Limitations Of The Axis Translation Technique

by

K. A. Bocking
Thurber Consultants Ltd.
Victoria, British Columbia

and

D. G. Fredlund
University of Saskatchewan
Saskatoon, Saskatchewan

Presented at the Fourth International Conference on Expansive Soils,
Denver, Colorado, U.S.A.
June 16-18, 1980

LIMITATIONS OF THE AXIS TRANSLATION TECHNIQUE

K. A. Bocking*
and
D. G. Fredlund**

ABSTRACT

The null type, axis translation technique is commonly used to measure the matrix suction of undisturbed and remolded soil samples. This paper develops the theory associated with the axis translation testing of soils with occluded air bubbles or a continuous air phase. The mathematical model includes the effect of the pore pressure measuring device and the high air entry ceramic disc. A variation of soil properties and measuring device parameters is examined along with the effect of air diffusing through the high air entry disc. The results indicate that the actual soil suction can be over-estimated if the sample contains significant amounts of occluded air. Also, air diffusion through the high air entry disc can cause an under-estimation of the soil suction.

INTRODUCTION

In order to develop a transmissible science for the behavior of unsaturated soils, it is necessary to isolate satisfactory stress variables which can be measured in a reproducible manner. Fredlund and Morgenstern (1976) suggested that the total stress, σ, the pore-air pressure, u_a, and the pore-water pressure, u_w, must be measured or computed in order to perform analyses for unsaturated soils. The stress state of an unsaturated soil can be described using any two of three possible independent stress state variables. These are: $(\sigma - u_w)$, $(\sigma - u_a)$ and $(u_a - u_w)$.

The main restriction to the advancement of a science with a sound theoretical context has been the difficulty associated with the measurement of the necessary stresses both in the laboratory and insitu. Serious difficulty has been encountered in developing suitable insitu systems to measure the pore-water pressure over the wide range of conditions encountered in practice. Generally the pore-water pressure can be several atmospheres negative on the absolute pressure scale. It is not possible to directly measure negative absolute pore-water pressures using pressure gauges or tensiometers because the fluid in the measuring system will cavitate.

* Geotechnical Engineer, Thurber Consultants Ltd., Victoria, British Columbia, Canada, V8V 3M8.
** Professor of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0.

In the laboratory, the pressure plate device has been quite successful in measuring the negative pore-water pressure. Hilf (1956) developed a null type, axis translation technique as a means of avoiding the cavitation problem. This technique has subsequently seen limited application in triaxial shear and volume change testing of unsaturated soils.

This paper presents the results of a theoretical study of the null type, axis translation testing technique. A mathematical model of the system consisting of a pore-pressure measuring device, a high air entry ceramic disc and a sample of unsaturated soil is developed. The effect of changes in various soil and device parameters was examined using the mathematical model. Limitations associated with the axis translation technique are inferred from the results.

REVIEW OF USE OF THE AXIS TRANSLATION TECHNIQUE

The device used (Hilf, 1956) to measure negative pore-water pressures is illustrated in Figure 1. An unsaturated soil specimen was placed in a pressure vessel. A pore-water pressure probe consisting of a needle with a saturated porous ceramic tip was inserted into the soil. The probe was connected by a tube filled with de-aired water to a null type pressure measuring system. Soon after the probe was inserted, the system would begin registering a negative gauge pressure. The movement of the water in the measuring system towards the sample was slowed, and eventually reversed by increasing the air pressure in the vessel. When equilibrium was reached (i.e., there was no further tendency for movement of the null point), the pore-water pressure was subtracted from the air pressure in the vessel. This difference was taken to be equal to the soil suction. According to Hilf (loc. cit.) the procedure simply translated the origin of reference for the pore-water pressure measurement from standard atmospheric conditions to the final air pressure value; hence the term 'axis translation'.

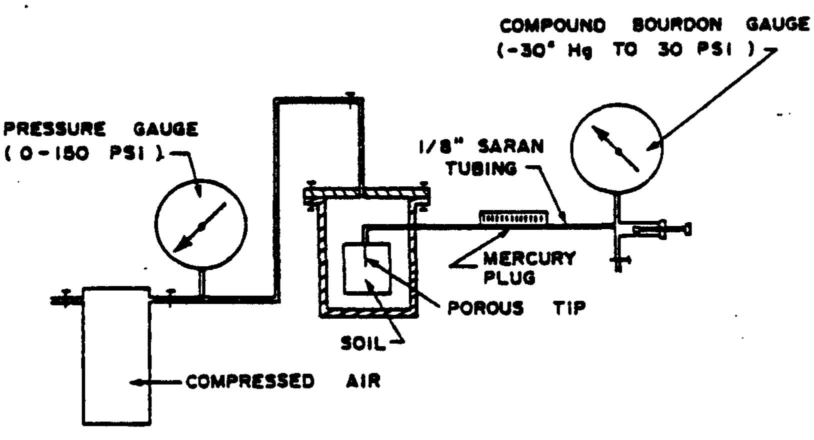

Figure 1 Hilf's Apparatus for the Measurement of Negative Pore-Water Pressure (From Hilf, 1956)

The pressure plate apparatus had previously been used by soil scientists to establish desired suctions in soil samples (Woodruff, 1940; Richards and Fireman, 1943). The equipment was later adapted for the measurement of existing suctions in undisturbed or remolded soil samples by Coffey and Gibbs (1963). A null type pressure plate apparatus developed at the University of Saskatchewan is shown in Figure 2. Triaxial testing equipment has also been adapted to the axis translation technique by Bishop and Donald (1961), Biggs and Coffey (1969) and Fredlund (1973).

THEORY OF THE AXIS TRANSLATION TECHNIQUE

Olson and Langfelder (1965) stated that the axis translation technique could be theoretically justified. They reasoned that an increase in air pressure in a soil sample will tend to isotropically compress both the soil particles and the water. However, since both are essentially incompressible, the air pressure increase cannot significantly change the curvature of air-water menisci. Consequently, the value of $(u_a - u_w)$ cannot change. They concluded that the axis translation "technique is valid provided all gas voids are interconnected". Pore-water containing occluded (i.e., non-interconnected) air bubbles renders the pore fluid highly compressible.

