THE MEASUREMENT OF SOIL SUCTION

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in the

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by

Yun Guan

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DISSEMINATION SUMMARY

Department of Civil Engineering
University of Saskatchewan

THEESIS TITLE: THE MEASUREMENT OF SOIL SUCTION

Ph.D Candidate: Yun Guan, Department of Civil Engineering

Supervisor: Dr. D.G. Fredlund, Department of Civil Engineering

Internal Committee Members:

- Dr. D.E. Pufahl, Department of Civil Engineering
- Dr. D.G. Fredlund, Department of Civil Engineering
- Dr. S.L. Barbour, Department of Civil Engineering
- Dr. G.W. Wilson, Department of Civil Engineering
- Dr. E. de. Jong, Department of Soil Science

External Examiner:

- Dr. P. Robertson, Department of Civil Engineering, Univ. of Alberta, Edmonton, Canada

College of Graduate Studies Representative:
THE MEASUREMENT OF SOIL SUCTION

Abstract

A suction probe was developed to directly measure matric suction greater than 100 kPa. The suction probe contains a small volume of water, a non-threaded high pressure transducer, and a 15 bar ceramic. An experimental study was performed to investigate the fundamental behavior of water subjected to high tensions. Cyclic pre-pressurization pressures up to 12,000 kPa were applied to dissolve the potential cavitation nuclei in the water in the suction probe, thus increasing the sustainable tension up to 1,250 kPa. Various factors that affect the tensile strength of water were identified. A high tension in the water could be sustained for a relatively long period of time and exhibited good reversibility. The behavior of water subjected to high tensions can be explained using the gas-trapping model of cavitation. The concept of a cavitation threshold was proposed to describe the ability of the system to sustain high tensions.

The high tensile strength of water forms a sound basis for the direct measurement of high suction in a soil. The suction probe was proved, using the axis-translation technique, to be accurate and rapid in response to negative pore-water pressures as low as -500 kPa. Measurements performed on various types of soils indicate that the suction probe is able to measure matric suction up to 1000 kPa with satisfactory accuracy. Discrepancies were observed for the measurements of matric suction in a compacted till, using the suction probe, the filter paper method, the null-pressure plate method, and the thermal conductivity sensor. The suction probe appears to be best suited for measuring wet clayey-type soils and may not be suitable for measuring soils with a degree of saturation less than about 40%.

Efforts were also made to investigate the possibility of using the ability of a saturated clay-water system to transfer high tensions for the measurement of soil suction. However, the use of a saturated clay for the measurement of soil suction does not appear to be a feasible approach because of the considerable hysteresis in the mechanical behavior of the clay. Nevertheless, it may be possible to use the water-absorbing properties of other materials, such as certain water-absorbing polymers, in the measurement of soil suction.
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University of Saskatchewan
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Canada
May, 1996
ABSTRACT

The development of soil suction measuring techniques has been slow relative to the rapid progress in theories for unsaturated soils. The indirect measurements of soil suction generally suffer from such problems as long equalization time, poor accuracy, hysteresis, and equipment deterioration. The direct in situ measurements of matric suction have, in general, been confined to less than 100 kPa. It is highly desirable to extend the range of direct measurements to cover matric suction values normally encountered in geotechnical and geo-environmental engineering.

The tensile strength of water was used to extend the range of direct measurement of matric suction. A tensiometer-type suction probe was developed using the principle of the high tensile strength of water. High positive pressures pre-applied to the suction probe were found to significantly increase the tension that could be sustained by the water in the suction probe. Various factors that may affect the tensile strength of the water in the suction probe were identified. The mechanism of cavitation in the suction probe was investigated. It was found that for a particular pre-pressurization procedure, a given suction probe has an approximate “cavitation threshold” of tension. If a tension does not exceed the cavitation threshold, the tension can be maintained for a relatively long period of time (e.g., several days). The cavitation threshold appears to be dependent on the nature of the ceramic used in the suction probe. The highest sustainable tension observed in this research program was about 1250 kPa.

Measurements of matric suction on different soils proved that the suction probe can be used to measure matric suction up to at least 1000 kPa with an accuracy of about ±20 kPa. The principle of axis-translation was proved to be correct for negative pore-water pressures as low as at least -500 kPa. The suction probe appeared to be most suitable for measuring wet and clayey-type soils. Difficulties were encountered in measuring soils with a degree of saturation less than 40%.

The developed suction probe provides a direct means by which the measurements of soil suction made by other conventional methods can be evaluated. Reasonable agreements were observed among the measurements using the suction probe, and those made by the filter paper
method and the thermal conductivity sensor for soils with a relatively high degree of saturation. The discrepancies became more pronounced with decreasing degree of saturation. On the other hand, the null-pressure plate gave higher values of matric suction than the suction probe for soils near or above the optimum water content. However, the discrepancies became relatively smaller as the degree of saturation was reduced.

In addition, efforts were also made to investigate the possibility of using the ability of a saturated clay-water system to transfer high tensions for the measurement of soil suction. The results of this research, however, were less rewarding. The use of a saturated clay for the measurement of soil suction does not appear to be a feasible approach because of the considerable hysteresis in the mechanical behavior of the clay. Nevertheless, it may be possible to use the water-absorbing properties of other materials, such as certain water-absorbing polymers, in the measurement of soil suction.
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This thesis is dedicated to my Parents and my Wife
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CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

The engineering behavior of an unsaturated soil is significantly influenced by the suction in the soil. The theoretical concepts pertaining to soil suction were originally introduced by soil scientists (Buckingham, 1907; Gardner, 1922; Richards, 1928) to describe the forces for migration and equilibrium of soil water, mostly for agricultural purposes. These concepts were later adopted in geotechnical engineering as a result of the need to establish the mechanics for unsaturated soils. A theoretical framework for unsaturated soil mechanics has been firmly established over the past two decades. While the behavior of a saturated soil is governed by a single effective stress, \((\sigma - u_w)\), the behavior of an unsaturated soil is generally predicted in terms of two independent stress state variables, namely, matric suction, \((u_a - u_w)\), and net normal stress, \((\sigma - u_a)\) (Fredlund, 1973; Fredlund and Rahardjo, 1993a).

Information about soil suction is necessary for the solution of various geotechnical problems involving unsaturated soils. Typical engineering problems are associated with slope stability, soil swelling and shrinking, soil collapsing, seepage, lateral earth pressures, and soil compaction. Analysis of the so-called “problematic” soils (i.e., swelling soils, collapsing soils, residual soils, and soft clays) is dependent upon the appropriate assessment of soil suction (Fredlund and Rahardjo, 1993b).

One of the important properties of unsaturated soils is the soil-water characteristic curve (i.e., the relationship between volumetric water content and matric suction). The soil-water characteristic curve represents the fundamental interaction between soil water and soil matrix. Recent studies have shown that many soil properties, such as hydraulic conductivity and shear strength, can be computed from the soil-water characteristic curve (Huang, 1994; Fredlund et al., 1995). Such an approach is particularly important for unsaturated soils for which direct measurements of hydraulic conductivity and shear strength are extremely difficult. The soil-water characteristic curve can be determined in a soil laboratory, using conventional methods.
such as pressure plate and desiccator. The insitu hydraulic conductivity and shear strength can be estimated if either the insitu volumetric water content or the insitu soil suction can be measured. In cases that direct monitoring of insitu volumetric water content may not be practical, particularly for non-destructive measurements, insitu measurement of matric suction is then more desirable. In other words, the application of soil-water characteristic curve is limited by the techniques available for insitu measurement of soil suction.

Over the last decade, geotechnical engineering has expanded to embrace a large number of problems occurring in the geo-environmental area which deals with subsurface environmental concerns. An important task of geo-environmental engineering is the measurement and control of fluid flows in the vadose zone. This problem is complicated by the superimposed multi-phase flows involving chemically different substances. These substances may be miscible or immiscible. The flux at the surface boundary can also constitute a complex coupled problem. Solutions of the related problems require the knowledge of two important soil water variables, namely, hydraulic conductivity and coefficient of diffusion. Both are related to soil suction (Fredlund and Rahardjo, 1993b). Therefore, the determination of soil suction plays an important role in geo-environmental engineering.

More than twenty different methods of soil suction measurement have been attempted over the past sixty years. However, none of these methods are considered to be satisfactory for all situations. Each of these methods suffers from some limitations. Table 1.1 presents a summary of the conventional methods along with ranges of measurement, advantages, and limitations.
Table 1.1 Conventional Methods of Soil Suction Measurement

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<th>Methods</th>
<th>Suction Components and Range</th>
<th>Advantages</th>
<th>Limitations</th>
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<tr>
<td>Ordinary Tensiometer and Suction Plate</td>
<td>matric, 0 – 100 kPa</td>
<td>1. relatively quick response</td>
<td>1. cavitation limits measurement to less than 100 kPa.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. low cost</td>
<td>2. difficulty with air bubbles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. easy handling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. lab and field measurements</td>
<td></td>
</tr>
<tr>
<td>Osmotic Tensiometer</td>
<td>matric, 0 – 2000 kPa</td>
<td>1. no cavitation</td>
<td>1. poor reliability due to drift of reference pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. high suction measurement</td>
<td>2. strict temperature control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. only for lab measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. equipment expensive</td>
</tr>
<tr>
<td>Pressure Membrane (Null Technique)</td>
<td>matric, 0 – 2000 kPa</td>
<td>1. no cavitation</td>
<td>1. long equilibrium time for high suction values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. high suction measurement</td>
<td>2. deterioration of membrane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. low cost</td>
<td>3. air diffusion difficulty</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. only for lab measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5. best for suction control rather than measurement</td>
</tr>
<tr>
<td>Pressure Plate (Null Technique)</td>
<td>matric, 0 – 1500 kPa</td>
<td>1. no cavitation</td>
<td>1. long equilibrium time for high suction values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. high suction measurement</td>
<td>2. diffusion difficulty</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. only for lab measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. best for suction control rather than measurement</td>
</tr>
<tr>
<td>Filter Paper</td>
<td>total or matric, entire range of suction</td>
<td>1. cover entire range of measurement</td>
<td>1. strict control of environmental conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. low cost</td>
<td>2. difficult handling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. poor accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. user dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. generally for lab measurement</td>
</tr>
<tr>
<td>Psychrometer (high suction)</td>
<td>total, 100 – 8000 kPa</td>
<td>1. wide range of measurement</td>
<td>1. constant temperature environment</td>
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<tr>
<td>Thermistor (high suction)</td>
<td></td>
<td></td>
<td>2. poor accuracy</td>
</tr>
<tr>
<td>Thermocouple (low suction)</td>
<td></td>
<td></td>
<td>3. generally for lab measurement</td>
</tr>
<tr>
<td>Hygrometer</td>
<td></td>
<td></td>
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<tr>
<td>Electrical Conductivity Sensors</td>
<td>matric, 0 – 500 kPa, and possibly up to 1,500 kPa.</td>
<td>1. may be good for clean sands and silts 2. long term automatic monitoring 3. lab and field measurements</td>
<td>1. sensitive to dissolved salts 2. temperature dependent 3. long equilibrium time 4. deterioration of resistance block</td>
</tr>
<tr>
<td>Thermal Conductivity Sensors</td>
<td>matric, 0 – 400 kPa</td>
<td>1. independent of dissolved salts and ambient temperature 2. long term automatic monitoring 3. lab and field measurements</td>
<td>1. long equilibrium time 2. accuracy needs improvement, especially for suctions greater than 170 kPa 3. deterioration of thermal block</td>
</tr>
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Soil suction measuring techniques can be classified into either direct or indirect measurements. The direct insitu measurement of matric suction would be highly desirable for most engineering practices. However, the direct insitu measurement of matric suction has been generally confined to less than 100 kPa because of the cavitation problem in the measuring system. Without the success in direct insitu measurement of matric suction over a wider range, any development in indirect measurement of soil suction could have difficulty in verification and interpretation. The common technical limitations for most indirect measurements are associated with long equalization time, unsatisfactory accuracy, hysteresis, and equipment deterioration.

Compared with the rapid progress in theories of unsaturated soils, the developments in soil suction measuring techniques are slow and less satisfactory, particularly in direct measurement. One important reason for the slow progress in the direct measurement of matric suction is the lack of understanding regarding the tensile strength of water. It has been generally accepted that water cavitates at a negative gauge pressure of -100 kPa. Tremendous progress has been made relative to the tensile strength of water since the 1960's. Much of this information, however, does not appear to have been communicated to soil researchers. The tensile strength of water, has been measured by many physicists to be greater than several atmospheres. The tensile strength of water appears to be largely dependent on the degree of elimination of the so called “cavitation nuclei” in water.

On the other hand, the mechanism behind the tensile strength of water is still not fully understood. One important reason may be the lack of means for directly generating and measuring high negative pressures in water. Physicists appeared to be generally unaware of the fact that a high negative pressure can exist in soil water, and it is possible to use the high negative pressure in soil water to study the tensile behavior of liquids in a more direct and convenient manner.

1.2 OBJECTIVES AND SCOPE OF THE RESEARCH

The principal objective of this research program is to develop a suitable technique for direct measurement of soil suction. The specific objectives are as follows:
1.) to explore the methods that can increase the tensile strength of water,
2.) to systematically study the fundamental behavior of water under a high tension and identify the major factors that may affect the tensile behavior of water,
3.) to develop a suction probe that uses the tensile strength of water for the direct measurement of soil suction greater than 100 kPa with improved accuracy, and
4.) to compare the direct and indirect measurements of soil suction over the range of the most common interest to geotechnical engineering (i.e., from 0 to 500 kPa or higher).

The findings from this research program are expected to make a significant contribution to the understanding of the tensile strength of water. Such a probe could prove useful for soil suction measurements and open a wide area of research into geotechnical engineering, geo-environmental engineering, and soil science.

As a secondary objective of this research program, investigations were made into the possible utilization of the anomalous properties of water around soil particles for soil suction measurement. One of the many anomalous properties of water around soil particles is its ability to withstand and transfer high tensions Therefore, efforts were made to investigate the possibility of simulating or making use of the high tensile ability of the soil-water system for soil suction measurement. The possibility of using a compressible saturated clay for soil suction measurement was investigated. The research should contribute to an understanding of the behavior of saturated soils where the pore-water pressure is negative.

1.3 THESIS ORGANIZATION

This thesis is organized into seven chapters. The objectives and scope of the research program are presented in Chapter 1.

Chapter 2, "The Literature Review", is divided into two parts. The first part includes a review of the conventional soil suction measuring techniques. The review mainly focuses on the principles used in these techniques. Recent developments of soil suction measuring techniques are summarized. The second part presents a review of the studies of the tensile strength of water. Based on the review of the tensile strength of water, the applications of the
tensile strength of water for direct measurement of high tensions in water by Gilbert (1960) and Ridley (1993) are discussed.

Chapter 3, "Strategies", outlines the strategies used to develop soil suction measuring techniques. Some strategic possibilities for soil suction measurements are proposed.

Chapter 4, "Laboratory Program", provides the testing program for this research. It is divided into two parts. The first part details the design of the suction probe and procedures for a systematic testing of the tensile behavior of water. The second part gives the procedures for testing the performance of the probe in soil suction measurements. Several other conventional techniques for soil suction measurements are used for a comparative study.

Chapter 5, "Presentation of Test Results", followed by Chapter 6, "Interpretation of Results", presents the test results corresponding to the testing program in Chapter 4. The test results are discussed and analyzed. The performance of the suction probe is evaluated.

Chapter 7 gives the summary and conclusions of the research program. Recommendations which are related to the design and future studies are also proposed.

As a supplementary, Appendix A gives a critical discussion on soil suction theories and soil suction measurement, particularly on the theoretical aspects with respect to the axis-translation technique. Appendix B presents discussions on the use of a compressible soil for soil suction measurement.
CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is presented in two parts. The first part provides a review of soil suction measuring techniques. Although improvements have been made for many of the techniques since their invention, the basic principles behind the techniques have remained largely unchanged. This review focuses mainly on the principles behind the techniques for soil suction measurement. The important historic developments for each technique are highlighted.

The second part of this chapter gives a review of the studies on the tensile strength of water. The review attempts to provide an in-depth understanding of both the theoretical aspects of cavitation and the principles behind the tests of the tensile strength of water conducted by various physicists. Two applications of the tensile strength of water in geotechnical engineering are reviewed. The review with regards to the tensile strength of water provides the background for the development of a tensiometer-type suction probe which is capable of directly measuring soil suctions greater than 100 kPa.

The following sign conventions are used throughout this thesis:

- negative pressure (-)
- tension (-)
- positive pressure (+)
- suction (+)
- tensile strength (+)

Comparisons of magnitudes of tensions and negative pressures are always made in terms of the absolute value. For instance, a tension of -800 kPa is said to be 300 kPa higher than a tension of -500 kPa, and vice versa.
PART 1

THE PRINCIPLES OF SOIL SUCTION MEASUREMENT

Conventional soil suction instruments include tensiometers, null-type pressure plate, null-type pressure membrane, psychrometers, filter paper, electrical conductivity sensors, and thermal conductivity sensors. A suction measurement can be categorized as either a direct or an indirect measurement. A direct measurement measures the equilibrium state of a soil-water system without involving an external medium for moisture equalization. An indirect measurement involves the use of an external medium for moisture equalization. The term "external medium" generally refers to a certain type of moisture absorbent, such as filter papers, gypsum blocks, and other porous materials. A direct measurement does not exclude the need for calibration.

Psychrometers, tensiometers, and null-type pressure plate technique fall into the category of direct measurements, whereas the filter paper technique, electrical conductivity sensors, and thermal conductivity sensors belong to the category of indirect measurements.

2.2 DIRECT MEASUREMENT OF MATRIC SUCTION

The direct measurement of matric suction requires a saturated porous disk as an interface between a soil to be measured and a pressure measuring system which contains water. The role of the porous disk is to maintain a pressure deficiency between the water phase held in the measuring system and the ambient air in the soil. The ability of a porous disk to maintain such a pressure deficiency is measured by the air-entry value of the disk which can be approximated using Eq. (2.1):

\[ \mu_a - u_w = \frac{2T_r}{r} \]  \hspace{1cm} (2.1)

where:

\[ T_r \] = surface tension of water at the temperature,
\[ \mu_a \] = pore-air pressure in the soil,
\[ u_w = \text{water pressure in the measuring system}, \]
\[ r = \text{radius of the curvature of the largest pore in the disk}. \]

A saturated porous high air-entry disk in connection with a pressure measuring system can be placed in contact with a soil. Under the action of a hydraulic gradient, water will flow through the disk between the soil and the pressure measuring system. At equilibrium the matric suction in the soil can be determined. The matric suction to be measured should never exceed the air-entry value of the disk.

The tensiometer, the null-type pressure plate, and the null-type pressure membrane are the devices commonly used to directly measure the matric suction of soils. A ceramic disk with a high air-entry value is the most common interface used in the direct measurement of matric suction. In the pressure membrane method, however, a high air-entry membrane is used as the interface. These direct methods do not measure the osmotic component since the solute molecules are allowed to move freely through the porous disk, or the membrane.

### 2.2.1 Tensiometers

Gardner et al. (1922) reported measurements of the capillary potential function proposed by Buckingham (1907) in soils, using devices named tensiometers. Since then a great variety of commercial and fabricated tensiometers have been made available. However, the basic components of the tensiometer have remained unchanged. The theory, construction, and use of tensiometers were recently summarized by Stannard (1986, 1992). Tensiometers can be generally divided into three categories according to the types of devices used for measuring tension in water. They are pressure-transducer tensiometers, manometer tensiometers, and vacuum gauge tensiometers.

Watson (1967) proposed the use of a tensiometer-pressure transducer system for field measurement of soil suction. The tensiometer is illustrated in Fig. 2.1. The tensiometer can be set in any depths up to 180 cm. Such type of tensiometer usually exhibits a rapid response and is suitable for automatic monitoring of soil suction.
Fig. 2.1 Illustration of the Tensiometer-Pressure Transducer Assembly
(after Watson, 1967)

The manometer-type tensiometers usually use a mercury manometer to record tension in water. Mottes (1975, U. S. Pat. 3,884,067) designed an interesting tensiometer in which a U-shaped mercury manometer was enclosed in the tubular housing of the tensiometer (Fig. 2.2). The tensiometer can be easily handled and transported in any position.

The vacuum gauge tensiometers use a vacuum gauge to measure negative pressure in water. Two popular commercial portable vacuum gauge tensiometers were built by Skaling (1975, U. S. Pat. 3,898,872; 1978, U. S. Pat. 4,068,525, Soil Moisture Equipment Corp., Santa Barbara, CA).

Tensiometers can be used for continuous multi-point monitoring of soil suction conditions if equipped with a scanning-valve system which can switch between different tensiometers at different locations. Only one pressure sensing unit is needed for a scanning-valve system. Since this pressure sensing unit can be at a location remote from the field tensiometers, a pressure transducer is best suited for such a task (Bianchi and Tovey, 1968; Anderson and Burt, 1977; Williams, 1978).
Fig. 2.2 The Manometer Tensiometer by Mottes (1975)

The major disadvantage of the tensiometer is its narrow range of measurement. Theoretically, the tensiometer can only measure a negative pressure up to the atmospheric pressure minus the vapor pressure of water because water in the measuring system usually cavitates under this condition. Once cavitation occurs, water is no longer capable of transmitting the full negative pressure (see the second part of this chapter). At 20°C, the lowest gauge negative pressure that the tensiometer can measure is about -99 kPa. However, due to the presence of air bubbles and other impurities, water usually cavitates at a gauge pressure of about -90 kPa or lower.

Another major problem associated with the direct measurement of matric suction is the formation of air bubbles in the measuring system. Air bubbles provide a flexible fluid system, reducing the sensitivity of the device. Air bubbles also allow water to flow from the measuring
system into the surrounding soil being measured. This phenomenon can lead to an underestimation of soil suction.

Air bubbles in a tensiometer can be removed by applying a vacuum to the measuring system, or by simply refilling the tensiometer through the service cup (e.g., Jet-Fill tensiometers, from Soil Moisture Equipment Corp., Santa Barbara, CA). An efficient and convenient procedure to remove air bubbles is to design a double-tubing tensiometer which was proposed by Richards et al. (1937). A typical example is shown in Fig. 2.3 (Stannard, 1986). This arrangement allows flushing the air from the interior of the cup. A similar principle is also applied in the Small-Tip Jet-Fill tensiometers (from Soil Moisture Equipment Corp.).

![Diagram of Double-Tubing Tensiometer]

Fig. 2.3 Schematic of Double-Tubing Tensiometer (after Stannard, 1986)
Hendrickx et al. (1994) studied the effect of tensiometer cup size on the measurement. Tensiometers with different cup sizes were used on a 20 m by 20 m field. It was found that an increase in tensiometer cup size reduced the variability of soil suction measurements and thus reduced the number of tensiometers needed for determination of soil suction status in field soils. The study suggested that the medium tensiometer cup size, which is presently used all over the world, should be replaced by a large cup size.

Peck and Rabbidge (1966) designed a special tensiometer to overcome the problem of water cavitation in conventional tensiometers (Fig. 2.4). The tensiometer was referred to as the osmotic tensiometer because it was based on the osmotic forces in a solution placed behind a semi-permeable membrane. A confined solution in contact with pure water via a perfect semi-permeable membrane will reach equilibrium at which the hydrostatic pressure is equal to the osmotic pressure. When the tensiometer is placed in a soil, the pressure in the solution will decrease at equilibrium by an amount equal to the total soil suction. However, the membrane separating the confined solution from a soil is highly impermeable to the confined solute but permeable to much smaller molecules and ions which existed in the soil. Therefore, only matric suction of the soil is indicated by the reduction in the hydrostatic pressure in the solution.

The advantage of this instrument over conventional tensiometers is that the direct measurements of matric suction can be extended up to 1,500 kPa and that it is not subjected to any hysteresis as water in the tensiometer is always subjected to a positive pressure. As a result, cavitation should not occur. The range of measurement is determined by the reference hydrostatic pressure which is developed after the confined solution is put into contact with free water.

The first major difficulty with the osmotic tensiometer is its inability to maintain a constant reference pressure with time (Peck and Rabbidge, 1969) due to the minute leakage of the confined solute through the semi-permeable membrane. It was found that the membrane is also susceptible to physical deterioration with time (Bocking and Fredlund, 1979). The second major difficulty is the significant effect of a temperature change on the measurement. It is
extremely difficult to measure the soil suction other than in a highly temperature-controlled environment.

Fig. 2.4 Osmotic Tensiometer (after Peck and Rabbidge, 1966)

2.2.2 Null-Type Pressure Plate and Pressure Membrane

The null-type pressure plate technique was first proposed by Hilf (1956). This simple technique greatly extended the range of direct measurement of matric suction. The null-type pressure plate technique has become a routine laboratory procedure in the measurement and control of soil suction.

The principle of the null-type pressure plate technique is illustrated in Fig. 2.5. An unsaturated soil specimen is placed in a closed pressure chamber over a high air-entry ceramic disk. A saturated water chamber maintained below the ceramic disk is connected to a null-flow indicator and a pressure control device. The null-flow indicator is used to ensure that the water content of the soil is maintained constant during the measurement. Hilf (1956) demonstrated that the pore-water pressure in the soil increased by an amount equal to an
increase in the ambient chamber air pressure. In other words, matric suction remained constant at various ambient air pressures under null-flow conditions. By increasing the ambient air pressure, the pore-water pressure in the soil can be increased to a desired value. The problem of water cavitation is, therefore, avoided. At equilibrium, the difference between the applied ambient air pressure and the pressure in the water chamber is numerically equal to the matric suction.

![Diagram of the Null-Pressure Plate Technique]

**Fig. 2.5 Illustration of the Null-Pressure Plate Technique**

The above technique is commonly called the null-type axis-translation technique because it translates the origin of reference for the pore-water pressure from the standard atmospheric condition to the final air pressure in the chamber.

A null-flow condition is important for soil suction measurement. There are two approaches to achieve the null-flow condition. One is to use a pressure control unit to apply a back-pressure to maintain a constant position of the null-flow indicator. The other approach is to adjust the applied ambient air pressure in order to maintain a null-flow condition while the water below the ceramic disk is open to the atmosphere.
The water chamber below the ceramic disk should remain saturated during measurement. Any presence of air bubbles in the water chamber below the ceramic disk can lead to an erroneous reading of the null-flow indicator. Therefore, it is important for the apparatus to have a system to flush air bubbles from below the high air-entry disk. Diffused air bubbles must be regularly flushed from the system during long term measurements.

The maximum suction to be measured by the pressure plate technique is about 1,500 kPa. The prolonged moisture loss through the vapor phase due to long equalization times at high suction values, and the increased rate of air diffusion at high air pressure can affect the accuracy of a measurement. When the degree of saturation of the soil is higher (e.g., 80%), the null-type pressure plate technique can produce an over-estimation of matric suction (Bock and Fredlund, 1980; Madsen et al., 1986; Campbell, 1988).

The null-type pressure membrane technique, first introduced by Richards (1941) for soil water extraction, works in a manner similar to the null-type pressure plate technique. The major difference is that a pressure membrane (e.g., a cellulose membrane) is used in conjunction with the high air-entry ceramic disk.

2.3 DIRECT MEASUREMENT OF TOTAL SUCTION

The psychrometer is a common instrument used to measure total suction in a soil. The psychrometer measures the total suction of a soil-water system by measuring the total free energy, or the relative humidity, of the vapor in equilibrium with the soil water. The relationship between the total suction, $\psi$, and the relative humidity (RH = $\varphi / \varphi_o$) is expressed by the equation (Fredlund and Rahardjo, 1993a):

$$\psi = \frac{R^* T}{v_w \sigma_v} \ln \frac{\varphi}{\varphi_o}$$  \hspace{1cm} (2.2)

where:

$R^*$ = universal gas constant (i.e., 8.31432J/mol.K),
$T$ = absolute temperature,
$\nu_w$ = specific volume of water,
\( \Theta \), = molecular mass of water vapor (i.e., 18.016 g/mol),

\( \rho_v \) = vapor pressure of free pure water,

\( \rho \) = vapor pressure of soil water.

Most psychrometers consist of a thermometer which has a wetted junction from which evaporation of water into the adjacent air causes a depression in the temperature of the junction as compared to that of a reference junction. The rate of depression is related to the vapor pressure in the vicinity. By calibrating the temperature depression against a known vapor pressure, the total suction of a soil-water system can be computed from the measurement of the temperature depression measured by the psychrometer.

There are basically several types of psychrometers: thermistor psychrometers, thermocouple psychrometers, hygrometers, and more recently transistor psychrometers. The most commonly used hygrometers include dew-point hygrometers and water-vapor adsorptive type hygrometers.

Most types of psychrometers utilize the principle of the Seedbeck effect except the water-vapor adsorptive type hygrometers. Seedbeck in 1821 discovered that an electromotive force (i.e., e.m.f.) was generated in a closed circuit of two dissimilar metals when two junctions of the circuit have different temperatures. This phenomenon allows the use of two dissimilar wires (i.e., a thermocouple) to measure temperature. The Seedbeck effect is used in the psychrometers to measure the temperature depression when water on one junction is evaporated.

The thermistor psychrometers differ from the thermocouple psychrometers and the dew-point hygrometers in the manner by which the evaporating junction is wetted in order to induce evaporation. The thermistor psychrometers involves wetting the evaporation junction by placing a drop of water on the junction. For this reason the thermistor psychrometers are also called wet-loop thermocouple psychrometers. The transistor psychrometers operate in a similar way as the thermistor psychrometers but transistors are used instead of thermistors as the temperature sensing elements. The thermocouple psychrometers and the dew-point hygrometers make use of the Peltier current effect to induce the condensation of a drop of water on the evaporating junction. Different from other psychrometers, the water-vapor
adsorptive hygrometers are based on the change in the electric resistance of a water-vapor adsorptive material coated on a hygrometric element.

A psychrometer calibration is usually conducted by suspending the psychrometer over a salt solution (e.g., NaCl and KCl) with a known osmotic suction in a chamber under isothermal conditions in a thermal bath. The psychrometer can be calibrated at various suction values by using different molalities (or osmotic suctions) for the salt solution.

A soil to be measured is placed in the same thermal bath. The psychrometer is suspended over the soil. The total suction can be calculated, based on calibration, from the measurement of temperature depression on the measuring junction of the psychrometer, or of the change in electric resistance (for the water-vapor adsorptive hygrometer).

2.3.1 Thermistor Psychrometers

Hill (1930) appears to be the first to introduce the use of a silver-constantan wire wound around a brass frame for measuring vapor pressures. Brady et al. (1951) proposed the use of matched thermistors which were incorporated into a Wheatstone bridge for measurement of vapor pressure of aqueous solutions. The term "matched" means the difference in electric resistance between the two thermistors should be less than 10%. However, this thermistor psychrometer was not directly applicable for measuring soil suction.

Richards (1965) designed a thermistor psychrometer suitable for soil suction measurement, based on a theoretical analysis. This psychrometer is illustrated in Fig. 2.6. The assembled psychrometer unit for measuring soil suction is shown in Fig. 2.7. The psychrometer is able to measure total suction from 10 kPa to 10,000 kPa with an accuracy of 15 kPa at the low end and 300 kPa at the high end.

Zollinger et al. (1966) found that the thermistor psychrometer gave a lower total suction than the thermocouple psychrometer. The difference was more pronounced in dry soils. The thermistor psychrometer added vapor to the soil from the water droplet inserted on the evaporating junction. It was concluded that the thermistor psychrometer could under-estimate the total suction of a soil.
Kay and Low (1970) modified the technique of Brady et al. (1951) for the measurement of vapor pressure of water in soils. The apparatus is illustrated in Fig. 2.8. Two matched thermistors were used as the temperature sensing elements. The matched thermistors were located close to each other but in separate compartments in order to compensate for temperature gradients. Identical water drops were placed on both thermistors to eliminate any imbalance in their heat dissipation. Results obtained by the psychrometer on a Brookston silt loam were shown to agree with those obtained by a pressure plate.
2.3.2 Transistor Psychrometers

With the rapid progress in microchip technology over the last ten years it has become possible to use transistors for measuring relative humidity. The transistor psychrometer has been developed in the last few years in Australia to effectively replace the thermistor psychrometer for total suction measurement. Woodburn et al. (1993) and Truong and Holden (1995) used silicon NPN type transistors and integrated circuits to replace the more expensive and more fragile thermistors in a psychrometer for measuring total suction. Fig. 2.9 shows the transistor psychrometer. The transistor psychrometer operated in a thermally insulated bath. The variation of room temperature was controlled to be within ±0.5°C. The transistor psychrometer was capable of measuring total suction ranging from 100 kPa to 10,000 kPa with an accuracy of about ± 10 kPa. This accuracy is greater than that required for most engineering applications. It was concluded that the transistor psychrometer is the best apparatus for total suction measurement in terms of cost, accuracy, range of measurement,
testing time, and ease of operation as compared with other techniques for total suction measurement.

![Diagram of Transistor Psychrometer](image)

Fig. 2.9 The Operation of Transistor Psychrometer (after Woodburn, 1993)

### 2.3.3 Thermocouple Psychrometers

Spanner (1951) described a method of measuring vapor pressure without the need to place a drop of water on the evaporating junction. The Peltier effect was used to condense a drop of water on the evaporating junction. Peltier in 1834 discovered that upon passing a current across a junction of two dissimilar metals, there is a liberation or absorption of heat at the junction, causing the temperature to rise or fall, depending upon the direction of applied current. If the degree of cooling is sufficient to bring the junction below the dew-point of the surrounding moisture, the moisture will condense on the junction and the thermocouple will become a delicate "wet-loop" thermometer. Upon the termination of the current, the dew will re-evaporate and a minute e.m.f. will be generated (due to the Seedbeck effect) more or less proportional to the "wet-loop" depression associated with the surrounding moisture. If a micro-voltmeter is connected to the thermocouple, it will be possible to calibrate this apparatus by enclosing the junction in a chamber containing solutions of known osmotic suctions. The principle of a typical Peltier thermocouple psychrometer can be illustrated in Fig. 2.10.
The degree of cooling which the Peltier effect can produce is limited by the effect of the ordinary Joule heating. The degree of Peltier cooling increases with the current, only up to the point at which the Joule heating begins to predominate. The Joule heating effect puts a limitation on the lowest dew-point that can be reached by the thermocouple, which in turn imposes a restriction on the lowest relative humidity or the highest soil suction that can be measured using a thermocouple psychrometer. The lower the relative humidity, the lower is the dew-point temperature associated with the vapor pressure.

Spanner (1951) proposed guidelines regarding the design of the thermocouple psychrometers: (1) the thermocouple should be made as small as possible to reduce the effect of air movement in the surrounding atmosphere, and to increase the response time; (2) the wires should be short and connected to relatively massive copper leads since not only the degree of maximum cooling can be doubled if the wires of the thermocouple are short, but also the electric resistance is reduced and so is the waste heat on the passage of the current; (3) the most satisfactory materials for the wires appeared to be bismuth and an alloy of bismuth with 5% tin.
The thermocouple psychrometers can cover the range of relative humidities from 94% to 100%, corresponding to the suction values up to 8000 kPa. However, in order to measure suctions to an accuracy of about 10 kPa, the apparatus must be capable of distinguishing dewpoints to the order of 0.001°C (Spanner, 1951). This factor puts a severe limitation on the accuracy of the thermocouple psychrometer technique. The reliable resolution of the thermocouple psychrometers is in the order of 100 kPa.

Many studies have been made to improve the design of the thermocouple psychrometers, particularly on the reduction of the effect of temperature gradients during measurement. Rawlins and Dalton (1967) developed a thermocouple psychrometer for insitu measurements in which the requirements for temperature control were diminished. Van Haveren and Brown (1972) developed a double-junction Peltier psychrometer (Fig. 2.11) to eliminate the drawbacks associated with a single junction psychrometer. The psychrometer output was measured between the two copper leads, N and P. Any electromotive force generated at one measuring junction due to a thermal gradient is compensated by an opposing electromotive force at the other measuring junction.

Brown and Collins (1980) became critical of the double-junction and end-window design features and developed a new screen-cage single-junction design. The design was based on the findings that single-junction thermocouple psychrometer with a concentrically located junction surrounded by a cylindrical sample surface appeared to be least subject to temperature gradient errors. A stainless steel screen cap with a 400 mesh screen liner was used to cage the thermocouple from the surrounding soil (Fig. 2.12). Calibration and measurement could be best performed by suspending the psychrometers in a stainless steel tube fittings (Fig. 2.13) over a solution with a known molality concentration and the soil, respectively. Liquid water will not penetrate the 400 mesh screen liner unless under positive pressure. The 400 mesh screen-caged psychrometer appeared to minimize errors caused by temperature gradients under field conditions.
Fig. 2.11 Double-Junction Temperature-Compensated Peltier Thermocouple Psychrometer (after Van Haveren and Brown, 1972)

The idea of building a protective shield to cover the thermocouple of a psychrometer so that the psychrometer can be used for field measurements was also used by Briscoe et al. (1981, U. S. Pat. 4, 242, 906). A psychrometer, similar to the one used by Brown and Collins (1980) is currently manufactured by Wescor Inc. in Logan, Utah, U.S.A. (Type PCT-55). The thermocouple is protected by a ceramic shield. Wan et al. (1995) applied this type of psychrometer to measure total suction and track moisture movements in heated clay in an insitu Buffer/Container experiment. Fig. 2.14 illustrates a vertical cross section of the Buffer/Container experiment. The test hole was 5 m deep and had a diameter of 1.24 m. Compacted sand-bentonite buffer was used. An electric heater was buried in the clay on the vertical axis of the borehole to provide the heat source. Calibration tests were conducted on 40 psychrometers. The effect of temperature was corrected by the following empirical equation:
Fig. 2.12 Illustration of the Single-Junction Screen-Cage Thermocouple Psychrometer (after Brown and Collins, 1980)

Fig. 2.13 Stainless Steel Calibration Chamber (after Brown and Collins, 1980)
\[ V_{25} = \frac{V}{0.325 + 0.027T} \]  

(2.3)

where:

\( V_{25} \) = corrected output voltage.
\( V \) = measured output voltage,
\( T \) = temperature.

Seventeen psychrometers were installed in the buffer close to the borehole wall. Temperature fluctuations during the course of measurement were minimized to less than ±0.001°C. However, satisfactory measurements could not be made because of the presence of thermally-induced vapor pressure gradients.

![Diagram of the Buffer/Container Experiment](image)

Fig. 2.14 Illustration of the Buffer/Container Experiment  
(after Wan et al., 1995)

### 2.3.4 Hygrometers

There are two types of hygrometers that are commonly used in soil science and geotechnical engineering. They are the dew-point hygrometers and water-vapor adsorptive hygrometers.
2.3.4.1 Dew-Point Hygrometers

The moisture vapor in a soil has a lower dew-point than the vapor over pure free water. Therefore, from the measurement of dew-point depression in the soil the vapor pressure of soil water can be calculated.

Campbell et al. (1973) reported the development of a dew-point hygrometer for water potential measurements. The dew-point hygrometer used the Peltier effect in a similar way as it is used in the thermocouple psychrometer. The dew-point depression was measured using two thermocouples having a common measuring junction. A current was passed through one thermocouple, cooling the measuring junction by the Peltier effect while the other thermocouple measured the junction temperature depression using the Seedbeck effect. The hygrometer operated on the principle that the temperature of the wet junction will always converge at the dew-point if there are no heat transfer mechanisms other than the evaporation or condensation. Accordingly, the dew-point can be determined by cooling the thermocouple below the dew-point temperature and condensing water onto the thermocouple; then the cooling current is manually decreased until the output curve which relates the measured temperature depression to the cooling current, reaches a flat portion. The temperature measured at this moment is the dew-point of the vapor (Fig. 2.15).

Fig. 2.15 Determination of Dew-Point from Temperature Depression of a Thermocouple
The advantage of the dew-point hygrometer over the thermocouple psychrometer is that it produces an output voltage which is higher and remains constant for a considerable period of time, allowing ample time to make the measurement (Campbell et al., 1973).

2.3.4.2 Water-Vapor Adsorptive Hygrometers

Richards (1969, U. S. Pat. 3,430,486) reported the use of a membrane-shielded hygrometer for soil suction measurement. Fig. 2.16 shows a typical design of the membrane-shielded hygrometer. The spherical membrane-shield, with a diameter of 1.5 to 3.0 cm and a wall thickness from 0.1 to 0.3 cm, was made of porous ceramic which had an air-entry value from 40 to 100 kPa. The porous ceramic allowed soil water to flow into the membrane-shield. The hygrometric element was supported on electric wires. The electrically-conducting, water-vapor adsorptive layer coated on the hygrometric element was made from partially hydrolyzed polyvinylacetate having an appropriate content of lithium chloride. The water content and hence the electrical resistance of this salinized coating is related to ambient humidity.

Fig. 2.16 Membrane-Shielded Hygrometer (after Richards, 1969)

2.4 INDIRECT MEASUREMENTS OF SOIL SUCTION

The conventional techniques of indirect soil suction measurement include filter paper method, electrical conductivity sensors, and thermal conductivity sensors.
2.4.1 Filter Paper Method

The filter paper method, introduced by Gardner (1937), has been used for soil suction measurements for over sixty years. This method has been probably subjected to far more controversies, denial or approval, than any other adopted methods. Yet, the advantages of the low cost, and the acclaimed wide range of measurement have intrigued many researchers to pursue its use for soil suction measurements.

