GR-85-8

REVIEW OF NEGATIVE PORE PRESSURE: ITS MEASUREMENT, AND TESTING OF THE CRL APPARATUS

September 1985
Engineering and Research Center

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TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. GR-85-8	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Review of Negative Pore Pressure: Its Measurement, and Testing of the CRL Apparatus		5. REPORT DATE September 1985
		6. PERFORMING ORGANIZATION CODE D-1541
7. AUTHOR(S) Kurt F. von Fay		8. PERFORMING ORGANIZATION REPORT NO. GR-85-8
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bureau of Reclamation Engineering and Research Center Denver CO 80225		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the E&R Center, Denver, Colorado.

Editor: RNW(c)

16. ABSTRACT

A broad review of negative pore pressure and various methods of measurement is presented. Suggestions are made for evaluating the capability of the CRL consolidation apparatus to measure initial suction and suction when a specimen is compressed one-dimensionally. Described are the terms used for negative pore pressure; the various components of suction and their significance; the types of equipment used to measure various components of soil suction; the CRL apparatus as it is used for soil-suction measurement; the mathematical relationships of pore-air pressure and pore-water pressure and their effects on the shear strength of a soil mass; basic equations relating pore-air pressure and pore-water pressure; and the shear strength of unsaturated soils and the effects of wetting and drying on shear strength and soil-suction relationships. Justifications are presented for the modification of the CRL apparatus for measuring soil suction. Determining the change in suction with compression may help determine the proper loading rate for unsaturated, UU triaxial shear tests. Information about specimen suction response to compression may be used to monitor unsaturated soil responses to construction activities. A testing program is suggested to evaluate the capabilities of the CRL apparatus to determine the suction characteristics of a material.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS--* CRL apparatus/ constant rate of loading/ suction/ soil-suction measurement/ pore-air pressure/ pore-water pressure/ shear strength of unsaturated soils/ unconsolidated-undrained triaxial shear tests/ negative pore pressure

b. *IDENTIFIERS--*

c. *COSATI Field/Group* M *COWRR:* 0813

18. DISTRIBUTION STATEMENT *Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161.*	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 30
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE

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by

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Denver, Colorado

September 1985

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The research covered by this report was funded under the Bureau of Reclamation Program Related Engineering and Scientific Studies allocation No. DR-268, "Soil Test Procedures".

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INTRODUCTION

This report presents a broad review of negative pore pressure (suction) and various methods of measurement. It also presents suggestions for evaluating the capability of the CRL (constant rate of loading) consolidation apparatus to measure initial suction pressure and to measure suction when a specimen is compressed one-dimensionally.

The report begins with a discussion of the terms used for negative pore pressure and defines appropriate terms. Next is a discussion of the components of suction and their significance.

The types of equipment used to measure the components of soil suction are discussed and described, starting with the devices first used and proceeding to devices currently used. The CRL apparatus is briefly described as it is used for soil-suction measurement.

Also described are the mathematical relationships of pore-air pressure and pore-water pressure and their effect on the shear strength of a soil mass. Basic equations relating pore-air pressure and pore-water pressure are presented, followed by a discussion of the shear strength of unsaturated soils and the effects of wetting and drying on shear strength and on soil-suction relationships.

Justifications are presented for modification of the CRL apparatus for measuring soil suction. Determining a soil's change in suction with compression can help determine the proper loading rate for unsaturated, UU (unconsolidated-undrained) triaxial shear tests. In addition, information about specimen suction response to compression can be used to monitor unsaturated soil responses to constuction activities.

Finally, a testing program is suggested to determine the capabilities of the CRL apparatus for determining the suction characteristics of a material.

SOIL-SUCTION TERMINOLOGY

Many terms describe soil-water interactions for partly saturated soils. Among these terms are soil pull, capillary potential, capillary pressure, suction, pressure deficiency, capillary tension, soil-moisture tension, total suction (and its two main components matrix suction and solute suction), pore pressure, and soil-water potential. This proliferation of terms has led to some confusion, especially because they all do not necessarily refer to the same phenomenon. For example,

Aitchison [1]* defined suction as "... expressing, either qualitatively or quantitatively, the actual or potential absorption or imbibition of water by soil." However, Marshall [2] suggested that two components of total suction (discussed later) be considered. He termed these components matrix suction and solute suction, with the former dependent mainly upon particle configuration and arrangement (moisture content and void ratio) and the latter dependent upon osmotic pressure (which results from the difference between the concentration of soluble salts in the soil-water and in the measuring-system water). In 1965 [3], the following definitions were proposed.

Total suction. – The negative gauge pressure, relative to the external gas pressure on the soil-water, to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable (permeable to water molecules only) membrane with the soil-water.

Matrix suction. – The negative gauge pressure, relative to the external gas pressure on the soil-water, to which a solution identical in composition with the soil-water must be subjected in order to be in equilibrium through a porous permeable wall with the soil-water.

Solute (osmotic) suction. – The negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil-water.

Richards [4] stated that "the most simple and flexible way for defining soil suction is in terms of the thermodynamic potentials." He defined soil-water potential and soil-water suction, according to the International Society of Soil Science, as follows:

"Soil water potential is the work done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water outside the absorptive force fields at a specified elevation and at atmospheric pressure to the soil water (at the point under consideration)."