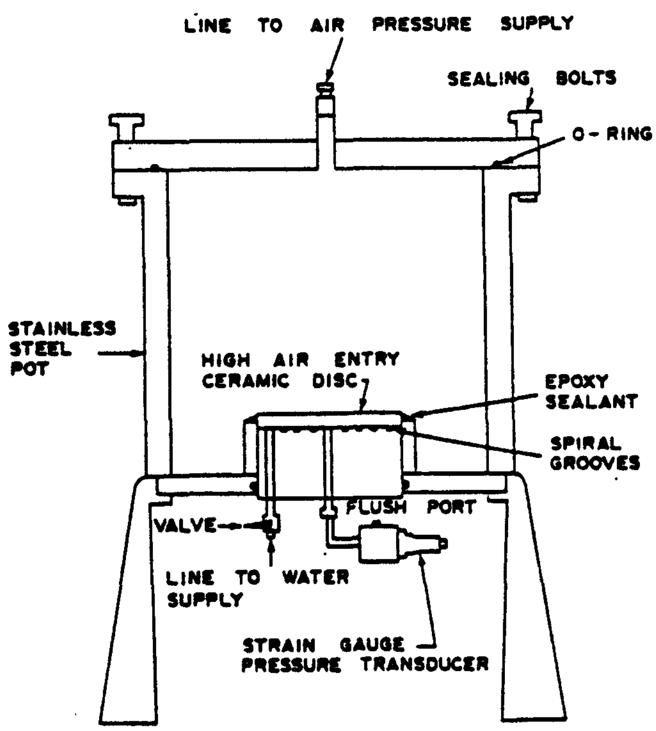

Figure 2 University of Saskatchewan
Pressure Plate Apparatus

For the axis translation technique to be valid it must be possible to increase the ambient air pressure around and within a soil sample without producing deformation. This implies that the value of stress state variables $(\sigma - u_a)$ and $(u_a - u_w)$ must be unchanged. In other words, $\Delta\sigma$, Δu_a and Δu_w must be equal. Clearly all pore-air must be interconnected to the surface of the sample in order for an increase in total stress (i.e., applied by increasing the air pressure around the sample) to induce an equal change in pore-air pressure throughout the sample. The experimental data presented by Hilf (1956) (Figure 3) demonstrates the equal translation of all stress components.

Experimental evidence indicates that air does become occluded in the pore-water of a soil. Numerous researchers (Corey, 1954; Corey, 1957; Ladd, 1960; Olson, 1963; Matyas, 1966; Langfelder, Chen and Justice, 1968; Barden and Pavlakis, 1971) have shown that the air permeability of an unsaturated soil decreases to essentially zero as the degree of saturation is increased to about 85 percent. In the case of remolded soils, this corresponds to approximately optimum water content. There has been debate regarding the pressure in the occluded air (Hilf, 1956; Barden, 1965; Schuurman, 1966; Fredlund, 1976). In this paper the air pressure in the occluded bubbles is assumed to become essentially equal to the pore-water pressure in accordance with experimental data (Bishop and Henkel, 1962). The effects of occluded air on the axis translation technique is examined using a separate formulation of this case.

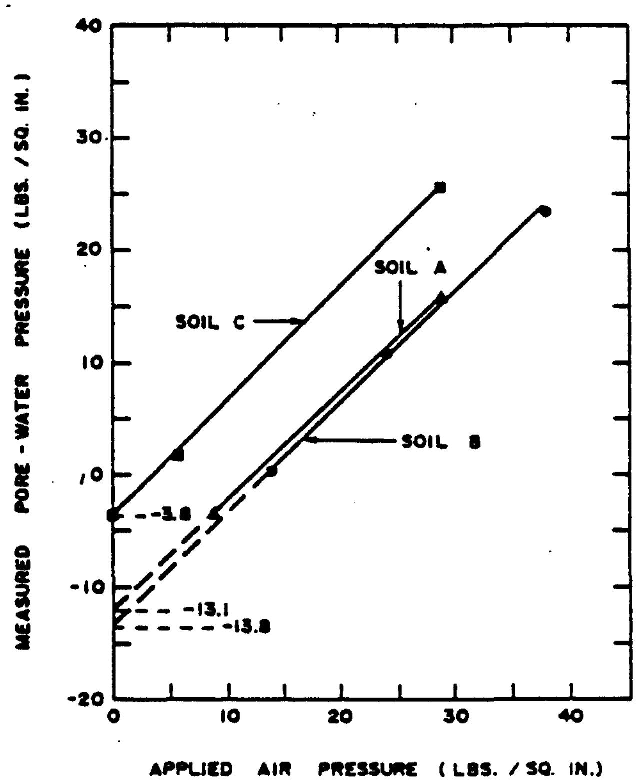

Figure 3 Comparison of Measured and Applied Pressures by Translation of the Origin (From Hilf, 1956)

When using the axis translation technique, the pressure plate apparatus employs a pressure measuring device such as a transducer or a nulling system below the high air entry disc. All such devices require the flow of a small but finite amount of water out of the soil sample in order to register pressure changes. It thereby follows that the soil sample must undergo some volume change during the test. Bishop and Henkel (1962) and Fredlund and Morgenstern (1973) showed that even a slight flexibility in the pressure measuring system can greatly affect the response time.

MATHEMATICAL MODEL AND PARAMETRIC STUDY

A mathematical model was developed to simulate the measurement of negative pore-water pressure in a pressure plate apparatus using the axis translation technique. Simultations were run using various soil and pressure measuring system parameters with the following aims: (i) to study the effect of pressure measuring system flexibility on the results of axis translation tests, (ii) to study the effect of the presence of occluded air bubbles on the measurement of suction, (iii) to gain insight into possible errors in the interpretation of axis translation test results.

Two versions of the mathematical model are developed. In Version I it is assumed that the pore-air is totally interconnected; in Version II it is assumed that the pore-air phase is totally occluded. Barden (1965) implied that such assumptions are appropriate for remolded clay samples compacted dry and wet of optimum water content, respectively. In the region of optimum water content there is a 'transition zone' in which some of pore-air is occluded and some is interconnected. The behavior of a soil in this transition zone should be intermediate between that of soils containing totally interconnected and totally occluded pore-air.

Derivation of the Mathematical Models

Deformation during an axis translation test will result from changes in the stress state variables. In the axis translation test there are two processes which may cause these variables to change: (i) water may flow into or out of the sample across its bottom boundary which is in contact with the high air entry ceramic disc. This in turn, will initiate flow of water throughout the sample, (ii) from time to time the total stress acting on the soil sample must be changed. If the sample contains occluded pore-air, the pore-fluid will compress. Therefore, a portion of the total stress is transferred to the soil structure which will then result in deformation.

Terzaghi (1923) derived a differential equation for the consolidation of saturated soils which can be written in the following form.

$$\frac{\partial u_w}{\partial t} = \frac{k}{\gamma_w m_v} \frac{\partial^2 u_w}{\partial z^2} \qquad (1)$$

where: u_w = the pore-water pressure,
t = time,
z = depth,
k = coefficient of water permability,
γ_w = density of water, and
m_v = the volume change coefficient (equivalent to m_1 used subsequently).