An extensive review of literature up to 1986 has been made by Gallen (1987). Recently, more studies were made by other researchers (Greacen et al., 1987; Fredlund and Rahardjo, 1988; Chandler et al., 1992; Miller, 1992; Deka et al., 1995; Swarbrick, 1995) which further contributed to the understanding of this method. It was only recently that the filter paper method was adopted by ASTM (D5298-92) as a standard method for soil suction measurement.

The filter paper method is based on the water-absorptive characteristics of a filter paper. When a filter paper is put into the environment of a soil, it will either absorb or desorb the moisture until the suction in the soil is equal to that in the filter paper. The suction in the soil can be estimated from the water content measurement. This method requires a calibration for suction versus water content relationship of the filter paper. The filter paper method can measure either the total suction or the matric suction over the entire range of soil suction, depending on the condition of contact between the filter paper and the soil.

The persistent use of filter paper for over half a century may be due to the following reasons:

1.) small differences in water-absorptive behavior within the same brand of filter paper,
2.) low costs of filter paper and measurement as compared to other existing methods,
3.) short equalization time over a wide range of suction due to the small thickness of filter paper,
4.) the ability of filter paper to maintain physical integrity and chemical stability during calibration and measurement, and
5.) failure to find other suitable moisture-absorptive materials.
The history of suction measurement using the filter paper method shows a wide variation of procedures. However, all the procedures, with the exception of blotting paper methods (Hansen, 1926; Gradmann, 1934), are under the same common guidelines which are typically represented by the ASTM (D5298-92) standard method.

The most commonly used filter papers include Whatman No. 42 filter paper and Schleicher & Schuell No. 589 filter paper. The Whatman No. 42 filter paper is generally used in Europe and Australia, whereas the Schleicher & Schuell No. 589 filter paper is more popular in North America. The standard method adopted by ASTM (D5298-92) recommended the best calibration curves (Fig. 2.17) which were presented by Greacen et al. (1987). The recommended calibration curves were obtained mostly from the research by Fawcett and Collis-George (1967) for Whatman No. 42 filter paper, and McQueen and Miller (1968) for Schleicher and Schuell No. 589 filter paper.

Fig. 2.17 Calibration of Suction-Water Content Curves for Wetting of Filter Paper (from ASTM: D5298-92, Greacen et al., 1987)

The calibration curves in Fig. 2.17 ignore the difference between different batches of filter papers. However, Deka et al. (1995) found that significant difference could exist between
different batches for the same type of filter paper. The filter paper technique tended to overestimate matric suction for dry soils. It was suggested that equalization periods longer than 7 days should be required for dry soils.

The limited accuracy for filter paper technique mainly comes from several reasons: inherent variations within the filter paper, sensitivity of the weighing balance, accuracy of calibration, environmental fluctuations (e.g., temperature and humidity conditions), and variations of skills among different users. The filter paper technique is generally considered only suitable for laboratory measurements.

Recently, a suction probe for insitu total suction measurement was developed at the Transport Research Laboratory (TRL), using the filter paper technique (Crilly et al., 1991; Gourley et al., 1995). The effects of temperature and equalization time were taken into account for calibration of Whatman No. 42 filter paper. A calibration equation was derived which included the filter paper water content, the equalization time, and temperature as variables. The scatter in experimental data was around ±10%, much lower than previously published calibrations (e.g., around +25% by Chandler and Cutierrez, 1986). However, the calibration was considered to be only specific to the TRL suction probe. This suction probe has been used in Australia, Brazil, and U.K. for various subsurface investigations.

Woodburn (1995) reported the use of a small inexpensive electronic balance which could be inserted within the soil sample container during filter paper measurement. The container had a lid about 75 mm diameter and a volume of about 400 cm³. Up to 300 grams of soil sample was placed in the container. A filter paper of approximately 0.05 gram was hung from the balance and weighed every minute. The results were electronically acquired and stored. This approach allows the immediate collection, transfer and calculation of data, thus reducing the user-dependence for the filter paper method. The filter paper in this method can not be in contact with the soil. Therefore, this method can not be used for matric suction measurement.

**2.4.2 Electrical Conductivity Sensors**

An electrical conductivity sensor for soil suction measurement includes a porous water-absorbing block. The electrical resistance of the absorbent block changes as its water content
changes. When a moisture absorbent block is placed in contact with a soil, water exchange occurs until matric suctions in the block and the soil are equal. The change in water content in the porous block leads to a change in its electrical resistance. Therefore, if the change in the electrical resistance of the porous block can be pre-calibrated against matric suction applied to the porous block, the matric suction in a soil can be computed by measuring the electrical resistance of the porous block in contact with the soil.

Bouyoucos and Mick (1940) concluded that desirable qualities of the absorbent materials were: (1) a hard, porous physical structure capable of rapid absorption and rapid drying with regard to water; (2) a large absorption capacity to ensure a useful order of sensitivity; (3) a moderate range of solubility to minimize the effects of changes in the soil salinity.

Cummings and Chandler (1940) pointed out that if the electrical field generated around the electrode fell outside of the absorbent block, the contact resistance between the block and the soil would become an undesirable factor in the measured resistance. Cronen et al. (1951) analyzed this problem and proposed a design with concentric electrodes to overcome this effect.

Numerous porous materials have been used to construct the porous block. Colman (1950, U. S. Pat. 2,526, 636) used compact woven glass fabric as a porous material. Bouyoucos (1953) used a rectangular sheet of woven nylon fabric between electrodes. Rosenthal and Tenafly (1956, U. S. Pat. 2,729,099) used plaster of paris as the material for the porous block and used a variable condenser to eliminate the lead capacitance of the porous block. Bouyoucos (1956, U. S. Pat. 2,740,032) proposed a plaster of Paris block impregnated with a water insoluble but permeable resin binder as the water-absorbing material. Turner Jr. et al. (1957, U. S. Pat. 2,793,527) developed a soil moisture apparatus which included a gypsum block as the conductive porous block. Hasenbeck (1979, U. S. Pat. 4,137,831) used a porous wall to house a granular material in which two electric plates were embedded (Fig. 2.18). Usable material for the porous housing includes polyethylene, ceramic, gypsum, or any inert material whose pore size is less than the pore size of the material contained.
Fig. 2.18 Electrical Conductivity Matric Suction Sensor (after Hasenbeck, 1979)

One of the disadvantages of the electrical conductivity method is that the influences of the soil salinity and temperature on the electrical resistance are significant. The effects of the temperature and salinity on the measurement of suction when using the electrical resistance measurement can be somewhat compensated. A typical method is to use double resistors. One resistor contains a relatively coarse, absorptive porous material to measure the overall electrical conductivity, while the other is filled with a relatively fine and saturated material to account for the effects of salinity and temperature. By including both resistors in the same electric circuit, the effects of temperature and salinity can be compensated. Patents based on this principle have been obtained by a number of researchers (Offermann, 1959, U. S. Pat. 2,869,359; Richards, 1974, U. S. Pat. 3,782,179; Cuming, 1985, U. S. Pat. 4,513,608; Richards, 1985, U. S. Pat. 4,561,293).

Hawkins (1993, U. S. Pat. 5,719,347) invented an electrical conductivity sensor which is in principle similar to the sensor made by Hasenbeck (1979). The sensor is illustrated in Fig. 2.19. An electrically conductive metal housing was built with perforations to admit moisture to an internal cavity. The cavity was lined with a woven nylon fabric to exclude particulate material which would tend to pass through the perforations. The liner also served to confine a
transfer matrix, made of tightly packed silica sand. Moisture from the soil can pass through the liner and penetrate the transfer matrix. A buffer made of compacted gypsum was placed against the transfer matrix. The gypsum buffer can pick up some electrolyte in moisture as it passes through, thus reducing the effect of the variations in concentrations of the salts in soil water on measured electric conductivity. The electrodes were embedded in an electrode matrix above the buffer. The electrode matrix, which was made of tightly packed silica sand, receives moisture which has passed through the gypsum buffer.

![Diagram of Electrical Conductivity Sensor](image)

**Fig. 2.19 Electrical Conductivity Sensor (after Hawkins, 1993)**

The electrical conductivity method generally suffers from some serious limitations as summarized by Aitchison and Richards (1965):

1.) the porous blocks follow a large hysteresis cycle and the resulting errors may be large,
2.) the influence of the soil salinity on the electrical resistance is significant; this method may be only suitable for non-saline sandy soils.

3.) the response time is slow; the porous blocks may not be used in a rapidly changing moisture environment.

Nevertheless, this method has some useful applications due to the following advantages:

1.) some porous blocks, such as gypsum blocks, are relatively sensitive over a wide range of suctions and are suitable for field use. For non-saline sandy soils, the sensitive range is from 30 kPa to 1500 kPa, and

2.) the blocks are of low cost and easy to handle.

2.4.3 Thermal Conductivity Sensors

The thermal conductivity sensors are based on the correlation between thermal conductivity and the water content of an absorbent block. Water is a good conductor of heat compared with air. When an absorbent block is put into contact with a soil, it will either absorb or desorb moisture until the matric suction in the block is equal to that in the soil. As a result, the thermal properties of the block are changed. By calibrating the thermal conductivities of the block against applied matric suctions, it is possible to measure the matric suction in a soil by measuring the thermal conductivity of the block in contact with the soil. An obvious advantage of thermal conductivity sensors over electric conductivity sensors is that the effects of salinity and temperature on thermal measurements are much smaller and in most cases negligible.

The idea of using the thermal properties of water for the measurement of soil suction was first introduced by Shaw and Baver (1939) who developed a device consisting of a temperature sensor and a heater. The device could be installed directly into the soil for measuring the thermal conductivity of the soil. However, different soils required different calibrations in order to correlate the thermal conductivity measurements to the water contents of the soil.
Johnston (1942) suggested that the thermal conductivity sensor be enclosed in a porous plaster of paris that has a standard calibration curve. This approach eliminates the need for the calibration associated with every soil to be measured. This concept has become a common practice in the development of thermal conductivity sensors for measuring soil suction.

A typical commercial thermal conductivity sensor is composed of a porous ceramic block containing a temperature sensing element and a miniature heater (Fig. 2.20, Fredlund et al., 1994). A controlled amount of heat is generated by the heater at the center of the block. A certain amount of the generated heat is dissipated throughout the block, depending on the amount of water present in the block. The undissipated heat will result in a temperature rise at the center of the block. The temperature is measured by the sensing element after a specified time interval, and its magnitude is inversely proportional to the water content of the porous block.

![Diagram of thermal conductivity sensor](image)

**Fig. 2.20 A Cross-Sectional Diagram of a Thermal Conductivity Suction Sensor (after Fredlund et al., 1994)**

The sensors are usually calibrated in a pressure plate by applying different matric suctions to a soil paste containing the sensor. By measuring the temperature rise or the related voltage...
output, the correlation between matric suction and the thermal measurements of the block can be obtained.

Richards (1955, U. S. Pat. 2,718,141) designed an electro-thermal element for measuring soil-water status (Fig. 2.21). The electro-thermal element was mounted in a standard porous medium contained in a porous ceramic cup with an air-entry value less than 10 kPa. The standard porous medium contains a major proportion of very fine sand and silt with a wide particle size range from 0.002 to 0.1 mm. A standard current passes through the heating coil for about 1 minute. The thermometer reads the temperature rise at the end of heating period. The temperature rise can be correlated to the soil water conditions, such as water content and matric suction.

![Fig. 2.21 Schematic of the Electro-Thermal Sensor (after Richards, 1955)](image)

Gypsum, ceramics, and mixtures of ceramics and castone were examined as potential water-absorbing materials by Phene et al. (1971). It was found that the ceramic was the most suitable material in that it exhibited a linear response and provided a relatively stable solid matrix.

Hasenbeck (1974, U. S. Pat. 3,847,351) developed a soil matric suction sensor based on the thermal conductivity of a water-absorbing material. The sensor is illustrated in Fig. 2.22. The electro-thermal element was enclosed in a porous material contained in a porous case
such as ceramic and gypsum. The porous material may include plaster sand, silica sand, sandy Palm Springs soil, or synthetic particles. This system was used for irrigation control.

![Diagram]

**Fig. 2.22 Electro-Thermal Matric Suction Sensor (after Hasenbeck, 1974)**

A commercial thermal sensor (229 Matric Water Potential Sensor) has been provided by Campbell Scientific Inc. since 1993. The sensor consists of a probe inserted axially in a porous ceramic cylinder which is 30 mm long and 15 mm in diameter. The probe consists of a stainless steel tube in which a heating element and a thermocouple (copper-constantan) are embedded. A heating period of 21 seconds allows for maximum heating time while the heat flux stays within the porous block. This sensor is being used in a variety of research and industrial projects in Western Canada.

Cumming (1994, U. S. Pat. 5,287,734) developed a thermal sensor which used a reference temperature zone for the temperature rise indicative of the thermal conductivity of a water-absorbing porous medium. The sensor is illustrated in Fig. 2.23. It consisted of two separate zones. The first zone had a cylindrical porous housing that allows soil water to enter or leave this zone. The heating element and temperature sensor were embedded in a porous media contained in the porous housing. The porous media may be glass beads, diatomaceous earth particles, or ceramic. The second zone was formed from a uniform media, such as an epoxy resin, which was dense and heat conductive. A reference temperature sensor was built in the second zone. Preferably a heater identical with the one in the first zone should be used in the second zone. By passing the same current through both heaters, variations in current would have less effect on the relative temperature between the two zones.
There are several important features that must be considered in designing thermal conductivity sensors:

1.) The block must be large enough to contain the heat pulse without interference from the surrounding soil, yet as small as possible to minimize the moisture equalization time. The optimum dimensions of the porous block were calculated by Phene et al. (1971), and Fredlund et al. (1994).

2.) The quality of the porous ceramic is crucial for the performance of the sensor. Firstly the ceramic should have a strong matrix. Secondly, the ceramic should have a linear variation in water content with suction over a wide range, which requires a wide distribution of pore sizes. Some large sizes are required in order for the sensor to be responsive to small suction values as low as 10 kPa (Fredlund, 1992; Fredlund et al., 1994). Thirdly, hysteresis between desorption and absorption should be as small as possible.

3.) The electronic units of the block should have strong resistance against damage due to prolonged flooding.

Research in the Soil Laboratory at the University of Saskatchewan has indicated hysteresis between desorption and absorption of the ceramic used in the thermal conductivity sensor is actually small (Sattler and Fredlund, 1989). However, currently a fully satisfactory ceramic is
not available. The commercial sensors (e.g., MCS 6000, AGWA-II, both currently not available) are only able to measure suctions ranging from 10 to 300 kPa. The accuracy of the suction measurements is generally low when the suction is above about 170 kPa. The ceramic tips are soft, friable and liable to crumble and crack during calibration and installation. The temperature sensing electronics are also prone to damage during extended flooding. The commercial thermal conductivity sensors are costly to build and the operating expenses are high.

Nevertheless, the thermal conductivity sensors still find an increasingly wide application in the geotechnical and geo-environmental engineering because of the versatility, relatively fast reaction, and the ability to be accessed by an automatic data acquisition system. These sensors are suitable for long time monitoring of soil-water conditions. A research program is currently being conducted in the Soil Laboratory at the University of Saskatchewan on the improvement of the quality of the porous ceramic used in the thermal conductivity sensor.

2.5 RECENT DEVELOPMENTS IN INDIRECT MEASUREMENT

Recent attempts to indirectly measure soil suction included use of new water-absorbent materials, use of electro-optical properties of soil-water, and use of ultrasonics.

2.5.1 Use of New Water-Absorbent Materials

Sibley and Williams (1990) tested Millipore MF filtration membranes and cellulose seamless tubing as alternatives for filter paper method. The calibration was obtained using a procedure similar to the calibration of filter paper. It was found that Millipore filtration membranes provide improved sensitivity over the range from 30 to 1000 kPa, as compared to Whatmans 42 filter paper and cellulose tubing. In the range from 30 kPa to 300 kPa, the greater sensitivity of the Millipore filtration membrane with the 0.025 μm pore size resulted in an increase of accuracy by 10% over that obtained using the filter paper. However, no data of measurement on soils was reported.
2.5.2 Use of the Electro-Optical Properties of Water

Use of optical properties of water for soil water measurements is a relatively recent matter (Auer, 1981, U. S. Pat. 4,266,878; Twersky et al., 1984, U. S. Pat. 4,445,788). Alessi and Prunty (1986) used the amount of light transmitted in a glass rod embedded in a pocket of glass beads to measure soil water content. The amount of light escaping from the glass rod was a function of the area of glass in contact with water. Kirkham (1987, U.S. Pat. 4,634,856) found that light reflected from a porous surface was related to the water content in the porous material.

Cary et al. (1989, 1991) suggested an electro-optical method for the measurement of soil suction and water content. The measurement was based on the theory that light tends to follow the tortuous path of an adsorbed water film through a piece of porous material because of the critical angle of light for water and air. The reflection characteristics of the pore walls are also likely to be involved. Thus some dry, rather opaque porous materials such as ceramics, nylon fabrics, and fritted glass transmit some light when water is present in their pores. The design is shown in Fig. 2.24.

![Fig. 2.24 Cross-Section of the Apparatus Used to Measure Liquid Content in Porous Materials (after Cary et al., 1989)](image-url)
Translucent materials with uniform nominal pore sizes are useful for irrigation control because as the suction exceeds the air-entry value, a break appears in the output signal from the electro-optical switch, which can control the turning on or turning off of irrigation.

Cary et al. (1991) assembled fritted glass disks with different pore sizes into a stack. A continuous change of resistance was shown as a function of water content which covered moisture conditions from air dry to saturation.

Similar to the thermal method, the optical methods are unlikely to be affected by the dissolved salts and ambient temperature. Another advantage of using electro-optical measurements is the low cost.

2.5.3 Use of Ultrasonics

Kasap et al. (1993) reported the use of low radio-frequency (~ 100 kHz) ultrasonic measurements to monitor the water content of a highly porous ceramic as an indirect means of evaluating matric suction. The principle was based on sending acoustic waves through a porous ceramic, measuring the magnitude of the transmitted wave as an output voltage on the receiving transducer. The output voltage was correlated to a volumetric water content. Therefore, a measurement was made of the attenuation of ultrasonic waves through the porous ceramic medium as a function of its water content.

The relationship between the output voltage of the receiving transducer and the volumetric water content of the ceramic was found to be approximated using Eq. (2.4),

\[
\ln \frac{V_{out}}{V_{in}} = A + B \theta_w + C \theta_w^2
\]

(2.4)

where:

\[ V_{out} = \text{output voltage}, \]
\[ V_{in} = \text{input excitation voltage}, \]
\[ \theta_w = \text{volumetric water content}, \]
\[ A, B, C = \text{constants for a given ceramic sensor}. \]
No application of this method for soil suction measurement was made, although it was considered to be suitable for matric suctions above 50 kPa. The main drawback of using ultrasonic measurements is the dependence of the measurement upon the salt concentration of water.
PART 2

TENSILE STRENGTH OF WATER AND ITS APPLICATIONS
FOR SUCTION MEASUREMENTS

2.6 INTRODUCTION

The use of the tensile strength of water to measure tensions greater than -100 kPa in water was first proposed by Gilbert (1960) in United States. It was suggested that a liquid sealed in a closed system without a free surface could be tensioned well below its vapor pressure without cavitation. An apparatus was developed to directly measure osmotic suction in sucrose solutions up to 620 kPa. Unfortunately, no measurements of soil suction were made and no further tests were reported.

After more than three decades, Ridley (1993) at Imperial College, U. K., found that a transducer, which was used to measure the pore-water pressure of a saturated clay during undrained-unloading tests in a triaxial cell, recorded tensions as high as -365 kPa for about 2 hours and suddenly jumped back to -100 kPa. The tensile strength of water was considered as the reason for this observation. A special tensiometer-type suction probe was further developed and used to measure soil suction. Following a series of tests, it was reported that suctions up to 1500 kPa could be measured.

The review presented here is a summary of the highlights with respect to the tensile strength of water. Both theories and historic experiments with respect to the tensile strength of water are examined. Tests conducted by Gilbert (1960) and Ridley (1993) are reviewed. The principal purpose of this review is to explore the background for the development of a suction probe based on the tensile strength of water.

2.7 TENSILE STRENGTH OF WATER

The review starts with an explanation of cavitation, followed by theoretical estimations of the tensile strength of water. Models for cavitation mechanism are briefly described. The
historic tests for the tensile strength are classified and chronologically highlighted in several sub-sections. Some interesting tests are described in a relatively detailed manner.

2.7.1 Boiling and Cavitation of Water

Hydrodynamic engineering has long been plagued by the phenomena of liquid cavitation in terms of its noise and physical damage to machinery. In soil science and geotechnical engineering, the measurement of negative pore-water pressure by some direct means, such as tensiometers, has been restricted to values lower than \(-100\) kPa due to the cavitation of bulk water.

The boiling and cavitation of water have been a research topic since at least 1873 when Reynolds investigated cavitation in constrictions. There are numerous research papers on the cavitation of liquids, including two authoritative textbooks (Knapp et al., 1970; Trevena, 1987).

The phenomena of boiling and cavitation can be explained from a thermodynamic point of view. Fig. 2.25 is the phase diagram of water. The point, O, is the triple point of water. Curve OA is where the vapor pressure is equal to the hydrostatic pressure in liquid at a given temperature. Curve OA defines the phase transition between the states of liquid and vapor. Curve OA is calculated from the equations given by Bridgeman and Aldrich (1964) which covers the entire transition range from \(0^\circ\text{C}\) to the critical point (i.e., \(374^\circ\text{C}\)). Curve OB defines the melting point of ice (i.e., ice-I). Curve OC defines the vapor pressure of ice. Both curves OB and OC are plotted from the data provided by Dorsey (1968).

Consider the transition between the liquid and vapor phases. At a given temperature, if the hydrostatic pressure is higher than the vapor pressure (i.e., the state falls above curve OA), water is in the liquid state (Point D), and vice versa. There are two paths along which D shifts to be on curve OA, on which the liquid state is broken up and vapor bubbles are formed. One path occurs when the hydrostatic pressure is reduced to a value equal to the vapor pressure at constant temperature. This is called "cavitation". The other path is to increase the temperature while maintaining a constant hydrostatic pressure. When the temperature is raised to such an extent that the resulting vapor pressure is equal to the hydrostatic pressure, vapor
Fig. 2.25 Phase Diagram of Water (from Bridgeman and Aldrich, 1964; Dorsey, 1968)
bubbles will occur. This phenomenon is called “boiling” because it is more violent or explosive. Fig. 2.26 gives the relationship between water vapor pressure and temperature from 0°C to 150°C. Because the vapor pressure of water at a temperature between 0°C and 100 °C is less than standard atmospheric pressure (i.e., 101.13 kPa), cavitation of the ordinary water usually occurs at negative pressures lower than -101.13 kPa gauge. For example, at 20°C, the vapor pressure is about 2.3 kPa. Thus, water can cavitate under a pressure of 2.3 kPa absolute, or -98.8 kPa gauge under standard atmospheric conditions.

As will be shown later, water at a state lying along curve OA is at a state of zero stress. Thus, the fact that water usually cavitates or boils when reaching curve OA indicates that generally water possesses no tensile strength under normal conditions. However, the following discussions will show that water should theoretically possess a definite tensile strength. A review of the historical experiments also indicates that water can exhibit significant tensile strength, though the values are much lower than the theoretical predictions.

2.7.2 Theoretical Estimation of the Tensile Strength of Water

One earlier estimation of the tensile strength of water was made from the atomic theory (Champion and Davy, 1936). The tensile strength of water was considered to be approximately equal to the “intrinsic pressure” existing between water molecules. According to this theory, the tensile strength of water could be as high as 1,000,000 kPa. This theory, however, was abandoned later because it was proved to be an unreasonable over-estimation (Vincent, 1941; Temperley, 1946, 1947; Harvey et al., 1947).

Frenkel (1946) and Fisher (1948), based on the calculation of the rate of growth of a gas bubble, predicated the tensile strength of water to be greater than 100,000 kPa.

One often-quoted estimation of the tensile strength of water is from the equation of state of substances, which is the van der Waals' equation (Temperley, 1947):

\[(P + a/V^2)(V - b) = RT\]  \hspace{1cm} (2.5)

where:

\[V = \text{volume of matter},\]
Fig. 2.26 Vapor Pressure of Water from 0°C to 150°C (from Bridgeman and Aldrich, 1964)
\[ P = \text{absolute pressure}, \]
\[ T = \text{absolute temperature}, \]
\[ R = \text{universal constant}, \]
\[ a, b = \text{constants}. \]

The theoretical tensile strength of a liquid was calculated to be equal to the vapor pressure at an absolute temperature which is equal to a value \(27/32\) of its absolute critical temperature. The critical temperature for water is 374 °C. The tensile strength of water, therefore, is about 50,000 kPa. Temperley (1947) found good agreement between the theoretical estimations for several liquids and the test results obtained by Kenrick et al. (1924), using the superheating method.

Kuper and Trevena (1952) developed a complex theory to calculate the effect of dissolved gases on the tensile strength of water. It was shown that the reduction in the tensile strength of water due to saturation of air at a pressure of one atmosphere is less than 0.5%, thus being negligible.

Many analyses on the tensile strength of water were based on pressures around a tiny gas bubble and the surface tension of water (Vincent, 1941; Kuper and Trevena, 1952; Fox and Herzfeld, 1954; Apfel, 1970; Knapp et al., 1970; Winterton, 1977; Gravnin, 1988). The actual approaches were diverse and complex. However, the fundamental background from which those analyses commenced can be traced to the analyses of the mechanical stresses in water. The rest of this section attempts to provide a simplified analysis of the tensile strength of water, based on the review of aforementioned literature.

The mechanical strength of a material is measured by the stresses at which the material ruptures or fails. Similarly, the tensile strength of a liquid is measured by the tensile stress at which the liquid ruptures or cavitates. Cavitation starts as the gas or vapor bubbles start to form in water. The vapor bubbles are triggered at gaseous or other hydrophobic surfaces which are commonly called potential cavitation nuclei. The stress condition at any point in water is shown in Fig. 2.27.
Fig. 2.27 Stresses in Liquid Water (the size of the nuclei is exaggerated)

At the surface of a potential nuclei, there is a tendency to form a minute vapor bubble, which tends to tear apart the surface into two and grow into a sphere. In other words, the vapor pressure, \( P_v \), acts as a tensile stress on the potential nuclei surface. On the other hand, the hydrostatic pressure, \( P_w \), tends to compress the liquid. The net normal stress, \( \sigma \), at a potential nuclei surface, before a bubble is formed, is expressed as:

\[
\sigma = P_v - P_w
\]  
(2.6)

The value of the stress, \( \sigma \), at the inception of bubble formation, measures the tensile strength of water, \( S_w \), which can be related to the surface tension, \( T_r \), of a sphere of a gas hole with a definite radius, \( r \).

\[
S_w = (P_v - P_w)_c = \frac{2T_r}{r}
\]  
(2.7)

where the subscript "c" refers to the value at cavitation.

The following three conditions may exist in water:

**Case 1:** \( P_v > P_w, \sigma < 0. \)

In Case 1, water is under compression and cavitation never occurs. Under atmospheric conditions within the common temperature range, \( P_v \) is negligible when compared to \( P_w \). The stress in water under this condition is nearly equal to the hydrostatic pressure.
Case 2: \( P_w \) is close to \( P_v \), \( \sigma \) is close to zero.

If water cavitates under the conditions of Case 2, the tensile strength of the water, \( S_w \), is zero. This is the normal case of cavitation, which occurs when the hydrostatic pressure is reduced to be equal to the vapor pressure at the corresponding temperature. Suppose there is a nuclei hole with a radius greater than 0.01 mm in ordinary water. According to Eq. (2.7), the maximum tension which can be applied prior to cavitation is less than 2 kPa absolute (\( T_r = 72.75 \times 10^{-3} \) N/m at 20\( ^\circ \)C). Therefore, the tensile strength of water is negligible.

Case 3: \( P_v > P_w \), \( \sigma > 0 \).

Under this condition, a tensile stress exists in water. If the radius, \( r \), is assumed to be the size of a water molecule (i.e., about 3 \( \times \) 10\(^{-7} \) mm), at the inception of the formation of a gas bubble, \( \sigma \) or \( S_w \) will be 48,000 kPa according to Eq. (2.7). Within the common temperature range, \( P_v \) is a negligible fraction of this magnitude. The normal stress, \( \sigma \), is numerically equal to the hydrostatic pressure which is negative. This means water can sustain a hydrostatic tension of about -48,000 kPa.

There is a special case where the vapor pressure, \( P_v \), can be much higher than the hydrostatic pressure, \( P_w \), before cavitation occurs. This case is referred to as superheating. If most of the gaseous nuclei have been removed, then under atmospheric conditions, water can be superheated to a much higher temperature than its normal boiling point without the formation of a cavity or bubbles (Briggs, 1955, Knapp, 1958). When water is superheated to such a high temperature that rupture occurs, the normal stress, \( \sigma \), which is equal to the corresponding vapor pressure minus the atmospheric pressure, measures the tensile strength of water at that temperature. The highest temperature at which water and vapor can co-exist is about 374 \( ^\circ \)C. Correspondingly, the tensile strength at this temperature could be as high as 22,000 kPa (Fig. 2.25).

The above discussions show that, although usually a liquid water will either cavitate or boil when its hydrostatic pressure is made equal to the vapor pressure, there is a possibility that water can be maintained in a liquid state even when the hydrostatic pressure is far less than the vapor pressure. That is, water can sustain a tensile stress without cavitation, or
boiling. The stress path in either case is shown in Fig. 2.28, which demonstrates that the difference between the vapor pressure and hydrostatic pressure measures the tensile stress in liquid water.

2.7.3 Mechanism of Cavitation

It is generally known that a liquid under tension is in a metastable state (Temperley and Chambers, 1946; Temperley, 1947; Chapmen et al., 1975; Trevena, 1987; Green et al., 1990). Metastable states are not true equilibrium states. The direction of change from the metastable states may irreversibly depend on certain triggering mechanisms. If tension becomes sufficiently high, the liquid will change irreversibly into a two-phase system. Metastability normally results from the lack of nuclei of the stable phase to form with sufficient size to be stable and grow. If a certain amount of undissolved nuclei are present in the liquid, the metastable states may not be necessarily realized and no tensile strength will be exhibited.

The measured tensile strength of water appears to fall short of the 1,000,000 kPa estimated from the mutual attraction between water molecules, or the "intrinsic pressure" within water. This is probably because breaking is not simultaneous across a unit cross-sectional area (Vincent, 1941). On the other hand, the wide variation of experimental values from 5 to 200 atmospheres, obtained by different researchers, may be a reflection of insufficient removal of small gas masses. The container is as important as the water in every experimental investigation of the tensile strength of water (Harvey et al., 1947). Not only must there be no gas nuclei on the walls but also there must be no hydrophobic surfaces present, since water does not adhere to these surfaces and readily separates from them. In other words, the measured tensile strength of water in a container does not represent the true property of water, but the overall ability of the water-container system to sustain tension. Today, it has been widely acknowledged that the undissolved nuclei within water and on the container walls are the main reasons for cavitation inception (Trevena, 1987).

Undissolved free air bubbles may not form the stable nuclei because either the surface tension would cause the bubbles to dissolve quickly, or the bubbles would rise to the surface and disappear (Knapp et al., 1970, Trevena, 1987). To account for the existence of the stable
Fig. 2.28 Tensile Stress in Liquid Water
cavitation nuclei, two main models of nucleation have been proposed. The first is the skin model (Fox and Herzfeld, 1954; Yount, 1979). A skin of organic impurity such as fatty acid is formed surrounding a spherical gas bubble. As the gas bubble starts to contract small enough under the influence of surface tension, the organic skin can inhibit any further shrinkage of the bubble. The bubble is then said to be stabilized. If the liquid is then subjected to tension, the skin will be torn apart. Gas diffuses into the bubble and cavitation is initiated.

The second model is the gas-trapping model. According to this model, the gases trapped in tiny crevices on the walls of the container and also in dust suspended in the liquid may become stabilized potential nuclei. This model was suggested by Harvey et al. (1944, 1947). The gas-trapping model was later used in explaining why pre-pressurization of a water-container system can effectively remove a significant portion of the potential nuclei, thus increasing the ability of water to resist cavitation when subjected to tension (Temperley and Chambers, 1947; Apfel, 1970; Winterton, 1977). As shown in Fig. 2.29, pre-pressurization of a liquid can increase the tension that can be sustained by decreasing the cavitation radius from the value at the cavity mouth to that inside the cavity. Pre-pressurization could be more important for the tensile strengths of liquids which have low advancing and receding contact angles with the surfaces of cervices. However, for a liquid that has a low wettability, the effect of pre-pressurization may not be significant. Temperley and Chambers (1947) also pointed out that increasing pre-pressurization does not always increase the tensile strength because the shape of the crevices may be altered.

Similar to pre-pressurization, heating water can also force water to penetrate into crevices because of the volume expansion of water. When the temperature drops, the water will contract. The liquid-gas meniscus will deflect back, but will resist the tendency retreating to the mouth of the crevice due to the restrain of the receding contact angle. As a result, an internal tension is developed in water. This mechanism probably explains that why high tensile strength of water can be measured on ordinary liquid water (e.g., without pre-pressurization), using the thermal method (see next section).
Fig. 2.29 Gas-Trapping Model: (a) Without pre-pressurization, cavitation occurs when liquid-gas meniscus develops at position 1 of the mouth of a crevice; (b) Pre-pressurization forces the meniscus at position 1 to convex, and penetrate into the crevice to position 2 when the advancing contact angle \( \theta_a \) is reached; (c) As tension is increased in the liquid, the meniscus becomes convex, and moves from position 2 to position 1 when the receding contact angle \( \theta_r \) is reached.

Both the skin model and the gas-trapping model assume that there already exist nuclei in the liquid before cavitation starts. Hayward (1970) suggested that there are at least three types of situations where cavitation nuclei can be started in an initially nuclei-free liquid. The first method by which cavitation nuclei can be formed is by the action of a high-energy atomic particle. The second method is tribonucleation in which cavitation is initiated when two solid surfaces immersed in a liquid under tension are gently rubbed together. The third method involves generating a tensile stress wave in the walls of the containing vessel by some mechanical impact.

Although the existence of the surface cavity nucleation sites is fairly widely accepted, these sites have not actually been "seen". Winterton (1977) calculated the radius of the cavities to be at least of the order of 1\( \mu \)m which is on the limit of resolution of optical microscopes.
2.7.4 Tests of the Tensile Strength of Water

Although no measurements of the tensile strength of water have ever reached the high magnitudes predicted by the theories, liquid water under certain favorable conditions, exhibits considerable tensile strength. In principle, the tensile strength of a liquid can be determined by applying tensile stresses to the liquid until it ruptures. The test methods in literature may be generally classified into three distinctive approaches for applying a tensile stress to a liquid. These approaches include thermal methods, hydrostatic methods, and dynamic methods.

The thermal methods can be further subdivided into two categories. The thermal contraction method utilizes the thermal properties of expansion and contraction upon heating and cooling, respectively. The superheating method is based on the fact that water can be superheated far above its normal boiling point without formation of air bubbles under certain favorable conditions.

For the hydrostatic methods, tension is directly applied to a liquid and no flow of the liquid occurs. In contrast, the dynamic methods involve either flow or kinetic impact in the testing liquids.

2.7.4.1 The Thermal Methods

I. The Thermal Contraction Methods

A liquid can expand and contract upon heating and cooling, respectively. If the volume change of a liquid is restrained by the surrounding environment, the thermal contraction will not be free upon cooling, and consequently, an internal tension is developed. If the effect of cooling is such that the liquid ruptures, the tension at rupture will measure the tensile strength of the liquid.

A classic thermal contraction technique, developed by Berthelot in 1850, has been frequently used to test different liquids. A basic Berthelot tube includes a glass capillary tube which is partially filled with degassed liquid and sealed. On heating, the liquid expands to force air into solution and fill the tube. On cooling, the tube remains full until the liquid ruptures under tension. The temperature drop between filling and rupture, plus the differential
thermal expansion of glass and liquid give the liquid volume change, from which the tensile stress can be calculated. The tensile stress at rupture measures the tensile strength of the liquid. Results of some earlier tests using the Berthelot tube are given in Table 2.1

Table 2.1 Tensile Strength Measurements with Berthelot Tubes
(from Knapp et al., 1970)

<table>
<thead>
<tr>
<th>Berthelot Tubes</th>
<th>Investigator</th>
<th>Liquid</th>
<th>Tensile Strength (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Glass Berthelot Tubes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berthelot(1850)</td>
<td></td>
<td>Water</td>
<td>5,000</td>
</tr>
<tr>
<td>Dixon(1909)</td>
<td></td>
<td>Water</td>
<td>5,000−15,000</td>
</tr>
<tr>
<td>Dixon(1914)</td>
<td></td>
<td>Sap</td>
<td>5,000−20,000</td>
</tr>
<tr>
<td>Meyer(1911)</td>
<td></td>
<td>Water</td>
<td>3,400</td>
</tr>
<tr>
<td>Meyer(1911)</td>
<td></td>
<td>Alcohol</td>
<td>3,900</td>
</tr>
<tr>
<td>Meyer(1911)</td>
<td></td>
<td>Ether</td>
<td>7,200</td>
</tr>
<tr>
<td>Vincent(1943)</td>
<td></td>
<td>Oil</td>
<td>11,900</td>
</tr>
<tr>
<td>Vincent(1943)</td>
<td></td>
<td>Water</td>
<td>15,700</td>
</tr>
<tr>
<td><strong>B. Steel Berthelot Tubes</strong></td>
<td>(1966,1967)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rees &amp; Trevena</td>
<td></td>
<td>Water</td>
<td>1,300</td>
</tr>
<tr>
<td>Rees &amp; Trevena</td>
<td></td>
<td>Carbon Tetrachloride</td>
<td>1,500</td>
</tr>
<tr>
<td>Rees &amp; Trevena</td>
<td></td>
<td>Aniline</td>
<td>2,100</td>
</tr>
<tr>
<td>Rees &amp; Trevena</td>
<td></td>
<td>Liquid Paraffin</td>
<td>2,200−2,900</td>
</tr>
</tbody>
</table>

The main disadvantage with Berthelot's original method is the problem of measuring pressure. An innovative modification of the Berthelot tube was made by Meyer (1911). The modified Berthelot tube is shown in Fig. 2.30. The glass at one end of a Berthelot tube was drawn out into a fine spiral tube and a small mirror was attached to the end of the spiral. The tube was then filled with the test liquid and the other end was sealed. Prior to this sealing, positive pressures were applied to the inside of the tube and the corresponding angles of twist
of the spiral were measured using a beam of light focused on the mirror. By this means the apparatus became a Berthelot tube with a built-in Bourdon-type pressure gauge.

Fig. 2.30 Meyer's Modification of the Berthelot Tube (1911)

Hayward (1964) used a strain-gauged "bomb" to measure tensions in a mineral oil which was sealed inside a thin-walled tube. The tube was heated to generate a pressure of about 20,000 kPa, then cooled to generate negative pressures in the liquid. A second strain-gauged "bomb" was used to offset thermal effects so that pressures were readily measured. However, no data on the tensile strength was given.

Chapman et al. (1975), and Richards and Trevena (1976) developed a new form of Berthelot tube in which the changes in pressure and tension in the enclosed liquid were measured directly by a diaphragm-type transducer. It was the first time that tensions as high as -3,000 kPa, which could hold for several minutes, were measured directly by a pressure transducer.
Evans (1979) used a transparent glass tube formed into a spiral coil to test tensions in water. The device was similar to the one used by Meyer (1911). Tensions as high as -3.000 kPa were reported.

Henderson and Speedy (1980) developed a glass capillary helix which functioned in a similar manner to the one used by Meyer (1911). The major advantage of this method was that the water volume was small (i.e., 2 to 4 mm³). The importance of the cleanliness of water and capillary was recognized. The highest tension measured was about -16,000 kPa. A tension as high as -10,000 kPa was sustained over a week without the occurrence of cavitation.

The Berthelot tube used by Richards and Trevena (1976) was further improved by Jones et al. (1980). The improved Berthelot tube is shown in Fig. 2.31. Flutes were made in the threaded steel rod so as to allow an initial evacuation of the test chamber and the subsequent filling of the test liquid. The cylindrical Berthelot tube was made of stainless steel. The main internal cavity had an axial length of 3.5 cm and an internal diameter of 0.7 cm. An unbonded strain-gauge pressure transducer was attached to this tube in such a way that the pressure-sensing diaphragm formed one of the end walls of the tube. The system was vacuum evacuated before the test liquid was admitted into the test chamber via the flutes. Then the pressure was raised to values ranging from 10,000 to 20,000 kPa by rotating the fluted rod to drive the copper cone into the top of the test chamber. The test liquid was then cooled by means of a refrigeration coil placed in the bath. All tensions obtained were higher than -500 kPa, and mostly above -1,000 kPa. It was concluded that the prior evacuation of the tube could deactivate most of the surface nucleate sites which would otherwise have triggered off cavitation at some lower value of tension.

Using a metal Berthelot tube which was similar to the one used by Jones et al. (1980), Ohde et al. (1988, 1992) studied the effect of repeated cavitation on the maximum tensile strength of water. A series of heating and cooling cycles were successively applied to water sealed in the Berthelot chamber. It was found that successive applications of tensile stress increased the tensile strength of water, and the weakest group of nuclei was on the copper plug surface. The increase in negative pressure with temperature cycles appeared to be due to
successive exhaustion of gas trapped in crevices on the copper surface. Tensions as high as -17,000 kPa were obtained.

