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16. Abstract The process of slope failures in high-plasticity clays involves formation of surface cracks, moisture infiltration through the cracks into the soil mass, a reduction in suction and hence shearing resistance of the soil, and ultimately slope failure when the driving stresses exceed the shearing resistance of the soil. Similar processes can impact other earth structures such as retaining walls and pavements. Two issues addressed in this report are the rate of moisture diffusion into the soil mass and the practical limit to which suction and soil shearing resistance degrade. The rate at which moisture diffusion infiltrates into the soil is a key factor in assessing the depth to which strength degradation due to seasonal fluctuations in moisture is likely to occur. This project adopts an approach originally proposed by Australian researchers for analyzing moisture infiltration through partly saturated soils. This approach utilizes a linear diffusion equation for characterizing moisture infiltration. This approach requires a single material parameter: a $\alpha$ -coefficient governing the rate of moisture infiltration. Researchers on this project developed a simple laboratory test for evaluating this parameter by measuring the changes in suction that occur in an undisturbed soil sample when one end of the sample is dried. Preliminary results are very encouraging, although improved methods of measuring soil suction would greatly improve the test. Researchers on this project also investigated the lower limit of suction that will occur in the field due to wetting of soils. These studies were largely based on back-analysis of apparent soil suction from documented slope failures. These studies showed that the matric suction at failure generally is in the range $pF=1.6$ to $1.8$ .					
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# **PROPERTIES OF HIGH-PLASTICITY CLAYS**

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## **DISCLAIMER**

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## **CHAPTER 1: INTRODUCTION**

High-plasticity clays occur in many areas of Texas and often offer the most economical material alternative for construction of highway embankments. When constructed with proper moisture and compaction control, embankments constructed of plastic clays can perform adequately with regard to overall stability. However, experience shows that the outer layers of these embankments can experience dramatic strength loss. Softening of the surficial soils can begin soon after construction and continue for decades. The consequent sloughing and shallow slide failures represent a significant maintenance problem for TxDOT. The problem of strength loss in high-plasticity clay soils can also impact other structures such as retaining walls, pavements, and riprap; the general issue of strength loss is addressed in the current project.

Two issues must be addressed regarding the problem of strength degradation: (1) the degree of strength loss occurring in the soil and (2) the depth to which this strength degradation will occur. The model proposed in this project for addressing the above questions entails the following:

- During dry periods, cracks develop in the soil surface. The depth and spacing of cracks will depend on the intensity and duration of the dry period as well as the type of vegetation on the slope.
- During wet periods, moisture penetrates into cracks and diffuses into the soil mass, thereby reducing the suction in the soil.
- The reduction in suction due to infiltrating moisture results in a reduction in soil strength. When the strength declines to levels less than the driving stresses associated with the weight of the soil mass, failure occurs.

Within the context of this model, the relevant material properties for compacted soils are as follows:

- *The magnitude of strength degradation* is controlled primarily by soil suction and the angle of internal friction  $\phi'$  of the soil. Note that soil suction in the field could vary from pF 2.5 to 5.5 (650 psf to 650,000 psf); i.e., three orders of magnitude. In contrast, the range of friction angles for natural high-plasticity clays is between 20 and 30 degrees. Hence, the suction characteristics of a soil are a key factor in understanding its behavior. A particularly important aspect of suction is the lower limit of suction that can be anticipated in the field, as this will play a crucial role in predicting the lower bound of soil strength. Therefore, in this project the primary effort has been directed toward understanding suction behavior, although some effort will be directed toward the friction angle for the particular soils under investigation.
- *The spatial extent of strength degradation* is controlled primarily by three factors: (1) the depth and spacing of surface cracks, (2) the magnitude and frequency of seasonal variations in moisture conditions at the exposed ground and crack surfaces, and (3) the moisture

diffusion properties of the soil. In this project, researchers are formulating two models for simulating this process. The first model predicts the depth and spacing of soil surface cracking. The second model predicts the depth of moisture infiltration for a given magnitude and frequency of climatic moisture variations at the ground surface. A fundamental parameter in the latter model is the  $\alpha$ -coefficient that controls the rate of moisture diffusion through the soil. As the  $\alpha$ -coefficient increases, the depth of influence of seasonal fluctuations in moisture at the ground surface will correspondingly increase. Hence, at this point the  $\alpha$ -coefficient appears to be a critical parameter in establishing to what depth strength degradation in high-plasticity clays is likely to be a problem.

The focus of this report is to address the material properties of high-plasticity clays that will control strength degradation. Hence, the above-mentioned moisture infiltration model is not presented further in this report, although it will be presented in the final report for this project.

The program for establishing the material parameters needed to predict the degree and extent of strength degradation of soils includes the following elements:

- A diffusion test for measuring the  $\alpha$ -coefficient is being developed. The test utilizes essentially any size undisturbed tube sample. By exposing one end of the sample to the atmosphere and sealing all other boundaries, moisture will migrate through the sample as drying occurs. The rate of moisture migration is monitored by measuring changes in soil suction as a function of time and location. In the current tests, thermocouple psychrometers measure the suction, although some promising more robust measurement devices may be considered in future projects and applications. Interpretation of the test is accomplished by finding the  $\alpha$ -coefficient (through a computer optimization procedure) that provides a best fit between theoretical and measured relationships of location, time, and suction. As this is not an established test procedure, considerable trial and error effort has been devoted developing a workable test procedure. At this point, seven tests have been performed, and refinements to the procedure are still in progress. Preliminary interpretations have been completed for three of the tests, presented later in this report. Like the test procedure, the computer code for interpreting the test is still being tested and refined.
- Suctions back-calculated from field slope failures are considered to be the most reliable means of establishing a lower bound of suction that is likely to occur in the field. A documented series of slope failures in Paris clays (16 sites) and Beaumont clays (18 sites) provides a solid database for back-calculating lower limits of suction in Texas high-plasticity clays. Researchers are also performing filter paper suction measurement tests on selected samples from the field to provide a database to support the back-calculated suction values.
- Review of the previous test data indicates that  $\phi'$  for these clays is consistent with  $\phi'$  versus plasticity index (PI) reported in the geotechnical literature. Therefore the friction angle  $\phi'$  is estimated on correlation to PI, with the main focus of the effort being directed toward establishing the diffusion  $\alpha$ -coefficient and the lower bound of suction.
- Conventional geotechnical index tests are being performed on soil samples used in the diffusion tests and other samples. These tests include consistency limits, specific gravity, and particle size analyses.

Chapter 2 of this report describes the high-plasticity clays obtained for this project and summarizes the results of the index property tests. Soil suction plays an important role in the strength degradation behavior of high-plasticity clays; Chapter 3 presents an overview of basic definitions and concepts relating to suction and briefly describes the methods of measuring suction that are being utilized in this project. Chapter 4 discusses the characterization of moisture diffusion properties of partly saturated clays. The discussion in Chapter 4 includes the theoretical development of a linearized diffusion equation and the definition of the  $\alpha$ -coefficient, the proposed test procedures for evaluating moisture diffusion properties, and preliminary test results. Chapter 5 summarizes the studies for identifying a lower bound for field suction and hence the lower bound of strength controlling failures in shallow soils. Chapter 6 summarizes the progress to date and planned future work.



## CHAPTER 2: TEXAS HIGH-PLASTICITY CLAYS

TxDOT arranged for the delivery of a number of high-plasticity clay samples to Texas A&M University (TAMU). Descriptions of the soil samples and summaries of the classification and index tests are contained in the following sections.