The following assumptions were made in the derivation of equation (1): (i) the soil is completely saturated, (ii) the soil particles are incompressible, (iii) the water is incompressible, (iv) Darcy's flow law is valid, (v) the coefficient of permeability, k, is constant, (vi) m_v is constant, and (vii) deformation is one-dimensional.

To model the axis translation test it is necessary to derive consolidation equations for the two cases of unsaturation previously described. Different assumptions are necessary. Assumption (i) does not apply while assumptions (ii), (iv), (vi) and (vii) must be retained.

Version I of the model assumes that the soil is a four-phase system consisting of soil particles, pore-air, pore-water and the contractile skin. The pore-air phase is compressible; however, because of interconnection it was assumed that the pore-air pressure is always equal to the air outside the sample (i.e., equal to the total pressure in the chamber, applied to the sample).

Version II of the model assumes the soil is a two phase system consisting of soil particles and a homogeneous, compressible pore-fluid made up of water and occluded air bubbles. Fredlund (1976) derived the following equation for the compressibility of water containing occluded air bubbles:

$$\beta_f = S\,\beta_w + B_{aw}\frac{(1-S)}{u_a} + B_{aw}\frac{S\,h}{u_a} \qquad (2)$$

where: β_f = the compressibility of the air/water mixture,
β_w = compressibility of pure water,
S = the degree of saturation,
h = the volumetric coefficient for the solubility of air in water,
u_a = the pore-air pressure, and
B_{aw} = the pore pressure parameter which accounts for a change in pore-air pressure with respect to a change in pore-water pressure.

The first term on the right hand side of the equation accounts for the compressibility of the pure water; the second term for the compressibility of the free air; and the third term for the solution of air in water. The assumption is made that B_{aw} is equal to 1. This means that the change in air pressure in the occluded bubbles is equal to the change in pore-water pressure.

Equation (2) can be rewritten in terms of a specific elemental volume, V, and in terms of the initial pore-air volume, V_{ao}, and the initial pore-air pressure, u_{ao}. The compressibility of water is neglected.

$$\beta_f = \frac{1}{V} \frac{(V_a + V_d)^2}{(V_{ao} + V_d)(u_{ao} + u_{atm})} \tag{3}$$

where: β_f = the compressibility of the pore-flûid in a elemental volume,
V_a = the current volume of free air in the elemental volume,
V_d = the volume of air dissolved in water, and
u_{atm} = standard atmospheric air pressure.

The coefficient of permeability with respect to the water phase, k, is assumed to vary with the degree of saturation according to the relationships developed by Corey (1957) (Figure 4).

$$k = k_s \left[\frac{S - S_r}{1.0 - S_r}\right]^4 \cdot 100 \tag{4}$$

where: k_s = the water permeability of the soil at saturation, and
S_r = the residual degree of saturation (decimal).

The residual degree of saturation is that degree of saturation at which the relative air permeability becomes 100 percent. A typical value of 0.42 was used for the residual degree of saturation. In the

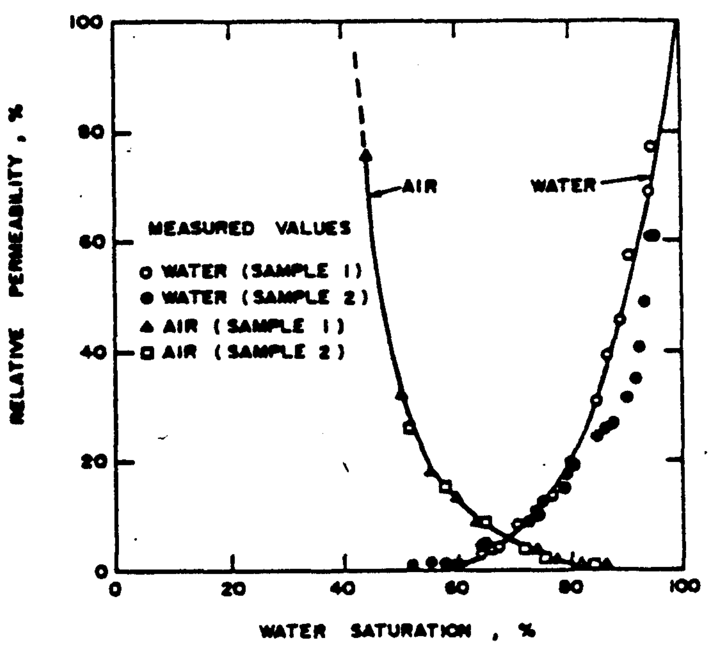

Figure 4 Relative Permeabilities of Air and Water as a Function of Degree of Saturation (From Corey, 1957)

Version II model (i.e., that with totally occluded pore-air) an assumption is necessary for computing the changes in degree of saturation with the flow of the pore-fluid. As suggested by Barden (loc. cit.) it was assumed that all occluded air was fixed to the soil particle matrix and that only pore-water flowed from the soil.

The continuity requirement for an unsaturated soil states that the sum of the volume changes of each component phase must be equal to the volume change of the soil structure (Fredlund, 1973). For Version I model, in which there is complete interconnection of the pore-air phase, the continuity requirement can be written:

$$\frac{\Delta V}{V} = \frac{\Delta V_w}{V} + \frac{\Delta V_a}{V} \qquad (5)$$

where: ΔV_w = volume of water in the elemental volume.

The change in volume of water, ΔV_w, is due to water flowing in or out of the element. The change in volume of air, ΔV_a, is due to both flow and compression of the air phase.

In the pressure plate apparatus air can flow into the soil sample both vertically and radially; consequently such flow cannot be rigorously calculated in a one-dimensional model. A simplifying assumption is made that the air permeability is infinite. Therefore, an increase in the external air pressure will result in a simultaneous equal increase in pore-air pressure throughout the sample. This implies that a change in external air pressure cannot cause any volume change in the sample. Volume change can only occur as a result of the flow of water into or out of the soil.

Two of the components of the continuity requirements (i.e., equation (5)) can be written in terms of the stress state variables (Fredlund and Morgenstern, 1976).

$$\frac{\Delta V}{V} = m_1\ \Delta(\sigma - u_a) + m_2\ \Delta(u_a - u_w) \qquad (6)$$

$$\frac{\Delta V_w}{V} = m_3\ \Delta(\sigma - u_a) + m_4\ \Delta(u_a - u_w) \qquad (7)$$

where: m_1 and m_2 = the constitutive moduli relating volumetric deformation of the soil structure to the $(\sigma - u_a)$ and $(u_a - u_w)$ stress state variables, respectively, and m_3 and m_4 = the constitutive moduli relating the change in the volume of water in the soil element to the $(\sigma - u_a)$ and $(u_a - u_w)$ stress state variables, respectively.