![Diagram of Modified Berthelot Tube](image)

**Fig. 2.31 The Modified Berthelot Tube (after Jones et al., 1980)**

Green et al. (1990) generated a negative pressure of about -100,000 kPa in an elaborate Berthelot tube apparatus. About $10^9$ gram of water was trapped within healed fissures of a quartz crystal. The success came from the small-size sampling principle (Henderson and Speedy, 1980) for minimizing nucleation probability.

II. The Superheating Methods

Kenrick et al. (1924) heated water in open capillary tubes in which the potential cavitation nuclei had been carefully removed. Pure water was heated in a thermal bath to about 240°C before explosion took place.

Briggs (1955) used capillary U-tubes drawn from clean glass to superheat water. The tubes were drawn just before using and were partially filled with freshly boiled water. The bore diameter of the tubes ranged from 0.2 to 0.5 mm. The water was superheated by
immersing the tubes in a thermal bath. If the liquid did not explode after the lower part of the U-tube had been immersed in the bath for over 5 seconds, the tube was withdrawn, the bath temperature was raised and the process repeated until rupture occurred. The measured boiling-points ranged from 200°C to 267°C. The tensile strength of water was calculated to be at least 5,000 kPa.

Figure 2.32 presents the measured tensile strength of water versus temperature by Briggs (1950, 1955), using several different methods for different portions of the curve. The results agree qualitatively with the tensile strengths deducted from the van der Waals' equation (i.e., Eq. (2.1)).

![Graph](image)

**Fig. 2.32 Measured Tensile Strength of Water as a Function of Temperature**

(from Briggs, 1950, 1955)

Knapp (1958) used the superheating method on pre-pressurized and unpressurized water samples in capillary tubes. Pressures as high as 133,000 kPa were applied to water samples before the samples were subjected to superheating. The results indicated that pre-pressurization could significantly increase the tensile strength of water. The amount of increase was more significant for the pressure level in order of 2,800 kPa, but seemed to reach an upper limit at about 14,000 kPa. The maximum tensile strength of water was measured to
be about 2,500 kPa. Knapp (1958) attributed this increase to the dissolution of gaseous or vapor nuclei under high pressure. The undissolved nuclei was thought to be a triggering mechanism of cavitation. The effect of pre-pressurization duration was found to be insignificant.

The effect of pre-pressurization on cavitation was also studied by Winterton (1977) using the gas-trapping model. Three apparatuses were set up for different levels of pre-pressurization. These are shown in Fig. 2.33 to 35. In the first apparatus, water was boiled inside a vertical, stainless steel tube. The tube was heated by passing a current through a resistance wire. Pre-imposed pressures between 10 and 100 kPa were used. In the second apparatus a 7.5m high U-shape polythene tube was raised in a vertical position. With this apparatus, a pre-imposed pressure (i.e., deactivation pressure) of 500 kPa, and a tension of -75 kPa at the top of polythene tube could be achieved. Cavitation was detected simply by noticing when the water started to drain out of the polythene tube into the two vertical glass tubes. Boiling measurements were made by dipping a length of the polythene tube into a constant temperature bath, and noting the formation of vapor through the semi-transparent walls. The third apparatus was constructed to withstand pressures up to 800 kPa, and provided with a glass window so that the position of nucleation could be directly observed. In all three apparatuses, pre-imposed pressures were applied for 15 to 30 minutes.

The results from those tests indicated that the measured vapor pressure increased with increasing pre-imposed pressure. The trend in the results was in agreement with predictions based on a gas-trapping model. Fig. 2.36 shows the effect of pre-pressurization on the radius of nucleation computed from both boiling and cavitation measurements. The effect of pre-pressurization was generally less pronounced than the theoretical predictions.

There were several common features in the above thermal experiments: a) the temperature was well controlled; b) the heating and cooling rates were high; c) measurements were completed within a short period of time and the increase in the tensile strength seemed just momentary, lasting from a few seconds to several minutes; d) great care was taken to degas the capillary tubing and the water.
Fig. 2.33 The First Apparatus for Boiling Measurements (after Winterton, 1977)

Fig. 2.34 The Second Apparatus for Boiling and Cavitation Measurements (after Winterton, 1977)
Fig. 2.35 The Third Apparatus for Boiling Measurements (after Winterton, 1977)

Fig. 2.36 The Calculated Radii of Nucleation from Test Results and the Gas-Trapping Model (after Winterton, 1977)
2.7.4.2 The Hydrostatic Methods

Tension can be applied to liquids by hydrostatic means. Vincent (1941) used a metal bellows to measure the tensile strength of ethyl alcohol, ethyl ether, and mineral oil. Great care was taken to remove gases. The tensile strength of these liquids were measured to vary from 0 to 282 kPa. The measured tensile strengths could remain up to 15 minutes. The maximum tension appeared to be controlled by the degree of success with which residual gas had been removed from the liquid. The device, however, was not suitable for testing water because of the relatively low viscosity of water.

Another hydrostatic technique is to produce tension in the liquid by applying centrifugal force. Reynold in 1882 reported a tension of about -480 kPa for ordinary tap water, using a U-tube on a centrifuge. Using the same U-tube as Reynold’s device, Temperley and Chambers (1946) produced maximum tensions spreading from -220 kPa up to -565 kPa for tap water in large-bore and small-bore tubes.

Briggs (1950), using a capillary Z-tube on a centrifuge, obtained rupture tensions from -21,000 to -27,000 kPa in the temperature range from 5 to 50 °C.

2.7.4.3 The Dynamic Methods

Harvey et al. (1947) studied the tearing of water from a glass surface moving with high speed. A cylindrical glass rod was moved rapidly through a small volume of water in a narrow glass container. Care was taken to remove hydrophobic spots and dust particles by washing and centrifuging. Pressures up to 121,000 kPa were applied to the water for 15 to 120 minutes in order to force gas nuclei into solution. The formation of air bubbles due to the rapid passing of the glass rods was photographed with a high-speed motion-picture camera. It was found that the absence of gas phases and hydrophobic substances resulted in increases in resistance against tearing.

Davis et al. (1956) produced dynamic pulse pressure in the liquid by using bullet-propelled pistons. The experiments indicated that sustainable tensions for water could range from -800 to -1,400 kPa.
Knapp et al. (1970) made dynamic measurements in which they attempted to determine the cavitation characteristics of pre-pressurized water under actual flow conditions. Glass Venturi tubes were made. A water sample contained in a large cylindrical reservoir portion was forced through a meter under a suddenly applied pressure difference. The length of a test run was normally 1 second or less. The entire process was photographed by a high-speed motion-picture camera. The highest cavitation tension for the pre-pressurized samples was calculated to be about -300 kPa. All the unpressurized samples produced cavitations at pressures close to the vapor pressure.

Couzens and Trevena (1969, 1974), and Sedgewick and Trevena (1976) described a dynamic stressing method in studying the limiting negative pressure of water. The water under investigation was contained in a cylindrical stainless steel tube (Fig. 2.37). This 140 cm long tube was mounted vertically by means of supports which provided thermal insulation to the tube. The upper end of the tube was open and its lower end sealed by a cylindrical piston. A .22 in calibre rifle was fixed below the tube. The impact of the bullet caused a pressure pulse to be propagated upwards through the liquid column and this pulse was reflected at the upper free surface of the liquid as a descending pulse of tension. The pressure measurements were made with piezoelectric transducers. The breaking tensions of several types of water that were measured are given in Table 2.2. The maximum tensions which can be sustained increased in the order of ordinary water, tap water, deionized water, boiled water and boiled deionized water.

Table 2.2 Breaking Tensions for Four Types of Water  
(after Sedgewick and Trevena, 1976)

<table>
<thead>
<tr>
<th>Type of Water</th>
<th>Breaking Tension (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary tap</td>
<td>-900</td>
</tr>
<tr>
<td>Deionized</td>
<td>-1,000</td>
</tr>
<tr>
<td>Boiled tap</td>
<td>-1,150</td>
</tr>
<tr>
<td>Boiled deionized</td>
<td>-1,450</td>
</tr>
</tbody>
</table>
Lackm (1978) used a direct and novel way of applying a tension pulse to a liquid. The essential part of his apparatus is shown in Fig. 2.38. A test specimen was contained in a sealed thick-walled tube, mounted with it axis vertical. The enclosed liquid column was 4 cm long and 1 cm in diameter. The liquid was supported by a vertical cylindrical aluminum bar A and a similar bar B rested on top of the liquid. A tension pulse was generated by a weight onto the plate at the bottom of bar A, causing a stress wave to travel up through the liquid to the upper bar B. A strain gauge mounted on bar A recorded the incident pulse entering the low end of the liquid column and a similar gauge on B recorded the transmitted pulse. The maximum tension that could be generated and measured by this apparatus was about -500 kPa.

2.7.5 Effect of Contaminants on the Tensile Strength of Water

In principle, a contaminant, if it is to affect the tensile strength of a liquid, should have the ability to affect the formation, growth, or collapse of the cavitation nuclei. To make any significant change in the growth or collapse of existing nuclei in a liquid, a contaminant must be able to change appreciably such physical properties as viscosity, density, surface tension, thermal properties, etc. of the liquid (Kermeen et al., 1955; Knapp et al., 1970). Knapp et al. (1970) suggested that the tensile strength of a liquid might be affected by the degree of
wettability of the liquid, (i.e., the strength of the bond at the interface between the liquid and the solid surfaces). A liquid having a low wettability for solid surfaces would cavitate freely whenever the hydrostatic pressure drops below vapor pressure.

Fig 2.38 Tension Generation by a Falling Weight (after Lackmé, 1978)

Knapp et al. (1970) also pointed out that surface tension always works in one direction, that is, to close a cavity that is opened in a liquid. An important effect of surface tension is to decrease the rate of growth of the nuclei into finite cavities. A miscible liquid, capable of increasing the surface tension of water, should have a positive effect on the tensile strength of water.

Contrary to the above expectations, considerable information is available on the types of contaminants that do not affect the tensile strength of water (Kenrick et al., 1924; Harvey et al., 1947; Knapp et al., 1970). The addition of a miscible liquid does not have significant effect on the tensile strength of water. It is generally accepted that the undissolved gases, in bulk water or in crevices, are the basic impurities that reduce the tensile strength of water from its theoretical value to the low values encountered in cavitation measurements.
2.8 USES OF THE TENSILE STRENGTH OF WATER FOR SUCTION MEASUREMENT

There were only two applications of the tensile strength of water for suction measurements. These are described in this thesis as the Gilbert's device (1960) and the Ridley's suction probe (1993).

2.8.1 Gilbert's Device for Measuring Tensions in Water

The device developed by Gilbert (1960) to measure high tensions in water is schematically shown in Fig. 2.39. The device was designed on the understanding that a liquid, when sealed in a closed system without a free surface, may be tensioned well below its vapor pressure without forming air bubbles. The device mainly consisted of a membrane chamber, a null-indicator section, and a high air-entry value ceramic disk which was embedded in a triaxial cell. The stainless steel membrane chamber contained two tiny chambers divided by a very stiff stainless steel membrane. One chamber (about 0.1 mm wide) could be connected to vacuum, or vent, and to the ceramic disk via a mercury null-slug. Great care was taken to saturate this chamber and the tubings connecting the mercury slug to the ceramic disk. The other chamber was filled with pressurized air.

When water in the ceramic was subjected to a tension, the tension was transmitted to the chamber containing water, causing the membrane to deflect, thus a movement of the mercury slug. By reducing the air pressure on the other side of the membrane by an amount equal to the tension, the mercury slug was restored to the initial position, indicating a null condition. Therefore the tension in the ceramic disk can be measured from the adjustment of the air pressure.

A vacuum and osmotic solutions were subsequently placed over the ceramic disk in the triaxial cell to calibrate the device. Sucrose solutions were used because the ceramic disk has a high osmotic efficiency against the large molecular size of the solute. Fig. 2.40 gives the typical examples of the adjusted air pressure with time for different molar concentrations. The tension in water (e.g., about -600 kPa) could last for more than 2 hours. Fig. 2.41 gives the calibration results. The lack of a one-to-one correspondence between air pressure drop and
induced tension was attributed to the flexibility of the system because the volume change due to the system flexibility could not be compensated by adjusting the air pressure. In addition, the flexibility of the system also resulted in a relatively slower response time than anticipated.

Fig. 2.39 Schematic of the Device for Measuring Tensions in Water
(after Gilbert, 1960)

The ceramic disk proved not to be a perfect semi-permeable membrane. However, the diffusion of the solute molecules through the ceramic disk in a relatively short period of time to reach equilibrium was considered negligible.
Fig. 2.40 Air Pressure Versus Time for the Measurement of Tensions in Water Induced by Osmotic Suctions (after Gilbert, 1960)

Fig. 2.41 Relationship Between the Applied Water Pressure and the Change in Air Pressure (after Gilbert, 1960)
2.8.2 Ridley's Suction Probe for Measuring Soil Suction

The first soil suction probe designed by Ridley (1993) at Imperial College in London included a PDCR81 transducer which was fitted with a specially cut 15 bar ceramic stone. The probe was pre-pressurized to a pressure of about 2000 kPa and released to atmospheric pressure. The probe was then placed in contact with a soil sample to which a matric suction of 471 kPa had been applied using a pressure plate. An equilibrium was reached at -469 kPa after about 40 minutes. The tension was maintained for about 2 hours after which the pressure jumped instantaneously to -100 kPa. Further tests showed that the time that the tension could be maintained depended on the magnitude of the suction being measured. Fig. 2.42 shows the length of time the transducer could sustain a negative pressure.

![Fig. 2.42 Length of Time the PDCR81 Could Sustain Negative Pressure (after Ridley, 1993)](image)

The transducer later malfunctioned and its construction was considered unsuitable for measuring negative pressures. An Entran EPX-500 series pressure transducer capable of working in the range of 3500 kPa was then obtained. The thread on the transducer was
machined back to allow a stainless steel shroud to be fitted to the end of the transducer. A 15 bar ceramic was fitted in the shroud to provide a gap between the backside of the stone and the front surface of the active face of less than 0.1 mm (Fig. 2.43). The ceramic stone and the gap were saturated with water. An electronic controller was used to apply cycles of pressures between -80 kPa and +1900 kPa to the probe. The probe was then used to measure suctions on compacted clay samples. The results were compared with the filter paper measurements. The suction probe gave much higher suction values than the filter paper method.

![Diagram of Imperial College Suction Probe](image)

Fig. 2.43 Schematic of the Imperial College Suction Probe (after Ridley, 1993)

In another test, a high pressure triaxial cell was modified to incorporate an Entran EPX-500 series transducer screwed into the base pedestal. A kaolin sample prepared from a slurry was consolidated isotropically to a known effective stress. After equilibrium had been reached, the drainage valve was closed and the cell pressure was reduced to atmospheric pressure. The suction was monitored until equilibrium had been established. The measured negative pressures produced by undrained-unloading were in excellent agreement with the subsequent effective stresses for the range from 0 to 1500 kPa. The extrapolation of calibration from positive to negative pressure for the transducer was justified from this experiment.

In a later design, an EPX-10W-1000 transducer with a working range up to 7000 kPa was used in the probe with all the threads being filled with "loctite". This gave a significant improvement in the response characteristics of the instrument. Different shrouds and stones
leaving gaps of 0.1 mm, 0.3 mm, and 0.5 mm were used. A pressure of 5000 kPa was used to pre-pressurize the probe for at least 12 hours. The tests led to the conclusion that the gap and the thickness of the stone did not influence the ability of water to withstand tensions greater than -100 kPa.

Finally, a new suction probe machined directly from a single piece of stainless steel was built to eliminate the need for a threaded section beneath the stone. Details of this instrument are shown in Fig. 2.44. The characteristics of this instrument were considered more satisfactory than the previous designs. The developed suction probe was used to measure the suction during unconfined shearing of both reconstituted and compacted kaolin samples. The measurement was considered highly successful and tensions as high as -1,500 kPa were measured.

![Diagram of suction probe](image.png)

**Fig. 2.44 Schematic of the Imperial College Suction Probe (after Ridley, 1993)**

Ridley and Burland (1994) found reasonable agreement between the matric suctions in a reconstituted London clay measured using the developed suction probe and the filter paper method. The osmotic efficiency of the suction probe was found to be negligible. It was suggested that the micro-structure of the soil, particularly the size of voids, may affect the measurement of matric suction using the developed suction probe. However, no experimental
data was provided. The developed suction probe was later modified to measure matric suctions for osmotically controlled oedometer testing (Dineen and Burland, 1995).

2.9 SUMMARY

Both theory and experiments have shown that liquid water has the ability to resist high negative pressure. Although the results of measurements of tensile strength of water are widely scattered, most of the values are greater than 500 kPa. However, the ability of water to sustain tension requires some favorable conditions. Ordinary water is usually considered as having no tensile strength.

A liquid under tension is in a metastable state, rather than in a true equilibrium state. The metastability is due to the presence of potential nuclei in water and on walls of container. Three types of nuclei have been identified:

a.) minute gas or vapor bubbles in water and on the surface of container walls, possibly stabilized by thin films of hydrophobic matter such as organic matter
b.) inorganic impurities, such as dust particles and insoluble minerals
c.) tiny crevices on the surfaces of undissolved dust particles and container walls.

The inherent metastability of the liquids under tension may be the primary reason for the wide scatter of the results of tensile strength experiments.

Studies have shown that the experimental tensile strength of water, if sufficiently boiled and deionized, mainly depends on the presence of potential nuclei on the surfaces of container walls (i.e., the tiny crevices).

Vacuum can remove some of the gas and vapor bubbles. Common detergents can help removing hydrophobic impurities in water and on container walls. The application of high positive pressures to water and its container walls can effectively dissolve the undissolved nuclei both in water and on container walls and thus can significantly increase the tensile strength of water. Heating water can also effectively dissolve the cavitation nuclei, thus increasing the tensile strength of water.
The tensile strength of water can last from 5 minutes to several hours, or even longer. No contaminant has been found which can significantly increase the tensile strength of water.

There were only two attempts that used the tensile strength of water for suction measurements (Gilbert, 1960; Ridley, 1993). According to the basic principle of tensile strength of water, the Gilbert's device has the following disadvantages:

1.) The volume of water involved is too large and the path of tension transmission is too long. Consequently, chance of cavitation is great and the rate of success could be low.

2.) Water in the membrane chamber is not pre-treated (e.g., by pre-pressurization). It was doubtful that tension in water generated by this method could be higher than -100 kPa. This problem could not be avoided because the effect of pre-pressurization on the tensile strength of water was not well known at the time when Gilbert developed this device.

3.) The flexibility of the measuring system is undesirable because it does not produce the one-to-one correspondence and more importantly, increases the response time.

Ridley's work (1993) was pioneering in the sense that the tensile strength of water was, for the first time, used for soil suction measurement. However, the investigations were not systematic and extensive. Many questions regarding the principle behind this method remain to be answered (see chapter 4). More independent developments are needed to verify this approach. Therefore, it was proposed that further studies of using the tensile strength of water for soil suction measurements will be the major part of the current research program.
CHAPTER 3

STRATEGIES FOR THE MEASUREMENT OF SOIL SUCTION

3.1 INTRODUCTION

This research program is directed towards achieving further breakthroughs with regards to soil suction measurement. Existing strategies by which the conventional techniques have been developed are critically analyzed. Possible new developments in accordance with existing strategies are investigated. Finally, the new strategies adopted in this research program are outlined. The information provided in this chapter is considered useful for future research.

3.2 INVESTIGATIONS FOR EXISTING STRATEGIES

The existing strategies involved in developing methods for measuring soil suction can be classified into four groups (Fig. 3.1):

1.) the use of a moisture absorbent for the gravimetric measurement of water content,
2.) a direct measurement of hydraulic equilibrium,
3.) the measurement of liquid water properties of soil water,
   ○ direct measurement of liquid water properties (i.e., thermodynamic properties),
   ○ indirect measurement of liquid water properties (i.e., physical properties).
4.) the measurement of vapor properties of soil water.

This research program does not investigate devices falling into the last strategy (i.e., measuring vapor properties). Investigations involving other strategies are described in the following sections.

3.2.1 Water-Absorbing Polymers

There are always the possibilities that new water absorbents suitable for soil suction measurement may be found. At present, it appears possible to use certain water-absorbent polymers for the measurement of soil suction. Such materials have been recently produced in
the polymer-chemistry industry and have been used as humidity sensors (i.e., water-absorbent hygrometers), thus being capable of measuring total suction.

Fig. 3.1 Existing Strategies for Soil Suction Measurements

The ability of many polymers to absorb and desorb water molecules opens a wide field of application of polymers in various industries. Many of these polymers are not unusual for researchers in soils. For example, some water-swelling polymers, which are 3-dimensional cross-linked polymer networks generically referred to as hydrogels, are able to absorb and retain large quantities of water. These polymers are used as soil modifiers and moisture-releasing agents in agriculture, mining, and sludge dewatering (Nagy, 1985; Huang et al. 1987; Masuda and Iwata, 1988, 1990).

The presence of absorbed water has many effects on the physical and mechanical properties of polymers. The properties affected include the swelling potential and shrinkage,
the tensile deformation behavior, the creep, the durability, the phase transition temperature, the dielectric relaxation, the electrical conductivity, the thermal conductivity, and the optical properties. Another important feature of these polymers is that during water absorption and desorption, the physical and compositional integrity are maintained and the processes are reversible. Detecting changes in the polymer properties can lead to an understanding of water conditions.

There are several indications that certain water-absorbent polymers may be suitable for the measurement of soil suction:

1.) Polymers are used as humidity sensors with small hysteresis

Solid polyelectrolytes have been studied as materials for humidity sensors because their electrical conductance varies with humidity. However, their long-term stability is limited because of their high solubility. Recently, the technique of interpenetrating polymer network films has been introduced to produce a more reliable sensing material with much less solubility in water (Sakai et al., 1991). The humidities that can be measured with such sensors range from 0% to over 90%. Little hysteresis has been observed.

Studies on the behavior of poly-methy-methacrylate (PMMA) subjected to increasing relative humidities (Bueche, 1954; Kawasaki and Sekita, 1957; Smith and Sauer, 1986) have shown that water concentration in the polymer is proportional to the partial vapor pressure. In some polymers, such as in poly-ether sulphone (PES), water uptake appears to vary linearly with water vapor pressure over the entire range.

2.) Water absorbency of some polymers is significantly affected by salt concentration.

Kulicke et al. (1990) produced hydrogels with networks of different varieties of polymers and cross-linking agents in aqueous solutions corresponding to different NaCl concentrations. The study showed that an increase in salt concentration reduces the water absorbency. Similar conclusions were found for some highly water-absorbent polymers (Masuda and Iwata, 1988). In these cases, chemical reactions were unlikely because the wetting-drying cycles were reversible and the composition integrity was maintained. Perhaps it is the osmotic forces in the solutions which act to resist the absorbent forces of the polymers on water molecules.
3.) There is a correlation between the mesh size of the polymer and its swelling characteristics. The term "mesh size" is used to study the transport of solutes through swollen polymeric networks. There is a characteristic correlation length which defines the average distance between consecutive cross-links and serves as an indicator of the screen effect of the network on solute diffusion. An example of the study of the correlation of mesh size of hydrogel PVA with its water-swelling ability has been given by Canal and Peppas (1989). The results imply that the larger mesh size tends to result in higher swelling potential when subjected to water.

4.) Different types of polymers can be synthesized to embrace a wide range of water contents. A conductimetric microsensor based on reversibly swelling polymer hydrogels was designed by Sheppard (1991). A planar inter-digitated electrode structure coated with a polymer gel can detect changes in conductivity of a polymer hydrogel layer as the water content of the gel responds to environmental changes. A number of hydrogels were synthesized with varying chemistries so as to yield gels with a wide range of water contents and conductivities. Fig. 3.2 shows the conductivity and water content of gels as a function of composition. The construction of the conductimetric sensor is shown in Fig. 3.3.

The water content of synthetic hydrogels is controlled by the structure of the polymer. The idea of synthesizing different hydrogels with uniform structures into one with a mixed structure is similar to that of mixing porous materials with different pore sizes so as to yield an absorbent capable of sustaining a wide range of suctions.

5.) Polymers are effective in removing water from various solid particles such as coal and clay.
Fig. 3.2 Conductivity and Water Content of Gels as a Function of Copolymer Composition (after Sheppard, 1991)
Fig. 3.3 Construction of the Conductimetric Sensor (after Sheppard, 1991)

There are certain synthetic high polymers which rapidly absorb tens to several hundreds of times their own weight of water. Such highly water-absorbent polymers were developed about ten years ago at the Department of Agriculture of U.S.A. (Cugliemeli et al., 1980). More water-absorbent polymers have been developed in Japan (Ogura, 1984; Tanaka, 1985; Huang et al., 1987; Masuda and Iwata, 1988, 1990). The polymers do not appear to dewater easily, even under high positive pressure (Tanaka, 1985; Ogura, 1984). These polymers with excellent water-absorbent properties have been used to remove water from various particulate materials.

Figure 3.4 shows measurements of the water absorbent properties of various series of polymers in pure water (Masuda and Iwata, 1990). The weight of water absorbed in the polymers in pure water is several times the polymer weight in all cases. The time to reach saturation is 5 to 10 min. Over the range 20 to 60°C, the effect of temperature is negligible. The polymers absorb water under high humidity and desorb water under low humidity and the absorption-desorption cycle is reversible.

Masuda and Iwata (1990) also investigated the dewatering of a Datung coal (i.e., from China), a clay, and a sludge, using highly water-absorbent polymers. It was found that dewatering was dependent upon components such as sodium and calcium ion concentrations.
in the material to be dewatered. Any ion contained in water has a detrimental effect on the absorbency of the polymer (Masuda and Iwata, 1988).

![Graph showing the variation of absorbed water content with time.]

Fig. 3.4 Variation of absorbed water with time (after Masuda and Iwata, 1990)

3.2.2 Dielectric Measurements of Soil-Water Properties

One of the important soil-water properties that could be used for the measurement of soil suction is the dielectric property. Water has a much higher dielectric constant (i.e., 80) as compared to that of air (i.e., 1) and soil particles (i.e., 2–4). For the soil-bound water, the dielectric constant generally varies from 4 to 80, depending on the volumetric water content, the temperature, and the frequency used in the measurement (Chernyak, 1967; Selig, 1975).

Millard (1953) suggested that the dielectric measurement held greater promise for water content determinations than the conductance measurement. The theories with respect to the dielectric methods for investigating soils were described by Chernyak (1967). A number of researchers (Matthews, 1961; Thomas, 1966; Chernyak, 1967; Selig and Mansukhani, 1975) used capacitance measurements to determine the water content of a soil. However, most of
these techniques were considered either unsatisfactory or unsuitable for insitu monitoring of water content conditions (Selig and Mansukhani, 1975).

Since the late 1970's, the use of the Time Domain Reflectometry technique (i.e., TDR) for the measurement of the water content of a soil has gained increasing attention. The TDR technique has, in fact, become widely accepted as an advanced technique particularly suitable for the measurement of the water content of a soil (Topp et al., 1988; Dalton, 1992; Zegelin et al., 1992).

A simplified TDR system used to measure water content is illustrated in Fig. 3.5. The TDR device generates a high frequency (0.5 ~ 1 GHz) step voltage pulse or signal (i.e., \( V_i \)) which travels along wave-guiding transmission electrodes inserted into a soil. The soil serves as a dielectric medium. The signal is reflected from the ends of electrodes and returns to the TDR. The propagation velocity and the amplitude of the received reflected signal (i.e., \( V_r \)) are used to determine the water content and salinity of the soil. Topp et al. (1980) found that the apparent dielectric constant is primarily a function of volumetric water content and only weakly affected by the soil type, soil density, soil temperature and salt content. Equation (3.1) was established by Topp et al. (1980) and is generally accepted as a universal calibration curve, particularly for sandy and silty soils,

\[
\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \quad (3.1)
\]

where:

\( \theta = \) volumetric water content,

\( K_a = \) measured apparent dielectric constant, determined from the measurement of wave transmission time, \( t \).

The return voltage attenuation, (i.e., \( V_r - V_i \)), is related to the electrical conductivity. Measurements of the pulse attenuation and wave transmission time lead to the determination of electrical conductivity (Dalton et al., 1984; Topp et al., 1988; Tanuka et al., 1988; Zegelin et al., 1989).
Fig. 3.5 TDR Technique for the Water Content Measurement

The use of the TDR technique for water content measurement has several advantages. The TDR technique is soil-type independent, extremely quick, non-destructive, and suitable for automatic and remote measurement. The performance of the equipment is generally reliable and the interpretation of the results is relatively simple.

Although much research has been done to improve the performance of TDR for water content measurement (Topp et al., 1982, 1984; Dasberg and Dalton, 1985; Dalton and van Genuchten, 1986; Zegelin et al., 1989, 1992; Dalton, 1992; Skaling, 1992; Hook et al., 1992; Dirksen and Dasberg, 1993; Hilhorst and Dirksen, 1994; Stacheder et al., 1994), no efforts have been made to use the TDR for the measurement of soil-water potential, or soil suction.

The idea of using the TDR for soil suction measurement involves embedding the TDR electrodes into a porous medium which acts as a soil-water absorber and a dielectric medium. The porous medium is placed in the soil. Once equilibrium is attained between the soil and the
porous medium, the water content of the porous medium can be measured using TDR. The corresponding matric suction of the soil can be determined through a calibration procedure.

A research program is presently being conducted at the University of Saskatchewan to use the TDR method for the measurement of soil suction. Porous ceramic is tested as a porous medium for the TDR technique. However, at present, it seems that significant progress is difficult to achieve because of the following problems:

1.) the ceramic presently manufactured exhibits reduced sensitivity when the matric suction is above 150 kPa,
2.) the electromagnetic theory behind the TDR technique has not been fully understood, particularly when a complex soil-water system, or a porous ceramic, acts as the dielectric medium,
3.) the condition of the electrode-ceramic contact could be a major concern for using TDR for the measurement of soil suction because the electromagnetic fields concentrate near the electrodes where unexpected air pockets may exist and play a detrimental role,
4.) Topp (1987) pointed out that the transmission lines should be at least 100 mm long at a minimum spacing of 50 mm. This requirement may pose a major drawback in using TDR for the measurement of soil suction because the required size of the porous ceramic would be very large. It would take considerable time to reach suction equilibrium between the ceramic and the soil.

3.3 ESTABLISHING NEW STRATEGIES

This section discusses some new approaches for the measurement of soil suction from a strategic point of view.

3.3.1 Problems with the Existing Strategies

There is a philosophical problem with the general understanding related to the properties of water. While the properties of the pore-water in the soil are to be measured, the pore-water is different from ordinary water. This fact is generally ignored. The paradox is that on the one
hand it is accepted that water will cavitate when suctions go beyond 90 kPa, while on the other hand, many methods still claim to measure soil suction up to thousands of kPa. These measurements assume that the water phase in soils is still continuous at high suctions.

Water is not an "ordinary" liquid, but is an extremely anomalous liquid (Luck, 1991). The anomaly becomes more significant for water layers close to the boundary of contacting solid surfaces. There is substantial evidence that the structure of water in surface layers and in thin layers is significantly different from its structure in bulk water (Tarasevich, 1989; Derjaguin and Churaev, 1987; Low, 1970; Ozeki et al., 1991).

A typical example involves the swelling behavior of clays. The electrical double layer theory has been generally accepted as responsible for the swelling behavior of clays. Many equations have been written to calculate the swelling pressure based on the osmotic forces in the double layer. However, recent studies have provided strong evidence that the swelling behavior of clays is mostly due to the abnormal behavior of water around clays particles, rather than the osmotic expansion of the double layer (Low and Margheim, 1979; Low, 1979, 1987; Viani et al., 1983; Sun et al., 1986; Fu et al., 1990). The hydration of clay surfaces is considered as the primary cause for the swelling of clays. The surfaces of clay particles have a fundamental effect on the structure-sensitive properties of the interlayer water, such as the density and the heat of immersion. Water around clay particles can no longer be considered as ordinary water, but rather as extremely anomalous water.

Soil-water has an advantage that ordinary bulk water does not have, that is, the apparent ability to withstand and transfer high tensions (Terzaghi, 1925; Skempton, 1961; Bishop et al., 1975). Such behavior is desirable for the direct measurement of soil suction. Thus, a question can be raised "Why not use the soil-water interaction of a soil-water system to measure the suction in another soil-water system provided the behavior of the former system can be evaluated?"

3.3.2 Establishing New Strategies

There are two additional strategies which could be used for the measurement of soil suction. The first strategy is to find certain physical conditions under which water is
different from the water we commonly encounter. For example, under these conditions, water should be able to withstand high tensions. By simulating these conditions, the range of suction measurements can be extended. For example, pure water can sustain high tensions without cavitation or boiling under some favorable conditions. The possibility of using such characteristics for the measurement of soil suction has been discussed in Chapter 2. Another interesting scenario is the controversial existence of modified water which was reported in 1960’s.

The second strategy is to make use of the water-retention characteristics of a given soil so that the water involved in the measuring system is by nature not different from the water in the soil to be measured. Therefore, water in the given soil should possess similar properties to the water around soil particles (i.e., the ability to sustain high tensions). By measuring changes in certain properties of a given soil-water system which has a connecting boundary with a second soil, the suction in the second soil can be determined.

3.3.2.1 Physical Simulation of Water Conditions Around Soil Particles

Investigations have been made to study the possibility of simulating the conditions by which water is held around soil particles. Unfortunately, after a search of the research literature, it is evident that the anomalous behavior of water around soil particles is extremely complex and beyond our present understanding. For example, the structure of water under high tension is likely subjected to considerable elongation or distortion. To elongate and distort a minute water droplet until the tension on the air-water boundary and the corresponding electrical forces come into equilibrium, an electrical potential as high as tens of kv is required (Macky, 1931; Taylor, 1964, Snowden and van Lint, 1986; Inculet and Kromann, 1989). Therefore, the ability of water to exist continuously around soil particles under high tension can not be simply attributed to the electric forces since the electrical potential around soil particles is only in the order of several hundred millivolts (Chan et al., 1984). Obviously, the continuous state of the water film around soil particles cannot be explained simply from the physical magnitude of the electro-magnetic field around soil
particles. More profound physio-chemical interactions are likely responsible for the observed behavior.

3.3.2.2 Modified Water and Water in a Soil-Water System

Numerous investigations have been done in the 1960's to examine the anomalous behavior of a water column condensed from unsaturated vapor in fine capillaries (Deryagin and Fedyakin, 1962; Chahal and Miller, 1965; Deryagin et al., 1965; Fedyakin et al., 1965; Deryagin et al., 1966; Deryagin and Churaev, 1967; Lippincott and Stromberg, 1969; Willis et al., 1969). In general, columns of several millimeters of anomalous water were condensed from unsaturated vapor (i.e., relative to free normal water, RH is equal to 0.95 to 0.98) in the capillaries with radii down to tens of microns. The capillaries were freshly drawn with two open ends. The condensation took from 6 to 15 hours. The unsaturated water vapor could be either produced by a salt solution in a desiccator which was air-evacuated, or by evaporation from normal water while maintaining a temperature difference between the normal water and the capillaries in the thermostatically controlled chambers. Movement of the unsaturated vapor relative to the absorbing surface of capillaries was necessary for the formation of the anomalous water columns.

The condensed water exhibited many properties different from normal water, including the structure-sensitive properties such as viscosity and thermal expansion. These differences indicate that the structure of the condensed water is different from that of normal water. The condensed water is a structure-modified anomalous water, named polywater.

The discovery of polywater produced a “big wave” in the scientific world for more than one decade. It was once considered as “one of the most important discoveries in the 20th century”, yet “the most dangerous” (Franks, 1981). Many practicing scientists were anxious to study its applications. Low (1970) was the first soil scientist to study the results obtained by aforementioned scientists. A comparison was made of the properties of the modified water condensed from unsaturated vapor with that of water in clay. There was indirect evidence that the modified water (i.e., polywater), or a similar species, could exist in a clay-water system. The evidence was as follows:
1.) the orientation and dissociation of water in clays are consistent with the proposed structure of polywater in that water molecules in clays are oriented parallel to the planar clay surfaces, and that proton dissociation is much higher than in normal water,
2.) polywater is birefringent, so is the water associated with clay,
3.) the thermal expansion of polywater is different from that of normal water. It has a lower temperature of maximum density and a greater coefficient of thermal expansion above this temperature. The same is true of water in clays,
4.) the viscosity of polywater is higher than that of normal water, which is also true of clay water.
5.) both polywater and clay water have a lower vapor pressure than normal water,
6.) supercooling and freezing depression occur both for polywater and clay water,
7.) polywater could remain in open capillaries at a temperature as high as 320°C (Willis et al., 1969) without boiling. Adsorbed water remains in clays at this temperature. Since ions dehydrate at much lower temperatures, the presence of adsorbed water at such a high temperature cannot be attributed to the hydration of exchangeable cations. The modified water structure must play an important role,
8.) polywater is best prepared by condensation in dry capillaries at reduced vapor pressures. It does not form to a measurable extent when the capillary is first wet inside with a film of normal water. When dry clays are exposed to water vapor, they will adsorb water until their 001 spacing is 19 to 20A (Foster et al., 1955; Emerson, 1962). However, when the clays are brought into contact with liquid water, they will adsorb water until their 001 spacing far exceeds this value. This suggests that the water adsorbed by clays from the vapor phase, like that water adsorbed by capillaries from the vapor phase, is different than water adsorbed from the liquid phase.

From the above comparisons, it was suggested that the structure of adsorbed water with thicknesses of several microns on the clay particle surface might be similar to that of polywater in capillaries.

Like clay water, polywater in capillaries may be able to sustain high tensions (because it can be superheated). It may be reasonable to suggest that the ability of clay water to sustain
high tensions at low water contents is also due to the modified water structure, rather than solely due to osmosis by cations.

Unfortunately, after more than ten years of debate and a dramatic series of rises and falls, the existence of the polywater was finally denied (Franks, 1981). It was argued that the modified water formed on the capillary walls was badly contaminated with silica that had dissolved from the walls of the capillary, and the unusual properties of the water were attributed to the silica and other contaminants. However, it was also admitted that no explanation had been given to account for the unusually greater dissolving power of the water in vicinity of solid surfaces than normal bulk water (Low, 1994). Research into the nature of polywater has essentially been discontinued.

There is a possibility that the anomalous water existing on soil particles might have been formed in a similar manner as the polywater in fine silica capillaries. However, the identity of polywater is so controversial that it has been decided not to pursue the use of polywater in the measurement of soil suction in this research program.

3.3.2.3 Use of a Known Soil-Water System to Measure Soil Suction

Soil scientists have long ago known that water in a clay-water system has the ability to sustain high tension without desaturation. Consequently, the high air-entry value of a saturated clay has been used to obtain soil solution from another soil (Joffe and Mclean, 1925). However, the principle has not been applied for the measurement of soil suction.

Water in a saturated, highly plastic clay has the ability to transfer tensions greater than 100 kPa, while still keeping the clay saturated. Such ability is measured by the air-entry value of the clay-water system. For example, a saturated Regina clay specimen can have an air-entry value well above 500 kPa. If such a clay-water system is placed in contact with another soil-water system which has a suction greater than 100 kPa, water transfer will occur between the two systems while the clay-water system still maintains in a saturated state. Consequently, the mechanical state of the clay-water system would be changed. If the change is measurable, the suction in the soil-water system could be back-calculated through proper pre-calibrations.
Using the above described principle, suctions greater than 100 kPa could be directly measured.

Suction measurements based on a saturated compressible clay may be the first technique for measuring soil suction which uses the principle of soil mechanics. In addition, investigations of this nature may also add to our understanding of the behavior of soils, particularly when the pore-water pressure is negative.

3.3.3 Strategies Used in Current Research

The following two strategies are adopted in the current research program. Both strategies are based on the ability of water to sustain high tensions. These strategies are:

1.) the measurement of soil suction based on the tensile strength of water, and
2.) the measurement of soil suction using a compressible, saturated clay.

The first approach constitutes the major part of this research program and will be elaborated upon in the next three chapters. The second approach which is discussed in Appendix B proved to be more difficult and less rewarding. The second approach does not appear to be suitable for the development of a suction sensor because of hysteretic effects associated with the mechanical behavior of clays.
CHAPTER 4

LABORATORY PROGRAM

4.1 INTRODUCTION

The laboratory program was designed to achieve the principal objective of this research program, (i.e., to develop a suction probe that works on the principle of the tensile strength of water and extends the range of direct measurement of soil suction). The laboratory program is divided into two parts. The first part includes a systematic experimental study of the tensile strength of water, using a special suction probe which was developed at the University of Saskatchewan. The purpose of this study is to provide a better understanding of the fundamental behavior of water under absolute tensile stress. The direct measurement of tensile stress in water is made possible through the use of a high air-entry ceramic disk which provides an interface between a body of water and an externally applied tension (i.e., suction). Knowledge of the behavior of water under absolute tensile stress will be, undoubtedly, of important scientific and technological value.

The second part of the laboratory program investigates the applicability of the developed suction probe for the measurement of soil suction. The suction probe was used to directly measure suction in various types of soils.
PART 1

EXPERIMENTAL STUDIES ON TENSION IN WATER

4.2 TESTING PROGRAM

The testing program included the following investigations:

1.) Sustainable tensions in the probe in response to the following conditions:
   a.) effects of magnitude, repetition, and duration of pre-pressurization,
   b.) effect of water volume in the probe,
   c.) effect of salinity and addition of a miscible liquid.

2.) Stability of water under tension

3.) Sustainable tensions in a bentonite suspension.