### SAMPLES COLLECTED FOR CURRENT PROJECT

Table 1 describes the samples from the Waco site.

**Table 1. Soil Sample Index – Waco Site.**

Sample	Depth	Description
1	8-10 ft	Light brown fat clay with coarse to medium sand, roots, maximum particle size coarse sand (CH)
2	6-8 ft	Orange-brown fat clay, with coarse sand and gravel, roots, maximum particle size gravel (CH)
3	12-14 ft	Medium brown fat clay with medium sand, roots, maximum particle size coarse sand (CH)
4	2-4 ft	Dark brown fat clay, with coarse sand and gravel, maximum particle size gravel (CH)
5	2-4 ft	Dark brown lean clay with coarse sand and gravel, roots, maximum particle size gravel (SC)

### SAMPLE PREPARATION AND TESTING

Table 1 shows the five different samples used in this project. The samples were prepared by removing large rocks and organic matter by hand. The samples were then placed in large bowls and soaked with an excess of distilled water for 24 hours. The samples were then mixed and allowed to air dry to a moist consistency.

After each sample was prepared, the Atterberg limits were determined following the American Society of Testing Materials (ASTM) Standards D854-58 methods (1). The liquid and plastic limit methods were repeated four times for each sample. Liquid limit, plastic limit, water content, and plasticity index were calculated. The samples were then allowed to completely air dry and were ground thoroughly.

Next, the specific gravity was determined for the samples. For each sample, 50 g of dry soil was weighed and poured into a 250 mL flask. Distilled water was added and the flask was then placed under a vacuum. The mixture was agitated for 20 minutes to remove air from the soil and water mixture. Each flask was placed in a temperature bath for 48 hours allowing for the temperature to equilibrate to 70° F. A 250 mL flask was filled with de-aired water and also placed in the temperature bath. After temperature equilibration, the researcher weighed both flasks. The flasks were each weighed and the soil mixtures were oven dried to obtain a dry soil weight. The specific gravity was determined based on the above measurements.

The particle size distribution was determined for each sample by a sieve analysis following ASTM Standards D854-58. Using the wet process, 50 g of each sample was passed through an ASTM No. 200 sieve opening of 0.075 mm. The samples were washed through the sieve with distilled water. The weights of the pan, sieve, and containers were recorded before and after the process to determine the percentage passing and retained. The percent fines (minus No. 200 sieve) was calculated for each sample.

A hydrometer analysis following the ASTM Standards D854-58 method was also completed on each sample. A 50 g sample of soil was mixed with distilled water and 125 mL of a sodium hexametaphosphate solution. The mixture was blended for two minutes and transferred to a 1000 cc cylinder containing distilled water. The cylinder was shaken and then, using an ASTM 151H hydrometer, readings were taken at specified times. The hydrometer was calibrated and the temperature was taken at the beginning and end of each experiment. The diameters of the particles were then calculated for each soil.

## SUMMARY OF INDEX PROPERTIES

Table 2 summarizes the properties of the five Waco site samples. Four of the five samples (Samples 1-4) contained more than 50 percent fines. Based on their location in the plasticity chart, these samples are classified as fat clays (CH). The fifth sample (Sample 5) contains fewer than 50 percent fines and is therefore classified as clayey sand (SC).

**Table 2. Summary of Index Properties – Waco Site.**

Sample	Liquid Limit	Plastic Limit	Plasticity Index	Specific Gravity	Fines Content (%)
1	66	22	44	--	92.3
2	58	22	36	2.71	78.1
3	56	22	34	2.69	55.5
4	62	25	37	2.66	56.1
5	39	17	22	--	45.3



## CHAPTER 3: SOIL SUCTION

Soil suction plays a central role in characterizing the strength, deformation, and permeability characteristics of partly saturated clays. This is particularly true for shallow soils, where mechanical stresses are small and effective stress on the soil skeleton is almost entirely due to suction. The following section reviews the basic definitions of suction and some basic methods of measurement relevant to this research.

### TOTAL, MATRIC, AND OSMOTIC SUCTION

Fredlund and Rahardjo define total pore water suction by the Kelvin equation (2):

$$h_t = (\rho_w RT/M) \ln (p/p_0) \quad (\text{Eq. 1})$$

where  $\rho_w$  = the mass density of the water (1000 kg/m<sup>3</sup> for water)

$M$  = molecular weight of water (0.01802 kg/mole for water)

$T$  = absolute temperature, degrees Kelvin

$R$  = universal gas constant, 8.314 N-m/mole-°K

$p$  = vapor pressure of water vapor

$p_0$  = saturated vapor pressure of pure water vapor

Noting that  $p/p_0$  is the relative humidity, RH, we can rewrite Eq. 1 as:

$$h_t = (\rho_w RT/M) \ln (RH) \quad (\text{Eq. 2})$$

Since the RH is always less than one, the total suction will necessarily be negative. The presence of impurities in the soil water (e.g., dissolved salts) requires a distinction between the saturated vapor pressure in distilled water versus the soil water. Eq. 1 is therefore expressed equivalently:

$$h_t = (\rho_w RT/M) \ln (p/p_s) + (\rho_w RT/M) \ln (p_s/p_0) \quad (\text{Eq. 3})$$

where  $p_s$  is the saturated vapor pressure of the soil water vapor. The first and second terms of Eq. 3 are defined as the osmotic suction  $\pi$  and matric suction  $h_m$ , respectively. Hence, the total suction in Eq. 3 can be expressed more simply as the sum of osmotic and matric components of suction:

$$h_t = \pi + h_m \quad (\text{Eq. 4})$$

## RELEVANCE TO ENGINEERING BEHAVIOR

The distinctions between total, osmotic, and matric suction must be understood in order to relate soil suction to engineering behavior. In particular, the following items are noted with regard to total and matric suction:

*Total suction:* Water seepage velocity is related to the free energy gradient; hence, the total suction  $h_t$  becomes the relevant variable for water seepage calculations. In this connection, it is noted that while the thermodynamic definitions of suction (Eqs. 1 and 2) may not initially appear directly relevant to the practicing geotechnical engineer, they become extremely useful when characterizing the boundary condition for evaporation water at a soil-air interface. That is, if the RH of the air is known, Eq. 2 establishes the ‘air suction’ that controls the rate of moisture evaporation from the soil. This point is pursued further in Chapter 4 of this report.

*Matric suction:* Intergranular stresses between soil particles are directly related to matric suction. Hence, the matric suction  $h_m$  together with the net mechanical stress exerts a strong influence on the stress-strain-strength properties of a soil. In shallow soils such as the shallow slope problem addressed in this project, the net mechanical stress becomes small, and the matric suction becomes the major variable controlling strength and deformation.

## MEASUREMENT OF SUCTION

Suction in soils can be measured by a number of well-established test methods, including psychrometers, filter paper, tensiometers, and the pressure plate apparatus (1,2). The psychrometers and the filter paper test being used in this project are briefly described in the following paragraphs.

*Thermocouple psychrometers* measure total suction by measuring the relative humidity of the air phase in a soil. The measurement of relative humidity is based on the temperature difference between an evaporating (dry bulb) and a non-evaporating (wet bulb) surface. Psychrometers can provide reasonably reliable measurements over a soil suction range of about pF 3.0 to 4.5.