"Soil suction is that negative gauge pressure, relative to the external gas pressure on the soil water (normally atmospheric pressure), to which a pool of pure water at the same elevation and temperature must be subjected in order to be in equilibrium with the soil water."

From these definitions, soil suction can be related to soil-water potential by expressing soil suction as the amount of negative pore-water pressure that would produce the same lowering of the soil-water potential as the soil.

* Numbers in brackets refer to entries in the bibliography.

SOIL-WATER INTERACTIONS

The branch of soil science known as agronomy may have been the first discipline concerned with the retention and movement of moisture in soils. In fact, much of the early work involving soil-moisture characteristics was done from an agricultural perspective.

As early as 1897, Briggs [5] considered the effects of three differently acting classes of water in soil: (1) gravitational, (2) capillary, and (3) hygroscopic. Later, Buckingham [6] introduced the concept of capillary potential, which he defined as the work that would have to be done against the "capillary field force" (a mechanical force involved in the attraction of soil for water) in transferring a unit mass of water from the soil to free water at zero hydrostatic pressure. The total attraction of water for soil is caused by a complex interaction of several components. Bolt and Miller [7] discussed the effects of the osmotic, absorption, pressure, and gravitational potentials of water in soil in their paper on combining Buckingham's [6] capillary potential concept and Edlefsen and Anderson's [8] thermodynamic analysis with Schofield's [9] application of the electric double-layer theory soil-water systems.

Two basic approaches are now used to describe water in soil:

1. The mechanistic approach, which describes the status of water in soil in terms of pressure deficiency or suction.

2. The energy approach, which uses thermodynamic principles to describe various water and pressure potentials, including Buckingham's capillary potential.

The mechanistic approach has some inherent limitations [10]; therefore, the current literature usually describes energy and water interactions in thermodynamic terms. This gives rise to the term soil-water potential. Soil-water suction is the term most often associated with engineering work.

The total soil-water potential can be divided into six components. They have been discussed by various researchers and summarized by Yong and Warkentin [11] and Yong [12] as follows:

"(1) $\Delta\psi$, the total potential, is the work required to transfer a unit quantity of water from the reference pool to the point in the soil. It is a negative number.

"(2) $\Delta\psi_m$, the matric potential, is a soil matrix property. This is the equivalent of Buckingham's capillary potential. It is the work required to transfer a unit quantity of soil solution, from a reference pool at the same elevation and temperature as the soil, to the point in the soil. $\Delta\psi$ cannot be calculated except for uniform spheres where it is related to curvature of air-water interfaces and $\psi_m = S[(1/r_1) + (1/r_2)]$, or in freely swelling clay plates where $\psi_m = RT \cosh(y_c - 1)$. $S =$ surface tension of the air-water interface; r_1, r_2, =radii of curvature of the air-water interface; $R =$ universal gas constant; $T =$ absolute temperature; $y_c =$ electrical potential midway between two clay plates. ψ_m can be subdivided into a component related to swelling forces and a component from air-water interface forces, but these components cannot be separated experimentally.

"(3) $\Delta\psi_g$, the gravitational potential, is the work required to transfer water from the reference elevation to the soil elevation.

$$\psi_g = -\gamma_w gh$$

where $\gamma_w =$ density of water.

"(4) $\Delta\psi_\pi$, the osmotic potential, is the work required to transfer water from a reference pool of pore water to a pool of soil solution at the same elevation, temperature, etc.

"(5) $\Delta\psi_p$, the piezometric or submergence potential, is the work required to transfer water to a point below the water table.

$$\Delta\psi_p = \gamma_w gd$$

where $d =$ depth below free water level.

"(6) $\Delta\psi_a$, the pneumatic of a pressure potential, refers to transfer of water from atmospheric pressure to the air pressure, P, on the soil.

$$\Delta\psi_a = P$$

"The three component potentials, matric, piezometric, and pneumatic are often taken together as the pressure potential, $\Delta\psi_p$.

$$\Delta\psi_p = \Delta\psi_m + \Delta\psi_p + \Delta\psi_a."$$

For laboratory tests, soil specimens do not usually have a measurable head difference (gravitational component); therefore, the total potential can be expressed as a function of the osmotic and pressure (matrix) components. For soil mechanics, suction represents a component of effective stress expressed in engineering units.

EQUIPMENT FOR SUCTION MEASUREMENT

Gardner and his coworkers [13] were among the first to relate pressure measurements (taken from moist soil samples with porous cups and vacuum gauges) to soil-water potential. Richards [14] analyzed some of the factors affecting the capillary function and succeeded in measuring capillary pressure with field tensiometers. In 1949, Richards [15] discussed various measurement techniques used to measure soil suction. However, at that time no apparatus was capable of measuring pressure deficiencies greater than 0.85 atm (86 kPa).