The constitutive surfaces corresponding to equations (6) and (7) are shown in Figure 5. The m_1 and m_3 moduli do not need to be evaluated since the change in the $(\sigma - u_a)$ stress variable can be assumed to be zero during the axis translation suction test. For this study, the m_2 and m_4 moduli were estimated from typical m_1 and m_3 values (Ladd, 1960;

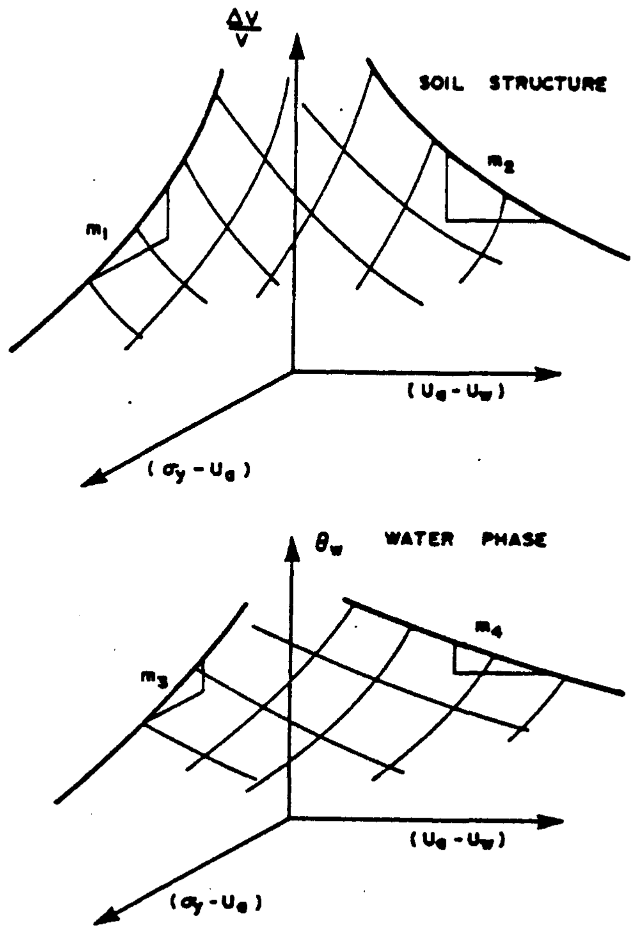

Figure 5 Constitutive Surfaces for an Unsaturated Soil

Bishop and Henkel, 1964). Substituting the constitutive equations (i.e., equations (6) and (7)) and the divergence of the water flow into the continuity requirement (i.e., equation (5)) yields the following equation.

$$\frac{k}{\gamma_w} \frac{\partial^2 u_w}{\partial z^2} dt = m_4 \, \Delta(u_a - u_w) \qquad (8)$$

For the Version II model in which the air phase is totally occluded, the continuity requirement is:

$$\frac{\Delta V}{V} = \frac{\Delta V_f}{V} \qquad (9)$$

where: V_f = volume of the pore fluid with the occluded air.

The pore fluid is compressible and the water portion is assumed to flow from the element. The compressibility of the fluid phase is expressed by equation (3). As the soil approaches saturation, the pore-air pressure approaches the pore-water pressure and the soil structure constitutive equation (i.e., equation (6)) reduces to:

$$\frac{\Delta V}{V} = m_1 \; \Delta(\sigma - u_w) \tag{10}$$

Substituting the divergence of water flow compressibility of the fluid phase (i.e., equation (3)), and the constitutive relationship for the soil structure (i.e., equation (10)) into the continuity requirement yields the following equation.

$$\frac{k}{\gamma_w} \frac{\partial^2 u_w}{\partial z^2} dt - \frac{1}{V} \left[\frac{(V_a + V_d)^2}{(V_a + V_{ao})u_{ao}} + u_{atm}\right] du_w = m_1 \; d(\sigma - u_w) \tag{11}$$

<u>Boundary Conditions and Solutions</u>

A closed form solution for equations (8) and (11) is difficult for the following reasons: (i) the stress boundary conditions are not constant with time. The total stress, σ, applied to the sample (i.e., the air pressure in the chamber) may be changed many times. Also the pressure in the high air entry ceramic disc and the transducer chamber will vary with time. (ii) equation (1) is non-linear and requires an iterative solution. Iteration is also required because changes in void ratio, degree of saturation and coefficient of permeability should be taken into account. A finite difference method (Scott, 1963) was used to obtain an approximate solution for the pore-water pressure at discrete points in the sample at discrete times. All iterative calculations were repeated until convergence within specified tolerances was reached.

Initial pore-air and pore-water pressures within the samples were assumed as input data. Generally a uniformly negative pore-water pressure was used and the pore-air pressure was taken either to be equal to the pore-water pressures (i.e., for occluded pore-air) or equal to atmospheric pressure (i.e., for interconnected pore-air).

A 'no-flow' condition was assumed at the top boundary of the sample. Flow through the high air entry ceramic disc at the base of the sample was characterized as flow through a rigid porous media. The following equation was used:

$$Q = \frac{k_p}{\gamma_w} \frac{(u_c - u_w)}{d} A \; \Delta t \tag{12}$$

where:
- Q = the volume of water flowing through the high air entry disc in the time increment, Δt,
- k_p = the coefficient of permeability of the high air entry disc,
- u_c = the pressure of the fluid in the transducer compartment,
- d = the thickness of the high air entry disc,
- u_w = the pore-water pressure in the bottom element of the soil sample, and
- A = the cross-sectional area of the soil sample.

It is necessary to compute the pressure in the compartment for each time increment for two reasons. First, to allow the calculation of the volume of water flow and second, to determine the magnitude and timing of adjustments to the applied chamber pressure on the soil sample. The transducer system was considered to have a finite flexibility (Fredlund and Morgenstern, 1973). Some free air will generally be present in the pressure measuring compartment because it is practically impossible to completely de-air the compartment prior to a test. Also, air will enter the compartment in solution through the porous ceramic stone and subsequently cavitate out of solution. The walls of the transducer compartment will also be slightly flexible and pure water has a finite compressibility. Neglecting the compartment flexibility, the continuity requirement for the transducer compartment can be written:

$$\frac{\Delta V_a}{V_c} + \frac{\Delta V_w}{V_c} = 0 \tag{13}$$

where: V_c = volume of the pressure measurement compartment below the high air entry disc.

The volume of air can change due to compression, diffusion through the ceramic disc and solution into the water phase. The volume of water can change due to flow from the pressure measurement compartment and compression within the compartment. The volume change associated with the diffusion of air through the high air entry disc can be formulated as follows:

$$\frac{V_a}{V_c} = D \frac{(u_{ad} - u_c)}{(u_c + u_{atm})} \Delta t \tag{14}$$

where: D = a diffusivity constant for the flow of air through water,
u_{ad} = the air pressure of the dissolved air at the base of the soil sample.
u_c = the chamber pressure during the time increment, Δt.

