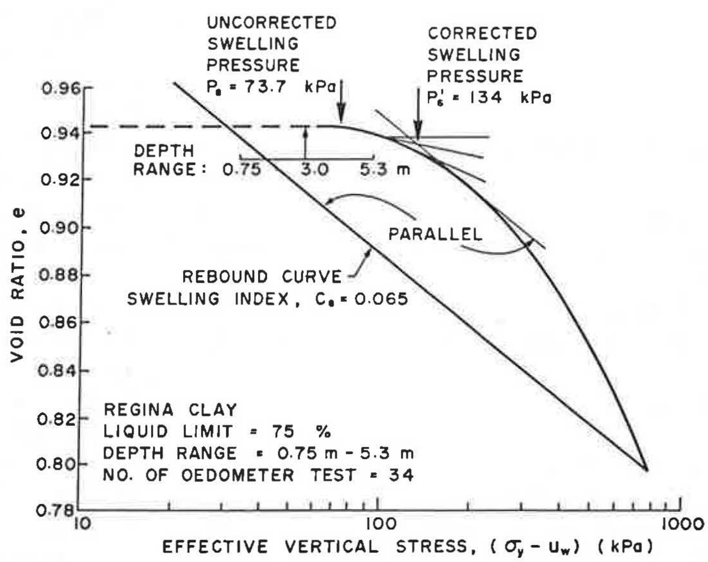

FIGURE 13 Average data from consolidation tests on Regina clay illustrating the swelling pressure correction *(20)*.

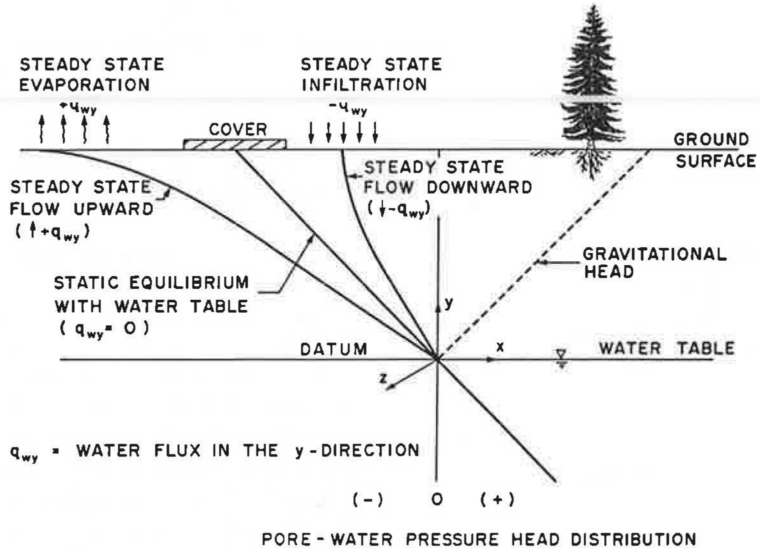

FIGURE 14 Pore-water pressure head distribution in the unsaturated zone during static equilibrium and steady state flow conditions.

is important to many problems relevant to highway engineering in arid and semiarid areas. Problems associated with volume change and shear strength can be analyzed and resolved with a consistent theoretical context. This eliminates the need for many empirical approximations that often depend on local practices.

Devices for measuring negative pore-water pressures or suctions have been developed and studies are required to ascertain their reliability and accuracy. Devices that measure total, matric, or osmotic suction are required. The measured quantities must be used in an appropriate manner in analyses.

Volume change and shear strength problems should be studied for changes that are taking place in the stress state variables. The end result will be the emergence of a technology that is more transferable from one region to another and from one climate to another.

GLOSSARY

Symbols and Variables Used in the Equations

E_r = Resilient modulus;
$(\sigma_3 - u_w)$ = Effective confining stress;
$(\sigma_1 - \sigma_3)$ = Deviator stress;
σ_1 = Major principal stress;
σ_3 = Minor principal stress (or total confining stress);
$(\sigma_3 - u_a)$ = Net confining stress;
τ = Shear stress;
c' = Effective cohesion intercept;
ϕ' = Effective angle of internal friction;
ϕ^b = Angle of shear strength increase with an increase in matric suction;
c = Cohesion intercept;
q_{ult} = Ultimate bearing capacity;
N_c = Bearing capacity factor for clay soils;
de = Change in void ratio;
e = Void ratio;
dw = Change in water content;
w = Water content;
a_v = Coefficient of compressibility;
$d(\sigma_y - u_w)$ = Change in effective vertical stress;
σ_y = Total vertical stress;
a_t = Coefficient of compressibility with respect to a change in $(\sigma_y - u_a)$;
$d(\sigma_y - u_a)$ = Change in net vertical normal stress;
a_m = Coefficient of compressibility with respect to a change in $(u_a - u_w)$;
$d(u_a - u_w)$ = Change in matric suction;
b_t = Coefficient of water content change with respect to a change in $(\sigma_y - u_a)$;
b_m = Coefficient of water content change with respect to a change in $(u_a - u_w)$;
v_w = Flow rate of water;
k_s = Water saturated coefficient of permeability;
$\partial h_w/\partial y$ = Hydraulic head gradient in the y-direction;
h_w = Hydraulic head;
y = Gravitational (or elevation) head;
$u_w/\rho_w g$ = Pore-water pressure head;
ρ_w = Water density;
g = Gravitational acceleration;
$k_w(u_a - u_w)$ = Unsaturated coefficient of permeability, which is a function of $(u_a - u_w)$;
$\partial k_w/\partial y$ = Change in water coefficient of permeability in the y-direction;
$\partial k_w/\partial x$ = Change in water coefficient of permeability in the x-direction;
$\partial h_w/\partial x$ = Hydraulic head gradient in the x-direction;
ρ = Total density of a soil;
ρ_d = Dry density of a soil; and
G_s = Specific gravity of a soil.

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