In 1956, Hilf [16] described methods that combined measurements and calculations to determine pore pressures of cohesive soils during triaxial testing. These methods were similar to the pressure membrane method described by Croney et al. [17], in which elevated air pressures were used to measure pressure deficiencies greater than 0.85 atm (86 kPa). Bishop and Blight [18] examined the effect of elevating the air pressure and found that it had no effect on the shear strength of lean, compacted Boulder clay. This, of course, holds true until the air pressure becomes high enough to cause a volume change. Croney et al. [17] also discussed several other techniques and their applicabilities. They concluded that the pore size of the measuring devices should not exceed 1.6 microns (0.0016 mm). During the same time period, Donald [19] used suction-plate techniques to study the shear strength of sands in triaxial compression and perform direct shear tests in which he imposed a known pressure deficiency in the pore water. In 1960, Bishop [20] described testing equipment for which the pore-air pressure was adjusted at one end of the specimen and the pore-water pressure was measured at the other end. In 1963, Gibbs [21] reported difficulty with that test procedure when testing impervious clays. In that same year, Gibbs and Coffey [22] introduced the exposed end-plate test used to measure initial negative pore pressures greater than 1 atm (101 kPa). They also reported that the new apparatus demonstrated a high degree of reliability and protected the water in the measuring system from tension separation.

In 1966, Knodel and Coffey [23] suggested some refinements in the equipment and procedure developed by Gibbs and Coffey to allow more accurate pore-pressure measurements. Further refinements in 1969 [24, 25], permitted accurate measurements of pore pressures throughout the loading sequence of an unsaturated, UU triaxial shear test.

In 1970, Dumbleton and West [26] described a rapid-method suction apparatus that used ceramic porous plates with extended range. This apparatus could be used to take suction measurements relatively quickly, both in the laboratory and in the field, to approximately 2 atm (202 kPa).

Much of the later work involved various forms of thermocouple psychrometers to make suction measurements. Psychrometers use two effects adopted from thermocouple theory. Seebeck discovered that when two junctions of a thermocouple circuit are at different temperatures, an electric current is induced in the circuit. This "Seebeck" effect is the basis for temperature measurement using thermocouples. Peltier discovered that, when an electric current is induced in a thermocouple circuit, one junction tends to cool and the other junction tends to heat. Reversing the current flow reverses the heating and cooling effects. Spanner [27] was the first to use the "Peltier effect" to cool one junction of a psychrometer below the dew point temperature to condense water onto the cool junction. After the cooling current is stopped, the condensed water droplet starts to evaporate, cooling the droplet and junction and inducing a measurable electric current. The amount of cooling is controlled by the relative humidity of the air surrounding the droplet. If a soil specimen is near the psychrometer probe and isolated from the surrounding environment, then the relative humidity of the air (and therefore the cooling of the probe) will be controlled by the soil-water potential of the soil specimen.

There are two classes of psychrometers. The first is Richard's Psychrometer, for which a droplet of distilled water is placed on the tip of the sensing device. Evaporation of the water droplet cools the sensing device, inducing a measurable current in the circuit. The second is the Spanner psychrometer, which uses the Peltier effect to cool one junction of a psychrometer below dew point by condensing a droplet of water on it.

In 1970, Kay and Low [28] provided a detailed description of a thermistor psychrometer and the results of comparative tests between the psychrometer and pressure-plate techniques. Their results show that, as clay concentrations increase, the differences between the apparatuses increase, and the psychrometer shows higher suctions. Kay and Low attributed the differences to the increase of dissolved solutes in the specimens with high clay concentrations.

Later, in 1972, Stevens [29] described a Spanner psychrometer for measuring in situ suction. He described the relative advantages and disadvantages of this type of psychrometer, its calibration, and field use. He also discussed the benefits of a double-junction psychrometer versus a single-junction psychrometer. He concluded that psychrometers offer the best method of measuring in situ suction, but that field proof-testing was still required.

In 1973, Baker et al. [30] described the different methods discussed by others [2, 17, 27, 31, 32, 33, 34, 35, 36, 37, 38] for measuring soil-water potential and suction. Table 1 presents a synopsis of the discussion. Baker et al. [30] went on to study the psychrometer technique because they believed that, overall, it had the most potential. They concluded that, although the psychrometer was promising, it had some disadvantages: (1) it had low sensitivity at low suction values, (2) calibration curves changed with time, and (3) every probe needed calibration, even when they were all from a batch manufactured under the same conditions.

In 1973, Peter and Martin [39] described a simple psychrometer for routine determinations of total suction in expansive soils. This psychrometer was a modified laboratory thermistor psychrometer capable of measuring the total suction from approximately 30 to 10 000 kPa. It was fairly accurate and easy to use. In that same year, Aitchison and Martin [40] described a modified oedometer in which an expansive clay could be subjected to the various stress components (direct vertical stress, matrix component of pore-water suction, and solute suction). A number of different stress paths could be followed, limited only by the measuring limits of the apparatus.

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Table 1. – Synopsis of methods for measuring soil-water potential and suction [30].