Values for diffusivity were obtained from measurements of air diffusion through high air entry discs (Fredlund, 1973 and 1975). The derivations for other components of equation (13) have been described by Bocking (1977).

In the axis translation test, the air pressure surrounding the soil sample is adjusted from time to time by the technician. The adjustments are the result of human decisions and are not completely systematic. In the mathematical model developed, these decisions are simulated by a logical subroutine by which the magnitude and timing of air pressure changes are calculated from current values and the rate of change of the pressure transducer compartment pressure. Each time the pressure of the air surrounding the sample is changed, the pore-air and pore-water pressures throughout the sample also change when the air voids are interconnected. This is also incorporated into the mathematical model as a change in boundary conditions. The change in the pore-air and pore-water pressures will be equal to the change in the applied air pressure.

When the pore-air in the soil sample is occluded, fluid flow can be neglected. The pore-pressure response is assumed to be instantaneous. The magnitude of the pore-pressure change is computed using the "B" parameter, which is computed using an iterative procedure.

Computer programs were written to solve Version I and Version II of the mathematical model. The programming language is Fortran IV and was implemented on an IBM 370/158 computer. The total storage requirement for each program is less than 140K bytes.

PARAMETRIC STUDY AND RESULTS

Numerous simulation runs were performed using Version I and Version II of the mathematical model. Various sets of input parameters were selected. The value or range of values used for each soil parameter was representative of soils commonly tested using the axis translation technique (i.e., silty clay or clays). The effect of three parameters on both Versions I and Version II models was studied. This was done by inputting several values of one parameter while holding the values of all other parameters constant. The three parameters were: (i) the soil structure compressibility, m_1, for Version II and the water phase compressibility, m_4, for Version I, (ii) the diffusion constant, D, and (iii) the minimum time interval between adjustments, TIMADJ, of the air pressure surrounding the soil sample. The results of these simultations are shown on Figures 6 to 11. The term 'average residual suction', is equal to the actual suction minus the average suction remaining in the sample at the end of the simultation. The 'ultimate suction' is estimated by adding the average residual suction to the computed suction, $(\sigma - u_c)$, at the end of the simulation.

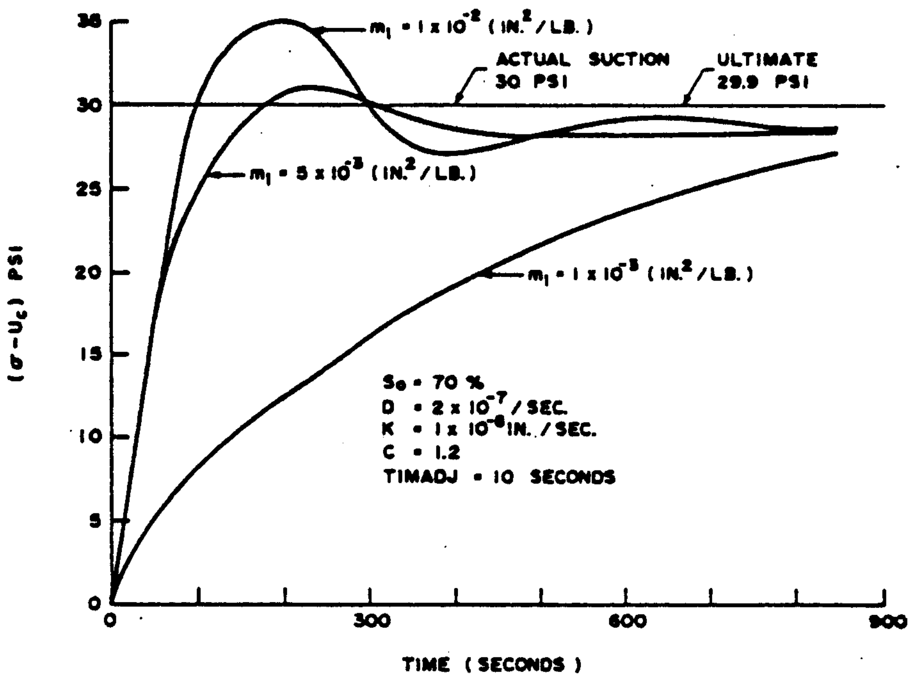

Figure 6 Typical Effect of m_1 on the Response of a Continuous Air Phase Soil

For typical input soil parameters, all iterative calculations converged to within 1 percent in 5 iterations or less. The results also appeared to be reasonable when compared to actual axis translation tests. Convergence failures were experienced when simulations were attempted for a very rigid structure soil with occluded air bubbles (i.e., Version II), (i.e., m_1 of 1 x 10^{-4} in ^{2}/lb, (1.45 x 10^{-5}/kPa)) using time increments greater than five seconds. In such cases, the value of the "B" pore-pressure parameter is very low and it becomes necessary to add very high air pressures to the sample to reverse the flow of water out of the transducer chamber. It would likely be extremely difficult to perform an actual test under these circumstances.

For all simulations of soils with a continuous air phase (i.e., Version I), the measured suction asymptotically approached the actual suction to within 1 percent. For soils with occluded air bubbles (i.e., Version II) the suction was invariably over-estimated, by up to 100 percent or even more. The magnitude of the error was primarily a function of the average value of the "B" pore-pressure parameter. As shown in Figure 7, the error is largest for soils having a highly compressible structure. The magnitude of the error is also somewhat dependent on the time interval between load adjustments (Figure 9).

Figure 12 shows typical volume change distributions computed using both Version I and Version II. The magnitude of these changes is dependent on the particular input variables used, but the results are illustrative of the processes which take place in the axis translation test. For soils with a continuous air phase, volume changes of about 5 percent occurred near the base of the sample due to the flow of water out of the transducer compartment. The void ratios returned to their original values once flow equilibrium was attained. It should be