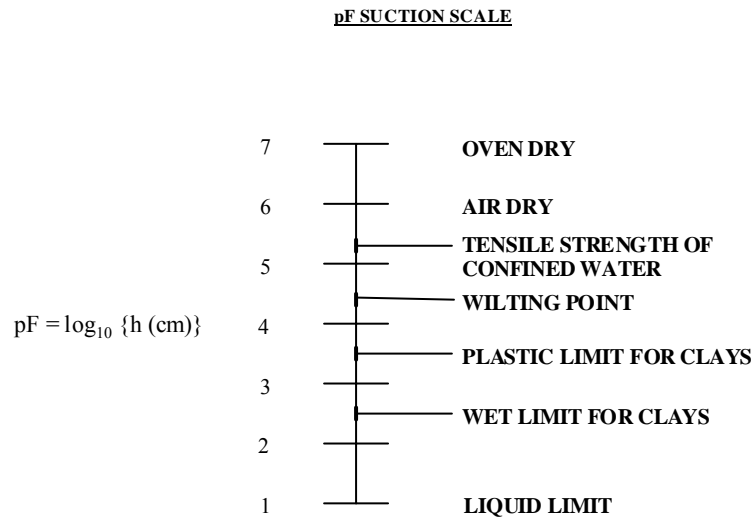
The *filter paper* test involves putting a piece of specially calibrated filter paper in a sealed container with a soil specimen. Over a sufficient time interval (about one week), moisture will flow from the soil to the filter paper until equilibrium is achieved; i.e., when the moisture in the soil and the filter paper are at the same suction. By measuring the water content of the filter paper, the difference between the wet and dry weight of the paper divided by the dry weight of the paper, the equilibrium suction can be determined based on the calibration curve appropriate for the specific type of filter paper. If the filter paper is not in direct contact with the soil, the test will measure the relative humidity of the air phase of the soil, thereby providing a measure of the total suction,  $h_t$ . If the filter paper is placed in direct contact with the soil, the water is absorbed directly from the soil pores into the paper, thereby providing a measure of matric suction,  $h_m$ .

## THE PF SCALE

A logarithmic scale for expressing suction used by soil scientists is defined as follows:

$$u(\text{pF}) = \log_{10} (-\text{suction, cm of water}) \quad (\text{Eq. 5})$$

Figure 1 shows the typical pF values for conditions of practical interest. It should be emphasized that on the pF scale, osmotic and matric suction are no longer additive, and calculations should always be made using Eq. 2 before converting to a pF scale. In addition to being useful for characterizing the wide range of suctions possible in soils, the pF scale will also prove very useful for partly saturated seepage calculations, as demonstrated in Chapter 4.



**Figure 1. The pF Suction Scale.**



## **CHAPTER 4: MOISTURE DIFFUSION THROUGH CLAY**

A key aspect of the present project is the evaluation of the moisture diffusion characteristics of high-plasticity clays, as these characteristics control the time at which significant weakening and possible consequent failures can occur in clay slopes or other earth structures. In general, moisture diffusion through a partly saturated soil is a highly non-linear process due to the dependence of both the soil permeability and the moisture storage properties on the degree of saturation. Hence, treatment of moisture diffusion through a partly saturated soil using a conventional approach would involve:

- An extensive experimental testing program to evaluate the permeability and moisture storage coefficients as a function of degree of saturation.
- A non-linear solution algorithm (e.g., non-linear finite element code) to simulate moisture diffusion in problems involving the complex boundary conditions and material variability that actually occurs in field problems.

Such an effort would realistically be feasible only on very large projects or for special research projects.

The approach adopted in this project is based on a simplified formulation proposed by Mitchell, when dealing with a similar moisture diffusion problem applied to shrink-swell in expansive clays (7). The approach simplifies the problem to a linear form. This simplified approach has the following substantial advantages:

- Material behavior is characterized by a single diffusion coefficient that can be evaluated with little ambiguity with a relatively simple test. Thus, needed material data can be obtained in a straightforward practical manner.
- Actual problems can be simulated with linear analyses that can be solved with relatively simple spreadsheet analyses or computer codes.

### **THEORETICAL FRAMEWORK**

The rate of diffusion of moisture through a partly saturated soil is governed by the soil permeability and by the moisture-suction characteristic curve.

#### **Permeability**

Permeability is defined by Darcy's law, which in one dimension is:

$$v = -k \, d\phi/dx \quad (\text{Eq. 6})$$

where  $v$  = discharge velocity  
 $k$  = permeability  
 $\phi$  = total potential (total head)  
 $x$  = distance

In saturated soils, the permeability  $k$  is essentially constant. However, in partly saturated soils, the permeability is dependent on the degree of saturation, or in a more convenient formulation, on the total suction  $h_t$ . It should be noted that the total suction is related to potential by:

$$\phi = h_t + z \quad (\text{Eq. 7})$$

where  $z$  is the vertical coordinate. Laliberte and Corey propose the following permeability suction relationship (4):

$$k = k_0 (h_0 / h_t)^n \quad (\text{Eq. 8})$$

where  $k_0$  = reference permeability (saturated)

$h_0$  = total suction corresponding to reference state (approx. 100cm or pF=2.0)

$n$  = material constant, approximately equal to 1 for clays

Mitchell proceeds to show that, if changes in elevation  $z$  are small relative to the magnitude of suction,  $\phi = h_t$ ; hence, if  $n=1$  (typical for clays) (7):

$$v = -k_0 (h_0 / h_t) (dh_t / dx) \quad (\text{Eq. 9})$$

Noting that  $dh_t / h_t = d \log_e h_t$ , it follows that:

$$v = - (k_0 h_0 / 0.434) d (\log_{10} h_t) / dx \quad (\text{Eq. 10})$$

Mitchell expresses this equivalently (7):

$$v = -p \, du / dx \quad (\text{Eq. 11})$$

where  $p = -k_0 h_0 / 0.434$

$u$  = total suction on a pF scale =  $\log_{10} h_t$ (cm of water)

Although Mitchell's proposed approach is an approximation, it permits linear solution of Laplace's equation. Hence, partly saturated seepage problems can be treated using the analytical tools that have been established for saturated flow including flow nets, closed form analytical solutions, and linear finite difference and finite element analyses – with the solution variable being  $u$ (pF) instead of potential  $\phi$ .

### Moisture Characteristic

The soil moisture characteristic curve defines the relationship between total suction and water content. This relation establishes the moisture storage term for unsteady partly saturated seepage problems. Mitchell defines the moisture characteristic  $c$  as the slope of the water content versus logarithm total suction ( $h_t$ ) curve, or if total suction is expressed on a pF scale, the slope of the water content versus suction (pF) curve (7):

$$c = dw / du \quad (\text{Eq. 12})$$

where  $c$  = moisture characteristic  
 $w$  = gravimetric water content = weight water/weight solids  
 $u$  = suction on pF scale

For purposes of a simplified analysis, Mitchell proposes a linearized analysis in which  $c$  is constant (7). Data presented by Mitchell indicates that this is a reasonable assumption for  $pF = 2.0$  to  $4.0$  (7). It is well known that the soil moisture characteristic curve can exhibit considerable hysteresis; i.e., the curve differs for wetting versus drying. However, in the simplified analyses described subsequently, hysteresis will be neglected (2).