Method of measurement	Reference	Description
Suction plate and tensiometer	Croney, Coleman, and Briggs, 1952 [17]	A soil specimen is placed on the upper surface of a ceramic disk that has fine pores that separate the specimen from the water source. The ceramic disk acts as a semi-permeable membrane and is permeable to salt in solution. A given suction is applied to the water source, and the system is allowed to reach equilibrium. At equilibrium, the suction applied to the water is the matrix suction. This device is only capable of measuring matrix suction. A tensiometer is a modified suction plate adapted for field use. Both these devices have a limited range and can only measure suctions less than 1 atm (101 kPa) because of cavitation of the water in the measuring system.
Pressure membrane	Croney, Coleman, and Briggs, 1952 [17]	This device is a variation of the suction plate. Air pressure is applied above a cellulose membrane on top of which is the soil specimen. The water below the membrane remains at atmospheric pressure. The cellulose membrane is permeable to salt in solution. There is no solute or osmotic suction, so the device only measures matrix suctions. The apparatus can measure suctions to about 30 atm (101 kPa), limited by the air-entry value of the membrane. A possible disadvantage of this device is that the high air pressures used may change the unit weight of the soil and affect the suction measurements. Also, the device can be used only in the laboratory.

Table 1. – Synopsis of methods for measuring soil-water potential and suction [30]. – Continued

Method of measurement	Reference	Description
Filter paper and gypsum blocks	Fawcett and Collis-George 1967 [31]; Anderson, 1943 [32]; Politch [33], 1967	These methods compare the potential of water in the soil to the potential of water held in a porous media. For the filter paper method, a filter paper with known retention characteristics is placed in contact with a soil specimen. The salts are free to move into the paper, so matrix suction is measured. Using the known retention curve of the filter paper and by determining its moisture content, it is possible to evaluate the suction of the soil specimen. Some disadvantages of this method are the requirement for very accurate mass determinations, and the susceptibility of the paper to fungal growth. The gypsum block method is similar, but uses electrical resistance and impedence measurements to determine moisture contents. It can be used to make measurements in situ, but only measures matrix potential. However, there tends to be a great amount of scatter to the results. The gypsum block measures suctions in the range 0.4 to 40 atm (40.5 to 4053 kPa).

Table 1. – Synopsis of methods for measuring soil-water potential and suction [30]. – Continued

Method of measurement	Reference	Description
Osmotic method	Zur, 1965 [34]; Kassiff and Ben-Shalom, 1971 [35]	This method compares the soil-water potential of a soil specimen to the known potential of a high polymer solution (Carbowax). A semipermeable membrane prevents the movement of large polymer molecules of the solution into the soil specimen, but allows free migration of salts. The osmotic potential of the Carbowax solution is determined from the known concentration and is equal to the matrix potential of the soil specimen.
Sorption balance	Marshall, 1959 [2]; Croney, Coleman, and Briggs, 1952 [17]	This method compares the soil-water potential with the potential of a known salt solution. Migration of water molecules from the solution to the soil surface occurs through an air gap, which serves as an ideal semipermeable membrane until equilibrium is reached. The osmotic potential is determined from the concentration of the salt solution. This method measures the total potential of the soil specimen, which is its major advantage. Another advantage is its accuracy. However, long periods of time may be required for equilibrium to be reached.

Table 1. – Synopsis of methods for measuring soil-water potential and suction [30]. – Continued

Method of measurement	Reference	Description
Psychrometric (wet bulb) depression and Peltier cooling	Hill, 1930 [36]; Richards, 1965 [37]; Rawlins, 1966 [38]; Spanner, 1951 [27]	This method measures the potential of water vapor in equilibrium with the soil. It functions similarly to the sorption balance. However, response times are relatively long.

In 1974, Aitchison and Peter [41] discussed a technique to determine matrix and solute suction by subjecting samples to a series of successive approximations of the matrix and solute suctions until there was no volume change in the soil specimen (an expansive clay). Aitchison and Peter stated:

> "It is accepted that techniques for the direct measurement of solute suction are not of sufficient accuracy for present use and that consequently there is a requirement for the measurement of both total suction and matrix suction so that all three suction values may be expressed quantitatively."

The method Aitchison and Peter proposed applies only to expansive clays; it has little or no value for nonexpansive soils. However, Richards [4] questioned the validity of their technique.

Richards [4] discussed the definitions of soil suction and the reliability of measurement of the components of total suction (matrix and solute suctions) for expansive clays. He questioned the meaningfulness of measuring the total soil-suction components in expansive clays because of the interdependent mechanisms for water retention in soils. Richards provided evidence that independent quantitative determination of matrix and solute components of suction was impossible. He suggested that total-suction measurement and the determination of salts content are the only useful variables for practical problems. Richards stated:

"In none of the determinations did solute suction by either pressure extract or electrical conductivity methods equal the difference between total suction by the psychrometric method and matrix suction by the pressure membrane method, as it should do by definition."

Johnson [42] stated that a pressure membrane (or pressure plate) device can measure only matrix suction because the pore sizes of the ceramic stones are much too large to prevent diffusion of the soluble salts through the membrane into the water of the measuring system. However, for some soils, the time required for the diffusion may be considerable [4]. The difference between matrix suction and total suction is usually not significant for sandy or gravelly soils. However, the difference may be quite large for expansive clays [5]. In his discussion of swelling soils and heave prediction, Brackley [43] said that pressure plates (pressure membranes) give values between matrix and total suction. In addition, the effects of osmotic suction may not be observed if the water external to the soil is identical with the pore water, or if the pore water contains negligible amounts of dissolved salts [42].