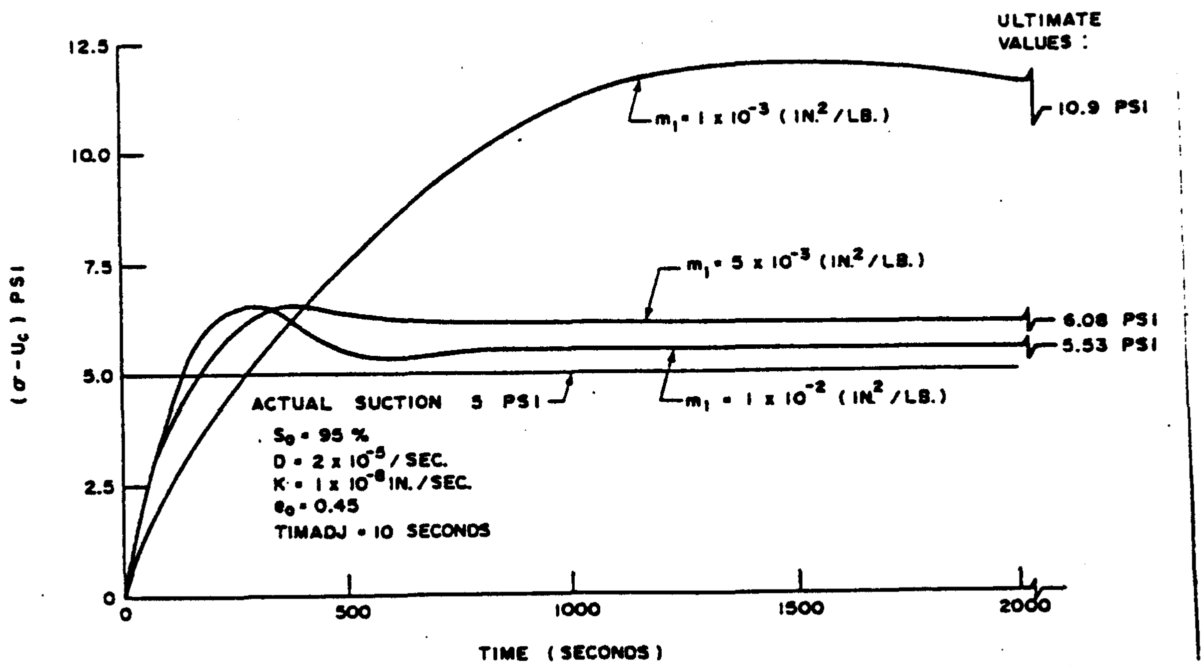

Figure 7 Typical Effect of m_1 on the Response of an Occluded Air Phase Soil

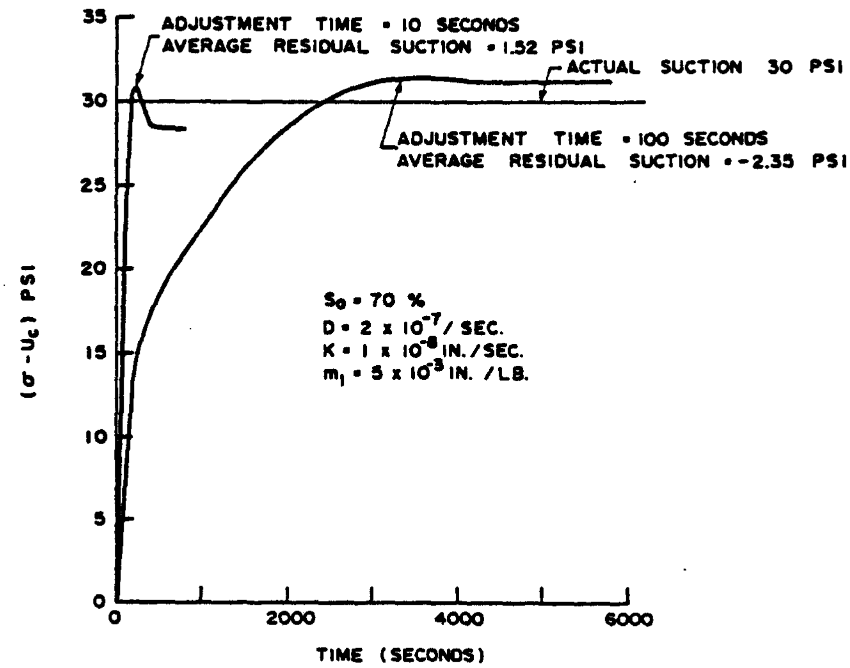

Figure 8 Typical Effect of Adjustment Interval on the Response of a Continuous Air Void Soil

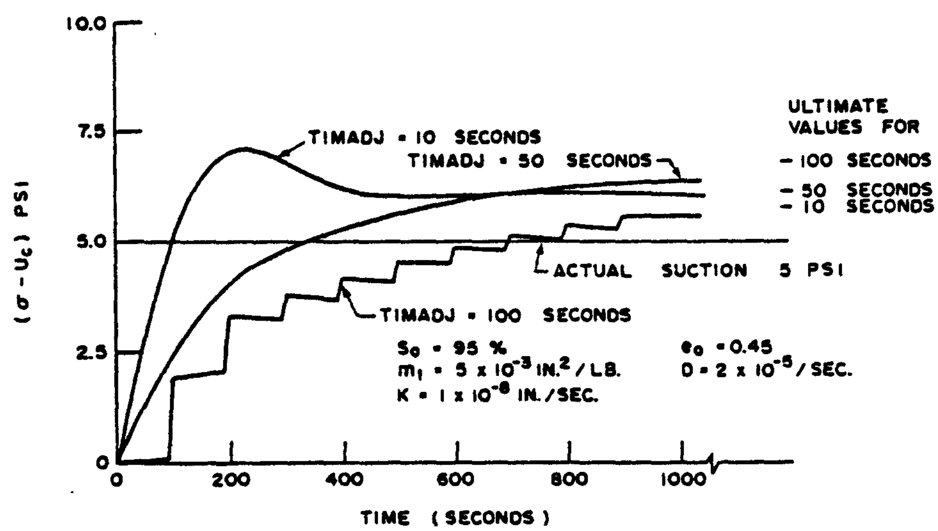

Figure 9 Typical Effect of Adjustment Interval on the Response of an Occluded Air Phase Soil

noted that hysteresis in the constitutive relationship was assumed to be negligible. The temporary, reversing volume change at the base of the sample was also noted for soils with occluded air bubbles. However, there was an additional permanent decrease in volume throughout the sample due to compression of the pore-fluid under increasing external air pressure. In the particular simulations performed, the compression was about 2 percent.

Temporary increases in degree of saturation of up to 10 percent were noted at the base of soils with a continuous air phase. This very significantly affected the coefficients of permeability. The coefficient of permeability did not vary extensively for the soils with occluded air bubbles.

It is apparent from Figures 6, 7, 8 and 9 that the shape of the response curves are affected by different values for compressibility moduli and time adjustment increment. For soils with a continuous air phase, these parameters do not affect the ultimate suction value. For soils with occluded air bubbles, the ultimate suction value is in error. With relatively compressible soils and/or short adjustment intervals an over-shooting response curve may be obtained. This also applies for soils with a continuous air phase.

The effect of the diffusion of air through the porous ceramic disc on axis translation test results is illustrated by Figures 10 and 11. For soils with occluded air bubbles, this effect is not significant because, as the sample nears equilibrium, both the pore-water and pore-air pressures approach the measured compartment pressure. For soils with a continuous air phase, the effect of air diffusion may or may not be significant, depending on the value of diffusivity and the test duration. In cases in which it is significant, diffusion will cause a gradual increase in the measured compartment pressure until, ultimately it approaches the applied chamber pressure. In this case, the measured suction will peak and then drop off, and the actual suction may be under-estimated.