4.) Effect of a saturated cellulose membrane enclosed in the probe.

   The following questions regarding the fundamental behavior of water under tension and
   the performance of the probe were addressed through these experimental investigations. These
   questions are listed below:

   a.) What are the major factors influencing the ability of the probe to sustain tension?
   b.) What is the mechanism of cavitation in the probe?
   c.) Is it possible to improve the ability of the probe to sustain tension by adding a hydrophilic
      agent in water, such as a cleaning agent, or a highly plastic bentonite?
   d.) Is it possible to increase the ability of the probe to sustain tension by placing a
      compressible film in the probe?
   e.) Is the probe suitable for long term laboratory and field measurement of soil suction?
4.2.1 Design and Fabrication of the Suction Probe and Accessories

Figure 4.1 shows a cross-section sketch of the fabricated suction probe which consists of two principal parts. The first part is a high pressure transducer manufactured by Entran Devices, Inc., Fairfield, USA (Model EPN-0762A1*-150SY). The transducer is used as the tension sensing unit. Its operational working range is 0 to approximately 150 bar. The sensing area is a smooth, circular surface with the diameter being 7.0 mm. The cable connection is water-proof. It was decided that the thread-type transducer should not be used because the surfaces of threads are difficult to saturate and may constitute an important source of potential cavitation nuclei. The pressure transducer is connected to a data acquisition system.

![Diagram](image)

**Measuring water chamber (0.1 mm - 2.5 mm)**

**Epicast Nine**

**15 bar ceramic**

**Entran transducer**

**Stainless steel shroud**

**To readout connection**

Fig 4.1 The Construction of the Suction Probe

The second part of the probe is a stainless steel shroud which was precisely machined to embrace the transducer. A 15 bar ceramic was fitted into the shroud, using a newly developed epoxy (i.e., Epicast Nine, Soilmoisture Corp., Santa Barbara, CA). Shrouds with different sizes were manufactured so as to be assembled together with the transducer under water, leaving a saturated gap, (i.e., the measuring water chamber) of 0.1 mm, 0.3 mm, 0.5 mm, and 2.5 mm, respectively. Probes with gaps of 0.1 mm, 0.3 mm, 0.5 mm, and 2.5 mm are hereafter
designated as 0.1 mm probe, 0.3 mm probe, 0.5 mm probe, and 2.5 mm probe, respectively. The initial purpose of using a small gap was to reduce the probability of nucleation to a minimum. All metal surfaces in contact with the water chamber were well polished. Plate 4.1 is a picture of the components of the probe. Plate 4.2 is a picture of an assembled suction probe.

Plate 4.1 Components of the Suction Probe

The most effective procedure to make the suction probe capable of sustaining high tension is to pre-pressurize the probe to dissolve potential cavitation nuclei. A rigid stainless steel cup was designed to pre-pressurize the suction probe. The assembly of the cup and the probe is shown in Fig. 4.2.
The pressurizing cup was constructed on a pressurization board which also includes a mechanical pistol, a pressure gauge, and connecting brass tubing (Plate 4.3). The construction of the pistol is shown in Fig. 4.3. The pistol can produce a pressure up to 15,000 kPa. The pressure which is registered on a high pressure gauge can be maintained for several days. The range of pressure that the pistol can produce is regulated using a spring-type pressure regulator. Figure 4.4 illustrates the flow-chart for the pressurization board. A separate brass vacuum inlet was constructed to provide the cup with a negative pressure as high as -85 kPa. A valve was used to switch between the positive and negative pressures. The tubings were so arranged as to ensure that the whole system could be readily saturated with water. The pressurization system is simple and easy to operate.
Fig. 4.2 The Suction Probe and the Pressurizing Cup

Fig. 4.3 Schematic of the Construction of the High Pressure Pistol
Plate 4.3 The Pressurization Board
Fig. 4.4 Flow-Chart for the Pressurization System

To calibrate the transducer, a shroud identical to the shroud of the suction probe, but without the ceramic, was constructed. The transducer was assembled into the shroud and connected to the pressurization board.

The transducer is operated over two ranges of pressure. One is the pre-pressurization range from -85 kPa to over 12,000 kPa. The other is the measurement range varying from 0 to -1,500 kPa. Fig. 4.5 shows the calibration results when the pressure varies from -85 kPa to 700 kPa. The transducer exhibits a linear behavior. The internal construction of the transducer essentially allows the extrapolation of the calibration curve from positive to negative pressures.

A total of four batches of 15 bar ceramic plates (Soilmoisture Corp., Santa Barbara, CA) were used throughout the laboratory program. The ceramic plates varied from 3.0 mm to 3.15 mm in thickness. The texture, color and response times of the ceramic plates were different. Figure 4.6 shows the response times of the 0.3 mm suction probe with different batches of ceramic under a pressure of about 2,000 kPa.
Fig. 4.5 Calibration of the Entran Transducer

Fig. 4.6 The Response Times of Different Batches of Ceramic
A stainless steel stand was built. The suction probe can be mounted on the stand for the tensile strength tests and soil suction measurements. The whole testing setup is shown in Plate 4.4.

Plate 4.4 The System Setup for Testing the Suction Probe

4.2.2 Testing Procedures for the Suction Probe

The operation of the probe is based on the tensile strength of water in the measuring chamber. If pretreated by some special procedures, water in the probe should be able to sustain tensions beyond -100 kPa. Tension in the probe can be generated in one of two ways: one is to allow evaporation from the ceramic; the other is to place the ceramic of the probe into contact with a suction source, such as a soil.
In this experimental study, evaporation was used to generate tension in the probe. The tensile behavior of the probe (i.e., the behavior under tensile stress) may be characterized by the tensile ability (i.e., the sustainable tension) and the characteristics of the probe under tension. The characteristics of the probe under tension include the tension stability, the tension duration, the tension reversibility, and the salinity effects. These characteristics are of fundamental importance in the application of the probe to soil suction measurements.

4.2.2.1 Probe Saturation and Pre-Pressurization

The performance of the suction probe is dependent upon the procedures associated with the saturation and the prevention of the formation of cavitation nuclei in the water chamber. The probe must be made fully saturated before applying pre-pressurization which enhances the saturation. The procedure to saturate the suction probe was consistent for all the tests associated with the use of the probe. The saturation procedure was as follows:

1.) Conventional distilled and deaerated water from the Soil Laboratory at the University of Saskatchewan, was placed in glass flasks and boiled for about 15 minutes. A vacuum of about -85 kPa was then applied to the water for at least 8 hours. The pretreated water was used in most tests. However, the tensile strength of the distilled and deaerated water without boiling was also tested.

2.) The shroud with the 15 bar ceramic was mounted onto the pressurization board. The pretreated water was then used to flush the pre-pressurization system using a sanitary syringe. A vacuum of -85 kPa was applied to the system for about one hour and the system was again flushed. A pressure of about 1,000 kPa was then applied to the ceramic on one side to force water to flow through the ceramic to the other side open to atmosphere. Air bubbles appearing on the other side of the ceramic were removed using a small piece of soft wet cotton. The ceramic was considered essentially saturated when there were no air bubbles.
appearing on its other side. The shroud was then removed from the pressurization board and placed in the pretreated water in a clean glass container.

3.) The transducer and the shroud were then assembled under the pretreated water to ensure that no air bubbles were trapped in the measuring chamber. The assembled probe was mounted onto the pressurization board. Air in the pre-pressurization system was then flushed out using pretreated water. A vacuum of -85 kPa was then applied to the system for about 1 hour and then released. The system was once again flushed.

A given pre-pressurization pressure was applied to the probe at the rate of about 1,000 kPa per 15 seconds. In theory, if the measuring chamber filled with water was completely rigid, the transmission of the applied pressure to the transducer should be simultaneous. However, due to the flexibility of the transducer diaphragm and the compressibility of water, a finite amount of water is needed to flow into the measuring chamber in order to register the pressure change. As a result, there was a response delay for the transducer. There is a time period during which the pressures on the two sides of ceramic are not equal. Therefore, the pressure increase should not be excessively rapid in order to prevent breakage of the ceramic. Generally, the response delay for a pressure increase of 1,000 kPa was about 15 seconds (Fig. 4.6, except for No. 3 and No. 4 ceramics).

After the application of the high positive pressure for a given period of time, the pressure was gradually reduced to zero. A vacuum of -85 kPa was then applied to the suction probe for a given period of time. This formed a pre-pressurization cycle for the probe. Pre-pressurization pressures from 1,000 kPa up to 12,000 kPa were used in order to investigate the effects of pre-pressurization level on the cavitation behavior of the probe. The time duration for the application of positive pressure for each pre-pressurization cycle varied from 1 to 30 hours.
4.2.2.2 Free Evaporation Tests

Free evaporation tests were conducted to determine the maximum tensile strength of the probe and the optimal pre-pressurization procedure. The probe was mounted onto the stand after pre-pressurization. Free evaporation was allowed until cavitation occurred and the system lost its ability to sustain tension. Several groups of tests, as listed in Table 4.1, were performed in order to identify the factors affecting the sustainable tension and the optimal procedure of pre-pressurization.

Table 4.1 Contents of Free Evaporation Tests

<table>
<thead>
<tr>
<th>Test Group</th>
<th>Purposes</th>
<th>Gap (mm)</th>
<th>Probe Ceramic</th>
<th>Pre-Pressurization Duration (hr)</th>
<th>Pre-Pressurization Pressure (kPa)</th>
<th>Pre-Pressurization Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>Effect of Pre-pressurization cycles</td>
<td>0.1</td>
<td>No. 1</td>
<td>1, 18</td>
<td>8,000</td>
<td>1, 3, 6, 8, 12</td>
</tr>
<tr>
<td>Group 2</td>
<td>Effect of Pre-pressurization duration</td>
<td>0.1</td>
<td>No. 1</td>
<td>0, 0.5, 1, 2, 10, 18</td>
<td>8,000</td>
<td>6</td>
</tr>
<tr>
<td>Group 3</td>
<td>Effect of Pre-pressurization magnitude</td>
<td>0.1</td>
<td>No. 1</td>
<td>1</td>
<td>0, 1,000, 3,000, 6,000, 8,000, 12,000</td>
<td>6</td>
</tr>
<tr>
<td>Group 4</td>
<td>Effect of ceramic</td>
<td>0.3</td>
<td>No. 1, 2, 3, 4</td>
<td>1</td>
<td>12,000</td>
<td>6</td>
</tr>
<tr>
<td>Group 5</td>
<td>Effect of water volume</td>
<td>0.1–2.5</td>
<td>No. 1, 2, 4</td>
<td>1</td>
<td>12,000</td>
<td>6</td>
</tr>
</tbody>
</table>

4.2.2.3 Impeded Evaporation Tests

The length of time during which the generated tension can be sustained is important if the tensile ability of the probe is to be used for the measurement of soil suction. Ideally, during an evaporation test, if the probe is covered after a specified tension is reached, the development of tension will be halted because evaporation is impeded. The time duration that the tension can be maintained at that magnitude should provide an assessment of the applicability of the probe to measure soil suction.
The impeded evaporation tests also attempted to find a proper procedure to cover the probe in order to reduce the effect of evaporation to a minimum. The impeded evaporation tests were performed using the 0.3 mm probe with the No. 1 ceramic.

4.2.2.4 Tension Reversibility Tests

An important question to be asked about the suction probe is, "If the tension is dropped due to environmental changes before cavitation occurs, will the system be able to sustain tension again when the environmental changes are reversed?" In other words, can the system reversibly respond to environmental changes as long as cavitation does not occur? The answer to this question should be obtained through the tension reversibility tests.

When a pre-determined tension is reached during an evaporation test, a small water droplet placed onto the ceramic will cause the tension to drop. As evaporation goes on, the tension is restored and will continue to rise. This procedure is called a cyclic evaporation. The repeatability of such cycles gives an idea of how well the probe can respond to environmental changes. The cyclic reversibility tests were conducted using the 0.3 mm probe with the No. 1 ceramic.

4.2.2.5 Contaminant Tests

It was suggested in Chapter 2 that a contaminant, if it is to affect the tensile strength of water, should have a significant effect on the properties of water. Typical properties would be the viscosity, the wettability, the density, the surface tension, and the thermal properties.

The commercial cleaning liquid "Fantastik" is miscible with water. "Fantastik" has a strong power to dissolve organic matter in water and increases the wettability of water. Therefore, adding "Fantastik" in water could probably increase the tensile strength of water. On the other hand, "Fantastik" decreases the surface tension of water, which should result in a decrease in the tensile strength of water.
The effect of adding "Fantastik" to water on the tensile strength of water was tested using evaporation tests. Three mass ratios of "Fantastik" to pure water were used in the tests (i.e., 1:20, 1:10, and 1:6.67).

Similar tests were also performed using a water-detergent mixture, a water-acetate alcohol mixture, and NaCl solutions.

4.2.3 Testing Procedure for the Tensile Behavior of a Bentonite Suspension

Bentonite has been known to have a high surface energy. Dry bentonite added into water in a proportion well above the liquid limit, forms a gel-like suspension. Water molecules are strongly absorbed around the bentonite particles. Experiments were conducted in this research program to investigate if the tendency of water to cavitate, when subjected to tension, is reduced in the presence of a bentonite suspension.

The liquid limits of several bentonites available in the Soil Laboratory at the University of Saskatchewan were tested. The highest liquid limit was found to be with the Wyoming Bara-Kade Standard Bentonite with a liquid limit of about 663%. A distinctive feature of this sodium bentonite is that the dominating smectite disperses in water into extremely thin sheet flakes in the order of 10⁻³ in thickness. Because of the structure of the flat surfaces of the individual particles, the water molecules adsorbed on these surfaces are oriented and have properties distinctive from normal liquid water (Grim, 1978). The orientation of the water molecules decreases outward from the surface. It was anticipated that this type of bentonite could have a significant tendency to change the tensile strength of water.

Three bentonite suspensions were prepared at water contents of 2000%, 1500%, and 1000%, respectively. Each suspension was thoroughly mixed using a magnet on an oscillating stirrer. The probe was assembled under these suspensions. The 0.1 mm, 0.3 mm, and 0.5 mm probes with the No. 1 ceramic were used in the tests. Evaporation tests were performed either with or without pre-pressurization.
4.2.4 Testing Procedure for the Probe Containing a Cellulose Membrane

The 0.1 mm gap between the ceramic and the transducer diaphragm is the minimum length that can be manufactured in the Engineering Workshop at the University of Saskatchewan. It was anticipated that certain types of film may be enclosed in the gap to further reduce the volume of free water, thus reducing chances of cavitation. A cellulose membrane provided by Soilmoisture Corp., Santa Barbara, CA, was chosen. The membrane has a high air-entry value of 15 bar and a thickness of 0.15 mm when saturated. It is also deformable when subjected to pressure and tension. When completely free of water, the thickness of the membrane reduces to about 0.07 mm. One major problem with the membrane is the occurrence of cracks if it loses excessive moisture.

A layer of the saturated membrane with a diameter equal to that of the measuring chamber of the probe was punched out of a large membrane sheet. The membrane was then placed over the ceramic in the shroud, under water. The transducer was slowly inserted into the shroud. The ceramic used in the probe was the No. 1 ceramic. After the probe was assembled, an evaporation test was performed to investigate the tensile characteristics of the water in the probe. Similar tests were also performed on the probe containing a two-layer membrane.
PART 2

TESTING THE SUCTION PROBE FOR SOIL SUCTION MEASUREMENTS

4.3 INTRODUCTION

A testing program was set up in order to further investigate the applicability of the suction probe for the measurement of soil suction. The testing program consists of two parts. The first part is the test of the performance of the probe in measuring soil suction. The second part includes a comparative study with several other conventional methods for measuring soil suction. The testing program was aimed at investigating the following aspects associated with the applicability of the suction probe for soil suction measurement:

a.) the suction components that can be measured,
b.) the range and accuracy of measurements,
c.) factors affecting the measurements, such as soil-ceramic contact and evaporation, and
d.) comparison of the suction probe with other conventional methods, particularly indirect measurements.

4.4 Testing Program for the Performance of the Suction probe

An existing pressure plate (i.e., a conventional Tempe Cell), was modified to test the extrapolation of the calibration from positive pressures to negative pressures. The axis-translation technique was used to calibrate the probe in the range of negative pressures. The probe was then used to measure a know soil suction. The suction component that the probe can measure was also investigated.

4.4.1 Soil Materials and Preparation

Two types of soils were used in the testing program: a Regina clay and a fine silt.
The Regina clay has been extensively tested in the Soil Laboratory at the University of Saskatchewan (Fredlund, 1964). Table 4.2 lists the typical properties of the Regina clay (Barbour and Fredlund, 1989). The Regina clay is generally considered to be a highly plastic, calcium-montmorillonite. The reason for using Regina clay, is that it has a high air-entry value and can remain nearly saturated when subjected to suctions as high as 1,000 kPa. When the suction probe is in contact with the clay, the condition of saturation ensures a good degree of contact between the probe and soil-water. Consequently, the effect of evaporation from the probe will be reduced to a minimum.

Table 4.2 Properties of Regina Clay (after Barbour and Fredlund, 1989)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atterberg limit</td>
<td></td>
</tr>
<tr>
<td>Liquid limit</td>
<td>75.5%</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>24.3%</td>
</tr>
<tr>
<td>Mineralogical clay fraction</td>
<td></td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>45.2%</td>
</tr>
<tr>
<td>Illite</td>
<td>27.7%</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>17.7%</td>
</tr>
<tr>
<td>Trichlorite</td>
<td>9.4%</td>
</tr>
<tr>
<td>Cation analysis</td>
<td></td>
</tr>
<tr>
<td>Cation exchange capacity</td>
<td>31.7 meq/100gm</td>
</tr>
<tr>
<td>Exchangeable cations</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>15.3 meq/100gm</td>
</tr>
<tr>
<td>Calcium</td>
<td>54.4 meq/100gm</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.59 meq/100gm</td>
</tr>
<tr>
<td>Sodium</td>
<td>1.77 meq/100gm</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.83</td>
</tr>
</tbody>
</table>

Air-dried Regina clay was machine-ground and passed through a No. 200 sieve. The sieved clay was made into a slurry at a water content of about 100%. The slurry was placed in an oedometer and consolidated to a pressure of 500 kPa. The sample prepared in this manner remains nearly saturated at a suction of 1,000 kPa (Fredlund, 1964).

The fine silt was made into a slurry and consolidated to a pressure of 800 kPa. The Regina clay and the silt, prepared in this manner, exhibit different soil-water characteristic
curves for the suction range from 0 to 700 kPa (Fig. 4.7). The silt desaturates at a low suction (about 10 kPa) and comes close to the residual water content at a suction of about 300 kPa. The purpose of using the silt was to investigate if the probe is suitable for measuring suctions in unsaturated soils, and to determine the effect that evaporation would have on soil suction measurements.

4.4.2 Design Details of the Modified Tempe Cell

The modified Tempe Cell is illustrated in Fig. 4.8. One 5 bar ceramic was placed at the bottom over a grooved water chamber which has two water-outlets. The suction probe was inserted into the cell through a rubber stopper sealed by a brass plug. A layer of prepared soil was placed between the suction probe and the 5 bar ceramic. A grooved brass block was placed over the probe to ensure good contact between the probe and the soil underneath. Water was added into the grooves of the block to maintain a constant humidity within the cell.

An air pressure was applied to the cell to force water in the soil to flow out through the 5 bar ceramic. The outflow was collected. When equilibrium was reached, the air pressure was quickly released to zero (i.e., atmospheric pressure). According to the principle of the axis-translation technique, at the moment of pressure release, a matric suction equal to the pre-applied air pressure should exist in the soil (Appendix A). Consequently, water in the suction probe should register a negative pressure numerically equal to the matric suction, or the pre-applied air pressure.

This apparatus allows for the direct verification of the axis-translation technique when the negative pore-water pressure is higher than -100 kPa.

4.4.3 Testing Procedures

The section describes the procedures of testing the performance of the developed suction probe in the measurement of soil suction.
Fig. 4.7 Soil-Water Characteristic Curves for Regina Clay and the Fine Silt
4.4.3.1 Measuring Osmotic Suction

Sucrose sugar ($C_{12}H_{22}O_{11}=342.30$) is a solute that is often used to test the osmotic efficiency of various membranes or ceramics. Three sucrose solutions were prepared with molar concentrations of 0.1 M, 0.18 M, and 0.24 M, respectively. The corresponding osmotic suctions at 25°C are about 242 kPa, 436 kPa, and 580 kPa, respectively. The pre-pressurized suction probe with the No. 1 ceramic, capable of measuring high tensions, was placed into the solutions. This test measured the osmotic efficiency of the 15 bar ceramic used in the probe.

Fig. 4.8 The Modified Tempe Cell for Calibration of the Suction Probe
4.4.3.2 Calibration of the Probe in the Range of Negative Pressures

The 5 bar ceramic in the modified Tempe Cell was saturated. A sample of reconstituted saturated Regina clay was placed over top of the ceramic. The pre-pressurized probe with the No. 1 15 bar ceramic was inserted into the cell as shown in Fig. 4.8. The water chamber underneath the 5 bar ceramic was flushed and filled with distilled and deaerated water. An air pressure of 200 kPa was applied as the first level of pressure. A glass bottle was used to collect outflow of soil water through the 5 bar ceramic. The outflow was checked from time to time. When the outflow ceased, the water underneath the 5 bar ceramic was approximately removed using an air pump. The air pressure was then quickly released to zero. Reduction in the water pressure in the probe was recorded. When the recorded pressure ceased to drop, the water chamber underneath was again flushed and filled with water. The air pressure was then increased to 300 kPa. The above procedure was again repeated. The test was continued for air pressures of 400 and 500 kPa. At the end of test, the water content of the soil was measured.

The collected water outflow was used to calculate the changes in water content during the equalization process at different air pressures. The degree of saturation of the soil was calculated based on the soil-water characteristic curve as shown in Fig. 4.7.

The above procedures were also followed for the test with the reconstituted silt sample.

4.4.3.3 Testing the Probe Against Pre-Applied Matric Suctions

This test was designed to evaluate the performance of the probe for the measurements of matric suction on both saturated and unsaturated soils. Samples of Regina clay were reconstituted by consolidating a slurry to a pressure of 500 kPa. Matric suction were pre-applied to a specimen in a conventional Tempe Cell. The outflow from the Tempe Cell was regularly weighed to check the state of equilibrium. After equilibrium was reached, the specimen was quickly removed from the Tempe Cell and placed on the stand to which the pre-pressurized suction probe had been mounted. Aluminum foil was then used to cover the specimen. A mass of 1 kg was placed over the specimen to exert a token pressure on the specimen against the ceramic. Electrical tape was used to seal the specimen from moisture loss
around the perimeter of the aluminum foil. The measurement setup is illustrated in Fig. 4.9 and Plates 4.5 and 4.6.

![Diagram of soil suction measurement setup]

**Fig 4.9 The Schematic Setup for Soil Suction Measurement**

Different degrees of contact were deliberately made between the ceramic of the probe and the soil specimen. The tests were performed as follows:

a.) **non-contact**: The surface of the 15 bar ceramic was made to recess below the surface of the probe. Therefore, the soil to be measured was not in direct contact with the ceramic.
b.) **contact through a clay slurry:** a small amount of Regina clay paste (about 0.2 mm thick) was placed between the recessed ceramic and the soil. Good contact should be established. The equalization time, however, should be influenced by the clay paste.

c.) **direct contact between soil and ceramic:** the ceramic surface was made to slightly protrude from the surface of the probe such that the soil specimen would be directly placed onto the ceramic surface.

---

Plate 4.5 The Setup for Suction Measurement Before a Soil is Positioned

Matric suctions, starting from 150 kPa, were pre-applied in a Tempe Cell, with each increment being 50 kPa, until 550 kPa. The suction probe with the No. 1 ceramic should be able to distinguish this suction increment satisfactorily.
The Regina clay, at a suction of 550 kPa, was still near saturation. However, measurements of matric suction in unsaturated soils, particularly dry soils, may encounter problems due to poor contact between the soil and the ceramic of the probe. There may also be an effect due to excessive evaporation into the dry pores of soils. This could result in several consequences: slow response times, inaccurate measurements, and possibly a failure to reach equilibrium due to excessive evaporation.

Plate 4.6 The Setup for Suction Measurement after a Soil is Positioned
To investigate the performance of the probe for measuring suctions in unsaturated soils, specimens of the fine silt were reconstituted by consolidating a silt slurry to a pressure of 800 kPa. Matric suctions up to 400 kPa, were pre-applied to a sample in a Tempe Cell. At a suction of 300 kPa, the specimen has a degree of saturation of about 37% (Fig. 4.7).

Matric suction measurements were conducted on the silt in a similar manner as on the Regina clay.

4.4.3.4 Total Suction Measurements

It was anticipated that the probe may possibly measure total suction if the equalization process is deliberately forced to occur in the vapor phase. To test this possibility, a 0.3 mm probe with a recessed ceramic was used to measure total suctions in reconstituted silt and Regina clay samples. The ceramic was recessed by 0.2 mm, or 0.4 mm, below the surface of the probe in order to investigate the effect of the volume in which equalization process took place. Matric suctions were pre-applied in a Tempe Cell to initially saturated specimens of both Regina clay and the fine silt. Measurements of total suction were then attempted using the probe. The pre-applied matric suctions were 50 kPa, 150 kPa, and 250 kPa.

4.5 TESTING PROGRAM FOR COMPARATIVE STUDIES

A comparative study was conducted to measure matric suction on a compacted soil, using four different methods. These methods included the suction probe, the null-pressure plate, the filter paper, and the thermal conductivity sensor. The purpose of this study, however, was not to verify the validity of the suction probe for the measurement of soil suction, but rather to provide a quantitative comparison between direct and indirect measurements.

4.5.1 Soil Material and Preparation

A glacial till obtained from Indian Head in Saskatchewan was selected for this part of the testing program. This soil has been extensively tested at the University of Saskatchewan over the past several years. The grain size distribution curve, the index properties, and the
compaction properties have been measured by Vanapalli (1994) and others (Gan et al., 1988). The results are presented in Table 4.3 and Figs. 4.10 and 4.11.

Vanapalli (1994) also measured the matric suctions at several compaction densities and water contents, using the null pressure plate method. The results are given in Table 4.4.

Table 4.3 Properties of the Glacial Till (after Vanapalli, 1994)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>2.73</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>35.5</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>16.8</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>18.7</td>
</tr>
<tr>
<td>Sand Size (%)</td>
<td>28</td>
</tr>
<tr>
<td>Silt Size (%)</td>
<td>42</td>
</tr>
<tr>
<td>Clay Size (%)</td>
<td>30</td>
</tr>
<tr>
<td>AASHTO Std. Compacted Dry Density (Mg/m³)</td>
<td>1.80</td>
</tr>
<tr>
<td>Optimum Moisture Content (%)</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Fig 4.10 Compaction Properties of the Glacial Till (after Vanapalli, 1994)
Fig. 4.11 Grain Size Distribution of the Glacial Till (after Vanapalli, 1994)

Table 4.4 Matric Suction Measurements on the Glacial Till Using the Null-Pressure Plate (after Vanapalli, 1994)

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Water Content relative to optimum</th>
<th>Dry Density (Mg/m$^3$)</th>
<th>Degree of Saturation (%)</th>
<th>Matric Suction (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.3</td>
<td>Optimum</td>
<td>1.80</td>
<td>86.5</td>
<td>152</td>
</tr>
<tr>
<td>13.0</td>
<td>Dry of Optimum</td>
<td>1.73</td>
<td>61.3</td>
<td>368</td>
</tr>
<tr>
<td>19.2</td>
<td>Wet of Optimum</td>
<td>1.77</td>
<td>96.3</td>
<td>68</td>
</tr>
</tbody>
</table>

In the current testing program, the soil was prepared using the procedure described by Vanapalli (1994). Five compaction densities and water contents were selected as given in Table 4.5. All five water contents were near, or on the dry side of optimum.

The required amount of distilled water was sprayed onto the air-dried soil passing through 2 mm sieve. The spraying was done in several layers on the soil. The soil was then left in a tightly sealed container and stored in a humidity controlled room for over 24 hours. The soil was then thoroughly hand mixed and passed though 2 mm sieve. This procedure
resulted in a uniform soil-water mixture with little or no soil clods for both dry and optimum water contents.

Table 4.5. Compaction Densities and Water Contents Used in Current Research

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Water Content relative to optimum</th>
<th>Dry Density (Mg/m³)</th>
<th>Degree of Saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.3</td>
<td>Optimum</td>
<td>1.80</td>
<td>86.5</td>
</tr>
<tr>
<td>15.0</td>
<td>Dry of Optimum</td>
<td>1.78</td>
<td>77.2</td>
</tr>
<tr>
<td>13.0</td>
<td>Dry of Optimum</td>
<td>1.73</td>
<td>61.3</td>
</tr>
<tr>
<td>11.5</td>
<td>Dry of Optimum</td>
<td>1.66</td>
<td>48.7</td>
</tr>
<tr>
<td>11.0</td>
<td>Dry of Optimum</td>
<td>1.61</td>
<td>43.1</td>
</tr>
</tbody>
</table>

The soil prepared at the required water content was statically compacted in three layers into a specimen of 101 mm in diameter and 20 mm in height. This specimen was used sequentially for the tests with the filter paper, the null-pressure plate, and the high suction probe. The tests with the thermal conductivity sensor required independent soil specimens which were at least 40 mm in height.

4.5.2 Equipment and Testing Procedures

The water contents before and after measurement were measured.

4.5.2.1 The Filter Paper Measurements

The testing procedure recommended by ASTM (D 5298 - 92) was followed for the filter paper method. The filter paper used was the No. 589 Schleicher & Schuell White Ribbon filter paper. Two soil specimens prepared at the same dry density and water content were placed on top of each other with three stacked filter papers inserted in between. The specimens were then covered with two layers of aluminum foil, wrapped around with electrical tape, and placed in a sealed container (Fig. 4.12). The container was placed in a foamed polystyrene insulated chest and kept in a humidity-controlled room for seven days to reach equilibrium.
The balance used for weighing has a capacity of 30 g and a sensitivity of 0.0001 g. A clean tweezer was always used to transport the filter paper.

![Diagram](Image)

**Fig. 4.12 Illustration of the Filter Paper Measurement**

The matric suction was calculated from the water content of the middle filter paper, based on the calibration curve recommended by ASTM (D 5298 - 92).

To investigate the variations of the filter paper method, measurements were repeated on more soil specimens prepared at the aforementioned densities and water contents.

**4.5.2.2 The Null-Pressure Plate and Suction Probe Measurements**

Following the filter paper measurement, the soil specimens were placed over a saturated 5 bar ceramic plate in a pressure plate cell. The "null flow" condition was maintained by adjusting the magnitude of the applied air pressure. The matric suctions in the specimens were assumed to be equal to the applied air pressure at equilibrium. In cases of prolonged time for equalization, effort was made to remove the diffused air bubbles underneath the ceramic plate.

The specimens after the null-pressure plate test were moved to the stand. The matric suctions in the specimens were then measured using the suction probe with the No. 4 ceramic.
A slight amount of wet soil paste (containing less than 0.08 gram of water) was used between the soil and the suction probe in order to improve soil-ceramic contact. This resulted in an increase of water content of the soil by about 0.04%.

4.5.2.3 The Thermal Conductivity Measurements

The thermal conductivity sensors used in this study were provided from a joint research program between the University of Saskatchewan and Tsinghua University, Beijing, China. Each sensor was 28 mm long and 20 mm in diameter. The sensors were recently re-calibrated at the University of Saskatchewan as matric suction against output voltage. These sensors demonstrated improved performance characteristics as compared with previous sensors. The sensors appeared to have a rigid structure and a stable response. Variations among the sensors were relatively small. However, the sensitivity above 170 kPa was significantly reduced. A major problem with these sensors is the occurrence of cracks in the sensor after a usage of about one or two months.

Both desorption and absorption calibrations were attempted in a pressure plate used for the specific sensor. Five levels of air pressures were used for desorption: 30 kPa, 80 kPa, 160 kPa, 300 kPa, and 400 kPa. The absorption test should start from a dry state of the sensor in order to obtain the principal absorption curve for the sensor.

A hole equal to diameter of the sensor was drilled in a compacted soil specimen which was 4 cm in height. The sensor which was initially either wet or dry was pushed into the hole. When the sensor was initially wet, it was left to dry for several minutes before it was pushed into the soil in order to avoid excessive water flow from the sensor into the soil. A slight amount of excavated soil was carefully back-filled to ensure a good seal around the sensor. The specimen was then covered by two layers of aluminum foil and wrapped by electrical tape.

The soil and the sensor were then left for equalization of matric suction. Changes in thermal conductivity of the sensor were acquired using a CR10 Datalogger (Campbell Scientific Inc., U.S.A.) and expressed as output voltages. The matric suction in the specimen
was calculated from the output voltage at equilibrium, based on the obtained calibration curves.
CHAPTER 5

PRESENTATION OF TEST RESULTS

5.1 INTRODUCTION

All results of conducted tests as described in Chapter 4 are presented in this chapter. The presentation of the data is divided into two parts. The first part gives the results of the experimental studies on the tensile strength of water using the developed suction probe. This testing program is essentially a scientific experiment and is conducted in a somewhat “Trial and Error” manner. Details of test procedures are given whenever needed to explain the results.

The second part presents the results associated with the testing of the suction probe for measuring soil suction. The suctions in a reconstituted clay and silt were measured using the suction probe. Results of the measurements of matric suction on a compacted glacial till using the suction probe and several conventional techniques are presented.
PART 1

TENSILE BEHAVIOR OF WATER

5.2 EVAPORATION TESTS OF THE SUCTION PROBE

The effects of pre-pressurization on the sustainable tension in the developed suction probe were first investigated. This was followed by the study of various tensile characteristics of the suction probe.

5.2.1 Free Evaporation Tests

Five groups of free evaporation tests were conducted (Table 4.1) in order to investigate effects of pre-pressurization on the sustainable tension in the suction probe.

5.2.1.1 Effect of Pre-Pressurization Cycles

Figure 5.1 shows typical results of the tests from the first group (Table 4.1), using a 0.1 mm probe with the No. 1 ceramic. Each pre-pressurization cycle included the application of a positive pressure of 8,000 kPa for about 18 hours, followed by a negative pressure of -85 kPa for about 5 hours. The tension developed very quickly during evaporation, indicating a rapid response of the probe. When no pre-pressurization was used, water in the probe cavitated when the tension reached -100 kPa. In contrast, pre-pressurization increased the tension that can be sustained without cavitation. At the moment of cavitation, the negative pressure instantaneously dropped back to -100 kPa. Submerging the probe slowly restored the pressure from -100 kPa to zero. Cavitation occurred again at -100 kPa after the probe was once again subjected to evaporation.

It is obvious that increasing the number of cycles of pre-pressurization can increase the tensile strength of water. The highest tension, which was -540 kPa, occurred for the case where 12 cycles of pre-pressurization were applied.
Fig. 5.1 Tension by Free Evaporation and Effect of Pre-Pressurization on Sustainable Tension (0.1 mm Probe with No. 1 Ceramic)
After the pressure was restored to zero, the probe was pre-pressurized again without replacing the water in the chamber. The ability of water to sustain tension could be almost fully restored. This is shown in Fig. 5.2.

Figure 5.3 shows the effect of pre-pressurization cycles. The pre-pressurization pressure was 8,000 kPa and was applied to the suction probe for one hour during each cycle. The maximum tension was about -650 kPa which occurred after the probe had been subjected to 6 to 8 cycles of pre-pressurization.

5.2.1.2 Effect of Pre-Pressurization Duration

Figure 5.4 shows the effects of time duration of pre-pressurization on the tension that can be sustained by the 0.1 mm probe with the No. 1 ceramic. The pre-pressurization pressure was 8,000 kPa and 6 cycles were applied (i.e., Group 2 tests). The highest tension (i.e., around -650 kPa) occurred when the probe was pre-pressurized for one hour for each cycle. Prolonged pre-pressurization did not produce better results.

It appears that the number of cycles was more important than the time duration of pre-pressurization. However, when the number of pre-pressurizations exceeded 6, the benefit of using more cycles became less significant.

5.2.1.3 Effect of Pre-Pressurization Magnitude

Figure 5.5 shows the effect of the magnitude of pre-pressurization pressure on the tensile ability of the 0.1 mm probe with the No. 1 ceramic. The pre-pressurization duration for each cycle was one hour and 6 cycles were applied. The increase in tensile strength with the increase in the pre-pressurization pressure was significant for the pressure increases up to 5,000 kPa and became less significant when pre-pressurization pressures exceeded 5,000 kPa.

From the above tests, it was concluded that the optimum pre-pressurization procedure is to apply 6 cycles of pre-pressurization. Each cycle includes an application of a positive pressure of 12,000 kPa for 1 hour, followed by a negative pressure of -85 kPa for 1 hour. This pre-pressurization procedure was implemented hereafter throughout this research program, unless otherwise stated.
Fig. 5.2 Restoration of Tensile Ability After Cavitation by Pre-Pressurization (0.1 mm Probe with No. 1 Ceramic)
Fig. 5.3 Effect of Pre-Pressurization Cycles on Sustainable Tension (0.1 mm Probe with No. 1 Ceramic)
6 Cycles, 1 Cycle = Duration @ 8000 kPa & Duration @ -85 kPa

Pre-Pressurization Duration During Each Cycle (hour)

Fig. 5.4 Effect of Pre-Pressurization Duration on Sustainable Tension (0.1 mm Probe with No. 1 Ceramic)
Fig. 5.5 Effect of Pre-Pressurization Magnitude on Sustained Tension (0.1 mm Probe with No. 1 Ceramic)
5.2.1.4 Effect of Ceramic

A total of 4 batches of 15 bar ceramics were used in the evaporation tests using a 0.3 mm probe (Group 4 tests). Different batches of ceramics demonstrated different response times and sustainable tensions. The results of free evaporation tests are given in Table 5.1.

Table 5.1 Effect of Ceramics on Sustainable Tensions (0.3 mm Probe)

<table>
<thead>
<tr>
<th>Ceramics</th>
<th>Sustainable Tensions (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>-600 ~ -650</td>
</tr>
<tr>
<td>No. 2</td>
<td>-400 ~ -450</td>
</tr>
<tr>
<td>No. 3</td>
<td>-360, -1600 (only one occurrence)</td>
</tr>
<tr>
<td>No. 4</td>
<td>-1200 ~ -1250</td>
</tr>
</tbody>
</table>

Generally, each batch of ceramics appeared to have a particular range of sustainable tensions for a given pre-pressurization procedure. The No. 4 ceramic was found to have the highest tensile ability. The ceramic with the quickest response time (see Fig. 4.6) usually gives the highest sustainable tension. An exception was found for the No. 3 ceramic which had the slowest response. A total of four free evaporation tests were conducted on a probe with the No. 3 ceramic. The results are shown in Fig. 5.6. The first test gave an extraordinarily high cavitation tension of about -1,600 kPa. However, the subsequent three tests showed a different behavior than the first. The highest tension, which appeared in the first test, did not again occur. Replacing the ceramic with one from the same batch produced a cavitation tension of about -360 kPa. Compared to other batches, the No. 3 ceramic demonstrated a slower development of tension during evaporation.

A vivid “click” sound could be heard whenever cavitation occurred at a tension of above -800 kPa. Probably a significant amount of energy was released at the inception of cavitation. For the first test with the No. 3 ceramic in which cavitation occurred at about -1600 kPa, a loud “click” was heard at the moment of cavitation.

It was observed that, although generally each batch of ceramic appeared to have a particular range of sustainable tension under a given pre-pressurization procedure, the sustainable tension seemed to depend on the cavitation history. For example, the sustainable
Fig. 5.6 Tension by Evaporation from 0.3 mm Probe with No. 3 Ceramic
tension of the No. 1 ceramic was reduced to a range from about -300 kPa to -400 kPa after about 20 cavitations at about -600 kPa. Similar phenomenon was also observed in testing the probe for the measurements of soil suction as will be described in the second part of this chapter.

The above test results imply that the condition of the ceramic may be important relative to the tensile behavior of the suction probe.

5.2.1.5 Effect of Water Volume in the Probe

Free evaporation tests performed on the 0.1 mm, 0.3 mm, and 0.5 mm probes with the same batch of ceramics gave essentially the same results. The tensile strength of the 2.5 mm probe appeared to be lower than that of the other probes with smaller water volumes in the measuring chamber. Figure 5.7 gives the results of evaporation tests performed on 0.3 mm, 0.5 mm, and 2.5 mm probes with the No. 4 ceramic. The 2.5 mm probe had a cavitation tension of about -925 kPa, 300 kPa lower than the 0.3 mm and 0.5 mm probes.

5.2.2 The Characteristics of the Suction Probe Under Tension

The investigated characteristics of the suction probe under tension included: the metastability of the system under tension, the time duration for the tension to be sustained, the reversibility of tension, and the effects of solute concentrations, including an addition of a miscible liquid.

5.2.2.1 The Metastability of the System Under Tension

Water under a tensile stress is in a metastable state. External disturbance to the suction probe system while it is under tension may trigger the growth of cavitation nuclei. The metastability is easily observed from a bottle of deaerated water heated to about 65°C. Normally water at this temperature should not cavitate or boil under a negative gauge pressure of -70 kPa because the absolute stress in water is still positive (i.e., about +4 kPa). However, a slight shaking of the bottle at this moment will immediately cause boiling to start from the walls of the bottle.
Fig. 5.7 Tension by Evaporation from Probes with No. 4 Ceramic
Another observation on the behavior of the probe is as follows. After a tension is developed higher than -100 kPa by evaporation, a slight mechanical impact to the probe will immediately cause cavitation at which the negative pressure drops back to -100 kPa.