In summary, matrix suction (pressure component of suction) may be measured using a tensiometer, pressure-membrane cell, suction plate, or a similar device. Total suction (combined effects of matrix and solute suction) may be measured in terms of vapor pressure using a thermocouple psychrometer. However, as stated earlier by Aitchison and Peter [41], the measurement of solute suction is not so well defined. Richards [4] briefly mentioned using electrical-conductivity methods and pressure-extract methods to measure solute suction, but both methods yielded questionable results.

In 1984, von Fay and Cotton [44] described a versatile CRL apparatus for CRL consolidation tests. This apparatus combined a floating confining ring, an air-operated consolidation frame, and a CRL drive system. The apparatus applied a load to a soil specimen at a constant rate, allowing timely and accurate consolidation test data to be obtained. Recently, this apparatus was modifed by placing two diametrically opposed fine ceramic stones (high air-entry value) in the side of the floating confining ring and a fine ceramic stone in the center of the coarse carbon stone in the bottom end plate. The apparatus was then able to measure initial negative pore pressure (matrix suction) and the change of negative pore pressure as the specimen was compressed at a constant loading rate. In addition, by comparing the pore-pressure readings from the two fine ceramic stones, the correctness of the loading rate could be determined. If the readings were not approximately the same, then the loading rate was too fast to allow proper pore-pressure equalization.

The CRL appartus, as it is used for measuring suction pressure, falls into the class of devices known as pressure plates or pressure membrane cells (The ceramic stones serve as the membranes.). They are operated by applying a known air pressure, sometimes referred to as extraction air pressure, to a soil specimen when the suction approaches or exceeds 1 atm (101 kPa). The extraction air pressure elevates the suction pressure in the soil and, subsequently, less negative pore-water pressure is induced in the measuring system. This prevents cavitation. The actual negative pore pressure is determined by adding the recorded suction pressure at any time to the known extraction pressure at that time.

PORE PRESSURES IN UNSATURATED SPECIMENS

The problem of fluid pressure (air, water, etc.) in sealed, unsaturated soil as it compresses was apparently first dealt with theoretically, by Brohtz et al. [45], and then experimentally, by Hamilton [46]. The combined Henry's and Boyle's laws for ideal gases to determine the air pressure in a sealed, compressed soil specimen. Hilf [16] gave a complete derivation of the equation for pore-air pressure and showed that the pore-water pressure (curvature of the menisci of the soil-water) is independent of the pore-air pressure; consequently, pore-water pressure can be considered to be a relatively simple funcion of capillary pressure and pore-air pressure. Hilf [16], Gibbs [21], and others have used the following expression for determining the resultant pore pressure:

$$u = u_a + u_c \tag{1}$$

where:

u = resultant pore pressure,

u_a = pore-air pressure, and

u_c = capillary pressure $= -(u_a - u_w)$.

Bishop [20], Bishop et al. [47], Blight [48], Aitchison [11], and others have felt the need for a special parameter relating pore-air pressure and pore-water pressure. Bishop [20] proposed the following:

$$u = u_a - \chi(u_a - u_w) \tag{2}$$

where:

u_w = measured pore-water pressure, and

χ = an empirical parameter representing the proportion of the soil suction $(u_a - u_w)$ that contributes to the effective stress.

Bishop [20], Bishop et al. [47], Blight [48], Aitchison [11], and others discussed ways to determine χ.

The term $u_a - u_w$ represents the difference between pore-air pressure and pore-water pressure. It is caused by the surface tension of the pore water [18] and is equivalent to the matrix suction [40] in the soil specimen.

Gibbs [21] presented the following equation for determining pore-air pressure from a known volume change:

$$u_a = \frac{P_a \Delta e}{e_{ao} + h e_w - \Delta e} \tag{3}$$

where:

u_a = pore-air pressure,

P_a = atmospheric pressure,

Δe = change in void ratio,

e_{ao} = ratio of the initial volume of free air to the volume of solids,

h = 0.02, the coefficient of air solubility in water, and

e_w = ratio of water volume to volume of solids.

Gibbs and Coffey [24] presented a slightly different form of the above equation in 1969:

$$u_a = \frac{P_a \Delta v}{V_{ao} + h V_w - \Delta v} \tag{4}$$

where:

Δv = percent volume change,

V_{ao} = initial volume of free air, percent initial volume, and

V_w = volume of water, percent initial volume.

UNSATURATION AND SHEAR STRENGTH

Is it well established that many soils throughout the Western States are usually unsaturated. The relatively high soil suction in many of these soils increases their strength and could affect the results of soil analysis.

Examples of situations where the soil suction may have a significant impact on analysis results are (1) the long-term stability of earth embankments in arid or semiarid environments, (2) the heave of structures on unsaturated expansive clays, and (3) the long-term stability of roads and structures. Some of these problems involving unsaturated soils may be solved using an effective stress-type principle, as numerous authors have suggested. However, there are many difficulties with evaluating strength parameters for unsaturated soils in terms of effective stresses. Even the applicability of an effective stress-type principal to unsaturated soils [48] is questionable.