### Formulation for Unsteady Flow

By invoking the conservation of mass condition in a manner that parallels the well-known formulation for saturated flow, Mitchell shows the following diffusion equation (7):

$$\nabla^2 u = \frac{1}{\alpha} \frac{\partial u}{\partial t} \quad (\text{Eq.13})$$

where  $u$  = total suction on a pF scale  
 $t$  = time  
 $\alpha$  = a diffusion coefficient =  $p / \gamma_d c$   
 $\gamma_d$  = soil dry unit weight

Like the coefficient of consolidation  $c_v$  in saturated soils, the diffusion coefficient  $\alpha$  is not a fundamental material parameter. Rather it is proportional to the ratio of two fundamental parameters; namely, the permeability parameter  $p$  and the storage coefficient  $c$ . As adoption of the  $c_v$  parameter is convenient in test interpretation analysis of consolidation for saturated soils, the  $\alpha$ -coefficient will be shown to be quite convenient in test interpretation and analysis of moisture diffusion through partly saturated soils.

### Boundary Conditions

Solution of the diffusion equation requires definition of the boundary conditions. Two conditions are particularly pertinent to problems of practical interest: (1) a prescribed suction on a boundary and (2) evaporation of moisture from the soil. The first boundary condition is analogous to a prescribed total head on a boundary in fully saturated flow problems. Analytical treatment of this condition is straightforward and requires little further discussion here.

However, evaporation of moisture from the surface of a soil surface is not a conventional boundary condition for fluid flow problems; i.e., neither the potential on the boundary nor the flux across the boundary is prescribed. Mitchell proposes a boundary condition in which the moisture flow across the boundary is linearly proportional to the difference between the atmospheric suction and the suction at the soil surface (7). Equation 14 represents this thought.

$$\left( \frac{\partial u}{\partial x_n} \right)_s = -h(u_s - u_a) \quad (\text{Eq.14})$$

where  $h$  = an evaporation constant, assumed to be independent of suction  
 $u_s$  = the suction at the soil boundary  
 $u_a$  = the atmospheric suction

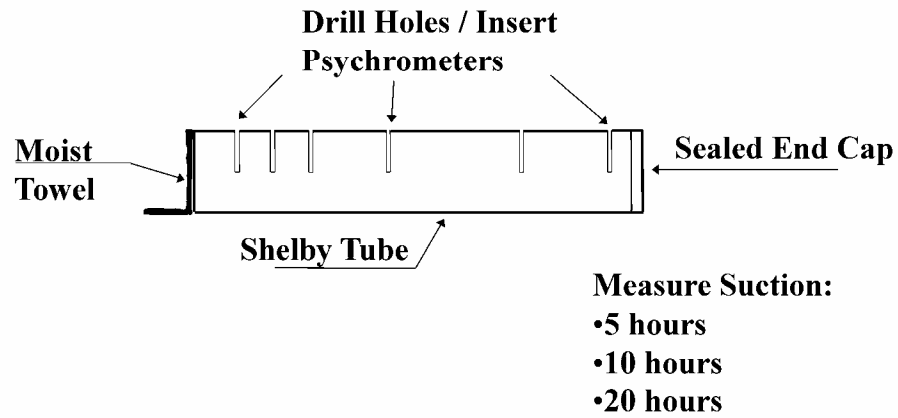
Mitchell reports a magnitude of  $h=0.54\text{cm}^{-1}$  for Australian high-plasticity clays (7).

## LABORATORY EVALUATION OF THE DIFFUSION COEFFICIENT

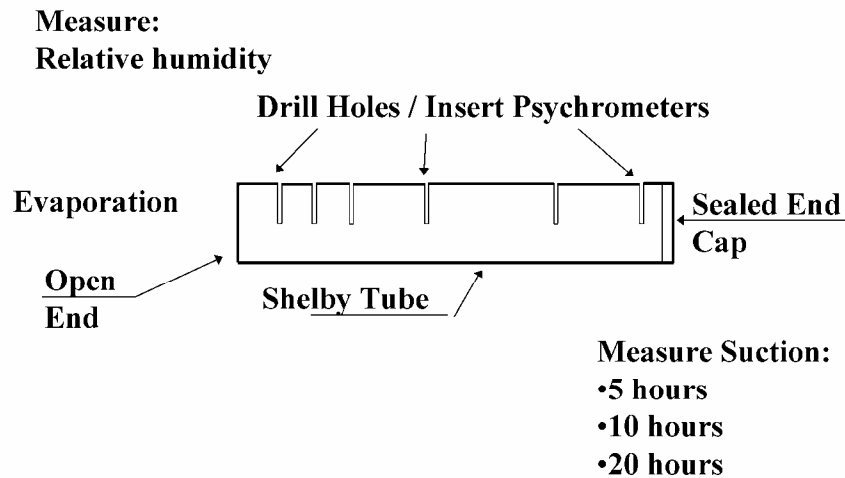
To evaluate the diffusion coefficient  $\alpha$  in the laboratory, Mitchell proposed two tests that could be performed on conventional undisturbed soil samples, such as Shelby tube samples (7). In both tests, the sides and one end of the sample are sealed as shown in Figure 2. The other end of the sample is left open to permit the flow of moisture into or out of the sample as will be discussed subsequently. Small holes are drilled in to the sides of sample at several locations and psychrometers are installed for measuring suction. For the recent tests performed at TAMU, six thermocouple psychrometers were installed. By measuring suction as a function of time and location, the theory developed in Chapter 4 of this report can be used to back-calculate the diffusion coefficient  $\alpha$ .

Different tests are possible by controlling the suction boundary at the open end of the sample. If the suction imposed on the boundary is less than that in the soil, water will flow into the soil. This 'wetting' test can be achieved by means of a wet cloth as shown in Figure 2, with one end of the cloth in contact with the open end of the soil and the other end put in a tray of water. Fixing the vertical distance between the tray of water and the soil specimen can control the degree of suction at the open end of the soil. Conversely, drying of the specimen can be achieved by exposing the open end to the atmosphere. Except for extremely dry soils, the relative humidity in the soil typically exceeds 99 percent, while that of the atmosphere is about 50 percent; hence, exposure of the open end to air will cause moisture to flow out of the soil at the open boundary. Interpretation of both the drying and wetting tests is possible using the analytical solutions shown in Figures 3 and 4.