The metastable state of water under tension can be broken by the generation of tensile stress waves near the walls of the container. This breakage can be due to the mechanical impact, resulting in the initiation of the formation of cavitation nuclei.

5.2.2.2 Impeded Evaporation Tests

After many pilot tests, it was found that an effective way to impede evaporation from the probe was to apply two layers of aluminum foil immediately onto the surface of the evaporating ceramic. Electric tape was then wrapped around the perimeter of the foil. This procedure must be carefully conducted in order to keep the mechanical disturbance to the probe to a minimum. However, placing the foil onto the ceramic unavoidably caused the air above the ceramic to compress, resulting in a slight decrease in tension. On the other hand, it was found that evaporation could not be completely prevented by the above covering procedure. This was attributed to the existence of some small unsaturated air pockets between the ceramic and the aluminum foil. Water from the ceramic could evaporate into these air pockets. The probe is extremely sensitive to even a minute amount of evaporation due to the small water volume in the probe and the rigidity of the probe. Consequently, the recorded tension in the probe would gradually rise.

Typical results of impeded evaporation tests are given in Fig. 5.8. When a tension rose to about -320 kPa during a free evaporation test, the 0.3 mm probe with the No. 1 ceramic was covered and the development of tension was then impeded. The results suggested that the probe could sustain a tension somewhere between -300 kPa and -500 kPa, or even higher, for at least several hours. In most cases, cavitation occurred around -600 kPa, no matter whether or not the water in the probe was replaced after the previous cavitation, or whether the evaporation was free or impeded. There was a range of sustainable tensions associated with a particular pre-pressurization procedure for a given probe. If a tension does not fall within this range, the tension could be maintained over a long period of time.
Fig. 5.8 Tension Development after Evaporation was Impeded (0.3 mm Probe with No. 1 Ceramic)
5.2.2.3 Tension Reversibility Tests

The reversibility tests proved to be an interesting series of tests in this laboratory program. Figs. 5.9a to 5.9e shows the results of such a reversibility test. During the 2 day testing period, cavitation did not occur even though thousands of evaporation cycles had been applied and the probe was intermittently submerged for time periods varying from 0.5 to 24 hours. During one phase of the test as shown in Fig. 5.9c, efforts were made to maintain the majority of tension values between -400 kPa and -500 kPa for over 5 hours. In the last phase of the test as shown in Fig. 5.9d, the majority of tension values were kept between -450 kPa and -550 kPa for about 2 hours until finally the tension fell within the cavitation range (i.e., from -600 kPa to - 650 kPa) and the probe cavitated.

Figures 5.10a to 5.10c shows another reversibility test which spanned over 17 days. The probe was, for most of the time, submerged in water. Each reversibility test lasted about 60 minutes. From Day 9, the probe was submerged in a NaCl solution of 2 molarities. The ability of the probe to respond to environmental changes was maintained. At the end of the 17th day, evaporation was allowed until the system cavitated at about -700 kPa. The solute concentration did not appear to affect the ability of the probe to sustain tension.

5.2.2.4 Contaminant Tests

The effect of adding "Fantastik" to water, on the tensile strength of the suction probe was tested using evaporation tests. Three mass ratios of "Fantastik" to pure water were used in the tests: 1:20, 1:10, and 1:6.67. Cavitation occurred at -100 kPa for all the three mass ratios without pre-pressurization. If the probe was pre-pressurized, cavitation occurred at about -580 kPa, -720 kPa, and -650 kPa, respectively. It appeared that the addition of the miscible "Fantastik" into water did not have a significant effect on the tensile strength of the water in the suction probe. Similar results were also obtained from tests using a water-detergent mixture, a water-acetate alcohol mixture, and NaCl solutions.
Fig. 5.9a Tension by Evaporation and Tension-Relaxation by Water-Droplets on 0.3 mm Probe with No. 1 Ceramic (to be continued)
Fig. 5.9b Tension by Evaporation and Tension-Relaxation by Water-Droplets on 0.3 mm Probe with No. 1 Ceramic (continued)
Fig. 5.9c Tension by Evaporation and Tension-Relaxation by Water-Droplets 0.3 mm Probe with No. 1 Ceramic (continued)
Fig. 5.9d Tension by Evaporation and Tension-Relaxation by Water-Droplets on 0.3 mm Probe with No. 1 Ceramic
Fig. 5.9: Tension by Evaporation and Tension Relaxation by Water-Droplets on 0.3 mm Probe with No. 1 Ceramic from the 95th minute to the 105th minute.
Fig. 5.10a Tension by Evaporation and Tension-Relaxation by Water-Droplets over 17 Days on 0.3 mm Probe with No. 1 ceramic (to be continued)
Fig. 5.10b Tension by Evaporation and Tension-Relaxation by Water-Droplets over 17 Dayson 0.3 mm Probe with No. 1 Ceramic (continued)
5.3 TESTS OF THE SUCTION PROBE CONTAINING A BENTONITE SUSPENSION

Figures 5.11 and 5.12 give typical results for evaporation tests performed when the probe contained bentonite suspensions with water contents being 2000% and 1500%, respectively. The 0.3 mm and 0.5 mm probes with the No. 1 ceramic were used. In all the tests without pre-pressurization, cavitation occurred at -100 kPa. If the probe was pre-pressurized, the tensile strength of the system was increased to about -280 kPa, -130 kPa, respectively. However, the magnitude of increase was far less than that for the pre-pressurized suction probe containing pure water. Pre-pressurization did not make any improvement for the tensile ability of the probe when the water content was reduced to 1000%. A repeat of the above tests gave very similar results.

The results from the tests using the 0.3 mm probe are summarized in Fig. 5.13. Increasing the bentonite concentration decreases the tensile ability of the system.

5.4 TENSILE ABILITY OF THE SUCTION PROBE WITH A BENTONITE-CLOGGED CERAMIC

It was anticipated that the ceramic might become clogged with absorbed bentonite during the above evaporation tests. Consequently, the response time of the probe with respect to the use of pure water was checked from time to time. After the tests with the bentonite suspension at a water content of 1000%, the ceramic was found to be severely clogged with absorbed bentonite. This resulted in a slower response.

The ceramic was mounted onto the pressurization board and an attempt was made to remove the absorbed bentonite by flushing water through the ceramic. A pressure of 1000 kPa was applied to the top side of the ceramic, forcing pure water to flow through the ceramic to the other side which was open to atmosphere. The probe was then assembled under pure water. Free evaporation was then allowed. Surprisingly the tension in the system rose well above -100 kPa and cavitation did not occur until the tension reached -460 kPa. The data is shown as Test 1 in Fig. 5.14a. The probe was then submerged for 24 hours for resaturation. Again the system cavitated at about -480 kPa by evaporation (Test 2, Fig. 5.14a). Immediately after cavitation the water in the chamber was replaced, but no efforts were made
Fig. 5.11: Tension by Evaporation in Suction Probes Containing a Bentonite Suspension (w = 2000%)
Fig. 5.12 Tension by Evaporation in Suction Probes Containing a Bentonite Suspension (w = 1500%)
Fig. 5.13 Sustainable Tension in 0.3 mm Probe Containing Bentonite Suspensions
Fig. 5.14a Tension by Evaporation from 0.3 mm Probe with a Bentonite-Clogged No. 1 Ceramic
(No Pre-Pressurization except in Test 6)
Fig. 5.14b Tension by Evaporation from 0.3 mm Probe with a Bentonite-Clogged No. 1 Ceramic
to saturate the ceramic. The evaporation test gave a cavitation tension of -365 kPa (Test 3, Fig. 5.14a). Repetition of this test gave a lower cavitation tension of -270 kPa (Test 4, Fig. 5.14a). The ceramic was then flushed. However, this time the system cavitated at -225 kPa (Test 5, Fig. 5.14a), much lower than after the first flushing. Pre-pressurizing the system increased the cavitation tension to -480 kPa (Test 6, Fig. 5.14a). Reflushing the ceramic again gave a lower cavitation tension of -190 kPa (Test 7, Fig. 5.14b). Submerging the probe another 24 hours without pre-pressurization again increased the cavitation tension to -480 kPa (Test 8, Fig. 5.14b).

It was not clear why the above different procedures gave different cavitation tensions. Nevertheless, the fact that the tension could rise well beyond -100 kPa even without pre-pressurization, suggested that possibly the extremely thin sheet bentonite flakes dispersed in the solution could have filled some of the tiny crevices on the chamber surfaces which might otherwise have been the sources of cavitation nuclei. In other words, the bentonite could play a role similar to pre-pressurization in eliminating some of the cavitation nuclei on the surfaces. Cavitation is likely to initiate on the ceramic rather than on the transducer.

To investigate the repeatability of these characteristics, the clogged No. 1 ceramic was replaced with a fresh ceramic from the same batch. The ceramic was submerged in a bentonite solution with a water content being 1000% for 14 days. The probe was assembled again under the bentonite solution and subjected to several cycles of pre-pressurization. The probe was opened and the bentonite was purged from the chamber. The probe was then assembled under pure water. The first evaporation test gave a cavitation tension of -100 kPa (Test 1, Fig. 5.15). Flushing the ceramic gave a cavitation tension of -290 kPa (Test 2, Fig. 5.15). More thorough flushing resulted in a higher cavitation tension of -460 kPa (Test 3, Fig. 5.15). Submerging the ceramic for 10 hours also gave a cavitation tension of about -430 kPa (Test 4, Fig. 5.15). In Test 5 (Fig. 5.15), the probe was pre-pressurized along with the transducer. The tensile ability of the system increased to -570 kPa.

In Test 6 (Fig. 5.15), a metal block, with a configuration duplicating that of the transducer, was assembled with the ceramic and pre-pressurized. The block was then replaced with the transducer. It was assumed that if the ceramic was responsible for inception of
Fig. 5.15 Tension by Evaporation from 0.3 mm Probe with a Bentonite-Clogged No. 1 Ceramic
cavitation, pre-pressurization of the ceramic without the transducer should give the same cavitation tension as observed for pre-pressurization with the transducer. This assumption, however, was not proved. Pre-pressurizing the ceramic without a transducer gave a normal cavitation tension (-100 kPa). Probably during the course of replacing the duplicated block with the transducer, certain cavitation nuclei had already been introduced onto the ceramic.

5.5 TESTS OF THE SUCTION PROBE CONTAINING A MEMBRANE

The procedure of testing the suction probe containing a compressible cellulose membrane has been briefly described in Chapter 4. More details are given in this section. The tests were conducted using a 0.1 mm probe with the No. 1 ceramic.

5.5.1 Evaporation Tests

In the first test, care was taken to ensure the membrane was not stressed when the transducer was inserted into the shroud. The evaporation test, however, gave a slow response and the tension could not go beyond -100 kPa. This was attributed to the unsatisfactory contact between the membrane and the transducer diaphragm.

The membrane was then replaced. The transducer was inserted into the shroud to exert a pressure of about 500 kPa to the membrane. The applied pressure returned close to zero because of the compressibility of the membrane. This procedure was called pre-stressing. An evaporation test was then carried out either with or without pre-pressurization.

The test results for the suction probe containing one-layer membrane are given in Fig. 5.16. The one-layer membrane, if pre-stressed in the probe, increased the cavitation tension by about 200 kPa, even though the system was not pre-pressurized. Moreover, 6 cycles of pre-pressurization were more efficient in increasing the tensile ability than 1 cycle of pre-pressurization. The application of 6 cycles of pre-pressurization for this system extended the cavitation tension to about -950 kPa, 300 kPa higher than for the suction probe containing solely water (see Table 5.1).

Figure 5.17 gives the results of evaporation tests using a two-layer membrane in the 0.1 mm probe. The results are similar to those using a one-layer membrane. Pre-pressurizing the
Fig. 5.16 Tension by Evaporation from 0.1 mm Probe with No. 1 Ceramic Containing One Layer of Membrane
Fig. 5.17 Tension by Evaporation from 0.1 mm Probe with No. 1 Ceramic Containing Two Layers of Membrane
probe without replacing the membrane after a previous cavitation did not restore the tensile ability of the system (Test 2 and 3). Probably, the previous cavitation had produced some leaks around the membrane.

In the above tests, a vivid "click" sound could be heard when cavitation occurred at a tension above -800 kPa. The tension usually did not drop to -100 kPa at cavitation, but fell somewhere between -70 kPa and -85 kPa. Calibrations of the transducer were made to assure that such behavior was not due to changes in the transducer. Such behavior may be attributed to partial expansion of the membrane, which may occur after the membrane is able to absorb some water from crevices after cavitation.

5.5.2 Tension Reversibility

Results of reversibility tests are given in Figs. 5.18 and 5.19. In Fig. 5.18, tensions were made to fluctuate mostly between -600 kPa and -700 kPa by placing water-droplets onto the ceramic to counter evaporation. The "click" cavitation occurred at the 77th minute. In Fig. 5.19, tensions are shown to fluctuate mostly between -650 kPa and -800 kPa. The "click" cavitation occurred after about 4 hours. It appears that the reversibility of tension in this system was not as satisfactory as that in the suction probe containing solely water.
Fig. 5.19 Tension by Evaporation and Tension-Relaxation by Water-Droplets on Pre-Pressurized 0.1 mm Probe with No. 1 Ceramic Containing One Layer of Membrane
PART 2

TESTING THE SUCTION PROBE ON SOILS

5.6 TESTS OF SUCTION PROBE ON RECONSTITUTED SOILS

This section reports the results of the tests using the suction probe on reconstituted Regina clay and silt. The axis-translation technique was used to calibrate the suction probe for negative pressures. The suction probe was then used to measure pre-applied matric suctions imposed on a soil. Results of measurements of total suction are also presented.

5.6.1 Measurements of Osmotic Suction in Sucrose Solutions

Attempts to measure osmotic suctions in three sucrose solutions using a pre-pressurized suction probe gave a null tension reading. The 15 bar ceramic has no appreciable osmotic efficiency. The suction probe only measures matric suction when it is in direct contact with the soil.

5.6.2 Calibration of the Suction Probe for Negative Pressures

The calibration tests on the suction probe for negative pressure formed an interesting part of the research program. The calibrations were based on the use of the axis-translation technique. The tests were conducted in a modified Tempe Cell (see Fig. 4.8). The detailed test procedure has been explained in Chapter 4.

Figure 5.20 gives the recorded changes in water pressure and degree of saturation with time during the tests on reconstituted Regina clay. Table 5.2 provides a summary of the measured water pressure, $u_w$, before and after application and release of each air pressure, $u_a$. When an air pressure of 200 kPa was applied to the Tempe Cell, the probe recorded an instantaneous increase in water pressure from 0 to 195 kPa. As soil water was gradually driven out of the soil in order to reach matric suction equilibrium, the recorded pressure gradually returned close to about 25 kPa within 42 hours. The inability of the probe to return to zero pressure was likely due to the extremely slow rate of soil-water flow out of the cell.
Fig. 5.20 Calibration of the Suction Probe for Negative Pressures in Regina Clay Using the Axis-Translation
under a relatively small pressure gradient. The limitation of accuracy of the high pressure transducer, which is about ±10 kPa, might also be a contributing factor.

Table 5.2 Summary of the Results of a Calibration Test on Regina Clay

<table>
<thead>
<tr>
<th>$u_{a1}$ (kPa)</th>
<th>$u_{a2}$ (kPa)</th>
<th>$u_{w2}$ (kPa)</th>
<th>$\Delta(u_{a2} - u_{a1})$ (kPa)</th>
<th>$\Delta(u_{w2} - u_{w1})$ (kPa)</th>
<th>$\frac{\Delta(u_{w2} - u_{w1})}{\Delta(u_{a2} - u_{a1})}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>195</td>
<td>200</td>
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<tr>
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Note: $u_{a1}$ and $u_{w1}$ are the air and measured water pressures before the change in air pressure, while $u_{a2}$ and $u_{w2}$ are the air and measured water pressures after the change in air pressure.

Releasing the air pressure from 200 kPa to 0 kPa caused the water pressure to immediately fall below zero and reach -158 kPa. The reduction in air pressure (i.e., -200 kPa) was close to the reduction in water pressure (i.e., -183 kPa). As water in the ceramic of the Tempe Cell started to flow into the soil, the water pressure slowly rose. When the pressure reached -151 kPa, an increase in air pressure to 300 kPa produced an instantaneous jump of water pressure to about 145 kPa, an increase of 296 kPa.

Further changes in air pressure resulted in similar water pressure response. That is, a change in air pressure instantaneously produced an approximately equal amount of change in water pressure in the suction probe. The maximum error was less than 8.5%. When the air pressure was reduced from 500 kPa to zero, the recorded water pressure immediately dropped from 44 kPa to -443 kPa, a change of 487 kPa. The Regina clay essentially remained saturated during the test period.

Figure 5.21 and Table 5.3 give the results of a calibration test on a reconstituted fine silt. Again, a change in air pressure instantaneously produced an approximately equal change in the measured water pressure. The maximum error was less than 7%. When the air pressure was
Fig. 5.21 Calibration of the Suction Probe for Negative Pressures in Silt Using the Axis-Translation
finally reduced from 500 kPa to zero, the recorded water pressure immediately dropped from 7 kPa to -473 kPa, a change of 480 kPa.

The fine silt desaturates at a matric suction less than 10 kPa (Fig. 4.7). The water content of the silt is close to the residual value when the matric suction is greater than 300 kPa. The above calibration tests demonstrated that the suction probe is suitable for measurement of negative pore-water pressure (i.e., matric suction) in both saturated and unsaturated soils. These tests also justifies the extrapolation of calibration of the transducer from positive to negative pressures.

Table 5.3 Summary of the Results of a Calibration Test on Silt

<table>
<thead>
<tr>
<th>$u_{s1}$ (kPa)</th>
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<td>-500</td>
<td>480</td>
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</table>

5.6.3 Measurement of Pre-Applied Matric Suctions

The tests included the measurements of matric suction on specimens of reconstituted Regina clay and fine silt. The effect of the contact conditions between the probe and the soil was investigated.

5.6.3.1 Measurements on Regina Clay

Figure 5.22 gives the suction measurements on a reconstitute specimen of Regina clay, using a 0.3 mm probe with a recessed No. 1 ceramic. The matric suction pre-applied in the Tempe Cell were 200 kPa, 300 kPa, and 400 kPa, respectively. In the first test, water from the
Fig. 5.22 Suction Measurements on Reconstituted Regina Clay (0.3 mm Probe with Recessed No. 1 Ceramic)
ceramic of the suction probe evaporated into the air between the soil and the ceramic. The system cavitated at a tension of about -650 kPa. The equilibrium was never reached.

In the remaining tests, a small amount of Regina clay paste (about 0.2 mm thick) was placed onto the recessed ceramic. The soil specimen was placed on the paste. The results indicated that placing the paste can greatly improve the soil-ceramic contact. Equilibrium was reached within approximately 3 to 5 hours and accurate measurements of matric suction were recorded. The higher the matric suction, the longer the time required for equilibrium. The suction probe did not lose the tensile ability for tensions up to -400 kPa over a 5 hour period. When the applied matric suction was 400 kPa, the system took approximately 5 hours for equilibrium. The system cavitated at a tension of about -400 kPa. This value was considerably lower than the sustainable tension determined for the No. 1 ceramic (i.e., from -600 kPa to -650 kPa). One reason was probably because this probe had been subjected to tensions and repeated cavitations over a long period of time. The above tests were performed after numerous tension-durability and tension-reversibility tests. Upon opening the probe it was found the inner face of the ceramic had become relatively soft. The surface of the ceramic could be peeled off with a slight scratch. Probably the previous cavitation history had weakened the ceramic. The ceramic was, therefore, replaced.

Figure 5.23 shows the results of measurements of matric suction in a Regina clay which was placed in direct contact with the ceramic of the probe. The pre-applied matric suctions varied from 150 to 550 kPa, with each increment being 50 kPa. The recorded curves were in good agreement with the pre-applied matric suctions up to 450 kPa. The recorded negative pressures for pre-applied matric suctions of 500 and 550 kPa developed much slower. This was probably due to the occurrence of a tension crack in the measured central part of the soil specimen when the pre-applied matric suction exceeded 450 kPa. The occurrence of the crack reduced the effective area of contact between the soil and the ceramic, thus increasing the time for equilibrium. However, the presence of the crack did not appear to influence the final magnitude at equilibrium.

For all the above tests in which the specimen had a good contact with the ceramic, the measured tensions were approximately equal to the pre-applied matric suctions. The response
Fig. 5.23 Matric Suction Measurements on Reconstituted Regina Clay in Direct Contact with the No. 1 Ceramic of a 0.3 mm Probe
time for the case of direct contact between the soil and the ceramic was much faster than the case when using an intermediate clay paste (Fig. 5.22).

5.6.3.2 Measurements on Silt

A total of eight tests were performed on silt specimens. The results are sequentially presented in Figs. 5.24 and 5.25. The measurements of matric suction on the reconstituted silt specimens raised a hypothesis about the procedure of suction control using a pressure plate for unsaturated soils.

In the first test, a saturated silt specimen was removed from a consolidation oedometer and directly placed onto the ceramic in a Tempe Cell. An air pressure of 150 kPa was applied. After reaching equilibrium, the soil was placed directly onto the ceramic of the suction probe. Equilibrium was reached in about 2 hours with a recorded tension of -159 kPa (Test 1, Fig. 5.24). The specimen was then placed back in the Temp Cell and an air pressure of 150 kPa was again applied. One week was allowed for equalization. The matric suction, however, was later measured to be only 92 kPa using the suction probe (Test 2, Fig. 5.25). To check if the error was caused by insufficient soil-ceramic contact during the measurement, a wet clay paste was used between the soil and the ceramic of the probe. Again the matric suction was measured to be about 92 kPa (Test 3, Fig. 5.25), which indicated the probe measured the same suction value in the silt regardless of whether a clay paste was used or not.

The above results would indicate that an air pressure applied to an unsaturated soil in the Tempe Cell did not necessarily result in a matric suction in the soil equal to the applied air pressure. When an unsaturated soil is placed onto the ceramic in the Tempe Cell, the contact between the water phase in the ceramic and the soil is not well established. Even a spring pressure exerted on the soil to push it against the ceramic could not improve contact condition in water phase. An effective contact, however, can be established by imposing a wet condition between the specimen and the ceramic.

A wet clay paste was placed onto the ceramic of the Tempe Cell in order to study the above mentioned hypothesis. The same unsaturated specimen as used in Test 3, was placed over a paste of wet clay. An air pressure of 150 kPa was applied to the soil. After 3 days, the
Fig. 5.24 Matric Suction Measurements on Reconstituted Silt (for Tempe Cell tests, the specimen was initially wet, or dry but clay paste was used between the soil and the ceramic)
Fig. 5.25 Matric Suction Measurements on Reconstituted Silt (for Tempe Cell tests, the contact between soil and ceramic was initially dry)
soil was removed from the Tempe Cell. The matric suction in the soil was measured to be about 160 kPa using the suction probe (Test 4, Fig. 5.24). The specimen was again placed onto the Tempe Cell, this time without using the clay paste. An air pressure of 200 kPa was applied. The matric suction was later measured to be only about 110 kPa (Test 5, Fig. 5.25). The specimen was then placed back onto the ceramic of the Tempe Cell using a wet clay paste. An air pressure of 200 kPa was applied. The matric suction in the soil was later measured to be about 186 kPa using the suction probe (Test 6, Fig. 5.24).

Another saturated reconstituted silt specimen was placed directly on the ceramic of the Tempe Cell. An air pressure of 300 kPa was applied. The measured matric suction in this soil was 282 kPa after 4.5 hours of equalization with the suction probe (Test 7, Fig. 5.24). The silt was placed back on the ceramic of the Tempe Cell, and water was sprayed onto the bottom of the soil. After one hour, an air pressure of 400 kPa was applied for over 24 hours. The matric suction was measured to be about 412 kPa using the suction probe (Test 8, Fig. 5.24).

The consistent results of the above measurements indicated that some water sprayed to the contacting surfaces of an unsaturated soil and the ceramic in a pressure plate can effectively improve the contact conditions. An alternative is to place a wet soil paste between the soil and the ceramic. The effective contact, however, could be lost if a unsaturated soil specimen is removed from the ceramic and placed back again without adding extra water to the bottom of the specimen.

When a saturated soil is placed onto the ceramic in a pressure plate, the contact between the water in the ceramic and the water in the soil is readily established. The surface tension of water tends to keep the water phase continuous. The contact in the water phase can be maintained even when an elevated air pressure has been applied to the soil and the soil has desaturated to a relatively dry state. However, if the unsaturated soil is removed from the ceramic, the air-water meniscus in the soil will retreat somewhat into the pores in the soil due to capillary pull. When the soil is placed back again onto the ceramic, the actual area of water contact is greatly reduced. Increasing the air pressure does not improve the contact in liquid water. The effective transfer of water in the liquid phase can virtually cease due to the extremely low hydraulic conductivity of the unsaturated soil. On the other hand, moisture
transfer can occur in the vapor phase from the ceramic to the soil as a result of the tendency of water vapor to condense on the particles at the surface of the soil specimen. Consequently, the water content in the soil may slightly increase.

Graduate students in the Soil Laboratory at the University of Saskatchewan have encountered the “erratic” behavior of some soils when conducting the pressure plate tests. Application of a higher air pressure resulted in, contrary to expectation, a higher water content or a “swelling” soil. This is particularly the case for the measurements of the soil-water characteristic curves of silts and ceramic blocks. This phenomenon was generally attributed to human errors, such as errors in the measurements of water content and dimensions of the specimen. However, the above direct measurements of matric suction strongly suggested that the actual values of matric suction in the soil could be lower than the applied air pressures because of a failure to reach equilibrium within the test period.

Based on the above analyses, it is suggested that for the measurement of the soil-water characteristic curves for unsaturated soils, the equalization process should start from an initially wet condition for every increment of pressure on the pressure plate.

The tests results, however, also show that the suction probe is capable of correctly measuring matric suction in unsaturated soils without the need of using a wet soil paste, which is contrary to the above conclusions. There may be two reasons for such differences. One possible reason is that the water in the probe is in an extremely rigid environment, which makes it extremely sensitive to even a minute change in moisture conditions. As long as there is an area of liquid water contact between the soil and the ceramic of the probe, the matric suction can be effectively transmitted. For the Tempe Cell test, the chamber beneath the ceramic is open to atmosphere. The outlet system is relatively flexible, disallowing sufficient liquid water transfer when the contact between the ceramic and the unsaturated soil is quite poor. The other possible reason is that the process of measuring soil suction using the probe is a absorption process for the soil. On the contrary, the equalization process in a pressure plate is a desorption process for the soil. The absorption process is more efficient and quicker than the desorption process for a given soil. Consequently, the matric suction can be more effectively transmitted in the suction probe than in a pressure plate.
5.6.3.3 Tension Duration During the Matric Suction Measurements

The measurements of matric suction on both Regina clay and silt specimens also indicates that, for the developed suction probe, the tension at equilibrium can be maintained for a long period of time.

Figure 5.26 shows three measurements of matric suction on reconstituted silt and Regina clay specimens, using the suction probe with a fresh No. 1 ceramic. The pre-applied matric suctions were 300 kPa, 350 kPa, and 550 kPa. After equilibrium has been reached, tensions in the probe can be maintained for over 72 hours. The time period over which a tension can be maintained in the suction probe does not seem to be dependent on the magnitude of tension.

5.6.4 Results of Total Suction Measurements

It was anticipated that the probe may possibly measure total suction if the equalization process is deliberately forced to occur in the vapor phase. The ceramic of the suction probe was recessed by 0.2 mm, or 0.4 mm, below the surface of the probe in order to investigate the effect of the volume in which equalization process took place.

Results of the proposed measurement of total suction on silt specimens are given in Fig. 5.27. When the pre-applied matric suctions were 50 kPa, and 150 kPa, it seemed that an equalization process was occurring. However, when the pre-applied matric suction was 250 kPa, equilibrium was never reached. It was possible that water from the suction probe could evaporate into the air through the contacting edge between the soil and the probe. If this was true, opening the aluminum foil during the measurement should cause an apparent increase in evaporation, thus an increase in the rate of recorded tension. However, this was not observed. No appreciable increase in the rate of recorded tension was observed when the aluminum was opened. It was concluded that evaporation continually took place from the probe into the dry pores in the silt. Repetition of the above tests gave similar results. It was concluded that the probe is not suitable for measuring total suction in unsaturated soils.

Figure 5.28 shows the proposed measurement of total suction on a Regina clay. The pre-applied matric suctions were 50 kPa and 150 kPa, respectively. Probes in which the ceramics were recessed by 0.2 mm and 0.4 mm respectively were used. Equilibrium was never realized.
Fig. 5.26 Matric Suction Measurements on Reconstituted Silt and Regina Clay in Direct Contact with No. 1 Ceramic of a 0.3 mm Probe
Fig. 5.27 Total Suction Measurements on Reconstituted Silt Using the Probe with Recessed (0.2 mm) Ceramic
Fig. 5.28 Total Suction Measurements on Reconstituted Regina Clay Using the Probe with Recessed Ceramic (0.2 mm or 0.4 mm)
Although there appeared to be a deflection point on a recorded tension curve, the deflection is too short to allow a meaningful determination of total suction. Furthermore, all four curves are so close to each other that it is not possible to distinguish increments in total suction due to increments in matric suction. It is concluded that the suction probe is not suitable for measuring total suctions of wet soils.

The failure of the suction probe to reach vapor equilibrium with the clay cannot be attributed to the movement of vapor from the ceramic of the probe into the clay since the clay is nearly saturated. It was found that there was conspicuous condensation of water vapor on the clay, particularly around the perimeter of the recessed ceramic. Water vapor can easily condense on the tiny dust particles, and possibly on the surface of contacting walls (Dorsey, 1968). Water from the suction probe can evaporate continuously into the environment. Consequently, equilibrium can never be reached.

Appendix A shows that from a thermodynamic analysis, the suction is extremely sensitive to the change in vapor pressure. Any suction determination based on vapor equilibrium is bound to suffer from poor accuracy.

5.7 COMPARISON WITH CONVENTIONAL METHODS

The results of measurements of matric suction on the glacial till compacted at various densities and water contents, using different methods, are summarized in Table 5.4. Also included is the degree of saturation at the end of each measurement and the change in the degree of saturation during each measurement. The degrees of saturation were calculated from water content measurements. The volume change during each measurement was considered very small and negligible. The approximate times needed for equalization are provided. The variations of measurements using the filter paper method are given. The results suggest that these tests were highly reproducible except for the filter paper method. Figure 5.29 plots measurements using the suction probe and the filter paper method. Figure 5.30 plots measurements using the suction probe, the null-pressure plate, and the thermal conductivity sensor. The measurements given by Vanapalli (1994) using the a null-pressure plate are also given in Fig. 5.30. The data are explained in the following sections. In all the
Table 5.4 Summary of Matric Suction Measurements on the Glacial Till

<table>
<thead>
<tr>
<th>$\rho_d$ (Mg/m$^3$), w (%), and S (%)</th>
<th>Method</th>
<th>S at end of test (%)</th>
<th>Range of $\Delta S$ during test (%)</th>
<th>Approximate equalization time</th>
<th>Matric suction (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.80, 16.3, 86.6</td>
<td>suction probe</td>
<td>87.2, 87.7</td>
<td>0.4</td>
<td>1 hr</td>
<td>73, 64</td>
</tr>
<tr>
<td></td>
<td>filter paper</td>
<td>87.2 ~ 87.9</td>
<td>0.9</td>
<td>7 days</td>
<td>61~ 65</td>
</tr>
<tr>
<td></td>
<td>thermal-conductivity*</td>
<td>87.9, 89.4</td>
<td>0.8</td>
<td>30 hrs, 5 hrs</td>
<td>32, 60</td>
</tr>
<tr>
<td></td>
<td>null-pressure plate</td>
<td>88.2, 88.6</td>
<td>0.5</td>
<td>8 hrs</td>
<td>138, 143</td>
</tr>
<tr>
<td>1.78, 15.0, 77.4</td>
<td>suction probe</td>
<td>77.3, 76.8</td>
<td>1.1</td>
<td>4 hrs</td>
<td>172, 175</td>
</tr>
<tr>
<td></td>
<td>filter paper</td>
<td>77.9 ~ 78.0</td>
<td>0.4</td>
<td>7 days</td>
<td>154~197</td>
</tr>
<tr>
<td></td>
<td>thermal-conductivity*</td>
<td>78.4, 76.4</td>
<td>0.8</td>
<td>40 hrs, 18 hrs</td>
<td>83, 119</td>
</tr>
<tr>
<td></td>
<td>null-pressure plate</td>
<td>78.7, 78.1</td>
<td>0.6</td>
<td>12 hrs</td>
<td>205, 213</td>
</tr>
<tr>
<td>1.73, 13.0, 61.3</td>
<td>suction probe</td>
<td>60.4, 61.5</td>
<td>0.8</td>
<td>4.5 hrs</td>
<td>320, 321</td>
</tr>
<tr>
<td></td>
<td>filter paper</td>
<td>61.0 ~ 62.4</td>
<td>0.6</td>
<td>7 days</td>
<td>209~342</td>
</tr>
<tr>
<td></td>
<td>thermal-conductivity*</td>
<td>60.7, 61.8</td>
<td>0.4</td>
<td>60 hrs, 10 hrs</td>
<td>243, 240</td>
</tr>
<tr>
<td></td>
<td>null-pressure plate</td>
<td>62.4, 62.5</td>
<td>1.0</td>
<td>16 hrs</td>
<td>369, 350</td>
</tr>
<tr>
<td>1.66, 11.5, 48.7</td>
<td>suction probe</td>
<td>48.1, 48.8</td>
<td>0.5</td>
<td>16 hrs, 24 hrs</td>
<td>813, 781</td>
</tr>
<tr>
<td></td>
<td>filter paper</td>
<td>48.5 ~ 49.2</td>
<td>0.4</td>
<td>7 days</td>
<td>524~752</td>
</tr>
<tr>
<td></td>
<td>thermal-conductivity*</td>
<td>48.9, 48.2</td>
<td>0.6</td>
<td>55 hrs, 20 hrs</td>
<td>362, 356</td>
</tr>
<tr>
<td></td>
<td>null-pressure plate</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>&gt; 700</td>
</tr>
<tr>
<td>1.61, 11.0, 43.7</td>
<td>suction probe</td>
<td>43.4, 43.2</td>
<td>0.3</td>
<td>18 hrs, 15 hrs</td>
<td>950, 907</td>
</tr>
<tr>
<td></td>
<td>filter paper</td>
<td>43.3 ~ 43.6</td>
<td>0.4</td>
<td>7 days</td>
<td>587~792</td>
</tr>
</tbody>
</table>

* The corresponding data in the last column are for the use of initially wet and dry sensor, but using the desorption calibration curve only. The absorption calibration curve was not obtained.
Fig. 5.29 Comparison of Matric Suction Measurements on the Compacted Glacial Till Using the Suction Probe and Filter Paper
Fig. 5.30 Comparison of Matric Suction Measurements on the Compacted Glacial Till Using the Suction Probe, the Pressure Plate, and the Thermal Conductivity Sensor.
graphic presentations, the degree of saturation (i.e., S) of the soil is used instead of the water content (i.e., w).

5.7.1 The Suction Probe Measurements

A 0.3 mm probe with the No. 4 ceramic was used to measure matric suction on the compacted glacial till. A slight amount of wet soil paste was used between the soil specimen and the suction probe in order to improve soil-ceramic contact. Fig. 5.31 shows the recorded tensions for the selected degrees of saturation of 86.6%, 77.4%, and 61.3%. Equilibrium was reached within approximately four hours. The values of matric suction at equilibrium were about 68 kPa, 173 kPa, 320 kPa, respectively. Reductions in the degree of saturation during measurements were generally less than 1%.

Figures 5.32 and 5.33 show the measurements when the selected degrees of saturation were 48.7% and 43.7% respectively. The measured matric suctions were about 800 kPa and 950 kPa, respectively. The approximate equalization time ranged from 15 to 24 hours. Again the results indicate that the tension in the probe can last for a period of time sufficient for equalization.

Figure 5.34 gives a summary of the measured matric suction plotted against gravimetric water content. The water content was found to be generally decreased by less than 0.10% after measurements.

5.7.2 The Filter Paper Measurements

Three series of measurements of matric suction were made using the filter paper method. Each series included measurements of specimens at five water contents. A total of 15 filter paper measurements were made. As shown in Fig. 5.29, the filter paper method produced measurements close to the values obtained from the suction probe measurements at matric suctions less than 200 kPa. As the soil became drier, the filter paper method generally gave matric suctions much lower than the suction probe. The wide scatter in the results indicates that the filter paper could be significantly affected by slight variations in environmental conditions and operational procedures.
Fig. 5.31 Matric Suction Measurements on the Compacted Glacial Till Prepared at S Equal to 86.6%, 77.4%, and 61.3%, Using the Suction Probe with the No. 4 Ceramic
Fig. 5.32 Matric Suction Measurements on the Compacted Glacial Till Prepared at S Equal to 48.7%, Using the Suction Probe with the No. 4 Ceramic
Fig. 5.33 Matric Suction Measurements on the Compacted Glacial Till Prepared at S Equal to 43.7%, Using the Suction Probes with the No. 4 Ceramic Degree of Saturation at end of test:

- 43.4%
- 43.2%

Elapsed Time (min)

Recorded Pressure (kPa)
Fig. 5.34 Measured Matric Suction Versus Water Content for the Glacial Till Using the Suction Probe
5.7.3 The Thermal Conductivity Measurements

Calibrations of the thermal conductivity sensor were carried out before and after measurements of matric suction were completed. The results indicate that the thermal property of the sensor remained nearly unchanged during the measurements of matric suction. Fig. 5.35 shows the desorption calibration for the thermal conductivity sensor used in this test program. The calibration results are in close agreement with those obtained in China. Unfortunately, cracks developed in the sensor after the desorption calibration and the sensor malfunctioned. The absorption calibration was not obtained.

The matric suctions are plotted against the output voltage for desorption in Fig. 5.36. The sensitivity was considerably reduced when the matric suction was higher than 160 kPa. Two regression curves are used to fit the calibration data. The two curves are:

for \(-5.96 < X < -4.65\) (or \(0 < Y < 160\)),

\[
Y = 598.07 + 319.76X + 41.269X^2
\]  
(5.1)

for \(X < -5.96\) (or \(Y > 160\)),

\[
Y = -2512.1 - 447.33X
\]  
(5.2)

where:

\(Y\) = matric suction (kPa),

\(X\) = output voltage (V).

Equations (5.1) and (5.2) were also used to calculate the matric suctions from measurements using an initially dry sensor (i.e., sorption measurements). Figures 5.37 to 5.40 show the measured development of matric suction for specimens prepared at degrees of saturation ranging from 86.6% to 48.7%. When the degree of saturation of the soil is higher than 77%, there is a difference of about 30 kPa in matric suction between the desorption and absorption calibrations. However, the desorption and absorption calculations converge to nearly the same value when the degree of saturation of the soil is reduced to less than 61%.
Fig. 5.35 Calibration of the Thermal Conductivity Sensor: Desorption
Fig. 5.37 Matric Suction Measurements on the Glacial Till Using a Thermal Conductivity Sensor
Fig. 5.38 Matrix Suction Measurements on the Glacial Till Using a Thermal Conductivity Sensor

Degree of Saturation at end of test:
- 78.39% (Desorption)
- 76.44% (Absorption)

Matric Suction (kPa)

Elapsed Time (min)
Fig. 5.40 Matric Suction Measurements on the Glacial Till Using a Thermal Conductivity Sensor
These results suggest that the hysteresis between the desorption and absorption for the sensor is significantly reduced when the sensor becomes relatively dry. When the soil is dry, using an initially dry sensor can considerably shorten the equalization time (e.g., less than ten hours).

Compared to the direct measurements using the suction probe (Fig. 5.30), the thermal conductivity measurements appear to under-estimate the matric suction values. The difference may exceed 30% when the degree of saturation of the soil is less than 75%. Nevertheless, the thermal conductivity sensor performed relatively well in the range from 0 to 100 kPa.

5.7.4 The Null-Pressure Plate Measurements

The measurements of matric suction using the null-pressure plate method showed close agreement with the results obtained by Vanapalli (1994). The null-pressure plate method produced higher matric suction values than the suction probe and the filter paper method, particularly for high degrees of saturation (i.e., near or above optimum water content). At the optimum water content (i.e., the degree of saturation is about 86%), the pressure plate over-estimated the matric suction by more than 100%. The relative difference, however, was significantly reduced when the degree of saturation was reduced to less than 75%. At the degree of saturation of 60%, the matric suction measured using the null-pressure plate was only 10% higher than that measured using the suction probe.
CHAPTER 6

INTERPRETATION OF RESULTS

6.1 INTRODUCTION

The laboratory results from testing the newly developed suction probe were presented in Chapter 5. In this chapter, the test results are further discussed. First, the fundamental behavior of water under tension is analyzed based on the results of evaporation tests on the developed suction probe. Tests on the suction probe containing a bentonite suspension and a cellulose membrane provide a better understanding of the mechanism of cavitation in the suction probe. The suitability of the suction probe for the measurement of soil suction is discussed.