The pore fluid of an unsaturated soil consists of two components, air and water. As a sealed specimen is compressed, the pressure of both components increases and can be measured. Pore-water pressures can be measured or controlled through a saturated fine-pore ceramic stone with a high air-entry value. Pore-air pressure can be measured or controlled through a coarse-pore ceramic stone with a moisture-retention capacity so low that the stone is unable to draw moisture from the soil.

The modified equation for effective stress, using the pore-pressure equation suggested in equation (2), is

$$\sigma' = \sigma - [u_a - \chi(u_a - u_w)] \tag{5}$$

The corresponding equation describing shear strength, τ', of an unsaturated soil in terms of effective stress is

$$\tau' = c + \{\sigma - [u_a - \chi(u_a - u_w)]\} \tan\phi \tag{6}$$

A major drawback to the use of equations (5) and (6) is the difficulty of determining. Another problem is the necessity of slowly performing undrained triaxial shear tests. When undrained triaxial tests are performed on unsaturated materials and pore pressures are measured, the tests must be performed slowly enough to allow the pore pressures to equalize throughout the samples. Because partly saturated soils are usually much less permeable to water flow, extremely slow testing rates may be needed to allow a relatively high degree of pore-pressure equalization.

In 1982, Ho and Fredland [49] used the following expression for the shear strength of unsaturated soils:

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{7}$$

where:

c' = effective cohesion,

σ = total stress,

u_a = pore-air pressure,

ϕ' = effective angle of internal friction,

u_w = pore-water pressure,

$(u_a - u_w)$ = matrix suction, and

ϕ^b = friction angle with respect to changes in $(u_a - u_w)$ when $(\sigma - u_a)$ is held constant. It can be determined during the performance of a multistage triaxial test.

The above equations may seem to indicate a unique relationship between soil suction and strength. However, recent work [4, 50] has indicated that the relationship between soil suction and strength may be more complex than shown here. This is because the relationship between soil suction and the wetting and drying of soil exhibits hysteresis. Yong [11] showed that for the same soil-water potential, neglecting other variables, it was possible to obtain at least two different values of shear strength. This results from the fact that, for the same soil-water potential, it is possible to obtain different values of moisture content, saturations, and dry unit weight, depending upon whether the soil specimen is on the adsorption or desorption portion of the moisture-content cycle. Three-dimensional plots may be prepared, which create a surface showing the relationship for a given soil between dry unit weight, moisture content, and soil-water potential.

Shackel [51] indicated that repeated loadings tend to reduce soil suction for a given combination of unit weight and degree of saturation. His work indicates the necessity to consider the effects of previous stresses when investigating soil suction. He established that the matrix suction was a function of both the degree of saturation and the dry unit weight, and that the suction, unit weight, and saturation relationship could be represented on a three-dimensional plot as a surface. Black and Lister [50] showed that measured suction values were functions of moisture content, dry unit weight, and stress history.

The differences in shear strength between the adsorption and desorption cycle is primarily caused by the unit weights of the soil at each particular soil-water potential. With this in mind, it is possible

to obtain a unique value of shear strength in terms of the soil-water potential at a given dry unit weight. When three-dimensional plots of shear strength, soil-water potential, and dry unit weight are prepared, a shear-strength surface is formed that provides a unique relationship between soil-water potential, shear strength, and dry unit weight.

Yong [11] concluded that:

> "... the problem of determination of unsaturated soil strength, which is pertinent particularly to the difficulties associated with stability analysis, can be successfully evaluated provided one can develop a set of relationships which describe the unsaturated soil strength in relations to the degree of unsaturation and water content."

He also questioned the use of a two-parameter failure theory (i.e., Mohr-Coulomb) to fully describe soil failure during the entire stage of soil unsaturation.

REASONS FOR CRL APPARATUS DEVELOPMENT

The CRL apparatus was modified to measure negative pore pressures, to solve a recurring problem encountered with the UU triaxial shear test, and to choose a loading rate compatible with the material being tested. Before modification, if the strain rate was too fast, measured pore pressures would not be representative of the pore pressures throughout the specimen. If the strain rate was too slow, valuable time was lost. As Bishop et al. [47, 52] and Ellis and Holtz [53] pointed out, when only one location is used to measure pore pressure, the shear test should be run at a rate that permits the pore pressure to equalize over the entire specimen. Otherwise, pore-pressure readings may lead to improper conclusions.

Ellis and Holtz [53] stated that one way to determine the maximum strain rate for testing a soil specimen, while ensuring accurate pore-pressure measurement, is to maintain a continuous plot of pore pressure versus volume change. A comparison between actual pore-pressure measurements and theoretical curves could be made. When the correct strain rate is used, the two curves should closely correspond.

Bishop et al. [47, 52] developed a theoretical relationship between time to failure, t, expressed as time factor, $T = c_v t/H^2$, for an undrained sample of height, $2H$, and degree of equalization of the nonuniformity in pore-pressure setup during shear. The value for c_v was determined from a dissipation test on partly saturated soil [54]. A strain rate was selected so that the specimen failed at time t.