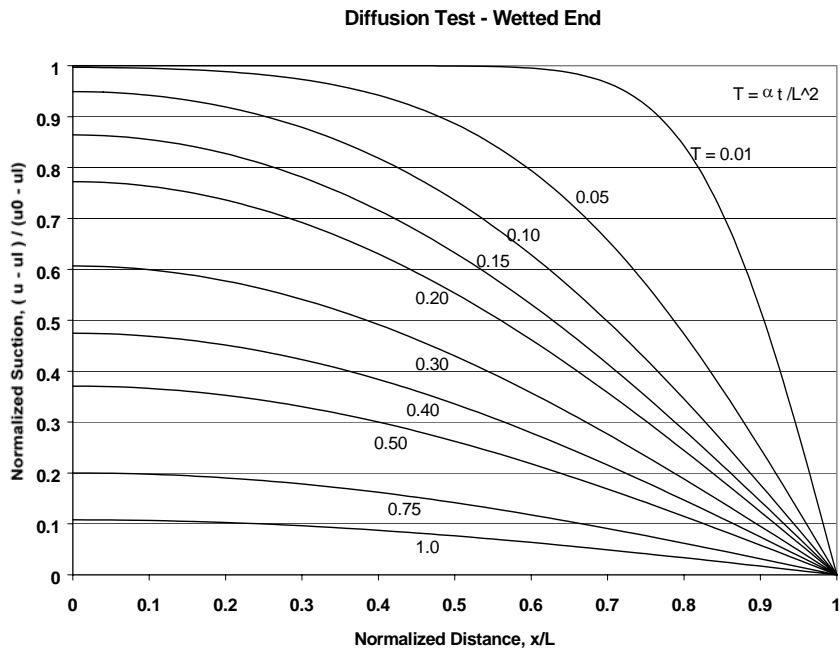


### **WETTED END – DIFFUSION TEST**

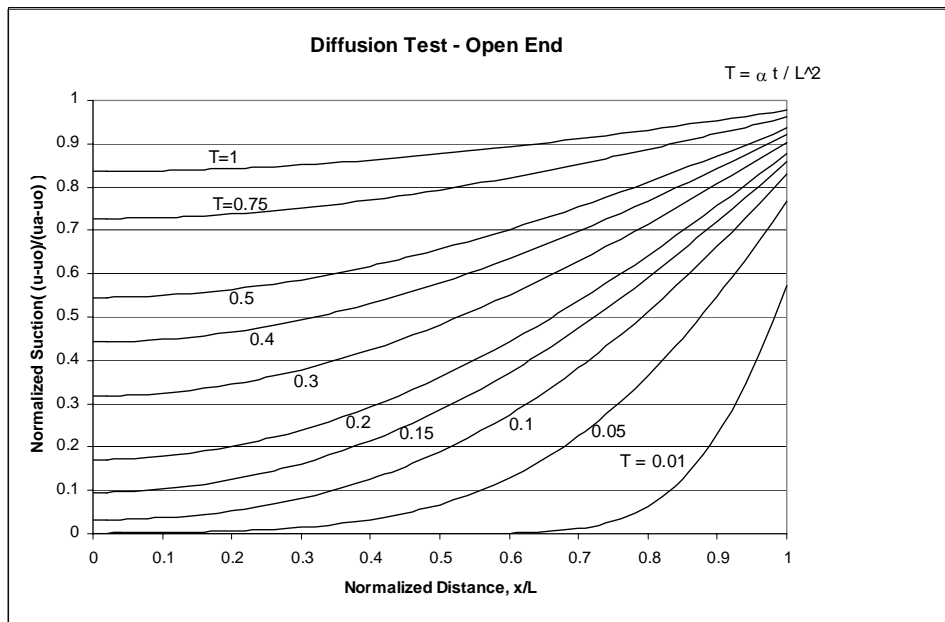


### **OPEN END – DIFFUSION TEST**

**Figure 2. Proposed Laboratory Tests for Measurement of Diffusion Coefficient  $\alpha$ .**



**Figure 3. Dimensionless Solution for Wet-End Diffusion Test**



**Figure 4. Dimensionless Solution for Open-End Diffusion Test.**

## Wetting Test

Mitchell presents an analytical formulation of the wetting test that results in a solution identical in form to the Terzaghi consolidation solution for single drainage (7). The solution is obtained from the diffusion equation (Eq. 13) with a zero flux boundary at the closed end and a prescribed suction at the open end. From a Laplace transform solution, Mitchell gives the following solution for suction  $u(x,t)$  as a function of time and coordinate in the soil sample (7):

$$u = u_l + \frac{4(u_l - u_0)}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{2n-1} \exp\left[\frac{(2n-1)^2 \pi^2 \alpha t}{4l^2}\right] \cos\left[\frac{(2n-1)\pi x}{2l}\right] \quad (\text{Eq.15})$$

where  $u_l$  = prescribed suction on boundary  
 $u_0$  = initial suction in soil  
 $\alpha$  = diffusion coefficient  
 $t$  = time  
 $l$  = sample length  
 $x$  = coordinate

With  $\alpha$  known, the distribution of suction at a given time can be predicted using Eq. 15. The solution is illustrated in dimensionless form in Figure 3. In the interpretation of the wetting test, an inverse procedure is employed in which a diffusion coefficient  $\alpha$  is selected which provides a best fit between Eq. 15 and experimental measurements.

## Drying Test

The formulation for the drying test is complicated by the evaporation boundary condition at the open end described by Eq. 10. The boundary condition for the closed end is identical to that for the wetting test. Applying these boundary conditions to the diffusion equation (Eq. 13), and employing a separation of variables solution technique, Mitchell presents the following solution for suction  $u(x,t)$  as a function of time and coordinate in the soil sample (7):

$$u = u_a + \sum_{n=1}^{\infty} \frac{2(u_0 - u_a) \sin z_n}{z_n + \sin z_n \cos z_n} \exp\left[\frac{z_n^2 \alpha t}{l^2}\right] \cos\left[\frac{z_n x}{l}\right] \quad (\text{Eq.16})$$

$$\cot z_n = \frac{z_n}{hl}$$

where  $u_a$  = atmospheric suction  
 $u_0$  = initial suction in soil  
 $\alpha$  = diffusion coefficient  
 $t$  = time  
 $l$  = sample length  
 $x$  = coordinate

$h$  = evaporation coefficient

As with the interpretation of the wetting test, a diffusion coefficient  $\alpha$  is selected which provides a best fit between Eq. 16 and experimental measurements. An illustration of the general solution in terms of dimensionless variables is shown in Figure 4.

## TEST INTERPRETATION

For both the wetting and drying tests, a test interpretation procedure was developed which is comprised of the following steps:

1. Measure and record the soil suction at each psychrometer (i.e., different x-coordinate values) and at different times.
2. Make an initial estimate of the diffusion coefficient  $\alpha$ .
3. For the assumed  $\alpha$ , compute the theoretical value of suction  $u(x_i, t_j)$ , corresponding to x-coordinate  $x_i$  and time reading  $t_j$ , using Eqs. 15 or 16 as appropriate.
4. Compute the difference between theoretical and measured suction:

$$\text{Err} = u(x_i, t_j) - u_{i,j}$$

where  $u_{i,j}$  is the measure value of suction.

5. Sum the square of the error for suction measurements at all psychrometer locations ( $x_i$ ,  $i=1$  to  $k$ ) and all time readings ( $t_j$ ,  $j=1$  to  $m$ ):

$$\text{Errsum} = \sum_{j=1}^m \sum_{i=1}^k (u - u_{i,j})^2$$

6. Successively refine the estimate  $\alpha$  such that the sum of the square of the error associated with each data measurement is a minimum. A number of optimization algorithms are commercially available for finding the value of  $\alpha$  that minimizes Errsum. Since this problem involves optimization with respect to a single parameter, the computational effort is relatively small and can be performed with commercially available spreadsheet programs.

## TEST MEASUREMENTS

Most of the soil samples received have been relatively wet, having suction values less than pF 3.5 in their in situ condition. Soils in this state were considered to be too wet to be suitable for the wet-end test; hence, only dry-end tests have been performed to date. To date researchers have performed seven tests. Of these, preliminary interpretations have been made for the first three of these tests. Figures 5 through 8 present the test curves.

From the test data reviewed to date, it appears that the most convenient approach is to plot the test data for a given psychrometer as a function of time and find the  $\alpha$ -coefficient that provides the best fit to Eq. 16. This approach has the advantage that the  $\alpha$ -coefficient can potentially be evaluated at various positions in the specimen. If severe variations occur this can

be an indicator of significant material heterogeneity or possibly the linearized formulation presented above is not valid for the soil being tested.