The results from laboratory tests on various soils demonstrated that the suction probe is able to measure matric suctions up to 1,000 kPa. However, the suction probe is extremely sensitive even to a minute loss of moisture. The recorded tensions during the measurement of matric suction appeared to increase slowly with time after an approximate equilibrium is reached. This phenomenon was more pronounced for measuring soils with a low degree of saturation.

The mass transfer between the soil and the suction probe during measurement is discussed. To obtain a more precise assessment of soil suction, an appropriate procedure should be developed to define the point of equilibrium. Any measurements of soil suction should be analyzed based on this procedure for determining equilibrium.

The measurements of matric suction on the compacted glacial till, using the suction probe were compared with the measurements made using several other conventional methods. The reasons for discrepancies among those methods are discussed.

Finally, the results of the laboratory program are compared with the results obtained by Ridley (1993) and Ridley and Burland (1994).
6.2 THE FUNDAMENTAL BEHAVIOR OF WATER UNDER TENSION

The investigation of the fundamental behavior of water under tension included a discussion of the factors that affect the sustainable tension, the duration and the reversibility of tension. The concept of cavitation threshold is proposed. The cavitation mechanism is discussed with respect to the evaporation tests where bentonite suspensions and a cellulose membrane were used in the measuring chamber of the developed suction probe.

6.2.1 Factors Affecting the Suction Probe to Sustain Tension

The factors that could affect the tensile ability of the developed suction probe may be divided into external and internal factors. The external factors include variables related to pre-pressurization, such as the magnitude, the duration, and the cycles of pre-pressurization. The internal factors refer to the conditions of water, the ceramic, and the surfaces in the measuring chamber in the suction probe. The condition of the water and the ceramic used in the suction probe were investigated in this laboratory program. The surfaces of the stainless steel in the measuring chamber were polished as fine as possible in manufacturing the suction probe.

6.2.1.1 Effect of Pre-Pressurization

The suction probe does not normally have the ability to sustain absolute tensile stress, even though the volume of water inside the probe is very small. One essential condition for the probe to sustain a high tensile stress is to dissolve cavitation nuclei into solution, thus reducing the presence of gases in the system. Dissolution of cavitation nuclei (i.e., tiny gas bubbles) in water is essential for the probe to sustain a high tensile stress. There are basically two methods to dissolve cavitation nuclei in water. One method is to heat the water. The expansion of water upon heating can dissolve cavitation nuclei both in water and in the container walls. The other method to dissolve cavitation nuclei is to apply a high positive pressure to the system. Dissolution of the cavitation nuclei is dependent upon the level of the positive pressure applied, and is also a time-dependent process. Consequently, the magnitude and duration of the pre-pressurization pressure should affect the tensile ability of the probe.
The test results indicated that the effects of magnitude and duration of pre-pressurization pressure have a limit. The increase in the tensile strength with an increase in the pre-pressurization pressure was significant for pressures up to 5,000 kPa and became less pronounced when applied pressures exceeded 5,000 kPa. The tensile strength of water in the probe seemed to reach an upper limit at a pre-pressurization pressure of about 12,000 kPa (Fig. 5.5). These results are in approximate agreement with those obtained by Knapp (1958) using the superheating method. Moreover, pre-pressurization for long periods of time did not seem to produce better results than one hour pre-pressurization (Fig. 5.4). This would indicate that dissolution of most cavitation nuclei may be complete using one hour of pre-pressurization.

Another important factor that was found to have a considerable effect on the tensile ability of the probe is the cyclic application of a positive pressure, followed by a vacuum. This was called “pre-pressurization cycles” in this laboratory program. Six cycles of pre-pressurization was more efficient in increasing the tensile ability of the probe than one cycle of pre-pressurization (Fig. 5.3). The effect of cycled pre-pressurization was even more pronounced than that of the duration of pre-pressurization (Figs. 5.3 and 5.4). However, the benefit of using cycled pre-pressurization became less significant when the number of pre-pressurization cycles exceeded six.

The effect of an applied vacuum on the tensile strength of water did not appear to be generally appreciated by physicists, but was realized by Jones et al. (1980). Although Ridley (1993) found cycled positive pressure and vacuum to pretreat water can increase the tensile strength of the water, the mechanism behind the role of the applied vacuum was not explained. Ohde et al. (1988, 1992) suggested that successive temperature cycles appeared to cause exhaustion of gas trapped in crevices on the container surfaces and increased the tensile strength of the water. Cyclic applications of positive pressure and vacuum may cause the exhaustion of cavitation nuclei in the system.

From the data provided in Figs 5.3 to 5.5, it was concluded that the optimum procedure for conditioning the suction probe to obtain the maximum tensile strength of the water is to apply six cycles of pre-pressurization. Each cycle includes the application of a positive
pressure of about 12,000 kPa for one hour, followed by a negative pressure of -85 kPa for another hour.

6.2.1.2 Water and Ceramic Used in the Suction Probe

Generally distilled and deaerated water was boiled and used throughout the laboratory program. Numerous pilot tests showed that it is not necessary to boil the distilled and deaerated water. Even ordinary tap water did not show an appreciable difference in tensile strength from the distilled and deaerated water. The high pre-pressurization pressure seemed to be able to dissolve all the undissolved gases in water. Once pre-pressurized, the tap water appeared to yield the same tensile characteristics as the distilled and deaerated water.

The volume of water in the chamber should be made as small as possible in order to reduce the probability of cavitation. However, water in the 0.1 mm, 0.3 mm, and 0.5 mm probes appeared to have the same tensile strength.

The ceramic, on the other hand, yielded much different results. Tests on four batches of 15 bar ceramic indicated the tensile ability of the suction probe is related to the type of ceramic used in the suction probe. The four batches of ceramic gave different maximum tensions which varied from -360 kPa to -1,250 kPa. Generally a ceramic with the quickest response time gave the highest tensile strength for the probe. The reason for this phenomenon, however, is not known.

It was also observed that the tensile strength of water in the suction probe could decrease after a number of cavitations. This could be attributed to the weakening of the ceramic by previous cavitations. In several cases the surfaces of the ceramic were found to be slightly soft after the ceramic had been used for a period of time.

The most convincing evidence that cavitation is related to the condition of the ceramic in the suction probe came from the evaporation tests on the suction probe with the bentonite-clogged ceramic. Without pre-pressurization, the bentonite-clogged ceramic could produce a tension of up to -480 kPa (Figs. 5.14 and 5.15), whereas a clean fresh ceramic would always lead to cavitation at -100 kPa.
The effect of the ceramic on the tensile ability of the suction probe was not reported by Ridley (1993) and others (Ridley and Burland, 1994; Dineen and Burland, 1995). The variation in the tensile strength of water was generally attributed to the random nature of the tensile strength of water and other factors, such as the cleanness of the measuring chamber, the threads of the transducer, and the suitability of the transducer to measure negative pressure. While these factors may influence the tensile strength of the water in the suction probe, the variation of the tensile strength of the water in a pre-pressurized suction probe, using a fresh ceramic, was observed to be generally less than 100 kPa in this laboratory program.

Tamari et al. (1993) calculated the evolution of a vapor bubble (i.e., a gas nuclei) in a liquid as the function of the liquid pressure. It was suggested that when the bubble grows to a critical radius, the metastability of the liquid can not be maintained and the liquid will cavitate. The critical radius is calculated as:

$$r_c = \left[ \frac{3r_o^3 [P_{lo} + P_v - 2T_s / r_o]}{2\sigma} \right]^{1/2}$$  \hspace{1cm} (6.1)

where:

- $r_c$ = critical radius,
- $r_o$ = initial radius,
- $P_{lo}$ = initial liquid pressure,
- $P_v$ = vapor pressure,
- $T_s$ = surface tension.

Correspondingly, there is a critical liquid pressure beyond which the liquid will cavitate. The critical liquid pressure, $P_{lc}$, is calculated as:

$$P_{lc} = P_v - \frac{4T_s}{3r_c}$$  \hspace{1cm} (6.2)
Figure 6.1 shows the critical pressure (gauge) versus the initial radius of the gas nuclei. When the radius of a gas nuclei is reduced to less than 1 \( \mu \text{m} \), the critical pressure can be significantly increased.

![Graph showing critical pressure vs initial radius](image)

**Fig. 6.1 Predicted Critical Pressure Versus Initial Radius of Cavitation Nuclei**

(from the theory by Tamari et al., 1993)

The cavitation threshold encountered in this research program varied from -360 to -1250 kPa, depending on the ceramic used. The corresponding initial radius of the gas nuclei is in the range from about 0.2 to 0.04 \( \mu \text{m} \). The pore size of the ceramics is within about the same range of magnitude (the nominal pore size of the ceramic is around 0.16 \( \mu \text{m} \)). It may be possible that the cavitation threshold is linked to the pore size of the ceramic. However, the following facts seem to contradict this conclusion:

1.) If the above conclusion is true, the ceramic with a pore size of 0.16 \( \mu \text{m} \) should be able to sustain a tension of about -450 kPa without pre-pressurization. This, however, is not true. The suction probe without pre-pressurization always cavitates at about -100 kPa.
2.) A small pore size should produce a low permeability for the ceramic, thus a slower response time. If the above conclusion is true, a ceramic with a slower response time should
have a higher cavitation threshold. This, however, is against the observation. Tests on different batches of ceramic showed that generally a ceramic with a slower response time had a lower cavitation threshold.

From the point of view of the tensile strength of water, the ability of a system to sustain a tension should, ideally, not depend on the size of the system if all cavitation nuclei are uniformly distributed in the system. For example, a tensiometer with a tube of 2 cm in diameter and a 1 bar ceramic should also be able to sustain a high tension if all the crevices on the solid surfaces are fully saturated (e.g., by pre-pressurization, or heating) and the tension is applied directly through the water phase. When an air-water meniscus is present in the ceramic of the tensiometer, the measured tension should not exceed the air-entry value of the ceramic because otherwise air bubbles will be introduced into the tensiometer. In other words, the ability of a ceramic in the suction probe to sustain a high tension is represented by the tensile strength of water as long as the air-entry value of the ceramic is not exceeded.

6.3 MECHANISM OF CAVITATION

The mechanism of cavitation can be interpreted from the results of the evaporation tests on the suction probe using different approaches. Of particular interest is the duration and reversibility of tension, effects of contaminants, and effect of enclosing a compressible membrane in the measuring chamber.

6.3.1 Behavior of the Suction Probe Containing only Water

The impeded evaporation tests and the tension reversibility tests on the suction probe containing water only showed that as long as the tension did not exceed the cavitation tension determined by a free evaporation test, the probe would not cavitate and the tension could be maintained for a long period of time. This conclusion is supported by the measurements of matric suction on the Regina clay and the silt during which the tensions were maintained at nearly constant values for several days (Figs. 5.23 and 5.26). These results suggest that for a given suction probe and a given pre-pressurization procedure, there is an approximate value below which a tension in the suction probe can be maintained for a relatively long period of
time. In other words, there is a cavitation threshold for a given suction probe. As long as a tension does not exceed the cavitation threshold, the tension can be maintained for relatively a long period of time.

The ability of water to sustain a tension, and to change the tension reversibly for a long period of time can be explained from the gas-trapping model for cavitation (Chapter 2). In the gas-trapping model as shown in Fig. 6.2, the gas-water meniscus penetrates into the crevice under pre-pressurization. When the pressure in the water changes, the gas-water meniscus acts like an elastic membrane and deflects back and forth inside the crevice. When the tension in water increases to a level such that the receding contact angle, \( \theta_n \), is reached, the meniscus will retreat out of the crevice and cavitation occurs. The tension under which the meniscus deflects to reach the receding contact angle, \( \theta_n \), may correspond to the proposed cavitation threshold. The elastic behavior of the meniscus inside the crevice is responsible for the remarkable reversibility of tension in the water in the suction probe.

![Diagram](image)

Fig. 6.2 Illustration of Cavitation Threshold Based on the Gas-Trapping Model: (a) Penetration of gas-water meniscus from position 1 to position 2 into the crevice under pre-pressurization; (b) Gas-water meniscus acts like an elastic membrane which deflects back and forth at position 2 but does not retreat to the mouth of the crevice unless the receding contact angle, \( \theta_n \), is reached.

### 6.3.2 Behavior of the Suction Probe Containing a Contaminant

Cavitation occurs because of the presence of the tiny crevices on the container walls which are filled with undissolved gases, according to the gas-trapping model. These tiny
crevices are the weakest points in the suction probe where cavitation may initiate. Any materials that affect the characteristics of the bonding between water and the crevices should affect the overall ability of the probe to resist tension. However, additions of “Fatanstik”, an acetate alcohol, and NaCl in the water, did not appear to have any appreciable effect on the tensile ability of the suction probe.

Contrary to the expectation of the researcher, the addition of a highly plastic bentonite slurry into the water in the measuring chamber reduced the tensile strength of the water. The results, however, provide support for the gas-trapping model. The addition of bentonite into the water may tend to hold water molecules together due to the strong absorbing power of bentonite particles. As a result, the bonding between water and the walls of the measuring chamber in the suction probe is reduced by the attraction of bentonite particles to the water molecules in vicinity of the walls. Consequently, the overall tensile strength of the water in the suction probe is reduced.

From the evaporation tests on the suction probe with a bentonite-clogged ceramic, it is suggested that cavitation is most likely to initiate near the ceramic. Possibly the extremely thin bentonite flakes dispersed in the water could have filled the tiny crevices on the ceramic which otherwise could have triggered cavitation.

6.3.3 Proposed Mechanism of Cavitation

A saturated cellulose membrane enclosed in the suction probe has been found to increase the sustainable tension by more than 200 kPa, with or without pre-pressurization (Figs. 5.16 and 5.17). The placement of a cellulose membrane into the suction probe decreases the volume of water in the measuring chamber, possibly reducing the chance of cavitation within the water. However, as pointed out earlier, cavitation of the system will not likely occur within the water in the measuring chamber, but rather at the boundaries (i.e., the crevices on the walls of the chamber and more likely on the ceramic). The membrane cannot improve the bonding between water and the crevices in the same way as does the pre-pressurization, and possibly as does the absorbed bentonite in the ceramic. Therefore, the increase in the tensile
strength of water in the suction probe with the enclosed membrane must be due to some other reasons.

It should be explained that local cavitation (i.e., formation of local bubbles) in the chamber should not necessarily cause the failure of the system to resist tension. The system fails to record tension because cavitation has propagated to the pressure diaphragm and the passage to the pressure diaphragm has been blocked by gaseous bubbles so that tension can no longer be transmitted onto the pressure diaphragm.

Cavitation starts at the crevices on the walls of the chamber, and likely near the ceramic for the current suction probe. Local cavitation normally starts from relatively large crevices, releasing some bubbles. For a suction probe containing solely water the propagation of cavitation is instantaneous. Once a local cavitation starts, it can immediately spread to the rest of the system (i.e., the measuring chamber), causing the system to lose the ability to sustain tension. This mechanism is illustrated in Fig. 6.3, in which the cavitation nuclei (i.e., tiny crevices containing gases) are exaggerated.

![Diagram of Transducer Diaphragm and Tension Transmission Blocked by Gas Bubbles](image)

a.) Initiation of Local Cavitation  
b.) Instantaneous Propagation of Cavitation

Fig. 6.3 Instantaneous Cavitation in a Suction Probe Containing Solely Water

The propagation of gas bubbles will be retarded if a cellulose membrane is enclosed in the measuring chamber and is in firm contact with the walls (due to pre-stressing). Without pre-pressurization, local cavitation occurs at -100 kPa. The system at this moment, however, still
has the ability to transmit a tensile stress through the water in the membrane. Therefore, the tensile ability of the system is increased. This mechanism is illustrated in Fig. 6.4. If the system is pre-pressurized, local cavitation starts in crevices at a tension equal to the tension that can be sustained by a pre-pressurized suction probe containing solely water. However, the system still has the ability to transmit tension because the propagation of gas bubbles is restricted by the saturated membrane and the tension can be transmitted through water in the membrane. The system is termed as cavitated when the tension reaches a magnitude at which the gas bubbles spread to the main area of the diaphragm.

![Diagram of transducer diaphragm with gas in crevice (Local cavitation)]

a.) Retardation of Propagation of Local Cavitation by Membrane: Tension Transmissible

b.) Cavitation of System: Tension not Transmissible

Fig. 6.4 Retardation of Local Cavitation by Cellulose Membrane

Tension reversibility tests have shown that the long term tension reversibility of the probe containing a cellulose membrane is not as good as the probe containing solely water (Figs. 5.18 and 5.19). This is probably caused by the non-uniform passage of water droplets into the system during a reversibility test. When the membrane loses excessive moisture at certain points during the reversibility tests, shrinkage of the membrane will occur around those points and the membrane becomes “leaky”. Local cavitation is able to propagate throughout the chamber, causing the system to lose its tensile ability.
6.4 SUITABILITY FOR SOIL SUCTION MEASUREMENTS

There are several observations from the evaporation tests which indicate that the developed suction probe is suitable for the direct measurement of matric suctions greater than 100 kPa:

a.) The suction probe is able to maintain tensions up to -1,000 kPa for a relatively long period of time, (e.g., 3 days).

b.) The suction probe is able to reversibly respond to changes in pore-water tension. The maximum tension (i.e., the cavitation threshold) that can be sustained in a given suction probe can be approximately predicted using an evaporation test. As long as a tension does not exceed the maximum tension, the ability of the probe to sustain the tension is maintained.

c.) Generally solutes in the soil-water do not have an adverse effect on the ability of the suction probe to maintain a high tension.

6.5 THE USE OF THE SUCTION PROBE FOR SOIL SUCTION MEASUREMENTS

The results of measurements of soil suction using the developed suction probe are discussed in this section. The tests were performed on reconstituted Regina clay and a fine silt. A procedure is proposed to define the point of equilibrium between the tension in the suction probe and the matric suction in the soil being measured.

6.5.1 Measurable Components of Soil Suction

The 15 bar ceramic used in the developed suction probe does not appear to have any appreciable osmotic efficiency. The suction probe only measures matric suction when in direct contact with a soil.

The suction probe is not able to measure total suction when the equalization process is forced to occur in the vapor phase. The suction probe fails to reach equilibrium in vapor phase due to the following reasons:
a.) The suction probe is extremely sensitive to moisture loss due to evaporation. Equilibrium cannot be reached before cavitation occurs due to the loss of moisture through evaporation into the soil.

b.) Water vapor tends to condense on the solid surfaces in the vicinity. Water vapor from the ceramic cannot be in equilibrium with water vapor from the soil before cavitation occurs in the suction probe.

On the other hand, any measurements of soil suction based on vapor equilibrium are bound to suffer from poor accuracy (Appendix A).

6.5.2 Accuracy and Response Time of the Suction Probe

The accuracy and response time of the suction probe in response to a change in an external tension are best established through use of the axis-translation technique. When a change in air pressure occurs in a pressure plate, an equal amount of change in pressure in soil water should take place simultaneously. The results from calibration tests of the suction probe for negative pressures indicate that the suction probe is highly accurate (Tables 5.2 and 5.3). The measurement errors are generally within ±20 kPa which is the same range of accuracy as for the high pressure transducer. In other words, the accuracy of a measurement is mainly limited by the accuracy of the transducer used in the suction probe.

The response of the suction probe to a change in an external tension is just a matter of a few seconds. The extremely quick response of the suction probe is attributed to the high degree of saturation and the high rigidity of the measuring chamber.

6.5.3 Mass Transfer During Measurement of Soil Suction

When the suction probe is put into contact with a soil, the moisture transfer takes place in both the liquid and vapor phases. On the one hand, moisture from the probe keeps evaporating into the soil and the vicinity surrounding the ceramic. As a result, a tension is generated in the water in the suction probe. On the other hand, the liquid water transfer, which occurs through the contact between the soil and the ceramic of the suction probe, forms the equalization process of matric suction. The development of tension in the suction probe during the
measurement of matric suction is a combination of evaporation and equalization of matric suction. Moreover, if moisture continuously evaporates out of the system during measurement, a continuous drift in tension should be observed.

The development of tension in the suction probe during the measurement of matric suction may be divided into several phases (Fig. 6.5). These phases are explained as follows:

**Fig. 6.5 Tension Response Curves During Measurements of Matric Suction**

**Phase I:** This is the initial phase of tension development. A significant amount of tension is rapidly produced during this relatively short period of time (e.g., 5 to 10 minutes). Generally the matric suction equalization is more dominant than the evaporation process (Curve 1, also see Fig. 5.23). Liquid water transfers from the probe into the soil.
Curve 2 (also see Fig. 5.31) occurs when the tension in the probe already starts to develop due to initial evaporation before the probe is put into contact with the soil. However, the process of matric suction equalization will soon become dominant as long as there is a good contact between the soil and the suction probe. Liquid water will transfer from the soil into the suction probe. The tension developed due to initial evaporation will drop and tend to reach equilibrium with the matric suction in the soil.

**Phase II:** Following Phase I is a process during which matric suction equalization is dominant but slow. At the end of this phase, an approximate equilibrium between the tension in the suction probe and the matric suction in the soil is reached. The liquid water may transfer from the soil into the suction probe to offset the loss of moisture from the suction probe due to evaporation.

From the point of free energy equilibrium for an isothermal system, liquid flow and vapor flow should always occur in the same direction. The suggestion that liquid water can flow from the soil to the probe to offset the effect of evaporation from the probe, however, does not contradict the free energy criterion. This phenomenon can be illustrated using Fig. 6.6.

If all the air voids in the soil are vapor-saturated relative to the energy status of the soil moisture, the liquid flow and the vapor flow should always occur from the probe to the soil, and the equilibrium will be established. However, it is possible that some under-saturated air voids can exist in a soil, particularly for the air voids near the surface of an unsaturated soil. In the water vapor in the surface voids has a lower free energy than the liquid soil water. In Fig. 6.6, it is assumed that the liquid water has an initial free energy equivalent of -200 kPa and the vapor in the surface voids has an initial free energy equivalent of -300 kPa (Fig. 6.6a). When the soil is in contact with the probe which has a free energy of zero, both liquid water and water vapor flow from the probe to the soil. Suppose the free energy in the probe quickly reduces to an equivalent -200 kPa and the free energy of the surface voids is increased to an equivalent of -250 kPa, water will continue to evaporate into the surface-voids. As a result, the free energy of the water in the probe tends to be further reduced. However, liquid water will move from soil particles to the probe to maintain the free energy of the water in the probe.
at an equivalent of -200 kPa (Fig. 6.6b). The above processes do not contradict the free energy criterion.

a.) At Time = 0

b.) Approximate Equilibrium in Liquid Water

c.) Equilibrium in Both Liquid and Vapor Phases

Fig. 6.6 Illustration of Mass Transfer During Measurement

Figure 6.6b shows that it is possible to reach equilibrium between the liquid soil water and the water in the suction probe, while the vapor-phase in the surface voids is still short of equilibrium with the liquid water. After the equilibrium is reached between the liquid soil water and the water in the suction probe, water may still continue to evaporate from the probe.
into the surface voids which have a lower free energy. If the transfer of liquid water from the soil to the probe is not able to offset the loss of water from the probe, the tension in the suction probe will continue to rise. In the long run, an equilibrium should be reached for both liquid and vapor phases (Fig. 6.6c) and the equilibrium should be represented by a relatively horizontal portion on the tension response curve. However, this is possible only if the moisture loss from the probe does not cause cavitation. For soils with a low degree of saturation, the volume of under-saturated surfacer voids may be too large and the permeability of the soil is too low. As a result, the horizontal portion may not be conspicuous. The tension continuously increases until the water in the suction probe cavitates.

**Phase III.** After a relatively horizontal portion occurred on the tension response curve, a slow drift in recorded tension was always observed for the measurement of both saturated and unsaturated soils in this testing program. This is mainly attributed to the moisture loss from both the soil and the suction probe during the measurement. For the soil specimens used in the testing program, the water content generally decreased by up to 0.1% after measurement of matric suction. However, handling of the soils before and after measurement also resulted in moisture loss for the soils. The rest of the 0.1 % decrease in water content must have occurred during the measurement. A decrease in water content by 0.1% could account for a drift in measured matric suctions from 10 to about 50 kPa for the glacial till, depending on the degree of saturation of the soil (Fig. 5.34).

The continuous drift in recorded tension should be caused by a continuous loss of moisture from the soil and the suction probe. Figure 6.7 illustrates the possible sources of continuous moisture loss from the soil and suction probe during the measurement. These sources are discussed as follows:

1.) Evaporation from the probe through the ceramic edge

The ceramic of the suction probe was made to slightly protrude the surface of the suction probe (by about 0.1 mm). It is possible that evaporation may occur at the edge of the ceramic. However, this evaporation was considered as insignificant due to two reasons: (a) the ceramic
edge was found to be embraced by the soil; (b) opening the aluminum foil during measurement did not produce apparent increase in the rate of recorded tension.

2.) Vapor diffusion through the aluminum foil

Vapor diffusion through the aluminum foil was analyzed in Appendix C. The moisture loss of the soil system due to the vapor diffusion through the aluminum is extremely small and its effect on the reading of the suction probe is negligible.

3.) Vapor leakage through the edge of the covering aluminum foil

The moisture loss from the system due to this mechanism is considered small because several layers of electric tape were used for the measurement. Moreover, no differences in recorded tension due to the possible differences in the sealing by the electric tape were observed.

4.) Condensation around the ceramic of the suction probe.

Condensation around the ceramic of the suction probe was observed for tests with Regina clay. Condensation has been known to likely occur on the dust particles and on the interfacing surfaces of materials.
5. ) Moisture leakage through the "O" ring placed between the suction probe and the stand on which the measurement of soil suction was taken (Fig. 4.9). The amount of the moisture loss, however, was difficult to evaluate.

6.5.4 Determination of Equilibrium

Phase II in Fig. 6.5 is important in that the approximate point of equilibrium is reached during this phase. However, determination of the horizontal portion on the tension curve is based on visual judgment which may involve subjective errors. The appearance of this horizontal portion may vary with respect to the time scale used in plotting the tension curve. Figure 6.8 shows tension response curves measured on Regina Clay and the fine silt, using a small time scale. The pre-applied matric suctions were 300 kPa, 350 kPa, and 550 kPa, respectively. The matric suctions estimated from the tension response curves are about 275 kPa, 325 kPa, and 520 kPa, respectively. Equilibrium appeared to be reached in less than 3 hours. However, when the tension curves are plotted on a large time scale as shown in Fig. 6.9, the horizontal portions become more evident after more than 10 hours for equalization. The tensions corresponding to these horizontal portions are in closer agreements with the pre-applied matric suctions than the matric suctions estimated from Fig. 6.8. The drift in recorded tension for Regina clay is more likely due to condensation.

The logarithm of time scale is often used in analyzing time-related problems in soil mechanics (e.g., soil consolidation). Use of the logarithm of time scale tends to convert the measured response curves into straight lines so that the point of equilibrium can be determined readily and consistently. The disadvantage of the logarithm of time scale, however, is that it gives a distorted image for measurements after a long period of time.

Figure 6.10 is obtained by converting Fig. 5.23 into the logarithm of time scale. The tension response curves after 10 minutes of equalization is plotted (i.e., approximately Phases II and III). A measured tension response curve is generally converted into two relatively straight curves. The relatively horizontal portions become shorter as compared to those in Fig. 5.23. The shortened horizontal portions are more evident of equilibrium since these portions occur over a time length that is long but visually compressed. The time to reach approximate
Fig. 6.8 Determination of Equilibrium of Matric Suction on a Small Time Scale
Fig. 6.9 Determination of Equilibrium of Matric Suction on a Large Time Scale
Fig. 6.10 Re-Plot of Fig. 5.23 Using the Logarithm of Time Scale

(Pre-Applied Matric Suction: 150kPa, 200kPa, 250kPa, 300kPa, 350kPa, 400kPa, 450kPa, 500kPa, 550kPa)

Log Time (min)

Recorded Pressure (kPa)
equilibrium conditions may be represented by the intersecting point of two lines which are
tangent to the nearly horizontal portion and the relative straight curve before the nearly
horizontal portion, respectively. Figure 6.11 converts the data in Fig. 6.9 into a logarithm of
time scale. Again, the determinations for equilibrium are obtained from the nearly horizontal
portions of the converted curves. Figure 6.11 also shows how the logarithm of time scale can
distort the image. When equilibrium was reached after about 18 hours of equalization, the
tension appeared to continue rising considerably. The rate of increase in tension after the
equilibrium is reached is visually exaggerated by the use of the logarithm of time scale.

Difficulties were encountered in determining the point of equilibrium for soils with a low
degree of saturation. Figure 6.12 converts three tension response curves from Fig. 5.24 to the
logarithm of time scale. For a pre-applied matric suction of 400 kPa, the horizontal portion is
not so evident. It is not possible to attain an accurate determination of equilibrium. The degree
of saturation at this matric suction was about 38% (Fig. 4.7).

Appendix D gives all the results of measurements of matric suction for the soils used in
this laboratory program. The measured tension response curves are converted into the
logarithm of time scale. The determined matric suctions at equilibrium and the approximate
times to reach equilibrium are listed in Tables D.1 to D.3. In cases where the nearly horizontal
portions are not evident, the tension response curves are extended until approximately
horizontal portions are obtained. However, the extension of the tension response curves for
the compacted glacial till, with a degree of saturation of less than 43%, becomes questionable
(Fig. D.7). The suction probe seems to be most suitable for the measurement of matric suction
of wet and clayey-type soils. The suction probe may have difficulties in measuring matric
suction when the degree of saturation of the soil is less than 40%.

6.6 COMPARISONS WITH OTHER METHODS

The measurements of matric suction on a compacted glacial till, using the developed
suction probe and several other methods, have been presented in Chapter 5.

The filter paper method gave measurements close to the values obtained from the suction
probe for matric suctions less than 200 kPa. As the soil became drier, the filter paper generally
Fig. 6.11 Re-Plot of Fig. 6.9 Using the Logarithm of Time Scale
gave lower values. The scatter in the results obtained by the filter paper method is more pronounced for soils with a low degree of saturation. Similar conclusions were also obtained by Ridley (1993). The reason is probably because the complete equilibrium is not achieved in seven days, particularly for soils at low degrees of saturation. Deka et al. (1995) suggested that equalization periods longer than seven days should be required for dry soils when using the filter paper method. Justification of this reasoning is difficult because measurements at low degrees of saturation can show considerable scatter.

The thermal conductivity sensor produced reasonably close measurements with the suction probe at matric suctions less than 100 kPa. The thermal conductivity sensor appeared to under-estimate the matric suction at values exceeding 100 kPa. There is considerable hysteresis between absorption and desorption at matric suctions less than 100 kPa. However, the hysteresis decreases with increasing matric suction and becomes negligible when matric suction is greater than about 150 kPa. Use of an initially dry sensor can considerably shorten equalization time as compared to use of an initially wet sensor.

The reason for the low values of matric suction measured by the thermal conductivity sensor is not clear. The water contents measured after the thermal conductivity measurements indicated that the changes in the water content of the soil were small. Furthermore, measurements using an initially dry sensor are close to those using an initially wet sensor. These results indicate that the low matric suctions measured are not primarily due to the initial water content in the sensor, nor due to the hysteresis of the sensor. At present, several reasons may account for the low values of measurements:

a.) the primary reason may be the low sensitivity of the sensor above 150 kPa,
b.) the heat pulse generated by the heating element could fall outside the sensor,
c.) only the bottom face of the sensor was in direct contact with the ceramic in a pressure plate during calibration, whereas the whole sensor was embedded in the soil during measurements. If the soil-water properties in the sensor are more or less anisotropic, a systematic error may be introduced in the calibration. An anisotropy in the ceramic is likely to
be introduced during the production of the sensor, which involved mechanical compaction in a mould.

The last two reasons, however, cannot be proved in this research program due to the malfunctioning of the thermal conductivity sensor. It is suggested that a more extensive investigation regarding those two aspects should be made in the future.

The null-pressure plate gave higher values of matric suction than the suction probe, particularly for soils at degrees of saturation over 75%. The relative difference, however, became less significant when the degree of saturation was smaller than 60%.

The over-estimation of matric suction when using the pressure plate method, particularly for soils at high degrees of saturation, was also found by Madsen et al. (1986), and Campbell (1988). The primary reason for the over-estimation of matric suction may be due to the occluded air bubbles in the soil water. A necessary condition for the use of the axis-translation technique in the measurement of soil suction is that the air phase in the soil be interconnected (Appendix A). Under this condition there will be no volume change in the fluid phases when the air pressure is increased. The axis-translation may not be suitable for the matric suction measurement when the soil is close to the optimum water content condition, since occluded air bubbles may exist when soil is near or on the wet side of optimum water content (i.e., degree of saturation above about 80%). Bocking and Fredlund (1980) made a theoretical analysis which indicated that occluded air bubbles in a soil can result in an over-estimation of matric suction when using the null-pressure plate technique.

A possible secondary reason for the over-estimation of matric suction when using the null-pressure plate method is the hysteresis involved in the measurement. A measurement of matric suction using a null-pressure plate, involves many small successive cycles of partial wetting and drying of the soil in order to maintain a null-flow condition. During each cycle, the increase in the air pressure needed to desorp a certain amount of water from the soil is higher than the reduction in air pressure needed to absorb the same amount of water into the soil. This can lead to an over-estimation of the matric suction in the soil. It is anticipated that the use of a pressure transducer to measure the water pressure can reduce the effect of hysteresis, thus producing more accurate results.
6.7 COMPARISONS WITH THE RESEARCH BY RIDLEY

The present study extends the research conducted by Ridley (1993) and Ridley and Burland (1994). Efforts were made to investigate the fundamental behavior of water in the suction probe. Various factors that may affect the tensile behavior of the suction probe were identified. The mechanism of cavitation in the suction probe was investigated. The suction probe was shown to be suitable for matric suction measurements on both saturated and unsaturated soils. The suction probe was tested on several soils with different soil structures. A procedure was proposed to determine the point of equilibrium. The difficulties in using the suction probe for measuring soils with a low degree of saturation were reported and analyzed. Measurements using the suction probe were compared with those using several other conventional methods.

The main differences in the construction and operation of the Ridley’s suction probe and the current suction probe developed at the University of Saskatchewan are outlined below:

1.) There are no threads on the transducer used in the U. of S. suction probe. The earlier suction probes developed by Ridley (1993) included transducers with threads.
2.) The U. of S. suction probe uses a transducer with a wider range of operating pressure than the transducers used by Ridley (1993). The U. of S. suction probe allows for the application of the pre-pressurization pressures up to 12,000 kPa. Ridley used a pressure of 6000 kPa for pre-pressurization. The duration and number of cycles of pre-pressurization used in the present research program were different from those used by Ridley.
3.) The present research uses a manual pressurization system to pre-pressurize the suction probe. This manual pressurization system can provide pressures from -85 kPa to 15,000 kPa, and is simple and worked well. Ridley (1993) used an automatic system for pre-pressurization.
4.) The present research used the axis-translation technique in a pressure plate apparatus to test the suction probe for negative pressures. Ridley (1993) conducted an undrained test in a triaxial cell to test the suction probe for negative pressure.

The following aspects in the present studies were found to be different from the conclusions obtained by Ridley (1993):
1.) The dependence of the duration of a tension on the magnitude of the tension does not appear to be as significant as claimed by Ridley (1993). There appears to be an approximate cavitation threshold for a given suction probe and a given pre-pressurization procedure. A tension can be maintained for a relatively long period of time (e.g. several days) as long as it does not exceed the cavitation threshold.

2.) Different ceramics used in the suction probe lead to different tensile strengths of water. The highest tensile strength in this research program was found to be about 1,250 kPa. The present suction probe is not able to sustain a tension of -1,500 kPa, or higher, as claimed by Ridley (1993, 1994). Furthermore, the tensile ability of the suction probe seemed to be reduced after a number of cavitations of the water in the suction probe.

3.) It is difficult to completely eliminate drift in recorded tension during measurement of matric suction. The measured tension appeared to increase slowly with time. Consequently, it is necessary to define the equilibrium point from the measured tension response curves. However, determination of equilibrium for soils with a degree of saturation less than 40% is difficult.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY

As the primary objective of this research program, a suction probe was successfully developed to directly measure matric suctions greater than 100 kPa. The suction probe is a direct measurement based on the tensile strength of water. An experimental study provided an understanding of the fundamental behavior of water under tension. An optimum procedure was determined for making the suction probe capable of sustaining high tensions. Various factors affecting the behavior of the suction probe under tension were investigated. The mechanism of cavitation in the suction probe was also studied.

The suction probe developed in this research program proved to be suitable for measuring matric suctions up to 1000 kPa. Measurements of matric suction using this suction probe gave satisfactory results. Limitations of this technique were also recognized. This research program extends the understanding of the use of the tensile strength of water for measuring soil suction as previously obtained by Ridley (1993) and others (Ridley and Burland, 1994; Dineen and Burland, 1995).

As a secondary objective of this research, some possibilities for utilizing the anomalous properties of water around soil particles for the measurement of soil suction were investigated. The behavior of a compressible saturated clay under the action of an external suction was analyzed (Appendix B). A preliminary experimental study showed that it is difficult to use a compressible saturated clay for the measurement of soil suction due to significant hysteresis in the mechanical behavior of the clay.

This chapter summarizes the main conclusions associated with the tests performed on the developed suction probe. Recommendations for future investigations into this method are also presented.
7.2 CONCLUSIONS

The conclusions regarding the fundamental behavior of water under tension are presented followed by the conclusions regarding the measurements of soil suction using the developed suction probe. Limitations of the suction probe are also summarized.

7.2.1 Tensile Behavior of the Suction Probe

1.) Normally water in the suction probe does not have the ability to sustain tensions higher than -100 kPa. Pre-pressurization can effectively dissolve gaseous nuclei present in the system, thus making the probe capable of sustaining tensions greater than -100 kPa. The main factors that may affect the sustainable tension in the suction probe include the magnitude, the duration, and the number of cycles, of pre-pressurization. The sustainable tension is also related to the ceramic used in the suction probe. The maximum sustainable tension was found to be about -1,250 kPa in this research program. No special procedure was required to pretreat the water used in the suction probe. However, the use of distilled and deaerated water is recommended.

2.) For a given suction probe and a given pre-pressurization procedure, there appears to be an approximate cavitation threshold. A tension less than the cavitation threshold can be maintained for a relatively long period of time (e.g., several days). The suction probe exhibits remarkable tension reversibility as long as the tension does not exceed the cavitation threshold. However, the cavitation threshold may decrease after the suction probe has undergone a number of cavitations.

3.) The addition of a miscible liquid into the water contained in the suction probe does not appear to have an appreciable effect on the sustainable tension. The addition of bentonite into the water in the suction probe appears to reduce the tensile ability of the probe. A suction probe with a bentonite-clogged ceramic, or a cellulose membrane, has the ability to sustain tensions above -100 kPa even without pre-pressurization. It appears that cavitation is likely to initiate from the ceramic of the suction probe.

4.) The tensile behavior of the water in the suction probe can be explained using the gas-trapping model for cavitation. The gas-water meniscus in the tiny crevices on the wall of
measuring chamber acts like an elastic membrane which can deflect back and forth in response to changes in water pressure.

5.) Local cavitation in the measuring chamber should not necessarily cause the immediate failure of the system to sustain tension. The suction probe fails to measure tension because cavitation has propagated to the pressure diaphragm of the transducer. If the propagation of local gas bubbles can be retarded, the system will still have the ability to transmit tensions.

6.) The suction probe is suitable for measuring matric suction in soils.

7.2.2 Measurements of Soil Suction Using the Suction Probe

1.) The suction probe can measure only matric suction in soils. The suction probe is not suitable for measuring osmotic suction and total suction.

2.) The suction probe is suitable for measuring matric suction in both saturated and unsaturated soils. The suction probe appears to be very sensitive to changes in the suction in a soil. The response of the suction probe is very rapid. The accuracy of the suction probe is mainly limited by the accuracy of the pressure transducer used in the probe (i.e., about ±20 kPa). The principle of the axis-translation technique was proved to be correct for negative pore-water pressures as high as -500 kPa.

3.) The measurement of matric suction using the suction probe involves combined processes of equalization with respect to matric suction, and evaporation from the suction probe. The suction probe is sensitive to even a minute loss of water from the soil and the suction probe during measurement. The suction probe is most suited to soils for which evaporation from the probe is less pronounced during measurement. These soils may include clays, clayey-type soil, and soils with a relatively high degree of saturation. The suction probe may not be suitable for measuring soils with large dry pores, or soils with a relatively low degree of saturation.

4.) The use of the logarithm of time scale for plotting the measured tension response curve can provide a satisfactory determination of the equilibrium point for matric suction. The time needed for equalization can vary from a few minutes to a few hours, depending on the contact conditions between the suction probe and the soil, the type and the degree of saturation of the soil. Generally the probe can measure matric suction in a wet soil more quickly than in a dry
soil. The probe may not be able to reach equilibrium with soils with a degree of saturation less than about 40%.

5.) When an unsaturated soil is placed onto the ceramic in a pressure plate for controlling the matric suction in the soil, the effective contact between the soil and the ceramic is not well established. The matric suction in the soil is not necessarily equal to the applied air pressure. The effective contact area, however, can be better established by imposing an initially wet condition around the bottom of the soil.

6.) The filter paper method gave measurements relatively close to the values obtained using the suction probe for matric suctions less than 200 kPa. The results of measurements using the filter paper method on dry soils were widely scattered and were generally lower than the values obtained using the suction probe.

7.) The thermal conductivity sensor produced measurements which are in reasonable agreements with the measurements using the suction probe at matric suctions less than 100 kPa. The thermal conductivity sensor appeared to under-estimate the matric suction at values exceeding 100 kPa. Use of an initially dry sensor can considerably shorten the equalization time when compared to the use of an initially wet sensor.