CONCLUSIONS

1. Solutions to both Versions I and II of the mathematical model converge provided reasonable values of input parameters are used. No direct comparison was made between simulation results and actual axis translation test results. However, all observations from the mathematical models are consistent with experimental observations.

2. Use of the axis translation test to measure soil suction is theoretically correct for soils with totally interconnected pore-air voids. For soils containing significant amounts of occluded pore-air, the measurements can be erroneous. In the latter case, the actual soil suction will be over-estimated.

3. Soil samples tested using the axis translation technique are subject to some volume change. The volume changes were assumed to be fully reversible in tests where the air phase was interconnected.

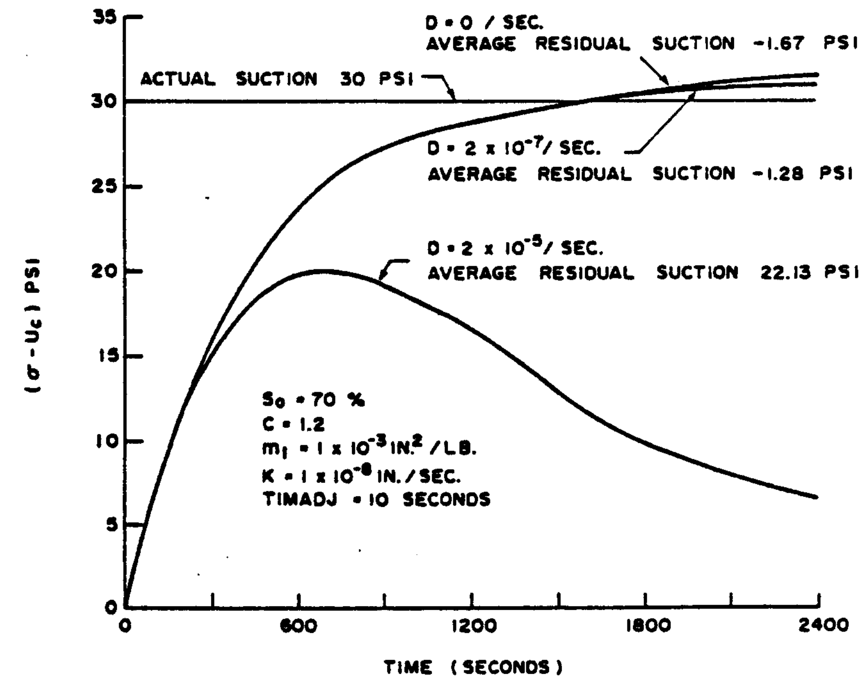

Figure 10 Typical Effect of Diffusion on the Response of a Continuous Air Phase Soil

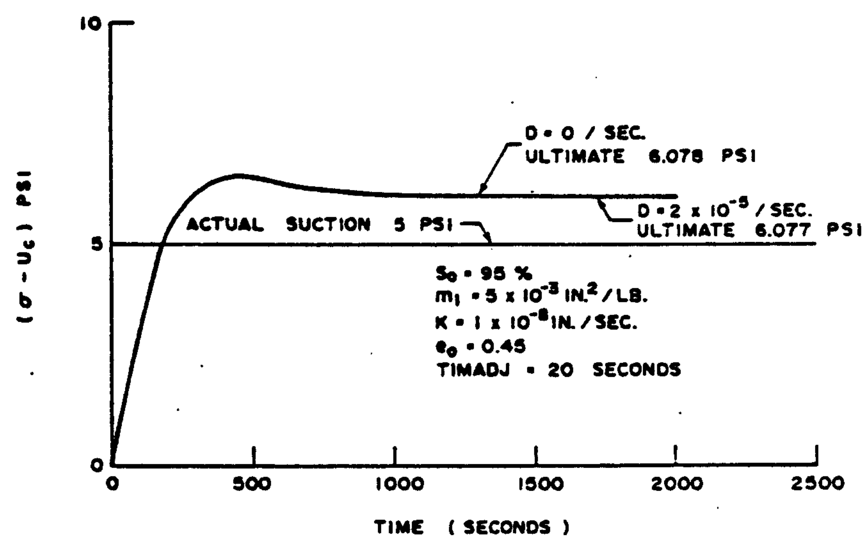

Figure 11 Typical Effect of Diffusion on the Response of an Occluded Air Phase Soil