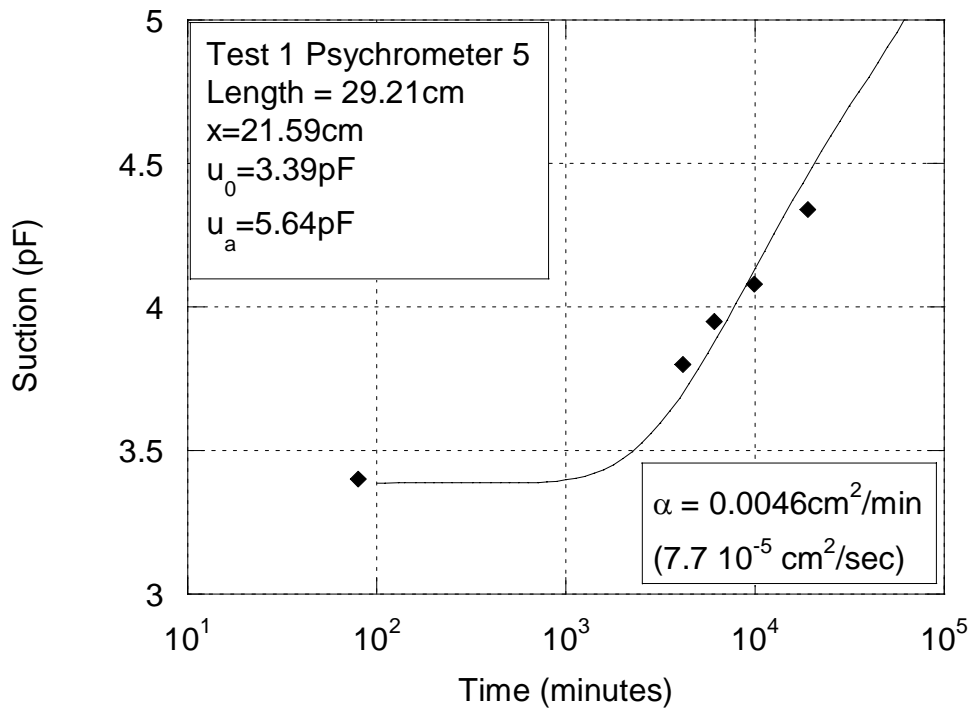
The  $\alpha$ -coefficients interpreted from Figures 5 through 8 are tabulated in Table 3. The most scatter in data and the most questionable  $\alpha$ -coefficient occurred in Test 1, which is anticipated since the test was being performed for the first time and the effects of operator inexperience were likely to be most significant. Nevertheless, the remaining tests showed considerably less scatter as well as a reasonable degree of consistency in  $\alpha$ -coefficients. Laboratory measurements of  $\alpha$ -coefficients reported by Mitchell for Australian clays were on the order of  $10^{-4}$  to  $10^{-5}$  cm<sup>2</sup>/sec (7). Except for Test 1, the  $\alpha$ -coefficients measured on Texas clays appears to be at the high end of the range reported for Australian clays.

The data for Test 3 show  $\alpha$ -coefficients varying by a factor of about 2 to 3: 4.0 versus 1.5 cm<sup>2</sup>/sec. Conventional consolidation tests on saturated soils typically show similar variability depending on how the test is interpreted; i.e., based on 50-percent consolidation (Casagrande's log-time method) versus 90-percent consolidation (Taylor's root-time method). Hence, the level of variability occurring in the partly saturated tests in this project is not unreasonable.

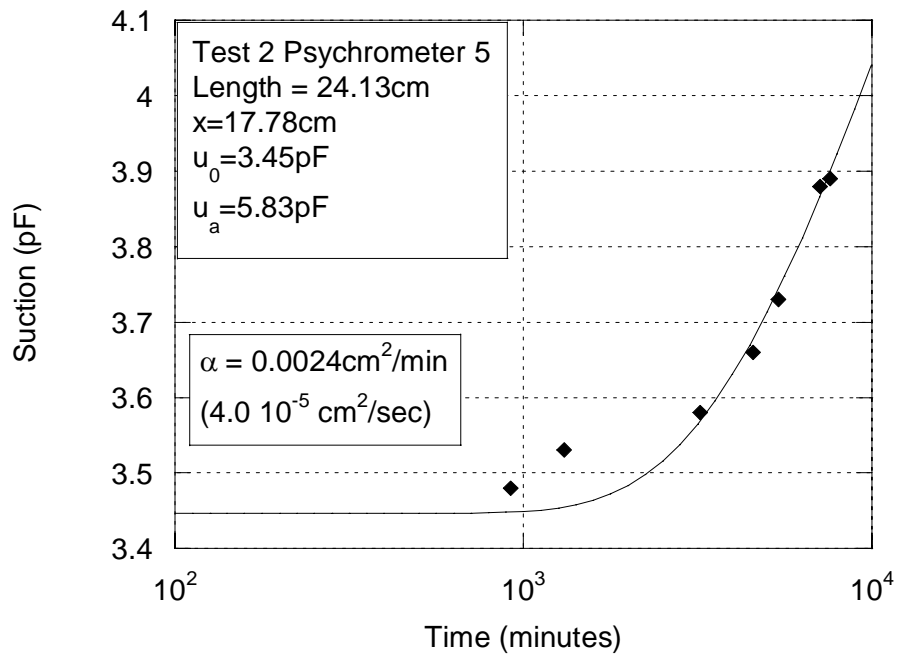
**Table 3. Diffusion Coefficients Interpreted from Dry-End Diffusion Tests.**

Test No./Psychrometer	Distance of Psychrometer from Open End (cm)	Interpreted $\alpha$ -coefficient $10^{-5}$ cm <sup>2</sup> /sec
1/5	7.6	7.7
2/5	6.4	4.0
3/5	6.7	1.5
3/6	2.5	2.0

Further testing and data interpretation are in progress. Particular attention is being given to consistency of  $\alpha$ -coefficient measurements within a single specimen.



**Figure 5. Moisture Diffusion Data for Test 1, Psychrometer 5.**



**Figure 6. Moisture Diffusion Data for Test 2, Psychrometer 5.**

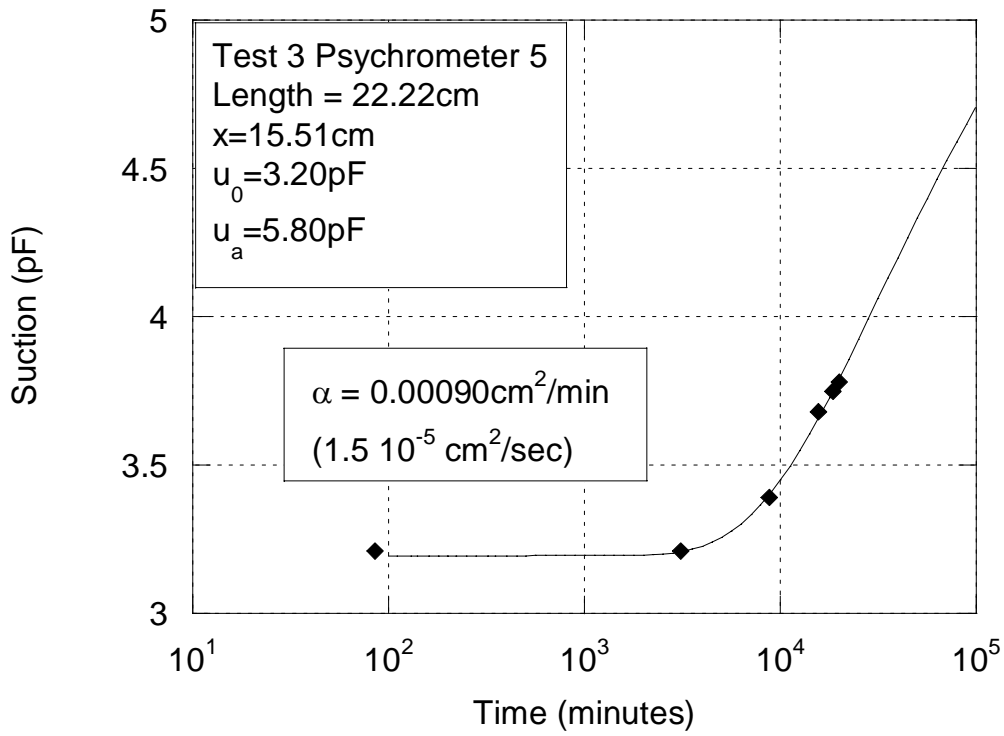


Figure 7. Moisture Diffusion Data for Test 3, Psychrometer 5.