Currently in the USBR (Bureau of Reclamation) laboratory, a measurement of maximum suction, u_c is made using the exposed end-plate method [24], and u_a is calculated using equation (4). From experience, a u_c line is generated, and from it and the u_a line, a u_w line is also determined (fig. 1). As the lateral pressure on the specimen is increased, measurements of pore-water pressure, u_w, are made. These measurements are made only when they are above approximately –8 lb/in² (–55.16 kPa) to prevent cavitation of the measuring system. If the measured u_w values are approximately the same as the calculated u_w values, the loading rate is correct. If the measured u_w values consistently fall above the u_w line, then the specimen is probably being loaded too fast, and the loading rate is decreased. However, remember that the location of the u_w line is an educated guess, and interpretation of the appropriateness of the loading rate involves judgment. After the lateral pressure is applied, the deviator stress is applied at 0.001 in/min (0.000 423 mm/s), and the specimen is tested to failure.

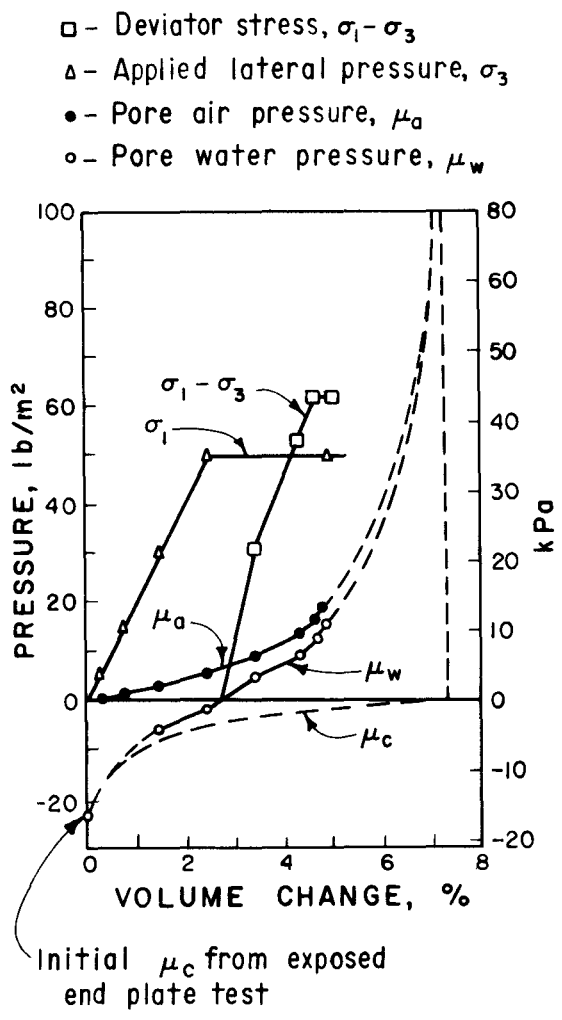

Figure 1. – UU test on an unsaturated specimen.

Various techniques have been used to measure the u_c line [24]. However, none have been successful. The new apparatus and test procedure were developed to solve problems inherent with the other techniques described above. The apparatus can measure initial suction pressure and suction pressure as a specimen is compressed. This allows a relatively accurate determination of the u_c line. Once this line is established, u_w can be determined and an appropriate loading rate selected.

When the suction response to the compression of a material is determined, the response of unsaturated foundation material can be checked against laboratory measurements. If anomalies are discovered, remedial action may be taken, if necessary, before potential problems become serious.

SUGGESTED TESTING PROGRAM

The capabilities of the CRL apparatus for determining the suction characteristics of a material should be determined. The following approach is recommended:

1. *Review the procedure.* Review the evaluation procedure for the CRL apparatus presented in the Geotechnical Branch memorandum in appendix A before the testing suggested in items 2, 3, and 4. The main points of this memorandum are

   a. Perform a more current literature search (from about 1980 to the present).

   b. Procure and evaluate a thermocouple psychrometer.

   c. Evaluate the use of the ceramic side stones in the floating confining ring.

   d. Evaluate the effect of specimen unloading techniques on C_{rb} (rebound index) values.

   e. Evaluate the modified bottom end plate.

2. *Initial maximum suction.* Compare the maximum suction values obtained with the CRL apparatus to values obtained from the exposed end-plate method. A number of comparisons should be made using a wide variety of soils with various suction characteristics.

3. *Suction change with compression.* All specimens placed in the CRL apparatus for determination of initial maximum suction should be compressed and their suction values recorded. All

tests should have duplicates run so that the repeatability of the CRL data can be determined. In addition, the use of a thermocouple psychrometer during this stage of testing should be investigated and, if practical, one should be used to check the readings from the CRL apparatus.

4. *UU triaxial shear tests*. Comparisons of results should be made between tests on soil specimens using conventional UU techinques and techniques modified (loading-rate adjusted) in accordance with the results from the CRL apparatus. In addition, the usefulness of thermocouple psychrometers should be investigated. Results from the psychrometer should be compared with the results obtained from conventional tests and, if appropriate, more comparisons and evaluations should be conducted to determine the applicability of such devices.