8.) The null-pressure plate gave higher values of matric suction than the suction probe, particularly for soils at degrees of saturation over 75%. The relative difference, however, became less significant when the degree of saturation was smaller than 60%.

7.2.3 Limitations of the Suction Probe

1.) The suction probe does not appear to be suitable for measuring matric suction in soils with a degree of saturation less than about 40%.

2.) The transducer used in the suction probe is sensitive to mechanical disturbance and temperature. Any measurements should be made in an environment at relatively constant temperature unless measures are used to compensate for the effects of temperature.

3.) With appropriate consideration for the effects of temperature, the suction probe may be used for field measurements when the in situ matric suction is predicted to be less than the
cavitation threshold, and the mechanical disturbance is a minimum. The suction probe has to be removed from the soil and pre-pressurized once cavitation occurs.

4.) It appears that the ceramic in the suction probe has to be replaced after having been used for a period of time, particularly if the probe has experienced many times of cavitation.

7.3 RECOMMENDATIONS

Recommendations are made with respect to the design of the suction probe. Proposals for research in the future are also given.

7.3.1 Design of the Suction Probe

The current suction probe could be further modified as shown in Fig. 7.1. These changes should result in a superior suction probe.

![Diagram of Modified Suction Probe]

**Fig. 7.1 Illustration of the Modified Suction Probe**

1.) The diameter of the ceramic should be reduced as small as possible in order to reduce chances of cavitation to minimum. However, a large contacting area between the ceramic and the soil to be measured is desirable in order to reduce the effect of local heterogeneity in soils (Hendrickx et al. 1994). One option is to use a trapezoid-shaped ceramic with the smaller end facing the transducer diaphragm. The epoxy “Epocast Nine” should be strong enough to keep
the ceramic from being popped out of the probe as long as the application of pre-pressurization is not too fast.

2.) The operation range of the transducer could be reduced to about 10,000 kPa in order to increase the sensitivity of measurements and reduce the cost of the transducer. Other types of transducers could be used since the ceramic appears more responsible for cavitation inception than the transducer. A suction probe machined from a single piece of stainless steel, similar to the one used by Ridley (1993) may be superior for reducing cavitation nuclei.

3.) Investigations should be made to find a “stronger” ceramic that can provide a cavitation threshold greater than -1,250 kPa. Tests may be conducted on the use of a permeable cellulose membrane in conjunction with a 15 bar ceramic in a suction probe. The construction of this suction probe could be similar to that of the osmotic tensiometer developed by Peck and Rabbidge (1966, see Fig. 2.4).

4.) The simplicity of the pressurization system developed in this research program is appreciable. However, it may be useful to design a pre-pressurization system which can automatically shift between a high positive pressure (e.g., 10,000 kPa) and a vacuum (e.g., -85 kPa). The effect of pre-pressurization can be better evaluated with such a pre-pressurization system.

7.3.2 Future Studies

1.) The effect of evaporation on the measurement of matric suction using the suction probe should be further studied. Measurements of matric suction should be made in a humidity-controlled environment in which evaporation from the probe is reduced to minimum. Large soil specimens should be used to reduce the relative influence of loss of soil moisture during measurement.

2.) The tensile strength of the water in the suction probe appears to be related to the microstructure of the ceramic used. More studies using various types of ceramic are needed to investigate the mechanism behind this phenomenon.

3.) More independent studies involving measurement of matric suction using the developed suction probe should be made. The effects of soil structure (i.e., the size and distribution of air
voids) and the degree of saturation on the measurement of matric suction should be investigated.

4.) One of the important applications of the suction probe is to evaluate the existing methods for soil suction measurements. Evaluations of the existing methods have been difficult because errors included in each technique are too complex to assess with certainty. The developed suction probe should provide a direct means by which critical evaluations of some taken-for-granted practices related to soil suction measurements become possible.

5.) The development of the suction probe based on the tensile strength of water can open a wide area of research possibilities. The suction probe can be used to deal with many geotechnical and geo-environmental problems which involve negative pore-water pressures. For example, the suction probe could be adapted to measure negative pore-water pressures in triaxial shear tests, direct shear tests, and in soil compaction. The suction probe could also be useful for the insitu studies of soil-water movement, contaminant transport, and flux-boundary problems.
REFERENCES


APPENDIX A

Theoretical Aspects Of Soil Suction
A.1 INTRODUCTION

The theoretical background of soil suction is critically discussed in this section. The terminologies and concepts widely accepted to understand soil suction are briefly reviewed. Thermodynamic principles are used to investigate the basis for the measurement of soil suction and the theoretical conditions for the axis-translation technique.

A.2 SOIL SUCTION COMPONENTS

The terminologies used to describe the components of the potential of soil water were stated by the International Society of Soil Science quoted by the “Review Panel” (Aitchison, 1965). The soil-water potential can be identified in terms of soil suction which is expressed as the pressure deficiency in soil water relative to free pure water. Total suction, which is equivalent to total water potential, consists of two components; namely, the matric suction and the osmotic suction. The components of soil suction were defined as follows (Aitchison, 1965):

1.) “the matric suction, \( u_a - u_w \), is 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”;

2.) “the osmotic suction, \( \pi \), is the negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane with a pool containing a solution identical in composition with the soil water”;

3.) “the total suction, is 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 semi-permeable membrane with the soil water”.

Two types of distinct physical models are often used to interpret the suction of a soil-water system. These are mechanical models and thermodynamic models.
A.3 THE MECHANICAL MODELS

The suction mechanism in the mechanical models is solely attributed to the mechanical behavior of water in capillaries or pores due to the surface tension of water. There are generally two mechanical models for soil suction, namely, the capillary model, and the contractile skin model.

A.3.1 The Capillary Model

The capillary model was the first model used to illustrate the pressure deficiency of water in a soil (Buckingham, 1907; Richards, 1928). The principle of the capillary model is illustrated in Fig. A.1. When a small diameter glass tube is inserted into water under atmospheric conditions, water will rise in the tube due to the surface tension of water. The air-water meniscus concaves toward the water phase, indicating a pressure deficiency in the water in the tube relative to the atmosphere.

![Capillary Model Diagram]

a.) Water Rise in a Capillary Tube  
b.) Water Pressure

Fig. A.1 Capillary Model Illustrating Matric Suction
The pressure deficiency at the meniscus can be calculated from the hydrostatic equilibrium of the meniscus,

\[ u_a - u_w = \frac{2T_s}{r} \cos \alpha \]  \hspace{1cm} (A.1)

where:

- \( u_a \) = air pressure over meniscus,
- \( u_w \) = water pressure under meniscus (i.e., at B),
- \( T_s \) = surface tension of water,
- \( r \) = radius of the capillary tube,
- \( \alpha \) = contact angle of air-water meniscus with the capillary wall, and
- \( h_c \) = height of water rise in the capillary tube.

The water pressure above datum at A (i.e., water table) is negative and linearly distributed.

The above capillary model demonstrates the ability of surface tension to support a column of water in a capillary tube. In an unsaturated soil, the continuous pore spaces act as capillary tubes in a similar manner to pull water up from the water table. The height of capillary rise, \( h_c \), represents the pressure deficiency in the soil water. The smaller the pore size, the greater the tendency for water to move along the pore spaces. Such a pressure deficiency in a soil-water system represents the interaction between water and soil matrix and is usually defined as matric suction. Equation (A.1) is frequently used to correlate matric suction with the pore-size characteristics of a soil.

**A.3.2 The Contractile Skin Model**

Fredlund (1973) introduced the concept of the contractile skin phase to explain the engineering behavior of unsaturated soils by extending the concepts of the continuum mechanics. The air-water interface, namely, the contractile skin, is identified as an independent phase since it has different properties from the contiguous phases (i.e., water, or air), and has definite bounding surfaces. The contractile skin phase is important because of its distinctive ability to exert a tensile pull. The contractile skin behaves like an elastic membrane under
tension interwoven throughout the soil structure. The contractile skin model extends the capillary model by demonstrating the tensile effect of the air-water interface on the mechanical behavior of unsaturated soils (Fredlund, 1993).

A.4 THE THERMODYNAMIC MODEL

Thermodynamic principles are generally used by soil scientists to understand the soil-water interaction. Soil suction is quantitatively related to the Gibb's specific free energy of the soil water from the context of thermodynamics. However, the thermodynamic principles are generally not used in geotechnical engineering. This section attempts to examine some important thermodynamic aspects for a soil-water system.

A.4.1 A Brief Review of the Free Energy Concept

Gibb's free energy is a useful concept in thermodynamics. The free energy of a species of matter in a system can be expressed as:

\[ f = e + P v - T s \]  \hspace{1cm} (A.2)

where:

\[ f = \text{specific free energy}, \]
\[ e = \text{internal energy}, \]
\[ P = \text{internal pressure}, \]
\[ v = \text{specific volume}, \]
\[ T = \text{absolute temperature, and} \]
\[ s = \text{entropy}. \]

For a liquid, \( P \) is the internal hydrostatic pressure. For a gas, \( P \) is the partial pressure of the species concerned. Differentiating Eq. (A.2) gives:

\[ df = de + P dv + v dP - T ds - s dT \]  \hspace{1cm} (A.3)

Considering a reversible process,
\[ Tds = dq = de + Pdv + d\omega_m \]  \hfill (A.4)

where:

\( q = \) heat content,
\( d\omega_m = \) all the work done by or on the species, except the work done by expansion against pressure \( P \).

Generally, \( d\omega_m \) may include work done by electric, magnetic, and gravitational forces (Edlefsen and Anderson, 1943).

Substituting Eq. (A.4) into Eq. (A.3) gives,

\[ df = -sdT + vdP - d\omega_m \]  \hfill (A.5)

For an isothermal process, the change in free energy, when removing a species from state \( A \) to state \( B \), is:

\[ \Delta f = \int_{A}^{B} vdP - \int_{A}^{B} d\omega_m \]  \hfill (A.6)

and if no work is done except expansion against the pressure \( P \), \( d\omega_m \) is zero. Then,

\[ \Delta f = \int_{A}^{B} vdP \]  \hfill (A.7)

The free energy concept is useful in that it provides a criterion of equilibrium of the same species at different states, particularly of different phases. If species, \( i \), can exist at the same time at both states \( A \) and \( B \) as illustrated in Fig. A.2, the free energy of \( i \) at state \( A \), \( f_A \), must be equal to that at state \( B \), \( f_B \):

\[ f_A = f_B \]  \hfill (A.8)
<table>
<thead>
<tr>
<th>Species ( i )</th>
<th>Species ( i )</th>
</tr>
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<tr>
<td>State A</td>
<td>State B</td>
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Fig. A.2 The Free Energy of Species \( i \) at Different States

Usually, it is the difference in the free energy between two states that is of interest. A datum is selected in order to evaluate the relative magnitudes of free energy at different states. If state A is chosen as the datum, its free energy, \( f_A \), is then set to zero. The datum usually has the following characteristics:

1.) A at the same temperature as B,
2.) the free energy at A due to gravitational position is set as zero,
3.) any pressure exerted on datum A, is arbitrarily taken as the zero pressure in calculating the free energy of B, and
4.) A is free of all extraneous fields, such as adsorption fields surrounding soil particles, with the exception of gravitation.

In general, a flat pure water body used as the datum whose free energy is taken as zero.

Considering a solution in which water acts as a solvent, the following variables are defined:

\[
A = \text{free water at the same temperature as the solution}, \\
V_A = \text{vapor phase over } A, \text{ with a vapor pressure, } p_o, \\
B = \text{water in the solution, and} \\
V_B = \text{vapor phase over } B, \text{ with a vapor pressure, } p. 
\]
Suppose the solution is in equilibrium with a pure water through a semi-permeable membrane which only allows the passage of solvent water. A hydrostatic pressure is applied to the solvent water in order to prevent the pure water from flowing through the membrane into the solution. At equilibrium, the free energy of the solvent is equal to that of pure water on the other side of the membrane, which is designated as zero. Therefore, the increase of the free energy of the solvent in the solution is calculated by Eq. (A.7). The original free energy of the solvent is equal to the negative of Eq. (A.7).

Alternatively the free energy of the solvent \( f_s \) can be calculated from the free energy of its vapor phase \( f_{v_s} \), which contains no adsorptive forces,

\[
f_s = f_{v_s} = \int \frac{v}{v_a} dp
\]  

(A.9)

Assuming an ideal gas behavior for the vapor phase,

\[
pv = RT
\]  

(A.10)

where:

\[
R = \text{molar gas constant for water} = 461.496 \text{ J/kg.K}
\]

Then,

\[
f_s = f_{v_s} = \int \frac{RT}{p} dp = RT \ln \frac{P}{P_o} < 0 = f_A
\]  

(A.11)

The free energy concept is also useful in determining the relative movement of the species between different states. Generally, there is the following relationship for a spontaneous change from state A to state B:

\[
\Delta f < 0, \text{ or } f_A > f_B > 0
\]  

(A.12)
Equation (A.12) implies that a species can spontaneously move from a state of high free energy to a state of low free energy. Since water spontaneously flows from a flat water body into an unsaturated soil, the free energy of water in the unsaturated soil must be lower than that of free pure water.

### A.4.2 Factors Affecting the Free Energy of Water in a Solution

The main factors that influence the free energy of water in a system include the temperature, the hydrostatic pressure, the solute concentration, the surface tension, and the adsorptive forces. Most of the equilibrium processes in geotechnical engineering practices are considered as isothermal processes. Only the effects of hydrostatic pressure, the solute concentration, and the surface tension are of primary concern for a solvent solution; while the effects of the adsorptive forces must be considered for a soil-water system (Edlefsen and Anderson, 1943).

#### A.4.2.1 Effects of Hydrostatic Pressure on Free Energy and Vapor Pressure

When a solution is subjected to hydrostatic pressure \( \Delta P \), the free energy of the solvent will increase according Eq. (A.7). The influence of a change in hydrostatic pressure, \( \Delta P \), on vapor pressure can be calculated from the equilibrium condition of the liquid phase and the vapor phase:

\[
\Delta f_L = \nu \Delta P = \Delta f_v = RT \ln \left( 1 + \frac{\Delta p}{P} \right)
\]  \hspace{1cm} \text{(A.13)}

where:

\( \Delta f_L = \text{free energy change in liquid water, and} \)

\( \Delta f_v = \text{free energy change in vapor phase.} \)

Therefore,

\[
\Delta P = \frac{RT}{\nu} \ln \left( 1 + \frac{\Delta p}{P} \right)
\]  \hspace{1cm} \text{(A.14)}
At a temperature of 20°C (i.e., 293°K),

\[
\Delta P = \frac{461.496 J/ \text{kg} \cdot K \cdot 293 K}{1/l \text{m}^3/ \text{kg}} \ln(1 + \frac{\Delta p}{p})
\]

\[
\Delta P = 134,948,022 \ln\left(1 + \frac{\Delta p}{p}\right) (J/ \text{m}^3)
\]

\[
\Delta P = 134,948,022 \ln\left(1 + \frac{\Delta p}{p}\right) (kPa)
\]  

(A.15)

Figure A.3 plots the relationship of \( \Delta P \) versus \( \Delta p/p \) when \( \Delta P \) ranges from -10,000 kPa to 10,000 kPa at 20°C.

![Graph showing the relationship between change in hydrostatic pressure and vapor pressure](image)

**Fig. A.3 Influence of Hydrostatic Pressure on Vapor Pressure**

The vapor pressure changes linearly with changes in hydrostatic pressure within hydrostatic pressures of -10,000 kPa to +10,000 kPa. However, the absolute magnitude of change in vapor pressure is small when compared to the magnitude of the hydrostatic pressure.
pressure change. For example, when hydrostatic pressure changes from 0 kPa to -2,000 kPa at 20°C, the vapor pressure decreases by only 1.5%, or 0.0345 kPa (i.e., the vapor pressure of pure water under atmospheric pressure at 20°C is about 2.3 kPa). In other words, even for an infinitely small change in vapor pressure, there will be a substantial change in the pressure in liquid water. Consequently, any suction measurements based on vapor pressure measurement could suffer from inaccuracy problem.

A.4.2.2 Effects of Solute Concentration on Free Energy and Vapor Pressure

The equations relating the free energy, $\Delta f$, the osmotic pressure, $\Delta P_o$, and the vapor pressure of a solution, $p$, to the molar fraction of the solute, $c$, are respectively given as follows (Edlefsen and Anderson, 1943):

$$\Delta f = -RTc$$  \hspace{1cm} (A.16)

$$\Delta P_o = \frac{RT}{v}c$$  \hspace{1cm} (A.17)

$$p = p_o e^{-c}$$  \hspace{1cm} (A.18)

A.4.2.3 Effect of Surface Tension on Free Energy

Assuming a curved air-water interface has a radius of curvature of $r$, the vapor pressure over the free water is $p_o$, and the surface tension is, $T_s$, the following equation can be obtained:

$$\ln \frac{p}{p_o} = \frac{v}{RT} \left[ \frac{2T_s}{r} + \left(p_o - p\right) \right] = \frac{v}{RT} \frac{2T_s}{r}$$  \hspace{1cm} (A.19)

For a concave surface, the radius, $r$, is negative.

Combining Eqs.(A.11) and (A.19), the free energy near the curvature is:

$$\Delta f = \nu \frac{2T_s}{r}$$  \hspace{1cm} (A.20)
Alternatively, the liquid phase under the curvature is subjected to a hydrostatic pressure, \( \Delta P \), and,

\[
\Delta f = v \Delta P
\]  \hspace{1cm} (A.21)

Combining Eqs. (A.20) and (A.21) gives,

\[
\Delta P = \frac{2T_i}{r}
\]  \hspace{1cm} (A.22)

Equation (A.22) implies that, if the equilibrium of a liquid with its vapor can only exist under a concave surface under atmospheric conditions, the hydrostatic pressure in the liquid near the curvature, \( P \), is equal to \( 2T_i / r \), which has a negative value.

### A.4.3 Application of Thermodynamics to Unsaturated Soils

There is a fundamental difference between a soil-water system and a simple solution in which water acts as a solvent. In a soil-water system, the complex physio-chemical interaction between the water phase and soil particles could contribute significantly to the free energy of soil water. Such contribution is represented by the absorptive force work, \( d\omega_a \).

#### A.4.3.1 Free Energy of Water in Relatively Moist Silty and Sandy Soils

For certain soil-water systems, such as relatively moist silty or sandy soils, a significant portion of water phase may lie beyond the influence of the relatively weak adsorptive forces field. Therefore, the free energy due to the adsorptive forces field may be negligible as compared to other energy mechanisms, such as the capillary forces. Since the absolute water pressure at datum is equal to the ambient air pressure, \( u_a \), the free energy of soil water is calculated as:

\[
\Delta f = \int_A^B v dP = v \Delta P = v(u_w - u_a)
\]  \hspace{1cm} (A.23)
where:

\[ u_w = \text{pore-water pressure.} \]

For an unsaturated soil, the pore-water pressure, \( u_w \), is lower the pore-air pressure, \( u_a \), and \( \Delta f \) is negative (i.e., the free energy of soil water is less than that at the datum). If the free energy at datum is taken as zero, the free energy of water in the soil is negative.

Alternatively, the free energy of soil water can always be calculated in terms of the free energy of vapor phase as:

\[
\Delta f = \int_A^B \nu dp = \int_A^B \frac{RT}{p} dp = RT \ln \frac{P}{P_o}
\]

(A.24)

On the other hand, when the free energy of soil water is only due to the surface energy of a concave air-water interface, the free energy is expressed by Eq. (A.19). Combining Eqs. (A.19), (A.23), and (A.24) gives the Kelvin's equation for the capillary model:

\[
u_a - u_w = -\frac{2T_s}{r} + p - p_o = -\frac{2T_s}{r}
\]

(A.25)

where \( r \) is negative.

The above equations imply that the capillary model applies only to certain types of inert soil-water systems where the effects of physio-chemical interaction between water and soil particles on water potential are negligible.

### A.4.3.2 Free Energy of Water in Plastic Clays and Dry Soils

Equation (A.19) assumes that the soil particles do not attract the water molecules lying in the air-water interface. This assumption, however, is not justified for soils at low water contents, or for plastic clays. At low water contents, the adsorptive forces must affect the vapor pressures and cause a deviation from Eq. (A.19). Edlefsen and Anderson (1943) measured vapor pressure in small capillaries and found the measured values were much smaller than those predicted by Eq. (A.18) plus Eq. (A.19). The adsorptive forces play an important role in soil water at least at water contents lower than the permanent wilting
percentage. More recently, Mohamed et al. (1992) found that the soil-water potential at a particular temperature is considerably higher for clayey soils than predicted from the change in the surface tension of water. The effect is more prominent in bentonite and at low water contents for plastic clays. The results indicated that there must be some significant energy mechanisms other than the surface tension.

The free energy change when isothermally moving water from a free pure water to a soil, could be expressed as:

\[ \Delta f = \int_A v dP - \int_A d\omega_m = v(u_u - u_w) - \Delta \omega_m \] (A.26)

where \( \Delta \omega_m \) is not equal to zero. Meanwhile the hydrostatic pressure, \( u_w \), in the soil should include the following components (Edlefsen and Anderson, 1943):

1.) capillary tension,
2.) hydrostatic pressure due to the presence of the adsorptive field, in a similar way to the hydrostatic pressure in a water reservoir due to gravitation, and
3.) osmotic pressure due to the concentration of solute.

A.5 COMPARISONS OF SOIL SUCTION MODELS

The mechanical models tacitly assume that water is held in soils as a result of capillary forces. On this basis, it is possible to derive equations which relate the energy of soil water retention to the radius of curvature of the soil water, or to the pressure within the soil water. It follows from this assumption that if the energy of soil-water retention is measured by some means, the radius of curvature and the hydrostatic pressure can be computed in conformity with the laws of mechanics, such as the Kelvin's equation.

It has been recognized, however, by some soil scientists (Richards, 1928; Edlefsen and Anderson, 1943; Babcock and Overstreet, 1955) that there are limitations in the conclusions based on the laws of mechanics, and that thermodynamics offers the opportunity to include effects other than capillary forces.
The advantages of the thermodynamic approach over the mechanical approach can be summarized as follows:

1.) Thermodynamics principles offer a powerful tool for testing hypotheses related to the "microscopic" state of a system. Some hypotheses deal with variables that are not subjected to direct observation. These hypotheses can be tested only by their usefulness in predicting certain macroscopic properties of the system that can be calculated by means of thermodynamics from experimental measurements. Typical examples include testing the hypotheses of water abnormality around soil particles by measuring the structure-sensitive, heat-related properties of soil water, such as the heat of immersion, the entropy, and the freezing-point depression. There is abundant evidence from these measurements that the properties and structure of the water phase around a soil particle are different from those of normal water, and the degree of difference increases as the water content decreases (Anderson, 1924; Bouyoucos, 1925; Hoseh, 1937; Puri and Hoon, 1939; and Robins, 1952). Such evidence indicates that the capillary potential alone cannot account for the abnormal behavior of water around soil particles. Robins (1952) concluded from entropy measurements that the dominant forces in soil-water retention in unsaturated soils for water contents up to the permanent wilting point, are the absorptive forces and, to a lesser extent, the salts present in the soil solution. The surface tension forces apparently remain of secondary importance.

2.) No matter how complicated the soil-water interaction may be, the thermodynamic approach offers a good context for obtaining information about the soil water by measuring its vapor pressure. The vapor pressure, being a property representing the free energy at the surface of water films, is fundamentally related to other properties such as the osmotic pressure, the freezing-point, the surface tension, the capillary potential, the soil structure, and the intensity of adsorptive forces field around soil particles.

In fact, soil suction components were also defined from a thermodynamic perspective by the "Review Panel" (Aitchison, 1965).
3.) Theoretically, the soil-water potential based on the mechanical model may not be directly measured by a mechanical device, particularly for plastic and dry soils. Babcock and Overstreet (1955) pointed out that the capillary pressure cannot be directly obtained by means of the tensiometer. It can only be concluded that the soil water and the pure water in the tensiometer have the same chemical potential (i.e., free energy) at equilibrium and use this fact to calculate the potential of the soil water.

A.6 INTERPRETATION OF SOIL SUCTION MEASUREMENTS

This section seeks an interpretation of soil suction measurements based on thermodynamic principles. Confusions related to the use of soil suction concepts are discussed. The principle of axis-translation technique which is commonly used for soil suction measurements is also examined.

A.6.1 Confusions Related to the Suction Concept

The term “soil suction” in soil science generally refers to the measured “pressure deficiency” in soil water; while it usually refers to the difference between the pore-air and pore-water pressures in geotechnical engineering. While the soil scientists have repeatedly warned not to confuse soil suction with pore-water pressure, the geotechnical engineers have continuously used the pore-water pressure as an equivalent of the soil suction. Geotechnical engineers tend to overlook the fact that water coming into the measuring system is no longer the same water as in the soil-water system. Consequently, the role of pore-water pressure in a soil might be over-emphasized because the soil-water system is an extremely complicated system. To soil scientists, the pore-water pressure is only one of the components which contributes to the behavior of the soil-water system.

The reason that “soil mechanics”, which is based on the concept of pore-water pressure, can be used is because all the experimental evidence about “pore-water” is obtained from actual measurements, rather than from the “true pore-water pressure”. The confusion, therefore, can be overcome by keeping in mind that the so called “pore-water pressure”, as used in theories and experiments in geotechnical engineering, is a measured property. The
consistent correctness of the established pore-water concept in soil mechanics implies that the measured property is a good indicator of the overall energy state of the soil water which controls the behavior of the soil.

The use of the term "pore-water pressure" in unsaturated soil mechanics has been unarguably inherited from Terzaghi's saturated soil mechanics. While the measured water pressure for moist soil is largely due to the true pore-water pressure, the measured water pressure for dry and highly plastic soils may be far different from the true pore-water pressure. Other energy mechanisms may play the dominant role. It may, therefore, be inappropriate to say that the negative pore-water pressure in a dry or highly plastic soil can be millions of atmospheres. However, it is reasonable to say that the energy of the soil water could be equivalently that high.

Another misleading concept is the confusion that soil suction is represented by the free energy in the equation:

\[ u_a - u_w = \frac{RT}{v} \ln \frac{P}{P_o} \]  \hspace{1cm} (A.27)

The contradiction occurs when an elevated air pressure is applied to an unsaturated soil-water system. Soil suction, which is measured by a water-containing system, is considered to remain constant. On the other hand, the free energy of soil water is increased due to the elevated air pressure. Thus, Eq. (A.27) is not always correct. The confusion arises because the fact is ignored that the soil water and the water in the measuring system are no longer under the same ambient reference pressure. This phenomenon will be discussed later.

A similar difficulty is encountered in the interpretation of the term, \( u_a \), in Eq. (A.25) which is often used to estimate the maximum tension that a rigid hole filled with water can sustain. The water tension, \( u_w \), is often considered to be the same as the suction term, \( (u_a - u_w) \), because \( u_a \) is usually the atmospheric pressure for soils. However, a casual identification of the tension with suction can lead to some misunderstandings even though there is no elevated air pressure involved. For example, it may be tempting to say that a body of water sealed in a chamber of 0.1 mm diameter can sustain a negative pressure of almost...
zero according to Eq. (A.25). This, of course, is wrong, since water in a tensiometer with a 2 cm-diameter tube can sustain a negative pressure of at least -90 kPa. The misunderstanding arises because the term, \( u_a \), which should be the ambient pressure in the tensiometer, is confused with the air pressure in the soil. In fact, the ambient pressure in the tensiometer is almost the same as the water pressure, thus both sides of Eq. (A.25) vanish for the tensiometer. The equality of the term, \( u_a \), with the term, \( u_w \), for a sealed water chamber is readily evident for some types of tensiometers, in which an air cavity is deliberately enclosed above the water in the measuring tube.

\textbf{A.6.2 The Essence of a Suction Measurement}

Let us consider the case of a tensiometer. If the water in the tensiometer and the soil water are both referenced to the same air pressure, \( u_a \), the free energy of water in the tensiometer is calculated as:

\[ \Delta f = \nu (u_a - \overline{u_w}) \]  
(A.28)

where:

\[ \overline{u_w} = \text{the measured water pressure.} \]

The free energy of the water in the tensiometer should be in equilibrium with that of the soil water:

\[ \nu (u_a - \overline{u_w}) = \nu (u_a - u_w) - \Delta \nu_m \]  
(A.29)

Even if the osmotic effect is ignored, the measured pressure, \( \overline{u_w} \), by the tensiometer, can never be equal to the true pore-water pressure, \( u_w \), in the soil. The measured pressure, \( \overline{u_w} \), should also include the effect of adsorptive forces, particularly for clays where the adsorptive field may have a relatively large influencing space. Nevertheless, \( \overline{u_w} \), is a measure of the overall energy statue of soil water. It is therefore more suitable to define the term suction as the difference between the reference air pressure and the \textbf{measured} water pressure (i.e., the \textbf{measured} pressure deficiency). If the osmotic pressure is not included in the measurement,
what is measured is representative of the interaction between water and soil matrix; namely, matric suction.

In the above example, the water in the measuring system and the soil water are referenced to the same air pressure (i.e., atmospheric pressure). The suction could simply be defined as the measured negative water pressure and is numerically equal to the free energy of the soil water.

### A.6.3 Free Energy and Hydrostatic Pressure in the Axis-Translation Technique

In soil suction measurements, an air pressure greater than the atmospheric pressure is often applied to the soil to increase the water pressure above -100 kPa so that cavitation will not occur in the measuring system (Hilf, 1956). This procedure is commonly called the axis-translation technique. It is interesting to know how the free energy and hydrostatic pressure should change in response to the elevated ambient pressure.

Suppose, at state 1, the soil water, under an air pressure, $u_{a1}$, has a hydrostatic pressure, $u_{w1}$, a vapor pressure, $p_1$, and a free energy, $f_1$ (Fig. A.4). On the other hand, the datum, a flat, pure water body under the same air pressure, has a hydrostatic pressure equal to $u_{a1}$, and a vapor pressure, $p_{o1}$. If the effect of the adsorptive field is ignored, the free energy of the soil water, as referenced to the datum, is:

$$
\Delta f_1 = RT \ln \frac{p_1}{p_o} = \nu (u_{w1} - u_{a1})
$$

At state 2, the air pressure is elevated to $u_{a2}$. All the above variables associated with the soil water are changed to variables denoted with a subscript '2'. The free energy of the soil water, as referenced to its corresponding datum under $u_{a2}$, is:

$$
\Delta f_2 = RT \ln \frac{p_2}{p_{o2}} = \nu (u_{w2} - u_{a2})
$$
Fig. A.4 Free Energies of Soil Water and Datum at Different Ambient Air Pressures

The change of free energy from datum 1 to datum 2 is:

$$\Delta f_o = \int_1^2 df = \int_1^2 (vdP - dw_s) = \int_1^2 vdP$$  \hspace{1cm} (A.32)

For the liquid phase,

$$\Delta f_o = v(u_{w2} - u_{w1})$$  \hspace{1cm} (A.33)

For the vapor phase,

$$\Delta f_o = RT \ln \frac{P_{v2}}{P_{v1}}$$  \hspace{1cm} (A.34)

The free energy change of the soil water in going from state 1 to state 2 is:
\[ \Delta f_{1-2} = f_2 - f_1 = -\Delta f_i + \Delta f_o + \Delta f_2 \]  

(A.35)

Considering liquid phase,

\[ \Delta f_{1-2} = \nu(u_{a1} - u_{w1}) + \nu(u_{a2} - u_{a1}) + \nu(u_{w2} - u_{a2}) = \nu(u_{w2} - u_{w1}) \]  

(A.36)

Considering vapor phase, from Eqs. (A.34) and (A.35),

\[ \Delta f_{i-2} = RT \ln \frac{P_{o1}}{P_i} + RT \ln \frac{P_{o2}}{P_i} + RT \ln \frac{P_2}{P_i} \]

\[ \Delta f_{i-2} = RT \ln \frac{P_{o1}}{P_i} \]

(A.37)

It has been shown in Section A.4.2.1 that increasing the ambient air pressure will result in an increase in vapor pressure. Although the magnitude of the increase is small, it is great enough to make a significant increase in the free energy. The hydrostatic pressure of in soil water also increases significantly.

**A.6.4 Theoretical Conditions for the Axis-Translation Technique**

This section derives the equation for the axis-translation technique from the thermodynamic context. Combining Eqs. (A.36) and (A.37) gives,

\[ \nu \Delta u_{w1-2} = RT \ln \frac{P_2}{P_i} \]  

(A.38)

and combining Eqs. (A.33) and (A.34) yields,

\[ \nu \Delta u_{a1-2} = RT \ln \frac{P_{o2}}{P_{o1}} \]  

(A.39)
Subtracting Eq. (A.38) from Eq. (A.39) gives,

\[ \nu(\Delta u_{a,1-2} - \Delta u_{w,1-2}) = RT \left[ \ln \frac{p_{o1}}{p_{o2}} \frac{p_1}{p_2} \right] = RT \left[ \ln \frac{p_{o2}}{p_{o1}} + \ln \frac{p_1}{p_2} \right] \]

\[ \nu(\Delta u_{a,1-2} - \Delta u_{w,1-2}) = \Delta f_1 - \Delta f_2 \]  \hspace{1cm} (A.40)

If the effect of adsorptive forces is ignored, then the free energy of soil water is only due to capillary tension and osmotic pressure. The free energy change when moving water from free pure water to soil water is expressed as the summation of Eqs. (A.16) and (A.20),

\[ \Delta f = \nu \frac{2T_s}{r} + RTc \]  \hspace{1cm} (A.41)

The surface tension, \( T_s \), is primarily dependent on temperature. If the radius, \( r \), and the solute concentration, \( c \), remain constant when changing the air pressure, \( \Delta f \) will be independent of the ambient air pressure. It then follows that,

\[ \Delta f_1 = \Delta f_2 \]  \hspace{1cm} (A.42)

and therefore,

\[ \Delta u_{a,1-2} - \Delta u_{w,1-2} = 0 \]  \hspace{1cm} (A.43)

This is the equation for the axis-translation as stated by Hilf (1956). Equation (A.43) indicates that an increase in air pressure will result in an equal amount of increase of hydrostatic or pore-water pressure.

To maintain a constant radius, \( r \) and, a constant concentration, \( c \), the volumetric water content of the soil has to be maintained constant. To do so, there should not be any occluded air bubbles present, and water and soil particles must be incompressible. Since water and soil particles are generally considered incompressible, there are only two cases where the volumetric water content can be maintained constant. One is when the soil is fully saturated; the other is when the air phase is interconnected so that no occluded air bubbles exist.
Equation (A.43) applies for soils where the adsorptive forces around the soil particles are ignored. If the adsorptive forces are not ignored, the following equations similar to Eqs. (A.38) and (A.39) can be obtained,

\[ \Delta f_{l-2} = \nu \Delta u_{w, l-2} - (\Delta w_{m_2} - \Delta w_{m_1}) = RT \ln \frac{P_1}{P_2} \]  
(A.44)

\[ \nu \Delta u_{a, l-2} = RT \ln \frac{P_{o2}}{P_{o1}} \]  
(A.45)

Subtracting Eq. (A.44) from Eq. (A.45) yields,

\[ \nu (\Delta u_{a, l-2} - \Delta u_{w, l-2}) + (\Delta w_{m_2} - \Delta w_{m_1}) = \Delta f_1 - \Delta f_2 \]  
(A.46)

Assuming that the dimensions of water film around soil particles and the particle surfaces are not changed for the elevated air pressure, and thus that the effects of adsorptive field on the free energy of water film are quantitatively the same for State 1 and State 2, it then follows that,

\[ \Delta f_1 = \Delta f_2 \]  
(A.47)

and,

\[ \Delta w_{m, l-2} = \Delta w_{m_2} - \Delta w_{m_1} = 0 \]  
(A.48)

thus,

\[ \Delta u_{a, l-2} - \Delta u_{w, l-2} = 0 \]  
(A.49)

Since the water film and the soil particles are almost incompressible, Eq. (A.49) will be valid for a soil with a constant volumetric water content and an interconnected air phase. Therefore, it may be concluded that the difference between the pore-air pressure, \( u_a \), and the pore-water pressure, \( u_w \), is independent of the change in the ambient air pressure, as long as the air phase in the soil is interconnected and no air bubbles are present.

On the other hand, it is conceptually wrong to define matric suction as an apparent function of the pore-water pressure. The matric suction that has been used in geotechnical
engineering is in fact the difference between the pore-air pressure and the measured water pressure. If a change in ambient air pressure, $u_a$, has no effect on the adsorptive forces acting on water phases around soil particles, the effect of adsorptive forces as embraced in the measured $\bar{u}_w$ in Eq. (A.29) will be also independent of ambient air pressure. Similar to Eq. (A.49), the following axis-translation should be valid if the air phase is interconnected,

$$\Delta u_a - \Delta \bar{u}_w = 0 \quad (A.50)$$

In other words, matric suction remains constant in the axis-translation technique.

For a soil that contains occluded air bubbles, an increase in air pressure produces decreases in the volume of fluids and the soil. The contribution to free energy by the capillary forces and absorptive forces will increase. Use of the axis-translation for measuring matric suction will result in an over-estimation of matric suction. Nevertheless, since the volume change in soil water due to the occluded air bubbles is relatively slow, the axis-translation should be rigorously correct for soils with occluded air bubbles for at least a short period of time after the air pressure is changed.

A.7 CONCLUSIONS

1.) The thermodynamic principles offer a more comprehensive understanding of the concept of soil suction than do the mechanical models.
2.) The definition of matric suction as the difference between the pore-air, $u_a$, and pore-water pressures, $u_w$, is conceptually incorrect. It is more suitable to define matric suction as the difference between the pore-air pressure, $u_a$, and the measured water pressure, $\bar{u}_w$, or the measured pressure deficiency.
3.) The free energy and the hydrostatic pressure of a soil-water system are increased when the ambient air pressure is increased. If the degree of saturation of a soil is such that the air-phase is interconnected and no air bubbles are present, the difference between the pore-air pressure, $u_a$, and the pore-water pressure, $u_w$, and the difference between the pore-air pressure, $u_a$, and the measured water pressure, $\bar{u}_w$, are then independent of the ambient air pressure.

Matric suction remains constant during the application of the axis-translation technique.
4.) Use of the axis-translation technique for measuring matric suction of a soil with occluded air bubbles can lead to an over-estimation of matric suction.
APPENDIX B

Behavior Of A Saturated Clay Under Suction
B.1 INTRODUCTION

As has been pointed out in Chapter 3, water in a saturated clay-water system has the ability to transfer tensions greater than 100 kPa while still keeping the soil saturated. This ability is measured by the air-entry value of the soil. Meanwhile, the mechanical state of a saturated clay-water system can be changed under the action of an external suction. It was anticipated that the above characteristics could be used for the measurement of matric suction.

The principles regarding the use of a saturated compressible clay for measuring soil suction are briefly described. The behavior of a saturated clay under a suction is theoretically analyzed. An experimental study was then conducted to see if the behavior of the clay proved reasonable agreement with the theoretical predictions. Finally, the feasibility of using a saturated clay-water system for the measurement of matric suction is evaluated.

B.2 PRINCIPLES OF SOIL SUCTION MEASUREMENTS USING A SATURATED COMPRESSIBLE CLAY

The proposed development of an apparatus for measuring matric suction involves pre-consolidation of a saturated compressible clay (hereafter referred to as the "sensing soil") to a pre-determined pressure in an oedometer-type ring. The preloaded sensing soil is then put into contact with a soil (hereafter referred to as the "target soil") through a saturated high air-entry ceramic disk. The matric suction in the sensing soil is to equalize with the matric suction in the target soil. The change in matric suction in the sensing soil tends to produce a volume change. However, in an attempt to maintain the soil volume constant due to the confinement of the preloading device, the pre-determined pressure against the preloading device will be reduced by an amount similar to matric suction in the target soil.

The purpose of setting a preloading pressure is to realize a monotonic behavior of volume change of the soil when it is subjected to an external suction. The confinement also acts to reduce the response time to a minimum. This concept is drawn from swelling pressure tests. For example, a relatively rapid equalization process is realized in a constant volume test or in a restrained swell test, as compared to that in a free swell test. The response time of the proposed suction apparatus will be analyzed later.
If the reduction in the preloading pressure induced by the external suction can be consistently calibrated, an apparatus using the above principle can be developed to measure matric suction in a soil.

In its simplest form, the apparatus to be developed should consist of a sensing soil, a ceramic disk, and a rigid pressure-measuring unit (Fig. B.1). The sensing soil must be preloaded into a confining shroud. A rigid metal cap which contains a pressure sensing element is in direct contact with the sensing soil. The cap acts as both a preloading device and a vertical confining device which detects changes in vertical pressure in response to the application of a suction to the sensing soil.

The choice of the sensing soil is important to this method. The sensing soil should meet the following requirements:

Fig. B.1 Illustration of the Concept of the Suction Apparatus

1.) it should have the ability to remain saturation under a high tension (e.g., -500 kPa),
2.) the compressibility of the sensing soil should be as high as possible, and
3.) the drainage path (i.e., the thickness of the sensing soil) should be made as small as possible, and the permeability of sensing soil should be as high as possible.

The sensing soil is placed behind a saturated 5 bar ceramic. The ability of the system to sustain a high tension without desaturation is represented by the resistance of the soil water against the formation of gas bubbles. A clay-water system with a high air-entry value is generally considered to possess the ability to remain saturation under a high tension. Therefore, it is desirable to use a clay with a high air-entry value as the sensing soil.