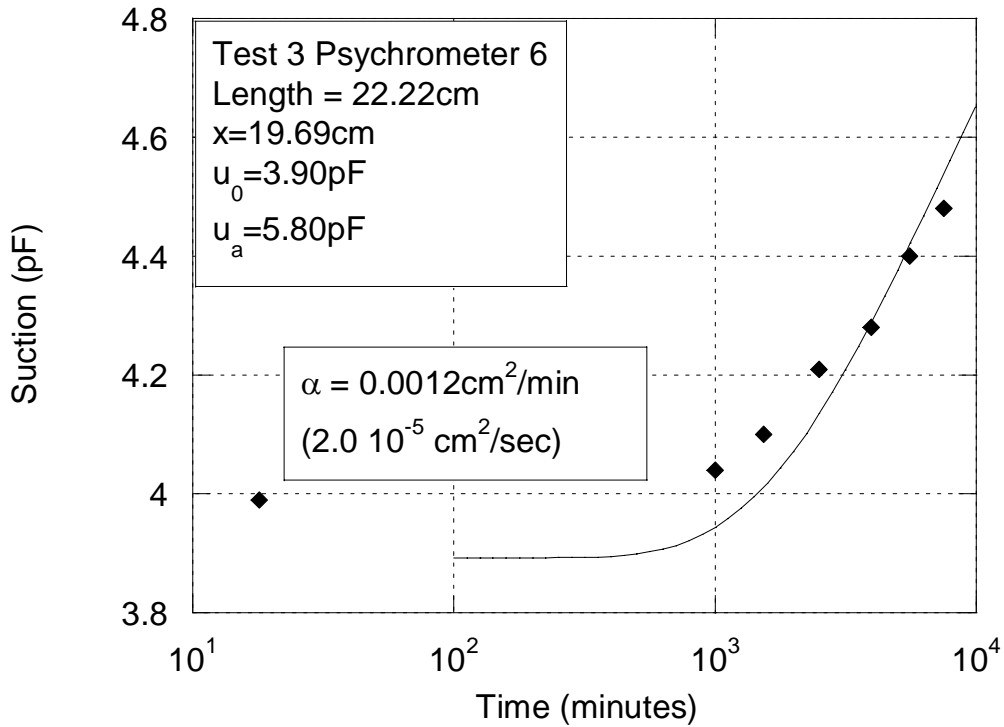


Figure 8. Moisture Diffusion Data for Test 3, Psychrometer 6.





## CHAPTER 5: LOWER LIMIT OF FIELD SUCTION IN HIGH-PLASTICITY CLAYS

While laboratory measurements can provide supporting data, field measurements of the levels of soil suction associated with slope failures can provide the most important source of data regarding the level to which soil suction, and hence soil strength, will decline as moisture infiltrates into the soil. This chapter presents the methodology for interpreting data from slope failures in estimating the lower bounds of suction that occur in high plasticity clays in the field.

### SUCTION-STRENGTH RELATIONSHIP

To understand the mechanisms of strength loss, the factors contributing to soil strength must first be identified. Fredlund and Rahardjo present a general expression for soil shearing resistance, including the effects of suction in the pore water suction, as (2):

$$\tau_f = c' + p \tan \phi' + h_m \tan \phi'' \quad (\text{Eq. 17})$$

where:  $c'$  = effective cohesion

$p$  = net mechanical stress is the total stress minus pore air pressure

$\phi'$  = mechanical stress internal friction angle

$h_m$  = matric suction is the pore air pressure minus pore water pressure

$\phi''$  = suction friction angle

$\tau_f$  = failure shear stress

The above equation is a simple extension of the classical Mohr-Coulomb strength equation ( $\tau_f = c' + p \tan \phi'$ ) with an additional term ( $h_m \tan \phi''$ ) added to account for frictional resistance due to pore water suction. With regard to the above equation, note the following:

- The 'apparent cohesion' occurring in plastic clays is a consequence of pore water suction which is accounted for by the third term ( $h_m \tan \phi''$ ) in the above equation. True cohesion due to cementation bonds between soil particles can usually be considered negligible in compacted soils.
- The net mechanical stress term  $p$  is analogous to the effective stress term used in classical saturated soil mechanics,  $\sigma'$ . In shallow slopes, mechanical stresses are low, and strength is dominated by pore water suction,  $h_m$ .
- The matric suction  $h_m$  is a function of the water content of the soil. Suction decreases as the degree of saturation increases; however, as will be discussed subsequently, suction does not decline to zero even as full saturation is approached.

From the above discussion it is clear that for conditions of low mechanical stresses (e.g., shallow slopes) shear strength is controlled by the third term in [Equation 17](#); i.e., the frictional resistance due to soil suction. Unlike mechanical stress, suction does not necessarily contribute

fully to frictional resistance, since water does not act on the entire surface of the soil particle in a partly saturated soil. Lamborn, who investigated this effect, gives the following relationship (5):

$$\tan \phi'' = f \Theta \tan \phi' \quad (\text{Eq. 18})$$

where:  $\phi''$  = suction friction angle

$\phi'$  = mechanical stress internal friction angle

$\Theta$  = volumetric water content (volume water/total volume)

$f$  = factor ranging from  $f=1$  to  $f=1/\Theta$

Equation 18 is very useful as it allows the suction friction angle  $\phi''$  to be expressed in terms of well-established parameters from classical soil mechanics; i.e., water content and effective friction angle  $\phi'$ . The exact magnitude of the  $f$  factor is a topic that has yet to be fully resolved. Since lower and upper bounds have been established for  $f$  (1 to  $1/\Theta$ ), this uncertainty poses no significant practical limitation with regard to the proposed research.

## ANALYSIS OF SHALLOW SLIDES

Based on the above discussion, a simple model for shallow slope failures can be established. First, soil shear strength can be defined in terms of an 'apparent cohesion' derived from soil suction:

$$c_{\text{app}} = h_m f \Theta \sin \phi' / (1 - \sin \phi') \quad (\text{Eq. 19})$$

Second, the stability of a shallow slide mass can be evaluated based on a simple infinite slope analysis of a cohesive slope:

$$F_s = c_{\text{app}} / \gamma H \sin \beta \cos \beta \quad (\text{Eq. 20})$$

where  $F_s$  = factor of safety against sliding

$\gamma$  = total unit weight

$H$  = depth of slide

$\beta$  = slope angle

Using Equations 19 and 20, data from actual slides in plastic clay slopes can be used to back-calculate inferred suction values at failure, as the factor of safety is known,  $F_s=1$ :

$$h_m = \gamma H \sin \beta \cos \beta (1 - \sin \phi') / f \Theta \sin \phi' \quad (\text{Eq. 21})$$

## CASE HISTORIES

Based on material parameters presented by Kayyal and Wright and slope failure geometries presented by Stauffer and Wright, soil suctions at failure were back-calculated for a series of 18 slope failures in Paris clays (16 sites) and 16 slope failures in Beaumont clays (3,8). As noted earlier, lower and upper bounds have been established for the  $f$  factor. Since failures are likely to occur as the soil approaches a saturated condition, and since  $f = 1/\Theta$  as full saturation is approached, the slope failures were analyzed assuming  $f\Theta = 1$  in Eq. 21. Inferred suction values based on this assumption and Eq. 21 are tabulated in Tables 4 and 5. These calculations do not account for possible changes in suction due to changes in mean and shearing stresses during loading. Accounting for such changes will likely result in apparent suctions that are somewhat greater than those shown in Tables 4 and 5. This topic will be considered in future research.