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APPENDIX A

RECOMMENDED EVALUATION PROCEDURE FOR THE CRL (CONSTANT RATE OF LOADING) APPARATUS

Memorandum
Geotechnical Branch Files

Denver, Colorado
March 11, 1985

Chief, Geotechnical Branch
Section Head, Soil Testing Section
Supervisor, Unit No. 2, Soil testing Section

Kurt von Fay, Civil Engineer

Recommended Evaluation Procedure for the CRL (Constant Rate of Loading Apparatus

Geotechnical Branch Memorandum Reference No. 85-22

Written by: Kurt von Fay

SUMMARY, INCLUDING RECOMMENDATION

This memorandum presents a procedure for evaluating the CRL apparatus. Included in the appendix is a brief description of the apparatus and testing progress, providing background information about the apparatus.

The evaluation procedure should be performed before conducting any other extensive research activities.

SUGGESTED EVALUATION PROCEDURE

Below is the suggested evaluation procedure for the CRL apparatus. Several aspects fo the CRL apparatus are recommended for investigation because of findings from literature and results from previous CRL testing.

1. Perform another literature search on soil suction, soil water potential, negative pore pressure*, etc., from 1980 to the present.

2. Procure and evaluate, if possible, a thermocouple psychrometer for measuring soil water potential. Compare the results from the psychrometer to those from the CRL apparatus and exposed end plate method.

* Generally speaking, soil suction, soil-water potential, and negative pore pressure are equivalent quantities.

3. Evaluate the size and function of the ceramic side stones in the floating confining ring. This may be done as follows:

(a) Place a saturated specimen in the floating confining ring, and allow the pore water to drain through the top end plate only.

(b) Test the specimen at a loading rate fast enough to generate a pore pressure ratio of 30 percent to 40 percent.

(c) Check to see that the pore pressure readings of the side stones are in agreement with what they theoretically should be, assuming a parabolic pore pressure distribution in the specimen.

(d) If the readings do not correlate, then one or more problems exist. Among the possible problems are:

(1) The ceramic side stones may be too large.

(2) There may be a smearing effect across the surface of the ceramic stones.

(3) Piping may occur between the side of the specimen and the specimen container.

4. Evaluate the effect of specimen unloading procedure on Crb (rebound index) values. Differences between Crb values from the CRL and the STD apparatus were documented in a draft of the initial CRL report prepared for ASTM [1]*.

5. Evaluate the modified botton end plate to determine if it functions as anticipated.

(a) The modified bottom end plate incorporates a small fine ceramic stone placed in the center of

* Numbers in brackets refer to entries in the bibliography.

the carborundum disk; it was designed for use during compression of unsaturated, undrained soil speciments. If the specimen is being loaded at a loading rate slowly enough to allow pore pressure equalization, the bottom ceramic stone pore pressure reading should approximately equal the side ceramic stone pore pressure readings.

(b) Deflection of the bottom ceramic stone will cause erroneous pore pressure readings; if that occurs a smaller stone may alleviate the problem.

(6) Conduct the research outlined in the draft [2] of the report on negative pore pressure.

By performing this evaluation of the CRL apparatus, a greater understanding of its potential, usefulness, and limitations will be obtained.

RECOMMENDATION

Performing the evaluation procedure for the CRL apparatus is recommended before conducting any other extensive research activities.

Attachments

Copy to: D-915
D-1540
D-1541
D-1541 (von Fay)

Kvon Fay: baf

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[1] von Fay, Kurt F., and Charles E. Cotton, draft of "CRL (Constant Rate of Loading) Consolidation Test," prepared for the ASTM Symposium on Consolidation Behavior of Soil, January 24, 1985, and for an upcoming ASTM Special Technical Publication (STP) to be published in 1985.

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Ed. note: Biblio. [1] to be published in the 1st quarter of 1986 in ASTM STP 892

APPENDIX

During the early 1980's, a constant rate of loading (CRL) consolidation apparatus was developed. It's main components are:

1. A floating confining ring embedded with two diametrically opposed ceramic stones for pore pressure measurement

2. Carborundum porous disks in the top and bottom end plates, for draining soil water

3. A constant rate of loading drive system

At that time, a multistaged investigation process was initiated. Among the features identified for investigation were:

1. The CRL apparatus consolidation testing capabilities
2. The capability of the ceramic stones to measure both the initial suction pressure and the suction pressure as the specimen was compressed one-dimensionally

Literature searches were conducted prior to and during the performance of these studies.

As a result of the investigation process, the following reports were prepared:

1. A report [3] was published discussing the results of comparative consolidation testing performed using the CRL apparatus and standard incremental loading (STD) device, and findings from the literature search.

2. A draft report [2] was prepared discussing various aspects of negative pore pressure measurement and soil-water potential determination. The draft report presents a broad review of much of the literature through about 1980, and discusses various theories concerning soil suction and soil-water potential measurement, use, and evaluation. A testing program is also suggested in the draft for determining the suction measurement capabilities of the CRL apparatus.

GPO 848-786

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The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

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