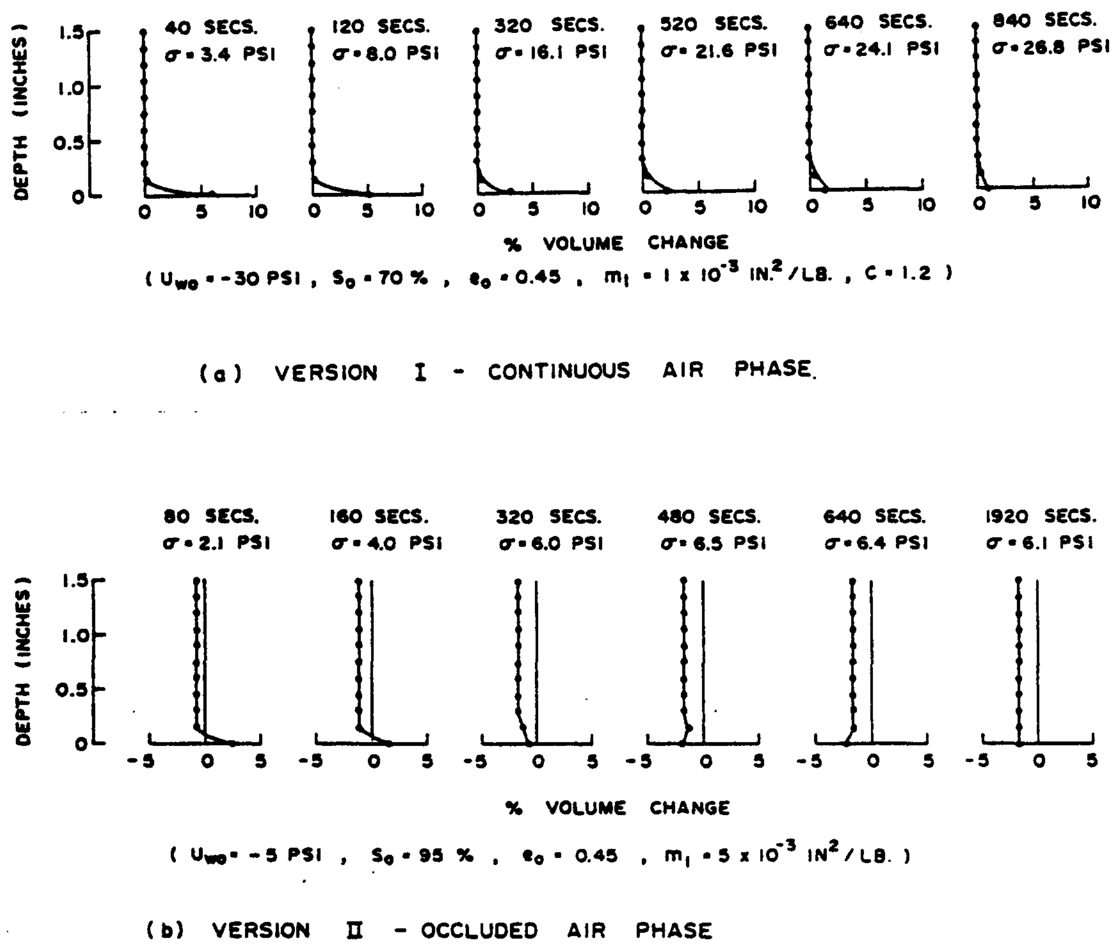

Figure 12 Typical Volume Change During an Axis Translation Test

There will not be significant errors in the measurement of suction in this case. When the soil contains significant amounts of occluded air, non-reversible volume changes occur.

4. Interpretation of the axis translation test results should be done while considering the following points: (i) because of the asymptotic nature of the transient flow of pore-water, flow equilibrium will be approached but never truly attained. (ii) the diffusion of air through porous ceramic discs imposes a practical limit on the length of time that should be taken to run the test. The rate of air diffusion should be measured for each axis translation apparatus. (iii) depending on the rate of application of the chamber air pressure to the sample and on the compressibility of the soil, it is possible to temporarily over-shoot the actual suction value. In such a case the peak should not be interpreted as the

actual suction, nor should the subsequent down-turn of the curve be interpreted as the onset of significant air diffusion. (iv) the actual suction will be over-estimated if the soil sample contains significant amounts of occluded pore-air.

LIST OF REFERENCES

Barden, L. (1965), "Consolidation of Compacted and Unsaturated Clays", Geotechnique, Vol. 13, No. 2, pp. 267-286.

Barden, L. and Pavlakis, G. (1971), "Air and Water Permeabilities of Compacted Unsaturated Cohesive Soil", Journal of Soil Science, Vol. 22, No. 3, pp. 302-318.

Bishop, A.W. and Donald, I.B. (1961), "The Experimental Study of Partly Saturated Soil in the Triaxial Apparatus", Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 13-22.

Bishop, A.W. and Henkel, D.J. (1962), "The Measurement of Soil Properties in the Triaxial Test", Second Edition, William Clowes and Sons Ltd., London.

Bocking, K.A. (1977), "Methods of Measurement of Negative Pore-Water Pressures", M.Sc. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan.

Coeffey, C.T. and Gibbs, H.J. (1963), "Measurement of Initial Negative Pore Pressure of Unsaturated Soil", Laboratory Report No. EM-665, Bureau of Reclamation, Denver, Colorado, U.S.A.

Corey, A.T. (1954), "The Interrelation Between Gas and Oil Relative Permeabilities", Producer's Monthly, pp. 38-41.

Corey, A.T. (1957), "Measurement of Water and Air Permeability in Unsaturated Soil", Proceedings of the Soil Science Society of America, Vol. 21, No. 1, pp. 7-10.

Fredlund, D.G. (1973), "Volume Change Behavior of Unsaturated Soils", Ph.D. dissertation, University of Alberta, Edmonton, Alberta.

Fredlund, D.G. (1975), "A Diffused Air Volume Indicator for Unsaturated Soils", Canadian Geotechnical Journal, Vol. 12, No. 4, pp. 533-539.

Fredlund, D.G. and Morgenstern, N.R. (1973), "Pore Pressure Response Below High Air Entry Discs", Proceedings of the Third International Conference on Expansive Soils, Haifa, Israel, Vol. 1, pp. 97-108.

Fredlund, D.G. and Morgenstern, N.R. (1976), "Constitutive Relations for Volume Change in Unsaturated Soils", Canadian Geotechnical Journal, Vol. 13, No. 3, pp. 261-276.

Fredlund, D.G. (1976), "Density and Compressibility Characterisitcs of Air-Water Mixture", Canadian Geotechnical Journal, Vol. 13, No. 4, pp. 386-396.

Hilf, J.W. (1956), "An Investigation of Pore-Water Pressure in Compacted Cohesive Soils", (Ph.D. Thesis), Technical Memorandum No. 654, United States Department of the Interior Bureau of Reclamation, Design and Construction Division, Denver, Colorado, U.S.A.

Ladd, C.C. (1960), "Mechanisms of Swelling by Compacted Clay", Highway Research Board Bulletin No. 245, National Academy of Sciences - National Research Council (USA), Publication 731, pp. 10-26.

Langfelder, L.J., Chen, C.G. and Justice, J.A. (1968), "Air Permeability of Compacted Cohesive Soils", Journal of the Soil Mechanics and Foundation Division, Proceedings of the American Society of Civil Engineers, Vol. 94, No. SM4, pp. 981-1001.

Matyas, E.L. (1966), "Air and Water Permeability of Compacted Soils", Permeability and Capillarity of Soils, American Society for Testing and Materials, Special Technical Publication, No. 417, Philadelphia, Pa., U.S.A.

Olson, R.E. and Langfelder, L.J. (1965), "Pore-Water Pressures in Unsaturated Soils", Journal of the Soil Mechanics and Foundation Division, Proceedings of the American Society of Civil Engineers, Vol. 91, No. SM4, pp. 127-160.

Richards, L. and Fireman, M. (1943), "Pressure-Plate Apparatus for Studying Moisture Sorption and Transmission by Soils", Soil Science, Vol. 56, pp. 395-404.

Schuurman, I.E. (1966), "The Compressibility of an Air/Water Mixture and a Theoretical Relation Between the Air and Water Pressures", Geotechnique, Vol. 16, No. 4.

Scott, R.F. (1963), "Principles of Soil Mechanics", Addison-Wesley Publishing Co. Inc., Reading, Mass., U.S.A.

Terzaghi, K. (1923), "Die Berechnung der Durchlassigkeitsziffer des Tones aus dem Verlauf der Hydrodynamischen Spannungerserscheinungen", Sitzber, Akad, Wiss. Wien, IIa, Vol. 132.

Woodruff, C.M. (1940), "Soil Moisture and Plant Growth in Relation to pF", Proceedings of the Soil Science Society of America, Vol. 5, pp. 36-41.