The back-calculated *matric* suction values at failure appear to fall within a pF range of 1.6 to 1.8, with a relatively small deviation. Lytton conducted several soil suction profiles in Louisiana and Texas (6). The findings from this project, as well as from an ample body of prior experience, indicated a field lower bound of *total* suction of about pF=2.5 for clays. Accounting for some level of osmotic suction due to pore water salts, the matric suction should be somewhat less than the total suction. Hence, the lower bound matric suctions back-calculated from the slope failures are consistent with Lytton's observation.

**Table 4. Inferred Suction Values from Slope Failures in Paris Clay.**

Slope Ratio	Slope Angle (degrees)	Depth of Slide Mass (ft)	Inferred Matric Suction (psf)	Inferred Matric Suction (pF)
3.0	18.4	4	98	1.7
2.5	21.8	4	113	1.7
2.9	19.0	8	201	2.0
2.8	19.7	6	156	1.9
2.7	20.3	10	266	2.1
2.3	23.5	4	119	1.8
2.8	19.7	6	156	1.9
2.3	23.5	6	179	1.9
3.0	18.4	5	122	1.8
2.7	20.3	4	106	1.7
3.2	17.4	2	47	1.4
2.7	20.3	4	106	1.7
2.3	23.5	6	179	1.9
2.3	23.5	6	179	1.9
3.0	18.4	4	98	1.7
2.7	20.3	4	106	1.7
<b>Mean</b>			<b>140</b>	<b>1.8</b>
<b>Standard Deviation</b>			<b>60</b>	<b>0.2</b>

**Material Parameters Used in Analysis**

Specific Gravity, $G_s$	2.72
Dry Unit Weight, $\gamma_d$	77.7 pcf
Water Unit Weight, $\gamma_w$	62.4 pcf
Void Ratio, $e$	1.19
Gravimetric Water Content, $w$	43.6%
Volumetric Water Content, $\Theta$	54.3%
Total Unit Weight, $\gamma$	107 pcf
$f$ (lower and upper bound)	1 to 1.84
Liquid Limit, LL	80
Plasticity Index, PI	22
Friction Angle, $\phi'$	25 degrees

**Table 5. Inferred Suction Values from Slope Failures in Beaumont Clay.**

Slope Ratio	Slope Angle (degrees)	Depth of Slide Mass (ft)	Inferred Matric Suction (psf)	Inferred Matric Suction (pF)
2.5	21.8	3.5	108	1.7
3.0	18.4	4.3	115	1.7
3.1	17.9	2.4	63	1.5
3.4	16.4	3.5	85	1.6
2.6	21.0	4.0	120	1.8
3.1	17.9	3.0	78	1.6
2.4	22.6	5.0	158	1.9
3.1	17.9	2.5	65	1.5
2.1	25.5	3.0	104	1.7
2.7	20.3	2.0	58	1.5
2.7	20.3	5.0	145	1.9
2.6	21.0	5.0	149	1.9
3.0	18.4	3.0	80	1.6
3.1	17.9	3.5	91	1.6
2.5	21.8	2.5	77	1.6
3.0	18.4	2.0	53	1.4
2.4	22.6	3.0	95	1.7
3.1	17.9	3.5	91	1.6
<b>Mean</b>			<b>96</b>	<b>1.6</b>
<b>Standard Deviation</b>			<b>33</b>	<b>0.1</b>

**Material Parameters Used in Analysis**

Specific Gravity, $G_s$	2.70
Dry Unit Weight, $\gamma_d$	96.8 pcf
Water Unit Weight, $\gamma_w$	62.4 pcf
Void Ratio, $e$	0.74
Gravimetric Water Content, $w$	27.4%
Volumetric Water Content, $\Theta$	42.5%
Total Unit Weight, $\gamma$	114 pcf
$f$ (lower and upper bound)	1 to 2.35
Liquid Limit, LL	73
Plasticity Index, PI	21
Friction Angle, $\phi'$	25.7 degrees



## **CHAPTER 6: SUMMARY, CONCLUSIONS, AND FUTURE WORK**

The strength of high-plasticity clays will degrade due to climatic variations in moisture at the ground surface. This project addresses the questions regarding the amount of strength loss that will occur and the depth to which it will be of engineering significance. While much of the effort is directed toward shallow slope failures, these issues are relevant to a wide range of geotechnical structures including pavements, retaining walls and riprap. The methodology developed in this project, particularly that concerning moisture diffusion into a soil mass due to moisture variations at the ground surface, is therefore likely to be applicable to other problems besides slope stability such as expansive soils.

Degradation of the strength of high-plasticity clays is governed by a process involving surficial cracking that provides a pathway for moisture into the soil mass, moisture diffusion into the soil mass, and reduction in soil suction with a concomitant loss of soil strength. This project involves the development of three models for simulating this process: a crack formation model, a moisture diffusion model, and model relating soil suction to strength. The key material parameter for the diffusion model is the  $\alpha$ -coefficient governing the rate of moisture infiltration into the soil mass. A special test for evaluating this parameter for undisturbed soil samples is being developed in this project. Suction-strength behavior, in particular the lower bounds of suction and strength that occur in a soil subjected to wetting, is being evaluated by back-calculating apparent suctions and strengths from documented shallow slope failures in high-plasticity clays. Additional laboratory testing to evaluate index properties and friction angles of Texas high-plasticity clays is being performed to supplement the data on diffusion and suction-strength properties, but it is not considered the main thrust of this project.

Data from the initial moisture diffusion tests are very encouraging, with the measurements showing trends that are very consistent with theoretical formulations. Like all new tests, the test procedures require considerable refinement to ensure reliable results. Issues still to be addressed include determining the optimal location of suction measurements and the optimal time schedule for the measurements. Further ahead, likely beyond the scope of the current project, is the use of improved measurement devices for the suction measurements. One exciting prospect is the use of recently developed tensiometers that are not subject to some of the inconsistencies and irregularities of the thermocouple psychrometers currently in use.

A review of slope failures shows a remarkable consistency in soil matric suction values at failure of about pF 1.6 to 1.8. This result is consistent with previous data indicating that clays in the field will not be wetted to below a total suction of about pF 2.5. The above differences in total and matric suction can be attributed to osmotic suction associated with salts in the pore fluid.

This report focused on the properties of high-plasticity clays, the chief parameter of concern being the diffusion coefficient  $\alpha$ . This parameter controls the rate of moisture diffusion into a soil mass. Developing a means for measurement of  $\alpha$  and obtaining typical values for high plasticity clays were therefore necessary steps in fulfilling the project goals of predicting the rate of suction and strength loss in various earth structures. Future work in fulfilling the project

goals will involve implementing finite element solutions of the diffusion equation to predict the time rate and spatial distribution of strength loss for common cases of embankments protected by vegetation, embankments protected by riprap, embankments with walls on both sides, and possibly open faced cuts in soil nail wall construction.



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