Figure B.2 shows typical curves from an unconfined shrinkage test. The straight line, AB, parallel to the 100% saturation line represents a desorption process for the soil under nearly saturated conditions. A deviation away from the 100% saturation line is attributed to the presence of some entrapped air in the soil. The length of the curve, AB, indicates the maximum amount of volume change which can occur before desaturation can be produced by changing matric suction. The longer the curve, AB, the greater the volume change prior to desaturation. Some plastic clays, such as Regina clay can experience up to 20% volume change due to an increase or a decrease in matric suction up to 1000 kPa (Fredlund, 1964).

**Void Ratio**

![Void Ratio Diagram](Image)

**Water Content**

Fig. B.2 Typical Shape of a Shrinkage Test Curve
B.3 THE THEORETICAL BEHAVIOR OF A PRELOADED CLAY UNDER THE ACTION OF AN EXTERNAL SUCTION

The theoretical behavior of a preloaded clay under the action of an external suction is analyzed in this section.

B.3.1 Sensitivity and Response Time of the Sensing Soil

The inherent response time of the sensing soil under an external suction is primarily dependent upon two factors; namely, the consolidation rate of the sensing soil under suction, and the coefficient of permeability of the ceramic disk. The effect of the consolidation rate of the sensing soil is discussed in this section. The effect of the coefficient of permeability of the disk is discussed later.

Suppose the sensing soil is formed from consolidating a slurried soil to a pressure $p_0$. If the bottom of the preloaded soil is subjected to a suction, $S_0$, the suction will be transmitted and superimposed onto the soil structure. To maintain a constant volume the vertical pressure will be reduced. Fig. B.3 illustrates the development of profiles of pore-water pressure, total stress, effective stress, and volume change, under the assumption that the pressure measuring system (i.e., the preloading device) has an indefinitely large stiffness relative to the sensing soil. The total volume change for the soil is zero.

Terzaghi's one-dimensional consolidation theory can be applied to the consolidation process of the sensing soil under suction. The one-dimensional consolidation equation for the sensing soil is:

$$\frac{\partial \sigma^\prime}{\partial t} = c_r \frac{\partial^2 u}{\partial z^2}$$ \hspace{1cm} (B.1)

where:

$$c_r = \frac{k_r}{\rho_w g m_v}$$

- is coefficient of consolidation,
- $k_r$ = saturated permeability of the sensing soil,
- $\rho_w$ = water density,
- $m_v$ = compressibility of the sensing soil $= \frac{\Delta V}{V \cdot \Delta \sigma^\prime}$,
Fig. B.3 Profiles of Stresses and Volume under a Suction Equal to $S_0$ for an Very Stiff Preloading Device

\[ u = \text{excess pore-water pressure induced by the suction, and} \]
\[ \sigma' = \text{the effective stress induced by the suction.} \]

Substituting $\sigma' = \sigma - u$ into Eq. (B.1) yields,

\[ c_r \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \frac{\partial \sigma'}{\partial t} \quad \text{(B.2)} \]

where:

\[ \sigma = \text{change in total vertical stress induced by the suction.} \]

The deformation of the sensing soil must be compliant with that of the preloading system. If $\alpha$ denotes the volume change coefficient of the preloading system, the compliance is satisfied by the following relation:

\[ H \int_0^H \varepsilon dz = - \alpha A \sigma \quad \text{(B.3)} \]

where:
\( \varepsilon = \text{strain at depth, } z. \)

H = thickness of the sensing soil, and

A = cross-sectional area of the sensing soil.

Substituting \( \varepsilon = m_\sigma \sigma' = m_\sigma (\sigma - u) \) into Eq. (B.3) gives,

\[
\sigma = \frac{m_\sigma}{m_\sigma H + \alpha A} \int_0^H udz = \frac{\bar{\delta}}{H} \int_0^H udz = \bar{\delta} \bar{u}
\]  

(B.4)

where:

\( \bar{\delta} = \text{stiffness factor} = \frac{m_\sigma H}{m_\sigma H + \alpha A} \), and

\( \bar{\delta} \bar{u} = \text{mean value of induced pore-water pressure.} \)

\( \alpha \) equal to zero represents a no swelling condition. \( \alpha \) equal to infinity describes a free swelling condition. Appendix B1 provides a finite difference solution for the case when the external suction directly acts on the bottom of the sensing soil.

**B.3.2 Influence of the Impedance of the Ceramic Disk.**

A ceramic disk with a high air-entry value must be used as an interface between the sensing soil and the target soil. Fig. B.4 illustrates this suction transmission system.

There is no volume change for the incompressible ceramic, therefore,

\[
\frac{\partial^2 u_1}{\partial z^2} = 0
\]  

(B.5)

Integrating Eq. (B.5) gives,

\[
u_1 = c_1 z + c_2
\]  

(B.6)

Equations (B.2), (B.4) and (B.6) must be simultaneously solved, using the following continuity conditions at the interface between the ceramic and sensing soil,
At $z = H_c$, 

$$u = u_1 = u_b$$  \hspace{1cm} (B.7) 

and, 

$$k_s \frac{\partial u}{\partial z} = k_c \frac{\partial u_1}{\partial z}$$  \hspace{1cm} (B.8) 

where:

$u_b$ = pore-water pressure at the base of the sensing soil.

And at $z = 0$, 

$$u_1 = u_o$$  \hspace{1cm} (B.9) 

Combining Eqs. (B.6), (B.7), and (B.9) yields,

$$u_1 = u_o - \frac{u_b - u_o}{H_c} z$$  \hspace{1cm} (B.10) 

A numerical solution for the above model is given in Appendix B2.
B.4 THEORETICAL BEHAVIOR OF REGINA CLAY UNDER SUCTION

Regina Clay is a highly plastic clay with approximately 45.2% montmorillonite, 27.7% illite, and 17.7% kaolinite. About 75% of exchangeable cations are calcium (Barbour and Fredlund, 1989). It is a typical calcium montmorillonite.

The effects of osmotic forces on the volume change of Regina clay are neglected in the analyses due to the following reasons:

1.) the consolidation and swelling curves of a calcium montmorillonite are essentially independent of both the electrolyte concentration and the pH (Mesri and Olson, 1970).
2.) the magnitude of volume change due to osmotic consolidation is considered secondary and very slow as compared to that due to conventional effective stress consolidation (Barbour, 1989).

B.4.1 Response of Regina Clay Without the Impedance of the Ceramic

Table B.1 lists some properties of Regina Clay calculated from the data as compiled by Fredlund (1964). At a preconsolidation pressure of about 5 bar, $c_v$ is about 0.36 mm²/min. These data are used in the finite difference program. The thickness of Regina clay, H, is assumed to be 10 mm. A suction of 1 bar is assumed to act on the bottom of the sensing soil.

Table B.1 Consolidation Properties of Regina Clay (from Fredlund, 1964)

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Water content (%)</th>
<th>$c_v = \frac{G_s(w_1-w_2)}{\log(\sigma_1/\sigma_2)}$ (1/bar)</th>
<th>$a_s = \frac{G_s(w_1-w_2)}{(\sigma_1'-\sigma_2')}$ (1/bar)</th>
<th>$m_s = \frac{a_s}{1+wG_s}$ (1/bar)</th>
<th>$k_s = \frac{c_v a_s \rho G_s}{1+e_0}$ (cm/s)</th>
</tr>
</thead>
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<td>1</td>
<td>42</td>
<td>0.2201</td>
<td>0.0442</td>
<td>0.0209</td>
<td>1.25 x 10⁻⁷</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>0.5993</td>
<td>0.0398</td>
<td>0.0201</td>
<td>1.20 x 10⁻⁷</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figures B.5 and B.6 show, respectively, the calculated profiles of the induced pore-water pressure and strain, for a perfect vertical constraint which does not allow any volume change.
Fig. B.5 Profile of the Induced Pore-Water Pressure under 1 Bar of Suction for a Stiffness Factor of 1.0
Fig. B.6 Profile of the Vertical Strain under 1 Bar of Suction for a Stiffness Factor of 1.0
for the sensing soil. It takes an indefinitely short period of time to reach equilibrium. The reduction in preloading pressure at equilibrium is equal to the applied suction. The induced pore-water pressures along the profile could slightly exceed the value of applied suction in the early stages of equalization. This is because the zone near the bottom of the soil, where a suction is applied, tends to contract. In an attempt to maintain a constant volume, the vertical preloading pressure is immediately reduced. This creates an undrained unloading condition, which in turn immediately produces an additional suction in the sensing soil. There are two regions in the soil; one in tension and the other in compression. The lower zone in compression moves upward with time until equilibrium is reached. The volume change at all points returns to zero at equilibrium.

Figures B.7 and B.8 respectively show the calculated profiles of the induced pore-water pressure and strain for a stiffness factor of 0.9. All points in the soil are under compression. At equilibrium, the reduction in the vertical pressure is less than the applied suction.

**B.4.2 Influencing Factors**

The factors that affect the response of the sensing soil includes the stiffness factor, $\delta$, the impedance of the ceramic, and the thickness of the sensing soil.

Figure B.9 shows the effects of the stiffness factor, the impedance of ceramic, and the thickness of the sensing soil, on the time to reach 90% degree of equilibrium. For a given coefficient of permeability and compressibility for the sensing soil, a lower stiffness results in a longer equilibrium time. A stiff compression device is needed to decrease the response time of the sensing soil.

The influence of the ceramic is represented by an impedance factor $\lambda$ (Appendix B2). A small impedance factor indicates that a large number of time steps are needed to reach equilibrium. For $\delta$ equal to 0.9, the presence of the 5 bar ceramic increases the response time for 90% equilibrium from 3 minutes to about 45 minutes.

An increase in the thickness of sensing soil significantly increases the response time. For $\delta$ equal to 0.9, an increase in $H$ from 10 mm to 20 mm may increase the response time for 90% equilibrium from 45 minutes to more than 160 minutes.
Fig. B.7 Profile of the Induced Pore-Water Pressure under 1 Bar of Suction for a Stiffness Factor of 0.9
Fig. B.8 Profile of the Vertical Strain under 1 Bar of Suction for a Stiffness Factor of 0.9
Fig. B.9 Effects of Stiffness Factor, $\delta$, Ceramic Impedance, $\lambda$, and the Thickness of the Sensing Soil on the Time to Reach 90% Equilibrium
B.5 AN EXPERIMENTAL STUDY ON THE BEHAVIOR OF A SATURATED CLAY UNDER SUCTION

An experimental study was conducted to investigate the behavior of a confined saturated Regina clay under the action of an external suction. The results are compared with the theoretical predictions. This testing program investigated the following aspects:

1.) the effects of the stiffness factor, \( \delta \), and

2.) the effects of the coefficient of permeability and compressibility of the sensing soil, and the coefficient of permeability and thickness of the ceramic.

B.5.1 Testing Equipment and Materials

The test setup is shown in Fig. B.10. An existing Tempe Cell was modified to test the behavior of a preloaded clay under the action of suction. An unconfined compression device was used as the vertical loading unit. One 3 bar ceramic and one 5 bar ceramic were used to investigate the influence of the coefficient of permeability at the interface between the sensing soil and the suction source. A vacuum machine was used to supply a known suction between 0 and 56.6 kPa. A glass burette was erected to flush air bubbles in tubings and under the ceramic disk.

Air-dried Regina clay was first machine-grounded, and then passed through a #200 sieve. The sieved clay was made into a slurry with a water content of about 100%. A slurried specimen was then placed into a modified Tempe Cell on an unconfined compression device. The initial thickness of the specimen was about 12 mm.

A conventional consolidation test was performed. The slurried Regina clay was consolidated to a preconsolidation pressure of 80 kPa and then moved to an oedometer for a consolidation test. The rebound and recompression tests were performed to provide both the virgin compression and recompression curves. A falling-head permeability test was also performed to provide the relationship between the coefficient of permeability and the compression pressure.
Fig. B.10 The Setup for Testing the Behavior of a Preloaded Soil under Suction
B.5.2 Testing Procedure

An initial vertical pressure of about 50 kPa was applied to the sensing soil. Upon equilibrium, a vacuum of -56.6 kPa was exerted to the bottom of the specimen through a 3 bar ceramic disk. The reduction in the vertical pressure was recorded with time. After equilibrium was reached, the suction was released and the increase in the vertical pressure was recorded. Several cycles of such “suction-loading” and “suction-unloading” were subsequently performed in order to evaluate the effects of preconsolidation, or previous cycles, on the behavior of the sensing soil.

The path of stress versus volume change for the first cycle was different from that for the subsequent cycles. This is shown in Fig. B.11. The path of stress versus volume change in the first cycle should follow the virgin compression curve, OA (i.e., 1→2). After the release of suction, the path will move along the rebound curve (i.e., 2→3). Increasing suction in the second cycle will cause the path of stress versus volume change to move along the recompression portion (i.e., 3→4). The compressibility of the soil in the second cycle is considerably reduced as compared to that for the suction increase in the first cycle. Further applications and releases of suction should cause the path of stress versus volume change to move along the rebound and recompression curves. Because of the hysteresis of the soil-water system and the wall friction on the oedometer ring, the vertical pressure at the end of each cycle does not restore to the initial value at the beginning of that cycle. However, the effect of such hysteresis in the subsequent cycles should be much less significant than in the first cycle.

If a suction less than the suction applied in the first cycle is subsequently applied, the path of stress versus volume change should also fall on the rebound or recompression curve. If the soil is consolidated to a higher vertical pressure (e.g., point 8), further applications and releases of suction will cause the path of stress versus volume change to move in a way similar to those for the first preconsolidation pressure (i.e., 8→9, 9→10, 10→11, etc.).
Fig. B.11 The Path of Stress-Volume Change for Different Cycles of “Suction-Loading” and “Suction-Unloading” (the distances between 2 and 4, 4 and 6, and 9 and 11 are exaggerated)

Table B.2 gives the initial preconsolidation pressures, the applied suctions, and number of cycles of “suction loading” and “suction unloading” for each suction applied.

**Table B.2 Contents of the Tests on Regina Clay Under Suction**

<table>
<thead>
<tr>
<th>Preconsolidation Pressure (kPa)</th>
<th>Sequentially Applied Suction (kPa)</th>
<th>Number of Cycles of Suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>56.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>36.6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td>2</td>
</tr>
<tr>
<td>95</td>
<td>56.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>36.6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td>1</td>
</tr>
<tr>
<td>187</td>
<td>56.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>36.6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td>1</td>
</tr>
<tr>
<td>295</td>
<td>56.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>36.6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td>1</td>
</tr>
</tbody>
</table>
To evaluate the effect of the coefficient of permeability of the ceramic, the 3 bar ceramic was replaced with a 5 bar ceramic. The same series of tests as shown in Table B.2 were performed again on another specimen of Regina clay.

B.5.3 Results and Discussions

Figures B.12 and B.13 show the results of compression tests and permeability tests, respectively. The compressibility and coefficient of permeability that can be obtained from these curves were used in the theoretical calculation of the behavior of Regina clay under suction. The results are compared with the experimental results.

Figure B.14 shows the reduction in the vertical pressure with time after the application of a suction equal to 56.6 kPa. The initial preconsolidation pressure is 187 kPa. A total of 5 cycles of suction were performed. A greater reduction was observed during the increase of suction in the first cycle than in subsequently cycles. This is because the path of stress versus volume change for the increase of suction in the first cycle was on the virgin consolidation curve for which the compressibility was considerably higher. Releasing the applied suction caused the path to fall on the rebound curve with a lower compressibility. This resulted in a recovery in vertical pressure. The magnitude of recovery, however, is less than the reduction in vertical pressure during application of the suction. Further applications and releases of suction caused the path of stress versus volume change to move on the recompression and rebound portion, for which the compressibilities are close. Thus, a nearly elastic behavior was observed.

Although the value of the stiffness factor, $\delta$, for the suction-loading in the first cycle is greater than for those in the subsequent cycles, the time factor of consolidation, $c_r$, during the increase of suction in the first cycle is lower due to the high compressibility of the soil. This results in a much longer equalization time.

Figure B.15 shows the changes in the vertical pressure under different suctions at an initial preconsolidation pressure of 50 kPa. All three tests were on the recompression and rebound portion. The soil demonstrated a pronounced linear behavior. Similar behavior was also observed for higher initial preconsolidation pressures. However the sensitivity was
Fig. B.12 Void Ratio Versus Pressure for Regina Clay Consolidated from a Slurry
Fig. B.13 Coefficient of Permeability Versus Pressure for Regina Clay Consolidated from a Slurry
Fig. B.14 Changes in Vertical Pressure under Suction: 3 Bar Ceramic, Initial Consolidation Pressure Equal to 187 kPa, Applied Suction Equal to 56.6 kPa
Fig. B.15 Changes in Vertical Pressure under Applied Suctions After the 2nd Cycle of Loading: 3 Bar Ceramic, Initial Consolidation Pressure Equal to 50 kPa
reduced for higher initial preconsolidation levels as shown in Fig. B.16. This is probably because the recompression compressibility decreases with increasing consolidation pressures (Fig. B.12).

Changes in vertical pressure versus time under different stress conditions were calculated. Figures. B.17 and B.18 gives typical results calculated for the cases when the initial consolidation pressures were about 187 kPa and the ceramics used have an air-entry value of 3 bar and 5 bar, respectively. The applied suction was 56.6 kPa. The coefficient of permeability of both ceramics were obtained by laboratory measurements. Using a 5 bar ceramic prolonged the equilibrium time as compared to using a 3 bar ceramic. The effect is more pronounced for the increase of suction in the first cycle, and less pronounced for the subsequent cycles.

The measured changes in vertical pressure are slower than the predicted results. Figure B.19 compares the theoretical predictions for the changes in vertical pressure with the measured values. All measured values fall below the predictions. The friction between the soil and oedometer metal wall, and the creep of the soil are two possible reasons for the discrepancies.

**B.5.4 Conclusions**

1.) Use of a soil based on virgin compression can create a more sensitive suction apparatus, but will result in a slower response than when based on recompression.

2.) A quantitative evaluation of the effects of such factors as the wall friction, and the creep of the soil, are difficult.

3.) The use of a saturated compressible clay for the measurement of soil suction does not appear to be a feasible approach because of the considerable hysteresis in the mechanical behavior of the clay. However, it may be possible to develop a suction apparatus which is based on the change in the mechanical behavior of other water-absorbing materials, such as water-absorbing polymers (see Chapter 3).
Fig. B.17 Comparison of Calculated Changes in Vertical Pressure with Experimental Results: 3 Bar Ceramic, Initial Consolidation Pressure Equal to 187 kPa, Applied Suction Equal to 56.6 kPa
Fig. B.18 Comparison of Calculated Changes in Vertical Pressure with Experimental Results: 5 Bar Ceramic, Initial Consolidation Pressure Equal to 187 kPa, Applied Suction Equal to 56.6 kPa
Fig. B.19 Comparison of Calculated Changes in Vertical Pressure with Experimental Results:
Initial Consolidation Pressures Equal to 95 kPa, 187 kPa, and 295 kPa

Ratio of Vertical Pressure Change to Applied Suction

1st Cycle for 3 bar ceramic
3rd Cycle for 3 bar ceramic
1st Cycle for 5 bar ceramic
3rd Cycle for 5 bar ceramic
--- theory
Appendix B1: Response of the Sensing Soil

The induced pore-water pressure due to the applied suction at the bottom of the confined sensing soil can be described using Terzaghi’s theory of one-dimensional consolidation:

\[
\frac{c_v}{\Delta z^2} \frac{\partial^2 u}{\partial z^2} = \frac{\partial \sigma}{\partial t} - \frac{\partial u}{\partial t}
\]  

(B1.1)

The total vertical pressure, \(\sigma\), induced by the applied suction, is a function of time. A finite difference expression for Eq. (B1.1) is (see Fig. B1.1):

\[
u(i, t + \Delta t) = \sigma(t + \Delta t) - \sigma(t) + u(i, t) + \beta[u(i + 1, t) + u(i - 1, t) - 2u(i, t)]
\]  

(B1.2)

where:

\[
\beta = \frac{c_v}{\Delta z^2}
\]  

(B1.3)

The volume change of the sensing soil should be compliant with that of the vertical preloading device:
\[ \int_0^H \varepsilon \cdot dz = - \alpha \cdot A \cdot \sigma \]

that is,

\[ \int_0^H m_0 \sigma'^d z = \int_0^H m_0 (\sigma - u) dz = - \alpha \cdot A \cdot \sigma \]

or,

\[ m_0 \sigma H - \int_0^H udz = - \alpha \cdot A \cdot \sigma \quad \text{(B1.4)} \]

therefore,

\[ \sigma(t) = \frac{m_0 \int_0^H udz}{m_0 H + \alpha \cdot A} = \frac{\delta \int_0^H udz}{H} = \delta \cdot \bar{u} \quad \text{(B1.5)} \]

where:

\[ \delta = \frac{m_0 H}{m_0 H + \alpha \cdot A} \quad \text{stiffness factor,} \]

\[ \bar{u} = \text{average of induced pore-water pressures at time } t. \]

Let \( j \) denote time step number. Equation (B1.5) can be numerically expressed as:

\[ \sigma(j) = \frac{\delta}{N} \sum_{k=1}^N u(k, j) \quad \text{(B1.6)} \]

Equation (B1.2) can be written as:

\[ u(i, j) = \frac{\delta}{N} \sum_{k=1}^N u(k, j) - \sigma(j - 1) + u(i, j - 1) + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)] = \frac{\delta}{N} \sum_{k=1}^N u(k, j - 1) + \sigma(j - 1) + u(i, j - 1) + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)] = \frac{\delta}{N} \sum_{k=1}^N u(k, j - 1) + C(i, j - 1) \quad \text{(B1.7)} \]
where:
\[
C(i, j - 1) = \frac{\delta}{N} u(N, j - 1) - \sigma(j - 1) + u(i, j - 1) + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)]
\]
\[
\sum_{i=1}^{N-1} C(i, j - 1)
\]

For \( i = 1 \),
\[
u(i - 1, j - 1) = u(i + 1, j - 1)
\]

For all time during equalization, \( u(N, j) \) is equal to the applied negative pressure at node \( N \) (i.e., \( u(N, j) = -1 \) bar). Adding those \( N-1 \) equations together gives,
\[
\sum_{k=1}^{N-1} \sum_{k=1}^{N-1} C(k, j - 1)
\]

which yields,
\[
\sum_{k=1}^{N} C(k, j - 1) = \frac{\frac{N}{\delta + N(1 - \delta)} + u(N, j)}{\delta + N(1 - \delta)}
\]

Substituting Eq. (B1.9) into Eq. (B1.6) gives,
\[
\sigma(j) = \frac{\delta}{N} \left[ \frac{N}{\delta + N(1 - \delta)} + u(N, j) \right]
\]

Combining Eqs. (B1.7), (B1.8), and (B1.10) gives,
\[
u(i, j) = \frac{\delta}{N} \frac{N}{\delta + N(1 - \delta)} \sum_{k=1}^{N-1} C(k, j - 1) + C(i, j - 1)
\]
\[
\sum_{k=1}^{N-1} C(k, j - 1) + C(i, j - 1)
\]

\[
i = 1, 2, \ldots \ldots N - 1
\]
Hence values at time \( j \) can be calculated from values at time \( j-1 \). The procedure repeats until a satisfactory convergence is reached.
Appendix B2: Response with the Impedance of Ceramic

Equation (B.10) is applicable for the case of an incompressible ceramic,

\[ u_t = u_0 - \frac{u_b - u_a}{H} z \]  
(B2.1)

Equation (B.8) can be written as (see Fig. B2.1),

\[ k_s \frac{u_b - u_a}{\Delta z} = k_c \frac{u_c - u_b}{\Delta z} \]

or

\[ k_s (u_b - u_a) = k_c (u_c - u_b) \]  
(B2.2)

At \( z = H_c - \Delta z \), Eq. (B2.1) yields,

\[ u_c = u_0 - \frac{u_b - u_a}{H_c} (H_c - \Delta z) \]  
(B2.3)
Substituting Eq. (B2.3) into Eq. (B2.2) and solving for \( u_b \) gives,

\[
  u_b = \frac{u_o + \lambda u_o}{1 + \lambda} \tag{B2.4}
\]

where:

\[
  \lambda = \frac{k_e \Delta z}{H_c} = \text{impedance factor of the ceramic.} \tag{B2.5}
\]

Adopting the notations as used in Appendix B1, the relationship between the induced pore-water pressures at nodes \( N-1 \) and \( N \) with the applied suction is expressed as:

\[
  u(N, j) = \frac{u(N - 1, j) + \lambda u_o}{1 + \lambda} \tag{B2.6}
\]

where:

\[
  u_o = u(N, j - 1) = u(N, j) = \text{constant}
\]

Therefore, Eq. (B1.7) can be rewritten as:

\[
  u(i, j) = \frac{\delta}{N} \sum_{k=1}^{N-1} u(k, j) + \frac{\delta}{N} \frac{u(N - 1) + \lambda u_o}{1 + \lambda} - \sigma(j - 1) + u(i, j - 1)
  + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)]
  = \frac{\delta}{N} \sum_{k=1}^{N-2} u(k, j) + \frac{\delta}{N} u(N - 1, j) + \frac{\delta}{N(1 + \lambda)} u(N - 1, j)
  - \sigma(j - 1) + u(i, j - 1) + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)]
  = \frac{\delta}{N} \sum_{k=1}^{N-2} u(k, j) + \frac{\delta(2 + \lambda)}{N(1 + \lambda)} u(N - 1, j) + C(i, j - 1) \tag{B2.7}
\]

where:

\[
  C(i, j - 1) = C(i, j - 1) = \frac{\delta \lambda}{N(1 + \lambda)} u_o - \sigma(j - 1) + u(i, j - 1)
  + \beta[u(i + 1, j - 1) + u(i - 1, j - 1) - 2u(i, j - 1)] \tag{B2.8}
\]
Substituting Eq. (B2.8) into Eq. (B2.7) gives,

\[ N \cdot u(i, j) = \delta \sum_{k=1}^{N-2} u(k, j) + \frac{\delta(2+\lambda)}{N(1+\lambda)} u(N-1, j) + N \cdot C(i, j-1) \]

or

\[ \delta \sum_{k=1}^{N-2} u(k, j) - N \cdot u(i, j) + \frac{\delta(2+\lambda)}{1+\lambda} u(N-1, j) = -N \cdot C(i, j-1) \quad (B2.9) \]

\[ i = 1, 2, \ldots, N-1 \]

There are \( N-1 \) linear equations which can be solved simultaneously. These equations can be expressed in a matrix form,

\[ [A][u] = [C^*] \quad (B2.10) \]

and

\[ [u] = [A]^{-1}[C^*] \quad (B2.11) \]

where:

\[
A = \begin{bmatrix}
\delta - N & \delta & \cdots & \delta & \frac{\delta(2+\lambda)}{1+\lambda} \\
\delta & \delta - N & \cdots & \delta & \frac{\delta(2+\lambda)}{1+\lambda} \\
\vdots & \cdots & \cdots & \cdots & \frac{\delta(2+\lambda)}{1+\lambda} \\
\delta & \delta & \cdots & \delta - N & \frac{\delta(2+\lambda)}{1+\lambda} \\
\delta & \delta & \cdots & \delta & \delta(2+\lambda) - N \\
\end{bmatrix}
\]

\[
u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_{N-2} \\ u_{N-1} \end{bmatrix} \text{ for time } j
\]
\[
[C^*] = -\begin{bmatrix}
C_1 \\
C_2 \\
\vdots \\
C_{N-2}
\end{bmatrix}
\] for time \(j\)

The matrix, \([A]\), is a constant matrix at all times. The step-forward solution starts with the initial and boundary conditions in calculating \([C^*]\) when \(t\) is equal to zero,

\[
u(i,0) = 0, \quad i = 1,2,\ldots N-1
\]

and

\[
u(N,0) = \frac{\lambda}{1+\lambda} u_o
\]

At time number \(j\), Eq. (B2.11) is solved, based on the results of the previous step. Then \([C^*]\) at this time \(j\) is calculated from Eq. (B2.8). Solutions for time \(j+1\) can again be obtained from Eq. (B2.11). The procedure continues on until a satisfactory convergence is achieved.
APPENDIX C

Vapor Diffusion Through the Aluminum Foil during the Measurement of Soil Suction
C.1. ANALYSIS OF VAPOR DIFFUSION THROUGH THE ALUMINUM FOIL

C.1.1. Fick's law

The diffusion rate of water vapor through the aluminum foil is described by the Fick's first law:

\[ J = -D \frac{\partial c}{\partial x} \]  \hspace{1cm} (C.1)

where:

\( J \) = mass flux through unit cross-sectional area within unit time \((g/s \cdot L^2)\)

\( D \) = coefficient of diffusion \((L^2/s)\)

\( c \) = mass concentration of vapor \((g/L^3)\)

The conservation of mass gives Fick's second law for transient diffusion:

\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \]  \hspace{1cm} (C.2)

The total pressures on both sides of the aluminum foil are equal to the atmospheric pressure. The vapor flux across the foil, therefore, is only due to the vapor pressure gradient across the foil. On the inside is the vapor pressure, \( p_i \), of the soil which corresponds to a relatively humidity above 98%. On the outside is the vapor pressure, \( p_o \), under atmospheric condition which corresponds to a relative humidity from about 30 to 60%.

Figure C.1 shows the development of vapor concentration across the thickness of the aluminum foil. At time of \( t_s \), the steady state diffusion is reached. It is assumed that the concentration gradient is the same across the foil for the steady state diffusion. Then,

\[ c = c_o + c_1 x \]  \hspace{1cm} (C.3)

at \( x = 0 \), \( c = c_s \), then \( c_o = c_s \), and

at \( x = d = \text{the thickness of the foil} \), then \( c_1 = (c_o - c_s) / d \). Therefore,
\[ c = c_i + \frac{c_s - c_i}{d} x \]  \hfill (C.4)

Fig. C.1 Profiles of Vapor Concentration Across the Aluminum Foil

From Eq. (C.1),

\[ J = D \frac{c_i - c_s}{d} \]  \hfill (C.5)

From the ideal gas law,

\[ c = \frac{p}{RT} \]  \hfill (C.6)

where:

\[ p = \text{partial vapor pressure}, \]

\[ R = \text{molar gas constant for water (}=461 \text{ J/kg.K}), \text{ and} \]

\[ T = \text{temperature}. \]

Substituting Eq. (C.6) into Eq. (C.5) gives,

\[ J = \frac{D}{RTd} (p_i - p_s) \]  \hfill (C.7)

The term, \( p_i \), can be calculated from the relative humidity, RH, in the soil. The relative humidity, RH, can be calculated from the total suction of the soil. The total suction is equal to the measured matric suction plus the osmotic suction which was estimated to be from about 200 to 400 kPa for a wide range of water contents for the glacial till (Krahn, 1970). The term,
$p_e$, can be estimated from the relative humidity, RH$_a$, of atmosphere. The relationship between the total suction, $\varphi$, and vapor pressure is,

$$p = p_e e^{\frac{\varphi}{R' T}}$$  \hspace{1cm} (C.8)

where:

$p_e$ = saturation vapor pressure (about 2.3 kPa, at 20°C), 

$R'$ = specific molar gas constant for water.

at 20°C, $R'T = 134,948$ kPa.

The relative humidity can be expressed as,

$$RH = \frac{p}{p_e} = e^{\frac{\varphi}{R'T}}$$  \hspace{1cm} (C.9)

Substituting Eq. (C.9) into Eq. (C.7) gives,

$$J = \frac{D}{RTd} p_e (RH - RH_a)$$  \hspace{1cm} (C.10)

C.1.2. Coefficient of diffusion, $D$

No data of the coefficient of diffusion of water vapor through aluminum under room temperature was found in literature. It is generally believed that no gas can physically permeate any metal, except at high temperatures (e.g., over 250°C) and under high pressure gradients (Smithells, 1937; Norton, 1957). Most gas-metal diffusion measurements were performed on hydrogen that has a small molecule size. It was also found that the surface condition of the same metal could produce a difference of one order of magnitude in the diffusion rate (Smithells, 1937) of a gas. Other major factors affecting the gas-metal diffusion may include the pressure level and the impurities in the metal.

Generally, the following equation can be used to approximate the relationship between $D$ and temperature, $T$, (°C) (Norton, 1937),
\[ D = a \cdot e^{\frac{b}{T}} \]  

(C.11)

where:

\( a, b \) = constants

Equation (C.11) was used only to fit the values of \( D \) measured at high temperatures. The relationship between the rate of diffusion and temperature at low temperature (e.g., lower than 250°C) is not known. It is assumed that Eq. (C.11) can be used to estimate the value of \( D \) at room temperature.

The value of \( D \) for water vapor diffusion through aluminum is not available in literature. The approximate value of \( D \) for water vapor diffusion through aluminum can be probably estimated from the measured values of \( D \) for water vapor through copper.

Porter (1929) gave the values of \( D \) of hydrogen through copper as listed in Table C.1. Substituting the values into Eq. (C.11) gives,

\[ \begin{align*}
  a &= 6.323 \times 10^{-3} \text{ cm}^2/\text{s} \\
  b &= 1447 \, ^\circ\text{C}
\end{align*} \]

Table C.1 The coefficient of Diffusion \( D \) for Hydrogen-Copper

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>D (10^{-6} \text{ cm}^2/\text{s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.5</td>
</tr>
<tr>
<td>700</td>
<td>8</td>
</tr>
</tbody>
</table>

The value of \( D \) for hydrogen-copper at 20°C is then estimated to be \( 2.397 \times 10^{-36} \text{ cm}^2/\text{s} \).

At 700°C, the value of \( D \) for water vapor through copper was found to be about 0.065 times the value for hydrogen through copper (Porter, 1929). The value of \( D \) for water vapor through copper at 20°C is, therefore, estimated to be about \( 1.558 \times 10^{-37} \text{ cm}^2/\text{s} \).

The value of \( D \) for hydrogen-copper was smaller than the value of \( D \) for Hydrogen-aluminum by about one to two orders of magnitude (Smithells, 1937). It is assumed that the
same conclusion was also valid when the diffusing gas is the water vapor. Therefore, the upper-value of $D$ for water vapor through aluminum at 20°C is estimated to be in the order of $10^{-17}$ cm$^2$/s.

An extreme upper-estimation is to assume that the value of $D$ at 20°C is close to the value of $D$ at 250°C. The extreme upper-value for $D$ at 20°C is then estimated to be about $10^{-9}$ cm$^2$/s.

Table C.2 gives the estimations of $J$ and the total flux $Q$ across the aluminum foil covering the glacial till prepared at a water content of 11.0% (degree of saturation is 43% and the measured matric suction is about 950 kPa). The surface area of the aluminum foil used in the measurement of matric suction is about 227 cm$^2$. Other values of parameters are as follows,

$$d = 0.0001 \text{ m, } \varphi = 950 + 400 = 1350 \text{ kPa, } p_o = 2.3 \text{ kPa} = 2.3 \times 10^3 \text{ J/m}^3$$

$$\text{RH}_f = 0.990, \text{ RH}_s = 0.3, T = 293 \text{ K}$$

therefore,

$$\frac{(\text{RH}_f - \text{RH}_s) p_o}{RTd} = 1.1834 \times 10^{-3} \text{ g/cm}^4$$

**Table C.2 Estimation of Vapor Flux Across the Aluminum Foil**

<table>
<thead>
<tr>
<th>$D$ (cm$^2$/s)</th>
<th>$J$ (g/s.cm$^2$)</th>
<th>$Q$ (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9}$</td>
<td>$1.183 \times 10^{-12}$</td>
<td>$2.68 \times 10^{-10}$</td>
</tr>
<tr>
<td>$10^{-34}$</td>
<td>$1.183 \times 10^{-37}$</td>
<td>$2.68 \times 10^{-35}$</td>
</tr>
</tbody>
</table>

C.2 EFFECT OF VAPOR DIFFUSION ON SUCTION MEASUREMENT.

The effect of steady state vapor diffusion on matric suction in the glacial till can be estimated by doing the following calculations:

1.) Drift in suction reading
Figure C.2 shows the measurement of matric suction in glacial till prepared at a water content of 11.0%. The rate of drift at time close to the end of measurement is less than 0.132 kPa/min.

2.) Change in water content due to vapor diffusion

According Table C.2, the possible maximum rate of moisture loss due to vapor diffusion is about $1.61 \times 10^{-8}$ g/min. The dry mass of the specimen is 258 g. Therefore, the maximum rate of change in water content due to vapor diffusion is about $6.24 \times 10^{-9}$%/min.

3.) Change in matric suction due to reduction in water content.

The change of matric suction due to loss of water from the soil can be calculated from the soil-water characteristic curve (i.e., SWCC) for this specific soil specimen. Strictly speaking, the SWCC for the glacial till is not available. However, Krahn (1970) found that the matric suction of the glacial till is mainly dependent on the water content. Therefore, a plot of measured matric suction with respect to water content can be used to approximately represent the SWCC for the glacial till. Fig. C.3 shows the values of matric suction measured at approximate equilibrium versus the water content for the glacial till, using the suction probe and the null-pressure plate.

Figure C.3 shows that the slope of the SWCC is about 500 kPa /% at a water content round 11.0%. Therefore, the corresponding rate of change in measured tension due to vapor diffusion should be equal to,

$$\Delta P = 6.24 \times 10^{-9} \times 500 = 3.12 \times 10^{-6} \text{ kPa/min}$$

This is the extreme upper-estimation of the state-steady drift rate in matric suction, or in the measured tension, due to the vapor diffusion through the aluminum foil cover. This value is extremely small compared to the actual drift in the suction reading. Therefore, it is concluded that the drift in suction reading during the measurement is not due to the vapor flux across the aluminum foil.
Fig. C.2 Matric Suction Measurements on the Compacted Glacial Till Prepared at $S$ Equal to 43.7%, Using the Suction Probe with the No. 4 Ceramic
Fig. C.3 Measured Matric Suction Versus Water Content for the Glacial Till Using the Suction Probe
APPENDIX D

Determination Of Equilibrium Using The Logarithm Of Time Scale
Table D.1 Determination of Matric Suction for Regina Clay Using the Logarithm of Time Scale

<table>
<thead>
<tr>
<th>Condition of Contact</th>
<th>Pre-Applied Matric Suction (kPa)</th>
<th>Measured Matric Suction (kPa)</th>
<th>Approximate Time for Equilibrium (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using Paste</td>
<td>200</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>310</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>405</td>
<td>330</td>
</tr>
<tr>
<td>Direct Contact</td>
<td>150</td>
<td>147</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>180</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>245</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>280</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>330 (350)</td>
<td>100 (450)</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>385</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>440</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>475</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>505 (550)</td>
<td>180 (1000)</td>
</tr>
</tbody>
</table>

Note: The data in brackets are determined from tension curves measured over 3 days (Fig. D.3)
Table D.2 Determination of Matric Suction for Silt Using the Logarithm of Time Scale

<table>
<thead>
<tr>
<th>Pre-Applied Matric Suction (kPa)</th>
<th>Measured Matric Suction (kPa)</th>
<th>Approximate Time for Equilibrium (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>160</td>
<td>120</td>
</tr>
<tr>
<td>150</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>190</td>
<td>140</td>
</tr>
<tr>
<td>300</td>
<td>280 (300)</td>
<td>260 (800)</td>
</tr>
<tr>
<td>400</td>
<td>Equilibrium not evident</td>
<td></td>
</tr>
</tbody>
</table>

Note: The data in bracket is determined from the tension curve measured over 3 days (Fig. D.3)
<table>
<thead>
<tr>
<th>$\rho_d$ (Mg/m³), w (%) , and S (%) (Designed)</th>
<th>S after Tests (%)</th>
<th>ΔS during Tests (%)</th>
<th>Matric Suction (kPa)</th>
<th>Approximate Time for Equilibrium (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.80, 16.3, 86.6</td>
<td>87.2</td>
<td>0.2</td>
<td>73</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>87.7</td>
<td>0.4</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>1.78, 15.0, 77.4</td>
<td>77.3</td>
<td>0.8</td>
<td>172</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>76.8</td>
<td>1.1</td>
<td>175</td>
<td>4</td>
</tr>
<tr>
<td>1.73, 13.0, 61.3</td>
<td>60.4</td>
<td>0.7</td>
<td>320</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>61.5</td>
<td>0.8</td>
<td>321</td>
<td>4</td>
</tr>
<tr>
<td>1.66, 11.5, 48.7</td>
<td>48.1</td>
<td>0.5</td>
<td>813</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>48.8</td>
<td>0.4</td>
<td>761</td>
<td>24</td>
</tr>
<tr>
<td>1.61, 11.0, 43.7</td>
<td>43.4</td>
<td>0.3</td>
<td>950*</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>43.2</td>
<td>0.2</td>
<td>907*</td>
<td>15</td>
</tr>
</tbody>
</table>

*: Equilibrium not evident
Fig. D.1 Re-Plot of Fig. 5.22 Using the Logarithm of Time Scale (see Table D.1)
Fig. D.2 Re-Plot of Fig. 5.23 Using the Logarithm of Time Scale (see Table D.1)
Fig. D.3 Re-Plot of Fig. 6.9 Using the Logarithm of Time Scale (see Tables D.1 and D.2)
Fig. D.4 Re-Plot of Fig. 5.24 Using the Logarithm of Time Scale (see Table D.2)
Fig. D.5 Re-Plot of Fig. 5.31 Using the Logarithm of Time Scale (see Table D.3)
Fig. D.7 Re-Plot of Fig. 5.33 Using the Logarithm of Time Scale (see Table D.3)